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Groundwater-Level Decline and Quality Degradation in Libya: Drivers, Coastal Salinization, and Managed Recharge Options

Tarq Rahoumah[1]* | Eklas Almoushem[1]

[1]Libyan Centre for Research and Studies of Water, Soil and Combating Desertification, Sabratha, Libya.

ABSTRACT

Purpose: This study synthesizes the principal causes, manifestations, and management options associated with groundwater-level decline and quality deterioration in Libya, with emphasis on the coastal aquifers of the Jifarah Plain and the wider northwestern region.

Materials and Methods: A structured narrative review was undertaken using the supplied 46-page Arabic study as the primary source, supplemented by peer-reviewed Libyan hydrogeological studies and established guidance on seawater intrusion, drinking-water safety, and managed aquifer recharge. Historical electrical-conductivity observations reported for five coastal localities between 1979 and 2002 were transcribed and compared descriptively. No new field sampling or statistical inference was performed.

Results: The source material documents strong historical increases in electrical conductivity at Sorman, Zawiya, Qarqarish, Souq Al-Jumaa, and Tajoura. At the four sites with complete 2002 records, conductivity rose from 1979 values by approximately 95% to 510%. Independent studies of the Jifarah Plain also identify intensive abstraction, seawater intrusion, and upconing of deeper saline water as major drivers of deterioration. Managed recharge may support hydraulic recovery, but only where hydrogeological suitability, source-water quality, and clogging risks are rigorously assessed.

Conclusions: Libya's groundwater challenge requires demand management and protection of aquifers before reliance on recharge infrastructure. A staged programme combining abstraction control, monitoring, wastewater treatment, fit-for-purpose reuse, and carefully piloted managed aquifer recharge offers the most defensible pathway. The historical dataset should not be interpreted as a current status assessment. *(J Multidiscip Eng 2026;1:110-117)*

Keywords: Libya, groundwater depletion, seawater intrusion, groundwater quality.

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*Corresponding author:
Tarq Rahoumah
Email: tarqabwalgasm2@gmail.com

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1. INTRODUCTION

Groundwater is a strategic source of freshwater in arid and semi-arid environments because surface-water resources are limited, intermittent, and unevenly distributed. In Libya, the scarcity and irregularity of rainfall, together with the concentration of population and economic activity along the Mediterranean coast, have made groundwater central to domestic supply, agriculture, and industry. The supplied national study describes groundwater as providing more than 95% of total water use in the period addressed by that document; this figure is retained as a

historical statement from the source rather than treated as a verified current national statistic.[1]

The sustainability of an aquifer depends on the balance between recharge and abstraction, as well as on the hydraulic and geochemical conditions that govern groundwater movement. Where pumping persistently exceeds replenishment, groundwater heads decline, pumping costs increase, shallow wells may become unusable, and hydraulic gradients can reverse. In coastal aquifers, the reduction of freshwater discharge towards the sea weakens the natural hydraulic barrier that limits saline-water movement. Salinity may then increase through lateral seawater intrusion, vertical upconing of deeper saline groundwater, or mobilization of salts from coastal sabkhas and evaporitic formations. These mechanisms are well documented in the Jifarah Plain and other coastal aquifers.[2]

The problem is not limited to water quantity. The source study reports historical deterioration in electrical conductivity along the northwestern coast, while subsequent investigations in the Tripoli–Jifarah system identify chloride-rich water, cation exchange, and multiple sources of salinity. Recent work in Tajoura likewise reports widespread salinization and unsuitable groundwater for direct drinking in the sampled area.[3]

This paper therefore aims to: (i) synthesize the hydrogeological setting and principal groundwater pressures reported for Libya; (ii) examine historical coastal water-quality trends without presenting them as current measurements; (iii) distinguish the main mechanisms of salinization and contamination; and (iv) evaluate practical management options, particularly managed aquifer recharge (MAR), within a preventive and risk-based framework.

