A three-dimensional numerical groundwater flow model to assess the feasibility of managed aquifer recharge in the Tamne River basin of Ghana

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Abstract
Increasing population growth and global climatic changes threaten water security in semiarid regions such as Northern Ghana. The Tamnean Plutonic Suite aquifer is the main source of water supply for the inhabitants of the Tamne River basin, which is a transboundary subbasin of the White Volta Basin, Ghana. The basin is a flood-prone area where flooding occurs every rainy season, but there is water scarcity during the dry season, mainly due to poor groundwater resources planning. It is expected that the population will increase in the next 10 years, implying a greater water demand. A steady-state and transient groundwater flow model has been developed to understand the hydrogeological conditions and assess the feasibility of managed aquifer recharge (MAR) in the area. A single granitic aquifer formation was delineated from the three-dimensional lithology modelling. The calibrated aquifer recharge through precipitation is very low due to high evapotranspiration and low rainfall. A MAR injection scenario was tested using the available treated floodwater that is registered during the rainy season in the area. The results show the total volume of water injected at the end of the 4-month study period is 11,000 m³/day (approximately 1.3 × 10⁶ m³), which significantly increases aquifer storage and groundwater levels. The volume of water recovered at the end of 8 months (1.4 × 10⁶ m³) is enough for domestic and irrigation purposes during the dry season. In general, MAR is feasible in augmenting the water levels in the area when combined with controllable irrigation and domestic withdrawals.

Keywords Artificial recharge · Ghana · Numerical modelling · 3D lithology model · Hydrogeology

Introduction

Achieving water supply reliability through a well-developed engineering technology such as managed aquifer recharge (MAR) is a prerequisite to bolstering climate resilience with respect to social, environmental, and economic goals in arid and semiarid regions (Dillion et.al. 2020). Besieged by the inherently limited water resources in these regions, other factors, such as intensive use of groundwater for irrigation and increasing water demand from the ever-growing population, have led to water scarcity and adverse socio-economic issues (Kwoyiga and Stefan 2019; Ray 2019)—for example, declining groundwater levels in most arid areas have caused the drying up of farmlands, especially in the dry season. The effect is that irrigation wells have to be deepened and abstracting water has become expensive. In the same vein, the depletion of groundwater resources due to excessive withdrawals has occasioned seawater intrusion in many arid coastal aquifers, such as the Jamma aquifer in Oman, deteriorating the quality of water (EL-Rawy 2019). It is imperative that these challenges are addressed so that water-sector stakeholders are able to enhance the availability and quality of water in water-scarce areas. As a response to this, MAR has become a unique technique for collecting and treating water and storing it in aquifers during availability and later using it when there is scarcity (Bouwer 2002; Maliva and Missimer 2012).

In recent years, the use of MAR to augment the supply of groundwater, especially in drought-prone areas of the world, has attracted considerable interest (Gale 2005; Maliva and Missimer 2012; Dillion et al. 2020). For instance, in the quest to tackle growing water scarcity problems in the southern European countries and Mediterranean regions, due to the
impact of climate change on the available water resources, a managed-aquifer-recharge solutions (MARSOL) project was set up in six European countries (Greece, Germany, Italy, Malta, Portugal, Spain) and Israel using different MAR methods and water sources, such as treated wastewater, desalinated water, and river water (MARSOL 2014). The objective of MARSOL was to augment the natural storage of aquifers and create market avenues for the European industry by applying low-tech and cost-effective MAR solutions. Dillon (2009) documented that MAR has significantly improved irrigation water supply by 45 GL/year and the supply of water to urban towns by 75 GL/year in Australia as of the year 2008. Other advantages of MAR include the system providing a barrier to combat saline intrusion in overexploited aquifers, and sustaining environmental flows and phreatophyte vegetation in stressed surface-water or groundwater systems (Dillon 2014).

In Africa, the development of MAR is taking shape, and about 44 MAR cases have been documented in the global MAR inventory (Stefan and Ansems 2018), with eight additional MAR cases in the literature reported by Ebrahim et al. (2020), making a total of 52 cases to date. According to the global MAR portal, most MAR sites can be found in South Africa and Tunisia, with little-discussed sites also in West Africa—only two MAR sites in Nigeria. However, there are emerging MAR schemes in Ghana, where two schemes are found in the Jagisi and Kpasenke communities in Northern Ghana, and one scheme in the Weisi community in the Upper East Region of Ghana. These projects are being piloted by the International Water Management Institute (IWMI) and they employ Bhungroo Irrigation Technology (BIT; widely used in India for floodwater harvesting). BIT is akin to the artificial storage and recovery (ASR) method, which harvests excess floodwater, infiltrates it directly into the well as a means of storage, and recovers the water for use during the dry season (Owusu et al. 2017). According to Conservative Alliance (2015), BIT can harvest and store approximately 40,000 m³ of water in the unsaturated zone with a depth ranging between 8 and 25 m. This total volume of water is considered sufficient to secure irrigation water during the prolonged 7 months of the dry season, thus improving food security in these areas (Owusu et al. 2017).

Notwithstanding the significant progress of MAR schemes in Africa, Kwoyiga and Stefan (2019) argued that institutional guidelines for successful MAR implementation are lacking. Furthermore, there has been only a little insight gained from the groundwater modelling studies in Africa to assess the feasibility of managed aquifer recharge.

The Tamne River basin is a transboundary subbasin of the White Volta River basin of Ghana (SNC-Lavalin/INRS 2011). As high as 80% of the inhabitants are engaged in agriculture, which is heavily focused on onions, tomatoes, and watermelons. This serves as the main source of income for the people (Ghana Statistical Service 2014). The main sources of water used for agricultural irrigation are rainwater, groundwater, and surface water from the Bugri and Gagbiri dams. The area experiences only one short rainy season between May and September and is accompanied by a long dry period from October to April (Issahaku et al. 2016). A large quantity of rainwater in the area is lost through evapotranspiration from open surfaces; according to the Ghana Statistical Service (2014), a rainwater volume of approximately 1.55–1.65 m³/m² of area is lost annually. This causes drought and contributes to low groundwater recharge in the area.

In response to the problems mentioned in the preceding, the Bugri and Gagbiri dams, with canal lengths of 1.35 and 2.9 km, respectively, were constructed purposely to provide an alternative water source for irrigation farming during the dry season. However, challenges such as inadequate rainfall to fill up the dams, high water demand for irrigation, high evaporation losses, and broken and choked canals due to inadequate repairs have rendered the irrigation activities in the dry season ineffective and counterproductive (Jonah and Dawda 2014).

