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ESTIMATION OF GROUNDWATER RECHARGE OF THE HEAVILY EXPLOITED AQUIFER OF THE KETA STRIP USING THE WATER TABLE FLUCTUATION METHOD

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Abstract

Groundwater recharge estimation is essential for ensuring the sustainable use of water resources, as it helps determine the safe extraction limits of aquifers and prevents their over-exploitation. This study applied the water table fluctuation method with high-frequency (hourly) monitoring to estimate groundwater recharge in the Keta Strip, a shallow unconfined sandy aquifer in southeastern Ghana that serves as a critical resource for irrigation and domestic water supply. Water level data were collected from six monitoring wells between November 2022 and May 2024, while specific yield values (0.19 – 0.30, mean 0.25) were determined from grain-size analysis using empirical relations. Mean annual recharge is estimated at 635 mm/yr, representing approximately 41% of annual precipitation. Recharge exhibits strong seasonal variability, occurring predominantly during the wet season (April–October) with rapid response times (hours to days) to individual precipitation events, while negligible recharge occurs during the dry season (November–March). Spatial analysis reveals pronounced heterogeneity, with recharge rates ranging from 393 mm/yr (26% of precipitation) in the central-western coastal zone to 828 mm/yr (54%) at the northeastern and western extremities, controlled primarily by local variations in sediment texture and hydraulic conductivity rather than proximity to saline boundaries. Combined with high permeability (13–59 m/day) and shallow water tables, this creates acute vulnerability to saline intrusion and contamination. Zone-specific management strategies are recommended, restricting dry-season pumping in low-recharge corridors while optimizing high-recharge zones. Aligning agricultural cropping calendars with natural recharge cycles and establishing real-time monitoring are essential to ensure long-term water security in the Keta Strip.

Keywords
Groundwater recharge, Water table fluctuation method, Keta Strip, Coastal aquifer, Sustainable groundwater management

Introduction

Groundwater constitutes a critical global freshwater resource, particularly in regions characterized by seasonal, scarce, unreliable surface water availability and rainfall paucity. Groundwater supports approximately 40% of global irrigation, underpinning agricultural productivity and food security (Siebert et al., 2010). Intensifying demand, driven by population growth, climate variability and agricultural expansion, has rendered groundwater indispensable for rural livelihoods and economic development. However, intensive exploitation in major agricultural regions such as India, Iran, China and USA has frequently resulted in aquifer depletion, water quality degradation, and land subsidence (Wada et al., 2012).

In sub-Saharan Africa, groundwater's reliability during rainfall paucity makes it increasingly vital for agriculture. Nevertheless, sustainable management is hindered by a critical paucity of quantitative recharge data, posing significant threats to future water security (MacDonald et al., 2012; Taylor et al., 2012). Ghana exemplifies these challenges within tropical Africa. Concentrated seasonal rainfall leads to unreliable surface water, establishing groundwater as the primary source for rural domestic and agricultural needs. While offering advantages like lower development costs and reduced susceptibility to surface contamination, Ghanaian aquifers face unsustainable exploitation due to insufficient hydrogeological monitoring and a lack of robust recharge data (Akurugu et al., 2025; Duah et al., 2021).

The Keta Strip, southeastern Ghana, presents a salient case study of groundwater dependence and sustainability challenges. The region is underlain by a shallow, unconfined Quaternary aquifer, predominantly comprising highly permeable sands and silts (Nerquaye-Tetteh, 1993). A significant economic transition from fishing to irrigated vegetable farming (>85,000 farmers cultivating shallots, okra for local and export markets; Ghana Export Promotion Authority (2020); Kortatsi et al. (2005)) has driven increased groundwater abstraction via mechanized systems (Kortatsi et al., 2005; Lamptey et al., 2013). Despite local perceptions of abundance, the aquifer is demonstrably stressed (Nielsen et al., 2007). Coastal proximity and high pumping rates create significant saltwater intrusion risk (Kippo, 2012). Furthermore, the aquifer is vulnerable to contamination from multiple sources, including domestic sewage, septic systems, agricultural fertilizers, and solid waste (Kippo, 2012; Yidana and Chegbeleh, 2013). Quantifying aquifer recharge, thus the volume of water percolating through the vadose zone to replenish the saturated zone (Healy, 2010) is therefore fundamental for sustainable management. Reliable recharge estimates are essential to balance extraction against replenishment capacity averting the high uncertainty associated with management decisions. Despite its critical importance, quantitative, locally calibrated recharge data for the Keta aquifer remains limited (Duah et al., 2021).

This knowledge gap poses substantial risks of potential aquifer depletion beyond natural recovery, water quality deterioration and falling water tables, mirroring crises as earlier asserted (Earth Policy Institute, 2001; Wada et al., 2012). Previous studies in the basin have employed numerical modeling to infer recharge via hydraulic conductivity estimates (Yidana and Chegbeleh, 2013). However, such approaches are constrained by data limitations, inherent model assumptions, and the non-uniqueness of solutions, highlighting the need for complementary, field-data-driven recharge estimation methods. Multi-method approaches are widely recommended to mitigate unquantifiable errors inherent in recharge estimation, acknowledging that consistency between methods does not guarantee absolute accuracy (Healy, 2010; Scanlon et al., 2002).

The Water Table Fluctuation (WTF) method provides a robust, physically based approach for quantifying diffuse recharge in unconfined aquifers where water table rises can be causally linked to discrete recharge events (predominantly rainfall infiltration). It estimates recharge (R) to groundwater through the specific yield (Sy)of the aquifer and change in hydraulic head (Δh) (net rise in water table elevation) (Healy, 2010). The method's applicability has been validated in analogous hydrogeologic settings in Ghana (Kortatsi et al., 2005; Obuobie et al., 2012). While reliant on assumptions of negligible lateral flow and groundwater evapotranspiration losses during the measurement period, the WTF method remains a valuable tool, particularly in data-scarce environments lacking dedicated instrumentation for direct recharge measurement.

This study employs the WTF method to quantify recharge rates in the shallow unconfined aquifer of the Keta Strip. Utilizing high-resolution (hourly) groundwater level data from six monitoring wells and specific yield values derived from grain-size analysis, the research aims to generate empirical recharge estimates essential for sustainable groundwater resource planning and management. The results are intended to provide stakeholders with a quantitative evidence base for understanding aquifer dynamics, mitigating over-extraction risks, and enhancing long-term water security amidst climate variability and escalating agricultural demand.

