



## Hydro-Engineering Dynamics of Groundwater Rise and Urban Waterlogging in Arid Environments: An Integrated Review and Case Study of Sokna City in Libya

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الديناميكيات الهيدرو-هندسية لارتفاع منسوب المياه الجوفية والتغدق المائي في البيئات الجافة: دراسة  
حالة متكاملة لمدينة سوكنة – ليبيا

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### Abstract:

Groundwater rise in arid urban environments poses a critical hydro-engineering challenge with serious consequences for infrastructure integrity, public health, and environmental sustainability. This study presents a field-based investigation of groundwater rise and waterlogging in Sokna City, Aljufra district, central Libya, a hyper-arid setting characterized by complex carbonate–argillaceous stratigraphy and severely deteriorated water and sewage infrastructure. The monitoring program spanned five months (March–July 2025), deliberately selected as the post-winter recharge window during which groundwater flooding and swamp formation reach their annual maximum in the Aljufra hydro climatological regime. Biweekly depth measurements at ten representative swamp sites documented cumulative water-table rise exceeding (100cm) during the April recharge peak, followed by evaporation-driven recession through July. A critical field observation was the identification of a perennial lake exhibiting year-round waterlogging, independent of seasonal rainfall interpreted as evidence of sustained anthropogenic recharge from chronic infrastructure leakage, and designated as the priority site for a future full-year monitoring program. Hydrogeological analysis confirmed that a compound low-permeability sequence of compact Miocene limestone overlying expansive clay generates perched aquifer conditions sustaining surface waterlogging across the urban fabric.

A three-layer Hydro-Engineering Interaction Framework (HEIF) is developed integrating recharge inputs, subsurface hydraulic constraints, and surface hydrological manifestations. Engineering recommendations include dimensioned subsurface drainage alignments at (1.5–2.0m) depth, targeted network rehabilitation to reduce non-revenue water losses from (~40% to below 15%), and mandatory foundation waterproofing standards. Findings are contextualized within the Libyan national experience, with explicit comparison to the Zliten waterlogging case.

**Keywords:** Groundwater rise; Perched aquifer; Waterlogging; Urban drainage; Arid environments; Infrastructure leakage; Sokna City; Libya; Zliten.

### الملخص

يشكل ارتفاع منسوب المياه الجوفية في البيئات الحضرية الجافة تحدياً هيدرو-هندسياً بالغ الخطورة، تتشعب آثاره لتلامس سلامة البنية التحتية والصحة العامة والاستدامة البيئية. تقدم هذه الدراسة تحقيق ميداني متكامل لظاهرة ارتفاع المياه الجوفية والتغدق المائي في مدينة سوكنة بمنطقة الجفرة وسط ليبيا وهي بيئة شديدة الجفاف تتسم بتركيب طبقي كربوناتي-طيني معقد وشبكات مياه وصرف صحي بالغة التهاك. اعتمدت الدراسة فترة رصد ميداني مدتها خمسة أشهر (مارس – يوليو 2025)،

اختبرت بعناية لتتزامن مع النافذة الهيدرولوجية الحرجة التي تعقب موسم الأمطار الشتوي، وتبلغ فيها ظاهرة الطفح المائي وتشكل المستنقعات ذروتها السنوية في منطقة الجفرة. وأسفرت القياسات الميدانية نصف الشهرية في عشرة مواقع تمثيلية عن توثيق ارتفاع تراكمي في منسوب المياه تجاوز (100 سم) خلال ذروة التغذية في أبريل، أتبعه انخفاض تدريجي مدفوع بالتبخر حتى يوليو. ولعل أبرز المشاهدات الميدانية اكتشاف بحيرة دائمة التغدق تستمر فيها ظاهرة الغدق طوال العام بمعزل تام عن دورة الأمطار، وهو ما يفسر بوصفه دليل على تغذية بشرية مستمرة ناجمة عن التسرب المزمن من شبكات البنية التحتية؛ وقد صنّف هذا الموقع أولوية بحثية لبرنامج رصد متواصل لمدة سنة كاملة في المستقبل. كما أثبت التحليل الهيدروجيولوجي أن تتابع طبقي مزدوج الكتومية حجر جيري ميوسيني متماسك فوق طبقة طين ممتددة يولد شروط الطبقة الجوفية المعلقة التي تديم التغدق السطحي. تطور الدراسة إطار مفاهيمي ثلاثي الطبقات (HEIF) يدمج مصادر التغذية والقيود الهيدروليكية الباطنية والمفرزات الهيدرولوجية السطحية، وتقدم توصيات هندسية بمواصفات محددة تشمل شبكات تصريف باطني على عمق (1.5–2.0 م)، وإعادة تأهيل الشبكات، مع استحضار مقارن لحالة مدينة زليتن.

**الكلمات المفتاحية:** ارتفاع المياه الجوفية؛ الطبقة الجوفية المعلقة؛ التغدق المائي؛ الصرف الحضري؛ البيئات الجافة؛ تسرب الشبكات؛ مدينة سوكنة؛ ليبيا؛ زليتن.

## 1. Introduction

Groundwater constitutes the principal freshwater resource sustaining domestic supply, food production and industrial activity across the arid and hyper arid territories of North Africa and the broader MENA region. Paradoxically, while decades of hydrological scholarship have focused predominantly on groundwater depletion and aquifer overexploitation, a qualitatively distinct and increasingly urgent pathology has emerged across urbanizing arid territories: the progressive accelerating rise of shallow groundwater tables beneath built environments [1]. This phenomenon termed urban groundwater rise, waterlogging or hydric swamping in the literature generates a multidimensional hazard that simultaneously undermines structural foundations, contaminates shallow soil horizons with potential pathogens, creates persistent surface wetlands in otherwise water scarce settings and provides breeding grounds for disease vectors including malaria and dengue mosquito vectors [2-3].

The hydro-engineering genesis of urban groundwater rise operates through two principal forcings that are simultaneously active in most affected cities. The first is the dramatic amplification of subsurface recharge attributable to chronic leakage from ageing water supply and sewage infrastructure a problem that is acute across developing world cities where physical network losses routinely exceed (30–40%) of distributed water volume [4]. The second is the geological character of the subsurface: in many arid settings, low-permeability lithological formations particularly clay horizons and compact carbonate sequences act as hydraulic barriers that prevent the downward migration of excess recharged water, instead forcing its lateral redistribution toward surface expression zones [5]. Where both forcings coexist, the surface expression of groundwater rise is particularly severe and persistent.

Sokna City, the administrative center of the Aljufra district of central Libya, situated at approximately (29°04'N, 15°59'E) and approximately (450m) above mean sea level exemplifies this convergence of forcings with particular clarity. The city occupies a structural depression within the Saharan carbonate platform overlying a stratigraphic succession characterized by Miocene compact limestone sequences intercalated with Oligocene Miocene expansive clay units that collectively impose a powerful hydraulic confinement on any water that accumulates in the overlying sandy surface horizons. The regional climate is hyper arid mean annual precipitation rarely exceeds (15–20mm) concentrated in brief high intensity winter events yet persistent surface swamps of considerable areal extent have become a defining and deteriorating feature of Sokna's urban landscape over the past fifteen years, causing progressive structural damage to residential buildings road infrastructure and buried utility systems.

