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Comparative Research Progress on Hydrogeological Potential of Major Geological Complexes: A Case Study of Togo and China

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ABSTRACT

Groundwater is one of the most important sources of freshwater globally, but its availability and sustainability vary greatly depending on geology and climate. This study provides a comparative analysis of groundwater potential in Togo and China, with particular attention to lithology, aquifer characteristics, and management challenges. In Togo, aquifers are largely developed within fractured Precambrian crystalline rocks, where water storage is confined to weathered layers and fracture systems. These aquifers generally display low transmissivity (10^{-4}–10^{-2} m²/s), storage coefficients below 0.01, and average specific yields of about 2%. Recharge is mainly linked to seasonal rainfall, typically ranging from 50 to 150 mm per year, which makes these systems highly sensitive to climate variability and limits their ability to support long-term water supply. Moreover, China has extensive sedimentary basins, alluvial plains, and karst aquifers that are considerably more productive. Transmissivity values often exceed 10^{-2} m²/s, specific yields commonly reach 10–15%, and recharge averages around 120 mm per year, with values above 500 mm per year in humid karst regions. While these aquifers provide large storage and high yields, they are under intense pressure from long-term overuse, particularly in the North China Plain where groundwater levels are dropping by 0.5–1.5 m annually. Water quality is also a major concern, with widespread nitrate, salinity, and heavy metal contamination. The comparison shows two distinct challenges: Togo faces localized limitations and severe data gaps, while China struggles with systemic depletion despite having advanced monitoring and modelling systems. Nonetheless, both regions offer lessons for one another. Techniques such as numerical modelling, isotope hydrology, and machine learning used in China could enhance groundwater assessment in Togo, while Togo's low-cost, field-based methods may provide useful approaches for rural or data-inadequate areas in China. Therefore, the study demonstrates that effective groundwater management depends not only on geological conditions but also on institutional capacity and the adoption of appropriate technologies to balance recharge, abstraction, and quality protection. These insights support the development of cross-regional strategies aimed at improving groundwater resilience in the face of growing climate and socio-economic pressures.

INTRODUCTION

Togo

Togo, a West African country, is underlain by a diverse set of geological formations that strongly influence its hydrogeological characteristics. The substratum consists of Precambrian basement rocks, Paleozoic sedimentary sequences, and younger Cenozoic deposits, each contributing differently to groundwater occurrence and distribution (Tossou *et al.,* 2017). Geographically, Togo is bordered by Burkina Faso to the north, the Atlantic Ocean to the south, Benin to the east, and Ghana to the west (Figure 1). The country covers an area of approximately 56,785 km², stretching about 600 km in length, with a width varying between 50 and 150 km. Administratively, it is divided into five economic regions: Maritime, Plateau, Central, Kara, and Savannas. The Maritime region provides access to the Atlantic and hosts Lome, the national capital. According to the International Monetary Fund (2025), Togo has a population of about 9.52 million. Agriculture, agri-food industries, trade, mining, and service sectors largely drive its economy. The country's relief is heterogeneous, consisting of plains, hills, plateaus, valleys, and mountains, much of which reflects the legacy of the Pan-African orogeny some 600 million years ago. This tectonic event gave rise to the Dahomeyide orogenic belt, which traverses the country from the southwest to the northeast. Togo's geology is structured around five principal complexes: the Paleoproterozoic Basement Complex, the Neoproterozoic Pan-African Belt, the Voltaian Basin, the Coastal Sedimentary Basin, and the Atakora Structural Unit (Duku *et al.,* 2015). Each of these units has undergone distinct tectonic and lithological evolution, resulting in varying levels of groundwater potential. This diversity is central to understanding the hydrogeological dynamics and the availability of water resources across the country. Climatically, Togo is characterized by a tropical regime with two distinct zones. The northern part experiences a dry tropical climate with one rainy season and one dry season, while the southern part is more humid,

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featuring two rainy and two dry seasons annually. These climatic patterns, in conjunction with the geological framework, exert strong control over the distribution and sustainability of groundwater resources vital for agriculture, domestic supply, and industry. Groundwater is the most widely accessible source of freshwater on Earth, providing essential supply for nearly half of the global population across domestic, agricultural, and industrial sectors (Barry, 2022; Tang *et al.,* 2022). In areas where surface water resources are scarce, particularly across much of Africa and Asia, groundwater serves as the main source of safe and dependable drinking water (Nyika *et al.,* 2023; Gaye, 2019). Growing pressure on these reserves has raised urgent questions about their sustainability, natural recharge capacity, and long-term management in the face of climate variability and rising demand (Orowale *et al.,* 2023; Fontodji *et al.,* 2019). Togo offers a representative case of the challenges facing sub-Saharan Africa, where hydrogeological research remains relatively limited. The country's groundwater occurs primarily in fractured crystalline basement aquifers and, to a lesser extent, in localized sedimentary basins. Yet systematic studies of aquifer productivity, recharge processes, and vulnerability are still scarce (Egbueri *et al.,* 2025; Coulidiati *et al.,* 2025). Most available work has focused on site-specific investigations, such as small-scale geophysical surveys or borehole yield measurements, with little integration into broader regional frameworks. This lack of comprehensive data and modelling restricts effective groundwater management and weakens the capacity of national water strategies to address the impacts of climate change (Akara *et al.,* 2021).

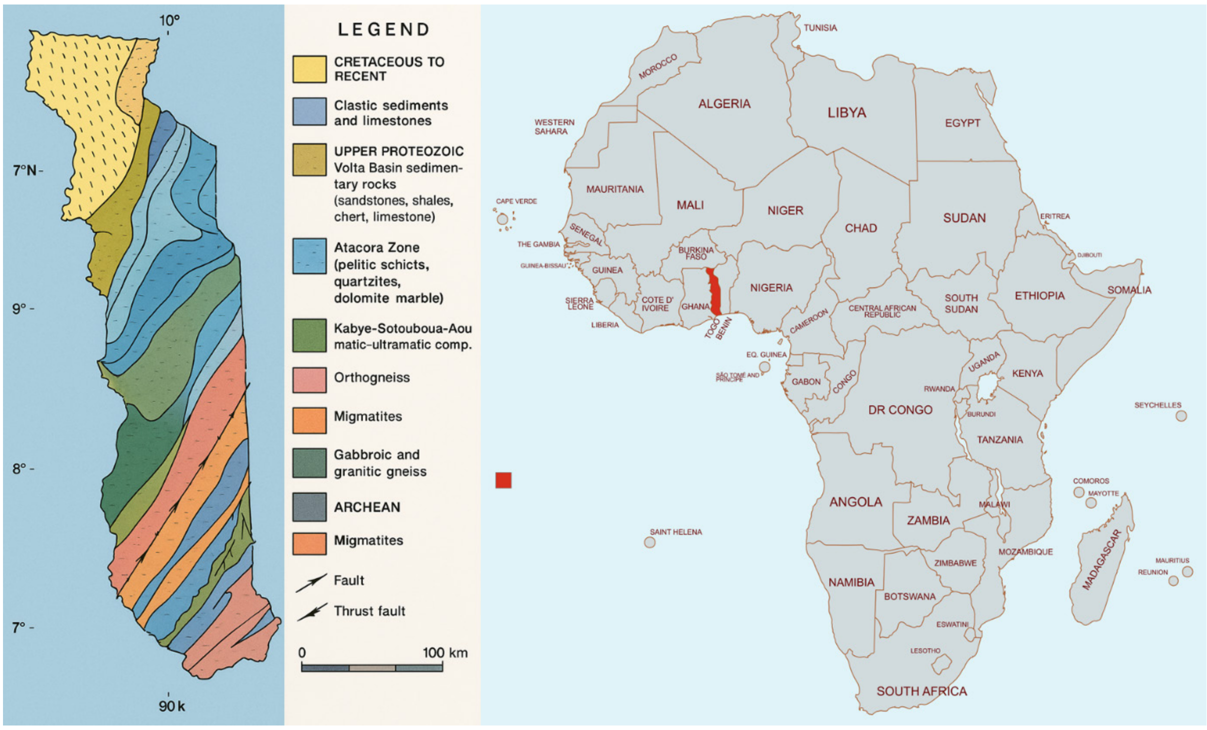


Figure 1: Geological and Location Maps of Togo: (a) Geological map illustrating the principal lithological units and structural features; (b) Map showing Togo's position within the African continent

China

China, one of the world's largest countries, maintains a highly complex geological history that strongly shapes the distribution and availability of its groundwater resources. Whereas Togo's hydrogeology is largely defined by Precambrian crystalline rocks and younger Phanerozoic units, China's vast territory encompasses an exceptionally wide range of geological environments. These extend from ancient cratonic terrains to extensive sedimentary basins, offering a broader diversity of aquifer systems. Groundwater plays a critical role in China, particularly in the northern regions where surface water is scarce (Hao *et al.,* 2017). The contrasting geological settings, climate regimes, and management approaches in Togo and China therefore give rise to markedly different hydrogeological characteristics. China's groundwater systems display strong spatial variability, reflecting the country's diverse geology and geomorphology. As shown in Figure 2(a), the extensive alluvial deposits of the North China Plain and the Songnen Plain form some of the nation's most productive aquifers, serving as crucial sources of irrigation water and urban supply. These unconsolidated sediments provide substantial storage and recharge potential. Elsewhere, piedmont and deltaic environments such as the Jianghan and Poyang basins host mixed sedimentary aquifers that support both agriculture and large population centers. In southern China, karstified carbonate formations dominate the hydrogeological framework. Dissolution processes in limestone and dolomite create aquifers of considerable capacity, though they are highly heterogeneous and particularly vulnerable to contamination. In contrast, mountainous regions like the margins of the Sichuan Basin are characterized by fractured bedrock aquifers. These systems provide important localized water sources but are generally limited in storage and yield.

Extensive tracts of impervious bedrock, particularly across the Qinghai–Tibet Plateau and parts of Inner Mongolia, limit groundwater occurrence and impose natural constraints on water availability. In addition, permafrost zones in the high-altitude Qinghai–Tibet Plateau and northeastern China restrict infiltration, thereby reducing recharge potential. These conditions contrast sharply with the fertile alluvial plains, highlighting the pronounced spatial unevenness of groundwater resources across the country. Figure 2(b) situates China within the Asian continent, emphasizing its vast territorial extent and the resulting diversity of hydrogeological conditions. Together, the maps illustrate the decisive influence of geological structure and climatic setting on groundwater occurrence, recharge processes, and the spatial distribution of aquifer systems. Unlike Togo, China has made substantial investments in hydrogeological research and groundwater management. Large-scale investigations have been conducted in the North China Plain, the Loess Plateau, and the karst terrains of southern China, generating comprehensive datasets on aquifer properties, recharge processes, and groundwater surface water interactions (Lu *et al.,* 2021; Liu *et al.,* 2022). Advanced analytical and modelling approaches including MODFLOW-based numerical simulations, isotope hydrology, and machine learning techniques have been widely applied to characterize aquifer systems and to forecast their response to over-extraction and climate variability (Panthi *et al.,* 2023; Atta *et al.,* 2024). Despite this progress, China continues to confront serious challenges, including groundwater depletion, contamination, and marked regional imbalances in availability, underscoring the urgency of sustainable management strategies (Du & Chilton, 2024; Lancia *et al.,* 2022). The comparative perspective between Togo and China illustrates two ends of the hydrogeological research spectrum: one dominated by data scarcity and limited investigation, the other by advanced modelling but mounting sustainability concerns. The critical research gap lies in the lack of integrative, cross-regional analyses that explore how methods developed in data-rich contexts can be adapted for application in under-studied regions. This study therefore seeks to (i) document the present state of hydrogeological knowledge in Togo, (ii) contrast it with the research progress and ongoing challenges in China, and (iii) outline potential pathways for methodological transfer, innovation, and policy development. By connecting these perspectives, the work aims to advance a more globalized understanding of groundwater potential and the requirements for its sustainable use.