Materials and Methods

Location and Setting

The Keta Strip is a narrow coastal landform bordered by the Keta Lagoon to the north and the Gulf of Guinea to the south. It forms part of the larger Keta Basin; a transboundary sedimentary basin that stretches along the Gulf of Guinea and into parts of Togo, Benin, and Southwestern Nigeria (Kippo, 2012). This study focused on five communities within the strip: Dzita, Atorkor, Anloga, Tegbi Xekpa, and Vodza. Two monitoring wells were installed in Anloga (one closer to the Keta Lagoon and the other closer to the Gulf of Guinea), bringing the total number of monitoring wells to six (Figure 1). The study area lies between latitudes 5^{o}45'N and 6^{o}03'N and longitudes 0^{o}42'E and 1^{o}02'E as shown in Figure 1. According to Kippo (2012), the strip spans approximately 27 Km in length, with a maximum width of 2 Km.

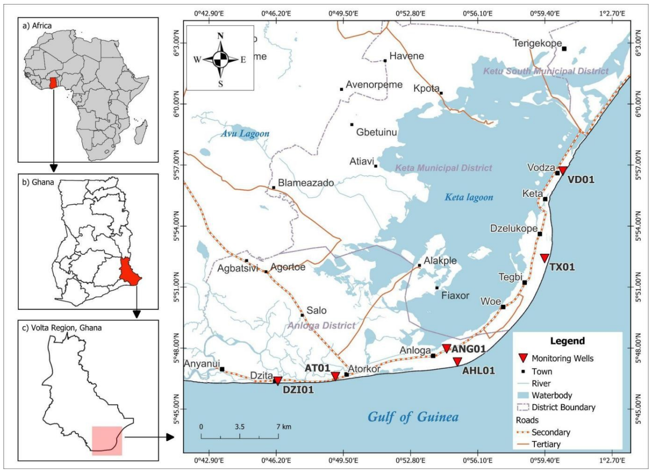


Figure 1. Location map of the Keta strip showing towns and monitoring well locations.

The study area lies within a dry equatorial climatic zone, characterised by an average temperature of 27.5°C and distinct wet and dry seasons. Yidana and Chegbeleh (2013) indicate that the dry season persists from November to March annually, while the wet season features dual rainfall peaks: a primary rainy period from April to July followed by a secondary period between September and October. Annual precipitation averages between 740 mm and 890 mm. As noted in previous studies (Dickson and Benneh, 1988; Yidana and Chegbeleh, 2013)), the regional climate is predominantly governed by the Intertropical Convergence Zone (ITCZ), which marks the boundary between two major air masses which are the dry northeast trade winds that prevail during the arid season and the moisture-laden southwest monsoon winds that dominate the wet season.

The study area is classified into five distinct vegetative zones, each with unique flora: the northern zone supports tall grasses and moderately dense medium-sized trees; the central zone is typified by shorter grasses and smaller trees, including baobabs; the southwestern zone features mangrove vegetation along the Volta estuary alongside tall grasses traditionally used for fuel and handicrafts; and the southeastern coastal zone displays short grasses with abundant neem trees (Dickson and Benneh, 1988; Kippo, 2012). Examination of Soil in the study area reveals three primary types: coastal savanna Ochrosols (Oyibi-Muni Association), sodium Vleisols (Oda-Oyibi Association), and coastal sands (Toje Alajo Association) (Kippo, 2012; Kortatsi et al., 2005). These researchers describe the coastal savanna Ochrosols and coastal sands as pale-yellow substrates that are generally deficient in humus. In contrast, the sodium Vleisols, particularly those adjacent to the Keta Lagoon, support the cultivation of coconut, shallot, okra, pepper, and other vegetables when manured. The coastal savanna ochrosols and vleisols supports mangroves and pasture grasses but is unsuitable for arable crops, while the coastal sands are suitable for cassava, maize, and legumes.

The topography of the region is generally low-lying, with maximum elevations reaching approximately 53 meters above sea level in the gently rolling northern sectors. However, as Kippo (2012) documented, coastal settlements such as Vodza, Keta, and Kedzi actually lie 1 – 3.5 meters below sea level, rendering them exceptionally prone to coastal erosion. This persistent threat has necessitated the construction of protective sea defense along vulnerable shoreline sections.

Agriculture is the primary economic activity in the study area, with most residents engaged in crop cultivation, particularly tomatoes and shallots, as well as animal husbandry and fishing. The Ghana Statistical Service (2022) reports a population of 173,757 people in the area as of June 2021. Due to the nature of the landscape and the reliance on year-round irrigation, groundwater resource is under increasing pressure. The continuous expansion of irrigation activities heightens the risk of freshwater depletion and salinization. As such, understanding groundwater recharge is essential to this study, as it provides the knowledge needed for sustainable water management and the long-term protection of agricultural livelihoods.

Geology and Hydrogeology

Geologically, the Keta Basin is a fault-controlled sedimentary basin from the Mesozoic/Tertiary period, located along the southeastern coast of the Gulf of Guinea (Jørgensen and Banoeng-Yakubo, 2001). The basement complex is made up of early Precambrian Dahomeyan gneisses, migmatites, and schists, which were influenced by the Pan-African orogeny and are exposed along the northern edges of the basin (Kesse, 1985). The basin is bordered to the northeast by scattered unconsolidated gravel and sand (Nerquaye-Tetteh, 1993). The basal sedimentary layer in the basin consists of Lower to Middle Devonian marine shale, sandstone, and siltstone, overlain by Jurassic dolerites and sills. The eastern edge of the basin features Cretaceous–Eocene marine sediments, including limestone, shale, and glauconitic sandstone. The central region of the basin is characterized by Quaternary unconsolidated coastal sediments, marine sands, and gravels, which average 30 meters in thickness around Keta and increase in thickness towards the Volta River estuary (Yidana and Chegbeleh, 2013).