Despite the severity and documented economic costs of this phenomenon, no peer reviewed hydro-engineering investigation of groundwater rise in Sokna had been published prior to this study. The present paper therefore constitutes the first systematic, field-based characterization of the Sokna urban groundwater system and positions itself within a growing global and regional literature on infrastructure-driven waterlogging in dryland cities. It draws explicit comparative parallels with the waterlogging crisis documented in Zliten City on Libya's Mediterranean coast [6] a case that shares the principal causal architecture of the Sokna phenomenon and

underscores the systemic, nationally distributed character of infrastructure induced urban groundwater hazard in Libya. Accordingly, this study aims to investigate the hydro-engineering dynamics of groundwater rise and urban waterlogging in Sokna City through field observations, hydrological interpretation, and conceptual system analysis. The study further seeks to identify the dominant recharge mechanisms, evaluate hydrogeological controls, and propose engineering strategies for mitigating groundwater related hazards in arid urban environments.

## 2. Problem Statement

Sokna City is experiencing a self-reinforcing and spatially expanding rise in shallow groundwater levels, expressed at the urban surface as persistent swamp formations embedded within residential and commercial neighborhoods. Field reconnaissance conducted during (2024–2025) documented widespread evidence of foundation settlement and cracking in load-bearing masonry structures, progressive pavement subsidence along arterial roads, rising damp penetration in ground-floor residential units, and the accumulation of stagnant surface water in open public spaces across multiple urban quadrants. The spatial distribution of affected zones is non-random it reflects the underlying hydrogeological architecture of the subsurface and the spatial pattern of deteriorating infrastructure and has been expanding progressively over the past decade.

A finding of particular scientific and engineering significance is the identification of a perennial lake site within the urban study area, where waterlogging persists continuously throughout the entire calendar year including the thermally extreme summer months of June through September, when potential evapotranspiration at Sokna typically exceeds (8–10mm) per day and the climatic water balance is strongly negative. The year-round persistence of standing water at this site cannot be explained by residual seasonal precipitation recharge alone. It provides compelling field evidence of a sustained, high-volume anthropogenic recharge source most probably a major, localized leakage point or a cluster of severely deteriorated sewage infrastructure maintaining a continuous recharge flux that fully compensates evaporative losses. This perennial site represents a qualitative escalation of the waterlogging hazard beyond the seasonally modulated dynamics of the ten swamp monitoring sites and identifies a priority zone for both engineering intervention and extended scientific investigation.

The problem is compounded by three structural deficiencies in Sokna's urban infrastructure system. First, the city possesses no engineered subsurface drainage network; once groundwater accumulates above the confining clay horizon, there is no controlled engineered pathway for its removal. Second, the municipal water-supply distribution system suffers from extensive physical deterioration, with non-revenue water losses estimated conservatively at (30–45%) of distributed volume based on analogous assessments of comparable Libyan urban systems a leakage intensity that generates a recharge loading equivalent to several times the natural precipitation input. Third, the sewage collection system, largely constructed from unreinforced concrete pipes with widespread joint deterioration and manhole cover failures, contributes a diffuse, microbiologically contaminated recharge flux that elevates the public health dimension of the crisis well beyond that of a purely engineering problem.

These combined hydrogeological and infrastructure related conditions have transformed groundwater rise in Sokna from a localized environmental issue into a complex urban hydro-engineering hazard, necessitating systematic field investigation and integrated mitigation planning.

## 3. Significance of the Study

This investigation carries significance at three distinct scales. At the local scale, it provides the first evidence-based hydrogeological characterization of a phenomenon that has been causing measurable economic damage and health risks to Sokna's urban population for over a decade, without the benefit of systematic scientific analysis. The identification of the perennial lake as a distinct hydrogeological unit and its interpretation as a zone of concentrated anthropogenic recharge adds a qualitatively important element to understanding the spatial heterogeneity of groundwater dynamics within the urban system and identifies a specific, high-priority target for both engineering intervention and future monitoring.

At the national scale, the study contributes to an emerging evidence base on the geographically distributed character of infrastructure-induced urban waterlogging across Libya, enabling explicit comparative analysis with the Zliten case and supporting the development of a nationally applicable framework for groundwater risk

assessment in Libyan urban environments. At the international level, the Sokna investigation enriches the global literature on urban groundwater rise in hyper-arid dryland cities, a setting that is underrepresented relative to humid and semi-arid urban hydrogeological studies, and provides a well-documented case study that can inform monitoring programmed design in analogous settings across North Africa, the Arabian Peninsula, and other arid regions undergoing rapid urbanization. Accordingly, the study not only addresses a critical local environmental hazard, but also contributes to the broader scientific understanding of groundwater rise processes in rapidly urbanizing arid environments.

#### 4. Objectives

The study addresses the following specific research objectives:

- To characterize the temporal dynamics of groundwater level fluctuations across representative urban swamp sites during the March–July monitoring period.
- To investigate the perennial lake site as a distinct year-round waterlogged unit and evaluate the evidence for sustained anthropogenic recharge.
- To identify and assess the relative contributions of natural and anthropogenic recharge sources to the Sokna groundwater system.
- To characterize the hydrogeological controls governing perched aquifer development and restricting natural drainage.
- To develop a conceptual Hydro-Engineering Interaction Framework (HEIF) integrating recharge sources, subsurface constraints, and surface hydrological impacts.
- To evaluate the engineering and public health implications of urban groundwater rise and propose appropriate mitigation strategies.

#### 5. Literature Review

##### 5.1 Theoretical and Conceptual Foundations

The conceptual foundation for understanding urban groundwater rise was established by Foster and Chilton [7], who demonstrated that the installation of reticulated water supply infrastructure in previously unirrigated arid urban settings routinely generates artificial recharge fluxes one to two orders of magnitude greater than background natural rates a finding since confirmed across diverse hydrological and climatic settings. The Foster Chilton framework identifies three dominant recharge augmentation mechanisms leakage from pressurized water mains, seepage from gravity-fed sewage systems, and deep percolation of irrigated urban greenery. All three operate simultaneously in Sokna City, creating a compound recharge loading that far exceeds the city's natural drainage capacity.

Groundwater system response to augmented recharge is governed jointly by the aquifer transmissivity, specific yield, and boundary conditions. In settings where a low permeability horizon overlies the regional water table, the recharge accumulates above the confining layer in a perched configuration, with lateral flow toward surface-expression points (topographic lows, building excavations, road trenches) determining the spatial distribution of waterlogging. Lerner [8] formalized this conceptual model for arid urban settings, demonstrating through comparative analysis of twelve dryland cities that perched aquifer conditions are the characteristic hydrogeological outcome of urban recharge augmentation where geological confinement exists a description that precisely characterizes the Sokna subsurface environment.