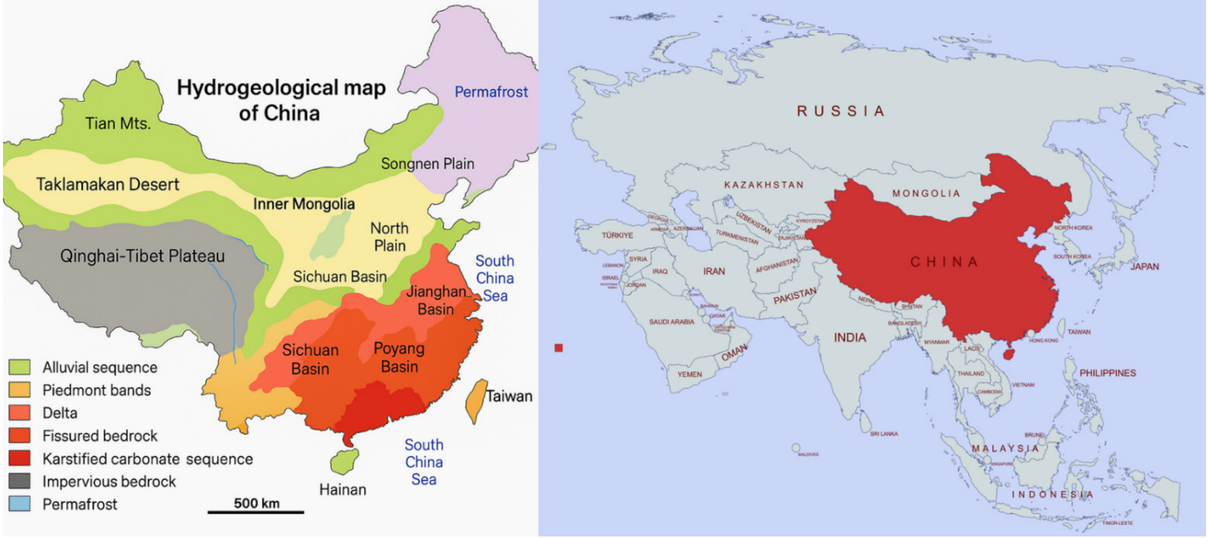


Figure 2: Hydrogeological and location maps of China: (a) Overview of major aquifer systems, sedimentary basins, plains, plateaus, and permafrost zones; (b) Map showing China's geographical position within Asia

Geological and Hydrogeological

The hydrogeological structure of any region is largely determined by its lithology, structural characteristics, and stratigraphic development. Assessing groundwater potential therefore requires careful consideration of the underlying geology, aquifer architecture, and associated hydraulic properties. Togo and China illustrate two markedly different settings: Togo is dominated by crystalline basement aquifers with limited storage capacity, whereas China hosts vast sedimentary and karst systems that can support large-scale groundwater exploitation.

Togo: Crystalline Basement Aquifers and Weathered Zones

The hydrogeology of Togo is largely controlled by Precambrian crystalline basement rocks, including granites, gneisses, schists, and quartzites (Zondokpo *et al.,* 2022; Kalsbeek *et al.,* 2012). Although these rocks are inherently impermeable, secondary porosity created through fracturing and weathering allows for limited groundwater storage. The most productive water-bearing zones occur within the regolith aquifer system, where a weathered mantle, typically 10–40 m thick, overlies fractured basement formations. Aquifer transmissivity is generally low, ranging from 1.0×10^{-4} to 1.0×10^{-2} m^2/s (Table 1), and borehole yields are highly variable, commonly between 0.2 and 2.5 L/s. Recharge is primarily derived from direct rainfall infiltration, making these aquifers highly sensitive to seasonal and interannual climatic variability (Akpataku *et al.,* 2019). The major hydrogeological provinces of Togo as presented in Figure 3, categorized by dominant lithological units. In the Maritime region, sedimentary and alluvial deposits form relatively shallow aquifers with moderate productivity. The Plateaux region, underlain by quartzite and schist, supports groundwater storage mainly through secondary porosity related to fracturing and weathering. In the Centrale region, granite and gneiss dominate, and groundwater is generally confined to localized fractured zones. The Kara region is also composed mainly of metamorphic and crystalline rocks, where aquifer potential is limited by low primary porosity. Similarly, the Savanes region in the north is underlain by crystalline and metamorphic units, with groundwater occurrence dependent on weathered and fractured zones. The hydrogeological framework of Togo (Figure 4a) reflects the predominance of crystalline basement terrains, where aquifer productivity is closely tied to the degree of weathering and fracturing. By contrast, the sedimentary and alluvial deposits of the southern part of the country provide more favourable conditions for groundwater development.

China: Sedimentary Basins, Karst Systems, and Loess Aquifers

China shows a wide range of hydrogeological provinces, a reflection of both its vast territorial extent and its complex geological evolution. As illustrated in (Figure 4b), the country's major sedimentary basins such as the North China Plain consist of thick accumulations of unconsolidated alluvial and semi-consolidated deposits. These units host highly productive aquifers, with transmissivity values frequently exceeding 1.0×10^{-2} m^2/s (Chen *et al.,* 2011). In southern China, extensive karst terrains form one of the largest carbonate aquifer systems in the world, marked by dissolution features including conduits and channels that facilitate rapid groundwater circulation (Li *et al.,* 2020). A further distinctive setting is the Loess Plateau of north-central China, where fine-grained aeolian sediments act as porous aquifers, though they are susceptible to collapsibility and often develop perched water tables (Derbyshire *et al.,* 2001). Compared with the aquifer systems of Togo, these provinces generally provide far greater storage and yield. Nevertheless, they remain vulnerable to intensive abstraction and widespread contamination, highlighting the persistent challenge of ensuring sustainable groundwater use.

Stratigraphic and Lithological Contrasts

The fundamental hydrogeological distinction between Togo and China lies in the geometry of their aquifers and the influence of lithology. In Togo, fractured crystalline aquifers are typically shallow, discontinuous, and limited in storage capacity. By contrast, China's aquifer systems are dominated by extensive sedimentary basins and karst terrains that are multi-layered and capable of sustaining regional-scale water supply. These lithological differences shape contrasting recharge processes: in Togo, recharge occurs mainly through diffuse infiltration across thin regolith layers, whereas in China it is strongly influenced by large river aquifer exchanges and rapid recharge through karst conduits. This structural divergence not only

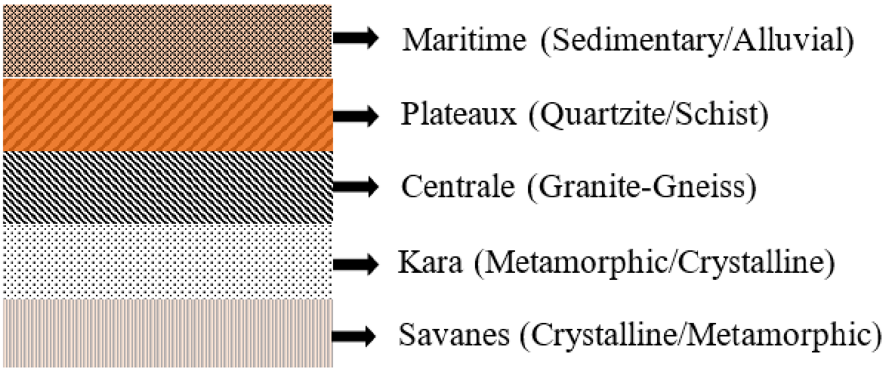


Figure 3: Geological outline of Togo showing the major hydrogeological complexes by region

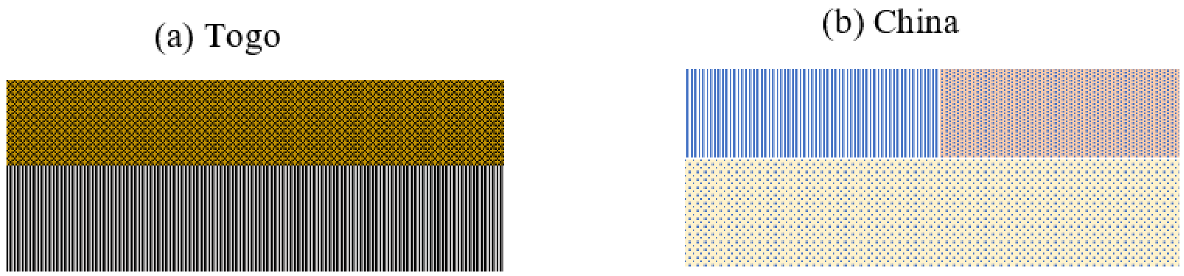


Figure 4: Comparative hydrogeological provinces illustrated in schematic cross-section: (a) Togo – crystalline basement aquifers formed within fractured and weathered rocks (gray), overlain by a weathered regolith zone 10–40 m thick (gold); (b) China – sedimentary basin aquifers, both unconfined and confined (yellow), the Loess Plateau aquifers (orange), and extensive karst carbonate systems (blue).

governs groundwater potential but also determines the degree of susceptibility to depletion and contamination.

A comparative stratigraphic outline for Togo and China is presented in Figure 5, highlighting the key lithological and temporal differences that govern groundwater occurrence and aquifer development. In Togo, the succession is dominated by an extensive Precambrian basement (>1500–2000 Ma), composed mainly of crystalline rocks including granite, gneiss, schist, and quartzite. This unit represents the structural foundation of the country's hydrogeological system. Aquifer potential within the basement is largely secondary, controlled by weathering mantles (10–40 m thick) and networks of fractures. Above this basement, limited Paleozoic sedimentary sequences (<500 Ma) are present, hosting localized porous and fractured aquifers with modest transmissivity. At the surface, relatively thin Cretaceous to Quaternary deposits (0–100 Ma) comprising sandstones, lateritic sediments, and alluvial materials occur intermittently. These younger formations support shallow aquifers of moderate productivity, particularly within the southern coastal plain and along major river valleys.

