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A SIMULATION/OPTIMIZATION MODEL FOR GROUNDWATER RESOURCES MANAGEMENT IN THE AFRAM PLAINS AREA, GHANA

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A groundwater flow simulation model was developed using available hydrogeological data to
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describe groundwater flow in the Afram Plains area. A nonlinear optimization model was then developed and solved for the management of groundwater resources to meet irrigation and household needs. The objective was to maximize groundwater extraction for irrigation activities from the shallow aquifers of the southern Voltaian Sedimentary Basin that underly the area This would improve food security, raise the standard of living and ultimately alleviate poverty in the Afram Plains. The calibrated flow model is in tandem with the general hydrochemical evolution of groundwater in the area and fits the observed data with about a 98% degree of confidence. Groundwater resources may not be the limiting factor in the development of irrigated agriculture. Groundwater has tremendous potential to meet current and future irrigation needs. It was determined from this study that profit from maize irrigation in the Afram Plains area could rise from US$301, 000 in 2007 to over US$3.5 million by the end of the last management period (2013) as irrigation practice is improved, and the economic strength to increase the acreage for irrigation improves. Even with these margins of profit, the drawdown constraint was not reached in any of the management periods. It is expected that recharge from the irrigation water would reclaim the lost hydraulic head. The single significant constraint was the amount of land area that could be developed for irrigation in the area. The profit obtained per unit cubic meter of water used also improved over the same management period.

INTRODUCTION

The Afram Plains is one of the areas on the Volta Basin, Ghana, where chronic poverty is the main cause of environmental degradation, which continues to undermine sustainable economic development since poverty drives populations into unsustainable exploitation and use of resources. The district is cut off from the rest of the country due to limited physical access. It is virtually a peninsula cut off on three sides by the Volta Lake and on the fourth by lack of a connecting road to the outside world (Figure 1). The population of the district is estimated to be 161,754 and growing at an estimated rate of 3.6% (Ghana Statistical Services, 2000). Estimated per capita water demand in the area is about 36 l/c/d (0.036 m^3/c/d). This figure is expected to rise sharply as development progresses and flush toilets replace improved latrine systems currently in use. Poverty rate in the district is about 87% among the rural communities, compared to the national rate of 42%. The district's isolation has resulted in a small population scattered over vast areas of land that is suited for the production of various agricultural products. Arguably, the Afram Plains District has tremendous potential in the agricultural sector to contribute significantly to the improvement of the well-being of its inhabitants. If the district's potentials in irrigated agriculture were adequately harnessed with unlimited water supply year round, there could be sustainable food production, and a corresponding improvement in the living conditions of the inhabitants. The current practice is rain-fed peasant farming. With the irregularity of rainfall patterns in the area in recent times, this practice has been unsustainable leading to unemployment and poverty. Associated with high poverty levels in these communities is the incidence of rural – urban migration whereby the energetic youth migrate from rural deprived communities to nearby urban centers in an attempt to escape the scourge of poverty and deprivation. This has aggravated environmental problems in the nearby urban centers. Crime rate is on the rise as aggressive migrants bent on making a living at any cost, indulge in illicit activities in the urban areas. The spread of HIV/AIDS and other diseases has been linked to this increasing trend of rural-urban migration.

Groundwater development has been identified as the solution to most of the economic and social problems in the Afram Plains area and other rural communities in Ghana. Sustainable exploitation of groundwater can help irrigated agriculture provide employment for youth with interest to engage in this enterprise. It has the promise of offering year-round employment and a significant increase in the standard of living. There is therefore the need to develop a management support system to aid in the development and management of groundwater to meet all needs in the area.

Groundwater flow simulation models have been used widely to advise management decisions on the management of groundwater resources to meet growing needs, and at the same time preserve ecological balance and water table stability. Flow simulation models help determine the direction of groundwater flow, distribution of hydraulic heads and flow magnitudes. In essence, they help determine the most optimal locations to drill boreholes and wells and provide guidelines on maximizing groundwater extraction from wells and boreholes in a watershed. They have been used effectively in such countries as India, China, and Pakistan among others, to influence groundwater management paradigms (Shamir et al., 1984; Willis and Finney, 1988; Finney et al., 1992; Emch and Yeh, 1998; Ebraheem et al., 2003; Zhou et al., 2003; and Uddameri and Kuchanur 2007) and prove to be universal in their applications. Simulation models are more effective when combined with optimization models whereby a set of management objectives are achieved in the

