



## Simulation of Steady State Groundwater Flow in the Lower Pra Basin, Ghana

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**ABSTRACT:** This study conceptualized the groundwater flow system; estimate the distribution of hydraulic conductivity and groundwater recharge in the lower Pra Basin in Ghana using the Groundwater Modeling System (GMS). It gives a detailed description of the site which consists of the Geographical, Hydrogeological and aquifer Characteristics of the region. The model was built by first developing a conceptual model which describes the hydrogeological framework, distribution of spatial and temporal boundary conditions, groundwater sources and sinks. This conceptual model was further converted to a numerical model for the flow simulation. Model calibration and sensitivity analysis were performed on the numerical model by comparing the observed hydraulic head with the simulated hydraulic head during calibration while model parameters were varied to obtain the most sensitive parameters in the model. The model performance was estimated to give RMSE = 3.32,  $R^2 = 0.99$  and ME = 0.07. This gives a high model performance for the study area.

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Supply of potable water for domestic, industrial and commercial purposes in Ghana, especially rural areas, has with a myriad certainty poses potential threat to groundwater resources in the country. In most communities, groundwater resource is the main source of water supply due to surface water depletion and constrains on pipe water supply from surface water sources. With an effort to increase access to potable water and further extend water supply coverage in the country, several projects both locally and internationally funded, like the Danish International Development Agency (DANIDA), Rotary Foundation etc. have favoured water supply to communities through the use of groundwater sources either through mechanized or hand pumps. However, with increasing population and anthropogenic activities, individuals and smaller organizations also engage in groundwater abstraction thus causing a silent and yet serious effect on this resource. As such it is important that groundwater resource study be conducted in areas with high borehole drilling projects to assess the potential problems and to serve as an advisory support tool for

policy makers and other stakeholders directly or indirectly involved with groundwater resource management. Fortunately, the proliferation of borehole projects has provided a fair amount of data on aquifer thickness, abstraction rate, static water level and other relevant groundwater study data which can be used to simulate groundwater flow scenarios. Groundwater flow simulation models have been recognized as an effective support tool for groundwater resource management. These models try to simplify and replicate groundwater flow condition in the subsurface by using mathematical equations to define the domain and codes. These models represent physical domain with reasonable amount of accuracy which depends on the data quality and quantity to precisely conceptualize the model domain and the numerical code used (Lutz et al., 2007). MODFLOW (Harbaugh et al., 2000) has been globally recognized to be one of the most effective simulation code used widely in simulating local and regional groundwater flow conditions. It is a finite difference numerical code which is based on the assumption that groundwater is

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of uniform density and viscosity throughout the basin. Though groundwater studies have been conducted in the country, (Lutz et al., 2007; Abd-Elhamid and Javadi, 2011; Hu, Chen and Chen, 2011; Mark et al., 2011; Yidana et al., 2014), this study focuses on the lower Pra basin in southern Ghana. The hydrological and hydrogeological information of the basin have been obtained from borehole data and literatures of related groundwater flow studies. This information provides good understanding of the basin and were used to construct a steady state flow model to simulate groundwater flow condition. The study will help to conceptualize the groundwater flow system in the region, estimate distribution of hydraulic conductivity and groundwater recharge. This research seeks to develop an understanding of the regional groundwater flow and distribution of aquifer hydraulic conductivity. It also will estimate potential groundwater recharge rate.

## MATERIALS AND METHODS

**Site Description:** This research site focuses on the lower portion of the pra basin. The lower pra basin is located between 05 00' 0" N and 060 0'0" N and 010 0'0" W and 020 0'0" W. the lower pra basin drain about 25 % of the total pra basin of approximately 23,200 km<sup>2</sup>. It encloses part of the central and western regions of Ghana. These regions are underlain by gently rolling terrain and mostly drained by rivers. The climate is tropical with a mean annual temperature of 26.1°C and characterized by two rainy seasons. It has similar characteristics as the wet semi-equatorial climatic zone of Ghana. It is quite humid, with a relative humidity of 60-95 % and annual rainfall ranging from 1500mm to 2000 mm. its mean monthly minimum and maximum temperatures are 21°C and 32°C respectively, for the cooler periods of the year which usually is from June to October (Dickson and Benneh, 2004; Tay, 2015). The description of the location of the study is shown in figure 1.

