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Urban Groundwater Rise in Arid Cities: Comparative Analysis and Sustainable Management Framework for Ajdabiya, Libya

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Abstract

Rising groundwater levels pose significant environmental and infrastructural challenges in urban areas worldwide, resulting in subsurface flooding, structural damage, soil salinization, contamination, and elevated public health risks. Recent studies highlight the increasing dominance of anthropogenic factors in driving groundwater table rise in cities. This paper reviews international case studies from diverse hydrogeological, climatic, and urban contexts to identify primary causes and effective mitigation strategies, while assessing their applicability to Ajdabiya City, Libya.

Comparative analysis shows that principal drivers include artificial recharge from leaking water-supply and sewage networks, reduced groundwater abstraction following external supply importation, excessive irrigation, and sea-level rise in coastal zones. A key distinction exists between uncontrolled groundwater rise in arid, data-scarce cities with weak governance, and managed groundwater rebound in post-industrial cities supported by proactive regulatory frameworks.

In Ajdabiya, groundwater depths frequently under 1 meter cause chronic waterlogging, damage to foundations and pavements, utility corrosion, and sewage-derived contamination risks. These issues are

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exacerbated by the city's flat topography, highly permeable carbonate aquifer, rapid unplanned expansion, network leakage, proximity to coastal sabkhas, and the absence of systematic monitoring.
Drawing on successful approaches from comparable arid-region cities like Zliten and Riyadh, this study proposes a tailored integrated management framework for Ajdabiya. Key recommendations include systematic leak detection, targeted subsurface drainage installation, optimized stormwater reuse, continuous monitoring network establishment, and mandatory hydrogeological assessments in urban planning. These findings offer practical, transferable guidance for sustainable urban groundwater management in Ajdabiya and other Libyan cities facing analogous challenges.

Keywords: Rising groundwater levels, Artificial recharge, Infrastructure damage, Urban groundwater management; Arid cities.

ارتفاع منسوب المياه الجوفية في المدن القاحلة: تحليل مقارن وإطار إدارة مستدامة لمدينة أجدابيا، ليبيا

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الملخص:

يشكل ارتفاع منسوب المياه الجوفية تحديات بيئية وبنيوية كبيرة في المناطق الحضرية حول العالم، مما يؤدي إلى فيضانات تحت سطح الأرض، وأضرار إنشائية، وتملح التربة، وتلوثها، وارتفاع مخاطر الصحة العامة. وتُبرز الدراسات الحديثة تزايد هيمنة العوامل البشرية في ارتفاع منسوب المياه الجوفية في المدن. تستعرض هذه الورقة دراسات حالة

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دولية من سياقات هيدروجيولوجية ومناخية وحضرية متنوعة لتحديد الأسباب الرئيسية واستراتيجيات التخفيف الفعّالة، مع تقييم مدى ملاءمتها لمدينة أجدابيا في ليبيا.

يُظهر التحليل المقارن أن العوامل الرئيسية تشمل التغذية الاصطناعية من شبكات إمداد المياه والصرف الصحي المتسربة، وانخفاض استخراج المياه الجوفية نتيجة استيرادها من مصادر خارجية، والإفراط في الري، وارتفاع مستوى سطح البحر في المناطق الساحلية. ويوجد فرق جوهري بين ارتفاع منسوب المياه الجوفية غير المنضبط في المدن القاحلة التي تفتقر إلى البيانات وتفتقر إلى الحوكمة الفعّالة، وبين انتعاش منسوب المياه الجوفية المُدار في المدن ما بعد الصناعية المدعومة بأطر تنظيمية استباقية.

يوجد فرق جوهري بين ارتفاع منسوب المياه الجوفية غير المنضبط في المدن القاحلة التي تعاني من نقص البيانات وضعف الحوكمة، وبين انتعاش منسوب المياه الجوفية المُدار في المدن ما بعد الصناعية المدعومة بأطر تنظيمية استباقية. في أجدابيا، تتسبب أعماق المياه الجوفية التي تقل في كثير من الأحيان عن متر واحد في غمر مزمن بالمياه، وتلف الأساسات والأرصفة، وتآكل المرافق، ومخاطر التلوث الناتج عن مياه الصرف الصحي. وتتفاقم هذه المشكلات بسبب تضاريس المدينة المسطحة، وخزان المياه الجوفية الكربوناتية عالي النفاذية، والتوسع العمراني السريع غير المخطط له، وتسرب الشبكة، وقربها من السبخات الساحلية، وغياب المراقبة المنهجية.

بالاستناد إلى المناهج الناجحة في مدن مماثلة في المناطق القاحلة مثل زليتن والرياض، تقترح هذه الدراسة إطارًا إداريًا متكاملًا مصممًا خصيصًا لأجدابيا. تشمل التوصيات الرئيسية الكشف المنهجي عن التسربات، وتركيب أنظمة تصريف تحت سطحية موجهة، وإعادة استخدام مياه الأمطار على النحو الأمثل، وإنشاء شبكة مراقبة مستمرة، وإجراء تقييمات هيدروجيولوجية إلزامية في التخطيط العمراني. تقدم هذه النتائج إرشادات عملية قابلة للتطبيق لإدارة مستدامة للمياه الجوفية في أجدابيا وغيرها من المدن الليبية التي تواجه تحديات مماثلة.