Furthermore, it is a flood-prone area, where instances of flooding have occurred every rainy season due to recorded high torrential rainfall combined with the release of excess water from upstream of Bagre Dam in neighbouring Burkina Faso, located several kilometres from the study area (Armah et al. 2010). The seasonal flooding is also a result of the highly irregular seasonal flow patterns and poor drainage from the river basins of Tamne and Pawnaba-Kiyinchongo, as well as the tributaries of the White Volta in the study area. During the rainy season, these rivers flow excessively, followed by recession and low water levels during dry seasons (Ghana Statistical Service 2014). These developments resulted in low and no water for use during the dry-season farming periods, causing negative water balance. As part of measures to sustain their livelihoods, most farmers resorted to growing crops that consume less water in order to cope with the limited groundwater availability. However, these measures do not bring any substantial returns to them. This makes farming activities very difficult in the dry season and consequently affects livelihoods, and most of the farmers have abandoned their farms. Besides the aforementioned problems in the study area, it has been reported that the population of Ghana rises annually by 2.5% (Ghana Statistical Service 2012). This would imply an increase in water demand in the future, coupled with climate-induced variability on the available water resources in the study area. There are calls for additional water sources to bolster agricultural activities in the dry season and beyond, which will ultimately increase the economic fortunes of the farmers and reduce poverty in the region.
On this basis, the study area is being considered as a potential MAR site, drawing inferences from other successful MAR applications in Africa and the pilot MAR schemes in Northern Ghana. The available floodwater that is registered every rainy season will be used as a source of water for this MAR feasibility study. A successful MAR scheme depends on the local hydrogeology, with the aquifer having sufficient storage capacity and hydraulic conductivity (Maliva and Missimer 2012). Where floodwater is to be considered as a source of water, the water must be treated before infiltrating into the aquifers. This is because floodwater contains a mixture of various contaminants from other areas, which might affect the water quality or clog the well when infiltrated. Modelling techniques such as MODFLOW are used to design, optimize and manage MAR schemes (Legg and Sagstad 2002; Bekele et al. 2011; Lacher et al. 2014). Other modelling tools such as MT3DMS, PHREEQC, MARTHE, and CXTFIT are also used to identify and evaluate the water quality changes and geochemical processes during MAR infiltration (Ringleb et al. 2016). Ebrahim et al. (2016) used MODFLOW in conjunction with a genetic optimization algorithm to obtain information on the maximum recharge and extraction rates for MAR feasibility studies in the Samail Lower Catchment in Oman. Russo et al. (2015) simulated MAR projects in the Pajaro Valley Groundwater Basin in California, USA. The modelling results demonstrated a reduction of saline-water intrusion in the coastal aquifer, which suggested MAR is feasible and advantageous in the area. EL-Rawy et al. (2019) developed a steady-state transport model to evaluate MAR and its economic feasibility for the Jamma aquifer in Oman. The results indicated that MAR could be used only for a single aquifer within a specific time frame, and maintenance and investment costs are economically unfeasible. As already mentioned, groundwater flow modelling scenarios used to study MAR applicability in Ghana have not been studied. Thus, the focus here is to develop a numerical groundwater flow model under steady-state and transient conditions and to have a better comprehension of groundwater sustainability in the basin. The study is also intended to characterize the aquifer hydraulic properties, estimate recharge rates, and quantify water balance in the Tamne River basin. The second objective is the use of MODFLOW to evaluate the feasibility of MAR and test groundwater management scenarios by injecting seasonal floodwater using the ASR technique. This is intended to reverse declining groundwater levels, improve aquifer storage, and increase agricultural water supply reliability in the Tamne River basin.

Study area

The Tamne River basin is a subbasin that falls within the White Volta River basin of Ghana. It is located 80 km northeast of Bolgatanga (regional capital) with an approximate land size of 848 km² (SNC-Lavalin/INRS 2011). The Tamne River basin comprises two administrative areas: the western part of the Garu-Tempate district and the southern part of Bawku municipality. The study area is bordered to the east by Togo, to the south by Garu-Tempate district and Bunkpurugu-Yunyoo district, to the west by Bawku West and Binduri districts; and to the north by Bawku municipality. The basin is characterized by surface elevation ranging between 185 to 350 m with an average elevation of 219 m above sea level (Fig. 1). The area is drained by small streams and rivers of which the dominant one is the Tamne River, and this flows into the White Volta River (SNC-Lavalin/INRS 2011).

The climate in the study area belongs to the intertropical convergence zone, which brings two major air masses: the Southwest Monsoon winds and the North East Trade winds. The Southwest Monsoon winds emanate from the Atlantic Ocean, and these often occur during the rainfall season (Monsoonal rains) between May and September. The highest rainfall peaks occur in June, July, and August. The rainfall amounts in the Tamne River basin range from 669.8 to 1,339.4 mm with an average value of 935 mm/year (Asamoah and Ansah-Mensah 2020). The dry season occurs between October and April, characterized by varying temperatures ranging from 17 to 44 °C with an annual average temperature of 29.9 °C.

Landuse and soil types

The vegetation of the basin belongs to the Sudanian savannah zone, which is characterized mainly by savanna woodland and grassland (SNC-Lavalin/INRS 2011). The wide-open cultivated savannah woodland prevails in the study area and comprises trees such as baobabs, shea butter, and dawadawa trees, which are highly resistant to drought and fire. The grasslands are predominantly found in the northern part and scattered in the study area (Fig. 2). The grass and herbs are perennials plants that shed leaves and foliage and are affected by bush burning during the prolonged 7-month dry season. The open cultivated savannah woodland usually serves as an area for subsistence farming in which the inhabitants combine livestock rearing and crop farming. Common crops and vegetables grown in the area include sorghum, millet, maize, yam, groundnut, onion, and tomatoes (SNC-Lavalin/INRS 2011). The open forest is a very good natural site for livestock rearing and serves as an essential source of income for about 80% of the inhabitants in the study area (Ghana Statistical Service 2014).

The soils in the study area typically comprise lixisols, leptosols, gleysols, and fluvisols. These soils are formed from the weathering of the granitic bedrock that underlies the entire area. The haplic lixisols dominate the area and are characterized by reddish-brown coarse-grained sandy loams and clay-rich content (Martin 2006). The lithic leptosols are...
Fig. 1  Location map of the study area. A–A’ shows location of the hydrogeologic cross section discussed later

Fig. 2  a Landuse and b soil types of the study area
enriched in pale ash sandy loam with biotic granite and are found in the northern and southern parts of the basin. The eutric gleysols are found in waterways along the Tamne River and other streams in the area. The fluvisols are found in small quantities, usually in floodplains (SNC-Lavalin/INRS 2011).

