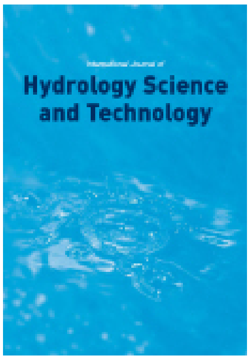


International Journal of Hydrology Science and Technology

ISSN online: 2042-7816 - ISSN print: 2042-7808
https://www.inderscience.com/ijhst

Estimation of groundwater recharge in Southern Ghana

Delaiah Antwi Nyarko, Larry Pax Chegbeleh, Elikplim Abla Dzikunoo, Edward Kofi Ackom, Sandow Mark Yidana

DOI: 10.1504/IJHST.2024.10062601

Article History:

Received:	21 June 2023
Last revised:	29 November 2023
Accepted:	07 December 2023
Published online:	03 December 2024

Estimation of groundwater recharge in Southern Ghana

Delaiah Antwi Nyarko, Larry Pax Chegbeleh*, Elikplim Abla Dzikunoo, Edward Kofi Ackom and Sandow Mark Yidana

Department of Earth Science,
University of Ghana,
Box LG 58, Legon, Accra, Ghana
Email: nyarkodelaiah4@gmail.com
Email: lpchegbeleh@ug.edu.gh
Email: eadzikunoo@ug.edu.gh
Email: ekackom@ug.edu.gh
Email: smyidana@ug.edu.gh
*Corresponding author

Abstract: The rainfall infiltration breakthrough (RIB) model has been applied to estimate groundwater recharge over parts of the saprolite aquifer unit in Southern Ghana. This method relies on rainfall and groundwater level data monitored simultaneously over a period, and properties of the aquifer material. The water table fluctuations (WTF) technique was applied independently to validate the results of RIB technique. Both methods were executed based on specific yield (Sy) values in the range of 1%–5%. The results suggest a wide range of variations in groundwater recharge rates over the terrain. Groundwater recharge rates fall in the range of 0.58%–21.36% of annual precipitation based on the RIB. The results indicate that the lag period between rainfall and eventual groundwater recharge ranges between 0 and 9 months, depending on the thickness and content of the unsaturated zone. Estimates of groundwater recharge suggest variably good fortunes for groundwater.

Keywords: RIB model; WTF method; groundwater level fluctuation; groundwater recharge; shallow unconfined aquifer; saprolite aquifer system; lag time; lag length.

Reference to this paper should be made as follows: Nyarko, D.A., Chegbeleh, L.P., Dzikunoo, E.A., Ackom, E.K. and Yidana, S.M. (2025) 'Estimation of groundwater recharge in Southern Ghana', *Int. J. Hydrology Science and Technology*, Vol. 19, No. 1, pp.73–92.

Biographical notes: Delaiah Antwi Nyarko holds a Master of Philosophy in Hydrogeology. His research interests include water quality analysis, geospatial analysis, groundwater modelling and environmental impact assessment. Currently, he is a Co-founder of Geomates Engineering Limited, where he provides consultancy services on Environmental and Earthworks projects to companies. Additionally, he serves as a Labeller at Farmerline Limited, offering consultancy services on geospatial analysis projects.

Larry Pax Chegbeleh's discipline is in the area of applied geology with specialisation in environmental geoscience, hydrogeology and engineering geology. His research interest includes water resources development and

management, geo-environmental hazards and risks assessment/protection, ground improvement techniques and slope stability analysis, and engineered barrier system/cut-off walls construction for seepage control. Besides teaching and research experiences, and field implementation programmes, he employs his expertise in diverse ways by providing consultancy services to the public in the research areas mentioned above. Many of his findings have been published in very good publication outlets.

Elikplim Abla Dzikunoo is a researcher in the area of applied geophysics with applications for hydrogeology and structural geology. She currently teaches geophysics, geostatistics, remote sensing, and GIS in the Department of Earth Science, at the University of Ghana. She is interested in using her knowledge to address humanitarian and environmental challenges such as access to potable water. As an early career researcher, she is working steadily on increasing her research and publication portfolio by applying for grants and seeking collaborations with other researchers.

Edward Kofi Ackom is a Lecturer in Hydrology and Engineering Geology at the Department of Earth Science, University of Ghana, and a professional member of the Ghana Institution of Engineering with over ten years of professional experience in Civil/Water Resource Engineering and Management. His specific areas of research interest include hydrological, geohydrological, and hydraulic modelling of hydrologic systems, risk assessment, and climate and land use impact studies in Water resources development. Besides teaching and research experiences, he employs his expertise in diverse ways by providing consultancy services to the public in the research areas mentioned above. His research findings have been published in very good journals.

Sandow Mark Yidana is a Professor of Hydrogeology with significant contribution to the global discourse and knowledge base on groundwater resources development and management. He is also an experienced administrator at the tertiary education level and is currently the Dean of the School of Physical and Mathematical Sciences, University of Ghana. He has trained over two dozen professionals at the PhD level and over 40 others at the MSc/MPhil levels. His research output has been cited copiously across all continents and he is clearly visible in all authentic scientific databases.

1 Introduction

Groundwater recharge estimation is a crucial component for the efficient and lengthy management of groundwater systems. For long-term planning and management of groundwater, precise measurement of groundwater recharge is essential, especially in arid and semi-arid Regions with significant evapotranspiration and groundwater recharge (Alejandro et al., 2019; Xu et al., 2019). Although groundwater recharge measurement is crucial for evaluating groundwater balances, modellers have faced substantial hurdles due to the complex geological nature of aquifers, difficulties in acquiring field data, and the unpredictability associated with a given area's meteorological data (Ahmadi et al., 2012; Ghafari et al., 2018; Majdabady et al., 2020). Due to the difficulty of measuring groundwater recharge directly, a number of groundwater recharge estimation systems have been developed, ranging from physical methods to numerical modelling approaches (Singh et al., 2019; Walker et al., 2019). Due to the lack of accurate data and the dynamic nature of conditions over time and distance, researchers often emphasise the need for a staged and iterative approach to recharge estimation (Barthel et al., 2021; Sajil Kumar et al., 2022). Methods focused on surface water and unsaturated zone data offer potential recharge estimations, while those relying on groundwater data provide calculations of actual recharge (Singh et al., 2019; Zeinali et al., 2020; Zhang et al., 2020). Therefore, it is a standard procedure to employ multiple methods for recharge estimation to enhance the accuracy of recharge estimates (Ferede et al., 2020; Walker et al., 2019).

Due to the large diversity of natural phenomena that have an impact on groundwater recharge, numerous methodologies have been developed to quantify groundwater recharge (Ahmadi et al., 2014; Ferede et al., 2020; Moeck et al., 2020; Singh et al., 2019). The findings of using these methodologies revealed that when alternative techniques and input datasets were employed, groundwater recharge estimations from different researches differed considerably. The majority of groundwater recharge approaches have been designed for wide range of applications, while few details are available regarding mechanisms at the local level (Aloui et al., 2023). To calculate groundwater recharge, the chloride mass balance (CMB) approach has also been widely utilised (Aliewi et al., 2022; Gebru et al., 2019; Hassen et al., 2021; Kisiki et al., 2022; Uugulu et al., 2020; Xu et al., 2019). The method, however, might not yield a credible picture of recharge rates if used in isolation. The method's limitations and underlying assumptions must be taken into account when assessing the results. Therefore, the method may not be applicable and result in an underestimating of recharge in areas where excessive levels of the groundwater chloride arise from processes that dissolve minerals or are impacted by reactions that lower their levels in groundwater. The technique is inapplicable in locations where evaporation is present or where saline water emerges or mixes. It is also worth noting that recharge computed by tracer methodology is a mean transport velocity grounded on Darcy's principle and is not the most recommended approach when the recharge is extremely modest (under 20 mm/year) (Wu et al., 2016). According to Yidana and Chegbeleh (2013), even the most comprehensive groundwater studies rarely use conventional hydrogeological tracer experiments because of the high cost of setting them up.