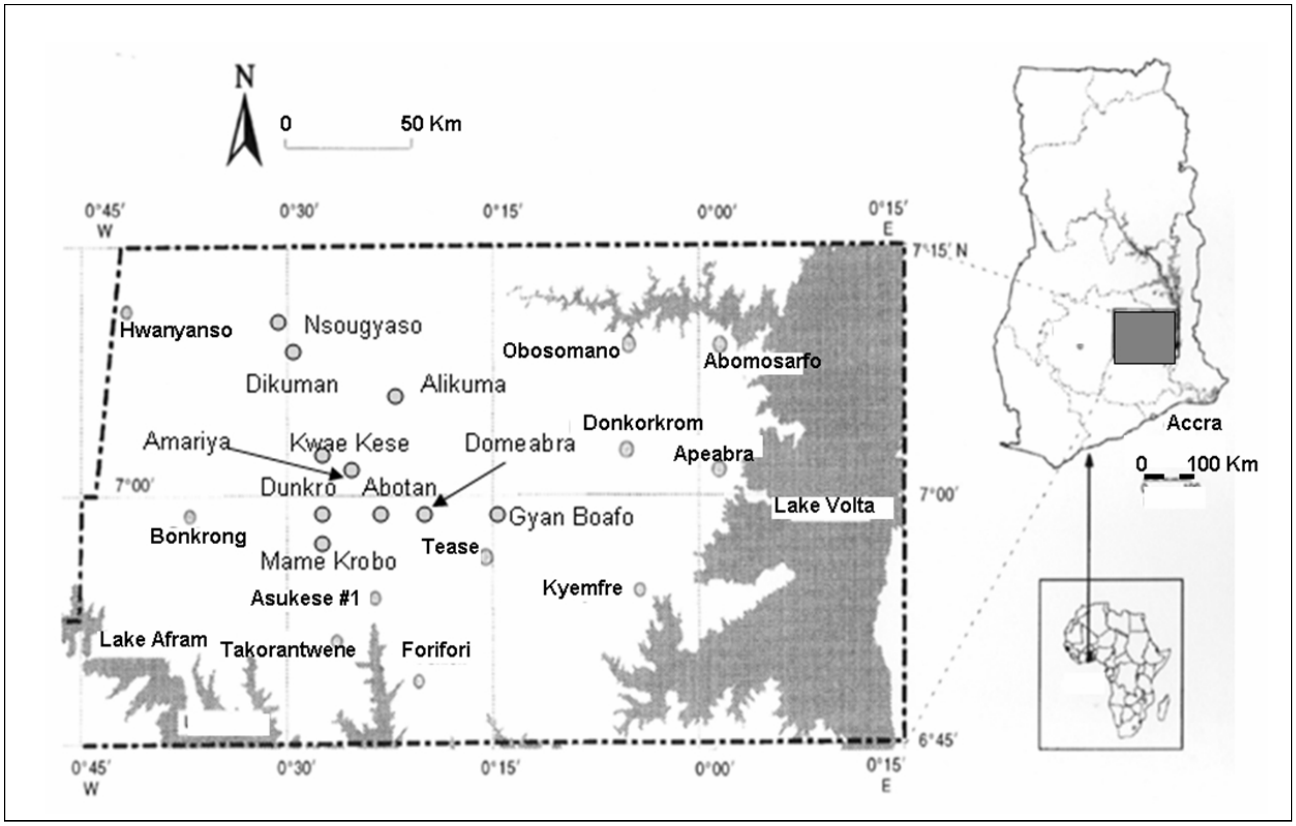

Figure 1. Location map of the study area.

context of several environmental and socioeconomic constraints. Don et al. (2006) for instance coupled a numerical simulation model with an optimization model to predict groundwater response to settlement and to determine the most optimal safe yield for groundwater without violating physical, environmental and socio-economic constraints in the Shiroishi area in the Saga Plain in Japan. This model enabled managers to determine the effects of climate and various pumping scenarios on the aquifer system.

This research uses a simulation and optimization model to devise a decision support system to aid in the exploitation of groundwater resources for use in irrigation and households in the Afram Plains area, Ghana. A three dimensional groundwater flow model is built from available hydrogeological data to calculate hydraulic head distribution in the entire area. An optimization model specifying the objective to be achieved and the environmental and socioeconomic constraints that limit extraction levels, is linked with the groundwater flow model to determine the most optimal extraction levels in each of twenty wells/boreholes in the area for use in irrigation and households. Profit margins from irrigation practice using groundwater resources during the management period are discussed.

GEOLOGY AND HYDROGEOLOGY OF THE SOUTHERN VOLTAIAN SEDIMENTARY BASIN

The Afram Plains area is underlain by rocks of the southern Voltaian sedimentary Basin. Aquifers of the basin consist of sandstones, mudstones, conglomerate, siltstones, shale and limestone. The rocks in this part of the terrain are popularly referred to as the Obusum beds. Detailed geology and hydrogeology of these rocks is contained in reports by Junner and Service (1936), Junner and Hirst (1946), Gill (1969), Acheampong (1996), and Acheampong and Hess

(1998). Drilling projects and hydrogeological investigations indicate that a shallow prolific aquifer capable of delivering water of sustainable quantities for domestic consumption exists in the area (Minor et al., 1995). Previous studies indicate that primary porosities are very low due to the impervious nature of the rock. However, where secondary porosity by the fracturing and weathering of rocks occurs, the hydrogeological properties of these rocks are very much enhanced. Therefore the hydrogeological parameters are based on secondary permeabilities in the form of joints developed after the primary porosities had been destroyed in the wake of rock compaction and slight metamorphism (Acheampong and Hess, 1998; Yidana et al., 2007). The nature, aperture and degree of interconnection between joints determine the hydrogeological features of the rocks. The structural grain consists of NNE-SSW fracture systems, which control the hydrogeological character of the Voltaian sedimentary rocks in general. This structural grain is due to pressure release by to erosion and tectonic activities related to the Pan-African tectono-thermal event. Where secondary porosities do not exist to provide for infiltration and recharge, the aquifer properties are very poor. Where weathering of these rocks is intense, secondary permeability is enhanced and they serve as better aquifers.