2. MATERIALS AND METHODS

2.1. Study design and evidence base

The paper is a narrative technical review and evidence synthesis, not a new field investigation. Its primary source is the supplied Arabic study, which compiles national hydrogeological descriptions, historical groundwater-level observations, coastal electrical-conductivity records, and proposed artificial-recharge methods. The source was reviewed in full and its quantitative tables and recommendations were extracted. To contextualize and check the interpretation, peer-reviewed studies focused on the Jifarah Plain and Tajoura were consulted, together with international guidance on seawater intrusion, managed aquifer recharge, and drinking-water safety.[3-5]

2.2. Historical data extraction and treatment

The original study reports electrical conductivity (EC) measurements for five coastal localities Sorman, Zawiya, Qarqarish, Souq Al-Jumaa, and Tajoura for 1979, 1992, 1995, and 2002. Values were transcribed as reported in microsiemens per centimetre (µS/cm). The 2002 value for Qarqarish is missing in the source and was not estimated. Percentage change was calculated only for localities with complete 1979 and 2002 records, using $[(EC_{2002} - EC_{1979})/EC_{1979}] \times 100$. No inferential statistics were applied because the original sampling design, analytical uncertainty, and well-by-well metadata are not sufficiently documented.

2.3. Review scope and limitations

The synthesis prioritizes evidence directly relevant to Libyan aquifers, especially the northwestern coastal system. Historical national figures and measurements are reported with their original dates and are not extrapolated to the present. The source manuscript does not provide a reproducible sampling protocol, complete laboratory records, or a fully traceable bibliography for all historical observations. Consequently, the numerical results are interpreted as documentary evidence of past trends, while contemporary status must be established through updated field monitoring.[6]

3. HYDROGEOLOGICAL CONTEXT AND PRESSURES

3.1. Climate, water resources, and aquifer systems

Libya has a predominantly arid climate. The supplied study states that annual rainfall is below

100 mm over approximately 96% of the country, with higher but spatially variable rainfall in northern coastal areas. Surface-water flow is largely episodic and concentrated in seasonal wadis; the source estimates that potentially usable annual runoff from these wadis does not exceed about 200 million m³. These conditions constrain natural recharge and increase dependence on groundwater.

The national aquifer framework is heterogeneous. Northern basins include shallow and deeper systems in Quaternary, Tertiary, and Cretaceous formations that may receive modern recharge from rainfall and runoff. Large sedimentary basins in central and southern Libya contain extensive groundwater reserves, much of which accumulated during wetter climatic periods and is effectively non-renewable on human planning timescales. The distinction between renewable and fossil groundwater is essential: large stored volumes do not imply that abstraction can be sustained indefinitely.

In northwestern Libya, the Jifarah Plain contains a complex Upper Miocene–Pliocene–Quaternary aquifer system with variable sandstone, limestone, marl, clay, and silt units. The coastal and inland parts differ in lithology, hydraulic connectivity, and salinity sources. Published hydrochemical work identifies intensive pumping, seawater intrusion, and upward movement of deeper saline water as major controls on groundwater quality.[7]

3.2. Groundwater abstraction and water-balance imbalance

The primary pressure identified in the source material is abstraction exceeding natural recharge. Irrigation is a major demand driver in the coastal plain, while urban and industrial demand adds further pressure. Persistent overdraft lowers groundwater levels and may create localized cones of depression around well fields. In the coastal zone, declining freshwater heads reduce the seaward hydraulic gradient and can allow saline water to move inland. In inland areas, drawdown may induce saline water from deeper formations or adjacent sabkhas to enter previously fresher aquifers.

Groundwater depletion is therefore not simply a reduction in stored volume. It changes flow directions, increases the risk of salinity migration, raises pumping energy requirements, and can progressively reduce the recoverable freshwater fraction. Recovery after abstraction is reduced may be slow, particularly where aquifers have low transmissivity, limited recharge, or large-scale drawdown.