The application of the rainfall infiltration breakthrough (RIB) model in general groundwater resources management and groundwater modelling represents one of the most reliable methods in hydrogeological investigations. The RIB model has been used to facilitate a wide range of applications and decision-making processes such as the development of management decision support systems for groundwater resources. The RIB method has been performed in almost all environments and has produced successful results of groundwater recharge (e.g., Ahmadi et al., 2014; Aveni 2023; Danzan et al., 2020; Majdabady et al., 2020; Muavhi and Mutoti 2023). The RIB method is based on the cumulative rainfall departure (CRD) method (Xu and Van Tonder, 2001). The methodology is based on assumption that rises in groundwater levels as a result of rainfall percolating through the unsaturated zone to the water table.

The RIB technique has been proven to be simple but reliable method for estimating groundwater recharge. The method accounts for the actual mechanisms of rainwater percolating through the unsaturated zone to the groundwater table. This method also provides an opportunity to characterise the spatial distribution of groundwater recharge and therefore, serves to provide data for constructing conceptual models in readiness for numerical modelling since every good model is based on a good understanding of the hydrogeological framework of which groundwater recharge is a critical component. The method has also been utilised in other nations, including Iran, Mongolia, and the USA. Based on rainfall time series data, the method was originally applied to calculate groundwater recharge in South Africa (Sun et al., 2013).

Groundwater recharge is an important parameter in the overall characterisation of groundwater potential and sustainability in an area. Therefore, decision making plans on resource allocation requires adequate knowledge of the nature and quantitative estimates of groundwater recharge. This is particularly important in regions where climate change has been noted to manifest in irregular rainfall patterns and unpredictable water resources availability for various uses. In addition to natural climate fluctuations and the implications on water resources, the growing impacts of anthropogenic activities on water resources provide sufficient grounds for prudent decisions on resource allocation and equitable sustainable management.

In the Birim north district in Ghana, groundwater is the main source of water for domestic uses among the largely rural communities. The resource is abstracted through hand dug wells, boreholes, and dugouts completed in the saprolite aquifer unit. In recent times, a monitoring program of groundwater levels suggests a decreasing trend in most parts of the district. There is a proliferation of surface mining activities (both large scale and artisanal) which will pose a potential toll on groundwater resources sustainability. This situation, coupled with rising population growth in the area has accentuated the need for prudent management decisions on groundwater resources in the area. It is based on the above, that it has become urgent to deploy reliable methodologies for estimating groundwater recharge as an initial but integral aspect of scoping the resource for efficient allocation and utilisation.

Previous investigations in the area have primarily been on groundwater hydrochemistry and thus, there has been paucity of data on the quantitative aspects of groundwater resources evaluation in the area. There has been no documented published literature on groundwater recharge estimation in the area.

In this research groundwater recharge is being estimated using the water table fluctuations (WTF) method and RIB methods. These two methods are amongst the best approaches for estimating recharge, especially in unconfined aquifer systems such as pertains in the study area. The RIB method has not been used anywhere in Ghana and much of the West African sub-region. This is on account of a paucity of data and expertise. In this study, the objective is to demonstrate the utility of these techniques in the sub-region to assist in decision making on groundwater resources allocation and sustainable management. The WTF method was used as a backup to the RIB model. By combining these innovative methodologies, our study aims to provide a nuanced understanding of groundwater recharge dynamics in a specific, yet underexplored, geographical context, contributing valuable insights to the broader field of hydrogeology.

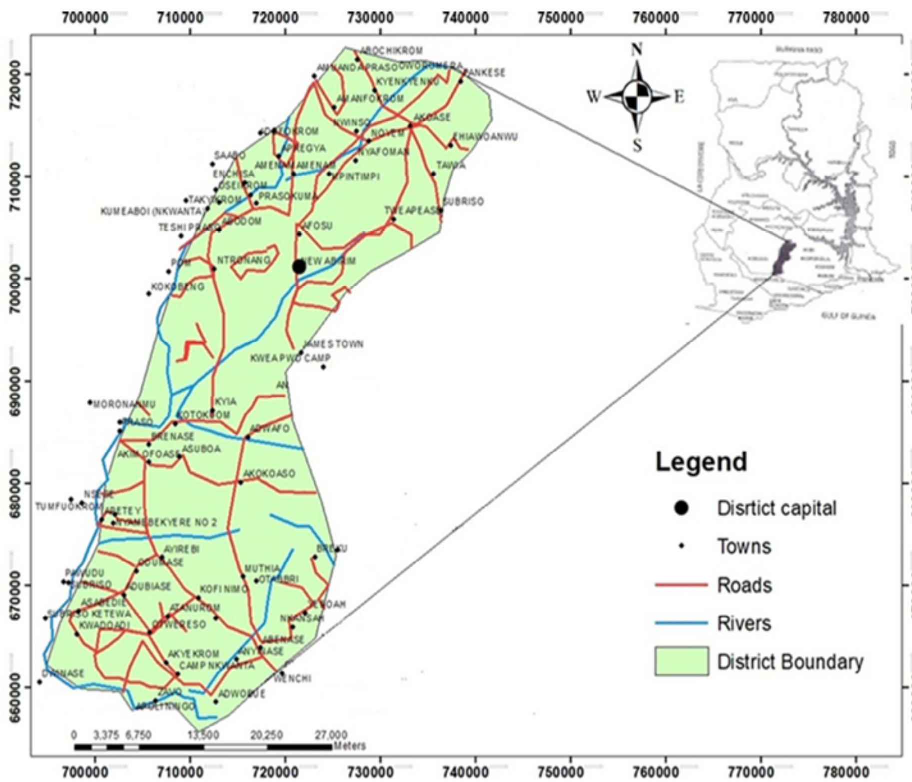
One of the primary limitations encountered in this study relates to the challenge of accurately measuring the specific yield (Sy) of the aquifer when employing the RIB and WTF techniques for groundwater recharge assessment.

2 Study area

2.1 Location, climate, topography and drainage

The area (Figure 1) is located between latitudes 6.15°N, 6.35°N and longitudes 0.20°W, 1.05°W (Owusu, 2012). The district has a projected overall land size of 1,250 km^2 accounting for approximately 6.47% of the overall land size of the Eastern Region.

Figure 1 Map of Birim north district showing various towns, roads and rivers (modified from Darimani et al., 2013) (see online version for colours)



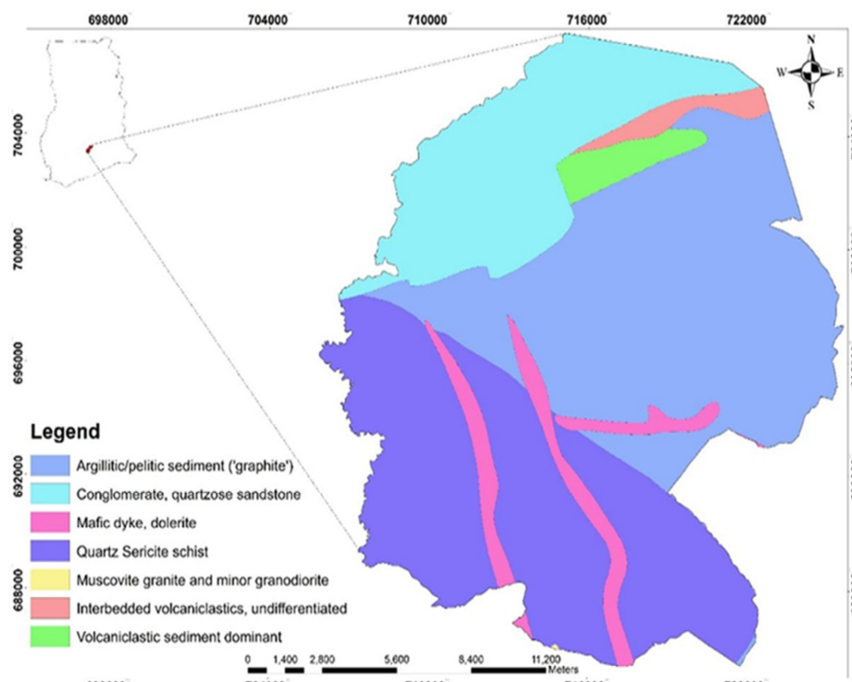
The area falls within the climatically moist semi-equatorial region that experiences a trend of rainfall with two peaks. The climate is tropical, with a daily temperature range from approximately 14.0°C to 36.4°C, according to data collected by Clear Creek Consultants in 2009 (Clear Creek, 2010). However, monthly average temperatures in the model area range from about 24.3°C in August to 26.6°C in February and March (Clear Creek, 2010). The first rainfall season starts in late March and ends in early July. The second season begins in mid-August and concludes in late October. The district receives between 1,500 mm and 2,000 mm of precipitation per year. Generally, rainfall for high areas is about 1,700 mm per annum (Nartey et al. 2011). Monthly average relative humidity at the Akyem project site range from approximately 66.9% in January to 88.8% in July (Clear Creek, 2010).

