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Assessing the importance of geo-hydrological data acquisition in the development of sustainable water resources framework in Nigeria

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Abstract

Lack of access to safe drinking water and basic sanitation facilities suggests that water resources management is not at its optimal level in Nigeria. Also, literature indicates transformation in the approaches of water resources management from the more traditionally approach which rely largely on physical solutions, to a new concept that blends resource development with ecological concerns. However, the trade-offs in the transformation requires more detailed geo-hydrological data in its implementation. Hence, the aim of this paper is to demonstrate the importance of the need for acquisition of continuous and consistent geo-hydrological data for the development of sustainable framework for water resources in Nigeria. The methodology adopted is to compare the development of two MODFLOW based groundwater flow model scenarios for Lagos metropolis, Nigeria, and Birmingham, UK; evaluate the sufficiency of the required input data, and assessed the emanating implications for the model outputs. The results showed that Lagos metropolis model was plagued with dearth of the required geo-hydrological data and this greatly limited the reliability and prediction capability of the model. Recommendations include wide availability of quality assured, retrievable and accessible data, effective coordination and interactions between the various relevant government agencies, and Water Resources Bill that mandates professionals to submit all data acquire from government and privately funded projects and researches. Others include pro-active engagement between professional bodies and government agencies, as well as implementation and enforcement of the existing regulations.

KEYWORDS: Groundwater models, water resources, sustainability, ecological preservation

1 Introduction

Historically, availability of water resources has played major role in ancient civilization, and has underpinned the rate of growth of socio-economic development as well as the resulting quality of life (Priscoli, 1998; De Feo *et al., 2011;* Flores *et al., 2011*). However, in the contemporary Nigeria, water resources management is not at its optimal level. According to the WHO/UNICEF Joint Monitoring Programme (WHO/UNICEF, 2012), approximately 109 million Nigerians lack access to basic sanitation facilities, and 63 million are not within the reach of improved source of safe drinking water. Diarrhoea in children constitutes the second main cause of infant mortality (after malaria), and the third main cause of under-five mortality in Nigeria. Therefore, effective and efficient water resources management will play a significant role in the development of sustainable framework for a healthy society.

Literature (Melloul and Collin 2003; McClain, 2012) indicates that the approaches to management of water resources is widely varied, and are also being transformed from the more traditionally approach which rely largely on physical solutions to a new concept that blends resource development with ecological concerns. The traditional water resources management approach which solely relies on sourcing of new reserves to mitigate increasing water demands caused by population increase and technological advancement (among others) is facing increasing opposition and claims of derogation (Oladeji *et al.,* 2012; Asiwaju-Bello and Oladeji, 2001). Conversely, the new approach incorporates environmental restoration and ecological design programs into the water resources management policy, and thereby it is considered to provide more efficient use of the resource.

However, the trade-offs in the transformation of the management options is that the newer approach requires more detailed geo-hydrological data in the understanding of the environment. These requirements include the need for detailed characterization of the spatial and temporal variability of the resource, exploring efficiency improvement in water use, implementing options for managing demands, as well as resource re-allocation to ensure sustainable use. In order to achieve these requirements, a tool with simulating and predictive capabilities for characterizing and understanding the environmental systems, its behavior, as well as for assessing ecological responses to the management of the resource is required.

A major tool in the assessment of water resources management scenarios is a model, due to its capability to enable decision makers to compare alternative actions and take management decisions to achieve efficiency goals without violating specified constraints. However, the accuracy of any solution produced by a model is directly dependent on the input of the geo-hydrologic data and other boundary conditions that characterize the domain and the problem being solved. The reliability of the solution increases with increasing model discretization, but the detail and amount of the input data requirements also proportionally increases greatly. Hence, the aim of this paper is to demonstrate the importance of the need for acquisition of continuous and consistent geo-hydrological data for the development of sustainable framework for water resources in Nigeria.