**Geology of the Lower Pra Basin:** The study area is underlain by two main granitoids namely cape coast granitoids and dixcove granitoids and accompanied with other rock types like the Birimian and Tarkwaian rock groups. These granitoids are also known as basin and belt respectively (Leube et al., 1990). Figure 2 shows the geological features of the study area.

**Granitoids:** These are mainly two kinds of granitoids found in the lower pra basin which are the cape coast granitoids and dixcove granitoids (Junner, 1940; Kesse, 1985). Using the degree of foliation, it is assumed that the cape coast granitoids intruded during regional deformation before the intrusion of the dixcove granitoids (Tay, 2015). Cape coast granitoid;

this is also known as the sedimentary basin granitoids usually occur as synorogenic foliated batholiths which are peraluminous and generally granodioritic in nature (Leube et al., 1990; Tay, 2015).

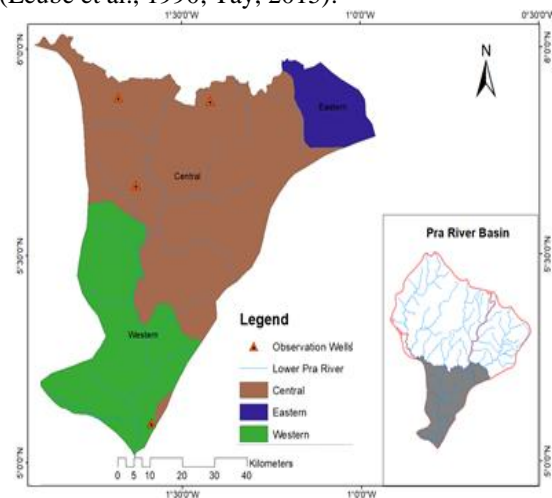


Fig 1: Map showing the Lower Pra Basin

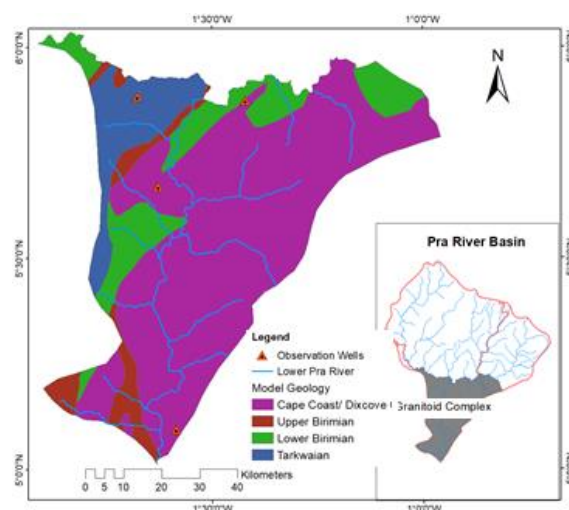


Fig 2: Geological Map of the Lower Pra Basin

The characteristic features of the basin or cape coast granitoids is foliation (Kesse, 1985; Tay, 2015). While its characteristic mafic mineral is hornblende, and biotite. The granitoid types include; tonalite and trondhjemite, granodiorite, adamellite and granite which is more frequent in the basins that the belt (Leube et al., 1990). The bulk of the granitoid fall into the peraluminous domain and therefore are considered to have been derived mainly from anatexis of continental crust (Tay, 2015).