Topographically, the district is primarily undulating and hilly in nature, rising to more than 61 m above sea level in certain places. The drainage network in the area is dominated by the Pra river system which drains the north western parts of the terrain. The Nyafomang river drains the northern parts of the terrain while the Mamang river drains the southern and southeast of the domain (Figure 1).

2.2 Geology and hydrogeology

Akyem is underlain by Birimian metasedimentary and metavolcanic rock units (Figure 2). These include northeast-trending belts of folded, metamorphosed volcanic and sedimentary rocks of the early Proterozoic that underlie the study area. The southeast side of the area is underlain by rocks of the Birimian supergroup. In this region, the Birimian terrain comprises northeast-trending belts of volcanic and volcanoclastic material separated by broad turbidite-dominated sedimentary basins. Tarkwaian sediments unconformably overlay the Birimian volcanic belts in the north western portion of the study area. The Birimian rocks consist of black phyllites, metasiltstones, metagreywackes, tuffaceous sediments, tuffs, and hornstones (Ewusi et al., 2013; Frimpong et al., 2016). Tarkwaian sediments consist of conglomerates, sandstones, and phyllites. Structural features of the Birimian and Tarkwaian units display a strong northeast-southwest trend (Leaders et al., 2018; Nunoo, 2021).

Figure 2 Geological map of the study area showing the major lithologies (modified from AMEC Geomatrix, 2010)



In-situ weathering of bedrock defines the hydrostratigraphy in the model area. Weathering of bedrock to tens of metres depth is caused by the tropical climate. Highly weathered bedrock (saprolite), moderately weathered bedrock (saprock), and fresh rock (bedrock) are the three basic hydrostratigraphic units (Banoeng-Yakubo et al., 2011; Frimpong et al., 2016). Localised zones of increased permeability have emerged from structural characteristics in bedrock and quartz veining. In the flood plains of streams and rivers, alluvial deposits lie on top of saprolite. The saprolite is unconfined and generally thicker than the saprock. However, due to high clay content, the hydraulic conductivity is low compared to the saprock (Frimpong et al., 2016). The conductive, prolific zone is the region between the lower part of the saprolite and the saprock, as well as the fractured bedrock (Banoeng-Yakubo et al., 2011). The hydraulic and storage parameters are highly variable due to the heterogeneity of the terrain. In the study area, the rural communities derive their domestic water supply from shallow hand dug wells completed in the saprolite. Groundwater recharge occurs directly from rainfall since the material is loose and unconfined. Although the saprolite is generally less conductive, it serves as a good source of water for rural communities since abstraction levels in such areas are low.

3 Methodology

3.1 General concept

The RIB methodology was developed by Xu and Van Tonder (2001) as a revised and updated version of the CRD method (Bredenkamp et al., 1995). The method is centred on the connection between ground WTF and the departure of rainfall from the average rainfall of a preceding time. It is formulated as presented in equation (1). The principle is similar to that of the CRD methodology.

$$RIB(i)_m^n = r\left[\sum\nolimits_{i=m}^{n} P_i\left(2-\frac{1}{P_{av}(n-m)}\sum\nolimits_{i=m}^{n} P_i\right)\sum\nolimits_{i=m}^{n} P_t\right] \quad (1)$$

$(i = 1,\ 2,\ 3,\ \ldots I)$

$(n = i,\ i-1,\ i-2,\ \ldots N)$

$(m = i,\ i-1,\ i-2,\ \ldots\ M)$

$m < n < 1$

where

RIB(i) is the cumulative recharge from m to n rainfall events

r is the fraction of CRD

P_i is the rainfall amount at the i^{th} (daily, monthly, or annually) timeframe

P_{av} denotes the average precipitation across the whole time series

P_t is a threshold value indicating aquifer boundary conditions (P_t ranges from 0 to P_{av}).

A P_t value of 0 denotes a closed aquifer system, implying that the recharge at i^{th} timescale is solely dependent on preceding rainfall events from P_m to P_n; whereas the value of P_{av} denotes an open system, which indicates that the recharge at the i^{th} timescale is dependent on the difference between the average rainfall of preceding rainfall events from P_m to P_n and the mean rainfall of the whole time series). During the simulation process, both r and P_t values are determined.

It is thought that groundwater recharge estimated by the RIB method is linearly proportional to groundwater level changes under natural conditions. The connection between natural rainfall and water level fluctuations is defined by equation (2) (Sun et al., 2013).

$$Dhi = \left(\frac{1}{S_y}\right) * RIB(i)_m^n \tag{2}$$

Where *Dhi* denotes the water-level fluctuation that is equivalent to the difference between the mean water level of the whole time series and the measured water level at i^{th} time scale; A positive value reflects a rise in water level, whereas a negative value represents a fall in water level.

S_y represents the aquifer's Sy.

Equations (1) and (2) state that the moving mean of a rainfall time series, which is based on significance, determines how the variation in water level at the i^{th} time scale (daily, monthly, or annually) is impacted by earlier rainfall events from P_m to P_n (*mn*) (equation (3)).

$$\left(2 - \frac{1}{P_{av}(n-m)} \sum\nolimits_{1=m}^{n} P_i\right) \tag{3}$$

Whether or not the moving mean rainfall is exceeded throughout the interest period will determine whether the weighting element's value is positive or negative.

Groundwater level fluctuations are related to the RIB model through equation (4) (Sun et al., 2013):

$$Dhi = \left(\frac{1}{S_y}\right) \cdot \left(RIB(i)_m^n\right) - \frac{Q_p + Q_{out} + Q_{oth}}{A.S_y} \tag{4}$$

$$(i = 1,\ 2,\ \ldots I)$$

where: A is the area of the catchment, Q_p, Q_{out} and Q_{oth} denote groundwater abstraction, outflow, and volume changes caused by other activities, respectively.

It is apparent that groundwater level fluctuations occur as a function of the CRD from the mean rainfall series. It is worthy of note, however, CRD and earlier RIB approaches struggle to describe situations where the continual deviations are negative but the measured water level rises, and the meaning of r, which stands for the fraction of recharge, in the CRD and preceding RIB systems is unclear. The formulation of the CRD approach is shown in equation (5).

$$CRDi = \sum\nolimits_{n=1}^{i} R_n - k \sum\nolimits_{n=1}^{i} R_{av} (i = 1, 2, 3, \ldots, N) \tag{5}$$

where R denotes the amount of rainfall, with subscript '*i*' indicating the i^{th} month, '*av*', $av = (Q_{outi} + Q_{pi})/AS_y$ the average, $k = 1$ indicates that pumping does not occur and $k > 1$ if pumping and/or natural outflow takes place. It was believed that a CRD has a linear relationship with a monthly water level change. Bredenkamp et al. (1995) suggested equation (6).

$$Dh_i = \left(\frac{r}{S_y}\right) * CRD_i \tag{6}$$

where *r* is a fraction of the CRD that results in recharge from rainfall, which was calculated as the departure (difference) from normal rainfall at a period.