Four distinct aquifer types have been identified within the basin according to Nerquaye-Tetteh (1993), and Jørgensen and Banoeng-Yakubo (2001). These include weathered Dahomeyan gneiss along the northeastern rim of the basin, surficial Neogene continental deposits of unconsolidated to semi-consolidated limonitic argillaceous sands in the northeastern and central parts of the basin, Quaternary coastal marine sands and gravels in the Volta River estuary and Keta Lagoon area, and Cretaceous–Eocene marine limestones and sandstone beds, which are exploited for drinking water in the central and southeastern parts of the basin. The Quaternary coastal marine sands and gravels in the Volta River estuary and Keta Lagoon area consist of unconsolidated sands and gravels and are typically associated with high groundwater recharge. This study was conducted within the Quaternary aquifer, which is exposed at the land surface at a depth of approximately 2 meters, making it directly recharged by precipitation. The limestone aquifer has an average transmissivity of 5.38 × 10-4 m^2/day whereas the Quaternary aquifer exhibits a much wider range of transmissivity values, from 0.7 to 1,624 m^2/day, with a mean of 22.2 m^2/day (Kippo, 2012). The average yield of wells in the area is 13,135 liters per hour. Boreholes tapping into limestone aquifers along the coast have an average yield of 21.3 cubic meter per hour, with yields ranging from 4.5 to 5.4 cubic meter per hour. Chemical analysis of groundwater in the region indicates that the water is of usable quality, particularly for irrigation purposes. The average electrical conductivity (EC) in the study area was 222.29 which corresponds to a total dissolved solids of approximately 142.27 mg/liter (Banoeng-Yakubo et al., 2010).

Field Work and Data Collection

Monitoring Well Installation and Lithologic Logging

Shallow tube groundwater monitoring wells were installed in the shallow unconfined quaternary sandy aquifer at average depths of about 7 m (range: 3 m minimum–14 m maximum), although the water table is usually within 1 m from the surface (Awadzi et al., 2008). Wells were advanced with a hand-powered rig (auger type) capable of advancing in loose sediments (Misstear et al., 2006). In total, 8 new wells were drilled and 2 existing points were adapted, totalling 10 monitoring points well spatially distributed across the strip However, for this study, data from only 6 wells were used (Figure 1) based on two criteria: (i) availability of consistent data within the time duration under consideration (November 2022 to May 2024), and (ii) location away from heavily irrigated areas where pumping-induced fluctuations may overwhelm precipitation signals (Crosbie et al., 2005; Duah et al., 2021). For instance, wells on intensively irrigated farmlands (e.g., Ministry of Food and Agriculture farm in Woe, and a farm in Tengekope) were excluded to prevent misinterpretation of water level changes due to pumping as recharge events.

During installation, PVC tubes were set as monitoring wells. Each tube was fully slotted (screened) over the saturated interval, with the bottom end capped. This configuration allows lateral inflow along the screened interval while preventing sediment entry from the base (Driscoll, 1986; Nielsen and Schalla, 1991)). The shallow completion design targets the unconfined portion of the aquifer that responds most directly to recharge (Healy and Cook, 2002).

During drilling, the recovered cuttings were logged continuously. Changes in color, grain size, sorting, and visible fines content were recorded with depth to produce a basic lithologic log for each well. At visually distinct depth intervals, bulk samples were collected. These samples represent the in-situ aquifer material surrounding each screened interval. Because the aquifer is unconsolidated and uncemented, the collected cuttings are considered representative of formation texture at the sampled depth (Koltermann and Gorelick, 1996). After collection, samples were bagged for laboratory grain size analysis.

Water Level Monitoring

Water level fluctuations were monitored using HOBO pressure transducers ("divers") deployed in each tube well. The loggers recorded total pressure head and temperature at hourly intervals (Onset Computer Corporation, 2012). Depth to water level was determined by correcting the recorded pressure for atmospheric pressure (barometric compensation) and referencing to land surface by subtracting a one-time manual depth-to-water measurement at installation (Freeman et al., 2004). The result is a continuous time series of groundwater head for each location.

These high-frequency groundwater level records are required for application of the Water Table Fluctuation (WTF) method, which estimates recharge according to Equation 1 above (Crosbie et al., 2005; Healy and Cook, 2002). Because the WTF method is directly proportional to Sy, obtaining realistic, site-specific values of specific yield was treated as a core objective of this study.

Grain-Size Analysis and Grading Parameters

Field samples were air-dried and dry-sieved using standard U.S. sieve sizes from 4 mm to 0.063 mm (ASTM International, 2007). The cumulative percent passing versus particle diameter was used to construct grain size distribution curves for every sampled depth interval.

From each grain size curve we extracted standard grading characteristics (Cabalar and Akbulut, 2016; Peche and Houben, 2023):

- D_{10}, D_{30}, D_{50}, D_{60} (mm): particle diameters at 10%, 30%, 50%, and 60% passing,
- Uniformity coefficient $Cu = D_{60}/D_{10}$,
- Coefficient of curvature $Cc = D_{30}{}^2/(D_{10} \text{ x } D_{60})$,
- Percent finer than 0.125 mm and 0.0625 mm (read directly from the grain-size curve for use in empirical relations).

These metrics were also used to classify each interval under the Unified Soil Classification System (USCS) (ASTM International, 2007). The majority of intervals classify as poorly graded sand (SP), consistent with a high-energy, unconsolidated coastal/alluvial setting (Folk, 1980).

Estimation of Porosity and Hydraulic Conductivity

Porosity (n) for each depth interval was estimated empirically from the grading characteristics. We adopted an established relationship between porosity and the uniformity coefficient, Cu (Vuković and Soro, 1992):

$$n = 0.225(1 + 0.83^{Cu}) \tag{1}$$

This porosity estimate is appropriate for uncemented granular materials and has been used in previous studies of unconsolidated sands (Odong, 2007; Vuković and Soro, 1992).

Hydraulic conductivity (K) was estimated for each depth interval to characterize the overall hydraulic behavior of the aquifer. Multiple published grain-size-based formulas were evaluated, including Kozeny-Carman, Hazen (original and modified), Chapuis, Slichter, Beyer, Harleman, and Alyamani & Sen (Odong, 2007; Rosas et al., 2014; Svensson, 2014). However, the Kozeny-Carman equation was selected as the primary method due to its physically based formulation and widespread application to clean, unconsolidated sands (Carrier III, 2003). The Kozeny-Carman relationship is expressed as:

$$K = \frac{g}{\nu} \times \frac{n^3}{(1-n)^2} \times \frac{d_{10}^2}{180} \tag{2}$$

where:

K: hydraulic conductivity (m/s)
g: gravitational acceleration (9.81 m/s^2)
ν: kinematic viscosity of water (assumed 1.0×10^{-6} m^2/s at 20°C)
n: porosity (dimensionless)
d_{10}: effective grain size (m)

The Chapuis (2004) and Harleman et al. (1963) methods, both developed for uniformly graded fine to medium sands, yielded estimates generally consistent with Kozeny-Carman values. Other methods (e.g., Beyer, Slichter) showed greater variability, with some approaches developed for well-graded or coarser heterogeneous materials being less appropriate for the predominantly poorly graded fine sands encountered in this study area (Rosas et al., 2014; Salarashayeri and Siosemarde, 2012).