الكلمات المفتاحية: ارتفاع منسوب المياه الجوفية، التغذية الاصطناعية، تضرر البنية التحتية، إدارة المياه الجوفية الحضرية؛ المدن القاحلة.

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1. Introduction

In recent decades, rising groundwater levels have been reported in numerous cities worldwide, emerging as a significant urban environmental challenge. Rapid urbanization has profoundly altered natural groundwater systems, primarily through modifications in recharge patterns, land surface characteristics, and subsurface hydrological processes. As the majority of global population growth now occurs in urban areas (Hibbs and Sharp, 2012), anthropogenic pressures on aquifer systems have intensified considerably. Among the most influential factors is indirect artificial recharge resulting from leakage in water supply and sewerage networks, which can contribute substantial volumes of water to underlying aquifers (Garcia-Fresca and Sharp, 2005, Emhanna et al, 2020, Bin Issa and Said, 2024, Dean and Sholley, 2006, Rushton and Al- Othman, 1994, Al-Sefry and Zekai, 2006, Al-Senafy et al, 2015, Selim et al. 2014, El-Sayed et al, 2012, Krogulec et al., 2020, Yihdego et al, 2017, Yao et al, 2021)

Consequently, many urban centers are experiencing progressive groundwater table rise, leading to a range of environmental and infrastructural impacts. These include urban flooding, structural deterioration of buildings and road networks, soil salinization, and groundwater quality degradation (Becker et al., 2022, Li et al., 2025, Kacimov et al, 2021, Mourad et al, 2025). The severity of these impacts is particularly pronounced in developing cities, where rapid population growth is frequently accompanied by aging infrastructure, limited maintenance capacity, and inefficient water and wastewater management systems. In such contexts, the imbalance between artificial recharge inputs and natural discharge mechanisms can trigger persistent groundwater accumulation, intensifying socio-environmental vulnerabilities and undermining long-term urban sustainability.

In Ajdabiya, the problem has been evident since 2015. Previous investigations indicate that the phenomenon is driven by a hydrodynamic imbalance within the shallow aquifer system, resulting from a persistent mismatch between groundwater recharge and abstraction. The cessation of pumping from the shallow aquifer in 1993 disrupted the long-standing natural–anthropogenic

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equilibrium, leading to a gradual and continuous rise in the groundwater table (Emhanna et al., 2020; Emhanna, 2025).
Despite increasing studies on urban groundwater rise, limited research has comparatively evaluated mitigation approaches applicable to Libyan arid cities, particularly Ajdabiya.

1.1 **Problem Statement**

Over the past decade, Ajdabiya has experienced a continuous rise in groundwater levels, leading to structural damage to buildings and roads, soil deterioration, and increased risks of waterborne diseases in residential areas. Addressing this issue requires a scientific and systematic approach based on an integrated understanding of urban and hydrogeological processes. Reviewing international case studies of similar groundwater rise problems can help identify effective and sustainable solutions suitable for Ajdabiya's environmental and infrastructural conditions.

1.2 Objectives

The specific objectives of this study are to:

- Analyze previous international case studies to identify the principal drivers controlling urban groundwater table rise.
- Assess the impacts associated with elevated groundwater levels
- Propose a sustainable groundwater and urban water management framework to mitigate current impacts and prevent future occurrences

2. Methodology

This study adopted a systematic qualitative–comparative approach to investigate the causes, impacts, and mitigation strategies of rising groundwater levels in urban areas. The methodology consisted of four stages:

2.1 Literature Search and Selection of Case Studies

A systematic literature review was conducted using the databases Scopus, Web of Science, and Google Scholar. The search included publications from 1990 to 2025 using combinations of the following keywords:

- Rising groundwater level

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- Urban groundwater flooding
- Groundwater rebound
- Urban recharge
- Groundwater management
- Groundwater mitigation

A total of **29 case studies** from different climatic and geographical settings were selected according to the following criteria:

Inclusion Criteria

- Documented occurrence of groundwater level rise in urban or peri-urban areas.
- Clear identification of the primary cause(s).
- Description of impacts and/or mitigation measures.
- Availability of peer-reviewed articles, technical reports, or official publications.

Exclusion Criteria

- Studies lacking hydrogeological evidence.
- Duplicated case studies.

2.2 Comparative Case Study Analysis

Selected international case studies were analyzed to identify:

- Primary drivers of groundwater table rise
- Implemented mitigation measures
- Effectiveness and sustainability of adopted solutions

To identify dominant drivers of groundwater rise, each case study was assigned to its **primary controlling factor**. The percentage contribution of each category was calculated as:

$$Percentage = \frac{Number\ of\ cases\ in\ category}{Total\ number\ of\ cases} \times 100$$

where the total sample consisted of 29 case studies. Each case was counted once according to its dominant cause to avoid duplication.