Instead of considering the departure from average, the difference between consecutive departures should be considered as a recharge. If the difference is positive, the groundwater level will rise, and vice versa; recharge at the i^{th} time scale can be calculated as:

$$\begin{aligned} \text{Re}(i) &= RIB(i)_m^n = RIB(i-1)_{m'}^{n'} = \left(\frac{DQ}{A}\right) \\ &= [Dh(i) = Dh(i-1).S_y - \left(\frac{Qp + Q_{out} + Q_{oth} - (Qp + Q_{out} + Q_{oth})}{A}\right) \end{aligned} \tag{7}$$

$$(i = 2,\ 3,\ \ldots I,\ m < n < I, m' < n' < I,\ n - m + 1 = n' - m' + 1.\ \text{Re}(i) > 0)$$

$$\text{Re}(i) = Dh(1).S_y - \left(\frac{Q_{p1} + Q_{out1} + Q_{oth1}}{A}\right) \tag{8}$$

$$T_{RE} = \text{Re}(i) + \sum_{i=2}^{n} \text{Re}(i) \qquad (i = 2, 3, \ldots I) \tag{9}$$

where:

Re(1) denotes the recharge for the first-time step

Re(i) s the recharge estimate at the i^{th} time, that could be daily, monthly, or annually.

T_{Re} is the total recharge in mm for the whole time series. If the value of *Re*(*i*) in equations (7) and (8) becomes negative, no recharge on the i^{th} time scale is assumed.

A few data such as groundwater level measurements, rainfall, aquifer properties including Sy, transmissivity, unsaturated thickness, lateral inflow and outflow, and groundwater extraction dataset were required to implement the CRD and RIB models.

3.2 Construction of conceptual model

The research region was partitioned into five polygons (Figure 3) predicated on the monitoring boreholes that were employed, using GIS program and a geostatistical approach. Then, data on each sub-transmissivity, the Sy of each zone, monthly rainfall totals, abstraction wells, and lateral groundwater inflow and outflow were provided. The conceptual model was created using a time series of water levels.

Each of the five polygons has a conceptual model built for it (one for each observation well). From November 2011 to June 2017, the mean water level was computed, and the mean value was deducted from each monthly figure to determine the water level fluctuation (six years). The recharge estimations for each well were then estimated by simulating Sy, catchment area, water level fluctuation, and rainfall data using the RIB program.

The RIB program was written in excel spreadsheet because it offers the sophisticated programming language visual basic application (VBA), which allows one to use some or all of the program's features to manipulate, analyse, and display the data. spreadsheet has been widely used for designing the platform, and the RIB interface was designed to simulate the groundwater level and recharge amount based on the equations outlined above. It also has the ability to fill the water level data. A screenshot of the RIB graphical user interface is illustrated below (Figure 4). The solver function in Excel's data bar needs to be enabled prior to executing this program.

Calibration was performed for each individual observation well model to determine the fraction of cumulative recharge by rainfall (r), Sy, lag time, and length of related rainfall events. The calibration target (objective function) was aimed at reducing the difference between the estimated and observed groundwater table elevations in each individual observation well (individual polygon).

Before entering the data into the application, the time scale must be decided; it relies on the type of data that is accessible. The three categories of datasets were daily scale, monthly scale, and annual scale. To select the time scale, click the 'start' button. By selecting the 'graph' option, the computed water level fluctuation and recharge amount data are generated and shown inside a black frame. The graphic will automatically update and show the quantity of recharge using the RIB method as well as the calculated water level fluctuation using the CRD and RIB methods.

Figure 3 Location map and polygon of each borehole (see online version for colours)

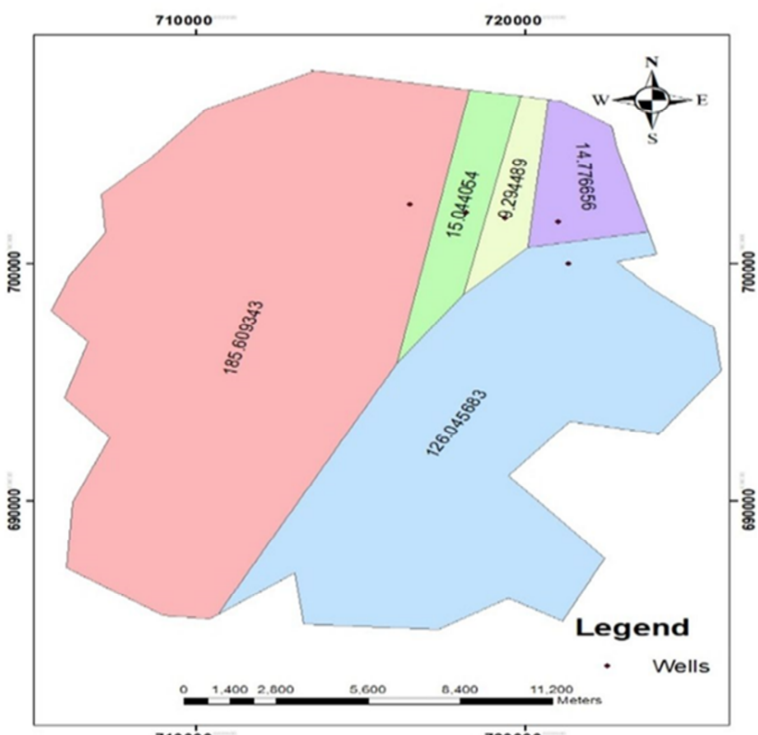
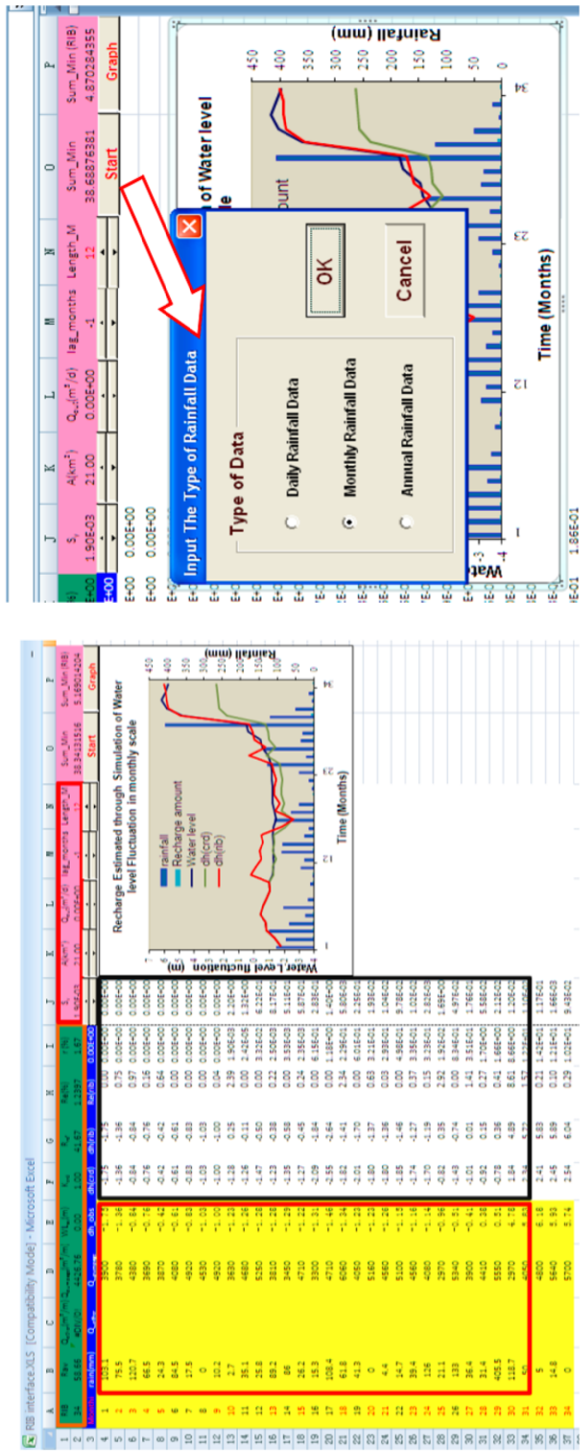


Figure 4 User interface of rib program (see online version for colours)