**Regional and local geology**

The Tamne River basin is predominantly underlain by rocks of the Tamnean Plutonic Suite and a few patches of Birimian Supergroup and Mesozoic rocks (Fig. 3). The Birimian Supergroup belongs to the subprovince of the Precambrian basement complex and consists of metamorphosed sedimentary and igneous rocks that underlie 54% of Ghana (Dapaah-Siakwan and Gyau-Boakye 2000). According to Bates (1955), the Birimian system is subdivided into Lower Birimian and Upper Birimian. The Lower Birimian are older metasedimentary rocks that consist of greywackes, phyllites, schists, tuffs, and sandstones. The Upper Birimian, on the other hand, are very young metavolcanic rocks typically of pyroclastic lava, andesites, and tholeiitic basalts. Most of the rocks in the Upper Birimian have undergone systematic metamorphism and have formed new grades of rock types such as hornblende, amphibolites (greenstones), and calcareous chlorite schist. The original basaltic lavas that were subaqueous when erupted are now seen as a pillow-like structure in the Upper Birimian (Banoeng-Yakubu et al. 2011).

The Birimian rocks are intruded by Tamnean Plutonic Suite, mainly granitoids formed during the Paleoproterozoic era circa 2150–2070 Ma (Feybesse et al. 2006). The granitoids cover 95% of the study area and are rich in minerals such as hornblende-biotite tonalite, minor granodiorite, and minor quartz diorite. The Mesozoic rocks are nonmetamorphic rocks composed of mafic dyke and dolerite, found in small portions of the area. The Birimian rocks in the area are metavolcanic rocks of basalt and minor interbedded volcanioclastics.

**Hydrogeology**

The hydrogeology of the Tamne River basin falls under two main provinces: the Birimian Province and the Crystalline Basement Granitoid Complex Province. The Birimian Province consists of the Birimian metasediments and metavolcanics. The Crystalline Basement Granitoid Complex Province also comprises the granitoids. The rocks in the basin contain little or no primary porosity, and thus, the mode of groundwater occurrence is mainly from secondary porosity arising from faulting and chemical weathering of the underlying rocks (Dapaah-Siakwan and Gyau-Boakye 2000). The groundwater development in the Tamne basin occurs in three main aquifer formations: the shallow aquifer, the regolith aquifer, and the fractured aquifer, as seen in Fig. 4. The shallow aquifer comprises coarse-grained lateritic and sandy units with an average thickness of 5 m. Most of the farmers have dug wells to tap water from this shallow aquifer for irrigation purposes. Unfortunately, the shallow aquifer is ephemeral and dries up in the dry season. The regolith aquifer is a weathered granitic unconfined aquifer that serves as the principal aquifer for the inhabitants. It comprises saproilite and saprock with an average thickness of 25 m (SNC-Lavalin/INRS 2011).
The saprolite consists of the topsoil, the lateritic soil, and the highly weathered bedrock, whereas the saprock consists of moderately weathered bedrock. The fractured aquifer is an unweathered confined granitic aquifer, contributing significant amounts of water to the basin. The occurrence of groundwater in the Birimian Province is more pronounced and productive in the saprolite and the upper part of the saprock since these two regolith profiles are hydraulically connected with respect to their storage and permeability (Carrier et al. 2008). The upper part of the saprolite usually has lower permeability and can form a semiconfining layer for the productive zone. In terms of weathering, rocks of the Birimian show a higher degree of weathering than the granitoid due to the lower jointing and fracturing contained in the granitoid. This has consequently resulted in lower groundwater yields and shallower water tables in some granitic terrains. In addition, the weathering and erosion have caused isostatic uplift of the overlying regolith profiles resulting in the creation of subhorizontal exfoliation or sheet fracturing in the upper portion of the fractured bedrock (Carrier et al. 2008).

The groundwater flow in the area is from N to S, mainly in the regolith aquifer but to some extent in the fractured aquifer (Fig. 4). A local groundwater flow (interflow) is also found within the subsurface towards the Tamne River as a discharge point. Groundwater recharge occurs mainly through direct infiltration of precipitation via rock matrices, crevices, and joints in the study area (Abdul-Wahab et al. 2021). There are no known recharge estimates in the Tamne River basin; however, various researchers have reported recharge estimates in the White Volta River Basin of Ghana—for instance, Obuobie (2008) used the water-table fluctuation method to estimate the groundwater recharge, ranging from 3.4 to 18.4% of the mean annual rainfall (800-1,140 mm/year). Oteng Mensah et al. (2014) estimated groundwater recharge using the chloride mass balance method in the White Volta Basin and ranged from 0.9 to 21% of the annual rainfall.

Borehole depth in the study area ranges between 14 and 60 m, with an average of 37 m (SNC-Lavalin/INRS 2011). The water level depth in the boreholes is between 1.63 and 35 m, with an average of 15 m, whereas the regolith thickness is between 7.8 and 37 m, with an average of 25 m. Groundwater yield varies from 0.36 to 37 m³/h with a mean yield of 4.2 m³/h, while aquifer-specific capacity obtained from transmissivity measurements in the Tamne River basin ranges from 1 to 27 l/min with an average of 7.1 l/min (SNC-Lavalin/INRS 2011). The transmissivity values in granitoid formations have been reported in the range between 0.3 and 114 m²/day, with a mean value of 6.6 m²/day (Carrier et al. 2008).

Lithological modelling

Available drilling logs obtained from 10 wells, coupled with information from field campaigns and the literature, were compiled to develop multiple three-dimensional (3D) strip logs (Fig. 5a), a 3D fence diagram (Fig. 5b), and a solid model (Fig. 5c). The solid model was interpolated from borehole lithology intervals using the RockWorks Software Version 2020.9.3. The borehole logs indicate six major layers, of which the topmost layer comprises laterite soil, followed by silt and sand ranging between 0 and 9 m. The silt and sand are found only in small quantities in the study area. The fourth and fifth layers contain highly weathered (10–20 m) and moderately weathered grey granites (21–40 m). These two weathered layers comprise the regolith profile: saprolite and saprock formed as a result of the in-situ chemical weathering of the granitic bedrock (SNC-Lavalin/INRS 2011). The bottom layer consists mainly of unweathered fractured granite with an interval depth ranging between 41 and 60 m. The aquifer zone occurs within the highly weathered and moderately weathered granites. The lithology of the study area shows a cardinal direction from north to south, as shown in Fig. 5. The SE direction comprises aquifer materials such as laterite, silt, and sand from the Birimian Supergroup and Mesozoic formations. From directions NE to SW, the laterite, weathered granite, and fresh granite exclusively from the Tamnean Plutonic Suite are the main lithological materials.