2.3 Local Context Assessment (Ajdabiya City)

The hydrogeological and urban characteristics of Ajdabiya were assessed based on:

- Geological and geomorphological setting
- Urban development patterns
- Water supply and wastewater infrastructure conditions
- Observed environmental and infrastructural impacts

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2.4 Applicability Assessment and Framework Development

The findings obtained from international case studies were evaluated against the hydrogeological, environmental, and infrastructural conditions of Ajdabiya City to develop a sustainable management framework suitable for local conditions.

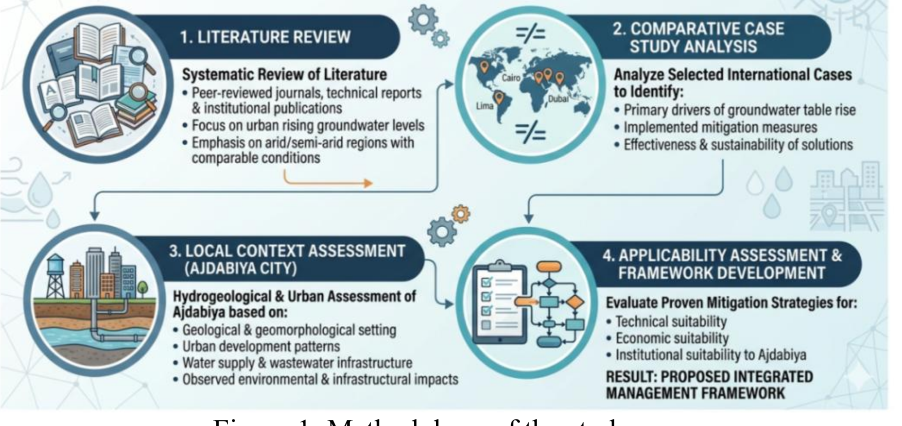

Figure 1: Methodology of the study.

3. Ajdabiya City Study Area Description

The Ajdabiya City, located in northeastern Libya, represents a strategic urban center linking the eastern, western, and southern regions of the country. The city’s low-lying flat topography, with elevations between -3 meters to 15 meters, creates a basin-like effect that lacks the natural gradients necessary for effective surface drainage (Fig. 2).

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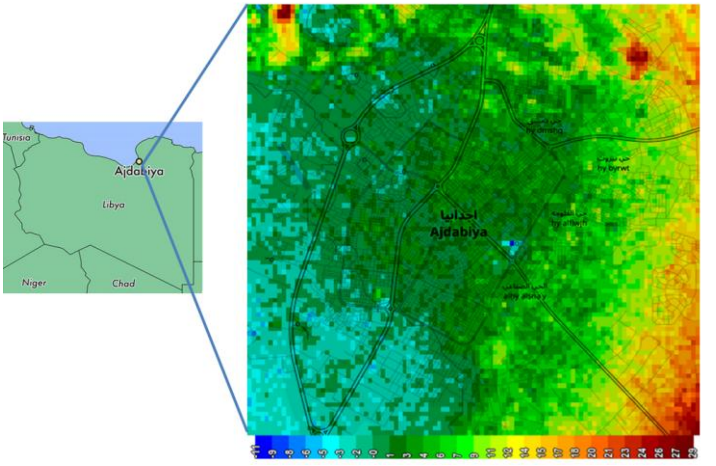

Figure 2: Location and topography Ajdabiya City (https://elevation.city/ly/1wrd).

This topographic depression unlined cesspits is underlain by the porous and fractured limestone of the Ajdabiya Formation (Fig, 3), which facilitates the rapid infiltration of fluids. The shallow aquifer system is therefore highly transmissive and possesses considerable storage capacity. Importantly, it is hydraulically connected to surface activities, making it highly sensitive to anthropogenic recharge sources.

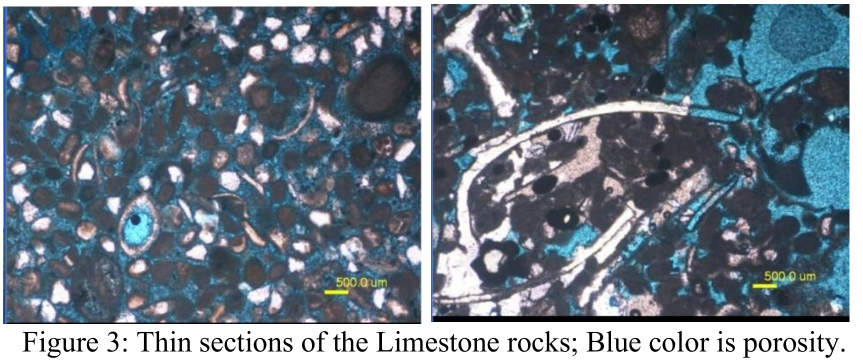

Figure 3: Thin sections of the Limestone rocks; Blue color is porosity.