The hydrogeology of this region is further subdivided into five hydrostratigraphic units on the basis of aquifer types (Acheampong and Hess, 1998). Unit A (Figure 2) consists of massive conglomerate and sandstone. It occurs at the northeastern part of the area and is exposed at Abomosarefo, and Donkorkrom (see Figure 1). Groundwater occurs mainly within the weathered and fracture zones, and the success rates of all drilling projects in this unit is 66%. The second unit (unit B) outcrops in the southern part of the region and is composed of unfractured shale and grey sandstones. Water quality is saline, and is not preferred for many purposes. Borehole depths range between 50m and 100m, with a water production success rate of 50%. Recharge potential varies between poor and moderate due to low permeabilities. Quartzitic sandstones and conglomerates form the third hydrostratigraphic unit (unit C), which outcrops in the central part of the area. The aquifer properties of rocks in this unit are based on the level of weathering and fracturing of the impervious quartzitic sandstones. It outcrops at Tease and surrounding areas. The fourth hydrostratigraphic unit (unit D) comprises feldspathic sandstones, arkose, siltstones and mudstones

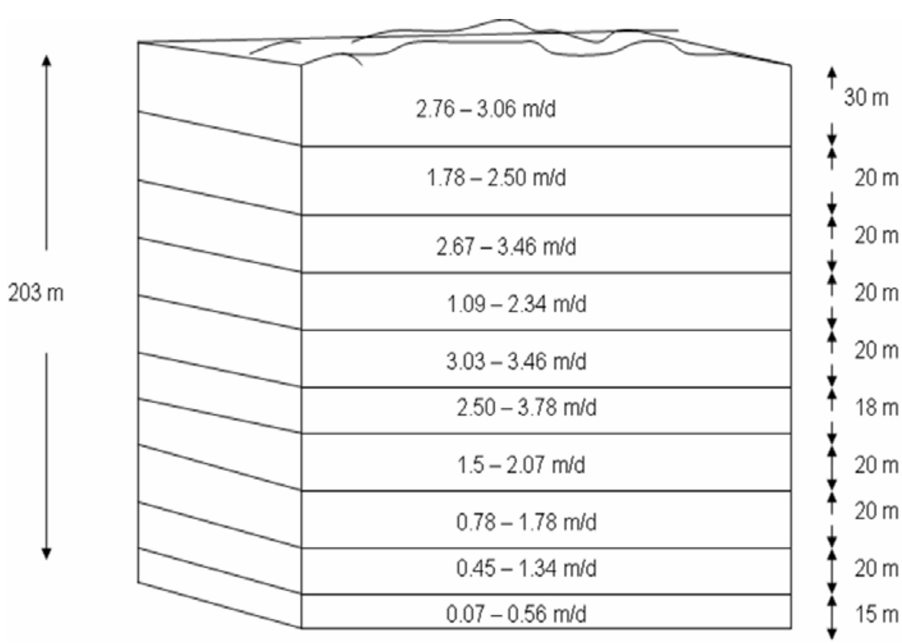

Figure 2. Conceptual framework of the hydrostratigraphic units in the Afram Plains area.

and occurs at the northwestern parts of the area. Prolific aquifers are identified with high degrees of weathering and deep fracture systems. Borehole success rate in this unit is approximately 66% and water has good chemical properties for a wide range of uses. Recharge is however very poor due to a re-cemented layer up to a depth of 60m. Deep holes may intercept weathered zones but the remoteness of these precludes direct recharge from the Lake Volta along fractures. The last unit (unit E) outcrops in the southeastern part of the area and underlies Apeabra and surrounding areas close to the Volta Lake. It consists of fractured shale and sandstone whose hydrogeological properties are poorly defined.

Groundwater flow patterns in the Voltaian System in general have been difficult to gauge properly, due to the complexity of the terrain. Acheampong and Hess (1998) postulated, based on static water levels in wells and the topography of the area, that three main flow paths could be traced in the area. Their study also determined that recharge, principally from precipitation is concentrated in the mid sections of the area and there is a general flow from these sections to the Volta Lake. Recharge amounts range between 13.4% and 16% of annual precipitation in the area (GEF – NEP, 2002). The quality of the water is presumed to alter along flowpaths. In general, the hydrochemistry of groundwater from these rocks is controlled by the incongruent weathering of silicate minerals (Acheampong and Hess, 1998; Yidana et al., 2007). Two water types (facies) exist in the area (Yidana et al., 2007): the calcium – sodium – chloride – bicarbonate facies, and the magnesium – potassium – sulfate – nitrate facies for the southern and northern sections of the Afram Plains area respectively.

HYDROGEOLOGIC FRAMEWORK AND CONCEPTUALIZATION

The modeled area measures 30 km by 20 km. It is bounded to the east, south and southwest, by the Volta Lake, which receives recharge from the aquifers in the area (Acheampong and Hess, 1998). The northern and western sections have no obvious physical boundaries. The area is underlain predominantly by sandstones and mudstones as revealed by data from shallow high yielding wells in the area. Using these data, these lithologies can be separated into ten (10) distinct hydrostratigraphic units on the basis of the hydraulic conductivities (Figure 2). Most of the wells in the area do not expose all the known hydrostratigraphic units, thus information from literature was used to complete the stratigraphy. The upper 60 – 100 m of materials reveals various shades of sandstone with different hydraulic properties. Below 100 m, there is a mixture of different lithologies with hydraulic conductivities that range from 0.07 to 3.78 m/d (Acheampong and Hess, 1998).

GROUNDWATER FLOW SIMULATION

The conceptual framework model was converted to a numerical model using the Groundwater Modeling System (GMS) 5.0 (EMRL, 2004). The domain was discretized into 50 cells in the x-direction by 50 cells in the y-direction. The hydrostratigraphic units shown in Figure 2 were converted to ten model layers. All the vertical boundaries of the model were assumed to be no-flow boundaries because they either coincided with flow symmetry below the Volta Lake or were far enough from the main recharge areas of interest in the middle of the domain. The bottom boundary was also assumed to be a no-flow boundary because hydraulic conductivity had decreased significantly, relative to the values in the top model layers. The eastern, southern and southwestern boundaries of the area were modeled as constant head boundaries, using the Volta Lake water level as the constant head for the top layer. This is because the water level in the Lake must be maintained at a constant level of 50 – 60m to forestall ecological instability. The Volta Lake receives recharge from aquifers in the neighboring terrains. Recharge in the area has been known to be concentrated in the mid sections of the Afram Plains area, principally from precipitation (Minor et al., 1995; Acheampong and Hess, 1998). Annual recharge amounts to 13.4% - 16% of the annual precipitation of 1000 mm to 1500 mm. Average daily recharge was computed accordingly. Maximum recharge values were assigned to cells in the mid sections of the area in the top layer, as per the information obtained from previous work (Acheampong and Hess 1998). Other cells in the top layer had very reduced recharge.

