Impact of increasing abstraction on groundwater sustainability within the Ga East and Adentan Municipalities, Ghana.

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ABSTRACT

The hydrogeological systems of the Ga East and Adentan municipalities of the Greater Accra Region, Ghana were studied using a numerical model. Historical hydrogeological and groundwater monitoring data on twenty boreholes were used in conceptualising the hydrogeological system. The objective was to estimate the aquifer recharge and hydraulic conductivity, as well as forecast likely effects of different groundwater recharge and abstraction scenarios on the sustainability of groundwater resources in the area. A calibrated steady-state groundwater flow model was developed for the terrain. A single aquifer system (quartzite-schist formation) was identified. The aquifer hydraulic conductivity estimates for about 90% of the terrain are lower than 15.0 m day^{-1}. The observed outliers are attributable to the fractured and jointed quartzites. The effective aquifer recharge through precipitation ranges from 2.70×10^{-5} m day^{-1} to 8.10×10^{-5} m day^{-1}, representing 1.2% to 3.6% of the average annual rainfall in the area. Cases of local and intermediate flow systems, and potential recharge areas were identified. The calibrated model suggests that the current groundwater recharge rates estimates can sustain groundwater abstraction up to 200% without any substantial geometrical change and drawdown in the hydraulic heads. This implies the system can support demands from groundwater usage for a period of 80 years, using the current population growth rate of 2.5% per annum. However, a reduction of 50% in groundwater recharge within the same period may result in considerable drawdowns throughout the terrain if the current abstraction rates are to be sustained solely by groundwater resource. An increase in groundwater abstractions by up to three times with a 10% reduction in the current recharge rates for the same 80-year period will result in considerable drawdown.

Keywords: Hydrogeological system, steady-state, Numerical Model, groundwater abstraction and recharge.

Introduction

Groundwater resource development and management is one of the prominent means to protect domestic water supply systems against the adverse effects of climate variability in developing countries. Groundwater resources have been known to serve a critical function in the water supply system in rural Ghana. However, this reliance has extended to most urban/peri-urban communities due to the insufficient and erratic supply of pipe-borne water. The Ga East and Adentan municipalities are two of such communities, where most households are exploiting groundwater by drilling boreholes and digging wells. The challenge, however, is the lack of adequate and useful information on the dynamics and fate of the groundwater resources in these two municipalities to help in the proper management of these resources.

The state and fate of groundwater can only be ascertained through credible and reliable data. Such information includes both geological and hydrogeological data on the domain under investigation, which provides the requisite knowledge about the physical configuration of the aquifer and important hydraulic properties. Much of the data are largely obtained during the drilling of boreholes and other geophysical processes. Hydrogeologists make use of such data to characterise the hydrogeology of the terrain and subsequently model the flow dynamics of groundwater. Details of flow and associated phenomena are studied using models which are derived through the combination of the Darcy law and the conservation of mass (Fetter, 2001). There are a variety of versions of the governing equations of groundwater flow and solutions to such equations provide useful information on the dynamics and fate of groundwater resources which assist in their effective management.

A variety of numerical codes have been developed over the years to assist in characterising subsurface fluid behaviour. They are all based on the fact that fluid flow is governed by differences in potential, as suggested by Hubbert (1940) and elaborated by Freeze and Cherry (1979). Solutions to numerical equations include spatial differences of flow and chemical transport. The generalised equation governing the flow of groundwater of constant density and viscosity through heterogeneous and anisotropic porous materials under transient conditions, given in equation (1), is of the form of the Laplace equation in three dimensions (Fitts, 2002).

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} \pm W = S_s \frac{dh}{dt}, \qquad (1)$$

where K_i, W, and S_s, respectively, represent the hydraulic conductivity in the direction *i*, sources/sinks, and aquifer specific storage. Also, *h* is the hydraulic head (which dictates the groundwater potential).

Groundwater budgets are best managed using groundwater models and this has been documented extensively in the literature (e.g. Alley *et al.*, 1999; Boronina *et al.*, 2003; Hu *et al.*, 2011). In Ghana and the rest of the West African sub-region, however, numerical hydrogeology is a growing field. Attandoh *et al.* (2013) intimate that, "groundwater modelling has not been popular in Ghana partly because of the lack of expertise in the area and the paucity of the hydrogeological data for extensive regional hydrogeological modelling". Generally, scarcity of data can be attributed to the lack of proper supervision and professionalism on the part of personnel engaged on drilling projects. Most boreholes are completed with limited information on their lithological logs and appropriate coordinate systems, besides aquifer test data. However, during the supervision of borehole drilling by professional bodies such as the Community Water and Sanitation Agency (CWSA), the challenges are resolved to a large extent.

This study, being the first of its kind in the study area, makes use of available data on static water levels (SWL) in various wells, boundary conditions and hydraulic heads to calibrate a steady-state groundwater model to study the details of flow in this terrain and provide the needed adequate and useful information for managing the groundwater resources in the Ga East and Adentan municipalities. Providing such information can assist in the efforts being made by the Community Water and Sanitation Agency in the Greater Accra Region (CWSA-GAR).

Study area

The Ga East and Adentan municipalities are located in the northern part of the Greater Accra Region between latitudes 5° 37' 50" N and 5° 49' 40" N and longitude 0° 16' 30" W and 0° 4' 30" W (Figure 1). The Ga East and Adentan municipalities used to be classified as rural fringe but due to population and urban sprawl, they can now be considered as urban/peri-urban fringe. They are rapidly urbanising, especially in the areas bordering Accra-Tema. As a result of the urban sprawl, the two municipalities have grown beyond the serviceable area of the Ghana Water Company.

The study area has a semi equatorial type of climate due to its position relative to the equator. Relative humidity averages 92% for the area. Annual rainfall ranges from 90 cm to 110 cm, with the heaviest typically recorded in the months of June and July. The rainfall pattern is bi-modal; the first season occurs from May to July while the second occurs between August and November. The average annual temperature ranges between 25.1 °C in August and 28.4 °C in February and March (MLGRD, 2006).