**Dixcove Granitoids:** the granitoid is also known as the volcanic belt granitoid are hornblendes bearing and most often from late-orogenic unfoliated intrusions with metaluminous characters. The volcanic belt granitoids are generally tonalitic in nature. This

granitoid type includes quartz diorite which are rarely found in the basin, tonalite and trondhjemite, granodiorite and adamellite (Leube et al., 1990; Tay, 2015). The birimian Super Group: the term birimian was introduced to describe rocks from the river Birim valley in the Atewa-kibi range in Ghana. Principally, Southern Ghana is covered by the Paleoproterozoic birimian super group (Odei and Hayford, 2012). The prominent features of the birimian super group is the existence of five parallel volcanic belts of several hundred kilometers in length, which comprise of metabasalt, metadolerites, quartzites and greywacke (Odei and Hayford, 2012). They are separated by compressional basins containing metasedimentary rocks made up of arenaceous and argillaceous subseries comprising of metasandstone, metagraywacke, phyllites and tufecious varieties and granitoids (Odei and Hayford, 2012; Tay, 2015). Two birimian stratigraphy were established by which are the lower series comprising of slate, phyllites, greywackes, tuffs and minor lavas, together with schist and gneisses and upper series comprising of greenstones, mainly metamorphosed basic and intermediate lavas and pyroclastic rocks with some hypabyssal igneous rocks and intercalated bands of phyllite and greywacke.

The lower birimian group represent flyschoid facies account for about 55 % of the area occupied by the entire birimian super group (Junner, 1940; Tay, 2015). The lowest part of the birimian successions are phyllites and greywacke. These changes upwards to phyllites and weakly metamorphosed tuffs, greywackes and feldspathic sandstones and sequence appears to pass conformably into the upper birimian (Kesse, 1985; Tay, 2015). the series is characterized by large thickness of isoclinically folded steeply dipping, alternating slates, phyllites, greywackes and argillaceous beds with some tuffs and lava (Kesse, 1985; Tay, 2015). The upper birimian unconformable overlies the lower birimian and occupied about 20 % of the entire are of the birimian super group. This comprises of large thickness of basaltic and andesitic lavas, beds of agglomerate, tuff and taffaceous sediment (Kesse, 1985; Tay, 2015). thus, the upper birimian is principally of volcanic origin consisting mainly of metamorphosed basaltic and andesitic lavas, now hornblende-adinolite-schists, calcareous chlorite-schists and amphibolites (Kesse, 1985; Tay, 2015). The Tarkwain Rocks: these rock are concentrated largely in the southwestern part of Ghana in the tarkwa area, where they outcrop in a northeast-southwest trending belt (Tay, 2015). It is believed that the tarkwaian rocks were deposited in elongated intracratonic rift basins which are bordered by granite-greenstone belts of the birimian super group (Kesse, 1985; Tay, 2015). They consist of coarse poorly

sorted, immature sediments with low roundness (Kesse, 1985; Tay, 2015). They comprised slightly metamorphosed shallow-water sediments, mainly sandstone, shale and conglomerate, resting unconformable on and derived from the birimian (Kesse, 1985; Tay, 2015). The tarkwaian series is an erosional product from the birimian super group consists of conglomerates, sandstones, arkose, quartzite, phyllites and shale (Tay, 2015).

*Hydrogeological settings of the lower Pra basin:* The granites and gneiss associated with the birimian rocks are significantly important in the water economy of Ghana due to the fact that they underlie extensive and usually well populated areas (Dapaah-Siakwan and Gyau-Boakye, 2000; Tay, 2015). The granites and gneiss are not inherently permeable, but secondary permeability and porosity have developed owing to fractures and weathering. They are found in low lying areas where precipitation is high and weathering processes penetrate deeply along fracture systems, while where the precipitation is relatively low, the granite occurs in massive poorly jointed inselbergs which rise beyond the secondary lowland (Dapaah-Siakwan and Gyau-Boakye, 2000; Tay, 2015). Weathered granite and gneiss in some areas, form permeable groundwater reservoirs. Other location for groundwater storage includes major fault zones. The birimian phyllite, schist, slate, greywacke, tuff and lava are generally strongly foliated and fractured as such water may percolate through the fracture where they crop out or are near to the surface (Dapaah-Siakwan and Gyau-Boakye, 2000; Tay, 2015). The tarkwaian rocks consist of slightly metamorphosed, shallow-water, sedimentary strata, mainly sandstone, quartzite, shale and conglomerate, resting unconformably on and derived from rocks of the birimian super group (Dapaah-Siakwan and Gyau-Boakye, 2000; Tay, 2015).