Estimation of Specific Retention and Specific Yield

Accurate estimation of groundwater recharge using the Water Table Fluctuation (WTF) method depends strongly on the reliability of the parameters involved, most notably the specific yield (Sy) of the aquifer material. Specific yield represents the fraction of the total aquifer porosity that can drain freely under the influence of gravity (Fetter, 2014). Although both field and laboratory methods exist for determining Sy (Healy and Cook, 2002; Johnson, 1967), direct measurements are often limited by time, cost, and sample disturbance. As a result, a wide range of Sy values has been reported for materials of similar texture, reflecting differences in geologic heterogeneity, water-table depth, measurement duration, and estimation approach (Johnson, 1967; Meinzer, 1923). Laboratory determinations of drainable porosity on undisturbed cores are ideal (Obuobie et al., 2012), but where such data are unavailable, empirical relationships based on grain-size characteristics can provide robust site-specific estimates (Morris and Johnson, 1967).

In this study, specific yield was determined from grain-size analysis data for sediment samples obtained during drilling of the shallow monitoring wells. Specific retention (Sr) was estimated empirically from the particle size data using the regression equations reported by (Robson, 1993). Robson developed five least-squares regression relationships that relate Sr to (i) log D_{50}, (ii) log D_{90}, (iii) log (D_{70} - D_{50}), (iv) percent finer than 0.0625 mm, and (v) percent finer than 0.125 mm. Although the original work focused on clastic units from the Denver Basin, Robson also validated the approach on unconsolidated alluvial materials, showing that the regressions perform well in loose, non-indurated sandy aquifers similar to those in this study.

For each sample, all five equations were applied to compute five values of *Sr*, and corresponding *Sy* values were obtained using equation 3 (Freeze and Cherry, 1979):

$$Sy_i = n - Sr_i \tag{3}$$

where i = 1, . . . , 5 denotes the individual Robson regression.

The five Sy_i values were then averaged to produce a representative specific yield for that depth interval. Averaging across the five regressions reduces the influence of any single predictor (e.g., reliance solely on D_{50} versus fines fraction) and follows the intent of Robson's approach, which treats the equations as complementary rather than exclusive (Robson, 1993).

This procedure yields depth-specific Sy values at each monitoring location, derived entirely from site material rather than from generic textbook values. This is important because Sy can vary strongly with texture, packing, and fines content, and Sy exerts a first-order control on recharge estimates from the WTF method (Healy and Cook, 2002; Scanlon et al., 2002).

For each monitoring well, all depth-interval Sy values were summarized to characterize the specific yield of the aquifer contributing to observed water level fluctuations at that location. We report the minimum Sy value (representing the lowest drainable porosity observed across the screened interval) and the maximum Sy value (representing the highest drainable porosity) which were subsequently used to create a range of recharge estimates. Since no aquifer materials were acquired at the well at Vodza to allow for grain size analysis and subsequent Sy calculations, the range estimated for the closest well location (Tegbi Xekpa) was used for recharge estimation.

Groundwater Recharge Using the Water Table Fluctuation Method

The Water Table Fluctuation (WTF) method, as outlined by Healy (2010), operates on the fundamental assumption that observed rises in groundwater levels within unconfined aquifers are primarily attributed to direct recharge reaching the water table. It presumes negligible influence from lateral flow or other components of the groundwater budget during the recharge period and defines the recharge volume per unit area as the product of the specific yield and the height of the water within the column. The WTF method is particularly suitable for this context due to its ability to provide direct estimates of recharge by correlating changes in groundwater levels (Δh) with precipitation events. It is also recommended that the water table fluctuation method is applied to aquifers that are unconfined and have a shallow water table, which is the case for the study area (Crosbie et al., 2005; Healy and Cook, 2002). Given the vulnerability of the aquifer to saltwater intrusion, accurately estimating recharge is critical for sustainable water resource management in the region. Recharge was estimated using the water level data by applying equation 4 below:

$$R = \frac{\Delta h}{\Delta t} \times Sy \tag{4}$$

where:
R: recharge amount (mm/yr)
Δh: cumulative change in hydraulic head attributable to recharge over the monitoring period (mm)
Δt: duration of the monitoring period (years)
Sy: specific yield (dimensionless)

Changes in water level (Δh) were determined using an event-based approach. Individual recharge events were identified from the continuous water level hydrographs as distinct rises in groundwater level following precipitation. For each identified event, Δh was calculated as the difference between the trough (low point) immediately preceding the rise and the subsequent peak water level. No extrapolation of antecedent recession curves was applied; rises were measured directly from the observed hydrograph data. This approach, similar to the RISE method described by (Delin et al., 2007), provides a straightforward and reproducible means of quantifying water table response to recharge events, though it may yield conservative estimates as it does not explicitly account for concurrent aquifer drainage during recharge events (Nimmo et al., 2015).

For each well location, recharge was computed separately using both the minimum and maximum Sy values, providing lower-bound and upper-bound estimates that reflect both the spatial heterogeneity in aquifer properties with depth and the uncertainty inherent in empirical Sy estimation methods. A central recharge estimate for each location was calculated as the arithmetic mean of the lower-bound and upper-bound values. These central estimates were spatially interpolated in ArcGIS using the Inverse Distance Weighted (IDW) method, which estimates values at unmeasured locations based on a weighted average of nearby points, with closer points having greater influence (Childs, 2004). The resulting raster surface provides a spatial visualization of recharge distribution across the study area.

Daily precipitation data for the study area were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) Data Access Viewer (DAV) (NASA Langley Research Center, 2025; Stackhouse et al., 2018) to contextualize recharge estimates and express recharge as a percentage of annual rainfall. Given the coastal setting of the Keta Strip, potential tidal influences on groundwater levels warrant consideration. While this study did not explicitly account for tidal effects, future research could benefit from approaches such as those used by Rama et al. (2018), who investigated similar dynamics in comparable environments.