4. HISTORICAL WATER-QUALITY EVIDENCE

4.1. Electrical-conductivity trends along the northwestern coast

The historical EC dataset in the source study shows a consistent increase at the five monitored coastal localities over the period 1979–2002, although the magnitude varies substantially by site. Sorman increased from 1,490 to 5,500 µS/cm; Zawiya from 812 to 1,585 µS/cm; Souq Al-Jumaa from 1,032 to 4,160 µS/cm; and Tajoura from 938 to 5,720 µS/cm. Qarqarish increased from 1,496 µS/cm in 1979 to 3,100 µS/cm in 1995, but no 2002 value is reported (Fig 1).[8]

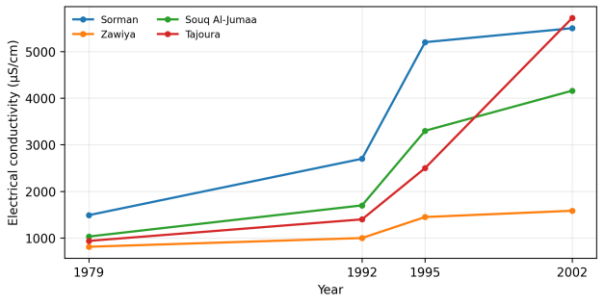


Fig. 1. Historical EC trends at four coastal localities with complete 1979–2002 records; Qarqarish is excluded from the plot because its 2002 value is unavailable.

The calculated increase between 1979 and 2002 was approximately 269% at Sorman, 95% at Zawiya, 303% at Souq Al-Jumaa, and 510% at Tajoura. These percentages are descriptive comparisons of the values printed in the source table; they do not establish that seawater intrusion was the only cause. EC is a useful screening indicator of total ionic content, but it is not a substitute for major-ion analysis, chloride/

bicarbonate ratios, isotopes, or a spatially controlled monitoring network.

4.2. Evidence from later investigations

Independent studies provide stronger process-based evidence for the Jifarah Plain. Al Farrah and colleagues analyzed groundwater from 134 wells and reported that most samples displayed hydrochemical compositions indicative of seawater intrusion; the dominant water types included CaCl, NaCl, and mixed Ca/Mg types, consistent with freshwater–seawater mixing and cation-exchange reactions.[1] A later regional assessment reported high EC and chloride, drawdown cones, and groundwater heads reaching substantially below mean sea level in parts of Tripoli, with both seawater intrusion and upconing of deeper saline water contributing to degradation.

A study of 26 wells in Tajoura based on 2021 sampling reported that most samples were sodium-chloride type and that approximately 70% were strongly affected by saline water according to chloride-related indicators. It also identified local wastewater disposal and car-wash activities as additional potential sources of deterioration.[4] These findings underline the need to distinguish marine salinization from urban and agricultural contamination rather than treating all increases in salinity as a single process.

4.3. Salinity sources and suitability for use

The principal salinity mechanisms include lateral seawater intrusion, vertical upconing of deeper saline groundwater, dissolution of evaporitic minerals, and interaction with sabkha deposits. Human-derived contaminants may include nitrate from fertilizers and wastewater, as well as microbial and organic contaminants associated with inadequate sanitation. A defensible assessment therefore requires a multi-parameter program including groundwater levels, EC, total dissolved solids, chloride, sodium, calcium, magnesium, sulphate, bicarbonate, nitrate, pH, and microbiological indicators where relevant.

Water suitability must be determined for each intended use. Drinking-water assessment should follow current national requirements and the latest WHO guidance, with health-based risk management rather than reliance on EC alone. Irrigation suitability requires evaluation of salinity and sodicity, including electrical conductivity and sodium adsorption ratio, alongside crop tolerance, soil drainage, and leaching conditions.[6]

5. THEORY AND MANAGEMENT FRAMEWORK

5.1. Groundwater balance and coastal hydraulic control

At the aquifer scale, the change in groundwater storage can be represented conceptually as:

$$\Delta S = R + I - P - D$$

Equation (1). Simplified groundwater-storage balance, where R is recharge, I is lateral inflow, P is pumping, and D is natural discharge and other outflows.