Over the past twenty-five years, Ajdabiya City has undergone rapid urban expansion and significant demographic growth, with its population rising dramatically from approximately 86,137

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inhabitants in the 1995 census (Borgia and Hammaly, 2020) to nearly 290,000 inhabitants (according to 2026 Civil Registry data). This accelerated increase has occurred without corresponding improvements in essential infrastructure, especially sewage networks, leaving many newly developed neighborhoods without connections to centralized wastewater systems and forcing residents to depend on cesspits (black wells) and open septic tanks for disposal.

The urban expansion has progressively encroached upon the sabkhas, which function as the city's natural discharge zones for surface and shallow groundwater. In northern west areas, these depressions have been artificially filled and subsequently developed for residential and infrastructural purposes (Fig. 4). This alteration has disrupted the natural drainage regime, reduced infiltration and contributed to the accumulation and rise of groundwater levels in adjacent urban areas.

Figure 4: Filling of the Sabkha Area Northwest of Ajdabiya City.

At the same time, water consumption has surged sharply, as reported by Great Man-Made River Project in 2026, with daily water supply escalating from about 5,000 m³/day in 1993 to 62,000 m³/day in 2026 (GMMRP, 2026). However, the existing sewage network and treatment facilities have maximum capacity of only around 15,400 m³/day (Water and Wastewater Company, 2026), meaning that nearly 46,600 m³/day equivalent to about 75% of the total supplied water fails to enter the sewage system, while only roughly 25% is properly collected and conveyed.

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This profound imbalance between water distribution volumes and wastewater collection capacity creates severe hydrological stress on the urban environment. The excess wastewater, predominantly discharged into cesspits and inadequately sealed tanks, infiltrates the subsurface and contributes directly to artificial recharge of the shallow aquifer.

Collectively, these factors have triggered a steady rise in the city's groundwater table, though the severity is unevenly distributed. In low-lying areas specifically the western and northwestern neighborhoods, Al-Farjan, and the behind Al-Nujoum Club the water level has reached a critical depth of less than one meter (Fig. 5). In contrast, the higher elevations of the southern and eastern neighborhoods remain secure, with groundwater levels ranging from 5 to 10 meters deep.

Figure 5: Wells photographs illustrating spatial variations in groundwater depth, ranging from less than 1 m below ground surface in the northwestern of the city (near Ajdabiya Municipality) to more than 6 m in the eastern sector (Damascus Neighborhood).

Ultimately, these spatial variations are primarily governed by the city's topographic gradient. The lower the elevation of a neighborhood, the greater the risk of groundwater surfacing. Low-lying areas function as natural collection zones, making them significantly more vulnerable to rising groundwater levels compared to the higher and more elevated parts of the city. As a consequence, the rising groundwater level has resulted in significant environmental and infrastructural impacts. Groundwater became

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contaminated due to infiltration from sewage systems, while stagnant water accumulated in low-lying areas, promoting excessive weed growth and insect infestations (Fig. 6).

Figure 6: Groundwater surfacing in Al-Farjan (Right) and 7th of October (Left) neighborhoods, showing Pool Formation and associated Weed growth.

Prolonged water saturation led to soil weakening, causing land subsidence and the development of cracks in buildings and road pavements, in addition to increased wall dampness within residential structures (Fig. 7).

Figure 7: Ground Subsidence (Left) and Rising Dampness (Right), Resulting in the Abandonment of Several Residential Buildings.

These conditions forced some residents to abandon their homes (Ehmann et al, 2020). Furthermore, the elevated groundwater level adversely affected electricity and water supply networks,

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complicating maintenance operations and increasing the risk of service disruptions.

4. Results and Comparative Analysis of Case Studies

A total of 29 urban case studies were analyzed from different climatic and hydrogeological settings worldwide. The selected cities included arid, semi-arid, humid, coastal, and inland environments. Despite significant differences in local conditions, common patterns emerged regarding the causes and impacts of groundwater level rise.

4.1 Classification of Groundwater Rise Cases

The analyzed cities were grouped into four major typologies:

A. Anthropogenic Recharge Cities

These cities experience groundwater rise primarily due to leakage from water distribution networks, wastewater systems, septic tanks, irrigation return flows, and other urban recharge sources.

Examples include Ajdabiya, Zliten, Riyadh, Kuwait City, Aswan, and Oued Souf.

In these contexts, even small inefficiencies in urban water systems create a sustained positive groundwater balance, gradually elevating water tables beneath built-up areas.

B. Coastal Groundwater Rebound Cities

Groundwater rise in these cities is mainly associated with sea-level rise and changes in coastal hydraulic gradients.

Examples include Lagos, Osaka, San Francisco, and New Zealand coastal cities.