*Aquifer Characteristics in the Lower Pra Basin:* Tay, (2015) studied borehole in the lower pra basin and revealed that borehole yield in the lower pra basin is generally low, ranging from 0.4 m<sup>3</sup>/hr to 51.7 m<sup>3</sup>/hr with a mean of 4.55 m<sup>3</sup>/hr and an associated depth range of 22-96 m with a mean of 44.42 m. Tay, (2015) also argued that since groundwater occurrence is related to regolith/fissure development, then the deeper the well and thicker the overburden or regolith it penetrates as such a possibility of higher chances of intercepting several fissures in the sap rock underneath the regolith and the higher the probability of obtaining higher yield. This research supports this claim as seen in figure 2. A total of 117 boreholes were analyzed in this research. Nine geological formation were penetrated by these wells with schist being the most

observed materials followed by granites/gneiss with sandstone being the least penetrated formation. It is seen that schists and granites/gneiss have the highest yield with an average value of 91.03 l/m and 89.12 l/m respectively and a corresponding average depth of 47.36 m and 39.87 m, while granite has the lowest yield value of 3.33 l/m, with a depth of 24.3m. This confirms that groundwater is stored in fractures or faults and the possibility to intersect water storage or increase borehole yield increases with depth. With analysis of the static water level a fair understanding of the distribution of recharge zones and hydraulic conductivity can be obtained.

*Methodology:* Relevant groundwater data such as monitoring data from water research institute (WRI), borehole data from Community water and sanitation (CWSA), physical boundaries, geology Ghana Geological Survey, and surface hydrology from Hydrological Services Department were obtained for this research. These data were processed into acceptable formats for the development of the conceptual model of the basin. This conceptual framework gave a simplified model of the site which was converted to a numerical model for steady state simulation.

*Conceptual Model Development:* Model conceptualization was done using the ArcGIS software to process the model data into acceptable format and then imported with the map tool in the Groundwater Modeling System (GMS) version 10.3. The model domain was first divided into zones for defining hydraulic conductivity and recharge based on the geological map of the basin. The domain sides were assigned the no flow boundaries which the model was assigned a specified head boundary at the northern part of the domain. The specified head boundary defines the river basin and offin which were used to define the model upper boundaries. The bottom of the basin is assigned a no flow boundary. The thickness of the model varies from one portion to another base on the thickness of the unit penetrated by the boreholes. The lower pra watershed map was used as a base map for defining the model extent. The model sources and sinks were defined using the well, river, specific head boundary packages. The well locations, flow rate and refinement were assigned to each well, while from the knowledge of the river, the river stage and bottom elevations were assigned with the river package. The model recharge was assigned to zones with the knowledge of groundwater recharge estimated from the previous chapter in this research. Hydraulic conductivity was assigned to seven zones using the hydraulic conductivity package. The application of zones for both recharge and hydraulic conductivity

was to produce a site representative model and also to speed up the calibration process. The static water level was subtracted from the top elevation of each boreholes obtained from a Digital Elevation Model map of the basin. The depth of each borehole was subtracted from the top elevation to get the model bottom. Four observation wells were used to obtain initial hydraulic conductivity to initialize the model calibration. The coverages were converted to a grid cells in the GMS after the completion of the model conceptualization.