2 Methodology

The approach adopted in this paper is to compare the developments of two groundwater flow model scenarios developed for Lagos metropolis, Nigeria, and Birmingham, UK. Groundwater model is used to demonstrate the concept presented in this paper because models integrates large amount of geo-hydrologic data that are required in most water resources development projects. In addition, calibrated models are used to evaluate management policies prior to their actual field implementation. The numerical code adopted for this work is MODFLOW 2000 (Harbaugh *et al.* 2000). The preparation of the input data and the presentation of the modelling output were facilitated by ArcGIS 9.1 and GRASS GIS 5.7 software, and complimented by customized FORTRAN utility programs, Microsoft Excel and MS WordPad.

2.1 Birmingham model

The model area covers approximately 221 km^2, and presented in Figure 1. Powell *et al.* 2000 showed that the area is underlain by Sherwood sandstone Group overlying the Westphalian Formations. These constitute the aquifer and impervious horizons, respectively. The constituent geological strata for the Sherwood Group are Kidderminster, Wildmoor, and Bromsgrove sandstone Formations. A major geological structure is the Birmingham Fault that juxtaposes the Triassic mudstone to the east against the Sherwood (Triassic) sandstone to the west (Figure 1). The flow model was setup and calibrated under transient conditions covering 20 years from January 1970 to December 1989.

The average length of the stress period was 90 days, making a total number of 80 stress periods. Each stress period was in turn divided into nine time steps, corresponding to approximately 10-day time step. The total number of time step was 720. In order to validate the model output and for future predictions, the model was further setup to run for a period of 30 years from March 1985 to February 2015, with the simulation length consisting of 120 stress periods. The length of each stress period varies between 90 and 91 days. The spatial discretization of the model was setup using 760 rows and 600 columns, with cell dimensions (Δy and Δx) of 25 x 25 m, making a total of 456,000 nodes. The model was set up as three layers representing the constituent aquifer horizons namely, Bromsgrove, Wildmoor and Kidderminster Formations, corresponding to model layer 1, 2 and 3, respectively.

Conceptually, the flows across the eastern and the southern boundaries of the aquifer geometry were restricted by imposing low hydraulic conductivity values along the fault paths. The presence of the Westphalian Formations along the western parts of the area supports the choice of the defined no-flow cells along the western boundary of the model. The northern boundary of the model was also defined as no flow boundary because of the presence of a groundwater divide. The initial conditions of the groundwater heads, aquifer properties and abstraction rates were obtained from the measured spatial and temporal field data. Distributed recharge values were computed for each model cell using series of spreadsheet calculations based Food and Agricultural Organisation methodology (FAO, 1998). The model was calibrated by minimizing the residuals between the observed and the simulated groundwater head data, coupled with graphical analysis of the model fit and constrained by the conceptual understanding of the study area. The convergence criterion for the hydraulic head observations was set to 0.01 m. The major geo-hydrological input data requirements in this model include geology for aiding the conceptual understanding and boundary conditions (Figure 1) and groundwater levels for head transient calibration (Figure 2). Data used for calculation of distributed recharge flux are precipitation (01 January 1961 – 10 January 2010) and evapo-transpiration (31 December 1969 – 29 November 2009), as well as soils, landuse, and vegetation cover types. The final calculated recharge flux for each stress period of the model simulation is presented in Figure 3. Simulation of external stress was based on records of groundwater abstractions (Figure 4) and aquifer characterization was based on field test data.