C. Groundwater Recovery Cities

These cities experienced groundwater rebound following reductions in industrial abstraction and the recovery of historical groundwater levels.

Examples include London, Birmingham, Paris, and Naples.

A classic example is London, where groundwater fell by up to ~65–70 meters (from about 35 m below ground level in the mid-19th century to nearly 100 m below ground level by the 1960s) due to prolonged industrial abstraction. Post-1960s reductions in pumping led to recovery rates of up to 3 meters per year in central areas (Morrison, 1994). Figure 7 illustrates this process, showing the decline in groundwater levels during intensive extraction followed

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by gradual rebound after pumping stops. Similar patterns occur in other European urban centers where industrial decline has reduced demand on groundwater.

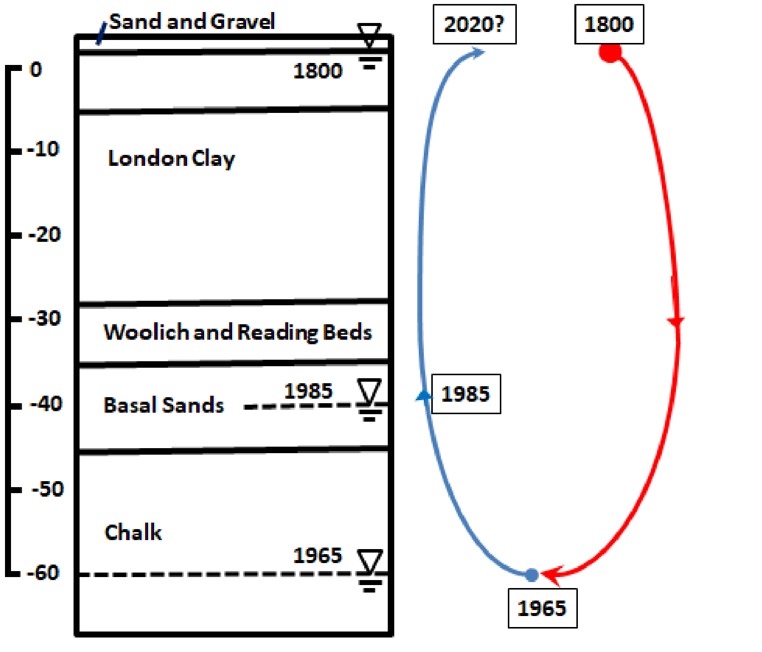

Figure 7: Schematic of groundwater levels beneath London (Morrison, 1994).

D. Climate-Driven Fluctuation Cities

Groundwater rise is mainly associated with seasonal rainfall variability, extreme precipitation events, or reservoir-induced recharge.

Examples include Germany andTaiwan.

E. Impact of Dams

Impact of Large Hydraulic Structures (Dams and Reservoirs) alter regional hydrology by increasing seepage from reservoirs and reducing downstream gradients, which can raise groundwater levels in adjacent or downstream areas.

Examples in Indonesia and Turkey (e.g., Kralkızı and Dicle Dam watersheds), where seepage and irrigation return flows elevate static

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water levels in cultivated zones, sometimes leading to waterlogging or salinization, though effects vary by site-specific geology and management.

4.1.1 Distribution of Main Causes

The analysis revealed that anthropogenic factors represent the dominant cause of groundwater rise worldwide. Of the 29 analyzed case studies:

- Anthropogenic recharge accounted for approximately 47% of cases.
- Sea-level rise and coastal response accounted for 25%.
- Groundwater recovery following pumping reduction represented 14%.
- Seasonal rainfall variability represented 7%.
- Dam-related impacts represented 7%.

These results indicate that groundwater rise is predominantly a consequence of human-induced modifications to the urban water balance rather than natural hydrological processes alone.

4.1.2 Comparative Pattern Analysis

The comparative analysis identified three recurring patterns:

- Arid and semi-arid cities are highly sensitive to groundwater rise because natural recharge is typically low, making even small leakage rates capable of generating long-term groundwater accumulation.
- Cities underlain by carbonate aquifers often experience rapid groundwater level responses due to the high transmissivity and interconnected fracture systems characteristic of carbonate formations.
- Flat topography reduces natural drainage efficiency, promoting groundwater accumulation and increasing the likelihood of waterlogging and infrastructure damage.

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Table 1: Summary of case studies on groundwater table rise and its causes.