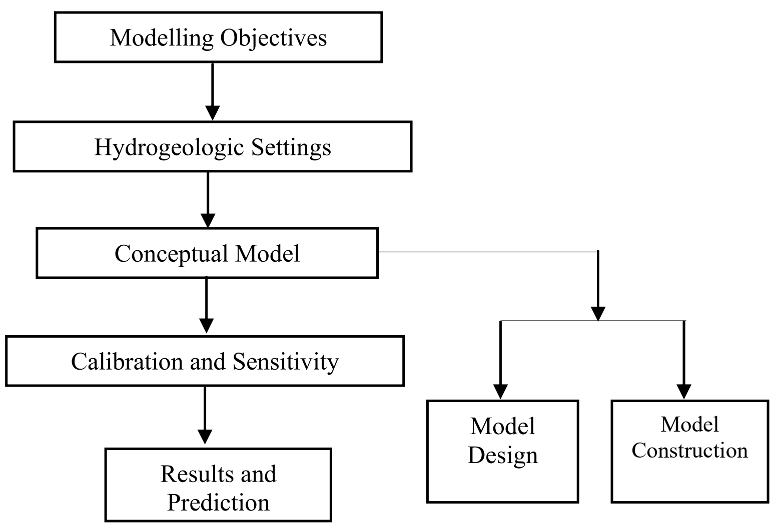


Source: Sun et al. (2013)

The necessary data include the amount of rainfall, the observed water level fluctuation, S_y, Q_p (abstraction volume due to pumping), Q_{out} (volume contributing to baseflow), and the area of the catchment. The available data must be input into a specific area, and the lag time and length must be adjusted using the spin buttons below each option. If the data are missing, other options (such as Q_p, Q_{out}, etc.) may be left empty (in places where pumping was modest, the effect of these parameters on water-level variations was deemed minimal in comparison to rainfall input).

The WTF were calculated using static water level observations from each of the five boreholes averaged over a six-year period. There are several methods to calculate the increase in groundwater level (Atta-Darkwa et al., 2013; Obuobie et al., 2012). In this study, the WTF value was calculated by subtracting the highest and lowest mean water levels for each borehole location. The net recharge for each well location was computed by multiplying the WTF data by the Sy of the aquifer media type at each well location. In the Keta strip in Ghana, Kippo (2012) employed this method to predict water level rise and net groundwater recharge in a quaternary aquifer. In order to apply the WTF and RIB method, an estimation of the Sy at a depth of WTF is required. In the study area, the Sy of the saprolite falls in the range of 0.01 (1%) and 0.05 (5%) (Golder, 2017). Thus, in this study, recharge estimates were made using Sy values of 0.01 and 0.05. Figure 5 depicts the modelling process employed for groundwater recharge in this study.

Figure 5 Flowchart of modelling protocol



4 Results and discussion

The simulations were done using a monthly time series of rainfall and groundwater levels. There were variances in the monitoring periods of each of the boreholes used for the simulation. This reflected in the lengths of the simulation periods. Table 1 presents the monitoring and simulation periods of all the boreholes used in this project.

Each polygon's monthly recharge and lag time were computed as a proportion of its monthly rainfall. Figure 6 illustrates the time series graphs of rainfall and computed groundwater recharge in mm (millimetres). On a monthly basis, the computed groundwater level fluctuation derived using the RIB technique almost matches the measured estimates after the (lag-month) and (length-month) were calibrated.

Table 1 Monitoring and simulation periods of boreholes used for the simulation

Borehole ID	*Monitoring period (months)*	*Simulated period (months)*
NW8	68	68
NMW8S	68	68
NMW10S	68	68
NMW12S	68	68
NMW17S	68	68

Groundwater recharge estimates from the RIB model at Sys of 0.01 (1%) and 0.05 (5%) are presented in Tables 2 and 3 respectively. The term lag-month was 9 months for boreholes MW8 and NMW8S; the time required for rainwater to percolate to the water table was less than 270 days. The term lag-month was 0 months for boreholes NMW10S, NMW12S, and NMW17S. This indicates that percolating rainwater reached the water table in less than a day. The term length months were 2, 2, 1, 2, 1 for boreholes MW8, NMW8S, NMW10S, NMW12S, and NMW17S monitored, respectively (Table 2 and Table 3). With an increased unsaturated zone depth, the recharge event's length is extended and the hydraulic conductivity of the material in the unsaturated zone. Irrespective of the thickness of the unsaturated zone material, the percentage of clay and other fine material is a limiting factor to vertical infiltration and percolation of rainfall.

Table 2 Groundwater recharge estimates from RIB model at specific yield of 1%

Borehole	*Time lag (Month)*	*Length of rainfall events (Month)*	*Specific yield*	*Groundwater recharge, yearly (%)*
NW8	–9	2	0.01	0.58
NMW8S	–9	2	0.01	0.67
NMW10S	0	1	0.01	4.20
NMW12S	0	2	0.01	1.64
NMW17S	0	1	0.01	4.27

Table 3 Groundwater recharge estimates from RIB model at specific yield of 5%

Borehole	*Time lag (Month)*	*Length of rainfall events (Month)*	*Specific yield*	*Groundwater recharge, yearly (%)*
NW8	–9	2	0.05	2.92
NMW8S	–9	2	0.05	3.36
NMW10S	0	1	0.05	21.01
NMW12S	0	2	0.05	7.32
NMW17S	0	1	0.05	21.36

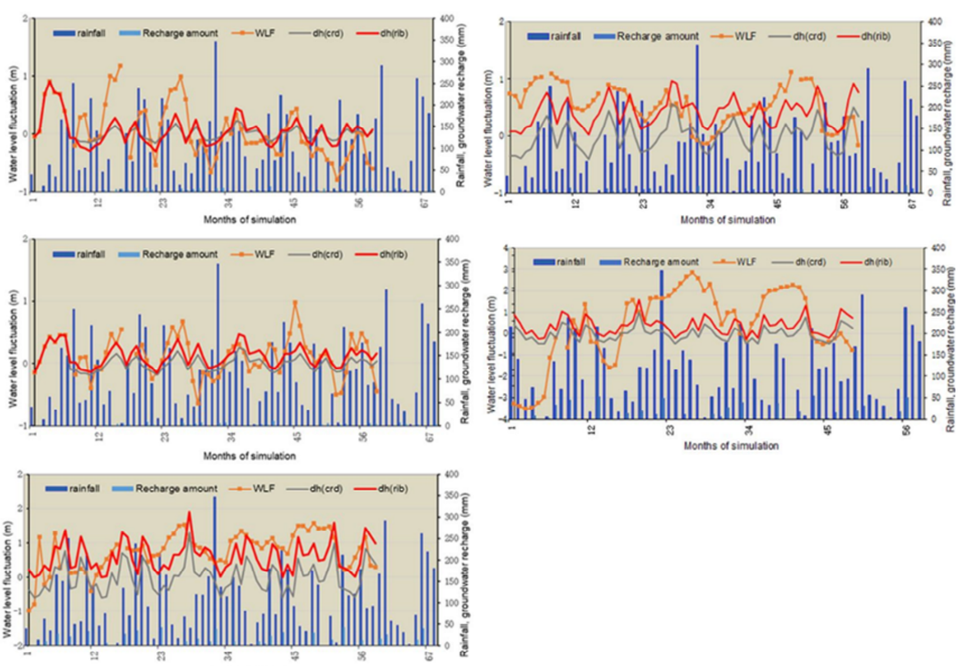
For a Sy of 0.01 (Table 2), the RIB method equation (4), estimated annual groundwater recharge of 0.58%, 0.67%, 4.20%, 1.46% and 4.27% of annual precipitation in boreholes MW8, NMW8S, NMW10S, NMW12S and NMW17S respectively. However, for a Sy of

0.05 (Table 3), the estimated annual groundwater recharge of annual precipitation are respectively 2.92%, 3.36%, 21.01%, 7.32% and 21.36% in boreholes MW8, NMW8S, NMW10S, NMW12S and NMW17S. It therefore goes without saying that groundwater recharge in the area falls in the range of 0.58%–21.36% of the annual precipitation, with a high level of spatial and temporal variability. The spatial variability is owed to the variations in the nature of the overburden and the effects on infiltration rates. The variability in the clay content has imposed considerable variability on the vertical hydraulic conductivity of the saprolite to reflect in such high spatial variability in the infiltration and groundwater recharge rates.