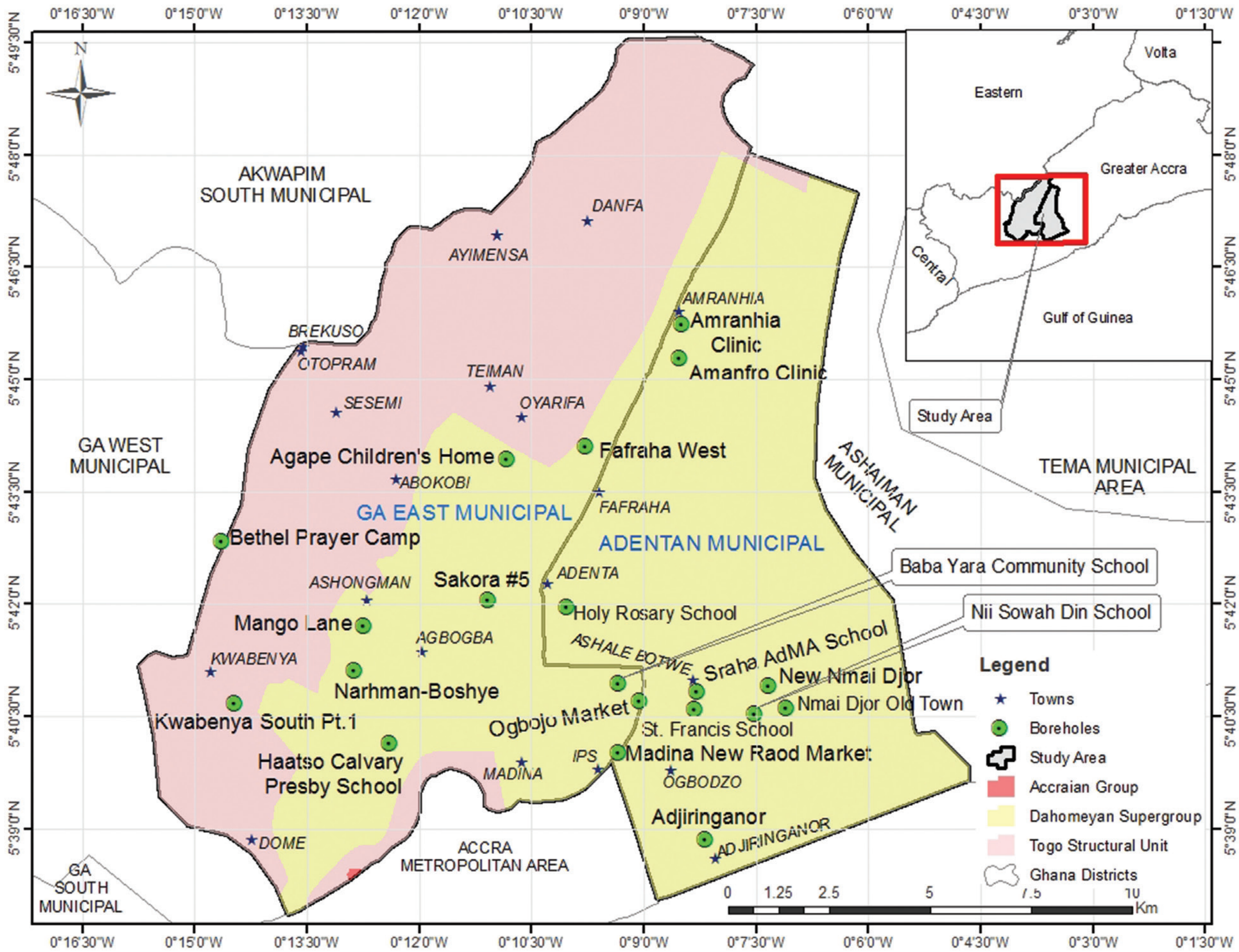

Fig. 1: Geological map of the study area illustrating the twenty borehole (well) locations (Source: Modified from the Geological Survey Authority of Ghana)

The study area had two main types of vegetation, viz. shrub lands and grassland. The shrub lands occurred mostly in the western outskirts and in the north towards the Aburi hills. The northern and northwestern parts of the area were mostly forested. The mountains and highlands host typical African sub-tropical deciduous forest. The grassland which occurred to the southern parts had been encroached upon by human activities, including settlements. The southern part had a thick cover of weathered lateritic materials, which formed a cover over the highly consolidated rocks beneath.

The northwestern part of the study area was generally mountainous, interspersed with lowlands. The highest elevations in the area included the mountains at Otopram; another was the hill at Quarters, east of Comet properties. The lowest elevations in the study area were towards the southern boundary.

The main rivers in the study area were the Ado, Labor and Onyasia rivers. The rivers generally flow from the northern part of the study area to the south. The Ado and Labor rivers flow in a southwesterly direction of the study area. River Onyasia in the southern-most part of the study area also flows towards the south. The rivers have a generally dendritic pattern, and they meander between the lowlands.

Geology and Hydrogeology

The study area (Figure 1) is predominantly Dahomeyides (Dahomeyan, covering the central to eastern part of the area and Togo Structural Units forming the western portion) with minimal traits of the Accraian formation. The Dahomeyide orogeny marks the southern segment of the Pan-African Trans-Saharan belt (TSB) which outcrops in SE Ghana and adjoining parts of Togo and Benin (Nude *et al.*, 2012). The TSB extends for over 2,500 km from the Sahara to the Gulf of Guinea and defines the eastern margin of the West African craton (Caby, 1987). In SE Ghana and adjoining parts of Togo and Benin, the Dahomeyide is interpreted to have resulted from easterly subduction after resorption of oceanic lithosphere at a rifted margin of the West African craton with preserved suture (Affaton *et al.*, 1991; Agbosoumonde *et al.*, 2004; Attoh and Nude, 2008).

The Dahomeyan Structural Unit underlies eastern and southern-eastern Ghana and forms part of the second major tectono-stratigraphic terrain of the country (Kesse, 1985). It also underlies the plains of Accra and extends eastwards into parts of the Volta Region of Ghana (Dapaah-Siakwan & Gyau-Boakye, 2000; Mani, 1978). It is the easternmost rock group in Ghana and differs significantly from other rocks in the country because of its composition of high grade metamorphic rocks. It consists of four lithologic belts of granitic and mafic gneiss (Holm, 1974). The Dahomeyan is generally a series of northeast trending lithologic belts with low to medium angled dips to the southeast. It shares a thrust folded contact with the Togo structural unit towards the west (Tairou *et al.*, 2012).