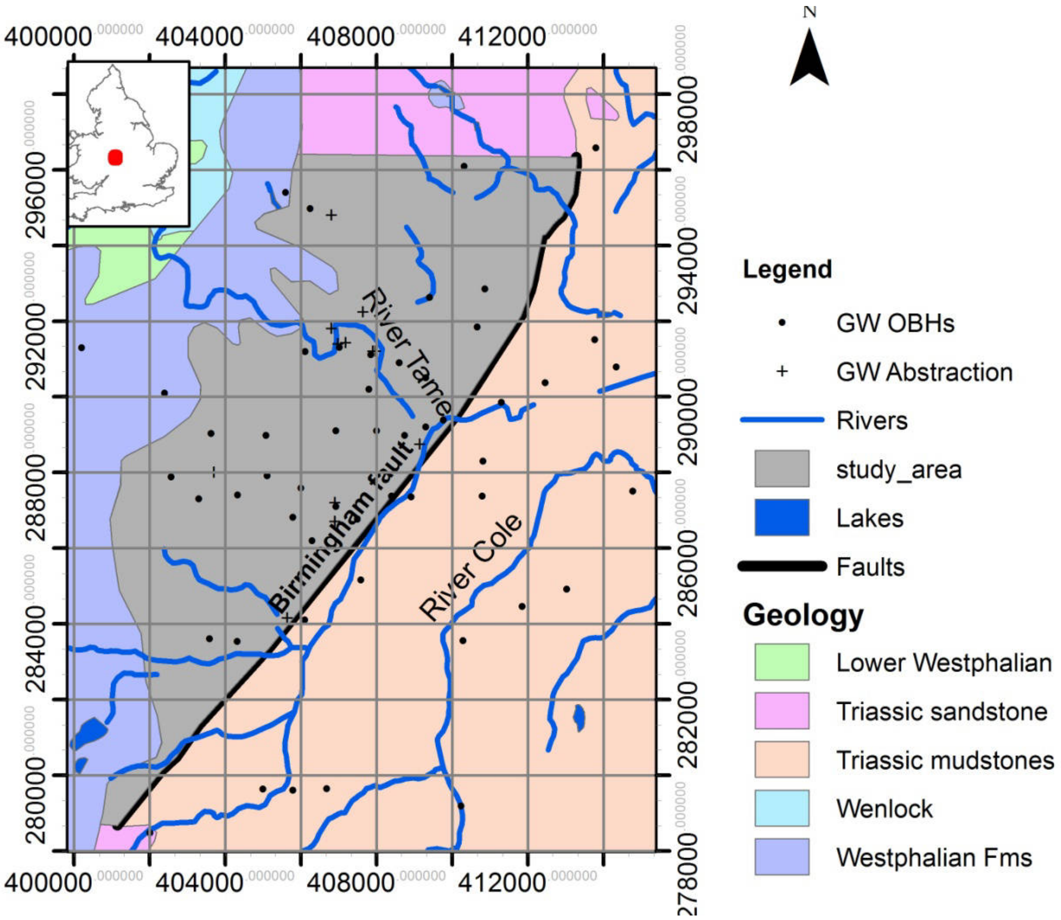

Figure 1. Birmingham model area

2.2 Lagos Metropolis model

The Lagos metropolis groundwater flow model area covering approximately 3672 km^2 is presented in Figure 5.