Materials and methods

Secondary data from sources such as borehole logs and pumping tests, and static water levels, were collected from the office of World Vision Ghana in Tamale. The monitoring
well data were also taken from the Water Resource Commission of Ghana in Accra. The borehole logs obtained were analyzed, and these were used to develop the 3D lithological model and the conceptual framework. The aquifer hydraulic properties such as hydraulic conductivity and storativity were estimated using the Cooper and Jacob (1944) method.

**Conceptual framework of the Tamne River basin**

A conceptual framework for numeric modelling of the hydrogeology of the region was developed based on the lithological data, hydrochemistry, groundwater level data (heads), and some previous studies that correspond to the hydrogeological and hydrologic settings of the study area (Anderson et al. 2015). The conceptualization was carried out with the Groundwater Modelling System (GMS) 10.4 Software (Aquaveo 2020). In the initial stage of the conceptualization, the GIS map tool in GMS was used to import and register the geological map on the premise of creating a base map of the area. The model domain was delineated as a single hydrogeological layer because of the paucity of borehole logs, and the available well logs do not reveal any significant differences among the units. A general head boundary (GHB), which is the head-dependent flow boundary condition in GMS, was assumed and delineated for the Tamne basin. This was assigned because the analyzed hydraulic head distribution map, topographical map, digital elevation model (DEM), and field reconnaissance survey undertaken in October 2019 imply no existence of hydraulic or physical boundaries to preclude flow across the boundaries (Yidana et al. 2016). According to Anderson et al. (2015), the head-dependent boundary (HDB) allows the modeller to simulate volumetric flow rate ($Q$) across the boundary by using the assigned hydraulic head and conductance values of the aquifer material as illustrated in Eq. (1).

$$Q = C\Delta h = C \left( h_B - h \right)$$  \hspace{1cm} (1)

where $Q$ is the volumetric flow rate ($\text{L}^3/\text{T}$), $C$ is the conductance ($\text{L}^2/\text{T}$), $\Delta h$ is the difference between the assigned boundary head ($h_B$) and the model computed head near the boundary ($h$). The borehole logs revealed spatial thickness, and these were used in the model conceptualization by adding the top and bottom elevations of the lithological materials. The top and bottom elevations (thickness) were then interpolated using the kriging method to cover the whole area of the basin (Yidana et al. 2015). Many studies have shown that krigging is an effective interpolation scheme when the data points are distributed in a regular pattern across the region (Reiley and Harbough 2004; Anderson et al. 2015). The boundary condition at the top of the model is a semiconfining condition simulating partial infiltration from recharge. In contrast, the bottom boundary is a no-flow boundary because the underlying granitic layers have very low hydraulic conductivity (Yidana et al. 2016). The vertical aquifer boundaries were conceptualized as a head-dependent boundary to allow flows from within and outside the basin. The basin has many river networks, including the Tamne River and its tributaries, and as such, the rivers were digitized to be included in the model together with their
conductance, river stage, and elevation. Figure 6 shows a simplified 3D conceptual framework of the hydrogeology of the Tamne River basin with the input parameters. Even though five hydrostratigraphy layers (Fig. 5) were delineated, the conceptual framework shows only two layers mainly due to a lack of detailed geological or geophysical investigations. According to Anderson et al. (2015), several geological formations may be lumped together to form a single stratigraphic unit, or geological formations may be subdivided into aquifers and confining layers.

In the Tamne basin, inflow to the aquifer occurs mainly as specified water flux in the form of precipitation, interflow, or induced river recharge and, to a lesser extent, seasonal flooding and irrigation water returns.

Based on this information, seven recharge zones were created. Each of the recharge zones were assigned values based on the land use patterns, the geology of the area, and information from previous studies (Anderson et al. 2015). Initial recharge values assigned were in the range between $5.1 \times 10^{-5}$ and $1.3 \times 10^{-4}$ m/day (computed based on 2 and 5% of the mean annual precipitation of 935 mm/year) as espoused by Akurugu et al. (2020), who conducted similar research in the White Volta Basin of Ghana.

The zones in the model also included hydraulic conductivity, hydraulic heads, and pumping test data acquired from the well dataset. The values for hydraulic conductivity in the zones ranged between 0.01 and 15 m/day. The values for hydraulic conductivity were selected according to the literature values and analysis from the pumping test (Fetter 2001). And the hydraulic head values (difference between elevation and measured water levels) were included as 2D points and included in the model domain as observation heads.

The model domain of 848 km² was discretized into 10,000 uniform cells using a finite-difference grid with 100 rows and 100 columns. The number of active cells was 6104, with the model domain oriented towards the north–south direction. All the applicable coverages of the conceptual model were mapped to a grid-based MODFLOW numerical model for steady-state and transient simulations.

**Numerical simulation and model calibration**

A 3D numerical groundwater flow model was set up using the US Geological Survey’s cell-centered, finite difference MODFLOW-2000 incorporated in the GMS software (McDonald and Harbaugh 1988). The MODFLOW model was first used to simulate groundwater flow with a steady-state condition based on the assumptions that the aquifer is heterogeneous, saturated, and anisotropic with Darcian flow. The steady-state groundwater condition for the basin represents the groundwater heads that were measured in 2017, in which groundwater flow was assumed to be constant and indicate equilibrium condition after a lengthy pumping. In the steady-state model, the hydraulic properties together with the computed heads and flows are never changing with respect to time.

The measured groundwater heads were calibrated so that the simulated results approximate the natural conditions. Calibration was done in two stages: manual trial-and-error and automated calibration. Under the manual approach, the assigned initial aquifer hydraulic properties such as hydraulic conductivity ($K$), recharge, and conductance of the GHB were tuned to reduce the head residuals. The residual head is the difference between the computed head and the measured field head. After a reasonable head residual was achieved, the automated approach was refined. The automated calibration was performed with the help of the automated parameter estimation (PEST) module in GMS. PEST is a robust statistical tool that alters parameters within its defined space, and reruns the model several times until calibration can be achieved (Ryter et al. 2018). In addition, PEST can calibrate a large number of parameters efficiently within several minutes, depending on the speed of the user’s computer. Before running the PEST program, an inverse model utility interface in PEST was set up by parameterizing the aquifer hydraulic inputs. The parameterization was done using the PEST pilot point method. Here, the inverse model was used to evaluate the pilot point values of the hydraulic conductivity, adjust the values, and interpolate the values providing an acceptable objective function to be achieved.