The Togo Structural Unit represents cover rocks of the basement Dahomeyide gneisses. According to Kesse (1985), the Togo unit is highly folded, faulted and metamorphosed. The main structural grain in the Togo structural unit is the NE-SW with dips to the west (Kesse, 1985). Quartzites and schists are among the main lithologies within the Togo unit (Attoh and Nude, 2008). Generally, the quartzites within the Togo unit are intensely deformed. Rocks of the Togo Structural Unit outcrop on the Akwapim ranges in Ghana, from the mouth of the Densu River to the boundary with the Republic of Togo.

The hydrogeology of the study area is of the basement complex mainly of the Precambrian igneous and metamorphic rocks belonging to the Dahomeyan System and the Togo Structural Unit. The Dahomeyan System is characterised by low yields of groundwater from hand-dug wells and boreholes (Dapaah-Siakwan & Gyau-Boakye, 2000). The low yield is due to the rock types (gneisses) made of crystalline colossal structure and the impervious nature of their weathered material (clay). Depth to groundwater table occurring within the Dahomeyan System is 5 m to 15 m, with relatively low recharge (GSD, 2006). Furthermore, the success rate for developing wells within the system is about 36% and yield within the range of $3\ m^3\ h^{-1}$ to $11\ m^3\ h^{-1}$ (Dapaah-Siakwan & Gyau-Boakye, 2000).

The Togo Structural Unit, which is highly fractured and jointed with folded layers of rocks, build a fracture flow aquifer system. Recharge to groundwater within this basement complex type is high, with highly variable depth to groundwater table (GSD, 2006). Borehole yields within the Togo Structural Unit are determined by the extent and degree of fracturing. Thus, the rocks have a relatively good potential for groundwater development, the most favorable areas being in the valleys where the rocks are highly fractured (Dapaah-Siakwan & Gyau-Boakye, 2000).

Thus, the geological formations characterising the study area suggest that the hydrogeological conditions would be controlled by secondary permeabilities arising from structures (fractures and joint systems) due to deformation.

Methodology

Data acquisition

The hydrogeological characterisation of the study area was achieved using historical hydrogeological and groundwater monitoring data. Data on pumping test and borehole lithological logs of twenty wells (ten in each municipality) drilled in the Ga East and Adentan municipalities under the Government of Ghana (GoG) 20,000 Borehole Drilling Project carried out in 2012 were accessed from the CWSA-GAR. Well depths ranged from 50 m to 90 m. Rainfall data for Accra, for the period January 2005 to December 2014, were obtained from the Ghana Meteorological Agency and used in estimating the recharge rates for the domain.

Maps on the geology, physical boundaries and drainage network of the study area were created with data acquired from the Remote Sensing and Geographic Information System Laboratory of the University of Ghana. Field reconnaissance was undertaken to verify and confirm some of the information received from the two municipal assemblies and the CWSA-GAR. These pieces of information were processed into acceptable formats for the characterisation and eventual conceptualisation of the hydrogeology of the domain.

Conceptualisation of the domain

Building a conceptual model simplifies the field problem and organises the associated field data so that the system can be analysed readily. For this study, the conceptual model was developed using the map tools in the Groundwater Modelling System (GMS version 10.0; Aquaveo, 2014). The domain was conceptualised as a single layer system since the hydrostratigraphy revealed by the well logs suggests insignificant differences amongst the groundwater-bearing units penetrated by the boreholes. The thickness of the modelled aquifer unit varied from one place to the other based on the thicknesses of the unit penetrated by the boreholes. This variability in the thickness of the aquifer unit was conceptualised by importing the top and bottom elevations of the aquifer as obtained from the borehole logs. A digitised geological map of the domain was imported and registered to serve as base map coverage for the construction of the conceptual model using the GIS map tools in GMS version 10.0. The top and bottom of the domain were conceptualised as semi-confined and confined, respectively, to depict the situation on the ground. The confining conditions at the bottom reflect the impervious nature of the materials at the lower limits of the terrain. The semi-confined conditions at the top mimic the limited direct vertical recharge from precipitation.

Coverages were generated and assigned initial values for the various aquifer parameters (viz. *River*, *Recharge*, *Horizontal Hydraulic Conductivity* (HK), *Abstraction Well*, *Observed Hydraulic Head*, and *General Head Boundary*) as part of the conceptualisation process. All the four vertical boundaries of the modelled domain were conceptualised as general head boundaries with varying conductances and head stages so that MODFLOW can adequately compute flows in and out of the domain. The study area has a number of perennial rivers and attributes whose networks were digitized and incorporated into the model as river coverage. Elevations were assigned to the river networks by extrapolating the contour height values for the study area from the general topography of the area using google earth. In the coverage for recharge, based on the lithology of the domain, sixteen zones were created using the map tools in GMS version 10.0 in an attempt to capture the spatial variability of groundwater recharge. The HK coverage, similar to that for recharge, was generated and assigned initial values based on the pump-test data associated with the boreholes, data on the borehole logs, and standard literature for the geology of the area. All twenty boreholes captured in this model are pumping wells. The discharge rates (Table 1) for the boreholes (in units of) obtained from pumping test results were used for the abstraction coverage. The hydraulic head values for all the boreholes together with their spatial positions were assigned to the observed hydraulic head coverage. The hydraulic heads were computed as the difference between the ground elevations and the static water levels for the individual boreholes.

Table 1: Initial abstraction rates for the various boreholes

Latitude	Longitude	Community	Abstraction rates
Y	X		
811891.0	-630880.5	Sakora #5	7.20
814271.8	-634701.4	Frafraha West	14.40
805643.5	-628311.1	Kwabenya South Pt.1	14.40
805298.0	-632296.6	Bethel Prayer Camp	17.28
815106.6	-627151.7	Madina New Road Market	17.28
815098.2	-628864.1	Baba Yara Community School	10.08
808592.8	-629139.9	Narhman-Boshye	72.00
812333.5	-634356.7	Agape Children's Home	14.40
808809.2	-630232.2	Mango Lane	86.40
809451.3	-627357.8	Haatso Calvary Presby School	7.20
816631.0	-637716.8	Adjiringanor School	40.32
816573.6	-636874.2	Nii Sowah Din School	43.20
819258.9	-628263.6	Amanfro Clinic	34.56
818818.8	-628818.0	Holy Rosary School	93.60
818489.7	-628115.4	Amranhia Clinic	31.68
815633.2	-628430.2	New Nmai Djor	30.24
817045.7	-628652.3	Nmai Djor Old Town	28.80
817007.7	-628231.0	Ogbojo Market	64.80
813829.5	-630730.2	Sraha AdMA School	288.00
817279.2	-625013.3	St. Francis School	28.80

Development of the numerical model

The conceptual model was translated into a numerical model to simulate the general groundwater flow under steady-state conditions. The numerical simulation was performed using the Modular Finite Difference groundwater flow simulation code, MODFLOW (Harbaugh, 2005), incorporated in GMS version 10.0. Developing the numerical model begins with the design of a suitable grid. The finer the grid, the better the modelling results. The domain was divided into 10,000 cells with 100 rows and 100 columns. The model grid was oriented north-south and covered a total of 5223 active cells over a single layer. With variable hydraulic properties, the domain was conceptualised as a single aquifer system. The imported aquifer thicknesses penetrated by the individual boreholes during the conceptualisation process were mapped to MODFLOW to define the thicknesses of the layers. Kriging was then used to interpolate the values to cover the entire domain. The starting heads were automatically generated from the data imported during the conceptualisation.