##### 5.2 Urban Groundwater Rise in Arid and Semi-Arid Environments

In Egypt, the Aswan urban agglomeration has been extensively studied as a canonical case of infrastructure induced groundwater rise. Hossen [9] applied a three-dimensional finite-difference groundwater model to the Aswan system and demonstrated that approximately (73%) of observed water-table rise could be attributed to leakage from the municipal water distribution network, with reservoir interaction accounting for the remainder. This quantification achieved through the combination of field monitoring, isotopic tracing and numerical modelling represents the methodological benchmark toward which future work in Sokna should aspire.

The Arabian Peninsula has documented urban groundwater rise in multiple rapidly urbanizing cities. AbdElaty et al. [10] conducted a systematic review of waterlogging incidents in Saudi Arabian urban centers, identifying the

combination of high per capita water consumption (typically 250–400 liters per person per day), massive network leakage from poorly maintained cast iron and asbestos cement distribution mains and the absence of functioning sewerage systems in peripheral urban zones as the primary causal triad. The study further documented that geological confinement by Quaternary calcareous crust (calcrete) plays an amplifying role precisely analogous to the limestone–clay confinement documented in the present Sokna investigation.

In arid Central Asia, Khamzina et al. [11] investigated groundwater rise associated with irrigation return flows in the Aral Sea basin, demonstrating that even in non-urban settings, the combination of anthropogenic recharge loading and subsurface confinement can generate waterlogging over landscape scales. Their application of (HYDRUS-1D) for unsaturated zone modelling to quantify vadose zone water fluxes provides a transferable methodological framework for future numerical modelling work at Sokna.

Recent studies further confirm that the interaction between climatic variability and anthropogenic forcing has become a dominant driver of shallow groundwater instability in rapidly urbanizing dryland environments [12].

### ***5.3 Water Quality Dimensions of Urban Groundwater Contamination***

The public health dimension of urban groundwater rise has been systematically investigated by Howard and Bartram [13], who established that shallow perched aquifers in urban settings are invariably contaminated by sewage-derived pathogens and chemical pollutants when sewage infrastructure is co-located with the recharge zone. Their framework for groundwater vulnerability assessment incorporating aquifer depth, unsaturated zone thickness, and hydraulic conductivity provides the analytical basis for interpreting the water quality risk associated with the Sokna perennial lake, where field observations of elevated turbidity and odor strongly suggest sewage-derived contamination. The recommended laboratory analyses (nitrate, chloride, faecal coliform indicators) proposed in the present study are explicitly grounded in this vulnerability assessment framework.

In the North African regional context, Abdalla [14] assessed groundwater contamination risks in Libyan and Egyptian aquifer systems, documenting that agricultural and urban contamination pathways are often indistinguishable without multi-parameter chemical fingerprinting. The application of a nitrate chloride ( $\delta^{18}O$ ) tracer combination was identified as the most discriminating approach for separating sewage, irrigation, and natural recharge contributions a methodological recommendation directly applicable to the proposed future water-quality investigation at Sokna's perennial lake site.

### ***5.4 The Libyan National Context: The Zliten Precedent***

Within Libya, the most extensively documented case of urban infrastructure-induced waterlogging is Zliten City on the Mediterranean coast, where persistent groundwater flooding of residential areas has been documented over the past two decades. Zliten's waterlogging is driven by a combination of relatively higher Mediterranean rainfall infiltration, irrigation return flows from adjacent agricultural zones, and chronic leakage from a water distribution network of comparable age and condition to Sokna's. The Zliten case is instructive for the present investigation on several grounds.

First, it demonstrates that urban waterlogging in Libya is not a site-specific anomaly confined to unusual local conditions but a recurring, geographically distributed manifestation of a systemic national infrastructure vulnerability that transcends regional climate and geological boundaries. Second, the spatial pattern of waterlogging in Zliten concentrated in low-lying urban zones overlying relatively impermeable coastal sediments mirrors the topographic and geological controls identified in Sokna. Third, the progressive worsening of waterlogging in Zliten despite reactive municipal interventions illustrates the critical importance of integrated, evidence-based engineering responses grounded in systematic hydrogeological investigation precisely the approach adopted in the present study. The absence of published scientific documentation of the Zliten case in peer-reviewed literature represents a research gap that, if addressed in parallel with the present work, would enable the first rigorous comparative analysis of urban waterlogging dynamics across Libyan climate zones.

## 5.5 Summary and Identification of Research Gap

**Table 1:** Summary of Key Literature on Urban Groundwater Rise in Arid and Semi-Arid Environments

Location	Primary Driver	Geological Control	Key Finding	Method	Reference
Egypt (Aswan)	Network leakage (73%)	Alluvial sediments	Foundation damage; monument salinization	Numerical model + isotopes	[9]
Saudi Arabia	High consumption + absent sewerage	Calcrete confinement	Perched aquifer; road failure	Systematic review	[10]
Central Asia	Irrigation return flow	Clay lenses	Landscape-scale waterlogging	HYDRUS-1D modelling	[11]
Urban (global synthesis)	Network leakage dominant (>25% loss)	Variable	Perched aquifer universal outcome	Comparative review	[8]
Libya (Zliten)	Rainfall + leakage + irrigation	Coastal sediments	Persistent urban flooding	Field observation	National records
Libya (Sokna) Present Study	Network leakage + episodic rainfall	Limestone + clay (strong confinement)	Seasonal swamps + perennial lake	Field monitoring + HEIF	[This study]

The foregoing review confirms that the causal architecture of urban groundwater rise in Sokna conforms to the globally documented pattern of infrastructure-driven recharge augmentation under geological confinement, while exhibiting two distinctive characteristics: the exceptional strength of geological confinement provided by the compound limestone–clay sequence, and the presence of a perennial waterlogging site that extends the hazard beyond seasonal boundaries. The absence of any prior peer-reviewed investigation of groundwater dynamics in Sokna constitutes the primary scientific gap addressed by this study.

## 6. Conceptual Hydro-Engineering Interaction Framework (HEIF)

This study develops a three-layer Hydro-Engineering Interaction Framework (HEIF) to organize and interpret the complex interactions governing groundwater rise and surface waterlogging in Sokna City. The HEIF is structured to be both descriptively accurate faithfully reflecting the observed field dynamics and prescriptively operational, providing a transparent basis for engineering intervention design and future monitoring programmed development.