Cause	City	References
Anthropogenic Recharge Cities	Ajdabiya - Libya	Emhanna et al, 2020
	Zliten - Libya	Bin Issa and Said, 2024 and Mourad et al, 2025
	Las Vegas and San Jose - USA	Dean and Sholley, 2006
	Riyadh - KSA	Rushton and Al-Othman, 1994
	Jedddah - KSA	Al-Sefry and Zekai, 2006
	Madinah City- KSA	Bob et al., 2016 and Hassan et al, 2024
	Kuwait - Kuwait	Al-Senafy et al, 2015
	Aswan - Egypt	Selim et al. 2014
	Bangar El Sukar area, Alexandria - Egypt	El-Sayed et al, 2012
	Warsaw - Poland	Krogulec et al., 2020
	New South Wales - Australia	Yihdego et al, 2017
	Xi'an - China	Yao et al, 2021
	Oued Soof - Algeria	Abdalsamid, 2023
Coastal Groundwater Rebound Cities	Lagos - Nigeria	Oyedele et al., 2009
	Osaka - Japan	Yasuhara et al., 2007
	Bangladesh	Singh et al., 2000
	San Francisco -USA	Hill et al., 2023
	California -USA	Gurdak et al, 2025
	Juelsminde - Denmark	Forchhammer Mathiasen et al, 2023
	New Zealand	Morgan, 2024
Groundwater Recovery Cities	London - UK	Morrison, 1994
	Birmingham - UK	Knipe et al., 1993
	Napoli - Italy	Allocca et al., 2016 and coda 2021
	Paris - France	Bergeron et al., 1983
Climate-Driven Fluctuation Cities	Elbe and Danube - Germany	Kreibich and Thieken 2008
	Kaohsiung - Taiwan	Hussain et al, 2022
Impacts of dams	Sakra District - Indonesia	Sulistiyono et al, 2021
	Dicle and Kralkızı dams, Turkey	Çelik, 2018

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The distribution of factors contributing to groundwater table rise in urban areas highlights the predominant role of anthropogenic influences (Fig. 9). Artificial recharge from human activities accounts for the largest portion at 47%, driven mainly by leakages from water supply pipelines, sewage and drainage networks, septic systems, and irrigation return flows that unintentionally add water to aquifers. Sea level rise contributes 25%, especially in low-lying coastal cities, where it alters hydraulic gradients and pushes groundwater tables upward.
Reduced groundwater abstraction combined with aquifer recovery makes up 14%, often as a rebound effect from decreased pumping due to shifts in water sourcing or contamination concerns. In comparison, natural or semi-natural factors like dams (7%) and seasonal rainfall variability (7%) play relatively minor roles. These findings underscore that urban groundwater rise stems primarily from deficiencies in water infrastructure and management practices rather than purely natural climatic or hydrological processes alone.

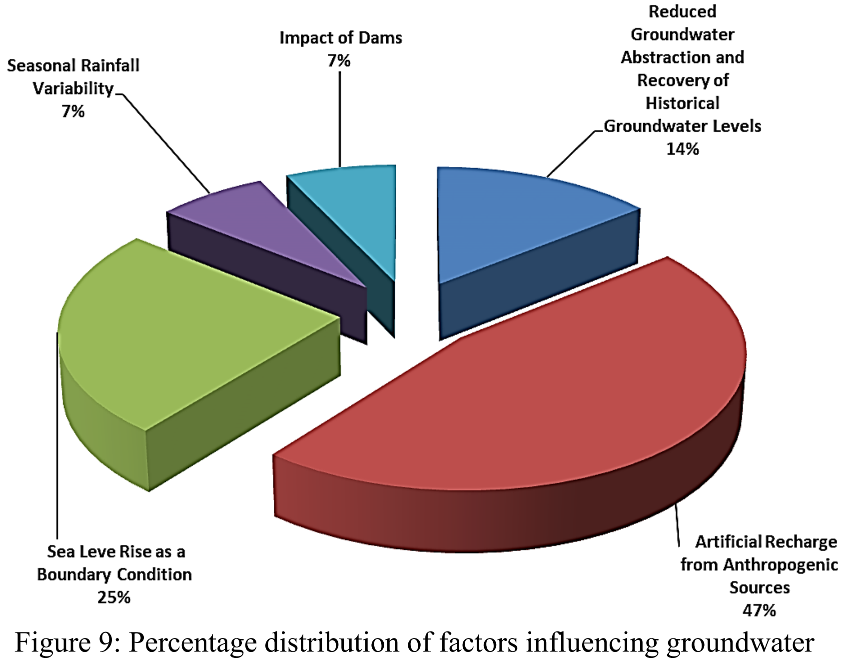

Figure 9: Percentage distribution of factors influencing groundwater level rise in the selected case studies.

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4.2 International Mitigation Strategies

A review of global case studies reveals that successful mitigation of rising groundwater levels requires integrated and long-term approaches rather than isolated engineering solutions.

4.2.1 Groundwater Control Measures

- **Controlled groundwater pumping** to restore hydraulic balance.
- **Subsurface drainage systems** (horizontal drains, relief wells).
- **Interceptor drains** in critical low-lying zones.

4.2.2 Urban Water Management Improvements

- Rehabilitation and leakage control of water supply networks.
- Upgrading wastewater collection and treatment facilities.
- Separation of stormwater and sewage systems.

4.2.3 Planning and Regulatory Measures

- Incorporation of hydrogeological assessments into urban planning.
- Land-use control in vulnerable zones.
- Continuous groundwater monitoring and data management.