Model calibration

Every model ought to be calibrated before it can be used as a tool for predicting the behaviour of a considered system. Model calibration entails tuning the model to mimic field conditions. The calibration was initially performed manually, by adjusting values of recharge and hydraulic conductivities for the sixteen zones created. The general head boundary conditions and the river bed conductances were also varied within acceptable limits towards achieving a calibration target of 1.0 m (indicating a close to perfect match between observed hydraulic head values and computed hydraulic head values). Further, to simulate a continuous hydraulic conductivity of the aquifer system, Parameter Estimation (PEST) and the Pilot Point methods were used until a close to perfect fit of values was obtained.

Sensitivity analysis

Sensitivity analysis is carried out in groundwater flow simulation to measure the stability of the model against subtle changes in some aquifer hydraulic parameters. According to Hill *et al.* (2000), "this is achieved by adjusting the values of key parameters and observing the impact on the calibrated model". A model that is highly sensitive to any of the model parameters is considered unstable and unsuitable for predicting scenarios. Such a model will have to be recalibrated. In this study, the sensitivity analysis on the calibrated model was carried out automatically through PEST. It was conducted for hydraulic conductivity and recharge, and a histogram was generated depicting the model's stability in relation to the named parameters.

Analysis of scenarios

The calibrated steady-state model was used to simulate the various management scenarios. The analysis was carried out on a set of unique realisations for the domain generated by stochastic simulations. Three management scenarios were simulated based on a number of considerations. The first consideration bordered on an increase in population with an accompanying increase in the per capita per day water usage. The final results of the 2010 Population and Housing Census (PHC, 2010) indicate that the Greater Accra Region population increased by 38.0 percent over the 2000 figure of 2,905,726. The Region is opening up significantly in the direction of the two municipalities under investigation, leading to the creation of a new municipality (La-Nkwantanang-Madina). The second consideration was global warming, which leads to increase in evapotranspiration. The anticipated effect is a decline in the levels of surface water bodies culminating in greater dependence on groundwater resource. The third consideration bordered on the incessant paving of open spaces that accompanies the inundation of the Region with construction projects in probable local groundwater recharge areas.

The first scenario, therefore, simulated the effects of increased groundwater abstractions from the twenty boreholes progressively by 10% percentage points up to 100%, and then by 200%, 300%, and 400% above the current abstraction rates under the same conditions of recharge at calibration. The second scenario simulated the effects of decreasing the groundwater recharge rates at calibration by 10%, 20% up to 90% while keeping the current abstraction rates unchanged. The third scenario simulated the effects of a 10% reduction in the recharge rates at calibration coupled with an increase in the current abstraction rates by 10%, 20% up to 100%, and then 200%, 300%, and 400%.

Results and Discussion

The stratigraphy

The study identifies a single aquifer unit in the domain. The aquifer occurs in the weathered zone, made up of the quartzite-schist formations. There is a laterite-clay overburden, posing as a semi-confined to confined aquifer system (Figure 2). The stratigraphy of the domain (Figure 2) was successfully developed as a major step towards the development of the conceptual model of the study area. One of the main benefits of using solid models to define stratigraphy for MODFLOW models is that it provides a grid-independent definition of the layer elevations that can be used to immediately re-create the MODFLOW grid geometry after any change to the grid resolution (Jones *et al*., 2002). Figure 2 captures the lithological units identified in the domain, namely laterite, schist, quartzite, and clay. The aquifer thickness ranges from 6.5 m to 31.5 m. The highest aquifer thickness occurs at Bethel Prayer Camp, which is located at the topmost elevation in the study area. The low aquifer thicknesses occur in the low topographic regions of the study area (e.g., Adjiringanor). Relating the identified lithological units to the established local and regional geology of the area, the quartzite and schist locally belong to the Togo Structural Unit of Ghana (Attoh *et al*., 1997). The clay and laterite emerge from alterations of the phyllites belonging to the Togo Structural Unit.

The groundwater flow patterns

A cross-section through the potential field of the domain revealed cases of local and intermediate groundwater flow systems, and identified potential recharge areas like the Bethel Prayer Camp, Mango Lane and Santeo (Figure 3). The potential field helps to ascertain the groundwater potential in a domain. It is the distribution of the hydraulic heads in the domain that provides a clue about the potential field. From the calibrated steady-state model, a close fit is noticed between the observed and hydraulic head values of the twenty boreholes. This close fit is described by a root mean squared weighted residual head of 3.84 and a co-efficient of regression (R-squared) value of 0.99. From the reasonably good match, it is safe to say that the head distribution in the study area from the calibrated steady-state model, which ranges from 53.0 m to 221.0 m, sufficiently represents the groundwater potential distribution in the study area.

The hydraulic conductivity field

One of the essential outputs of a properly calibrated groundwater flow model is the hydraulic conductivity field (Fetter, 2001). Hydraulic conductivity assists in conceptualising the general pattern of the transmissive properties of the aquifer and aids in understanding observed flow patterns. The HK field in the domain was established through the pilot point method. The estimated HK field at calibration is presented in Figure 4. The values range from 3.75 m day^{-1} to 105 m day^{-1}, with a mean of 13.1 m day^{-1}. Figure 3 shows that the HKs are lower than 15.0 m day^{-1} in much of the area. This is consistent with observed HK values for lithologies of the identified aquifer material (quartzite and schist) (Lewis, 1989). The HK field is largely heterogeneous for most part of the terrain

Secondary permeabilities created in the wake of fracturing and/or weathering control the hydrogeological properties of the aquifer in the study area. The HKs are high in places where the degree of secondary permeabilities are high. The very high conductivity values observed in the western parts and towards the north are outliers which can be ascribed to the fractured and jointed quartzite within the weathered zone. They enhance the conduits within the materials for rapid flow of groundwater (Tairou *et al*., 2012). The estimated HKs in this study have some resemblance to estimates obtained by Yidana *et al*. (2014) for portions of the Densu basin with similar lithologies. Their results ranged between 2 m day^{-1} and 37 m day^{-1} .