In contrast, China's stratigraphic succession shows a much wider variety of lithologies and depositional settings. As in Togo, a Precambrian crystalline basement (>1500–2000 Ma) forms the structural foundation, but it is overlain by a far more extensive sedimentary cover. Paleozoic basins (250–500 Ma) are particularly widespread and consist of sandstones, shales, and limestones that together form multi-layered aquifer systems. Younger sequences, including Mesozoic intrusive and metasedimentary formations (65–250 Ma), along with thick Cretaceous Cenozoic basin fills, contribute significantly to groundwater storage, especially in northern China. The most recent deposits comprise Quaternary alluvium and loess (0–2 Ma), which are

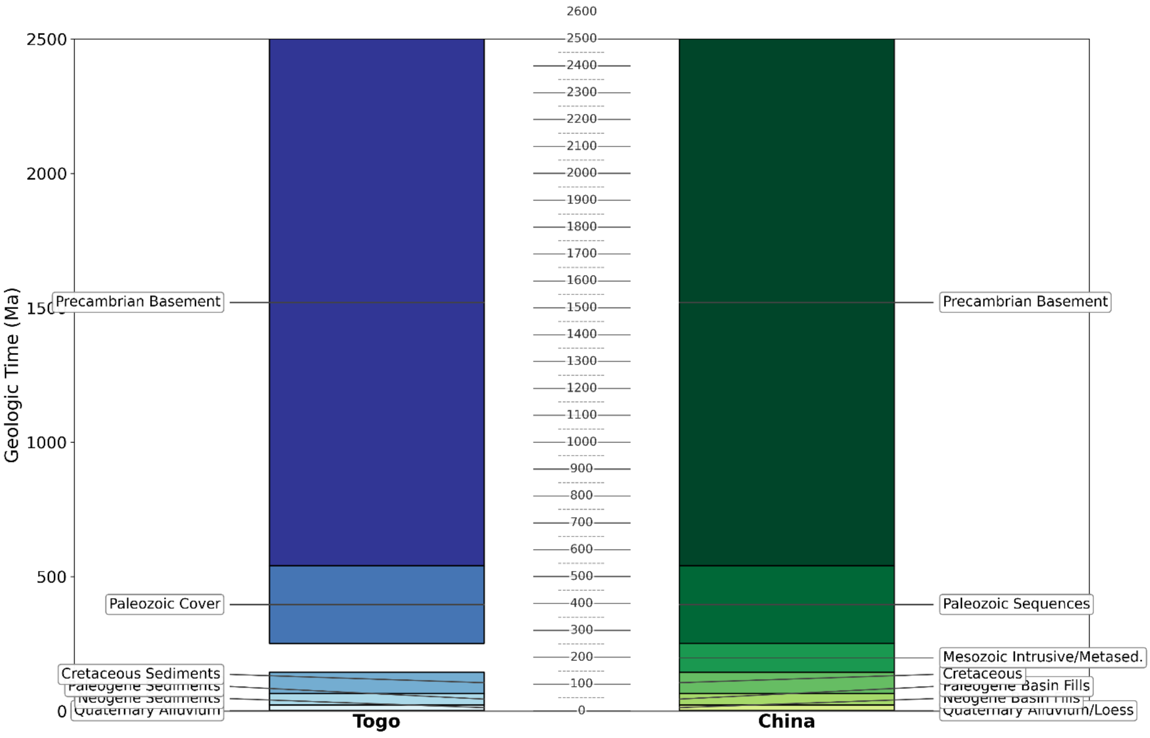


Figure 5: Stratigraphic correlation between Togo and China

m^2/s. This stratigraphic comparison underscores a fundamental contrast between the two countries. Togo's hydrogeological framework is constrained by a basement-dominated sequence capped by relatively thin sedimentary veneers, producing low-storage, fracture-controlled aquifers. By comparison, China's succession includes thick, multi-layered sedimentary basins and loess plains that overlie the basement, resulting in extensive, high-yield aquifer systems. However, these productive aquifers are also highly vulnerable to over-extraction and contamination. While both regions share the antiquity of a Precambrian basement (>2000 Ma), the divergence in younger sedimentary cover largely accounts for their contrasting groundwater potential and sustainability.

Table 1: Comparative hydrogeological characteristics of the principal geological complexes in Togo and China

Geological Complex	Aquifer Type	Hydraulic Conductivity (m/s)	Transmissivity (m^2/s)	Storage Coefficient (-)	Specific Yield (%)	Effective Porosity (%)
Togo; Crystalline Basement (gneiss, Granite, schist	Fractured/ weathered aquifer	10^{-7}-10^{-5}	10^{-4}-10^{-2}	10^{-5}-10^{-3}	0.5-2	2-5
Togo; Sedimentary Outliers	Local porous aquifer	10^{-6}-10^{-4}	10^{-3}-10-1	10^{-4}-10^{-2}	1-5	5-10
China; Sedimentary Basins (North China Plain)	Unconfined/ confined aquifer	10^{-5}-10^{-3}	10^{-2}-10^{-0}	10^{-3}-10^{-1}	5-15	20-30
China; Karst (South China)	Carbonate conduit aquifer	Highly variable	0.1-10	10^{-4}-10^{-2}	10-20	15-25
China; Loess Plateau	Porous loess aquifer	10^{-6}-10^{-4}	10^{-3}-10^{-1}	10^{-4}-10^{-2}	2-8	10-20

The hydraulic parameters presented in Table 1 can be quantitatively related to groundwater flow through Darcy's law, which expresses discharge in porous media as:

$$Q = - K \cdot A \cdot (\Delta h/\Delta l) \qquad ....(1)$$

Here, (K) denotes the hydraulic conductivity, (A) represents the cross-sectional area of flow, and $\Delta h/\Delta l$ corresponds to the hydraulic gradient. This formulation underscores the direct influence of lithological characteristics on aquifer productivity.

Methods Applied in Togo

Evaluating hydrogeological potential requires comprehensive methodological frameworks that bring together field surveys, geophysical investigations, geochemical and isotopic tracing, and predictive modelling. While both Togo and China have developed approaches suited to their geological settings, they differ greatly in terms of sophistication and spatial coverage. For this study, a systematic field campaign was carried out between June 27 and August 1, 2024, along the Lome–Dapaong corridor (National Route No. 1). This route provided access to key outcrops for direct geological observation. The survey documented a range of formations, including: (i) sandstones, tillites, barite-bearing carbonates, and flints within the Yemboure and Bamboli groups; (ii) the Mango Group, characterized by silto-micaceous claystones interbedded with sandstones; and (iii) garnet granulites in the Kabye Massif along with metamorphic units of the Dahomeyide Chain. GPS coordinates were recorded at representative sites to support accurate mapping and location-specific documentation. In addition, published reports and previous studies were consulted, and the application of geophysical methods was recommended to identify zones favourable for groundwater storage prior to borehole development. In Togo, hydrogeological exploration continues to rely primarily on traditional field and geophysical techniques. This reliance reflects both the crystalline basement environment, where groundwater occurs mainly in weathered and fractured zones, and the institutional and financial constraints that limit the adoption of advanced technologies. The most widely applied methods include:

(i) Borehole hydrographs and pumping tests: Borehole monitoring remains a cornerstone of groundwater assessment. Step-drawdown and constant-rate pumping tests are commonly used to estimate transmissivity and storativity, although the reliability of results is often limited by short test durations and restricted spatial coverage (Tizro *et al.,* 2014). The interpretation of these data is frequently carried out using the Theis analytical solution for confined aquifers, which expresses drawdown as a function of pumping time:

$$s = Q/(4_{\pi}\ T)\ W(u),\ u = (r^2\ S)/4Tt \qquad ....(2)$$

Where s denotes drawdown, Q the pumping rate, T the transmissivity, S the storativity, r the radial distance from the pumping well, and t the elapsed time. This formulation provides the theoretical basis for deriving aquifer parameters from field test data.

(ii) Geoelectrical surveys: Techniques such as Vertical Electrical Sounding (VES) and two-dimensional Electrical Resistivity Tomography (ERT) are commonly applied to identify weathered zones and fractured basement horizons that may serve as groundwater reservoirs. These methods are relatively cost-effective, though their interpretation can be ambiguous, particularly when attempting to distinguish between clay-rich strata and water-saturated layers.

(iii) Water-table mapping: Groundwater levels measured from dispersed boreholes are used to construct potentiometric maps. However, the limited density of monitoring wells restricts spatial resolution. Seasonal variations in groundwater levels clearly demonstrate the strong reliance of recharge on direct rainfall infiltration.

Although these methods yield valuable site-specific information, they are often applied in isolation and seldom integrated into regional-scale hydrogeological models. The absence of continuous time-series data further constrains predictive analyses and the evaluation of management scenarios. Figure 6 presents the typical workflow followed during hydrogeological field investigations in Togo, beginning with reconnaissance activities and extending to long-term monitoring. The diagram highlights the sequential integration of field surveys, geophysical investigations, drilling, aquifer testing, and ongoing monitoring, all underpinned by cross-cutting elements such as quality assurance, community participation, safety procedures, and systematic data management. The fieldwork phase generally starts with reconnaissance mapping at scales ranging from 1:10,000 to 1:50,000, providing baseline information on topography, access conditions, and hydrogeological indicators. This step is followed by detailed hydrogeological mapping, which emphasizes springs, structural lineaments, and lithological features that help delineate potential recharge and discharge zones. The geophysical stage primarily employs resistivity techniques, notably Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT). These methods, typically applied at depths of 30–200 m with profile lengths ranging from 0.5 to 2 km, are used to identify weathered zones, fracture networks, and subsurface heterogeneities favourable for groundwater occurrence. The results of geophysical surveys guide the subsequent drilling stage, which combines hydrogeological mapping with resistivity profiles to determine optimal drilling sites. Drilling operations include casing, screen installation, and gravel packing to stabilize boreholes and safeguard water quality. Lithological logs obtained during drilling provide confirmation of subsurface conditions and inform well design. The analysis phase follows, during which aquifer properties such as transmissivity (T), hydraulic conductivity (K), storativity (S), and specific capacity are evaluated. Standard analytical approaches, including Theis and Cooper–Jacob interpretations of pumping test data, are commonly used to assess aquifer performance. In the final stage, a monitoring network is established using observation wells equipped with water-level loggers and sampling points. These systems enable long-term tracking of groundwater levels, quality, and recharge dynamics, forming the basis for sustainable resource management. Importantly, the overall workflow is integrative rather than strictly sequential, with outputs from each stage feeding into the next. Supporting components including quality assurance and quality control procedures, stakeholder engagement, health and safety measures, and structured data management are essential to ensure the reliability and long-term applicability of hydrogeological investigations in fractured crystalline terrains such as those found in Togo.