*Numerical Model Development:* The conceptual model was converted into a numerical model to simulate groundwater flow in the basin. The numerical simulation was done with the MODFLOW (Harbaugh, 2005), incorporated in the Groundwater Modeling System (GMS). A uniform rectangular grid system was automatically generated over the model boundaries defined by the conceptual domain. The grid dimension use was 116.8 km by 124.9 km. The top and bottom elevation of the grid system was interpolated on to the borehole data imported during the conceptualization as the model top and bottom elevation used to define the thickness of the model layer. The initial head was automatically generated from the static water level mapped as a scatter plots. The layer Property Flow (LPF) and the Pre-Conditioned Conjugate Gradient 2 (PCG2) packages were used as the flow and solver packages for the simulation of a steady state flow condition.

*Model Calibration:* The model calibration for the lower Pra basin was achieved by comparing the computed head with the measured head at a minimum head difference. Since the hydraulic conductivity is the least known parameter in the basin, the inverse modeling calibration method was used with the PEST in GMS. The estimated basin recharge obtained in this research was used as an initial recharge value for the model calibration. In addition to varying the recharge and hydraulic conductivity using the automatic PEST and pilot point method for calibration, the river stage and conductance were also adjusted within acceptable limits in order to achieve a good model. A total of thirty boreholes were used to calibrate the model with a calibration target of 5m for all of the boreholes.

*Sensitivity Analysis:* In order to estimate the model parameter(s) that has most significant effect on the model output by adjusting its value, a model sensitivity analysis was conducted. The two most sensitive parameters are the recharge and hydraulic conductivity which were constantly been adjusted during the model calibration. These adjustments were done with the pilot point automatic PEST method until

the observed and computed groundwater head difference is reduce and model efficiency increased.

*Model Performance Evaluation:* The model efficiency was evaluated using the calibration target and assessment of error qualifying method which are the mean error, mean absolute error and root mean squared error as presented in equations 1, 2 and 3. Also, a scatter plot of computed head against observed was done to show calibration fit.

$$RMSR = \left[ \frac{1}{n} \sum_{i=1}^n (h_c - h_o)_i^2 \right]^{0.5} \quad 1$$

The mean error looks at the mean difference between the observed head and the computed head

$$ME = \frac{1}{n} \sum_{i=1}^n (h_c - h_o)_i \quad 2$$

The mean absolute error (MAE) is the mean of the absolute value of the difference in observed heads and computed heads

$$MAE = \frac{1}{n} \sum_{i=1}^n |(h_c - h_o)_i| \quad 3$$

Where; n is the number of observations, hc is the computed head and ho is the observed head

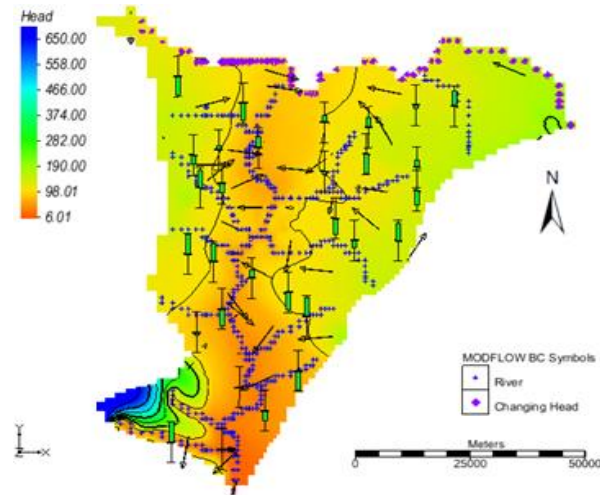
**Table 1:** Model Calibration Performance Results for the Calibration Targets

S/N	Objective Functions	Model Performance
1	RMSE	3.32
2	ME	0.07
3	MAE	2.93
4	R <sup>2</sup>	0.99