Table 4 Groundwater recharge from WTF method

Borehole ID	*Specific yield*	*Groundwater recharge (mm/year)*	*Groundwater recharge (%)*
NW8	0.01–0.05	15.1–75.5	1.2–6.1
NMW8S	0.01–0.05	12.0–60.0	0.96–4.8
NMW10S	0.01–0.05	19.5–97.5	1.56–7.8
NMW12S	0.01–0.05	8.0–40.0	0.64–3.2
NMW17S	0.01–0.05	50.0–250.0	4.0–22.6

Figure 6 Time series graphs of depth of rainfall, estimated groundwater recharge, and groundwater levels (see online version for colours)



The results of the RIB model demonstrate that the interval between rainfall infiltration and groundwater recharge (lag time) varies spatially, and indicates the various hydrogeological characteristics of the local regolith. The domain's MW8 and NMW8S polygons had the greatest lag time (9 months). This indicates that rainfall that occurred over the course of two months reached the water table after nine months. As expected, the lag times lengthen as groundwater depth rises. As the groundwater table's depth grows, evaporation from the unsaturated zone reduces percolation in the unsaturated zone, which in turn reduces recharge to the saturation zone, lengthening the delay time (Ahmadi et al., 2014; Majdabady et al., 2020; Shao et al., 2019). These were observed to be in great accordance with the physiologic surroundings of each subarea, depending on the depth of the water table. In addition to rain, evapotranspiration, atmospheric pressure, and trapped air can all significantly impact short-term changes in water level (Xin et al., 2022; Healy, 2010).

The recharge estimates utilising the RIB technique in this research area are compatible with calculations from hydrogeological studies carried out in similar geological environments. Groundwater recharge in the river Oda basin was measured in research by Atta-Darkwa et al. (2013). Groundwater recharge estimates from their study measured between 133 and 467 mm for 14 wells, or 9 to 31% of the yearly rainfall in 2009, and from 47.6 to 427.9 mm in 2010, or 4 to 34% of the yearly rainfall. Similar to this, Sanwidi (2007) applied similar technique for the Kompienga Dam Basin, which is close to Ghana in Burkina Faso, and determined that the groundwater recharge ranged from 5.3 to 29.4% of the annual rainfall. The results of the current study are in sync with other regional groundwater recharge estimates (e.g., McCartney et al., 2012; Obuobie, 2008; Obuobie et al., 2012).

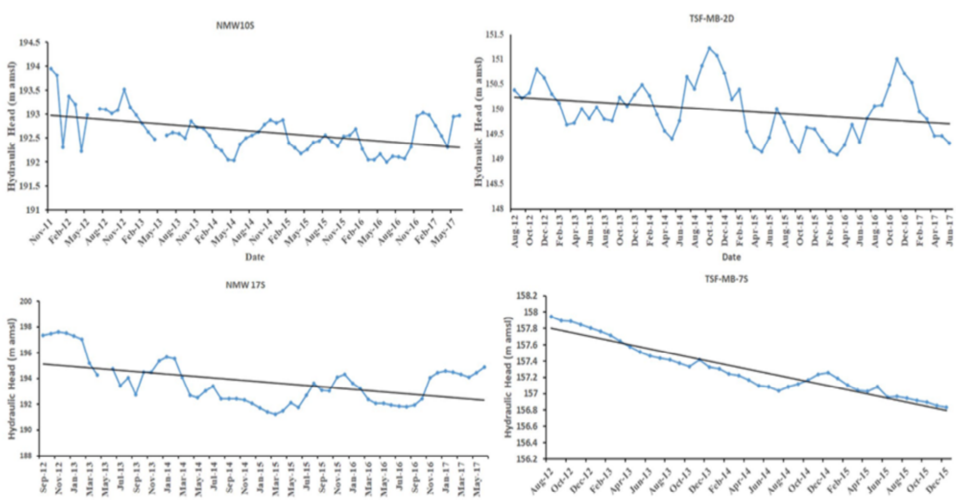
Table 4 displays the outcomes of groundwater recharge from the WTF method averaged over the six years period. The estimates were made using Sy values in the range of 0.01–0.05. This yielded groundwater recharge rates of 8 mm/yr – 250 mm/yr corresponding to 0.64%–22.6% of annual rainfall in the area. There is a wide range of variation, reflecting the variations in the thickness and content of the unsaturated zone material. Most of the locations present recharge values in the range of 8.0 mm/yr – 75.5 mm/yr, representing 0.64% to 6.1% of the annual rainfall in the area.

The groundwater recharge estimates achieved using the WTF technique in this investigation are comparable to those obtained with the RIB model. An analysis of spatially approximated groundwater recharge estimates derived with the RIB and WTF methodologies in the research area demonstrates that the two techniques agree on possible highest and lowest recharge zones in general. The two methods statistically agree in terms of the estimates and spatial distribution of groundwater recharge in the study area. The main source of uncertainty is the Sy data. By juxtaposing the RIB and WTF methodologies, our study enhances the reliability of groundwater recharge estimates. This comparative approach strengthens the validity of our results, acknowledging the inherent uncertainties associated with Sy data.

The groundwater recharge data estimated in this research are plausible and were close and consistent to groundwater recharge outcomes acquired with the WTF and other techniques in earlier hydrogeological investigations conducted in similar geology in many arid or semi-arid regions in Africa (e.g., Atta-Darkwa et al., 2013; Duah et al., 2021; Manu et al., 2023; Obuobie, 2008; Obuobie et al., 2012; Okrah et al., 2023; Sandwidi, 2007), despite the fact that the results of this study were slightly higher compared to some of the past research mentioned, it was anticipated that there would be some uncertainty. This is because the Sy results utilised in this research were acquired from literature and not tested for the specific aquifers in the study area. Using Sy outcomes obtained for the aquifers within the research region can improve the study's results' credibility. Our study not only contributes to the current understanding of groundwater recharge but also anticipates future scenarios under changing climatic and anthropogenic conditions. By highlighting potential trends, our work provides a basis for proactive water resource management in the face of environmental challenges.

Obviously, the available climate models have not reached a consensus on the trend of rainfall in the West African sub-region (Sylla et al., 2016); whereas some models predict increasing rainfall patterns, others predict reduction in annual rainfall. However, there has been a consensus on the trend of increasing temperatures and evapotranspiration rates. Therefore, even under conditions of constant or increasing rainfall, the effect of increasing potential evapotranspiration will likely lead to reduction in the net groundwater recharge in the area. The severity of the impacts of increasing potential evapotranspiration rates are expected to vary in space due to varying vertical hydraulic conductivity rates and for that matter differences in the travel times of infiltrating rainwater through the vadose zone. The longer the interval of time spent in transit, the higher the likelihood of evaporative losses and the lower the eventual effective groundwater recharge. Thus, under conditions of the predicted climate change, net groundwater recharge is expected to be lower. This will be accentuated by the current spate of land and forest degradation associated with illegal surface mining of gold (Oti et al., 2020), commonly referred to as Gallamsey. A holistic analysis of the overall hydrologic response of the Densu Basin (closed to the current study area) by Oti et al. (2020) indicates severe impacts of cumulative impacts of climate change and anthropogenic activities on water resources availability in the terrain in the medium to long term. This analysis appears to have been corroborated by observations of low progressive declines in groundwater levels in some four boreholes in the study area (Figure 7). The progressive declines in groundwater levels in these four boreholes suggest decreasing groundwater recharge rates.

Figure 7 Time series groundwater levels illustrating steady declines in possible groundwater recharge in parts of the study area (see online version for colours)



5 Conclusions

The RIB methodology has been successfully applied to estimate groundwater recharge in a shallow unconfined saprolite aquifer system in southern Ghana. The results indicate the possible impact of the variably clayey unsaturated zone in modulating groundwater recharge rates in the space of the terrain. Groundwater recharge in the terrain is highly variable in space and falls in the range of 0.58%–21.36%. Although spatially variable, this research finds that the current rates of recharge can sustain current water resources needs of the rural communities. The lag period between rainfall events and effective recharge ranges between 0 days (suggesting immediate recharge) and nine months. The rate of recharge and sustainability of groundwater resources in the terrain, are however threatened by ever increasing anthropogenic impacts dominated by illegal gold mining, land and forest logging activities. These activities have posed a threat to the vegetation cover and thus have the potential to reduce infiltration and recharge. The depleting forest cover also exposes the shallow aquifer to higher levels of evaporative losses and thus leading to lowering water tables. Field observations have indicated declining groundwater levels consistently since the year 2012. These declines have been practically felt in the dry out of some manually developed groundwater systems and mechanically developed boreholes. Thus, although this study reveals promise in some parts of the terrain, the impacts of natural and anthropogenic stresses have also been experienced and will likely be accentuated in the coming decades if prudent actions are not immediately taken to safeguard sustainable groundwater recharge rates through the protection of the forest cover and the land.