The equation that describes the three dimensional movement of groundwater of constant density through a porous earth material under equilibrium conditions is the partial differential equation (Don et al., 2006):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{dz}\right)=0 \quad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivities in the x, y and z directions respectively which are assumed to be parallel to the axes of hydraulic conductivity (LT^{-1}), h is the potentiometric head (L). The finite difference code, MODFLOW (McDonald and Harbaugh, 1988) in the GMS package was chosen to solve Equation 1 for hydraulic heads in the area. Steady state conditions were assumed for the Afram Plains since groundwater is mainly extracted for household needs, which does not impose significant stresses on the system to lead to transient conditions in the area.

The steady state model was calibrated using water levels in thirteen wells in the area in the year 2000, and piezometric surfaces developed by Acheampong and Hess (1998). Calibration was achieved by varying the hydraulic conductivities of each of the layers within the ranges given in Figure 2. The recharge was also varied within the range of 13.4% and 16% of the annual precipitation. Recharge and hydraulic conductivity values were adjusted until a good match was obtained between observed heads in the thirteen wells and model calculated heads. The observed hydraulic heads were taken from thirteen wells in Donkorkrom, Forifori and surrounding areas.

The final hydraulic heads for the calibrated steady state model were used as initial conditions for a transient simulation to predict the response of the hydraulic system to various scenarios of extraction in the wells in the basin. The transient simulation was performed for six (6) stress periods (January 2007 – December 2013). Twenty wells were sited on the basis of the distribution of the hydraulic heads in the area. Extraction levels were calculated such that the maximum drawdown around the extraction wells would not exceed 10% of the original steady state hydraulic heads. Under transient state conditions, the MODFLOW package solves Equation 2:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (2)$$

where W and S_s are respectively the extraction rate and storage coefficient, and $\partial h/\partial t$represents the drawdown rate.

FLOW SIMULATION MODEL RESULTS

The relationship between observed and the model calculated water levels in wells (Figure 3) suggests a high degree of calibration of the model. Figure 4 shows groundwater contours from the calibrated steady state simulation model. The highest hydraulic heads in the entire model area are concentrated in the middle sections of the area. Flow directions and the general orientation and distribution of hydraulic heads in the area follow the pattern developed by Acheampong and Hess (1998) using surface elevations and static water levels in wells. In addition, the flow pattern developed in this study conforms to the general pattern of salinity (electrical conductivity) variation from recharge areas to discharge areas identified in groundwater geochemical evolution studies. According to the Chebotarev (1955) sequence, in a groundwater reservoir, electrical conductivity or salinity increases from recharge areas to discharge areas. The central parts of the Afram Plains area, which the flow simulation model identifies as the recharge areas, have low concentrations of chloride and electrical conductivity, which increase outward to the outer discharge areas. At the recharge areas, groundwater is fresher and has low concentrations of dissolved ions. As it flows to discharge areas, the dissolved ion content increases due to interaction with minerals in the aquifer matrix, increasing the electrical conductivity of the water. Figure 5 shows chloride distribution in the Afram Plains area. The pattern of distribution of this chemical parameter in the Afram Plains area is very similar and follows the pattern ascribed by Chebotarev (1955) to geochemical evolution of groundwater from recharge areas to discharge areas. The variation of electrical conductivity in the area was found to be similar to that of the chloride.

Six (6) stress periods were used for the transient simulation of groundwater flow in the optimization part of the study. The extraction levels in the wells were based on the set objectives in the optimization model and the constraints outlined in each stress period. Figures 6 and 7 show the distribution of water level drawdowns at the end of the first and last stress periods respectively. In the simulation and optimization, groundwater level drawdown was not permitted to be more than ten percent of the original level at the end of the last stress period.

OPTIMIZATION MODEL

The objective of the optimization was to maximize the profit accruing from irrigation while not sacrificing household water needs. A per capita water demand value of 36 l/c/d, which is currently used by the Community Water and Sanitation Agency of Ghana, was applied to calculate the daily water needs of the communities for 2007. In the dry season months the inhabitants of the area rely solely on groundwater extraction to meet their household needs. If irrigation is practiced, groundwater would be required to support these irrigation schemes in the dry season months. In

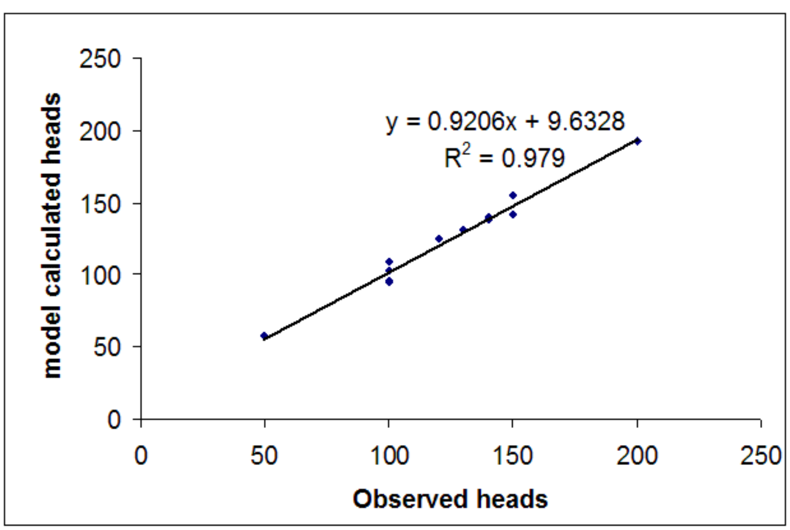

Figure 3. A plot of the model calculated heads and observed water levels in thirteen wells in the study area.