Table 1. Descriptive statistics of well-averaged aquifer properties across the Keta Strip

Parameter	Units	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Grain-size characteristics								
Effective grain size (D_{10})	mm	0.14	0.3	0.2	0.07	33.45	0.55	-0.93
Mean grain size (D_{50})	mm	0.25	0.68	0.43	0.18	42.5	0.37	-1.79
Uniformity coefficient (Cu)	-	2.08	3.58	2.49	0.63	25.28	1.89	3.57
Hydraulic properties								
Porosity (n)	-	0.36	0.38	0.37	0.01	2.25	-0.51	-0.61
Specific retention (Sr)	-	0.09	0.12	0.1	0.02	14.58	0.32	-3.08
Specific yield (Sy)	-	0.245	0.285	0.26	0.02	6.37	1.43	2.09
Hydraulic conductivity (K)	m/day	13.72	59.28	31.46	19.49	61.95	0.66	-1.01

Results and Discussion

Aquifer Characterization

Grain-size analysis of sediment samples collected from five monitoring wells across the Keta Strip revealed well-averaged effective grain size (D_{10}) ranging from 0.14 to 0.30 mm (mean = 0.20 mm) and mean grain size (D_{50}) ranging from 0.25 to 0.68 mm (mean = 0.43 mm), classifying the sediments as fine to coarse sand dominated by medium sand fractions (Table 1). Uniformity coefficients (Cu) ranged from 2.08 to 3.58 (mean = 2.49), characterizing the aquifer as predominantly poorly graded sand (SP) according to the Unified Soil Classification System.

Estimated porosity exhibited minimal spatial variation across the five monitoring locations, ranging from 0.36 to 0.38 (mean = 0.37, CV = 2.25%) (Table 1). Similarly, specific retention values showed limited variability (range: 0.09 – 0.12, mean = 0.10, CV = 14.58%). The resulting specific yield estimates ranged from 0.245 to 0.285 (mean = 0.256, CV = 6.37%), falling within the typical range reported for fine to medium sands (0.15 – 0.30; Johnson (1967); Morris and Johnson (1967)). The relatively low coefficient of variation for specific yield provides confidence in its application for recharge estimation using the water table fluctuation method, as Sy is a critical parameter that exerts first-order control on calculated recharge rates (Healy and Cook, 2002).

In contrast to porosity and specific yield, hydraulic conductivity displayed substantial vertical and spatial variability. Lithologic logging during well installation revealed a general fining-downward vertical stratigraphic sequence consisting of coarse sand with shell fragments in the upper 2.5m, transitioning to medium sand at intermediate depths, and fining to clay and silt layers at depths of approximately 4.5 m and below. This vertical sequence is reflected in the hydraulic conductivity distribution where individual depth-interval samples yielded K values ranging from approximately 1 – 260 m/day, with K typically decreasing with depth as finer materials and clay-rich layers were encountered. The highest K values observed in the upper coarse-grained, shell-bearing sands, while the lowest values corresponded to the fine sand and silty-clay layers at depth. This fining-downward sequence is consistent with a coastal depositional environment influenced by marine and lagoonal processes, with the coarser upper sediments reflecting higher-energy foreshore or beach deposits, and the finer basal sediments representing lower-energy lagoonal or back-barrier facies (Davis Jr and FitzGerald, 2009; Reading, 2009).

Spatially, well-averaged K values, representing the integrated hydraulic properties over each screened interval, ranged from 13.72 – 59.28 m/day (mean = 31.46 m/day, CV = 61.95%). The high coefficient of variation reflects significant horizontal heterogeneity across the Keta Strip, likely resulting from the lateral discontinuity of lithofacies and the presence of localized lenses of coarse marine deposits (shell hash and coarse sand) interbedded with finer sediments. These coarse lenses, deposited during high-energy events such as storms or periods of active shoreline progradation, create preferential flow pathways that enhance local hydraulic conductivity.

Previous studies in the Keta Strip have reported varying K estimates depending on the method employed. Kippo (2012), using the Kozeny-Carman method on grain-size data reported K values ranging from 26 to 150 m/day, while Yidana and Chegbeleh (2013), using calibrated steady-state groundwater flow modeling, estimated K values of 2 – 20 m/day (mean = 15 m/day). The wide range of K values across studies reflects both the aquifer's inherent vertical and spatial heterogeneity and methodological differences between sample-scale grain-size analysis and basin-scale numerical modeling (Vienken and Dietrich, 2011). The vertical stratification, with high-K coarse sands in the upper aquifer and low-K fine sands and clays at depth, creates a dual hydrogeologic function where the upper permeable zone facilitates rapid infiltration of precipitation, while the lower-permeability layers may act as local confining or semi-confining units that impede vertical flow and potentially influence lateral groundwater movement. Despite this variability, all approaches confirm that the Keta Strip aquifer exhibits moderate to high hydraulic conductivity typical of clean, unconsolidated coastal sands, making it highly responsive to precipitation and well-suited for shallow groundwater development for irrigation.

Groundwater Level Response to Precipitation

Season Water Level Fluctuations

Continuous water level monitoring was conducted at six wells across the Keta Strip over varying durations ranging from 10

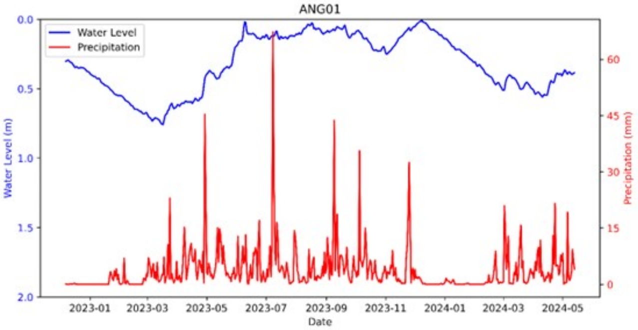


Figure 2. Temporal variation of water level and precipitation at Anloga (ANG01).

to 21 months between November 2022 and May 2024. During the monitoring period, water table depths across the monitoring network ranged from 0.2 – 3.2 m (mean ∼1.7 m) with considerable seasonal variability. These shallow water table conditions, combined with the high hydraulic conductivity of the upper sandy aquifer, create favorable conditions for rapid recharge.

Groundwater level hydrographs revealed a consistent and rapid response to precipitation across all monitoring locations. Figure 2 presents a representative example from Anloga (ANG01), showing the temporal variation of water level and precipitation over the monitoring period. The hydrograph clearly demonstrates that seasonal rainfall is the primary driver of groundwater recharge, with all wells exhibiting a consistent pattern of rising water levels during the rainy season (April – October) and declining water levels during dry periods (November – March). Water levels typically began rising in April-May at the onset of the wet season, reached peak elevations between June and August during the peak rainfall period, and then declined progressively through the dry season, reaching minimum levels by March – April.