References

Ahmadi, T., Ziaei, A.N., Davari, K., Rasoulzadeh, A., Faridhoseini, A.R. and Izadi A. (2012) 'Estimation of groundwater recharge using various methods in Neishaboor Plain, Iran, Iran', in Hadi and Copty (Eds.): *5th International Groundwater Symposium*, Kuwait, Nos. 9–15, Groundwater Modeling and Management under Uncertainty, Taylor & Francis Group.

Ahmadi, T., Ziaei, A.N., Rasoulzadeh, A., Davary, K., Esmaili, K. and Izady, A., (2014) 'Mapping groundwater recharge areas using CRD and RIB methods in the semi-arid Neishaboor Plain, Iran', *Arabian Journal of Geosciences*, Vol. 8, No. 5, pp.2921–2935, https://doi.org/10.1007/s12517-014- 1321-2.

Alejandro, J., Lomeli Banda, M.A. and Mizael, J. (2019) 'Allocation of groundwater recharge zones in a rural and semi-arid region for sustainable water management: case study in Guadalupe Valley, Mexico', *Water*, Vol. 11, No. 8, p.1586, https://doi.org/10.3390/w11081586.

Aliewi, A., Bhandary, H., Sabarathinam, C. and Al-Qallaf, H. (2022) 'A new modified chloride mass balance approach based on aquifer hydraulic properties and other sources of chloride to assess rainfall recharge in brackish aquifers', *Hydrological Processes*, Vol. 36, No. 3, p.e14513, https://doi.org/10.1002/hyp.14513.

Aloui, S., Zghibi, A., Mazzoni, A., Elomri, A. and Triki, C. (2023) 'Groundwater resources in Qatar: A comprehensive review and informative recommendations for research, governance, and management in support of sustainability', *Journal of Hydrology: Regional Studies*, Vol. 50, p.101564, https://doi.org/10.1016/j.ejrh.2023.101564.

AMEC Geomatrix (2010) *Hydrogeological Conceptual Model*, Akyem Project Eastern Region, Ghana.

Atta-Darkwa, T., Kyei-Baffour, N., Ofori, E., Mensah, E. and Agyare, W.A. (2013) 'Quantification of groundwater recharge in the River Oda catchment using the water table fluctuation method', *G.J. E.D.T.*, Vol. 2, No. 1, pp.96–103.

Aveni, S.S. (2023) *Modelling and Understanding Groundwater Fluctuation in the Volcanic Aquifer of Mount Etna, Southern Italy, and its Potential Relationship with Volcanic Events and Superficial Deformation Processes Identified by a Persistent Scatter Interferometric Synthetic Aperture Radar (PSInSAR) Analysis*, Master's thesis, Coventry University.

Banoeng-Yakubo, B., Yidana, S.M., Ajayi, J.O., Loh, Y. and Asiedu, D.K. (2011) 'Hydrogeology and groundwater resources of Ghana: a review of the hydrogeological zonation of Ghana', McMann (Ed.): *Potable Water and Sanitation*, Nova Science Publishers, New York, NY, USA.

Barthel, R., Stangefelt, M., Giese, M., Nygren, M., Seftigen, K. and Chen, D. (2021) 'Current understanding of groundwater recharge and groundwater drought in Sweden compared to countries with similar geology and climate', *Geografiska Annaler: Series A, Physical Geography*, Vol. 103, No. 4, pp.323–345, https://doi.org/10.1080/04353676.2021.1969130.

Bredenkamp, D.B., Botha, L.T., van Tonder, G.J. and van Rensburg, H.J. (1995) *Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity*, Report No. TT 73/95, Water Research Commission, Pretoria, p.419.

Clear Creek Consultants Inc. (2010) *Newmont Golden Ridge Limited Proposed Akyem Gold Mine Project- Ghana, Africa Meteorological Monitoring Program Data Summary and Review: The Year 2009*, Prepared for Newmont Golden Ridge Resources Ltd., January 2010.

Danzan, A., Nemer, B., Altangadas, E. and Purevsuren, U. (2020) 'Groundwater recharge estimation in Undai watershed area, southern Mongolia', in *EGU General Assembly Conference Abstracts*, Vol. 22, p.4500, https://doi.org/10.5194/egusphere-egu2020-4500.

Darimani, A., Akabzaa, T.M. and Attuquayefio, D.K. (2013) 'Effective environmental governance and outcomes for gold mining in Obuasi and Birim North Districts of Ghana', *Mineral Economics*, Vol. 26, pp.47–60, DOI:10.4236/jep.2011.29141.

Duah, A.A., Akurugu, B.A., Darko, P.K., Manu, E. and Mainoo, P.A. (2021) 'Groundwater recharge and potential exploitation in the Densu basin, Southwestern Ghana', *Journal of African Earth Sciences*, Vol. 183, p.104332, https://doi.org/10.1016/j.jafrearsci.2021.104332.

Ewusi, A., yeboah, S.O., Voigt, H.J., Asabere, S.B. and Bempah, C.K. (2013) 'Groundwater Quality Assessment for Drinking and Irrigation Purposes in Obuasi Municipality of Ghana, a preliminary study', *Research Journal of Environmental and Earth Sciences*, Vol. 5, No. 1, pp.6–17 [online] https://www.airitilibrary.com/Article/Detail?DocID=20410492-201301-201507200032-201507200032-6-17.

Ferede, M., Haile, A.T., Walker, D., Gowing, J. and Parkin, G. (2020) 'Multi-method groundwater recharge estimation at Eshito micro-watershed', *Rift Valley Basin in Ethiopia. Hydrological Sciences Journal*, Vol. 65, No. 9, pp.1596–1605, https://doi.org/10.1080/02626667.2020.1762887.

Frimpong, M., Ewusi, A., Amoako, R. and Appianing, E.J.A. (2016) 'Assessment of groundwater quality in the Akyem Mine Area of Newmont Golden Ridge Ltd. (NGRL)', in *4th UMaT Biennial International Mining and Mineral Conference*, pp.ES55–ES63.

Gebru, T.A. and Tesfahunegn, G.B. (2019) 'Chloride mass balance for estimation of groundwater recharge in a semi-arid catchment of northern Ethiopia', *Hydrogeology Journal*, Vol. 27, No. 1, pp.363–378.

Ghafari, H., Rasoulzadeh, A., Raoof, M. and Esmeali, A. (2018) 'Estimation of natural groundwater recharge using WTF method (case study: Ardabil Plain aquifer)', *Journal of Civil and Environmental Engineering*, Vol. 48, No. 1, pp.43–52.

Golder (2017) *Regional Groundwater Model for Akyem Mine*, Golder Associates, Accra.

Hassen, I., Slama, F. and Bouhlila, R. (2021) 'Groundwater recharge assessment in an arid region through chloride mass balance and unsaturated numerical modelling: the Kasserine aquifer system', *Arabian Journal of Geosciences*, Vol. 14, p.2282, https://doi.org/10.1007/s12517-021-08522-0.

Healy, R.W. (2010) *Estimating Groundwater Recharge,* Cambridge University Press, Cambridge.

Kippo, J.V. (2012) *DRAI-AHP Vulnerability Assessment of the Quarternary Aquifer in the Keta Strip*, PhD Thesis, University of Ghana.

Kisiki, C.P., Ayenew, T. and Mjemah, I.C. (2022) 'Estimation of groundwater recharge in Makutupora Basin located in a semi-arid region in Central Tanzania using soil moisture balance (SMB) and chloride mass balance (CMB) techniques', *Journal of the Geological Society of India*, Vol. 98, No. 5, pp.1605–1614, https://doi.org/10.1007/s12594-022-2217-5.