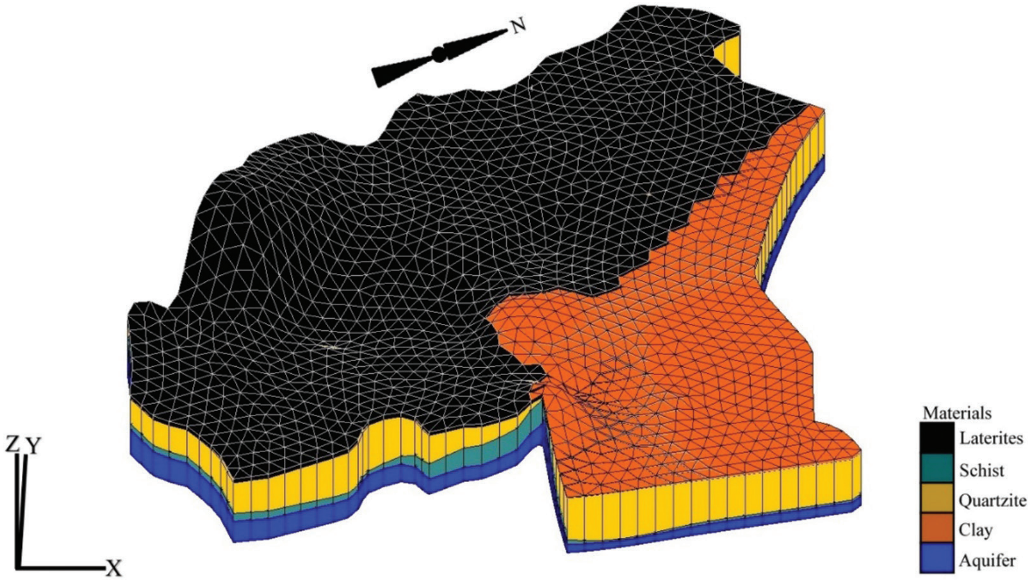

Fig. 2: The solid stratigraphy of the domain capturing the lithological units identified

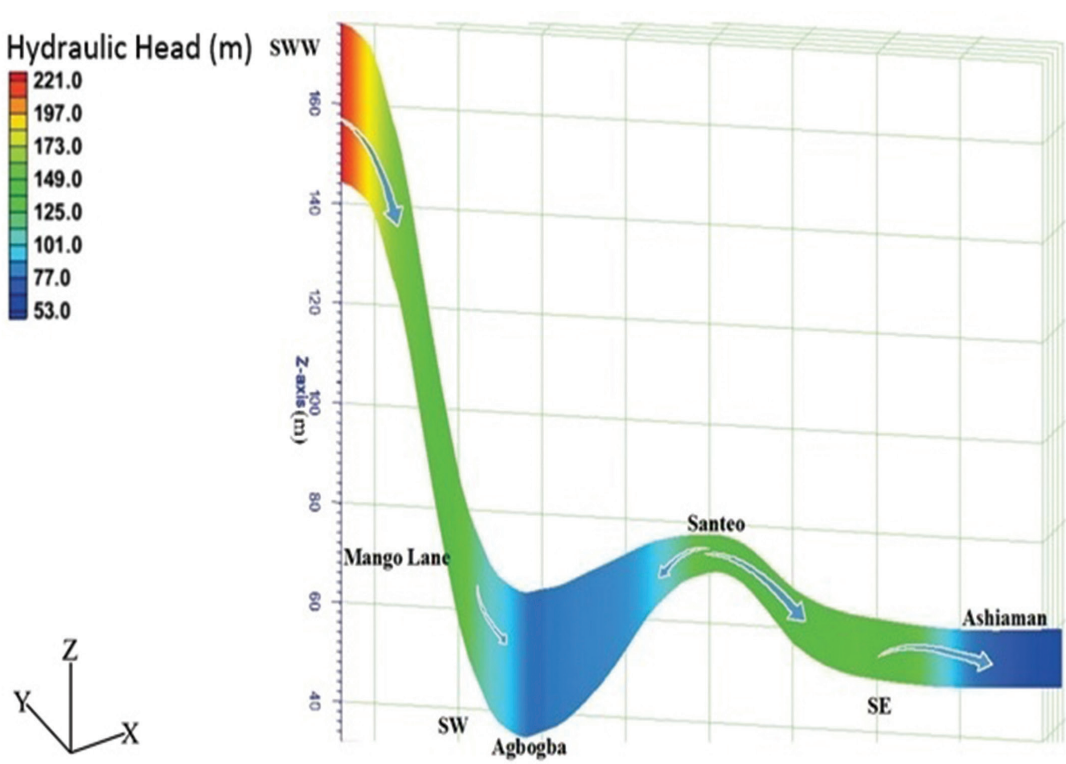

Fig. 3: Cross-section of the potential field showing the flow systems and potential recharge areas