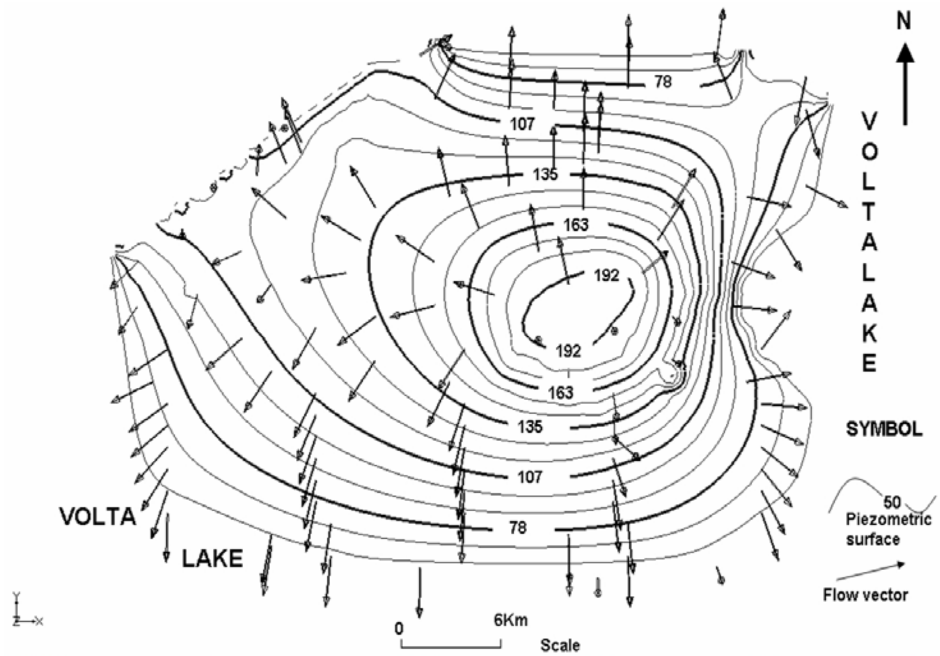

Figure 4. A piezometric surface map for the Afram Plains area based on the steady state simulation model.

the rainy season, on the other hand, rainwater supplements groundwater extraction. The per capita water demand value was increased by about 2.5% every year during each of the management periods under consideration, to account for the effects of development on water needs of the communities. Currently about 1350 ha of land is being used for irrigation in the area (ADF 2006) but the amount of irrigable land could be ten times this value. The development of available irrigable land for agriculture is based on the amount of labor the communities can afford and the economic will to invest in irrigation. In this study, a marginal 1400 ha irrigated land area was used for the 2007 irrigation. In the optimization, this figure was increased by about 30% to represent the maximum irrigable land available for 2007. In subsequent years, the maximum irrigable land available was increased by about 10% of the preceding year's value. The maize (corn) crop was used as the

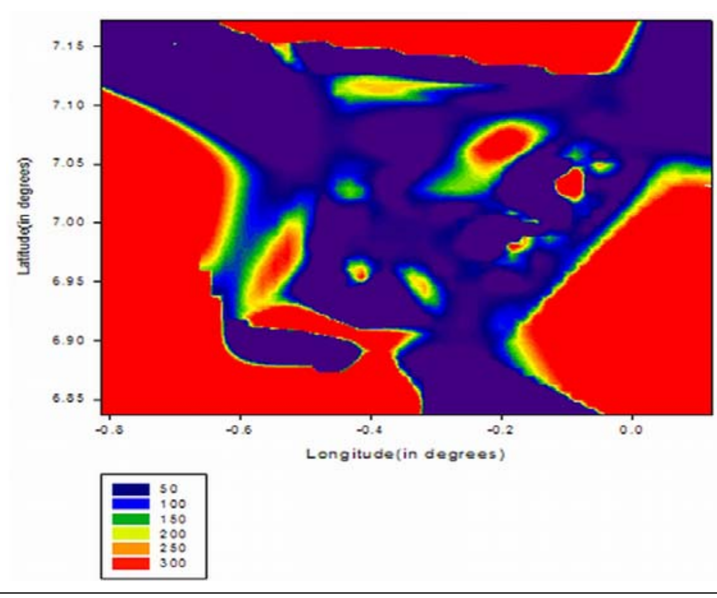

Figure 5. Contour map showing distribution of chloride (mg/l) for the Afram Plains area.