4.3 Applicability to Ajdabiya City: Comparative Framework and Sustainable Mitigation Strategy

The comparative analysis with similar case studies essential for developing a tailored mitigation strategy. Below, the lessons from Zliten (Libya) and Riyadh (Saudi Arabia), highlighting parallels and adaptations for Ajdabiya.

4.3.1. Lessons from Zliten (Libya)

Zliten provides a strong analogue to Ajdabiya due to shared hydrogeological and urban development contexts in Libya (Emhanna et al, 2020 and Bin Issa and Said, 2024). Both cities have seen groundwater rise attributed to:

- Rapid urbanization without adequate sewer infrastructure.
- Heavy dependence on septic systems and "black wells" for wastewater disposal.
- Leakage from aging water networks, including influences from the Man-Made River Project (MMRP).

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- Shallow aquifers exacerbated by minimal natural drainage.

In Zliten, additional factors include wadi influences and proximity to the Mediterranean, leading to polluted groundwater surges that affected over 2,000 families by early 2024 (Mourad et al, 2025). Unlike Ajdabiya, Zliten's coastal setting introduces risks of seawater intrusion, but the core anthropogenic recharge mechanisms such as excessive MMRP water supply and faulty sewage overlap significantly. Remediation in Zliten began with emergency measures like dewatering wells to pump and redirect excess water.
By 2025, authorities drilled additional wells and linked them to drainage lines, achieving measurable declines in water levels (Fig. 10). Monitoring by Al-Sadiq (2026) confirmed short-term success through hydraulic interventions, though long-term sustainability requires addressing root causes like wastewater management.
For Ajdabiya, which lacks coastal influences but shares urban recharge issues, these tactics demonstrate that targeted pumping and drainage can provide immediate relief while informing broader strategies.

Figure 10: Dewatering well and Line in Zliten (Higher Technical Committee for Monitoring the Groundwater Overflow Phenomenon page, 2026).

4.3.2. Lessons from Riyadh (Saudi Arabia)

Riyadh's experience offers a more structured, multi-tiered approach adaptable to Ajdabiya, despite differences in scale and climate.
Key similarities include:

- Arid/semi-arid environments with flat topography.

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- Urban-induced recharge from leaks, irrigation, and sewage.
- Rising water tables threatening infrastructure, though Riyadh's issues are compounded by massive aquifer depletion from agriculture.

Riyadh's framework emphasizes integrated management:

Step 1: Drawdown to Safe Levels – Deployment of horizontal and vertical drainage systems, including dewatering wells to reduce hydrostatic pressure.

Step 2: Source Control – Leak repairs in water networks, consumption rationalization, and sewage system expansions to curb recharge.

Step 3: Preventive Measures – Ongoing monitoring, use of resistant materials like sulfate-resistant cement, and modeling for predictive management.

Ajdabiya can adopt this holistic approach, prioritizing policy integration over isolated pumping, to ensure long-term viability in Libya's context.

4.3.3 Proposed Sustainable Management Framework for Ajdabiya

Drawing from Zliten's rapid interventions and Riyadh's comprehensive tiers, a phased strategy for Ajdabiya addresses immediate risks while building resilience. This aligns with local studies recommending conjunctive groundwater-surface water use and infrastructure upgrades.

Phase A: Short-Term (Immediate Relief)

Objective: Lower levels in high-risk districts (e.g., central and northwestern Ajdabiya).

- Install subsurface drainage like French drains and perforated pipes.
- Deploy acoustic leak detection for water network repairs.
- Implement controlled abstraction via temporary pumping to pre-1993 equilibria, with extracted water reused for non-potable needs.

Phase B: Mid-Term (Infrastructure Stabilization)

Objective: Establish monitoring and control.

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- Deploy strategic dewatering wells based on hydrogeological models; reuse pumped water for dust control, construction, or irrigation.
- Set up piezometer networks for tracking fluctuations and intervention efficacy.
- Rehabilitate water and sewage systems to minimize leaks.

Phase C: Long-Term (Policy & Urban Planning Integration)

Objective: Prevent recurrence amid Libya's water challenges, including over-extraction and climate impacts.

- Enforce hydrogeological zoning to limit development in shallow aquifer zones.
- Integrate groundwater data into urban master plans.
- Adopt Sustainable Urban Drainage Systems (SuDS), such as permeable pavements.
- Update building codes for resistant materials and waterproofing in vulnerable areas.

5. DISCUSSION

The findings of this study underscore that rising groundwater levels in urban environments are increasingly driven by anthropogenic activities rather than natural hydrogeological cycles. Globally, the finding that approximately 47% of urban groundwater rise is anthropogenic strongly mirrors the current situation in Ajdabiya, where rapid population growth (surging from 86,000 in 1995 to 290,000 in 2026) has severely outpaced infrastructure development.