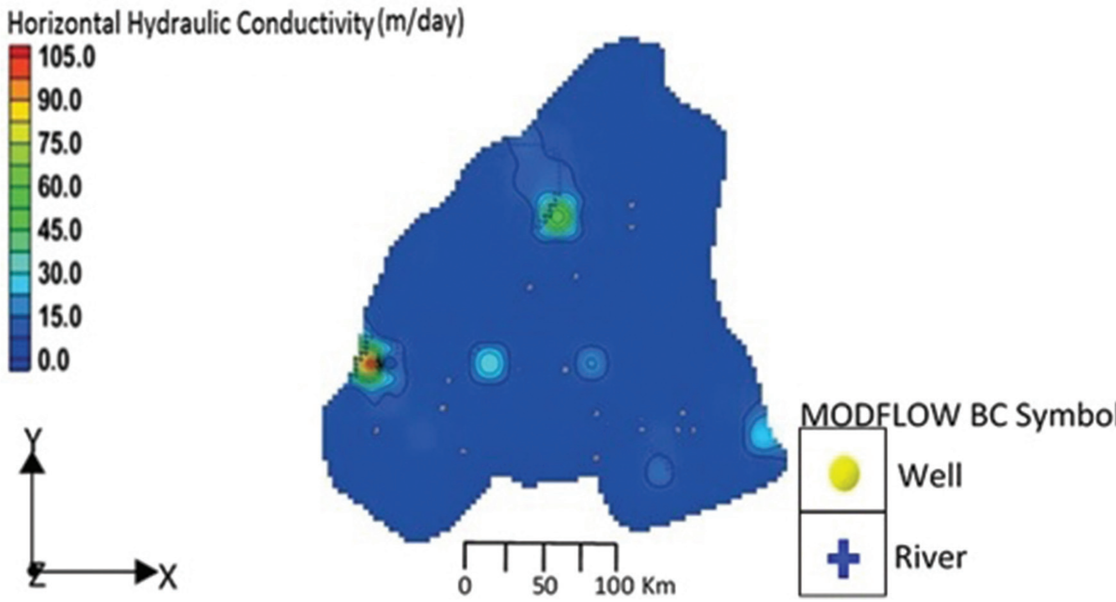

Fig. 4: Distribution of the calibrated horizontal hydraulic conductivities (plan view) in the study area

The recharge rate estimates

Groundwater recharge is key in modelling groundwater flow. Accurate estimation of groundwater recharge is imperative to ensure proper management and protection of valuable groundwater resources. In estimating the recharge rates for the domain under investigation, a recharge coverage was set up using 1% to 3% of the average annual rainfall value for Accra for the period January 2005 to December 2014. The calculated range of values were slightly varied and the model simulated during the calibration process. The average annual rainfall value for the stated period was computed to be 825.6 mm.

At calibration, groundwater recharge in the domain ranged from 2.70×10^{-5} m day-1 to 3.78×10^{-4} m day^{-1} (Figure 5). The groundwater recharge is less than 8.10×10^{-5} m day^{-1} for much of the area. Hence, using the range 2.70×10^{-5} m day^{-1} to 8.10×10^{-5} m day^{-1}, the groundwater recharge represents 1.2% and 3.6% of the average annual precipitation in the area. These low estimates reflect the barrage of construction projects impeding aquifer recharge through rainfall. The low recharge rates occurring in most parts of the study area can be attributed to the very low or non-existence of vertical hydraulic conductivity which restricts the vertical percolation of precipitation into the aquifer system. There were, however, high recharge values observed in some isolated parts of the domain which may be regarded as outliers, attributable to open systems and/or dug-outs enhancing recharge. Specifically, the highest recharge rate in the terrain occurred mostly within the topographic high areas in the western portions of the study area. This observation can be ascribed to the fact that the rocks occurring there are extensively fractured, thickly foliated and highly deformed. This implies that there are a lot of weaker zones in those areas, facilitating the movement and flow of water in the terrain.

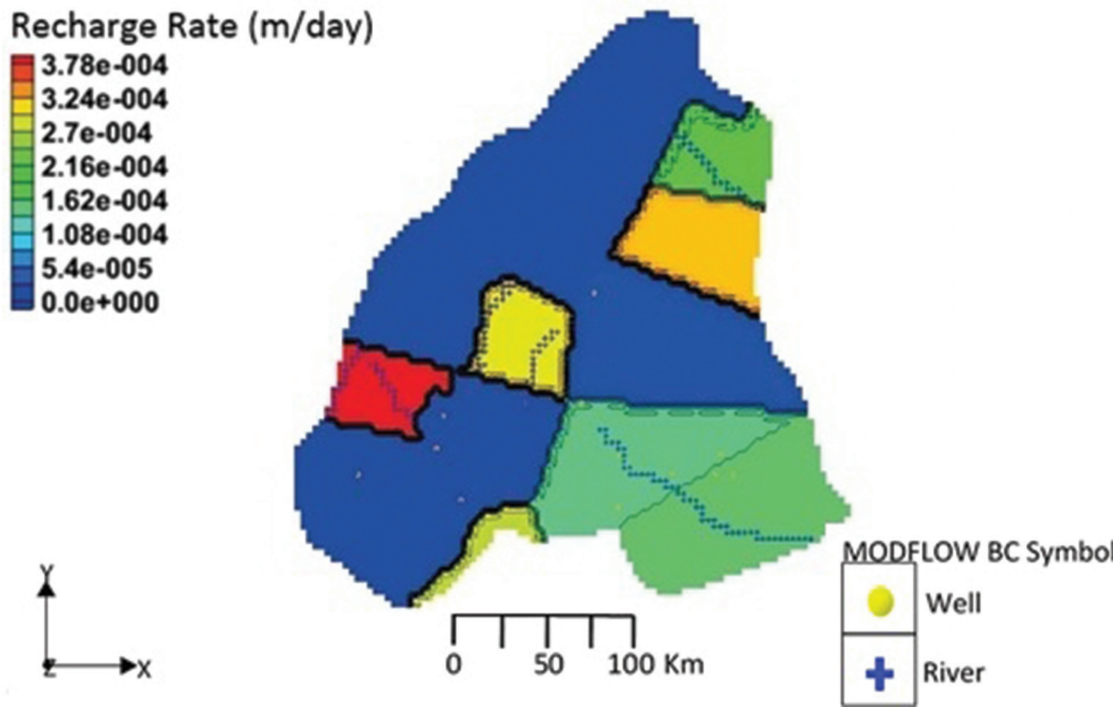

Fig. 5: Distribution of groundwater recharge in the study area (plan view)

The estimated groundwater recharge distribution in the area corresponds to the distribution of the groundwater hydraulic potential. This observation is consistent with the general hydrogeological knowledge that highlands and lowlands serve as recharge and discharge zones in groundwater flow systems. Thus, the surface topography is a subdued replica of the groundwater table elevation (Freeze & Cherry, 1979; Fetter, 2001; Yidana *et al.*, 2011).

Comparatively, recharge rates estimated for this study vary marginally from recharge estimates obtained from numerical simulations in a similar terrain (cf. Yidana *et al.*, 2014). Results from Yidana *et al.* (2014) conducted on the Densu basin, had recharge estimates for part of the terrain with similar lithologies ranging from to . The difference can be attributed to the variations in the extent of deformations at the different study areas. Additionally, this model is calibrated under steady-state conditions while that used by Yidana *et al.* (2014) is a transient model.