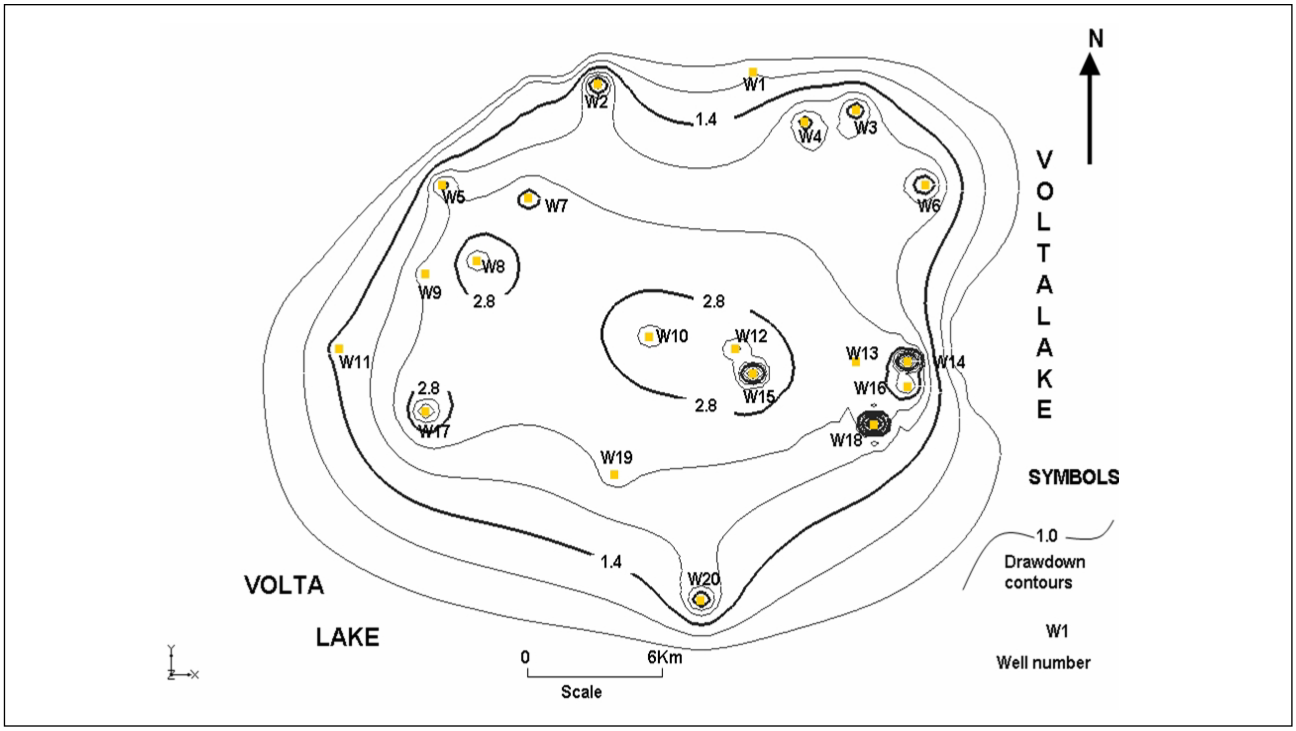

Figure 6. Groundwater drawdown at well locations after the first stress period.

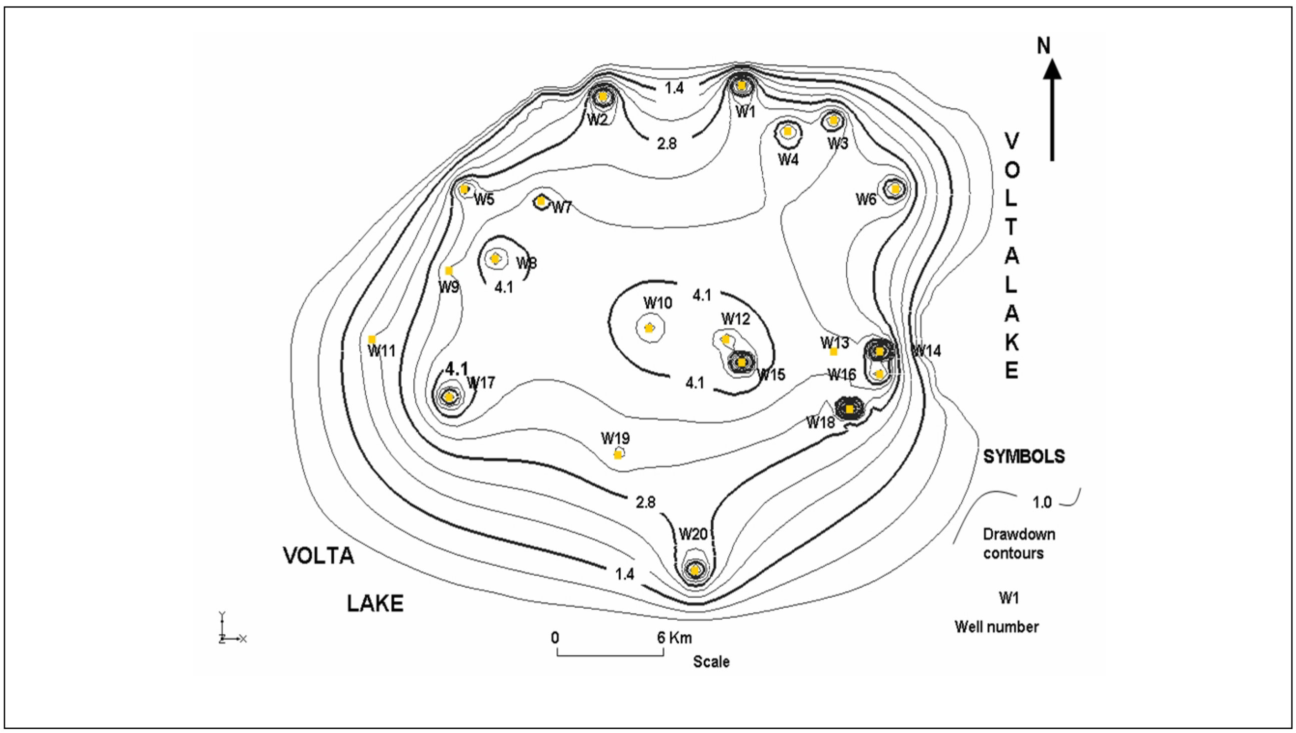

Figure 7. Groundwater level drawdowns after the last stress period.

irrigation crop for single crop irrigation. Table 1 provides information on the irrigation water requirements of the maize plant at the different stages of its development. The crop water need is calculated by multiplying the crop coefficient, k_c by the crop evapotranspiration rate, ETo. The maize (sweet maize) crop takes about 100 days to mature for harvesting (FAO 1975). The 100 days' maturation period is divided into three stages as shown in Table 1. Guidelines for predicting the irrigation requirements of crops are contained in comprehensive reports of FAO (1975). In order to determine how much water would be needed from groundwater extraction, the daily precipitation

Table 1. Irrigation water requirements of maize for all four stages of its development.