When pumping persistently exceeds recharge and inflow, storage declines. In coastal aquifers, maintaining freshwater heads above sea level and preserving a seaward hydraulic gradient are central to limiting seawater intrusion. Pumping reductions, relocation of production wells, seasonal operating limits, and distributed abstraction can reduce local drawdown. A subsurface freshwater pressure barrier may be considered only after numerical modelling and pilot testing establish that it is hydraulically effective and does not mobilize contaminants.

5.2. Managed aquifer recharge options

Managed aquifer recharge is the intentional addition of water to an aquifer for subsequent recovery, environmental benefit, or hydraulic control. It can be implemented through surface spreading basins, infiltration trenches and pits, recharge shafts, injection wells, or induced bank filtration (Fig 2). The source study discusses these methods and emphasizes that the choice depends on the aquifer sequence, permeability, depth to groundwater, morphology, and the objective of recharge.[9,10]

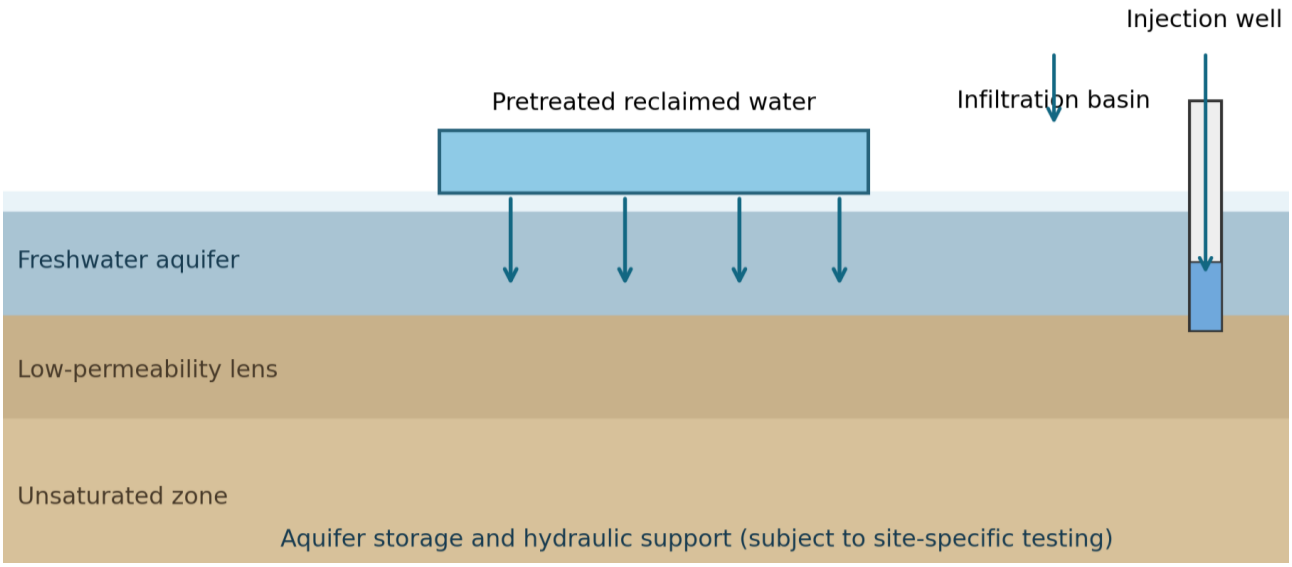


Fig. 2. Conceptual illustration of managed recharge through a surface infiltration basin and an injection well. The figure is schematic and is not a site design.

Surface spreading is generally appropriate where permeable soils and sufficient land are available. Pits and shafts may be useful where land is limited or where shallow low-permeability layers restrict vertical infiltration. Injection wells can deliver water directly to a selected aquifer but are more technically demanding and vulnerable to clogging, geochemical incompatibility, and operational failure. Induced bank filtration can capture surface water through aquifer sediments where a suitable river or lake connection exists.