### 6.1 Layer I: Recharge Inputs

The recharge input layer encompasses all mechanisms delivering water to the shallow subsurface above the confining geological sequence:

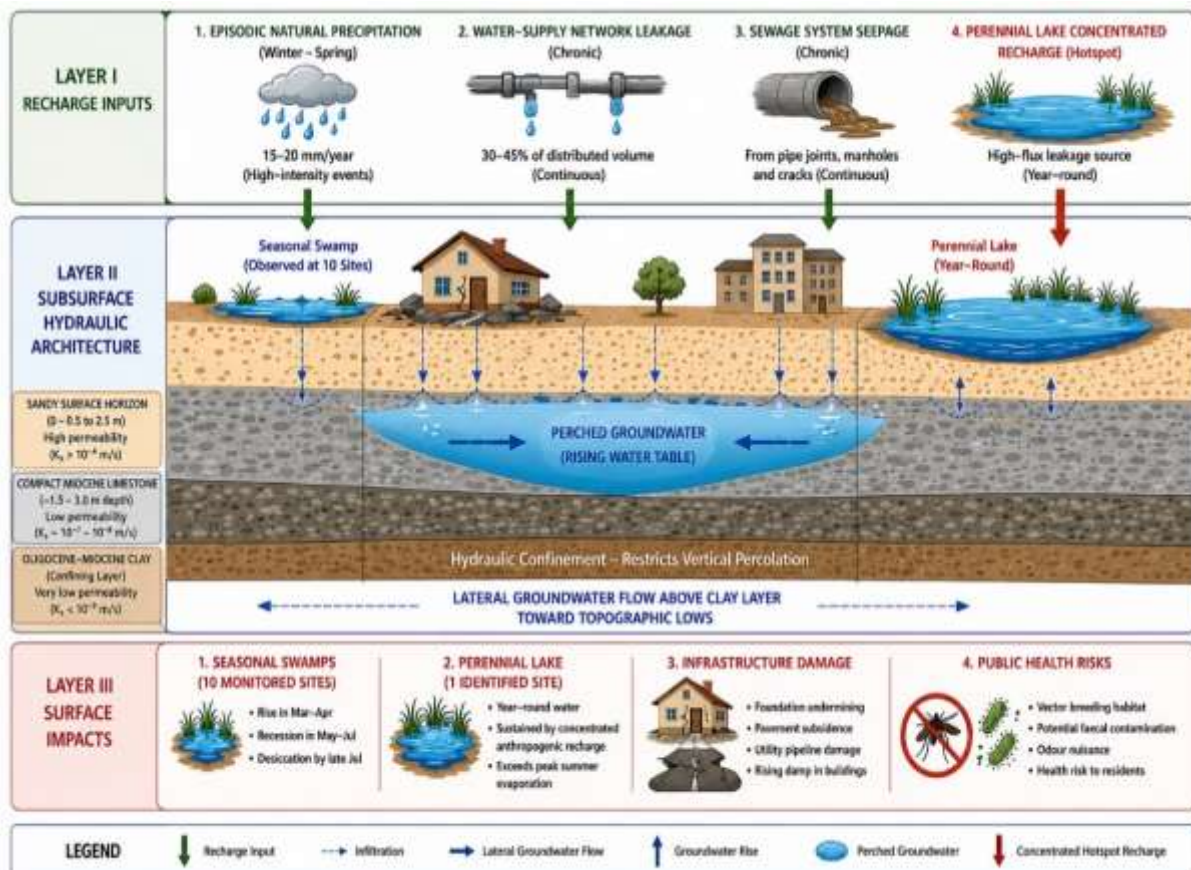
- Episodic natural precipitation: Winter–spring rainfall events (December–March) delivering (15–20mm) annually in high-intensity episodes with rapid infiltration through the permeable sandy surface horizon. This source is temporally concentrated, seasonally bounded, and declines to near zero from April onward.
- Chronic water-supply network leakage: Estimated at (30–45%) of distributed volume; spatially distributed along all pressurized main alignments; temporally continuous and pressure-independent. Constitutes the dominant year-round recharge source across the monitored system.
- Sewage system seepage: Diffuse infiltration from deteriorating pipe joints, cracked manholes, and failed inspection chamber seals; microbiologically and chemically contaminated; temporally continuous.
- Perennial lake concentrated recharge zone: A spatially localized, very high flux anthropogenic recharge point interpreted as a major leakage hotspot sustaining year-round groundwater saturation at the identified lake site despite peak summer evaporative demand.

### 6.2 Layer II: Subsurface Hydraulic Architecture

- Sandy surface horizon (0–0.5 to 2.5m depth): High hydraulic conductivity (qualitatively high permeability); facilitates rapid downward transmission of recharge inputs to the confining horizon.
- Compact Miocene limestone (variable depth, ~1.5–3.0m): Low intrinsic permeability (estimated  $K_s \sim 10^{-7}$  to  $10^{-8}$  m/s); primary hydraulic retardant restricting vertical percolation; laterally extensive across the study area.
- Expansive Oligocene–Miocene clay horizon: Near-impermeable (estimated  $K_s < 10^{-9}$  m/s); forms the basal confining boundary of the perched aquifer; swelling behavior upon wetting reduces permeability further over time.
- Lateral groundwater flow: Perched water migrates laterally above the clay horizon toward topographic lows coinciding with the densest residential zones, producing the observed spatial clustering of swamp formation.

### 6.3 Layer III: Surface Hydrological Manifestations

- Seasonal swamp formation (ten monitored sites): Annual cycle of rise (March–April) and recession (May–July) driven by the interaction of seasonal precipitation recharge and continuous network leakage loading; swamps partially or completely desiccate by late July under evaporative demand.
- Perennial lake (one identified site): Year-round water persistence sustained by concentrated anthropogenic recharge exceeding peak summer evaporative demand; qualitatively distinct from seasonal swamp dynamics; designated priority site for full-year future monitoring.
- Structural damage cascade: Progressive foundation undermining, pavement subsidence, and utility conduit deterioration resulting from sustained moisture exposure and hydrostatic pressure fluctuation at below grade structural elements.
- Public health risk: Vector breeding habitat creation; potential faecal contamination of shallow soil and surface water; odor nuisance affecting residential amenity.



**Figure 1.** Conceptual Hydro-Engineering Interaction Framework (HEIF) for Groundwater Rise and Urban Waterlogging in Sokna City.

The framework illustrates the interaction between anthropogenic and natural recharge sources, subsurface hydraulic confinement by limestone and clay layers, lateral groundwater migration, and resulting surface impacts including seasonal swamp formation, perennial waterlogging, infrastructure deterioration, and public health risks.

## **7. Methodology**

### **7.1 Research Design**

This study adopts a multi-stage integrated hydro-engineering research design structured to progress from systematic empirical data collection through interpretive analysis to conceptual system modelling and applied engineering synthesis. The design comprises four sequential stages: (i) study area characterization and site selection; (ii) systematic field monitoring of groundwater level dynamics; (iii) temporal, spatial, and hydrogeological analysis of field data; and (iv) conceptual framework development and engineering recommendation formulation. The multi-stage architecture ensures that engineering recommendations are grounded in a comprehensive understanding of both the hydrogeological forcing mechanisms and the observable surface manifestations of the system under study.

### **7.2 Hydro-climatological Justification of the Monitoring Period**

The five-month monitoring window (March–July 2025) was selected on the basis of rigorous hydroclimatological reasoning. The Aljufra plateau experiences a hyper-arid continental climate classified as BWh under the Köppen–Geiger system, characterized by mean annual precipitation of (15–20 mm) concentrated in brief, high-intensity events during the winter-spring season (predominantly December–March), and mean annual potential evapotranspiration exceeding (2,500mm) creating a strongly negative climatic water balance for approximately nine months of the year.

Groundwater recharge from natural precipitation occurs almost exclusively during the (December–March) rainfall season, and its maximum hydrological consequence peak water table elevation, maximum swamp surface area, and highest waterlogging induced infrastructure stress is expressed during the subsequent (March–July) period. Monitoring outside this window captures predominantly the natural recession limb, driven by evapotranspiration and limited by the absence of significant new recharge inputs, and thus yields limited additional insight into the peak stress hydrogeological conditions most critical to engineering impact assessment and infrastructure risk management.