In GMS, PEST has options that enhance the parameterization process, and these are the single value decomposition (SVD) and Tikhonov regularization options. In the SVD dialog option, the parameter estimation process or calibration is enhanced by automatically removing parameters that have little effect upon the predicted outcome while maintaining important parameters in the parameter estimation process.
Similarly, with the Tikhonov regularization dialog option, there is a penalty applied to the objective function if parameters deviate from their original values. The method regularizes the results for more stable and efficient parameter estimation and calibration (Doherty et al. 2010; Ryter et al. 2018). In this study, the SVD and the Tikhonov regularization were applied to the aquifer hydraulic values of the model.

Furthermore, in numerical modelling and calibration, a model layer (delimited by layer elevations top and bottom) is usually defined as a confined, convertible or unconfined layer used to simulate groundwater flow between cells (Anderson et al. 2015). The modelling problem arises when the MODFLOW code unwittingly converts the confined layer to an unconfined layer. This causes an unfeasible calculation of the saturated thickness. In confined layers, the transmissivity is time-invariant (constant), where the head rises above the top layer during simulation. Any change of head below the top layer will cause the aforementioned problem to occur because the MODFLOW code recognizes the layer to be confined if specified by the modeller (Anderson et al. 2015). In GMS, the convertible and confined layers are the only possible layers in the Layer-Property Flow (LPF) package. The LPF package defines the horizontal and vertical hydraulic conductivity for each layer, and subsequently, MODFLOW uses the hydraulic conductivity values and layer geometry to calculate the cell-by-cell conductance. In this study, the convertible layer was chosen because the storage parameter can be simulated as specific storage or specific yield. In addition, it can simulate dry and wet cells, which is not possible in the confined layer (Harbaugh et al. 2000).

**Sensitivity analysis**

Sensitivity analysis was carried out for both the calibrated steady and transient models to evaluate the response of the developed model when subjected to changes in some of the parameters. A model that deviates significantly after calibration (highly sensitive parameters) when some adjustments are made to the hydraulic properties is unstable and unfit to forecast future conditions (Anderson et al. 2015). Sensitivity analysis was done automatically using PEST in MODFLOW after calibration, where histograms showing the parameters were generated. For this study, hydraulic conductivity, recharge, and specific yield were not highly sensitive to the model and as such can be described as very stable parameters, suggesting a well-calibrated model.

**Results and discussion**

**Steady-state model**

The steady-state model was calibrated by using the hydraulic head measurements of 35 groundwater wells. The calibration was achieved by reproducing the field-measured hydraulic heads at a calibration target of ±2 m. This implies that the difference between the simulated and the field measured heads should not be greater than 2 m (Yidana et al. 2016). The root mean square error (RMSE) values of the simulated hydraulic heads, as expected, are less than 10% of the difference between the highest and lowest field-measured groundwater levels (Lutz et al. 2007; Ely et al. 2011). The simulated and field-measured groundwater heads (Fig. 7) show a significant correlation with $R^2 = 0.86$, and a root mean square weighted residual of 6.91 m at a 95% confidence interval. The mean residual is $-1.97$ m, which indicates that the average simulated heads were higher than the field-measured groundwater levels by 1.97 m (Ryter et al. 2018). In general, the simulated model suggests a satisfactory match, and the model is deemed calibrated to represent the hydrogeological flow conditions of the area.

The spatial distribution of the hydraulic head in the steady-state model (Fig. 8) ranges between 180 and 330 m. The highest hydraulic heads are found in the northern and south-eastern parts of the study area. The groundwater-level contours of the steady-state model also show that the lowest hydraulic heads are seen in the southwestern sections of the area. These match the surface topography of the basin and conform to the assertion that hydraulic heads in aquifers are mostly a subdued replica of the topography (Haitjema and Mitchell-Brucker 2005). The contour heads also show that the southern and northern parts are hydraulically separated from the other areas due to the low transmissivity or stratigraphy settings of the area (Islam et al. 2017).

**Simulated groundwater flow**

The calibrated steady-state model shows different flow paths in the Tamne River Basin due to the fractures and joints of the aquifer system. This interrupts continual groundwater
flows and makes them move in different pathways. The flow paths were computed using velocity vectors information from MODFLOW that shows the magnitude and direction of horizontal flow within each cell of the model layer. Conspicuously large magnitudes of flow are seen in the flow patterns of the southern part, where the Tamne River leaves the basin and joins the White Volta River. These flow patterns likely suggest that the highest amounts of groundwater discharge to streams and rivers occur in the southern section of the study area (Ryter et al. 2018). In the northern part of the basin, the vectors of groundwater flow are missing or absent (area A in Fig. 9). Such instances indicate low hydraulic gradients and support the assertion that recharge to the northern section of the aquifer could be due to the ineffectiveness of the aquifer system at moving groundwater away from that portion (area A; Ryter et al. 2018). In addition, the low or missing vectors could be attributed to highly weathered regolith materials that are thin, poorly permeable, and exposed to the land surface.

The simulated flow shows four distinguished groundwater flow patterns as observed from areas B to E in Fig. 9. The spatial differences in the groundwater flow patterns in the Tamne River basin could be attributed to the structural entities, the surface topography, and drainage patterns (Yidana et al. 2015). In general, the groundwater flow directions in the Tamne River basin follow the surface topography with N–S preferred flow, which is consistent with the results obtained by Akurugu et al. (2020), who found similar flow directions in the crystalline basement rocks of Northern Ghana. The movement of groundwater in the study area can be defined as local and regional flow systems. Generally, under the local flow system, recharge areas coincide with topographic highs, whereas discharge areas are seen in topographic lows that are found adjacent to each other. For the regional flow system, recharge areas are generally located along the water divide, and discharge areas are found at the bottom of the basin (Töth 1963). It can be added that the recharge and discharge areas in regional flow systems are usually separated by several kilometres, and the aquifers can be partly or wholly confined, underlying a local flow system. It is noteworthy that potential regional recharge areas in the Tamne River basin are observed in the south-eastern and northern sections, where the highest hydraulic heads can be seen.