The aquifer exhibited a rapid response to individual precipitation events, with observable water table rises occurring within hours to days following significant rainfall. This rapid response is characteristic of unconfined, shallow, sandy aquifers with high hydraulic conductivity and indicates that recharge occurs primarily through direct vertical infiltration of precipitation (Healy and Cook, 2002). The short response time contrasts with longer delays (2 – 4 months) reported in other Ghanaian basins such as the White Volta (Obuobie et al., 2012) and the Densu Basin (1 – 2 months; Duah et al. (2021)), where such lags are often attributed to deeper vadose zones and the need to satisfy antecedent soil moisture deficits before recharge occurs. In the Keta Strip, the combination of shallow water tables (typically < 2 m depth), highly permeable sandy sediments ($K = 13 – 59$ m/day), and thin unsaturated zones facilitates nearly immediate transmission of infiltrating precipitation to the water table. The relatively smooth recession curves between rainfall events reflect continuous drainage through lateral flow and evapotranspiration.

Notably, even during the dry season when precipitation was minimal or absent, the water table remained relatively shallow (typically 1 – 3 m below surface), suggesting sustained groundwater storage despite limited direct recharge. This persistence is likely attributable to a combination of geomorphic and hydrogeologic factors. First, the geomorphic setting of the Keta Strip is exceptionally low-lying, with specific zones situated 1.0 to 3.5 meters below sea level, naturally positioning the land surface in close proximity to the phreatic surface (Awadzi et al., 2008; Kippo, 2012). Second, regional groundwater flow from inland recharge areas, following the documented northeast-southwest flow pattern, likely contributes to maintaining water levels during dry periods (Yidana and Chegbeleh, 2013). Finally, the aquifer is bounded by the Keta Lagoon and Gulf of Guinea, which establish constant-head hydraulic boundaries that stabilize shallow water table positions. The high permeability of the aquifer facilitates rapid hydraulic equilibration with these boundaries rather than promoting drainage, as the minimal topographic gradient limits the potential for significant water table decline (Yidana and Chegbeleh, 2013). While these boundaries help stabilize groundwater levels, they also pose risks of saltwater intrusion, which is an established problem in the area due to the thin freshwater lens and increased groundwater extraction (Helstrup et al., 2007; Jørgensen and Banoeng-Yakubo, 2001).

The consistent seasonal pattern across all monitoring wells indicates spatially uniform recharge mechanisms across the study area, with variations in absolute water table elevation reflecting differences in topography and local drainage conditions rather than fundamental differences in recharge processes.

Diurnal Fluctuations and Pumping Effects

While the monitored wells generally exhibited water level patterns driven primarily by precipitation, wells located on heavily irrigated farmlands such as the Ministry of Food and Agriculture (MoFA) farm in Woe displayed pronounced diurnal water level fluctuations indicative of pumping influence (Figure 3). Examination of continuous hourly water level data from this well revealed consistent differences between daytime (6 am – 6 pm) and nighttime (6 pm – 6 am) water levels, with systematic drawdowns occurring during daylight hours and recovery during nighttime periods (Figure 3a). Water levels typically declined by 0.3 – 0.4 m during daytime hours (Figure 3b,d), corresponding to periods of active irrigation pumping on the farm, and subsequently recovered during the night when abstraction ceased (Figure 3c).

This diurnal signature was characteristic of aquifer response to nearby pumping and differs fundamentally from the precipitation-driven fluctuations observed at the other monitoring wells. The regular day-night pattern persisted even during periods without rainfall, confirming that pumping rather than recharge was the dominant control on water level behavior at this location. These findings support the decision to exclude wells located in active irrigation areas from recharge estimation, as recommended by Duah et al. (2021), to prevent misinterpreting the post-pumping recovery (refilling of the cone of depression) as natural recharge, thereby leading to a gross overestimation of groundwater replenishment.

Table 2. Summary of recharge estimates by location.

Location	Well ID	Longitude (X)	Latitude(Y)	Specific Yield	Range of Recharge (mm/yr)	Central Recharge (mm/yr)	% of Precipitation
Atorkor	AT01	0.8185	5.7766	0.24-0.27	386.26-436.65	411.46	26.8
Anloga	ANG01	0.9096	5.7993	0.23-0.26	368.87-416.98	392.92	25.6
Dzita	DZI 01	0.7713	5.7727	0.28-0.29	766.82-866.84	816.83	53.2
Tegbi Xekpa	TX01	0.9898	5.8733	0.19-0.30	607.05-686.23	646.64	42.1
Anloga	AHL01	0.9184	5.7884	0.24-0.28	671.50-759.09	715.30	46.6
Vodza	VD01	1.0047	5.9449	0.19-0.30	777.55-878.97	828.26	54
Average						**635.2**	**41.4**

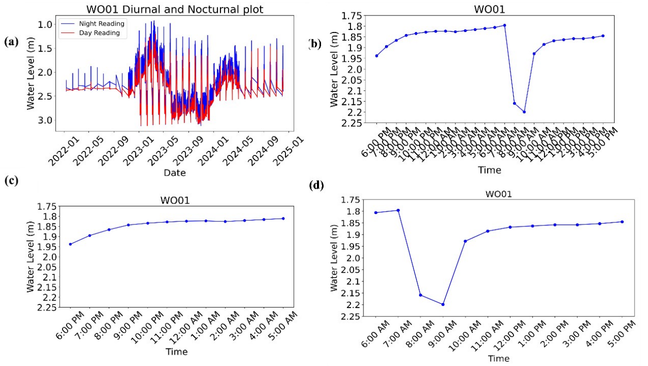


Figure 3. Diurnal water level fluctuations at the MoFA farm well (WO01) in Woe demonstrating pumping influence. (a) Comparison of daytime (6 am — 6 pm, red) and nighttime (6 pm — 6 am, blue) water levels over the monitoring period showing consistent diurnal separation. (b) Representative 24-hour water level cycle showing sharp daytime drawdown (~0.35 m) during pumping hours and nighttime recovery. (c) Nighttime water level recovery pattern showing gradual rise (d) Daytime water level decline pattern showing progressive drawdown during irrigation pumping.

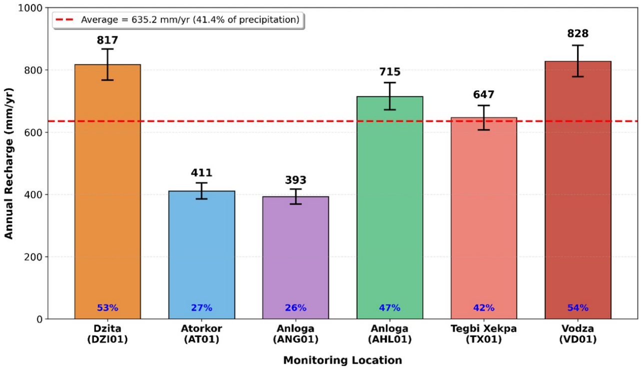


Figure 4. Bar chart showing annual recharge estimates at six monitoring locations arranged in spatial sequence from west to east. Error bars represent ranges of specific yield values. Numbers above bars indicate central recharge estimates in mm/yr. Percentages at the base of bars show recharge as a proportion of annual precipitation. Red dashed line indicates strip-wide average (635 mm/yr, 41.4%).