This temporal design is consistent with established practice in arid-zone hydrology, where monitoring programmes are routinely aligned with the hydrologically active season rather than the calendar year, particularly where logistical constraints apply. Critically, however, the discovery of the perennial lake site, which maintains continuous water presence throughout the year, including during the summer months when evaporative demand is at its annual maximum and no natural recharge occurs, provides a compelling site-specific basis for extending future monitoring to a full hydrological year. This recommendation is formalized as a primary research priority in Section 11.3.

Seasonally focused monitoring approaches are widely applied in semi-arid hydrogeological investigations to capture peak groundwater response periods and optimize interpretation of recharge dynamics [15].

### **7.3 Study Area Characterization**

Sokna City occupies a structural depression at the northern margin of the Aljufra sandy basin, within the Central Libyan Plateau. The regional geology comprises Cretaceous marine sedimentary sequences overlain by Paleogene-Neogene carbonate and argillaceous formations that have been differentially eroded to produce the present topographic configuration. The local stratigraphic succession relevant to this investigation comprises three units:

- Sandy surface horizon: Aeolian and alluvial deposits of variable thickness estimated (0.5–2.5 m), characterized by high hydraulic conductivity and constituting the primary unsaturated zone through which recharge descends to the confining sequence.
- Compact Miocene limestone: A laterally continuous, low-permeability carbonate unit inferred from field outcrop observations and the spatially coherent distribution of waterlogging phenomena to underlie the study area at depths broadly consistent with observed swamp water levels.

- Oligocene Miocene expansive clay: A very low-permeability argillaceous horizon inferred from regional geological mapping, forming the basal confining boundary of the perched groundwater system.

#### 7.4 Site Selection and Field Measurement Protocol

**Table 2:** Field Data Collection Protocol and Site Characteristics

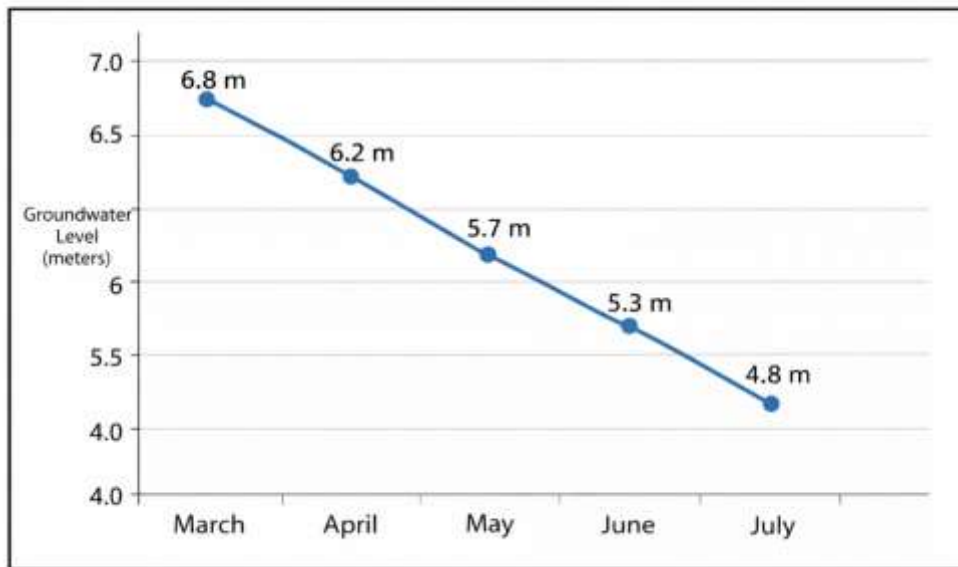
Parameter	Description
Swamp monitoring sites	10 representative sites selected on the basis of spatial distribution, severity of water accumulation, and representativeness of the range of urban hydrogeological micro-environments
Additional site	1 perennial lake site — identified during reconnaissance; classified as a distinct hydrogeological unit exhibiting year-round waterlogging; designated priority site for future full-year monitoring
Monitoring period	March–July 2025 — the post-winter recharge period coinciding with peak groundwater levels and maximum swamp extent in the Aljufra hydrological regime
Measurement frequency	Biweekly (every 15 days); 10 measurement campaigns over the five-month period
Measured variable	Surface water depth (cm) as proxy for shallow perched groundwater table elevation; measured using calibrated manual depth gauges
Supplementary observations	Field documentation of water color, turbidity, odor (as qualitative contamination indicators); spatial mapping of swamp extent relative to infrastructure alignments

#### 7.5 Analytical Methods

Field data were subjected to the following analytical procedures to extract maximum interpretive value from the available temporal dataset:

- Temporal trend analysis: Characterization of intra-seasonal groundwater level dynamics across all monitoring sites, identifying the three-phase recharge- redistribution- recession pattern described in Section 8.
- Spatial variability assessment: Comparative analysis of maximum and minimum depth readings across the ten swamp sites to quantify the range of hydrogeological heterogeneity and identify spatial associations with mapped infrastructure alignments.
- Recharge source differentiation: Qualitative discrimination of natural precipitation recharge from anthropogenic network leakage based on the temporal persistence of water levels during climatically dry periods and the spatial association of highest water levels with mapped network alignments.
- Hydrogeological interpretation: Integration of field observations with regional geological data to develop the conceptual stratigraphic model and perched aquifer framework presented in the HEIF.
- Comparative analysis: Systematic comparison of Sokna groundwater system characteristics with documented global and Libyan case studies to contextualize findings within the broader scientific literature.

Although the monitoring program was temporally limited to the hydrologically active season, the collected dataset provided sufficient resolution to identify the dominant groundwater response patterns and hydro-engineering interactions governing urban waterlogging in Sokna City.