The estimated recharge rates are quite significant compared to the observed abstraction rates of all the boreholes used in the study, as depicted by the water budget presented in Table 2. The observed groundwater recharge in the terrain could, however, be affected adversely by climate change. Transient groundwater flow simulation would be required to analyse such trends. Currently, the time-variable hydraulic head and flow data necessary for such analysis is unavailable.

Table 2: Groundwater flow budget of the modelled domain under steady-state condition

Sources/Sinks	Inflow	Outflow	Difference	Percent Discrepancy (%)
General heads	1495624.78	1528886.864	-33262.08425	
Rivers	36882.50363	26109.18981	10773.31382	
Abstraction wells	0	944.6400032	-944.6400032	
Recharge	23366.23151	0	23366.23151	
Total	1555873.515	1555940.694	-67.17891862	-0.004317669

Scenario analysis

The general observation from the scenarios of stresses carried out on the calibrated model is that it is stable to subtle changes in the aquifer parameters and can therefore be described as useful and suitable for predicting scenarios within the limits of the calibration error. No visible changes to the potential field is observed when the current abstraction rates increase from the existing boreholes increased by up to 200%. This suggests that the estimated rates of recharge of the aquifers in the terrain can sustain up to a threefold increase in the current rates of abstraction of groundwater in the area for both domestic and commercial purposes with minimal effects on the system. The current calibrated groundwater recharge rates can support population demands for 80 years at the current population growth of 2.5% per annum, if groundwater is to be the sole source for domestic water needs in the study area. However, noticeable changes are observed in the steady-state model when abstraction rates increase by 300% to 400%. For instance, dry cells emerge, indicating a considerable drawdown in the terrain (Figure 6). Variations in the flow pattern within the south-eastern portion of the domain are also more pronounced. This suggests that if the only source of water for both domestic and commercial usage is groundwater, then an increase in groundwater recharge is required to sustain an increase in the current abstraction rates by four times and beyond. It is necessary, therefore, to conduct more detailed research to identify and secure local and regional groundwater recharge sources. Also, the development of local dugouts for groundwater recharge would help reduce the annual quantities of rainwater lost through evapotranspiration and runoffs as a result of floods. This will assist in having additional water stored in the aquifers for use in time of need.

Incidence of dry cells plus noticeable changes in the flow pattern in the north-eastern towards the south-eastern portions of the domain occur when the current recharge rates are reduced by 50% to 90% at the current abstraction rates (Figure 7). The implication is that when the current rates of recharge decline by half or more, there will be considerable drawdown if the current abstraction rates are to be sustained solely by groundwater resource in the study area.

It was also observed that when the current abstraction rates are increased by 200%, 300%, and 400%, with the recharge rates reduced by 10%, dry cells emerge in addition to new contours forming within the south-eastern portion of the study area (Figure 8). This suggests that a marginal reduction in recharge of the aquifer through precipitation, coupled with an increase in the current abstraction rates by three to five times, would result in considerable drawdown.

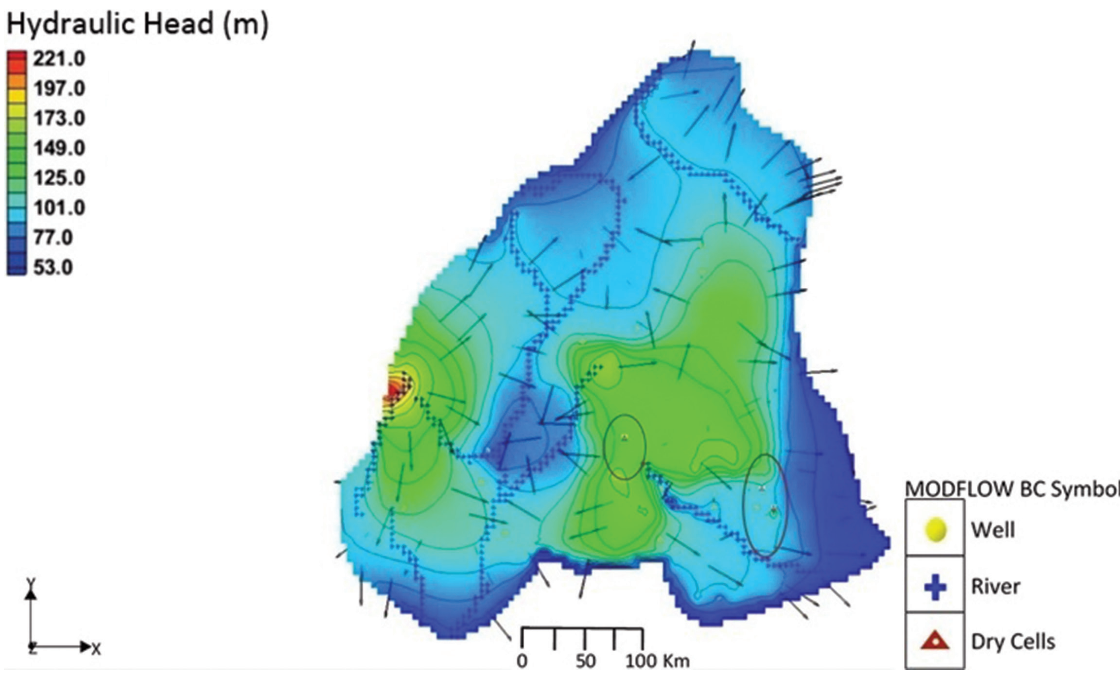

Fig. 6: Hydraulic head distribution and flow pattern after 400% increase in groundwater abstraction