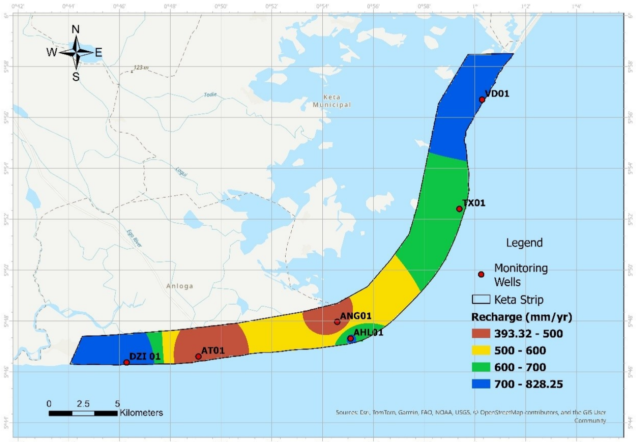
Groundwater Recharge

Groundwater recharge was estimated using the water table fluctuation (WTF) method at six monitoring locations across the Keta Strip between November 2022 and May 2024. During this period, the study area received an average annual precipitation of 1535 mm. Specific yield values determined from grain-size analysis ranged from 0.19 to 0.30 across the monitoring sites, reflecting spatial variability in sediment texture within the predominantly sandy aquifer materials.

Annual recharge estimates exhibited considerable variability across the monitoring network (Table 2, Figure 4). Using the minimum and maximum specific yield bounds at each location, recharge rates ranged from 369 – 417 mm/yr at Anloga (ANG01) to 766-867 mm/yr at Dzita (DZI01), with central estimates (arithmetic mean of bounds) spanning 393 to 817 mm/yr. The spatially averaged recharge across all six locations was 635 mm/yr, corresponding to approximately 41% of annual precipitation. Individual sites showed recharge rates ranging from 24% to 54% of local precipitation (Figure 4).

This recharge proportion is notably higher than values reported for other inland basins in Ghana but consistent with findings from similar coastal sandy aquifers. Obuobie et al. (2012) reported recharge rates equivalent to 7 – 8% of annual rainfall in the White Volta River Basin, while Duah et al. (2021) found rates ranging from 3.65% (Chloride Mass Balance method) to 5.74% (WTF method) in the Densu Basin. However, the recharge percentage observed in this study aligns closely with findings from Rama et al. (2018), who reported recharge equivalent to 43% of annual rainfall in a similar unconfined coastal sandy aquifer in southern Brazil. The high recharge rates and rapid aquifer response observed in this study are consistent with the documented hydrogeologic characteristics of the Keta Strip aquifer. The combination of shallow water tables, highly permeable sandy sediments, and thin vadose zones creates conditions highly favorable for direct vertical recharge. The rapid water table response to individual precipitation events (hours to days) provides independent confirmation that infiltrating precipitation efficiently reaches the water table with minimal delay.

Previous studies in the Keta Basin have reported varying recharge estimates depending on methodology and data resolution. Yidana and Chegbeleh (2013), using calibrated steady-state groundwater flow modeling approach, reported recharge rates ranging from 69 to 340 mm/yr with an average of 200 mm/yr (approximately 20% of precipitation). Kippo (2012), applying the WTF method, reported a broader range of 70 to 1550 mm/yr with an average of 810 mm/yr. The present study's estimates (393 – 828 mm/yr, average 635 mm/yr) fall between these previous assessments and show closer agreement with Kippo's WTF-based approach than with model-calibrated estimates. This similarity likely reflects the shared methodology, as the WTF method is inherently more sensitive to short-term water level variations and captures rapid recharge responses that may be smoothed or underestimated in steady-state numerical models (Healy and Cook, 2002). The



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5. Spatial distribution of recharge across the study area.

differences between model-based and WTF-based estimates highlight the importance of method selection in recharge assessment. Numerical modeling approaches provide spatially distributed estimates and can integrate multiple hydrogeologic processes, but their accuracy depends heavily on calibration data availability (Gumuła-Kawęcka et al., 2022; Healy and Cook, 2002), model structure and parameterization uncertainty (Ware et al., 2023), and may not fully capture localized rapid recharge in heterogeneous systems (Becke et al., 2024). Conversely, the WTF method provides direct field measurements at specific locations but requires high-frequency water level monitoring and accurate specific yield determination. The higher recharge rates obtained in this study compared to Yidana and Chegbeleh (2013) likely reflect the use of hourly data to capture rapid recharge pulses that lower-resolution monitoring would miss (Garcia et al., 2013; Nimmo et al., 2015), alongside the strategic exclusion of wells obscured by anthropogenic pumping (Alley et al., 1999; Garcia et al., 2013). Furthermore, these discrepancies highlight scale and conceptual differences, as point-scale WTF measurements of gross recharge naturally differ from regional model averages that often estimate net recharge after accounting for concurrent losses (Scanlon et al., 2002; Walker et al., 2019).

The spatial interpolation of annual recharge estimates (Figure 5) reveals pronounced heterogeneity across the Keta Strip, characterized by a distinct "high-low-high" zonal pattern. The highest recharge rates are concentrated at the geographic extremities of the study area: Vodza (∼54% of precipitation) in the far northeast and Dzita (∼53% of precipitation) in the far southwest, represented by dark blue zones on the interpolated surface. In contrast, the central-western sector, specifically Anloga (ANG01) and Atorkor, defines a prominent recharge trough where annual replenishment reaches its minimum values, represented by red-orange zones. The central and central-eastern coastal locations: Anloga (AHL01) (715 mm/yr, ∼47%) and Tegbi Xekpa (647 mm/yr, ∼42%) exhibit intermediate recharge rates (yellow-green zones), forming a transitional zone between the high-recharge extremities and the low-recharge central-western trough.