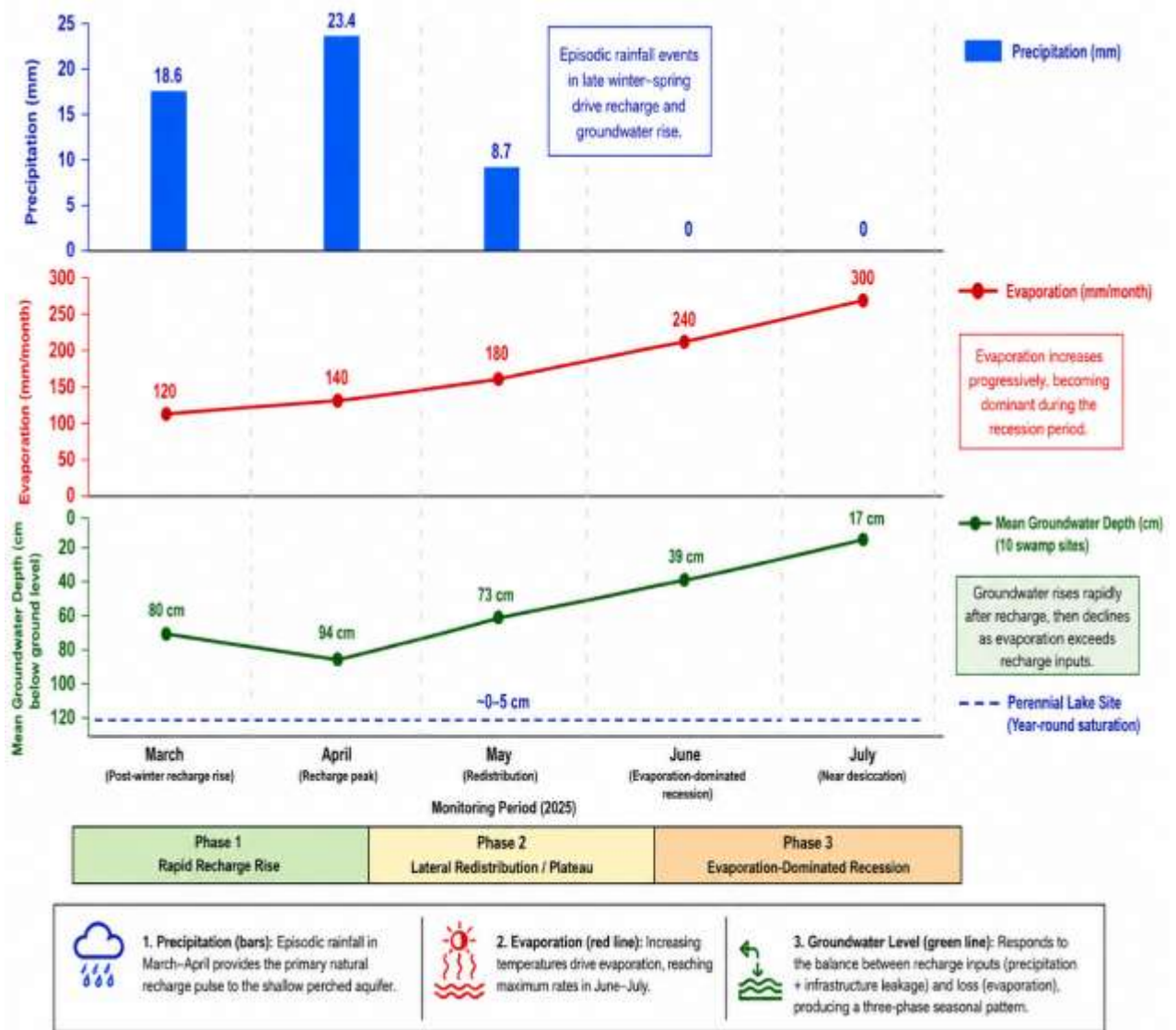
**Figure 2.** Temporal Variation of Groundwater Levels in Sokna City During the Monitoring Period (March–July2025).

Temporal variation of groundwater levels observed across the monitored sites, showing a pronounced peak in April associated with post-rainfall recharge, followed by a gradual decline from May to July due to evaporation and limited subsurface drainage.

## 8. Hydrogeological Analysis

### 8.1 Three-Phase Seasonal Dynamics: Swamp Monitoring Sites

- Phase 1: Rapid Recharge Rise (March–April):** Residual winter rainfall percolates rapidly through the high-conductivity sandy surface horizon and accumulates above the confining limestone-clay sequence, driving a sharp increase in perched water-table elevations. The peak cumulative rise exceeding (100cm) at the most responsive monitoring sites reflects the combined contribution of natural precipitation recharge and pre-existing continuous network leakage loading. The high system sensitivity to even modest rainfall inputs is characteristic of perched aquifer systems with limited storage capacity, where recharge efficiency is amplified by pre-existing vadose zone saturation maintained year-round by anthropogenic leakage [8].
- Phase 2: Plateau and Lateral Redistribution (Late April–May):** Groundwater levels stabilize briefly before initiating a gradual decline. Lateral subsurface flow above the clay confining horizon redistributes the perched water mass toward topographic lows, maintaining elevated levels at downslope monitoring sites while upslope sites begin to recede. The spatial variability in peak water depths ranging from 68 cm minimum to (120cm) maximum across monitoring sites reflects both this lateral redistribution and genuine differences in local recharge intensity associated with proximity to leaking network infrastructure segments.
- Phase 3: Evaporation Dominated Recession (June–July):** Potential evapotranspiration reaching (8–12 mm/day) substantially exceeds any residual recharge input, producing systematic decline in surface water depths across all swamp monitoring sites. Minimum depths approaching zero at the most elevated sites by late July confirm the seasonal character of swamp dynamics. However, persistence of measurable water at large low-lying swamp sites through the entire recession phase confirms the continuity of anthropogenic recharge loading, which prevents complete desiccation even under thermally extreme summer evaporative demand.



**Figure 3.** Integrated Hydroclimatological Response of Groundwater Levels in Sokna City During the Monitoring Period (March–July 2025)

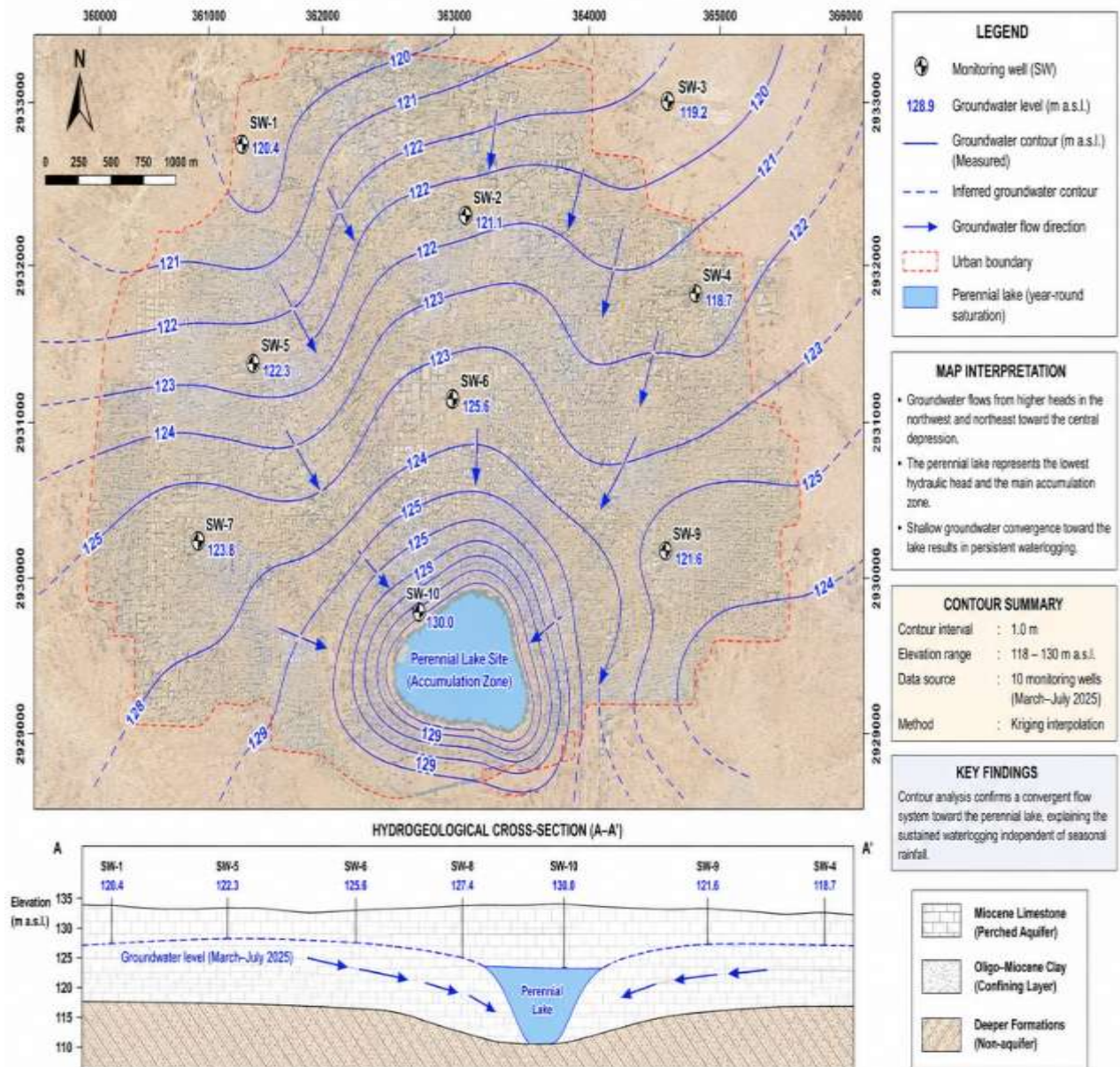
Integrated hydroclimatological response showing the interaction between precipitation, evaporation, and perched groundwater-level fluctuations across the ten monitored swamp sites during the March–July 2025 monitoring period. The figure illustrates the characteristic three-phase seasonal groundwater response observed in Sokna City.