5.1 Hydrogeological Mechanisms and Urban Theories

To transition from mere observation to hydrogeological explanation, the crisis in Ajdabiya must be interpreted through core subsurface flow principles:

- **Urban Recharge and Groundwater Balance:** In natural arid settings, groundwater systems maintain equilibrium with minimal meteoric input. However, because 75% of supplied municipal water (approx. 46,600 m^3/day) escapes into the unsewered subsurface, the groundwater balance equation is radically altered. According to Urban Recharge Theory, this constant anthropogenic injection transforms the

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city into an artificial recharge zone, overwhelming the aquifer's natural storage capacity.

- **Vulnerability of Carbonate Aquifers:** Arid urban zones overlying shallow, unconfined carbonate aquifers are uniquely vulnerable. The secondary porosity (fractures and dissolution features) of Ajdabiya's limestone allows rapid downward percolation of wastewater from septic "black wells." However, because regional hydraulic conductivity cannot disperse these massive volumes laterally, the water table rises rapidly toward the surface.
- **Topographic Controls on Hydraulic Gradients:** This accumulation is further compounded by the city's flat topography. A flat terrain results in an extremely low regional hydraulic gradient (dh/dl). Lacking the hydraulic slope necessary to drive lateral drainage toward natural outlets, groundwater movement stagnates. This hydraulic gradient disruption forces the system to form localized "groundwater mounds" directly beneath the urban center, causing vertical water table expansion into shallow infrastructure.

5.2 Comparative Context and Anthropogenic Signatures

This mechanism distinguishes Ajdabiya from post-industrial European cities like London, where groundwater rises is a "recovery" following the cessation of historical industrial pumping. Instead, Ajdabiya represents active, continuous sub-surface flooding.

While comparative models like Riyadh show that emergency dewatering wells can temporarily lower local water tables, they fail without Source Control because regional urban recharge rapidly refilling the cone of depression. Furthermore, encroaching onto sabkhas the city's natural geomorphological discharge zones has paved over the aquifer's natural evaporative outlets, effectively blocking the system's ability to naturally relieve its hydrogeological load.

5.3 Study Limitations

While identifying clear local trends, the predictive certainty of this study is constrained by three key hydrogeological limitations:

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- **Lack of Long-Term Monitoring:** The absence of a continuous piezometer network prevents the assessment of long-term transient groundwater dynamics and seasonal fluctuations.
- **Uncertainty in Recharge Estimates:** Quantifying R_{urban} relies on indirect water consumption estimates rather than direct physical tools like lysimeter measurements or stable isotope tracing (^2H and ^{18}O).
- **Absence of Numerical Modeling:** Without a calibrated 3D numerical groundwater flow model (e.g., MODFLOW), it is impossible to precisely simulate complex boundary conditions or predict the exact spatial-temporal propagation of the groundwater mound.

Ultimately, the groundwater crisis in Ajdabiya is a coupled hydro-social challenge requiring coordinated, data-driven infrastructural intervention.

6. Conclusions

- This review highlights that rising groundwater levels in urban areas constitute a complex global environmental and engineering challenge resulting from the interaction of anthropogenic and natural factors. Analysis of documented case studies indicates that human activities, particularly leakage from water supply and sewage networks, represent the dominant driving factor, while sea-level rise, changes in groundwater abstraction practices, and hydrogeological conditions further influence groundwater behavior in urban environments.
- This study provides a comprehensive synthesis of the causes, impacts, and mitigation strategies associated with urban groundwater rise and evaluate their applicability to the conditions of Ajdabiya City, Libya. By integrating international experiences with local hydrogeological characteristics, the research establishes a conceptual framework for understanding groundwater rise processes in arid and semi-arid urban settings.

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- The findings demonstrate that effective management of groundwater rise requires site-specific solutions that consider local geological, hydrogeological, climatic, and infrastructural conditions. For Ajdabiya, the evidence suggests that improving water network efficiency, rehabilitating sewage infrastructure, implementing controlled groundwater abstraction, and incorporating groundwater considerations into urban planning are essential measures for reducing environmental and infrastructural risks.
- Future studies should focus on detailed hydrogeological investigations, long-term groundwater monitoring programs, and numerical groundwater flow modeling to better quantify the relative contribution of different driving factors in Ajdabiya. Further research is also needed to assess the technical and economic feasibility of integrated groundwater management strategies and to develop early-warning systems that support sustainable urban development under changing environmental conditions.
- This study emphasizes that proactive groundwater management is not only necessary to mitigate current impacts but also fundamental for enhancing urban resilience and ensuring the sustainable use of groundwater resources in Libya and other arid region cities facing similar challenges.

7. Recommendations

- Given the severity and ongoing rise of groundwater levels in the Ajdabiya City, the study recommends urgent measures like Zliten's short-term solutions, alongside long-term strategies inspired by Riyadh to address the problem at its source.
- Based on the study's findings that approximately 25% of the reviewed cases were directly linked to rising sea levels worldwide, it is strongly recommended that comprehensive hydrogeological and urban vulnerability assessments be conducted for Libya's coastal cities.

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