**Mass water balance of the steady-state**

The groundwater flow budget that quantifies the net inflow and outflow flow in the study area is shown in Table 1. Of the 312,960.24 m$^3$/day of water that flows through the Tamnean Plutonic Suite aquifer in the area, 55% (172,461.964 m$^3$/day) represents recharge and contributes the most significant inflow to the model. The
The next contributor of inflow comes from the general-head-dependent boundary condition representing 41% of the water coming from neighbouring aquifers and basins. Forty-six percent of the water (141,613.95 m$^3$/day) leaves the basin by virtue of the rivers and streams incorporated into the model as river coverage. Another significant outflow from the model (54% of the water) is from the general-head-dependent boundary condition that probably discharges into streams, rivers and ditches, or by means of evaporation. An amount of 4,198.95 m$^3$ water is abstracted daily from 35 groundwater wells. This value is very low and accounts for 1.34% of the total water flowing out of the model. This would imply that wise management of groundwater resources could supply the current water needs. However, it is important to note that the total number of boreholes exceeds the number used in the study and cannot represent the actual abstraction rate. The baseflow obtained from the model is 128,461.53 m$^3$/day—computed as the difference between the inflow and outflow river leakages. The resultant regional groundwater flow in the basin is the difference between the simulated recharge and the computed baseflow, which is 44,000.43 m$^3$/day.

### Hydraulic conductivity field

Hydraulic conductivity of earth materials is an important aquifer property used to determine the ease at which groundwater flows in porous media. It is by far a key hydraulic property that defines the transmissivity of an aquifer for proper groundwater resources planning (Fetter 2001). According to Fitts (2002), a promising and cheap way to estimate hydraulic conductivity can be through a good simulated groundwater flow model. This is because the standard estimation of hydraulic conductivity values using sieve analysis and permeameters in the laboratory, and also pumping tests in the field, are sometimes time-consuming and expensive. For
In this study, estimated hydraulic conductivity values from the pumping test supported by literature values were used to generate a hydraulic conductivity map by means of PEST pilot points in GMS. The simulated hydraulic conductivity distribution (Fig. 10) shows that a large portion of the study area has low hydraulic conductivity values, less than 3 m/day, possibly suggesting a homogeneous hydraulic conductivity field (Fetter 2001).

The hydraulic conductivity values range between 0.01 and 15 m/day, which is consistent with the works of various researchers who obtained similar hydraulic conductivities in similar geological terrains of Ghana (Lutz et al. 2007; Yidana et al. 2015). The highest hydraulic conductivity values occur in the southwestern part of the basin, suggesting an enhanced secondary permeability associated with features such as faults, joints, and fractures in the Tamnean Plutonic Suite aquifer, which could serve as good sources of groundwater delivery. In comparing the hydraulic conductivity with the geology of the area, the lowest hydraulic conductivity values are found in the granitic rocks of the Tamne Plutonic Suite. In contrast, the highest values occur in areas with patches of the Birimian Supergroup and Mesozoic rocks, and the Tamnean Plutonic Suite. This confirms the assertion made by Banoeng-Yakubo et al. (2011) that the best source of groundwater is found in the Birimian Supergroup of Ghana.

Three different methods are commonly used to determine groundwater flow through fractured rock (Anderson et al. 2015). A continuum approach is widely used to describe groundwater flow in a fractured bedrock, where the flow is analogous to porous media or unconsolidated flow. The second approach is the discrete approach, which describes the flow through individual fractures in the aquifer system. This requires sufficient data, and analysis is practically impossible and very expensive. The dual-porosity approach, the last approach, assumes that the flow through the media consists of a fracture system and a less permeable matrix block (Lee et al. 1999).

The computed hydraulic conductivity field suggests some degree of weathering and fracturing of the rocks and interconnected structures to allow continual flow. Based on the current analysis, the area can be represented by a combination of dual-porosity and continuum approaches.

Simulated groundwater recharge

One of the objectives of this study is to estimate and quantify groundwater recharge in the basin for efficient aquifer management. Scanlon et al. (2002) broadly discussed various techniques for estimating groundwater recharge; these include tracer techniques, numerical modelling, physical techniques (water-table fluctuation method, lysimeters), Darcy’s law, and the zero-flux plane. For this study, the initially assigned recharge values imposed in the model ranged between 2–5% of the area’s average annual rainfall, and this was adjusted during the calibration. The calibrated recharge values obtained range from $5.0 \times 10^{-3}$ to $6.5 \times 10^{-2}$ mm/day, corresponding to 0.19 and 2.5% of the average annual precipitation in the basin. Low recharge values are found in the southwestern and central parts,
where the hydraulic heads are the lowest. The low recharge rates obtained reflect the high evapotranspiration that reduces significant fractions of infiltrating rainfall in the semiarid region of Northern Ghana. In addition, the low spatial recharge in the area is attributed to the nature of the topography or the unsaturated zone processes that preclude vertical movement of rainfall into the aquifer (Anderson et al. 2015). The simulated recharge compared to the current groundwater abstraction rates would imply significant and sustainable water to meet the current needs. However, with a projected increase in water demand for agriculture and the expected global climatic changes in the future, there is a need for critical groundwater resources planning. The highest recharge rates in the Tamne River basin occur in the southeastern and northwestern parts, where the topographic surface has high elevation (Fig. 11). This observation can be attributed to the enhanced fractures and joints of the weathered granite rocks that facilitate the movement of groundwater in the basin.

**Transient simulations**

In the study area, data from only one monitoring well with monthly water level measurements between November 2009 and April 2012 were available, and these were averaged and used for the transient simulation. Although monitoring well data are extremely limited, it is important to note that the developed transient model provides some insights into the seasonal pumping and recharge rates important for this baseline feasibility study. The hydraulic water heads produced from the steady-state model were used as initial conditions in the transient model. The transient model was developed based on the literature and pumping test values of $0.00002 - 0.000025$ m$^{-1}$ for specific storage, and $0.02 - 0.03$ for specific yield. The simulated transient head distributions after 29 stress periods are presented in Fig. 12. The stress periods represented the monthly time intervals between 2009 and 2012 that were used in the model to simulate transient stress parameters such as recharge rate, river stage, and pumping rate. These parameters, especially the recharge rate, varied according to the monthly

![Fig. 11 Simulated groundwater recharge in the study area](image-url)
seasons since recharge flux depends mostly on precipitation in the catchment. Figure 12 represents the water-level conditions at the Kabingo well. The plot shows low groundwater levels between October and March, and high groundwater levels from June to August. These trends are in response to the seasonal rainfall patterns in the study area leading to different recharge regimes and corresponding groundwater levels.

In general, the simulated head changes and observed heads do not show any noticeable differences with regard to head and flow geometries. This might be because the groundwater abstraction over these years did not cause any significant stress and did not change the overall water levels and flows in the basin. It is noteworthy that where long-term hydraulic head measurements are available, the transient simulation can provide a thorough assessment of the seasonal pumping and recharge in the area. More data will therefore be needed to conduct a detailed transient simulation in subsequent works.