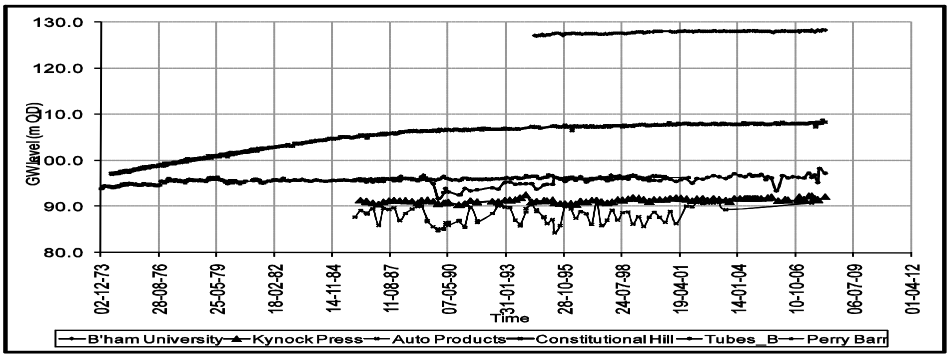

Figure 2: Groundwater monitoring data for model calibration

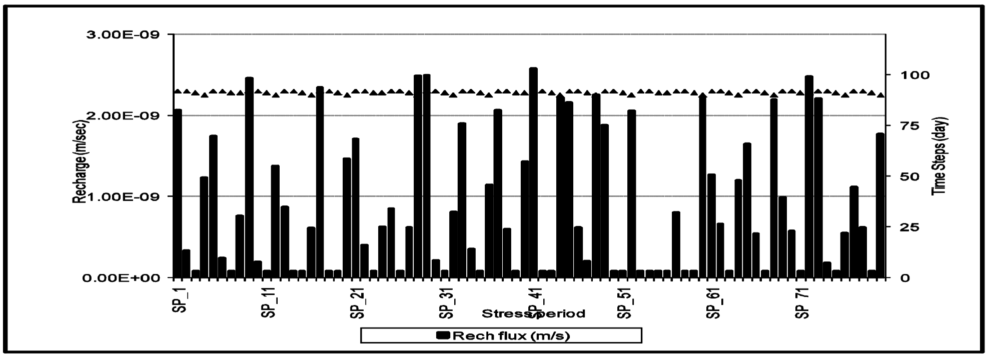

Figure 3: Groundwater recharge flux for stress periods

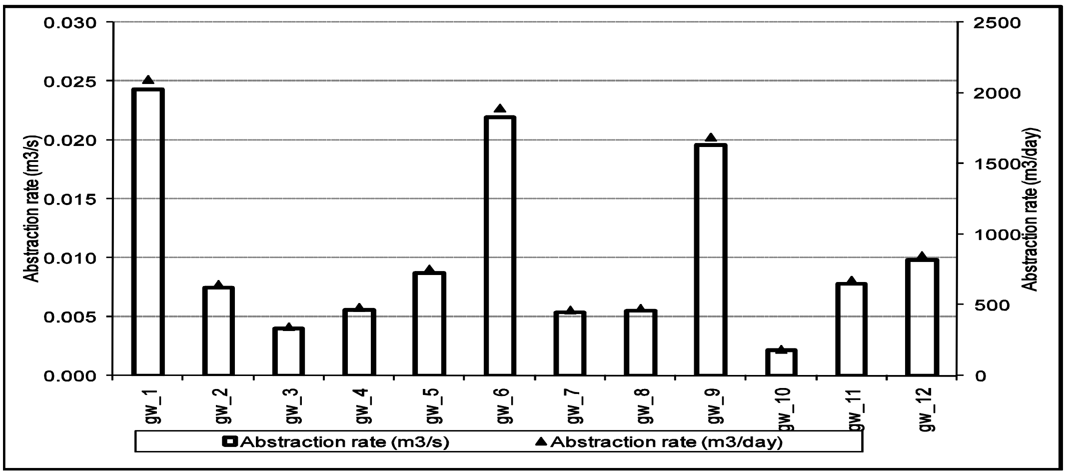

Figure 4: Groundwater abstraction data

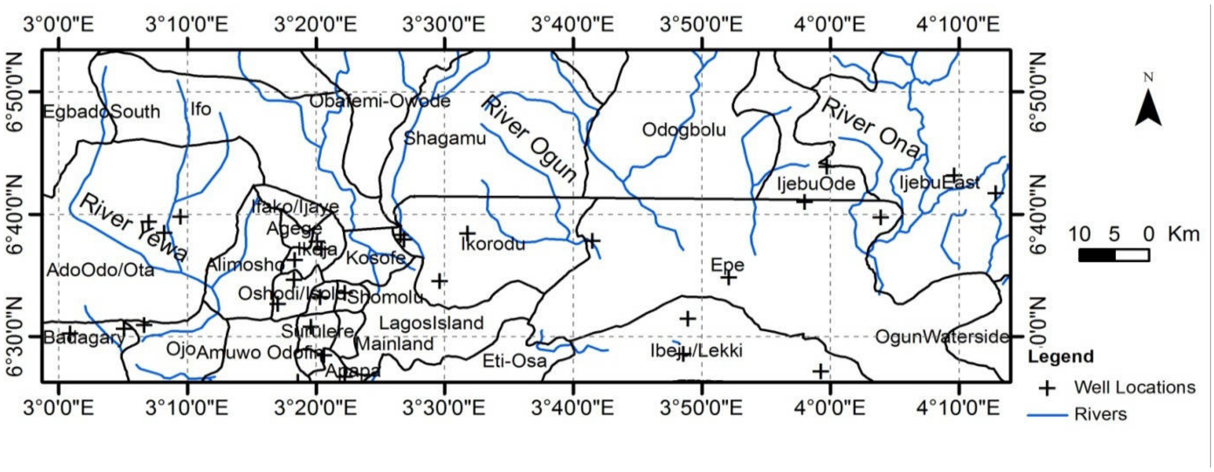

Figure 5: Lagos metropolis model area

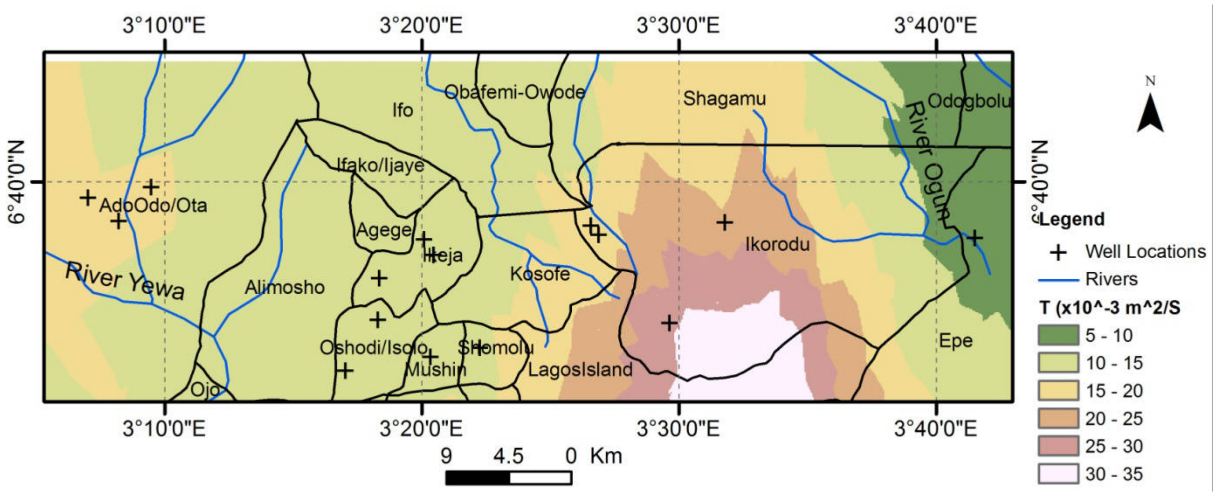

Figure 6: Transmissivity coefficient distribution of Lagos model area

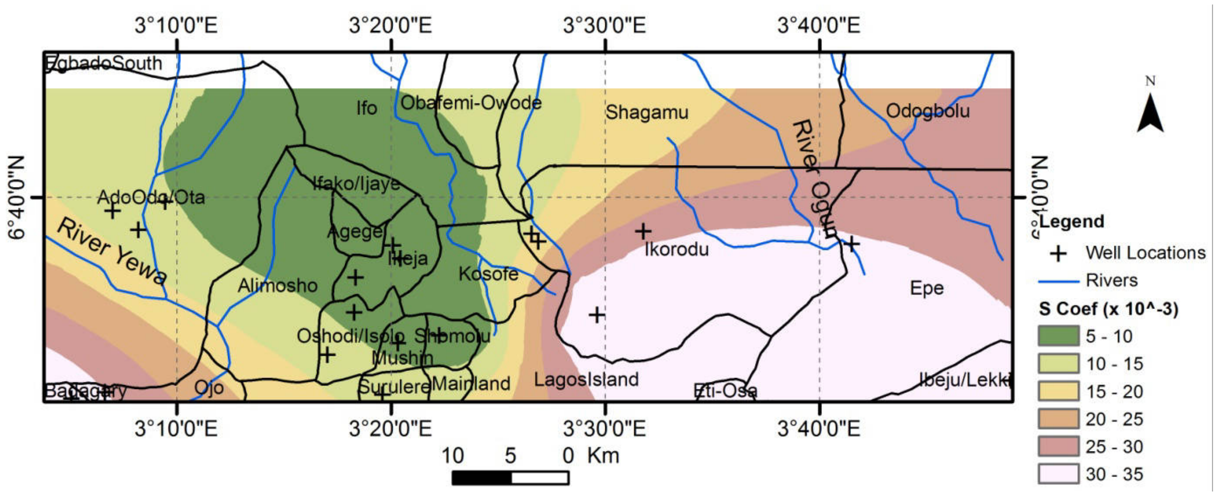

Figure 7: Storage coefficient distribution of Lagos model area

Available model data include borehole locations and logs, pumping test data and static water levels acquired from drilling contractors and well owners. Hydrostratigraphic model was developed by delineation of subsurface geologic horizons into aquifers and aquicludes. Transmissivity and Storage coefficients of the pumped aquifers were estimated from the analysis of the pumping tests data, using Aquiferwin 32 software. The study area was discretized into 403 nodes. The problem of dearth of data required extensive extrapolation and interpolation of the available data in order to fill the data gap. The spatial distribution of the interpolated Transmissivity and Storage coefficient values are presented in Figures 6 and 7, respectively. The input data for the two models are summarized and presented in Table 1.