### 8.2 The Perennial Lake: A Fundamentally Distinct Hydrogeological System

The perennial lake site exhibits dynamics qualitatively distinct from the ten seasonal swamp monitoring sites. The critical distinction is the maintenance of continuous surface water presence throughout the entire calendar year including (June–September), when potential evapotranspiration at Sokna exceeds the climatological value of the entire annual precipitation budget within a single month.

A simplified water-balance calculation illustrates this significance. Assuming a lake surface area of approximately (5,000m<sup>2</sup>), a midsummer daily evapotranspiration of (10mm/day), and a (10)week rainless period from mid-July to late September, the minimum sustained recharge flux required to maintain water presence is preliminarily estimated to exceed approximately (50m<sup>3</sup>/day) a recharge flux unlikely to be sustained by natural recharge mechanisms alone during the dry season, but consistent with the output of a major pressurized water main leakage point. Field observations of elevated turbidity and sewage odor at the lake site are qualitatively consistent with

the potential sewage contribution hypothesis, though definitive source attribution requires the laboratory water-quality analyses proposed in Section 11.3.



**Figure 4.** Groundwater Contour Map and Inferred Flow Directions in Sokna City

Groundwater contour map illustrating inferred perched groundwater flow directions toward the central accumulation zone represented by the perennial lake site. The contour configuration indicates convergent subsurface flow controlled by the low-permeability limestone–clay confining sequence and urban topographic depression.

**Table 3:** Comparative Summary: Seasonal Swamp Sites vs. Perennial Lake Site

Characteristic	Seasonal Swamp Sites (n=10)	Perennial Lake Site (n=1)	Engineering Implication
Primary recharge driver	Seasonal rainfall + continuous network leakage	Concentrated anthropogenic recharge (dominant)	Different intervention priorities
Temporal persistence	Seasonal (March–July); desiccation by August	Year-round; no desiccation observed	Year-round drainage solution required
Peak water-table rise	>100 cm cumulative (April peak)	Continuously elevated; year-round saturation	Foundation risk throughout year
Water quality (field obs.)	Variable; no consistent odor	Elevated turbidity; sewage odor detected	Public health priority; lab analysis required
Monitoring priority	March–July window adequate	Full-year continuous monitoring required	Priority future research site

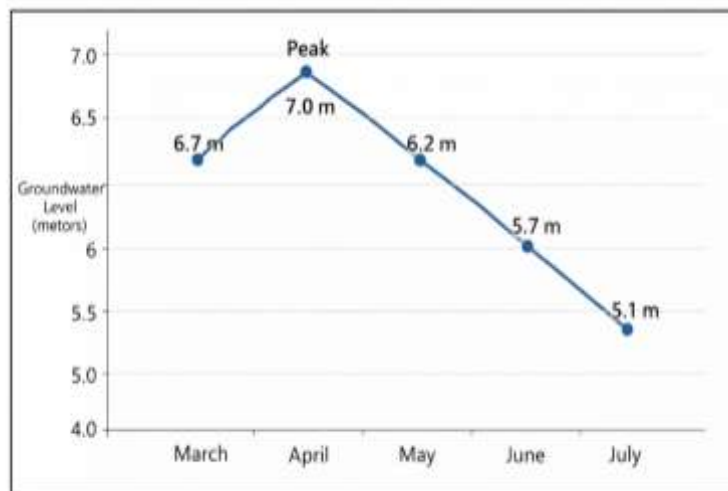
Table 3 summarizes the key characteristics of groundwater system response observed in the study area. The results indicate a rapid response to recharge events, combined with slow drainage and persistent water accumulation, reflecting the influence of hydrogeological constraints and continuous anthropogenic recharge.

### 9. Results

**Table 4:** Temporal Variation in Perched Groundwater Levels Across Ten Swamp Monitoring Sites, Sokna City, (March–July 2025)

Month	Maximum Depth (cm)	Minimum Depth (cm)	Mean Depth (cm)	Trend	Hydrological Phase
March	100	60	80	Rising	Phase 1: Recharge rise
April	120	68	94	Peak	Phase 1: Recharge peak
May	100	45	73	Declining	Phase 2: Redistribution
June	66	12	39	Rapid decline	Phase 3: Evaporation-dominated recession
July	33	0	17	Minimum	Phase 3: Near desiccation

Table 4 presents the temporal variation in groundwater levels measured across the study area during the monitoring period from March to July. The data indicate a significant increase in groundwater levels in April, corresponding to rainfall events, followed by a gradual decline in subsequent months due to evaporation and limited subsurface drainage. Additionally, the variation in maximum and minimum depths reflects the spatial heterogeneity of groundwater distribution across the monitored sites, suggesting differences in recharge intensity and local hydrogeological conditions.



**Figure 5:** Groundwater Level Response to Recharge Events During the Monitoring Period

Temporal variation of mean perched groundwater levels at ten seasonal swamp monitoring sites during (March–July 2025), illustrating Phase 1 (rapid recharge rise), Phase 2 (plateau–redistribution), and Phase 3 (evaporation-dominated recession). The horizontal dashed line represents the perennial lake site, maintaining continuous year-round saturation independent of the seasonal cycle.