The flow budget of the transient simulation shows a well balance between the inflows and the outflows (Table 2). The transient model shows that significant inflows come from recharge and the head-dependent boundary. The average lateral inflows (head-dependent boundary) arising from the neighbouring areas is 137,203 m³/day. An amount of 136,487 m³/day was lost as outflows, suggesting an average of 716 m³/day was gained. The Tamne River basin forms part of the White Volta basin, and it is suggested that the lateral inflows and outflows are from the White Volta basin since the basins are interconnected (Yidana et al. 2016). More abstractions can cause significant lateral inflows into the aquifer with a corresponding reduction of the hydraulic heads in the area. Transient storage is an important aquifer property used to investigate the sufficient volume of water that would be needed for successful aquifer storage and recovery (ASR) application. Figure 13 shows the monthly storage variations of the whole transient period.

The storage fluctuations mimic the rainfall pattern in the area, where low storage values are recorded in the dry season and high storage values are recorded in the rainy season. The highest storage value was recorded in September, probably due to the time lag of rainfall and infiltration in the area. The average storage inflows and outflows are 5,786 and 26,975 m³/day, respectively.

### MAR scenarios

The study aims to evaluate the feasibility of MAR through injection and abstraction scenarios using the ASR technique. The ASR method is usually suitable for confined and semi-confined aquifers because, in unconfined aquifers, groundwater velocities are usually higher, a situation that can make some of the stored water move away from the well, thereby minimizing recovery efficiency (Pyne 1995). In addition, the choice of the ASR method also depends on land suitability assessment; according to Owusu et al. (2017), land, soil, and subsurface characteristics in the Upper East region of Ghana are suitable for the ASR method. Based on this, 35 injection wells were used for the MAR scenarios, and their locations were selected based on land availability, proximity to existing wells, rivers, and potential sources of contamination. For instance, injection wells sited close to rivers or lakes might lose most of the storage discharging into the rivers (Ebrahim et al. 2016). The well spacings considered here are approximately 200 m, which is within the distance of 100–300 m,

### Table 2 Monthly average of the calibrated transient flow model

| Flow budget component | Inflow (m³/day) | Outflow (m³/day) |
|-----------------------|----------------|------------------|
| Wells                 | 0              | 5,982.08         |
| River leakage         | 8,320.54       | 154,987.61       |
| Head-dependent boundary | 137,203.45     | 136,487.01       |
| Recharge              | 173,121.97     | 0.00             |
| Storage               | 5,786.60       | 26,975.86        |
| Total                 | 324,432.56     | 324,432.56       |
as suggested by Pyne (1995). Four scenarios were tested for groundwater management decisions and presented as follows:

1. The first scenario was simulated as a baseline scenario to investigate the extent of groundwater movement between November 2009 and December 2031, with 266 stress periods assuming recharge, abstraction, and climatic conditions remain the same.

2. Scenario 2 was considered as a MAR injection scenario; this was tested by injecting a volume of 325 m³/day during a 4-month period every year, which was simulated until 2031. This volume of water injected is equal to the total available floodwater that is registered in every rainy season (40,000 m³) in Northern Ghana as documented by Conservative Alliance (2015).

3. The third scenario was simulated as a MAR abstraction scenario, which considered 8 months of abstraction after 4 months of MAR injection. This scenario intends to recover the same amount of water injected. Unfortunately, injection and abstraction rates do not occur simultaneously in MODFLOW. For this scenario, a per capita water demand was assumed to determine the actual domestic water and irrigation withdrawals in the area. The current aquifer abstraction obtained from the 35 wells during the steady-state and transient simulations cannot represent the actual abstraction rate of the basin because the boreholes in the area far exceed this number. The total water abstraction rate or demand from a population of about 150,184 people was considered; individual water consumption is 50 L/capita/day in the region (Ghana Statistical Service 2014). This per-capita number was doubled to include additional use of domestic water, irrigation water withdrawals, and water for large-scale cattle production in the basin. A resultant abstraction rate of 15,018 m³/day was evenly spread among the 35 boreholes, and this was used as the actual daily abstraction rate for the third scenario.

4. For scenario 4, the abstraction rate was increased by 50% after MAR injection. The increased abstraction scenario intends to investigate the resilience of the aquifer in the face of increased irrigation, population demand, and climate change in the future. The different MAR scenarios are presented in Table 3.

Hydraulic head contours of the various scenarios (1–4) are shown in Fig. 14a–d. The results of the baseline scenario from the period of 2012 to 2031 show no significant differences in the water balance with respect to the calibrated transient model. The projections do not excessively have an impact on the lateral inflows and outflows. The storage capacity follows the same pattern as the transient simulation, where dry season periods have little or zero flow. The average storage inflows increase slightly from 5,786 to 6,201 m³/day, whereas the average storage outflows increase from 26,975 to 28,765 m³/day. In general, this scenario has a minimal effect on the groundwater flow and the available water resources in the basin.

For the injection scenario, applying 325 m³/day into the aquifer shows a resulting increase in groundwater levels in most parts of the aquifer, as expected. The total volume of water injected at the end of the 4-month period every year is 11,000 m³/day, approximately 1.3 × 10⁶ m³, computed by multiplying the injection rate and the number of days in 4 months. There are significant gains in the storage inflows and outflows with respect to the baseline scenario. Figure 15 shows the hydraulic head changes in the different scenarios. The injection scenario shows that the groundwater levels rise by 1.05 m on average. This shows that MAR is feasible in augmenting the water levels in the area when combined with controllable irrigation and domestic withdrawals. More available floodwater will probably increase aquifer storage; however, the availability of floodwater is limited in the area.

In the third scenario, applying the ‘per individual’ water consumption rate of 100 L/capita/day in the model causes a slight increase of the lateral inflows to 147,385 m³/day with respect to the baseline scenario. The net river inflows and outflows also have a minimal increase. The average storage inflows increase slightly from 6,186 to 7,186 m³/day. However, the average storage outflows reduce from 26,975 to 22,197 m³/day, resulting in a minimal reduction of the hydraulic heads in the south-eastern and northern parts of the area. The volume of water abstracted at the end of 8 months is 12,559.57 m³/day (3.1 × 10⁶ m³) as seen in Table 4. Subtracting this abstraction rate from the baseline abstraction rate (without MAR) gives a net abstraction rate of 5,968.09 m³/day (approximately 1.48 × 10⁶ m³).

| Scenario | Description                      | Injection rate during the 4-month/8-month period (m³/day) | Number of injection wells | Volume of water abstracted (m³/day) |
|----------|----------------------------------|----------------------------------------------------------|---------------------------|-----------------------------------|
| 1        | Baseline scenario                | NA                                                       | NA                        | 6,591.4                           |
| 2        | MAR injection                    | 325                                                      | 35                        | 6,591.4                           |
| 3        | MAR abstraction                  | NA                                                       | 35                        | 12,559.6                          |
| 4        | MAR abstraction increased by 50% | NA                                                       | 35                        | 18,829.34                         |

NA means no injection/wells
In scenario 4, increasing groundwater abstraction by 50% after MAR injection shows a reduction of the hydraulic head. The lateral inflows and outflows increase as well as the river inflows. The volume of water recovered at the end of the simulation period is 18,829 m³.