3 Results and Discussion

The available required input data for each scenario were considered, evaluated their sufficiency, and emanating implications for the model outputs were assessed.

3.1 Birmingham model

The plot of the simulated groundwater head against the observed values is presented in Figure 8.

Table 1: Summary of model input data

S/N	Parameter	Birmingham Model	Lagos Model
1	Elevations (m OD)	Distributed values (Shapefiles)	Interpolated Values
2	Boundary Conditions	No flow conditions (†FBI)	Assumed no flow conditions
3	Geometry	3 Layer model; 1: Bromsgrove sst Fm; 2: Wildmoor sst; 3: Kidderminster Fm	1 Layer model (though geology shows 3 layers)
4	Spatial discretization	No of rows: 760; No of columns: 600; $\Delta x=25$ m; $\Delta y=25$ m	No of rows: 13; No of columns: 31; $\Delta x=4$ km; $\Delta y=2.5$ km
5	No of abstraction BHs	12, with time varied abstraction rates (†FBI)	9, with assumed constant flow rate
6	Observation boreholes	31 boreholes (see Figure 1 for locations).	None with temporal groundwater level data
7	River bed cond. (m/s)	Initial:1.296 x 10^{-5}; Final: 9.2593 x 10^{-6} (†FBI)	Assumed none required
8	Recharge rate (m/s)	Distributed values (modelled) (†FBI)	Gross Estimation
9	Horizontal hydraulic conductivity (m/s)	Bromsgrove Fm =5.787x10^{-6}; Wildmoor sst Fm =2.315x10^{-5}; Kidderminster Fm =3.472x10^{-5} (†FBI)	1.08x10^{-5} – 4.68x10^{-4}
10	Vertical hydraulic conductivity (m/s)	Bromsgrove Fm =5.787x10^{-8}; Wildmoor sst Fm =1.157x10^{-7}; Kidderminster Fm =5.787x10^{-8} (†FBI)	Not computed
11	Specific yield	Bromsgrove Fm = 0.12; Wildmoor sst Fm = 0.10; Kidderminster Fm = 0.12 (†FBI)	Not required
12	Specific storage	Bromsgrove =1x10^{-4}; Wildmoor Fm =5x10^{-4}; Kidderminster = 1x10^{-4} (†FBI)	1.90x10^{-4} – 2.87x10^{-3}
13	$K_{\text{Birmingham Fault}}$ (m/s)	Initial:1.0 x $10^{-12;}$ (†FBI); Final: 1.0 x 10^{-9}	Not required

†FBI: Field Based Information

Also, the observed groundwater head values against the corresponding residuals are presented in Figure 9. The respective final horizontal hydraulic conductivity values for the Bromsgrove, Wildmoor and Kidderminster sandstone Formations were 5.787x10^{-6}, 2.315x10^{-5}, and 3.472x10^{-5} m/s. The corresponding values for vertical hydraulic conductivity were 5.787x10^{-8}, 1.157x10^{-7}, and 5.787x10^{-8} m/s, respectively. The final horizontal conductivity values are within the same ranges compared to the values obtained by Allen *et al.* (1997) and Jones *et al.* (2000) from field test data, for the respective aquifer horizons, as well as to those values obtained by Knipe *et al.* (1993).