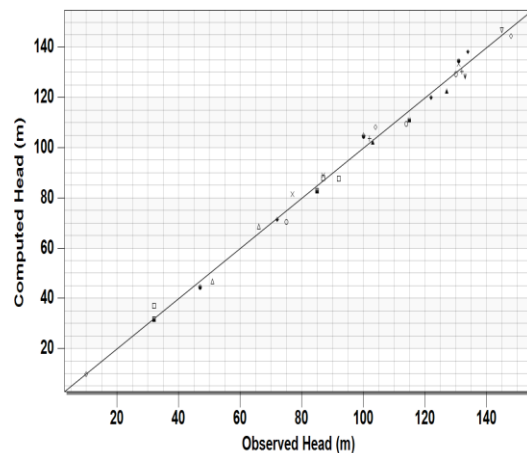
### RESULT AND DISCUSSION

The calibrated model is presented in Figure 3. While the corresponding model performance efficiency checks using the comparison of computed head against observed and the residual drawdowns within the calibration targets are shown in Figure 4 and Figure 5 respectively. Figure 4 shows a good fit between the computed head and the observed head over the basin. While the residual drawdown as shown in Figure 5 gives the deviation between the computed head from their corresponding observed head values. This indicates that the deviations are within the set calibration target. it shows the distribution of piezometric levels in the domain boundary and of the model and as well as the groundwater flow direction and velocity vector in the area. The distribution of groundwater heads can be attributed to the fact that groundwater flow through fractures and faults in the geological formation in the basin. The flow pattern is seen to move from region of high head to a lower flow head which follows the Darcy flow model. The highest

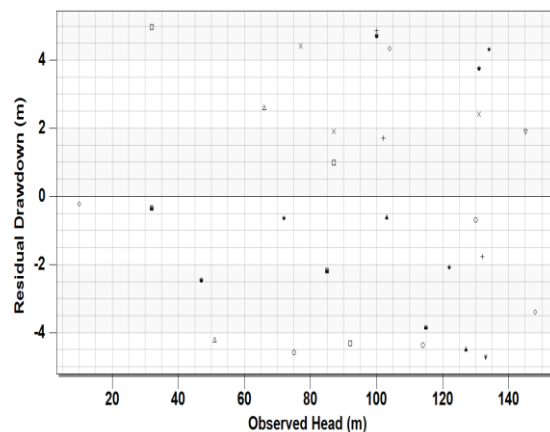
groundwater head is seen to be at the south-western direction of the model domain this may be as a result of inadequate calibration point of proper distribution of calibration points in the region of the model.



**Fig 3:** Groundwater flow Calibration Result for Lower Pra Basin

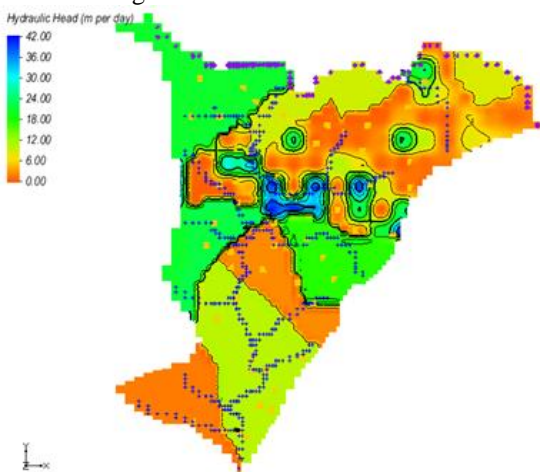


**Fig 4:** Comparison between Observed and Simulated Flow Head for calibration



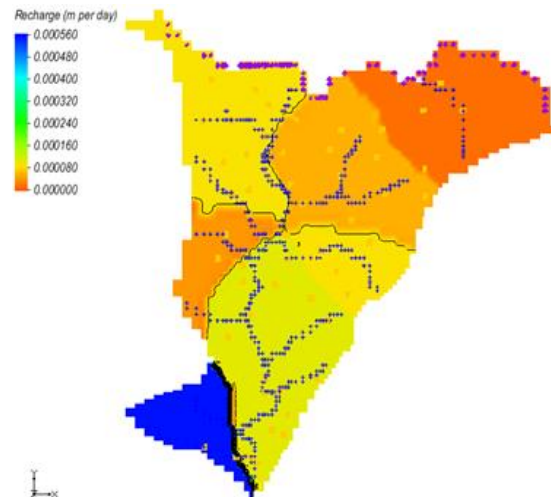
**Fig 5:** Residual Draw Down Versus Observed Head within Calibration Target.