Growth stage	Kc (crop factor)	ETo
Initial Stage	0.4	4.0 – 4.3
Crop dev't stage	0.8	4.3 – 4.4
Mid season stage	1.15	4.4 – 4.5
Late season stage	0.7	4.5 – 4.2

rate is subtracted from the crop water need, which varies from one month to the other, depending on the average daily temperature. This figure was then multiplied by the area to determine the amount of water needed in volumetric terms. In the rainy season, it was assumed that all the water needs of the plant during all the stages of its development will be provided by rain water. Groundwater extraction for irrigation constitutes the largest water demand on a daily basis.

The primary objective is to maximize groundwater extraction so as to maximize the amount of profit accruing from irrigation. Even if sufficient groundwater is available from the aquifers, the availability of sufficient land and capital for irrigation will limit the amount of water that will ultimately be extracted. The constraints in the optimization included, but were not limited to, the drawdown limitation, land area available for irrigation and the economic will to invest in irrigation. Equation 3 expresses the objective function. In this formulation, Equations 4, 5 and 6 express the constraints in the optimization process.

Objective function:

$$MaxZ = \sum_{m}^{M}\sum_{i}^{P}\sum_{j}^{S} q_{m,i,j} \quad (3)$$

where q is the amount of groundwater extracted at well i during the management period m to supply a subsection j, and Z is the objective being achieved.

Demand constraint:

$$\sum_{m}^{M} Q_{demand} \le \sum_{m}^{M}\sum_{i}^{P}\sum_{j}^{S} q_{m,i,j} \quad (4)$$

where Q_{demand} is the total amount of water demanded during management period m. Q_{demand} sums the total irrigation water requirements and the household water needs of the communities.

Groundwater head drawdown constraint:

$$\sum_{m}^{M}\sum_{i}^{P} \partial h \le \partial h^{s} \quad (5)$$

where ∂h is the drawdown at well i during management period m and ∂h^{s} is the target drawdown that should not be exceeded during the entire period of the management.

Land constraint:

$$\sum_{m}^{M}\sum_{j}^{S} l \le L \quad (6)$$

where l is the land available at subsection j for irrigation during the management period m and L

is the maximum allowable irrigation potential of the entire area.

LINK BETWEEN SIMULATION AND OPTIMIZATION

The link between the simulation model and optimization model is provided by Equation 7.

$$h_{m,i,j} = h_{m-1,i,j} - \frac{\partial h}{\partial q} q_{m,i,j} \tag{7}$$

where $h_{m,i,j}$ is the water level in well *i,* supplying subsection *j* during management period *m,* $\partial h/\partial q$ is the water level drawdown per unit discharge at the location of the well, and $q_{m,i,j}$ is the maximum amount of water extracted from well *i* during management period *m* to supply subsection *j*. The term $\partial h/\partial q$ is calculated from extraction and drawdown data on well *i,* and is different for every well. Its value depends on the hydraulic properties at the location of the well and the extraction rate. When *q* amount of water is extracted, Equation 7 can be used to predict the expected drawdown that is indicated by the flow simulation model.

OPTIMIZATION SOLUTION

The optimization equations were solved from the excel solver. A nonlinear programming method was applied to reach optimal solutions that would satisfy all constraints in the model. Table 2 summarizes the results for the management (stress) periods considered. The most significant constraint in each stress period in the optimization formulation for this research was the amount of irrigable land that would be available. The maximum irrigable land available in each management period was used up while the maximum groundwater drawdown permissible was not reached. In the year 2007 for instance, the maximum irrigable land available was given as 1800 ha. In the optimization, the model used up all the land without exceeding the groundwater drawdown limitation. The amount of developable land for irrigation is tied to the economic strength of the

Table 2. Projected profit margins from maize irrigation in the Afram Plains area using groundwater.

Year	Qgw, total groundwater used for irrigation, (m^3)	Profit from irrigation, ($)	Groundwater drawdown (% of original calibrated groundwater level)	Profit/cubic meter of water used, ($/m^3)
2007	5059800.1	301000	<5%	0.059489
2008	5980821.8	800000	< 10%	0.133761
2009	7440387.8	1020000	<10%	0.13709
2010	8062222	1900000	<10%	0.235667
2011	8890011.7	2658000	<10%	0.298987
2012	9883020.6	3426000	<10%	0.346655
2013	10631993	3554000	<10%	0.334274

Table 3. Estimated expected investment in the irrigation of maize in the Afram Plains area.

Year	Land area (Ha)	Investment ($)
2007	1800	779000
2008	2000	800000
2009	2200	1620000
2010	2400	980000
2011	2600	1437000
2012	2800	1614000
2013	3000	1846000

communities and investing bodies to develop more land, as well as the expertise available to handle large irrigation fields. Table 3 summarizes the projected land use and the calculated expected investments. The amount of land that can be developed is dependent on the amount of funds available for irrigation. In this study, only marginal figures were used as per the economic level of the community and the willingness of the national government to contribute to help this enterprise.