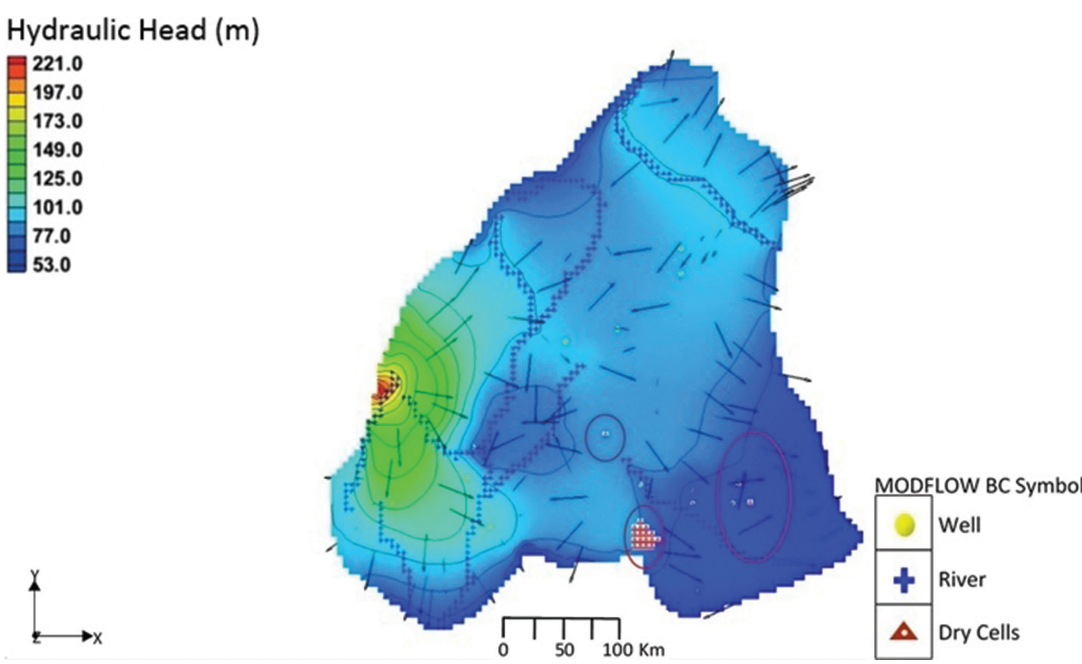

Fig. 7: Hydraulic head distribution and flow pattern after 90% reduction in groundwater recharge

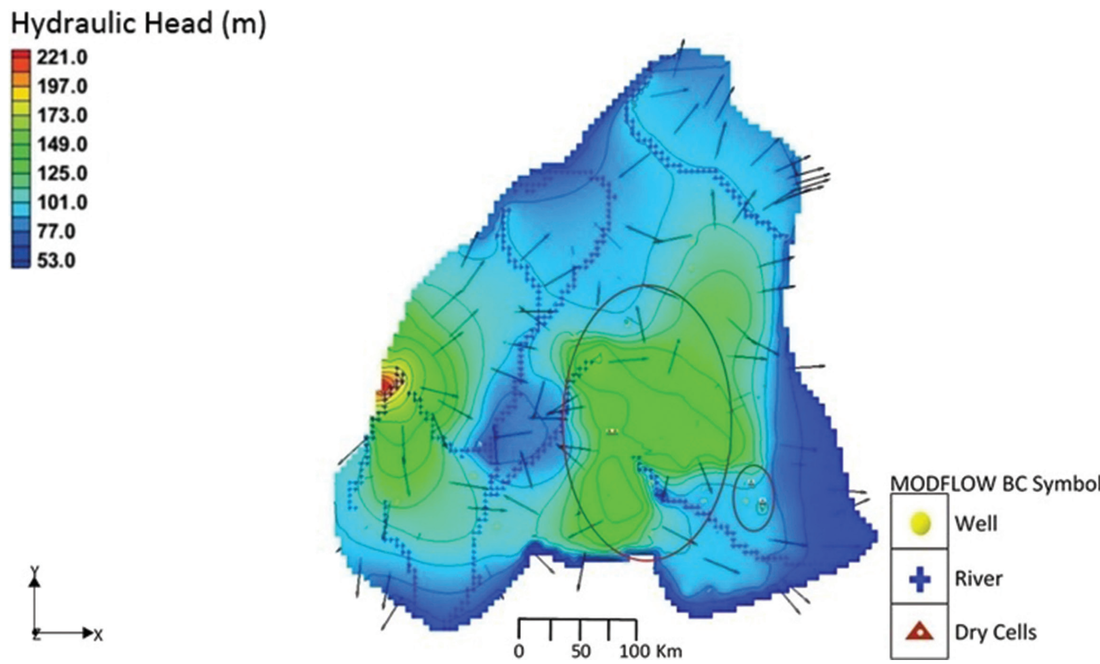

Fig. 8: Hydraulic head distribution and flow pattern after a 10% reduction in groundwater recharge and a 400% increase in abstraction

Conclusions

A steady-state groundwater flow model has been calibrated using aquifer characteristics of wells drilled in the year 2012 within the Ga East and Adentan municipalities. It has provided some useful information for the proper management of groundwater resources in the study area. However, it is a first step toward the development of a transient model for the terrain to provide predictive simulations, model verification and estimates on specific yield and precise storage coefficients of the aquifer in the study area. The model, within the limit of available data, identifies a single aquifer system made of quartzite-schist formations. The model indicates local and intermediate flow systems in the terrain. Estimated aquifer hydraulic conductivities are below 15.0 in much of the area, which is consistent with observed hydraulic conductivity values for lithologies of the aquifer material. The groundwater recharge estimates suggest that about 1.2% to 3.6% of annual rainfall reaches the saturated zone. These low estimates reflect the flood runoffs and barrage of construction projects in the Greater Accra Region which tend to impede aquifer recharge through rainfall. The estimated recharge rates can sustain up to a threefold increase in the current abstraction rates for both domestic and commercial purposes with insignificant changes in the groundwater flow geometry and drawdown in the hydraulic heads. This implies that the system can support demands from groundwater usage for a period of 80 years at the current national population growth rate of 2.5% per annum. However, for the same 80-year period, a reduction in groundwater recharge by up to 50% will result in considerable drawdowns throughout the terrain if the current abstraction rates are to be sustained solely by groundwater resource. Considerable drawdowns will also occur when groundwater abstractions increase by three to five times with a 10% reduction in the current recharge rates for the same 80-year period.

This study suggests that the groundwater potential in the terrain investigated is quite high and can sustain the regular domestic water needs and some commercial activities.

Acknowledgements

The authors are grateful to the staff of the Community Water and Sanitation Agency (Greater Accra Region) for assisting with the log data on the boreholes used for this study. We equally appreciate Mr. Kwame Johnson and Ms. Mary Mahama of the Ga East Municipal Assembly and Mr. Sylvester Sapaat of Mdumolga Hydrological Development and Services Ltd. for assisting with the field trips, as well as members of the study communities for their cooperation during field trips. We are also grateful to Nii Amartey Amartefio (formerly with the GIS laboratory at the Department of Geography and Resources Development, University of Ghana) for his assistance in developing the maps on the study area. Finally, special thanks to Mr. Emmanuel Tossou for his dedicated assistance.

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