This is in accordance with the general hydrogeological knowledge that the surface topography is a subdued replica of the groundwater table elevation (Mark et al., 2011). The flow pattern is seen to flow towards the river network at the center of the model and further south ward. This flow pattern shows a lower velocity vector on the eastern part of the model compared to the flow pattern on the western part of the model domain. This flow pattern corresponds to the geological unit underlying the model, as the Dahomeyan rock is composed of granite and gnessis which store water in fractures and faults that may have risen from series of post genetic deformation stresses the rock may have been subjected t over the years. The spatial distribution of the hydraulic conductivity in the Lower Pra Basin is shown in figure 6.



**Fig 6:** Spatial Distribution of Hydraulic Conductivity in the Lower Pra Basin.

The distribution of hydraulic conductivity is presented in Figure 6. It shows a distribution pattern relating to the geological formation in the basin. This distribution indicates a low hydraulic conductivity in the Dahomeyan formation, while the birimian formation holds a high hydraulic conductivity. The model estimated hydraulic conductivity ranges from 0.13 m/day to 40 m/day which correspond to other researches that have been conducted in similar formation and regions in Ghana (Mark et al., 2011; Yidana, 2011; Yidana et al., 2014). Figure 7 shows spatial distribution of groundwater recharge for the Lower Pra Basin. The spatial distribution of groundwater recharge as shown in figure 7, estimated by the model, gave a recharge range of 0.01032 mm/day to 0.551 mm/day. This is to be about 3.77 mm/year or 0.25 % to an upper value of about 201.12 mm/year or 13.41 % of the annual rainfall in the basin. This recharge range is in accordance with recharge estimated in the previous chapter of this research and related literatures (Darko and Krasny, 2003; Obuobie, 2008; WRC, 2012).



**Fig 7:** Spatial Distribution of Groundwater Recharge for the Lower Pra Basin.

The distribution of groundwater recharge is seen to follow the distribution of hydraulic conductivities in the basin with the highest hydraulic conductivity found in the center on the model on the granitoid formation followed by those of the birimian super group. The lowest hydraulic conductivity is distributed over the model. This observation correspond to the fact that hydraulic conductivities in the basin are based on secondary structural entities created in the wake of fracturing and weathering of the rock whose primary permeability are very much reduced (Yidana et al., 2014). In order to characterize the distribution of hydraulic conductivities a fracture controlled aquifer system, two approaches were recommended which are the continuum and discrete approach (Yidana et al., 2014). The continuum approach can be adopted for this research since it does not consider the location of the individual fractures in the system but considers the entire rock mass as an equivalent of a porous medium with homogenous hydraulic conductivities. Though the limitation in this approach which is the fact that the permeability of the rock mass is higher in locations with high degree of fracture density. This supports the fact in this study with the distribution of the highest hydraulic conductivities are within the Dahomeyan rock system and suggest areas where fracture and degree of weathering are high enough to impose high permeability on the rocks which will enhance the hydrogeological properties and knowledge of the basin.

**Conclusion:** It is seen that the hydraulic conductivity of the region is affected by the geologic formation of the region which defines the water storing capacity of the geological formation of the study area. The distribution of hydraulic conductivity also shows a corresponding effect on the groundwater recharge.

This indicates that the model was able to simulate the groundwater steady state condition of the region. The model performance indicators gave a good model fit as such the model parameters and results are best suited for the study.

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