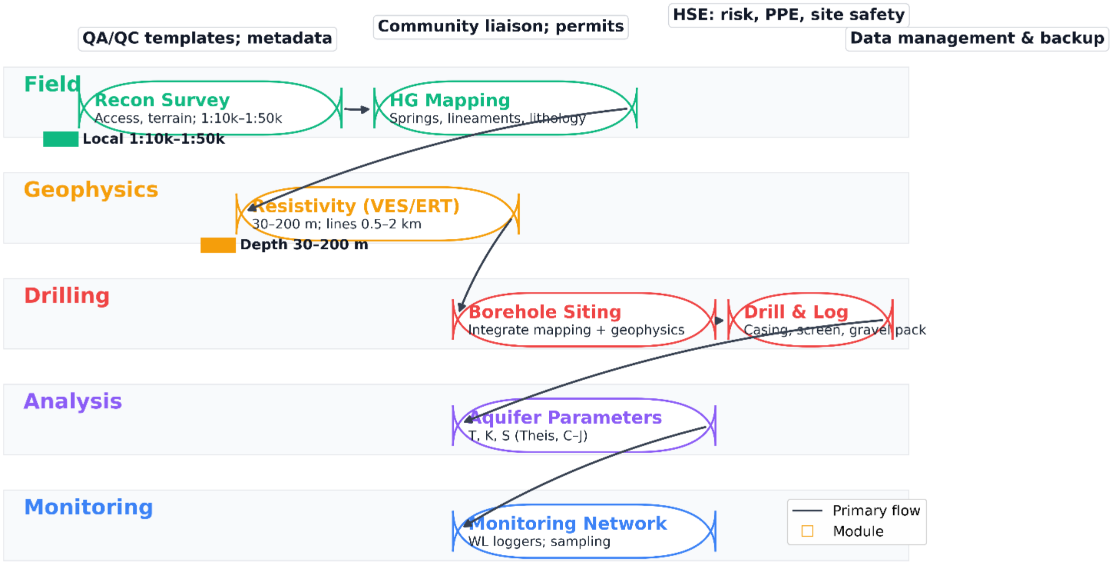


Figure 6: Methods for hydrogeological field studies in Togo

Figure 7 illustrates a conceptual cross-section of groundwater occurrence and flow in a typical crystalline basement aquifer system. The hydrostratigraphy comprises three main layers: a lateritic or regolith cover, an underlying saprolite zone of weathered bedrock, and the deeper fractured crystalline basement. While the regolith and saprolite offer only limited storage, the fractured basement forms the principal aquifer unit. Recharge is derived mainly from rainfall infiltration, which percolates downward to replenish the water table. Lateral groundwater movement is concentrated along the weathered interface between the saprolite and the fractured basement. Productive aquifers develop in areas where fracture networks are well connected, with transmissivity (T) closely controlled by fracture continuity. Reported hydraulic conductivity values generally range from 1×10^{-7} to 1×10^{-5} m/s, and specific yield typically varies between 1% and 5%. Groundwater discharge occurs through perennial streams and natural springs, maintaining baseflow even during the dry season. In practice, production boreholes are commonly completed within the fractured basement to secure deeper and more dependable groundwater supplies. The schematic underscores the reliance of groundwater availability on the extent of weathering, the connectivity of fractures, and the balance between recharge and discharge processes.

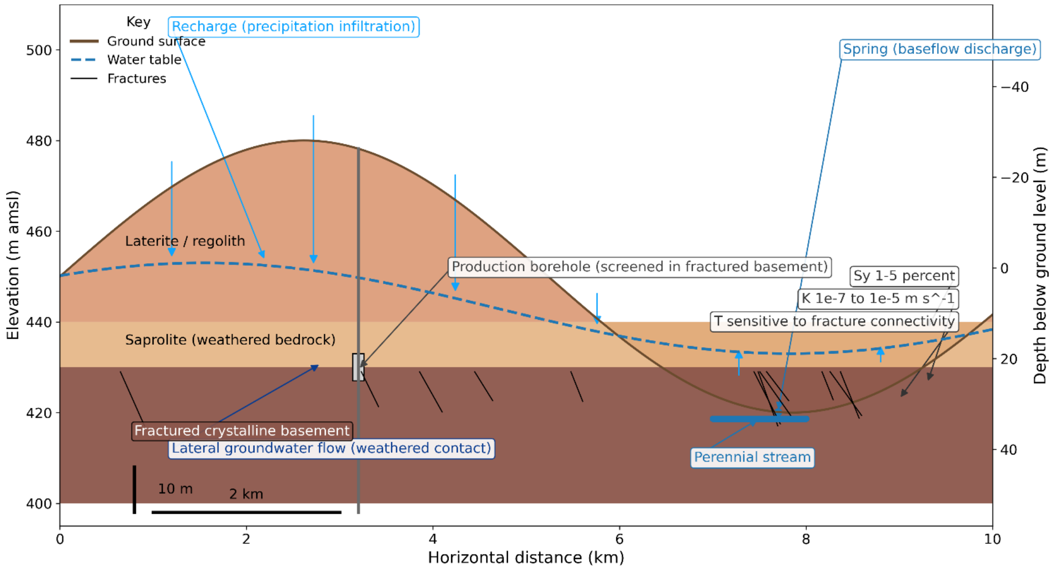


Figure 7: Conceptual type of groundwater occurrence and flow in a fractured basement aquifer system in Togo

Birrimian Base

The investigation of the Birrimian basement at Dapaong, in the Nanergou locality, led to the identification of an old granite quarry located at GPS coordinates 10°55'11"N; 0°9'47"E. Outcrops of pink and gray granite were observed at the site. The sampling zone forms a natural depression in which infiltration water accumulates, creating an open-air pond. The granite is marked by numerous horizontal fractures resulting from exfoliation, intersected by subvertical fractures conditions that strongly favor rainwater infiltration and storage at the base of the depression. An alteration mantle composed of quartzo-feldspathic sands was also identified, where surface runoff has carved a badlands-type landscape. During the survey, a borehole fitted with a manually operated foot pump was visited, which taps into these altered zones for water supply. It is noteworthy that the Birrimian basement rocks in this region are approximately 2,000 million years old.

The Volta Basin

Figure 8 presents a schematic cross-section of the Volta Basin, illustrating its stratigraphic sequence and major unconformities along a northwest–southeast transect. Field observations revealed a prominent basal unconformity of conglomeratic composition, which separates the Birrimian basement from the overlying Volta Basin near the Caroli Hotel. The basin itself is deposited in a monoclinal structure upon this basement. Its age is estimated between 1100 and 700 million years, and it is subdivided into two supergroups: Supergroup I, known as the Bombouaka Supergroup, and Supergroup II, referred to as the Oti Supergroup. Supergroup I is further divided into three constituent groups, which are described in detail below.

The Dapaong Group

The Dapaong Group consists predominantly of silty sandstones, commonly referred to as "Dapaong sandstone." During the field survey, an outcrop was examined near Dapaong at GPS coordinates 10°51'37" N; 0°12'50" E. Water from a nearby dam is utilized for multiple purposes, including agriculture and gardening, with off-season crops being sustained through its use. A second site was visited at GPS coordinates 10°46'52" N; 0°15'36" E, where a borehole equipped with a manually operated hand pump was observed.

The Lions' Den Group

The Lion's Den Group is subdivided into two main formations. From the base upwards, the sequence begins with the Natala Formation, which consists of two members: basal siltstones overlain by argillites. Above this lies the Kotare Formation, composed of claystones at the base, followed successively by sandstones and psammites. The Kotare argillites are separated from those of Natala by a ravinement unconformity of conglomeratic character, though this boundary is not continuous across the region. At Bombouaka, a surface reservoir was observed where runoff water accumulates due to the impermeable, clay-rich bedrock. This reservoir lies within the Kotare argillites. Along the roadside, these argillites appear in thin flakes or slices with a purplish to greenish-gray coloration. They contain silt and mica, giving rise to the term "silt-micaceous argillite." Being soft and impermeable, these clay-rich formations hinder fracture development, thereby restricting infiltration and rendering them largely unproductive in terms of groundwater potential. Overlying these units are the so-called "jumper" sandstones, which form prominent relief features visible from a distance. These sandstones gradually grade into psammites micaceous, clayey sandstones characterized by fracture development. These fractures facilitate infiltration, with water often seeping along psammite walls and producing gently sloping relief. During the survey, a borehole equipped with a wind-powered pump was observed tapping the psammites, demonstrating that this upper member of the Kotare Formation contains productive fractures and has greater groundwater potential compared to the underlying argillites.

Panabako Group

The Panabako Group is divided into two formations: the Bogou Formation at the base, resting directly on the psammites of the Lion's Den Group, and the Yemboure Formation at the summit. Both units are composed primarily of sandstones. The Bogou sandstones were observed above the psammites near the borehole fitted with a wind-driven pump, located not far from the Bombouaka market. From there, the survey ascended a slope leading into a pass formed by erosion within a prominent fracture zone, clearly visible in the surrounding relief. Sandstones were observed extensively in this area, displaying numerous fractures, particularly along the major fracture crossings, which may enhance groundwater productivity. The Yemboure sandstones were examined in Nabame village at GPS coordinates 10°36'42" N; 0°14'4" E. These rocks show evidence of oblique and cross-bedded stratification, similar to that seen in the Bogou sandstones but with inverted orientations, suggesting deposition under more turbulent marine conditions compared to Bogou. Although fractures are present within the Yembouré sandstones, they are less developed and not strongly penetrative, which may limit their hydrogeological potential relative to the Bogou sandstones.

Super group II or Oti Super Group

This supergroup is divided into two units: the Bamboli Group at the base and the Mango Group above it.

Bamboli Group

The Bamboli Group is composed of a tripartite sequence consisting, from base to top, of tillites, barite-bearing carbonates, and flints. At Nayega (GPS coordinates 10°44'31" N; 0°26'17" E), tillites impregnated with manganese were observed, forming a manganese deposit that overlies the Yemboure sandstone. Although barite carbonates were not encountered during the survey, flint outcrops were identified at Barkoissi (GPS coordinates 10°33'29" N; 0°18'3" E). These flints occur in centimetric to decimetric beds and display intense fracturing. Fresh flint is bluish-gray with a conchoidal fracture, while weathered surfaces exhibit a reddish-brown alteration rind. The high degree of fracturing facilitates rainwater infiltration, and the presence of productive wells in the area suggests a local groundwater potential.

Mango's Group

The Mango Group consists mainly of silty–micaceous claystones with thin intercalations of clay–micaceous siltstones. The sequence thickens progressively toward the southeast and shows a gentle dip in the same direction. Overall, the formations of the Mango Group are generally of low hydrogeological productivity; however, localized sandstone interbeds can occur, which may contain groundwater and provide limited yield.

The cross-section highlights a prominent unconformity that distinguishes the older basement formations from the overlying younger deposits, marking intervals of erosion and subsequent basin reactivation. The figure illustrates the structural and lithological complexity of the Volta Basin, where alternating sandstones and mudstones, punctuated by unconformities, reflect a dynamic geological history shaped by sedimentation, tectonic activity, and episodes of erosion.