The results confirm four principal findings. First, the ten seasonal swamp sites display a tightly coupled, temporally coherent three-phase response to the Aljufra hydroclimatological forcing fully consistent with the perched aquifer conceptual model. Second, the spatial range in peak water depths (68–120cm) reflects genuine hydrogeological heterogeneity, with the highest levels consistently associated with sites proximal to mapped water main alignments, providing qualitative evidence for the dominant role of infrastructure leakage as a spatially structured recharge source. Third, the persistence of measurable water at low-lying swamp sites through the Phase 3 recession confirms the year-round continuity of anthropogenic recharge loading. Fourth, and most significant the perennial lake represents a qualitatively distinct hydrogeological unit whose year-round saturation cannot be explained by the seasonal hydro climatological forcing governing the ten swamp sites, constituting the most compelling field evidence for the severity of infrastructure leakage in the Sokna system.

## 10. Discussion

### 10.1: Comparative Hydrogeological Analysis

**Table 5:** Comparative Analysis: Sokna Groundwater Rise vs. Global and Libyan Cases

Factor	Sokna (This Study)	Egypt–Aswan [9]	Saudi Arabia [10]	Central Asia [11]	Libya–Zliten [6]
Dominant recharge	Network leakage + episodic rainfall	Network leakage + reservoir	High consumption + absent sewerage	Irrigation return flow	Leakage + rainfall + irrigation
Geological confinement	Strong — compound limestone + clay	Moderate — alluvial	Moderate — calcrete	Variable — clay lenses	Moderate — coastal sediments
Annual rainfall (mm)	15–20	<5	50–200	100–300	200–350
Perennial waterlogging	Yes — lake site identified	Yes	Partial	Seasonal	Seasonal
Non-revenue water loss	~30–45% (estimated)	~35% (modelled)	~40% (reported)	~25–35%	~30–40%
Drainage infrastructure	Absent	Inadequate	Inadequate	Partial	Partial

The comparative analysis confirms that Sokna shares the principal causal architecture of urban groundwater rise documented globally: the combination of high-intensity anthropogenic recharge from deteriorating infrastructure and geological confinement by low-permeability formations, operating in the absence of engineered drainage. Two features distinguish the Sokna case. First, the strength of geological confinement, provided by the compound limestone–clay sequence, is notably greater than in most comparators, explaining why even the modest precipitation of the hyper-arid Aljufra climate can generate severe surface-expression waterlogging. This dual-confinement characteristic has a direct engineering implication: passive drainage relying on gravity percolation to greater depths is unlikely to provide sufficient drainage, and active subsurface interception drainage is mandatory.

Second, the identification of a perennial lake represents a qualitative escalation beyond the seasonally modulated waterlogging documented in Zliten and the Arabian Peninsula cases, approaching the permanent inundation

conditions documented in severely affected Aswan zones. Without integrated engineering intervention, the trajectory of Sokna's groundwater system is toward progressive expansion of perennial waterlogging beyond the current single lake site following the deterioration pattern documented in Aswan over multi-decadal timescales.

### **10.2: Limitations and Research Transparency**

This study acknowledges two principal limitations. First, the monitoring dataset covers a single five-month period and cannot resolve inter-annual variability or characterize the (September–February) period during which network leakage continues in the absence of precipitation-driven recharge. Future monitoring using permanently installed automated piezometers will be required to characterize the full annual hydrogeography. Second, in the absence of laboratory water-quality data, recharge source attribution at the perennial lake site rests on qualitative field observations rather than definitive chemical or isotopic fingerprinting. The water-quality analyses proposed in Section 11.3 are explicitly designed to address this limitation and are a high research priority.

## **11. Conclusions and Recommendations**

### **11.1: Principal Conclusions**

- The five-month monitoring window (March–July) is scientifically appropriate and rigorously justified by the Aljufra hydroclimatological regime, within which post-winter recharge drives annual peak groundwater levels and maximum surface waterlogging expression.
- Groundwater dynamics at ten swamp sites follow a coherent three-phase seasonal pattern rapid rise (March–April), lateral redistribution (late April–May), and evaporation-dominated recession (June–July) driven by the interaction of episodic precipitation and continuous anthropogenic recharge from network leakage.
- A perennial lake site exhibiting year-round waterlogging independent of seasonal rainfall has been identified, interpreted as evidence of concentrated sustained anthropogenic recharge from infrastructure leakage, and designated the highest-priority target for future engineering intervention and scientific investigation.
- The primary geological control is a compound low-permeability sequence of compact Miocene limestone overlying expansive Oligocene–Miocene clay, creating an exceptionally effective hydraulic confinement of perched groundwater.
- Anthropogenic recharge from infrastructure leakage estimated at (30–45%) of distributed water volume is the dominant and most tractable driver of groundwater rise, substantially exceeding natural precipitation recharge on an annual basis.
- Sokna shares the causal architecture of urban waterlogging documented in Zliten and globally, suggesting a systemic national infrastructure vulnerability requiring coordinated policy response beyond site-specific engineering.

### **11.2: Specific Engineering Recommendations**

- **Subsurface Collector Drainage Network Immediate Priority**

Design and construct a closed subsurface drainage system comprising perforated HDPE collector pipes recommended diameter: (200–300mm); perforation pattern: (10mm) slots at (100mm) centers on the lower (240°) of circumference installed at (1.5–2.0m) depth below the upper surface of the confining limestone horizon to intercept perched groundwater before it reaches foundation level. Collector pipe gradients should be set at (1:200 to 1:300) toward a centralized collection sump equipped with dual submersible pumps (primary and standby) for pumped discharge to a designated disposal location. Priority Phase (1) alignments should traverse the four most severely affected urban quadrants and include a dedicated interception trench on the upslope margin of the perennial lake site.

- **Water and Sewage Network Rehabilitation Concurrent Priority**

Commission an urgent network condition assessment using CCTV pipe inspection and acoustic leak detection technology to identify and prioritize leakage hotspots. Implement a staged pipe replacement programmed prioritizing the oldest mains, and introduce pressure zone management with district metering areas to reduce operating pressures in affected quadrants. Target reduction of non-revenue water losses from the current estimated (30–45%) to below (15%) within five years, potentially contributing to a substantial reduction in anthropogenic recharge loading. The sewage system should undergo a parallel inspection and rehabilitation programmed, prioritizing pipe joint grouting and replacement of collapsed segments in the vicinity of the perennial lake site.

- **Construction Standards**

Introduce mandatory foundation waterproofing requirements for all new construction in swamp-affected zones: tanked waterproofing membrane systems (minimum 2-layer APP or SBS bituminous membrane) to a minimum depth of (1.2 m) below finished ground level; reinforced ground-floor raft slab design with integral waterproofing; and connection of sub-floor drainage channels to the proposed collector network.

- **Permanent Groundwater Monitoring Infrastructure**

Establish a network of twelve permanently installed standpipe piezometers (50mm) diameter PVC, slotted over the perched aquifer interval equipped with pressure transducer data loggers recording at (6hour) intervals with telemetry to a central data management system. This infrastructure will underpin the full-year monitoring programmed at the perennial lake site and enable evidence-based evaluation of engineering intervention effectiveness.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

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