5.3. Source-water quality and clogging control

Recharge water must be fit for the receiving aquifer and the intended recovery use. Treated wastewater should not be injected or infiltrated solely because it meets an effluent discharge standard. A site-specific risk assessment should evaluate pathogens, nutrients, trace chemicals, salinity, suspended solids, dissolved gases, and the potential for geochemical reactions. Changes in pH, redox conditions, oxygen content, or ionic composition can trigger mineral precipitation or dissolution and alter aquifer permeability.[9,10]

Physical clogging by suspended particles, biological clogging by microbial growth, and chemical clogging by mineral precipitation can reduce infiltration rates or injection-well capacity. Preventive measures include pretreatment, filtration, sedimentation, controlled loading rates, alternating wetting and drying where appropriate, periodic basin scraping, well redevelopment, and continuous monitoring of injection pressure and water levels. Chlorination alone is not a complete solution and must be evaluated against the water-quality and aquifer-protection objectives.

5.4. Site-selection and feasibility criteria

A recharge scheme should proceed only after a staged investigation. The minimum assessment should include:

• Geological and geophysical characterization of aquifer geometry, confining layers, fractures, and potential preferential pathways.

• Hydrogeological testing to estimate hydraulic conductivity, transmissivity, storage properties, groundwater gradients, and seasonal head fluctuations. [11]

• Baseline groundwater-quality mapping, including major ions, nutrients, trace contaminants, and microbiological parameters appropriate to the source water.

• Assessment of land availability, source-water

reliability, pretreatment needs, energy demand, operating costs, and the ability to recover stored water.

• A calibrated groundwater-flow and solute-transport model to test pumping controls, recharge rates, barrier configurations, and potential impacts on neighboring users.[11]

Recharge should be avoided in sabkha areas or other settings where infiltration could mobilize highly saline porewater, unless a detailed assessment demonstrates that the risks can be controlled. It should also be avoided where the water table is too shallow, where karst conduits could permit rapid contaminant transport, or where the receiving aquifer cannot be adequately monitored.

6. RESULTS AND DISCUSSION

6.1. Interpretation of the evidence

The evidence converges on a coupled quantity–quality problem. Excessive abstraction lowers freshwater heads; in coastal settings this weakens the hydraulic barrier against seawater and may promote upconing of saline groundwater. At the same time, urban wastewater, agricultural inputs, and local industrial activities can introduce contaminants unrelated to marine intrusion. Consequently, an effective response must address both pumping and pollution sources.[12]

The historical EC series is useful because it shows that deterioration was already evident across several northwestern coastal localities by 2002. However, its age and limited metadata prevent its use as a contemporary baseline. The observed increases are consistent with the published interpretation of progressive salinization, but they should not be treated as a direct measure of current seawater-front position or as proof of a single causal mechanism. Contemporary monitoring must repeat measurements at georeferenced wells and include ionic and isotopic tracers capable of separating seawater mixing, evaporite dissolution, and wastewater influence.

In addition to groundwater management and aquifer protection measures, recent experimental research has examined electromagnetic treatment as a potential approach for reducing the salinity of extracted groundwater. One laboratory study investigated a treatment system combining aluminum electrodes with an applied magnetic field under controlled operating conditions. The results showed a reduction in total dissolved solids (TDS) from 30,633.3 ppm to 20,738.3 ppm after three hours of treatment, representing a decrease of approximately 32.3%. The study also reported reductions in electrical conductivity, total hardness, and the concentrations of major dissolved ions. X-ray diffraction (XRD) analysis identified the resulting precipitates as being composed mainly of sodium chloride (NaCl) and calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). These findings indicate the potential of electromagnetic treatment as a complementary option for improving the quality of saline groundwater after extraction. However, the results were obtained under laboratory conditions and do not establish the technique's effectiveness under field conditions or its ability to prevent seawater intrusion within coastal aquifers. Further investigations are therefore needed to evaluate long-term performance, electrode fouling, energy requirements, operational costs, and treatment efficiency at pilot scale before considering wider implementation.[13]

6.2. Management priorities for Libya

The first priority is demand-side control. Abstraction permits, metering, well inventories, seasonal pumping limits, and enforcement against uncontrolled drilling are prerequisites for any durable recovery. Agricultural demand should be addressed through irrigation scheduling, leakage reduction, crop selection suited to local water availability, and reuse of appropriately treated wastewater where soil and crop conditions permit.