Leaders, F.T., Lipson, R. and Kudzawu-D'Pherdd, R. (2018) *Gold Deposits of the Birimian and Tarkwaian in Ghana*, Society of Economic Geologists Foundation, Inc., SEG Student Field Trip 17. Guidebook Series, Vol. 57, Print ISSN 1547-3090, ISBN 978-1-629490-72-4. Online ISSN 2374-6955, ISBN 978-1-629494-94-4.

Majdabady, M.P., Rasoulzadeh, A., Kanoon, A. and Ahmadzadeh, G. (2020) 'Estimation of groundwater recharge originating from agricultural irrigation and rainfall in Shyramyn plain, Iran', *Irrigation and Drainage,* Vol. 69, No. 1, pp.107–120.

Manu, E., De Lucia, M., Akiti, T.T. and Kühn, M. (2023) 'Stable isotopes and water level monitoring integrated to characterize groundwater recharge in the Pra Basin, Ghana', *Water*, Vol. 15, No. 21, p.3760, https://doi.org/10.3390/w15213760.

McCartney, M., Forkuor, G., Sood, A., Amisigo, B., Hattermann, F. and Muthuwatta, L. (2012) *The water Resource Implications of Changing Climate in the Volta River Basin*, Vol. 146, IWMI, Colombo, Sri Lanka.

Moeck, C., Grech-Cumbo, N., Podgorski, J., Bretzler, A., Gurdak, J.J., Berg, M. and Schirmer, M. (2020) 'A global-scale dataset of direct natural groundwater recharge rates: a review of variables, processes and relationships', *Science of the Total Environment*, Vol. 717, p.137042, https://doi.org/10.1016/j.scitotenv.2020.137042.

Muavhi, N. and Mutoti, M.I. (2023) 'Using geospatial techniques and analytic hierarchy process to map groundwater potential zones', *Groundwater*, Vol. 61, No. 4, pp.494–509, https://doi.org/ 10.1111/gwat.13257.

Nartey, V.K., Klake, RK., Hayford, E. K., Doamekpor, L.K. and Appoh, R.K. (2011) 'Assessment of mercury pollution in rivers and streams around artisanal gold mining areas of the Birim North District of Ghana', *Journal of Environmental Protection*, Vol. 2, No. 9, pp.1227–1239.

Nunoo, S. (2021) *Origin and Age of Gold Mineralization in Nw Ghana: a Case Study of Selected Gold Deposits from the Julie And Wa-Lawra Belts,* University of Johannesburg (South Africa).

Obuobie, E. (2008) 'Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin, West Africa', *Ecology and Development Series*, No. 62, p.164.

Obuobie, E., Diekkrueger, B., Agyekum, W. and Agodzo, S. (2012) 'Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana', *Journal of African Earth Sciences*, Nos. 71–72, pp.80–86, http://doi.org/10.1016/j.jafrearsci.2012.06.005.

Okrah, C., Appiah-Adjei, E.K., Agyekum, W.A. et al. (2023) 'Comparative evaluation of SWAT and WTF techniques for recharge estimation in the Vea catchment, Ghana', *Sustainable Water Resources Management*, Vol. 9, No. 1, p.38, https://doi.org/10.1007/s40899-023-00813-6.

Oti, J.O., Kabo-bah, A. and Ofosu, E. (2020) 'Hydrologic response to climate change in the Densu River Basin in Ghana', *Heliyon*, Vol. 6, No. 8, pp.1–10.

Owusu, E.H (2012) 'Natural resources of Okyeman – an overview (2012)', *West African Journal of Applied Ecology*, Vol. 20, No. 3, pp.47–52.

Sajil Kumar, P.J., Schneider, M. and Elango, L. (2022) 'The state-of-the-art estimation of groundwater recharge and water balance with a special emphasis on India: a critical review', *Sustainability*, Vol. 14, No. 1, p.340, https://doi.org/10.3390/su14010340.

Sandwidi, W.J.P. (2007) *Groundwater Potential to Supply Population Demand Within the Kompienga Dam Basin in Burkina Faso*, PhD Thesis, Ecology and Development Series, No. 54, p.160, Cuvillier Verlag Göttingen.

Shao, J., Si, B. and Jin, J. (2019) 'Rooting depth and extreme precipitation regulate groundwater recharge in the thick unsaturated zone: a case study', *Water*, Vol. 11, No. 6, p.1232, https://doi.org/10.3390/w11061232.

Singh, A., Panda, S.N., Uzokwe, V.N. and Krause, P. (2019) 'An assessment of groundwater recharge estimation techniques for sustainable resource management', *Groundwater for Sustainable Development*, Vol. 9, p.100218, https://doi.org/10.1016/j.gsd.2019.100218.

Sun, X, Xu, Y., Jovanovic, N.Z., Kapangaziwiri, E, Brendonck, L. and Bugan, R.D.H. (2013) 'Application of the rainfall infiltration breakthrough (RIB) model for groundwater recharge estimation in west coastal South Africa', *J. Water S. Afr*., Vol. 39, No. 2, pp.221–230.

Sylla, M.B., Nikiema, P.M., Gibba, P., Kebe, I. and Klutse, N.A.B. (2016) 'Climate change over West Africa: Recent trends and future projections', *Adaptation to Climate Change and Variability in Rural West Africa*, Chap. 3, pp.25–40.

Uugulu, S. and Wanke, H. (2020) 'Estimation of groundwater recharge in savannah aquifers along a precipitation gradient using chloride mass balance method and environmental isotopes, Namibia', *Physics and Chemistry of the Earth, Parts A/B/C*, Vol. 116, p.102844, https://doi.org/10.1016/j.pce.2020.102844.

Walker, D., Parkin, G., Schmitter, P., Gowing, J., Tilahun, S.A., Haile, A.T. and Yimam, A.Y. (2019) 'Insights from a multi-method recharge estimation comparison study', *Groundwater*, Vol. 57, No. 2, pp.245–258, https://doi.org/10.1111/gwat.12801.

Wu, Q., Wang, G., Zhang, W., Cui, H. and Zhang, W. (2016) 'Estimation of groundwater recharge using tracers and numerical modeling in the North China Plain', *Water*, Vol. 8, No. 8, p.353.

Xin, P., Wilson, A., Shen, C., Ge, Z., Moffett, K.B., Santos, I.R., Chen, X., Xu, X., Y., Yau, Y.Y., Moore, W., Li, L. and Barry, D.A. (2022) 'Surface water and groundwater interactions in salt marshes and their impact on plant ecology and coastal biogeochemistry', *Reviews of Geophysics*, Vol. 60, No. 1, p.e2021RG000740, https://doi.org/10.1029/2021RG000740.

Xu, W., Meng, L., Liu, P. et al. (2019) 'Use of a modified chloride mass balance technique to assess the factors that influence groundwater recharge rates in a semi-arid agricultural region in China', *Environmental Earth Sciences*, Vol. 78, No. 7, p.241, https://doi.org/10.1007/s12665-019-8249-5.

Xu, Y. and Beekman, H.E. (2019) 'Groundwater recharge estimation in arid and semi-arid southern Africa', *Hydrogeology Journal*, Vol. 27, No. 3, pp.929–943, https://doi.org/10.1007/s10040-018-1898-8.

Xu, Y. and van Tonder, G.J. (2001) 'Estimation of recharge using a revised CRD method', *J. Water S. Afr*., Vol. 27, No. 3, pp.341–344.

Yidana, S.M. and Chegbeleh, L.P. (2013) 'The hydraulic conductivity field and groundwater flow in the unconfined aquifer system of the Keta Strip, Ghana', *Journal of African Earth Sciences*, October, Vol. 86, pp.45–52.

Zeinali, M., Azari, A. and Heidari, M.M. (2020) 'Simulating unsaturated zone of soil for estimating the recharge rate and flow exchange between a river and an aquifer', *Water Resources Management*, Vol. 34, No. 2, pp.425–443, https://doi.org/10.1007/s11269-019-02458-7.

Zhang, Z., Wang, W., Gong, C. and Zhang, M. (2020) 'A comparison of methods to estimate groundwater recharge from bare soil based on data observed by a large-scale lysimeter', *Hydrological Processes*, Vol. 34, No. 13, pp.2987–2999, https://doi.org/10.1002/hyp.13769.