The Pan-African Chain of the Dahomeyids

The chain is composed of an external zone and an internal zone, separated by a structural suture. The external zone includes the Buem structural unit, the Atakora structural unit, and the Kara–Niamtougou orthogneiss unit. The latter actually represents rocks of the internal zone that were tilted toward the external margin as a result of tectonic transport. The internal zone itself corresponds to the Benino–Togolese peneplain. Apart from serpentinite outcrops observed on a hill at Sokode–Kemeni, corresponding to part of the Buem Formation, the eastern subunit of the Atakora Range was the primary

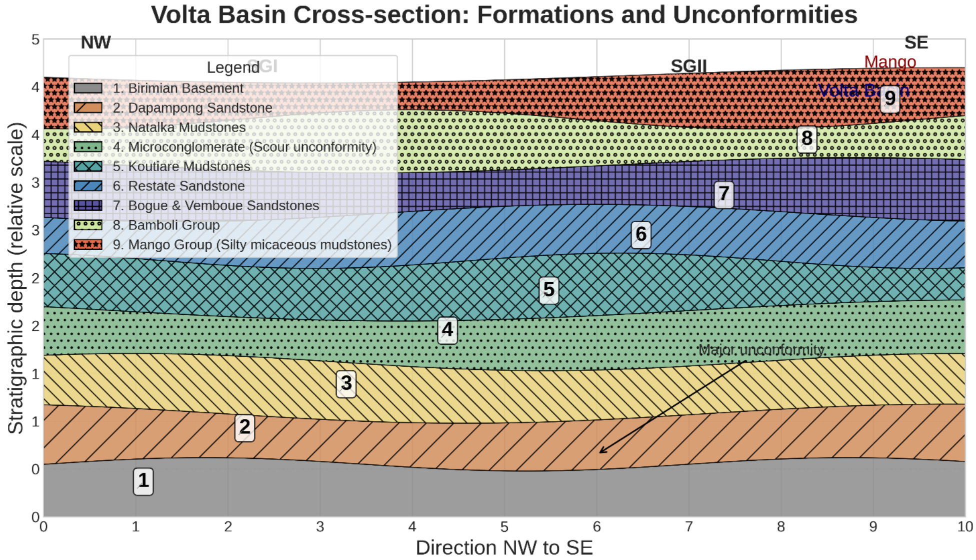


Figure 8: Volta basin cross-section: formations and unconformities

focus of investigation in the external zone. This subunit is dominated by quartzites with intercalated mica schists. The Atakora quartzites are heavily fractured, as evident from aerial photographs where vegetation alignments trace rectilinear fracture patterns in the relief. At the Defale spring, groundwater discharges naturally through fracture networks within the quartzites, converging to form a perennial spring. A reservoir has been constructed to collect and treat this water before distribution to local communities. The spring water is naturally clear and of good quality. In the surrounding relief, subvertical faults with sinistral strike-slip movement were also identified. Along the road to the spring, groundwater was observed seeping through fractures in the quartzites to form a small spring below the roadway. Further observations were made at Bafilo, in the locality of Daoudi, where an artesian spring has been developed into a public fountain (GPS coordinates 9°19’11” N; 1°4’27” E). The spring has an average discharge of 0.37 L/s. Additionally, from the main road past the town of Bafilo, a waterfall was visible cascading along a wide-open fracture within the quartzitic relief. This water is captured and piped to supply the town. At higher elevations, the relief is composed primarily of quartzites with interbedded mica schists.

The Suture Zone

Within the Pan-African suture zone, a field visit was conducted to the Kabye Massif in the locality of Wyande, where outcrops of garnet granulites were observed. These rocks form the main body of the massif. Although largely impermeable, they display evidence of fracturing.

The Internal Zone

The Dahomeyide Chain corresponds to the Benino–

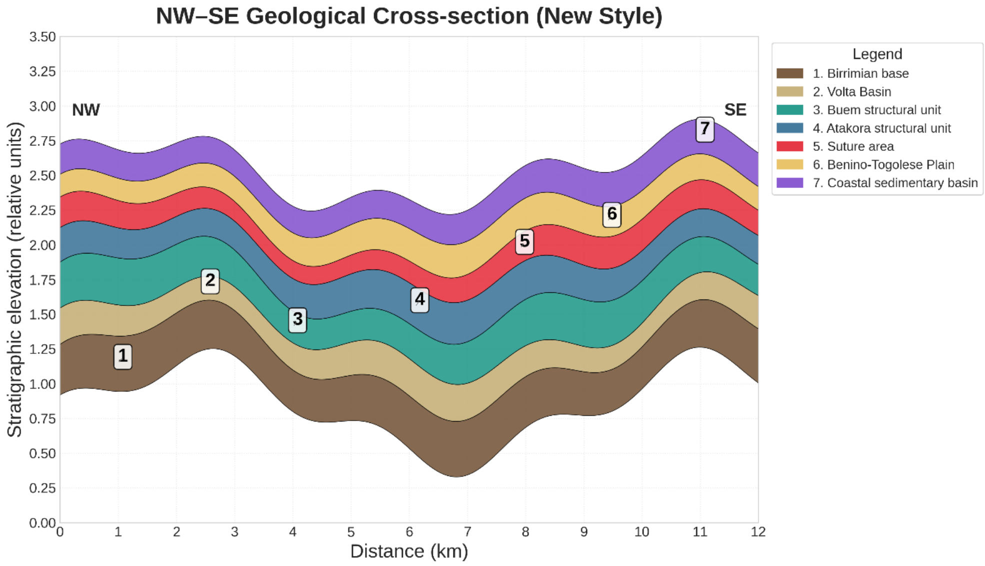


Figure 9: Morphostructural cross-section showing the major geological units of Togo

Togolese peneplain, which forms much of the Plateau region. It is composed predominantly of metamorphic rocks, including gneisses, migmatites, and various anatexites. At an abandoned quarry in the migmatites near Rodkkpe, groundwater was observed accumulating within the artificial depression left by rock extraction. The water originates from subsurface flow, having migrated along fracture networks within the rock mass before collecting at the base of the depression. This localized reservoir supports a small ecosystem, sustaining both plant and animal life around its margins.

The Coastal Sedimentary Basin

The coastal sedimentary basin of Togo rests in fundamental unconformity upon the formations of the Benino–Togolese plain. During the survey, a brief stop was made in the dry wedge area, where water scarcity is common due to the limited thickness of sediments and the proximity of the underlying basement formations. In such zones, geophysical investigations are essential to identify favourable environments for groundwater accumulation before siting boreholes. The coastal basin comprises three main aquifer systems: the Terminal Continental aquifer, the Paleocene limestone aquifer, and the Maastrichtian aquifer. Figure 9 shows a schematic cross-section from northwest (NW) to southeast (SE), depicting the principal stratigraphic and structural units of the region. At the base lies the Birimian basement (1), which forms the crystalline foundation of the sequence.

Above the crystalline basement lie successive sedimentary and structural units, beginning with the Volta Basin (2) and the Buem structural unit (3), followed by the Atakora structural unit (4). Overlying these is a distinct suture zone (5), which marks the tectonic boundary separating the older basement-derived complexes from younger deposits. Toward the southeast, the Benino–Togolese Plain (6) and the Coastal Sedimentary Basin (7) represent more recent depositional environments, shaped by prolonged subsidence and sediment accumulation. The cross-section illustrates the gradual transition from ancient basement rocks to structurally deformed belts, and ultimately to younger, relatively undeformed sedimentary basins along the NW–SE transect. This arrangement reflects the tectono-sedimentary evolution of the region, where Precambrian foundations are overlain by folded structural units and later capped by coastal deposits.

Atakora Structural Unit

The Atakora Unit is composed primarily of folded and faulted sedimentary rocks and generally exhibits moderate to low groundwater potential. This limitation arises from the prevalence of low-permeability formations such as shales and siltstones. Nevertheless, fractured sandstones and fault zones can function as secondary aquifers, though their yields are typically modest (Nti *et al.,* 2025). Groundwater also occurs locally in depressions and valleys, where natural reservoirs develop and provide supplementary water resources.

Methods Applied in China

Hydrogeological research in China is marked by the integration of advanced techniques across multiple scales, combining modelling, remote sensing, and geochemical/isotopic tools. This reflects both the intensity of groundwater use and the wide variety of hydrogeological settings across the country. The main methodological approaches include:

(i) Numerical groundwater flow simulations:

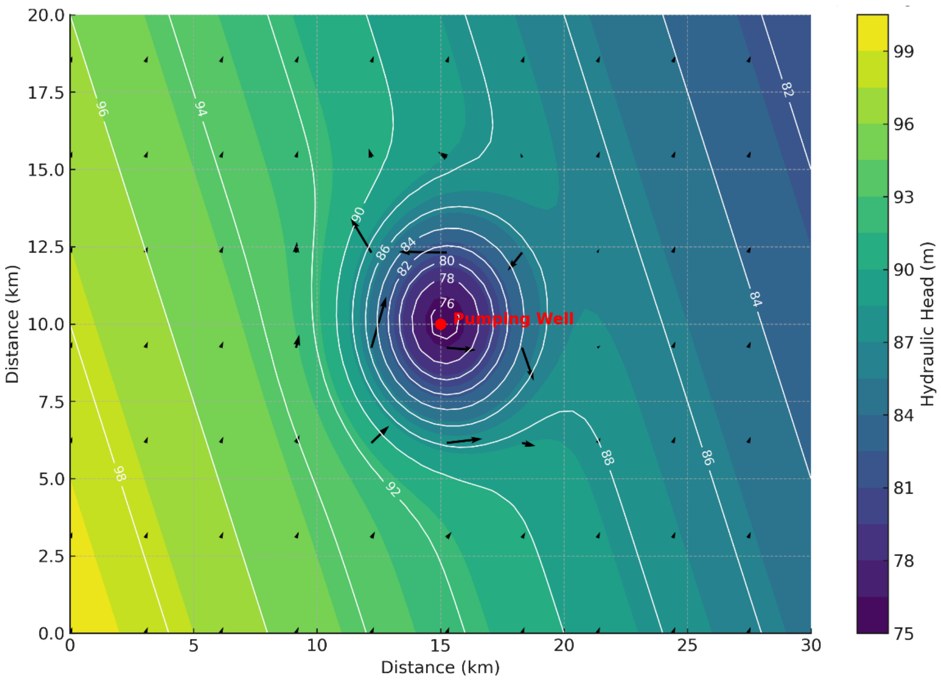


Figure 10: Numerical simulation of groundwater flow in a Chinese sedimentary basin (MODFLOW model output)

MODFLOW (Figure 10) and its derivatives, such as SEAWAT for density-dependent flow, have been widely applied in the North China Plain to quantify depletion, simulate drawdown under different pumping regimes, and evaluate managed aquifer recharge options (Yao *et al.,* 2015). In geologically complex areas, finite-element models are also used to complement finite-difference simulations.

(ii) Isotope hydrology: Stable isotopes ($\delta^{18}O$, δD) and radioisotopes (^{3}H, ^{14}C) are employed to trace recharge sources, estimate groundwater residence times, and establish linkages between surface and subsurface waters. These techniques have proven especially effective in characterizing recharge processes in karst aquifers (Yang *et al.,* 2011).

(iii) GIS and remote sensing integration: Geographic Information Systems provide a framework for combining lithological, hydrological, and climatic data, while satellite observations such as those from the GRACE mission offer large-scale estimates of groundwater storage variability (Liu *et al.,* 2018).

(iv) Artificial intelligence and machine learning: Methods including Random Forest (RF), Long Short-Term Memory (LSTM) networks, and hybrid AI–GIS platforms are increasingly being used to forecast groundwater levels, assess aquifer vulnerability, and map groundwater potential zones (Hu *et al.,* 2021).