The second priority is protection of groundwater quality. Sewerage collection and treatment, control of unlined wastewater ponds, safe disposal of industrial effluents, and nutrient management are necessary to prevent further contamination. Production wells should be protected by sanitary setbacks and routine testing, while high-risk wells should be removed from drinking-water service until their safety is

demonstrated.

The third priority is a national monitoring and information system. A coordinated network should measure groundwater levels and EC at regular intervals, with seasonal sampling for major ions and selected contaminants. Data should be stored in a shared geospatial database, quality-assured, and used to update potentiometric maps, salinity maps, and abstraction budgets. Early-warning thresholds should be defined for water-level decline, chloride increase, and EC change.

6.3. A phased managed-recharge program

MAR should be treated as a complementary supply-management instrument, not as a substitute for reducing abstraction. A practical sequence for Libya is:

• **Phase 1-** diagnosis: select candidate aquifers using water-level trends, hydrochemistry, lithology, land use, and source-water availability; exclude unsuitable sites.

• **Phase 2-** pilot design: compare infiltration basins, pits/shafts, and injection wells using site-specific tests and a calibrated groundwater model.

• **Phase 3-** water-quality assurance: establish treatment barriers and operational limits based on source-water risk, receiving-aquifer vulnerability, and intended recovery use.

• **Phase 4-** controlled operation: begin at conservative recharge rates, monitor heads and water quality, and inspect for clogging or unexpected geochemical changes.

• **Phase 5-** evaluation and scale-up: assess water recovery, storage efficiency, salinity response, environmental impacts, and lifecycle costs before expansion.

In coastal Jifarah, recharge may help maintain freshwater heads and reduce the inland movement of saline water if it is placed and operated correctly. Nevertheless, the design of a freshwater hydraulic barrier requires careful control of injection rates, well spacing, depth intervals, and the quality and density of injected water. Poorly designed recharge can instead cause waterlogging, mobilize saline water, or create new contamination pathways. The literature therefore supports a cautious, monitored, site-specific approach rather than a uniform national design.[7]

6.4. Research gaps and future work

The available material highlights several gaps: the historical monitoring record is fragmented; current abstraction volumes and well inventories are not consistently available in the source material; the effects of climate variability and sea-level rise are not quantified for each aquifer; and the feasibility of individual MAR sites has not been

Demonstrated through pilot operation. Future studies should establish a contemporary baseline, combine groundwater-level and hydrochemical monitoring with geophysical surveys, and develop transient density-dependent flow and transport models for priority coastal aquifers.

A further research need is the evaluation of treated wastewater as a recharge source under local conditions. This requires source-specific hazard identification, advanced treatment where necessary, compatibility testing, microbial risk assessment, and long-term monitoring. The objective should be to protect aquifer quality while determining whether reclaimed water can safely support irrigation, environmental flows, or indirect potable reuse under a regulated framework.

7. CONCLUSION

Groundwater depletion and quality degradation in Libya are closely linked, particularly in the northern coastal aquifers where high demand coincides with limited natural recharge. The historical records assembled in the source study show substantial increases in electrical conductivity at several northwestern coastal localities between 1979 and 2002, while later peer-reviewed investigations confirm that the Jifarah Plain remains vulnerable to seawater intrusion, upconing of deeper saline water, and additional urban and agricultural contamination. These findings demonstrate the need to interpret groundwater quality through combined hydraulic, hydrochemical, and land-use evidence. The most

urgent response is to restore balance between abstraction and recharge, protect aquifers from wastewater and agricultural pollution, and establish a reliable monitoring and regulatory system. Managed aquifer recharge can contribute to storage recovery and coastal hydraulic protection, but only when supported by detailed site characterization, reliable pretreatment, compatibility assessment, clogging control, and continuous verification. Because the historical dataset is not a current survey, updated field measurements and pilot projects are essential before quantitative investment or operating decisions are made.

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