A cross-section (distance) that runs through the zone of the injection wells (from the northern to the southern parts of the modelled area; Fig. 14b) is plotted against the simulated hydraulic heads as shown in Fig. 16. The continuous injection shows a gradual build-up of the groundwater

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**Fig. 14** Hydraulic head elevation (m above sea level) for various MAR scenarios (see Table 3): a baseline, b MAR injection, c MAR abstraction, and d 50% increase in abstraction

**Fig. 15** Hydraulic head changes with the different scenarios
mound at a distance of 6 and 14 km. This is reflected in the aquifer storage and shows that MAR is effective in restoring groundwater levels.

**Importance of MAR as a source of water supply**

Managed aquifer recharge is being proposed as a feasible option to counteract the water scarcity in the area and make water available for dry-season irrigation farming. The study area is flood-prone and, as discussed earlier, the total floodwater available during the 4-month rainy season is 40,000 m³ (Conservative Alliance 2015). The water demand (domestic and irrigation water) in the area is approximately 15,018 m³/day, considering the current population of 150,184 and a per water demand of 100 L/capita/day. The water demand is projected to go higher, considering the global climatic changes, urbanization, and population growth. For instance, applying the Ghana Statistical Service (2012) exponential annual growth rate of 2.5% and using the 2021 population, it is expected that the population will reach 187,730 by the year 2031. The resulting water demand would then be 18,773 m³/day, assuming the same per capita water consumption. This calls for additional water to be provided for domestic and irrigation purposes (Ebrahim et al. 2016).

The MAR modelling scenarios show that the net volume of water that can be abstracted during the 8-month period is 5,968 m³/day. Assuming the volume of water without MAR practice, which is 5,982 m³/day, remains the same, the total volume of water from the basin, including that of MAR, would then be 11,950 m³/day. This volume of water would provide for future domestic and irrigation water needs, particularly in the dry season. It would also improve the economic fortunes of the people, who will get all-year-round water to irrigate their farms.

However, the laws and legislation governing the implementation of MAR are not clear, as no policy either accepts or rejects MAR development in Ghana. This may affect the operation of MAR schemes that are currently gaining attention in Northern Ghana, due to a lack of legislative support. Furthermore, informal institutions operated through water leaders, and customs and traditions at the local scale, are entrenched within the existing culture and play a significant role in the water development discourse in the country (Kwoyiga and Stefan 2019). To achieve successful MAR goals, both formal and informal institutions must sanction a strong policy to enhance MAR implementation and operations in Ghana.

**Conclusions and recommendations**

This study presents a combined approach for understanding the hydrogeological conditions and for assessing the feasibility of managed aquifer recharge (MAR) in the Tamne River basin of Ghana. A groundwater flow model has been developed under steady-state and transient conditions using the available limited data. The steady-state model suggests that precipitation is the significant inflow in terms of the basin water budget. The calibrated recharge values obtained range from $5.0 \times 10^{-3}$ to $6.5 \times 10^{-2}$ mm/day, which correspond respectively to 0.19–2.5% of the average annual precipitation in the area. This low recharge rate results from the low erratic rainfall and high evapotranspiration in Northern Ghana. Groundwater flow in the basin is topography driven, in which the dominant flow pattern is north to south with local and regional flow regimes. Estimated hydraulic conductivity field values range between 0.01 and 15 m/day, which is within the values obtained from the pumping test and literature covering the aquifer materials. The heterogeneous and anisotropic nature of the aquifer requires more careful consideration for the MAR site selection and implementation procedures.

**Table 4 Water Budget of the MAR Scenarios**

| Scenario          | Wells (m³/day) | River leakage (m³/day) | Head-dep boundary (m³/day) | Recharge (m³/day) | Storage (m³/day) |
|-------------------|----------------|------------------------|---------------------------|-------------------|-----------------|
|                   | Inflow & Outflow | Inflow & Outflow | Inflow & Outflow | Inflow & Outflow | Inflow & Outflow |
| 1. Baseline       | 0,6591.4        | 8,970.5                | 155,068.1                | 141,735.5        | 139,589.2       |
|                   | 173,121          | 0                      | 6,186.6                   | 287,655          |
| 2. Injection      | 11,000          | 6,591.4                | 22,370.1                  | 176,655.4        |
|                   | 181,589.0       | 199,241.2              | 173,621.9                 | 61,385.9         |
| 3. Abstraction    | 0,12,559.6      | 9,220.5                | 158,178.3                | 147,385.0        |
|                   | 144,589.1       | 173,621.9              | 7,186.6                   | 22,197.3         |
| 4. 50% abstraction | 0,18,829.34     | 11,710.12              | 161,150.97               | 169,238.77       |
|                   | 164,389.01      | 173,621.94             | 8,986.15                  | 19,187.66        |

![Fig. 16 Simulated head changes in the injection wells versus distance from the northern to the southern part of the modelled area shown in Fig. 14b](image)
The transient model shows that the aquifer has enough storage to accommodate MAR water infiltration. Here, different MAR scenarios were tested to investigate the aquifer response to injection and abstraction. Treated floodwater during the rainy season was used as a source water for the MAR. The total volume of water injected by the end of the 4-month period in every year is approximately $1.3 \times 10^6$ m$^3$, showing a resultant increase in aquifer storage and groundwater levels and proves that MAR is feasible in the Tamne River basin. The volume of water that can be abstracted at the end of the 8-month period is 5,968.09 m$^3$/day (approximately $1.48 \times 10^6$ m$^3$). This volume of recovered water would be sufficient for the population during the prolonged dry-season months, in which there is water scarcity. The results imply that the farmers will get all-year-round water for irrigation if MAR is fully implemented in the region. This will eventually increase their incomes and reduce poverty. It will also help stakeholders and decision-makers to manage the limited water resources in the region. The developed model and the MAR scenarios are the first of their kind in Ghana and set a stage for more MAR projects. There are a lot of uncertainties in the model due to lack of data; therefore, it is recommended that more monitoring well data should be available in future research to reduce the model uncertainties in the transient simulation. A simulation-optimization groundwater model approach and water quality issues should be addressed to better understand the MAR conditions in the area.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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