Numerical models such as MODFLOW must be calibrated against observed groundwater levels, with their performance commonly assessed using the root mean square error (RMSE):

$$\mathrm{RMSE} = 1/n \sum_{i=1}(h_{obs,i} - h_{sim,i})^2 \qquad ....(3)$$

Where h_{obs} and h_{sim} represent the observed and simulated hydraulic heads, respectively. A lower RMSE value reflects a closer agreement between simulations and field measurements, indicating more reliable predictions of aquifer behavior.

Comparative Strengths and Limitations

As illustrated in Table 2, the methodological differences between Togo and China are substantial. In Togo, groundwater investigations rely on localized and low-cost approaches that are well adapted to crystalline basement terrains. However, these methods are constrained by limited temporal coverage and poor integration, while the absence of large-scale numerical modelling or isotopic studies leaves significant gaps in understanding recharge processes and long-term sustainability. However, China employs multidisciplinary and multi-scale methodologies that allow for more comprehensive assessments of groundwater systems. Yet advanced techniques are not without limitations: large-scale numerical models are highly data-intensive and sensitive to parameter uncertainty, while machine learning methods, despite their predictive strength, may overfit when not anchored in sound hydrogeological principles. Bridging this divide requires both transfer and adaptation of methodologies. China's advanced models and analytical tools could be adapted for Togo, provided that baseline data collection is improved to support their application. Conversely, Togo's experience with low-cost geophysical methods in remote and data-scarce settings offers practical lessons that could enhance groundwater exploration in less accessible regions of China.

Table 2: Comparative structure for hydrogeological studies and modelling in Togo and China

Togo: Traditional and Localized Methods	China: Advanced and Integrated Methods
Field Data Collection (Borehole Hydrographs, Pumping Tests)	Large Scale Data Integration (Geological, Climatic, Hydrological)
Geophysical Surveys (VES, ERT)	GIS and Remote Sensing (GRACE, Landsat, DEMs)
Water Table Mapping and Potentiometric Surfaces	Numerical Modelling (MODFLOW, SEAWAT)
Local Aquifer Characterization (Storage, Transmissivity)	Advanced Analysis (Isotopes, Machine Learning Prediction)

Hydrogeological Potential: Analysis and Comparative Results

The hydrogeological capacity of an aquifer is shaped by its geology, storage properties, ability to transmit water, recharge dynamics, and exposure to human or climatic pressures. A comparison between Togo and China demonstrates two contrasting situations. In Togo, groundwater resources are mainly tied to fractured basement aquifers, which provides limited storage and are highly sensitive to rainfall variability. Alternatively, China is characterized by extensive sedimentary and karst aquifers that can support substantial withdrawals, though they face serious challenges related to overuse and contamination.

Hydrogeological Potential of Togo

In Togo, most aquifer systems occur within crystalline basement rocks, which by nature possess very low primary porosity. As a result, groundwater occurrence is limited to the weathered regolith and networks of secondary fractures (Kouassi *et al.,* 2024). These aquifers typically show low transmissivity, generally between 1.0×10^{-4} and 1.0×10^{-2} m²/s, with borehole yields seldom exceeding 2.5 L/s. Recharge is strongly seasonal and closely tied to rainfall, with annual rates commonly estimated between 50 and 150 mm. The restricted storage capacity makes these aquifers particularly sensitive to climatic fluctuations. Extended droughts often cause sharp declines in groundwater levels, drying of wells, and reduced reliability of water supply in rural areas.

The challenge is compounded by the limited monitoring infrastructure, which hampers accurate assessment of storage variations and the development of adaptive management measures. Consequently, although Togo's basement aquifers remain a crucial source of drinking water for rural and peri-urban communities, their long-term sustainability is fundamentally constrained by their geological setting.

Hydrogeological Potential of China

China contains some of the world's most extensive aquifer systems. In the North China Plain, thick Quaternary alluvial deposits give rise to multi-layered aquifers with relatively high transmissivity and storage capacity (Zeng *et al.,* 2018). In the south, karst terrains further increase groundwater potential, where dissolution conduits support high-yield wells and allow for rapid recharge. Recharge rates in these regions are typically greater than 250 mm per year, and in humid karst settings may reach 500–600 mm annually (Shen *et al.,* 2023). However, these resources are under considerable pressure. Persistent over-extraction in the North China Plain has led to groundwater level declines of 0.5–1.5 m annually in some areas, with cumulative storage losses surpassing 60 km³ over certain decades (Lyu *et al.,* 2025). Widespread pollution compounds the problem, with nitrate, salinity, and heavy metals frequently detected in agricultural and peri-urban zones. Although China has established large-scale monitoring networks, the key difficulty remains in regulating abstraction and balancing the competing needs of agriculture, industry, and urban supply.

Comparative Analysis of Aquifer Potential and Sustainability

The differences between Togo and China are both striking and instructive. Figure 11 illustrates the spatial distribution of aquifer potential zones in each country, underscoring the regional variability in groundwater resources. In Togo, aquifer development is largely restricted by geology: crystalline basement aquifers offer low yields and show strong sensitivity to climatic fluctuations, limiting their suitability for large-scale agricultural or industrial use. Groundwater potential is unevenly distributed, with most areas classified as moderate. Low-potential zones occur in the Oti River Basin and parts of the Central Plateau, while higher-potential areas are mainly confined to the Coastal Alluvial Plain and sections of the Mono River Corridor. This pattern reflects the dominant role of localized weathering profiles and fracture networks in controlling groundwater availability. China, by contrast, possesses more extensive aquifer systems, yet faces challenges of sustainability and management. Its aquifer potential is more widely distributed, linked to broad sedimentary basins and alluvial plains. Regions such as the North China Plain and the Yangtze River Delta exhibit high to very high groundwater potential, supported by thick alluvial deposits and favourable recharge regimes. Moderate potential is observed in areas including the Loess Plateau, Sichuan Basin, and Songnen Plain, while low potential is characteristic of arid zones such as the Tarim Basin, where recharge is minimal. Although China's aquifers are far more abundant than those in Togo, decades of intensive extraction and contamination have compromised storage and water quality. In both contexts, long-term sustainability remains a central concern.

(i) In Togo, advancing methodological strategies is essential to optimize the use of limited groundwater reserves and to enhance resilience against climatic variability.

(ii) In China, effective regulatory and management measures are critical to halt progressive aquifer depletion and to reduce the impacts of widespread groundwater contamination.

Therefore, a comparison of the two contexts shows that China's well-established monitoring systems and modelling approaches have strong potential to improve groundwater management practices in Togo. At the same time, Togo's use of flexible, low-cost methods provides valuable insights for China, particularly in rural areas or regions with limited resources.

The figure draws out a sharp contrast between the two settings. In Togo, aquifers are localized and primarily fracture-controlled, whereas in China, groundwater is stored within extensive sedimentary basins. These differences reflect fundamentally distinct hydrogeological conditions and resource distributions. Figure 12 compares several key parameters transmissivity, recharge, storage coefficient, and specific yield for the two countries, presented through both bar and spider charts. The results show a marked disparity in aquifer productivity and resilience. Togo's basement-dominated aquifers display transmissivity values of about 5.0×10^{-3} m²/s, typical of fractured crystalline systems with poor hydraulic connectivity. By contrast, China's aquifers reach values near 5.0 m²/s, reflecting thick unconsolidated alluvial deposits and karst formations that sustain high-yield wells. This difference underscores the strong influence of lithology on groundwater flow. Recharge patterns further illustrate the divergence.

In Togo, average annual recharge is approximately 60 mm/year and closely tied to variable seasonal rainfall. China, on the other hand, records average values near 120 mm/year, particularly in humid alluvial and karst regions. While this greater recharge capacity supports replenishment, it also increases susceptibility to surface-driven contamination. Storage capacity reveals another contrast. Togo's aquifers exhibit very low storage coefficients, typically between 0.00 and 0.01, consistent with the limited capacity of weathered crystalline basement rocks. China's sedimentary and karst basins, by comparison, show coefficients as high as 0.1, enabling large-scale withdrawals and providing a buffer against seasonal variability. Specific yield (Sy) shows the clearest divergence between the two settings. In Togo, values average around 2.1%, reflecting shallow weathered regolith and fracture-controlled aquifers with limited water release. By comparison, China records

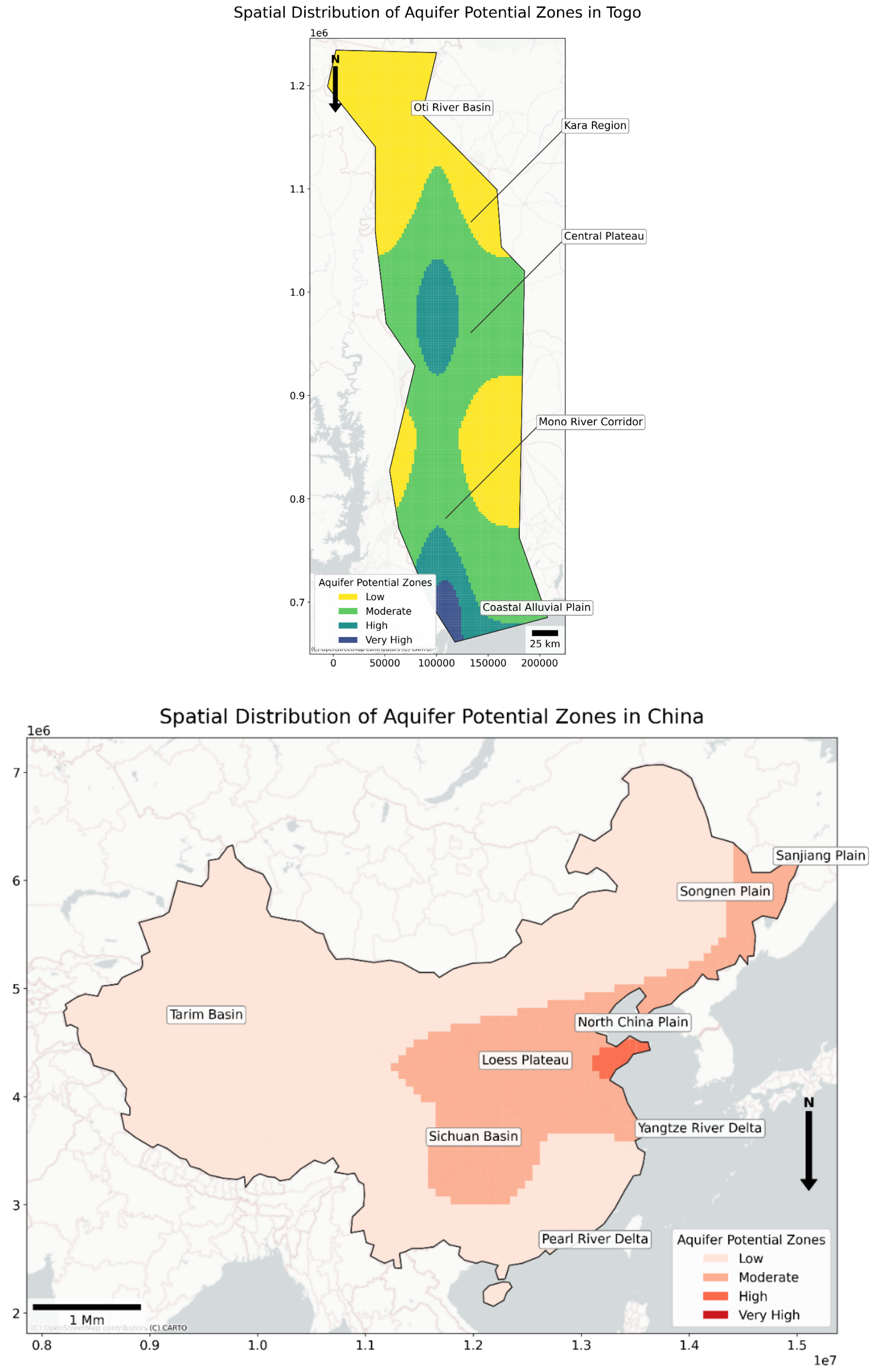


Figure 11: Spatial distribution of aquifer potential zones: (a) Togo and (b) China