This spatial pattern correlates strongly with the estimated variations in aquifer hydraulic properties. The high-recharge zones at Dzita and Vodza correspond to areas of coarser sediment textures (D50 = 0.55 mm at Dzita) and elevated hydraulic conductivity (59 m/day), facilitating rapid vertical infiltration of precipitation through the thin unsaturated zone. Conversely, the low-recharge trough at Anloga (ANG01) and Atorkor corresponds to finer-grained materials (D50 = 0.14 – 0.27 mm) with significantly lower hydraulic conductivity (approx 13 – 14 m/day), resulting in reduced infiltration capacity despite receiving comparable annual rainfall. The intermediate recharge rates at Anloga (AHL01) and Tegbi Xekpa align with their moderate-to-high textural and hydraulic properties (D50 = 0.24 – 0.68 mm, K = 28 – 42 m/day), confirming the dominant control of aquifer lithology on recharge efficiency across the study area.

Implications for Sustainable Management

While the high recharge potential in the Keta Strip suggests strong capacity for aquifer replenishment, it also raises important concerns about vulnerability and sustainability. The shallow water table and high permeability that facilitate rapid infiltration also render the aquifer highly susceptible to surface-applied contaminants, particularly agricultural inputs such as nitrogen fertilizers and pesticides. Kippo (2012) documented elevated nitrogen concentrations in groundwater associated with intensive shallot cultivation, emphasizing the direct hydraulic connection between land surface and the saturated zone. The rapid recharge pathways that enable efficient aquifer replenishment during wet seasons also provide minimal attenuation of dissolved contaminants, underscoring the need for protective land-use controls and systematic water quality monitoring in agricultural areas. Yidana and Chegbeleh (2013) recommended and encouraged afforestation in these sections of the strip to reduce evapotranspiration losses and provide natural filtration of infiltrating water, which still remain relevant given the present findings.

Moreover, the shallow nature of the aquifer exposes groundwater to high evapotranspiration losses, particularly during the extended dry season. While the WTF method estimates gross recharge (water reaching the water table), a portion of this stored water may be subsequently lost through direct evaporation from the shallow water table or uptake by phreatophytic vegetation. Consequently, net aquifer replenishment available for sustained abstraction may be lower than gross recharge estimates suggest, especially during prolonged drought periods when evapotranspiration demand is highest and precipitation inputs cease. Additionally, in the low-recharge central-western corridor (Anloga-Atorkor), the naturally low recharge (∼400 mm/yr, equivalent to only 26 – 27% of precipitation), and coastal proximity creates heightened vulnerability to saltwater intrusion under pumping stress, as documented by Nielsen et al. (2007), who mapped extremely thin freshwater lenses (0 – 5 m thickness) in near-coastal zones. Continued expansion of mechanized irrigation in this low-recharge corridor without corresponding reductions in abstraction rates could destabilize the freshwater-saltwater interface, leading to progressive aquifer salinization and loss of usable water resources (Kortatsi et al., 2005).

Limitations

However, several sources of uncertainty warrant acknowledgment. The specific yield values used in recharge calculations were derived empirically from grain-size analysis rather than from direct field drainage tests, introducing uncertainty related to empirical correlation errors and the representativeness of depth-interval samples (Crosbie et al., 2005). The range of recharge estimates at each location (Table 2) reflects this Sy uncertainty, with differences between upper and lower bounds ranging from 48 mm/yr at Anloga (ANG01) to 101 mm/yr at Dzita, representing approximately 12 – 13% relative uncertainty. Additionally, the event-based approach to identifying water table rises, while straightforward and reproducible, may yield conservative recharge estimates as it does not explicitly account for concurrent aquifer drainage during recharge events (Nimmo et al., 2015). Future studies employing direct specific yield measurements through field pumping tests or undisturbed core analysis, combined with longer monitoring periods spanning multiple annual cycles, would reduce these uncertainties and provide more refined recharge estimates for water resource planning.

Conclusion

This study employed the water table fluctuation method with high-frequency (hourly) monitoring to estimate groundwater recharge in the Keta Strip aquifer over November 2022 to May 2024. Mean annual recharge is estimated at 635 mm/yr, representing approximately 41% of annual precipitation (1,535 mm/yr). This proportion is substantially higher than previous numerical modeling estimates for the Keta Basin (Yidana and Chegbeleh (2013): ∼20%) but consistent with similar coastal sandy aquifers globally (Rama et al. (2018): 43% in Brazil). The higher estimates likely reflect detection of rapid recharge pulses through hourly monitoring, deliberate well siting away from pumping interference, and methodological differences between field measurements and regional model averages.

Recharge exhibits strong seasonal concentration during the wet season (April – October) with negligible recharge during the dry season (November – March). Individual recharge events respond rapidly (hours to days) to precipitation, reflecting the high hydraulic conductivity (13 – 59 m/day, mean 33 m/day) and shallow water table (0.2 – 3.2 m depth) characteristic of the aquifer. Grain-size analysis yielded specific yield values of 0.19 – 0.30 (mean 0.25), consistent with medium to coarse sand compositions.The aquifer is highly responsive to rainfall and exhibits a distinct “high-low-high” spatial recharge pattern controlled by sediment texture. Coarse-grained sediments at Vodza and Dzita facilitate high recharge (>800 mm/yr), while finer sediments in the central Anloga-Atorkor corridor limit replenishment to ∼400 mm/yr.

Recommendations

The pronounced spatial heterogeneity in recharge capacity necessitates zone-specific management strategies. High-recharge zones can sustainably support moderate year-round irrigation, while the low-recharge areas should restrict extraction primarily to the wet season, with alternative water supplies (rainwater harvesting, surface water storage) for dry-season demand. Implementation requires a permanent groundwater monitoring network with real-time data transmission. Agricultural practices should align with natural recharge cycles. Water-intensive crops (shallots, tomatoes, peppers) should be cultivated during the wet season (May – October) when groundwater recharge is active, while farmers transition to drought-resistant crops (millet, drought-tolerant vegetables) during the dry season (November – April). Water conservation practices (drip irrigation, mulching) should be mandated to minimize groundwater withdrawals.

High-recharge zones at Vodza and Dzita require protective zoning with land-use restrictions limiting impervious development and strict controls on agrochemical application, as rapid infiltration pathways provide minimal contaminant attenuation. To address saltwater intrusion risk, the monitoring network should be expanded to include coastal wells with continuous salinity sensors for early saltwater intrusion warning. Finally, community engagement through education campaigns in the local Ewe dialect and establishment of water user associations can facilitate collaborative management and enforcement. Institutional capacity of the Ghana Water Resources Commission should be strengthened for permit enforcement and compliance monitoring. Future research should continue high-frequency monitoring for 5 – 10 years, conduct direct specific yield determination through pumping tests, develop calibrated numerical flow models incorporating spatial recharge patterns, and assess climate change impacts on long-term aquifer sustainability.

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