Figure 8 illustrates the modeled annual water demands from groundwater during each of the time steps. This includes household water needs as well as projected irrigation water demands during the dry season months. Two irrigation periods were considered in each agriculture year. The first one begins in January and ends in April and the other one begins in September and ends in December. Irrigation water demands are different from one month to the next since the crop water demand differs from one developmental stage to the other. During the wet season months (May, June, July, August, September), rainfall is used for agricultural water needs. In addition, some household water needs are supplied through rainwater harvesting and surface water from perennial streams and rivers in the area. For this reason, during each of the management periods, less water is taken from groundwater to meet water needs in the rainy season months.

Currently, maize agriculture is practiced on a small scale using mainly rainfall. The inhabitants use unorthodox methods such as slash and burn and some rarely use fertilizer on their farms. Accordingly, the average annual yield of maize is 1.6 t/ha (ADF, 2006). In this research a target yield of 2.0 t/ha was used and this was increased by about 10% every year to account for improvement in technology and farming methods. The price of a bag of maize (100 Kg) varies from one location to the other in Ghana. On average it stands at about US $35. The profit accruing from irrigation was calculated by taking the difference between the total annual returns from irrigation

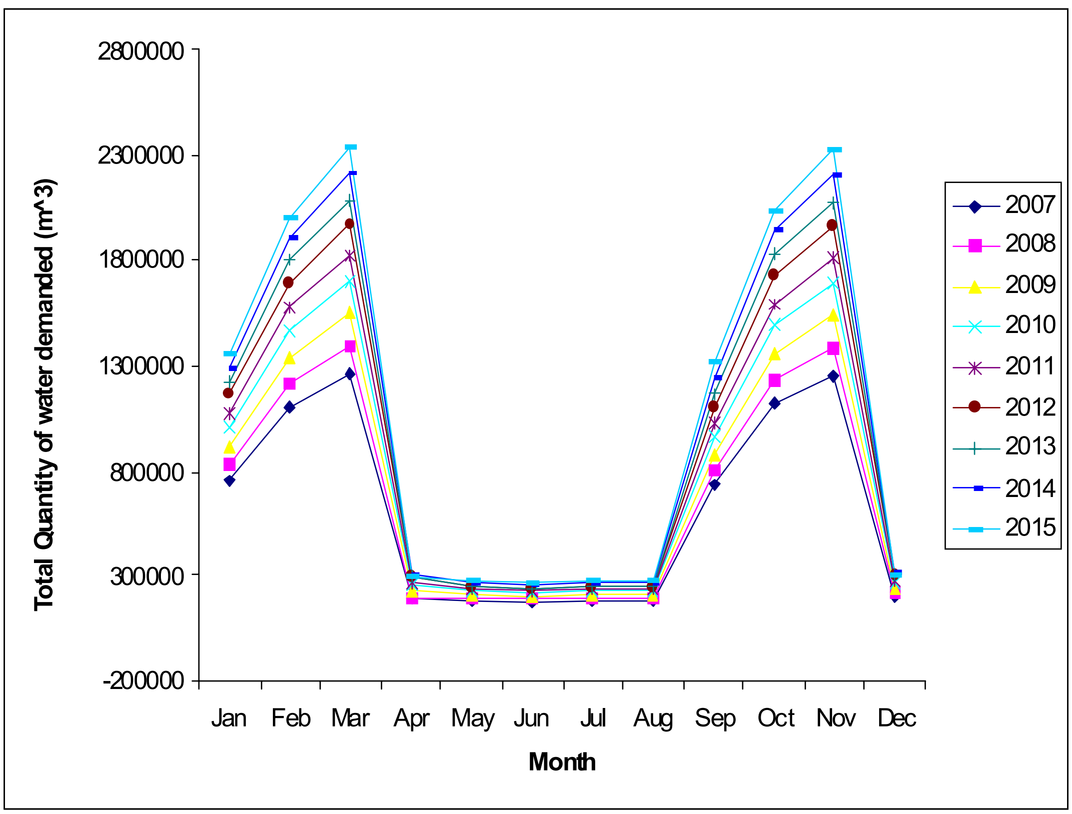

Figure 8. Projected yearly groundwater demand based on projected population increase and associated water demands in irrigation.

and the cost of well drilling and management, the cost of labor for the irrigation enterprise, and all other costs associated with irrigation of corn. Overall, the fall in groundwater level in each of the twenty wells used in this study was less than 10% after the six stress periods. This shows that groundwater in the Afram Plains area probably has tremendous potential to meet the economic needs of the population if adequately accessed for use in maize irrigation. Multiple crop irrigation may yield higher or better returns for each unit of groundwater used.

CONCLUSIONS

Groundwater flow simulation and quantity optimization models for the Afram Plains area indicate that the proper management of groundwater resources for irrigation has potential to reduce poverty and increase food security in the area and in the country as a whole. Twenty wells were sited in this research on the basis of a groundwater flow simulation model, to supply both irrigation and household water needs in the communities. This study reveals that groundwater is capable of supplying the total water needs for all sectors including maize irrigation between 2007 and 2013 with less than 10% drawdown in hydraulic heads at all the wells sited in this study. It was determined that the total acreage of land that could be developed for irrigation activities poses the most significant constraint in developing irrigation schemes in the area now. The development of land for irrigation is limited by the economic resources of the investing authority and the labor available. In addition, a substantial fraction of the drawdown in hydraulic head at the end of each growing season is expected to be recovered by recharge from irrigation water. From 2007 to 2013, profit from maize irrigation increased from US$301,000 per annum (covering two growing seasons) to over US$3.5 million at the end of 2013 as the land area for irrigation increased and better management and irrigation practices are introduced. This is capable of sustaining a vibrant economic activity in the communities and has the potential to raise the living standards of the inhabitants. It is envisaged that multiple crop irrigation involving rice and vegetables in the area has potential to increase the profit margins from irrigation using groundwater resources in the area.

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