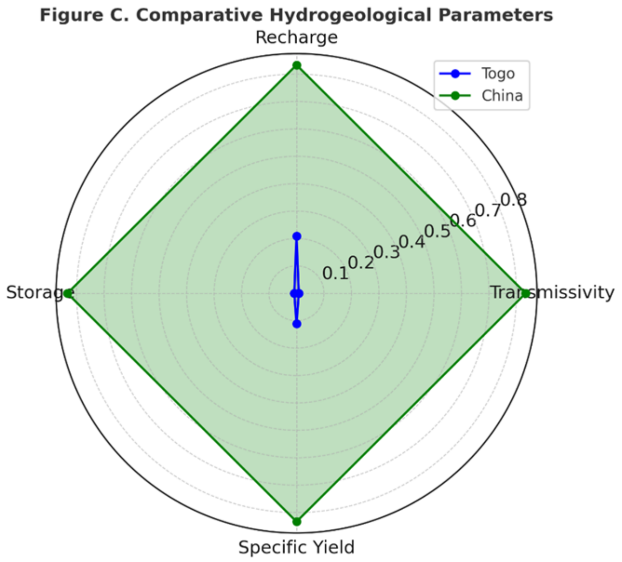


Figure 12: Comparison of hydrogeological parameters: (a) Togo; (b) China

much higher values of roughly 10%, characteristic of porous alluvial, loess, and carbonate formations where secondary porosity is well developed. Taken together, the bar and spider plots reveal a consistent pattern. Togo's aquifers are defined by low transmissivity, modest recharge, and limited storage, making them highly vulnerable to climatic fluctuations. China, in contrast, possesses extensive high-yield aquifers but faces long-term sustainability challenges linked to intensive pumping and contamination risks. Figure C underscores the need for groundwater management strategies tailored to each country's distinct hydrogeological conditions.

As shown in Figure 13 Groundwater Stress Indicators. It illustrates recharge deficit, over-extraction, and storage trends, capturing the temporal dynamics of groundwater stress through three complementary measures: recharge versus pumping fluxes, recharge balance, and storage change. Group (A) depicts the seasonal cycle of recharge associated with rainfall, set against steadily rising pumping rates. Red shaded intervals denote periods of over-extraction when abstraction exceeds natural replenishment. Group (B) quantifies the recharge balance, highlighting recurring deficits that vary from moderate to severe, especially during prolonged dry spells. Group (C)

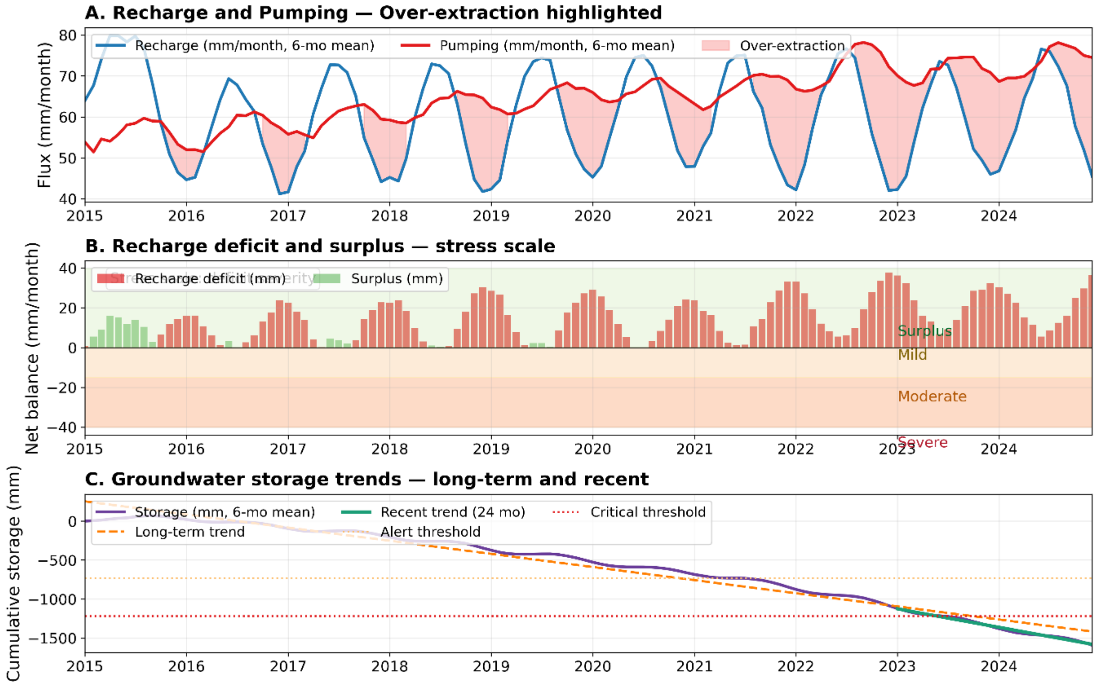


Figure 13: Indicators of groundwater stress: deficit, over-extraction, and storage change

shows the progressive decline in groundwater storage, with recent trajectories surpassing warning levels and nearing critical thresholds. Collectively, the three indicators point to a clear pattern of unsustainable groundwater use and continuing depletion.

In Togo, aquifers are highly sensitive to rainfall variability (50–150 mm/year), leading to seasonal deficits and borehole failures in dry years. Although overall abstraction is relatively low, it often becomes unsustainable during droughts. Water quality risks stem largely from naturally occurring iron and manganese, together with localized nitrate pollution. Monitoring capacity remains limited, with fragmented hydrographs that hinder reliable trend analysis. Climate change is expected to heighten these vulnerabilities through greater variability in rainfall. In China, groundwater stress is structural and widespread, with the North China Plain experiencing chronic deficits of up to 150 mm/year. Intensive agricultural withdrawals exceeding 300–500 mm/year drive declines of 0.5–1.5 m annually, with cumulative storage losses surpassing 60 km³. Contamination risks are both broader and more severe, encompassing nitrate, salinity, and heavy metals, particularly in peri-urban farming areas. Monitoring systems are more advanced, incorporating dense observation networks and satellite data. Climate pressures are strongly regionalized: northern China faces persistent drought-related deficits, whereas the south experiences recharge surpluses and periodic flooding. Table 3 summarizes the contrasting groundwater challenges in Togo and China. On the whole, Figure 9 and Table 3 highlight a fundamental contrast: Togo's groundwater stress is localized and climate-driven, while China's reflects large-scale over-abstraction compounded by contamination and uneven climatic impacts. Both cases emphasize the need for adaptive management strategies that are responsive to distinct hydrogeological conditions and socio-economic demands.

The Groundwater Stress Index (GWSI) serves as a key comparative indicator, calculated as the proportion of abstraction relative to natural recharge:

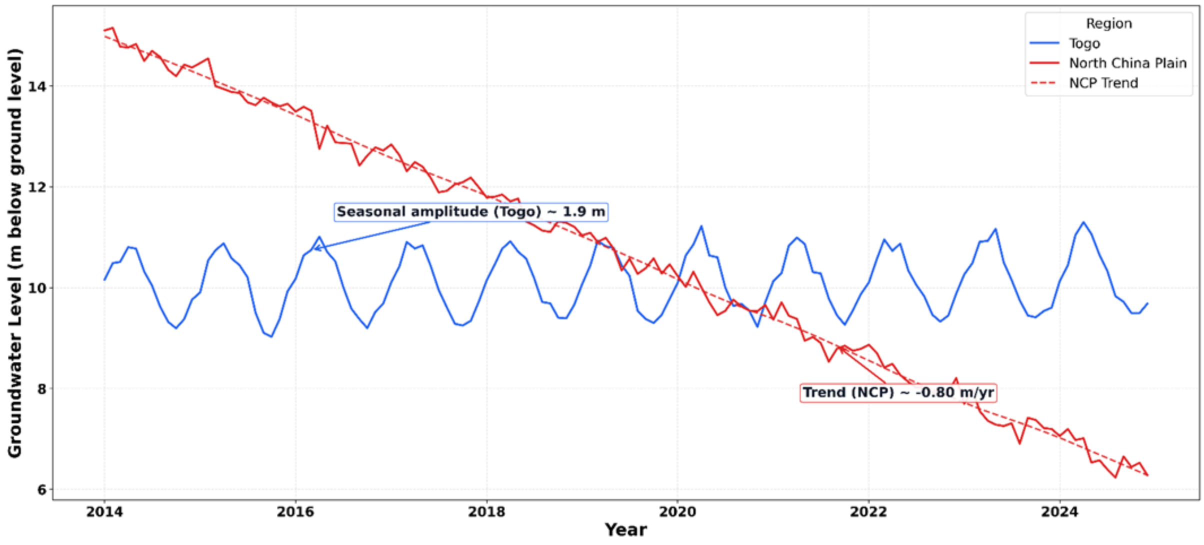
$$GWSI = Q_{abstraction}/R_{recharge} \quad ....(4)$$

Values exceeding unity signify over-exploitation, a condition commonly documented in China. In contrast, Togo generally records values below this threshold, though its aquifers remain highly sensitive to climatic variability.

Table 3: Groundwater challenges and stress indicators in Togo and China

Parameter	Togo	China
Recharge deficit	High sensitivity to rainfall variability (50-150mm/year); seasonal deficits common	Chronic imbalance in North China Plain; deficits up to -150mm/year
Groundwater abstraction	Low but locally unsustainable in drought years; < 10% of renewable supply	Excessive abstraction in agricultural basins (>300-500mm/year)
Storage trends	Stable to mildly declining; local borehole failures during dry seasons	Long term declines of 0.5-1.5m/year; cumulative storage losses of ~60 km3
Contamination risks	Iron, manganese, and localized nitrate contamination	Widespread nitrate, salinity, and heavy metals in agricultural and peri-urban zones
Monitoring density	Sparse borehole network; discontinuous hydrographs	Dense multi-scale monitoring networks with satellite integration
Climate stress	Extreme dependence on variable rainfall; projected stress from climate change	Variable impacts: drought stress in north, flooding and recharge surpluses in south

Figure 14 compares groundwater level fluctuations in Togo and the North China Plain (NCP) from 2014 to 2024, illustrating the contrast between seasonal variability and long-term decline. In Togo, groundwater levels (blue line) show pronounced seasonal oscillations with an amplitude of about 1.9 m, reflecting recharge during the wet season and drawdown in the dry months. Despite these fluctuations, the long-term trend remains largely stable, suggesting that fractured crystalline and regolith aquifers are strongly climate-driven but not yet subject to sustained decline. In contrast, the NCP (red line) exhibits a consistent downward trajectory, averaging a decline of ~0.80 m/year. The dashed regression line emphasizes this depletion, which is primarily the result of intensive abstraction for agriculture and urban supply in sedimentary aquifers. Seasonal variation is limited compared with Togo, underscoring the predominance of pumping over natural recharge in shaping water levels. The side-by-side comparison highlights distinct management challenges: Togo's aquifers are vulnerable to rainfall variability but retain local resilience, whereas China's aquifers, though highly productive, face systemic depletion under anthropogenic pressure. Together, the time-series evidence in Figure 14 reinforces the broader contrast between climate-driven and management-driven constraints on groundwater sustainability.



Notes: Monthly data; decomposition via STL (period=12). Units: m below ground level (b.g.l.). NCP trend shown as dashed line. Synthetic or aggregated where direct series unavailable.

Figure 14: Time-series analysis of groundwater dynamics: seasonal variability and long-term trends Notes: Monthly data; decomposition via STL (period =12). Units: m below ground level (b.g.l). NCP trend shown as dashed line. Aggregated where direct series unavailable.

Challenges, Prospects, and Innovations

Sustainable groundwater management depends not only on the physical characteristics of aquifers but also on the social and technical systems that guide their use, monitoring, and regulation. The comparison of Togo and China underscores their distinct challenges, while also pointing to opportunities for knowledge exchange and innovation that could benefit both settings.

Challenges

In Togo, the central constraint is limited data availability. Monitoring networks are sparse, with only a small number of boreholes providing hydrograph records. Many aquifer properties must be inferred indirectly through geophysical surveys, while existing datasets are often fragmented in time. These gaps make it difficult to carry out reliable long-term groundwater modelling or to develop adaptive management strategies. Institutional and financial constraints further impede the establishment of a comprehensive national monitoring system.

In China, the situation is quite different. Although extensive datasets exist, they coincide with serious resource stress and pollution. In the North China Plain, decades of intensive abstraction have produced annual groundwater declines of 0.5–1.5 m and the development of broad cones of depression. At the same time, water quality has been undermined by widespread nitrate inputs from agriculture, along with salinity and heavy metal contamination in peri-urban areas. The challenge here lies less in data collection and more in enforcing effective governance frameworks and reconciling competing demands on groundwater resources.

Prospects

The integration of machine learning with remote sensing, illustrated in Figure 15, provides a structured workflow for groundwater resource prediction. This conceptual layout introduces together remote sensing, GIS, field observations, and machine learning to support groundwater management. Its core strength lies in the systematic use of multi-source datasets, which enhances prediction accuracy, especially in areas where field data

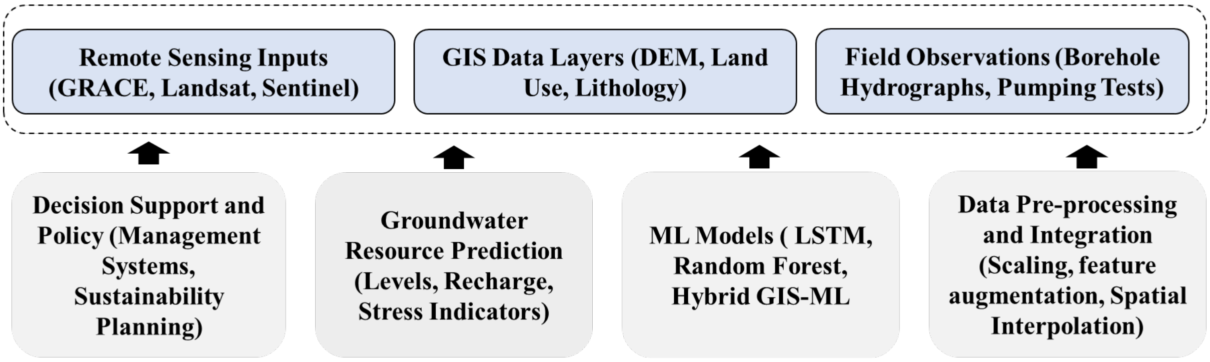


Figure 15: Approach to groundwater prediction through machine learning and remote sensing integration

are sparse. The workflow begins with remote sensing products such as GRACE, Landsat, and Sentinel, which capture regional patterns of recharge variability, evapotranspiration, and storage change. These are supplemented with GIS-based layers, including digital elevation models, land use patterns, and lithological maps, as well as field-derived data from borehole hydrographs and pumping tests. A key component of the process is data pre-processing and integration scaling, feature construction, and spatial interpolation designed to ensure consistency and comparability across diverse data sources. The processed datasets are then applied to machine learning models, including Long Short-Term Memory (LSTM) networks, Random Forest algorithms, and combined GIS–ML techniques, to generate forecasts of groundwater levels, recharge patterns, and stress indicators. The final component of the framework emphasizes decision support and policy integration, ensuring that technical outputs are connected to management strategies and long-term sustainability planning. As a whole, the figure presents a flexible and scalable methodology, demonstrating how the integration of machine learning with remote sensing can strengthen groundwater resource prediction and deliver practical insights in both data-rich regions such as China and data-limited environments such as Togo.

Innovations

The pursuit of groundwater sustainability rests on three key dimensions: institutional, technological, and collaborative innovation.

(i) Institutional Strengthening: In Togo, progress could be achieved through the creation of centralized groundwater monitoring systems, with technical and financial backing from international development partners. Lessons can be drawn from China, where basin-scale authorities provide an effective model of coordinated groundwater governance.

(ii) Technological Integration: Advances in remote sensing, GIS, and machine learning open new possibilities for groundwater assessment. For example, satellite-based recharge estimates can be incorporated into machine learning frameworks to deliver near real-time forecasts of aquifer conditions, offering direct support for policy and management decisions.

(iii) Cross-Continental Collaboration: Building lasting capacity will also depend on international partnerships. Collaborative research initiatives, student mobility programs, and shared data platforms between Chinese and Togolese institutions could enhance hydrogeological expertise in West Africa. Such initiatives are aligned with broader global efforts to secure sustainable groundwater resources under changing climatic conditions.

The structure in which governance, monitoring, modelling, and decision support as depicted in Figure 16 are identified as the four foundational pillars of sustainable groundwater management. The framework highlights that ensuring hydrogeological sustainability is not only a technical undertaking but also one that depends on institutional strength, systematic observation, and effective policy translation. At the top of the structure, governance creates the enabling conditions through regulatory systems, institutional mandates, and coordination among stakeholders. This tier provides the authority to implement monitoring networks, regulate groundwater abstraction, and align national strategies with international commitments to water security. The second tier, monitoring, emphasizes structured data collection through observation wells, geophysical investigations, and remote sensing tools. Reliable monitoring produces long-term datasets on groundwater levels, recharge rates, and water quality records that are indispensable for identifying aquifer stress. The comparison between sparse borehole networks in Togo and the denser, multi-scale monitoring systems in China illustrates how differences in capacity directly affect management outcomes. The third pillar, modelling, translates collected data into predictive understanding. Using numerical models, isotope hydrology, and increasingly machine learning techniques, this layer enables the simulation of recharge patterns, abstraction pressures, and climate variability scenarios. In doing so, modelling connects empirical evidence with forward-looking assessments, supporting early identification of risks such as depletion, salinization, and contamination.

Ultimately, pillar decision support, involves transforming scientific knowledge into practical strategies for management. This includes designing groundwater

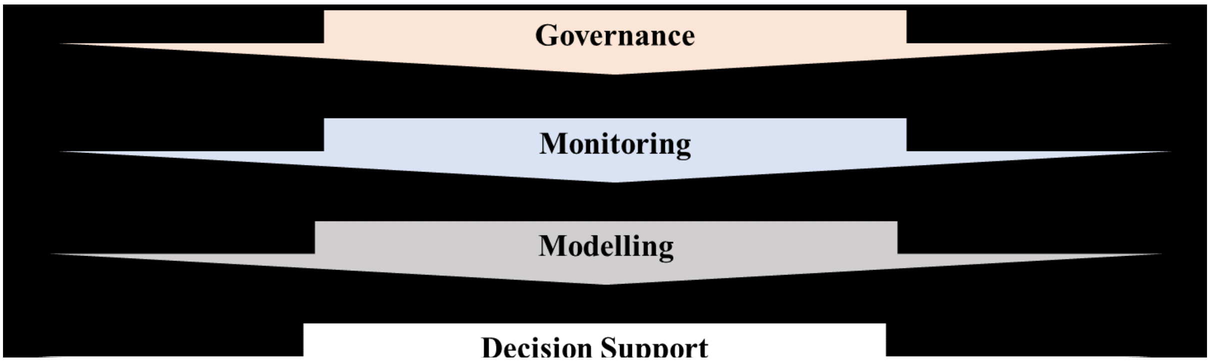


Figure 16: Integrated management and policy layout

allocation frameworks, establishing drought-response protocols, and developing early-warning systems that combine hydrological forecasts with socio-economic considerations. In this way, decision-support tools ensure that the outcomes of governance, monitoring, and modelling are translated into concrete measures for sustainable groundwater use. This structure provides the interdependence of institutional and technical components. Governance provides continuity for monitoring; monitoring supplies the data that make models reliable; and decision support ensures that scientific insights inform real policy action. Together, these interconnected elements create a comprehensive structure for adaptive groundwater management, applicable both in resource-constrained contexts such as Togo and in resource-intensive environments like China.

CONCLUSION

This study compares the hydrogeological conditions of Togo and China, showing how geology, climate, and management practices influence groundwater availability and long-term sustainability. In Togo, groundwater mainly occurs in fractured crystalline rocks and thin sedimentary layers. These formations hold limited storage, transmit water poorly, and depend strongly on seasonal rainfall, which makes water supply vulnerable during dry periods. In contrast, China possesses broad sedimentary basins, alluvial plains, and karst aquifers that provide higher yields and greater storage, though they are increasingly affected by over-extraction and contamination.

The findings point to two distinct challenges. For Togo, the priority is to improve hydrogeological data collection and strengthen institutional capacity for continuous monitoring. For China, the main concern is managing excessive abstraction and enforcing policies that balance agricultural, industrial, and domestic demands.

The research also demonstrates the value of mutual learning. China's advanced modelling, monitoring, and analytical tools could support more effective groundwater studies in Togo, while Togo's experience with simple, low-cost field methods offers lessons for managing rural or data errors regions in China. Therefore, sustainable groundwater development depends not only on geological potential but also on coordinated governance, data sharing, and technological adaptation.

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