Furthermore, the final values for the specific yield were 0.12, 0.10 and 0.12, and for the specific storage were 1x10^{-4}, 5x10^{-4}, and 1x10^{-4}, respectively for Bromsgrove, Wildmoor and Kiderminster Formations. The value reported by Allen *et al.* (1997) for the specific yield of the undivided Sherwood sandstone Group is 0.12. Knipe *et al.* (1993) and Rushton and Salmon (1993) respectively reported specific yield value of 0.15, and 0.10 for the Bromsgrove sandstone Formation. The values obtained in this work are similar to these referenced values. Also, the recharge value of 112 mm/yr obtained in this work is comparable to 115 mm/yr obtained by Knipe *et al.*, (1993). Buss *et al.*, (2008) obtained similar value of 121 mm/yr for year 1996 and relatively higher value of 131 mm/yr for year 2000. Generally, a sufficient degree of match was obtained between the measured head observations and the simulated equivalents (Figure 8). The simulated data are within ± 2 m of the observed data. The percentage numerical error associated with the volumetric balance is less than 0.1 % throughout the duration of the simulation. The final refined value for the hydraulic conductance along the Birmingham fault was 1.0 x 10^{-9} m/s. This value is less than the hydraulic conductivity values obtained for the sandstone layers (5.787x10^{-6} - 3.472x10^{-5} m/s), and indicates that the fault acts as a barrier to groundwater flow, and not conduits. This conclusion agrees with the earlier work of Knipe *et al.* (1993), who modelled the faults as reduced thickness to achieve the required lower transmissivity value along the fault path. The spatial distribution of the calibrated and predicted groundwater head obtained for layer 3, and the associated drawdown values are presented in Figure 10.

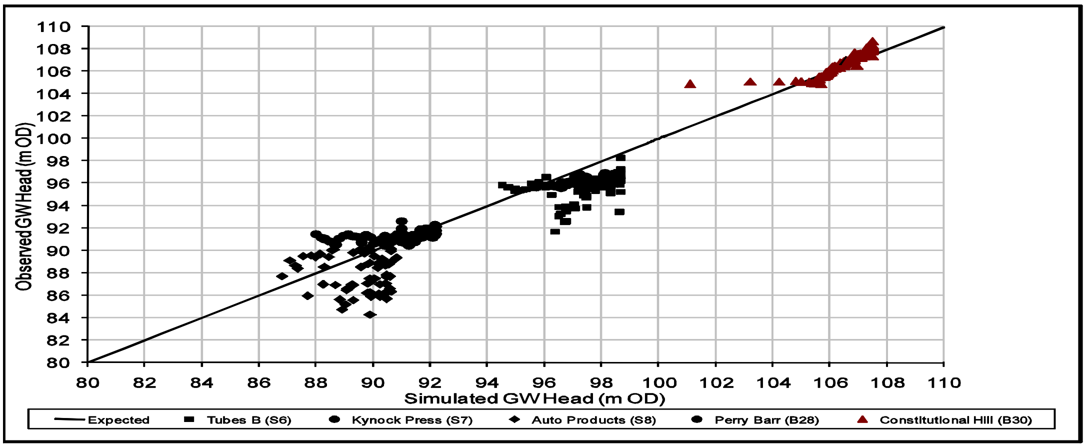

Figure 8: Field and simulated groundwater heads

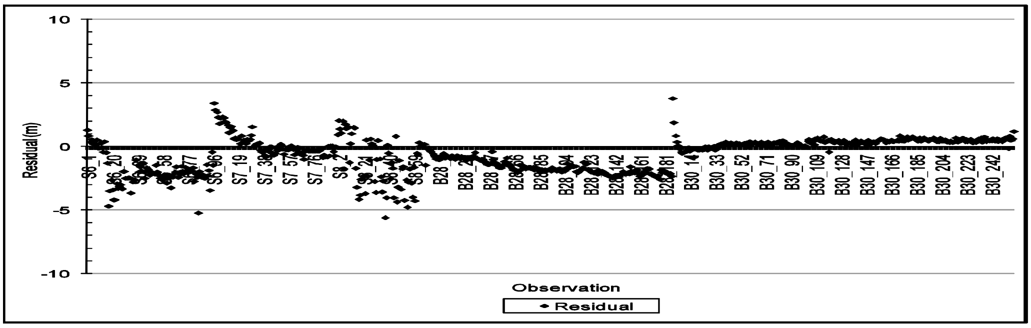

Figure 9: Residual values simulated at observation locations

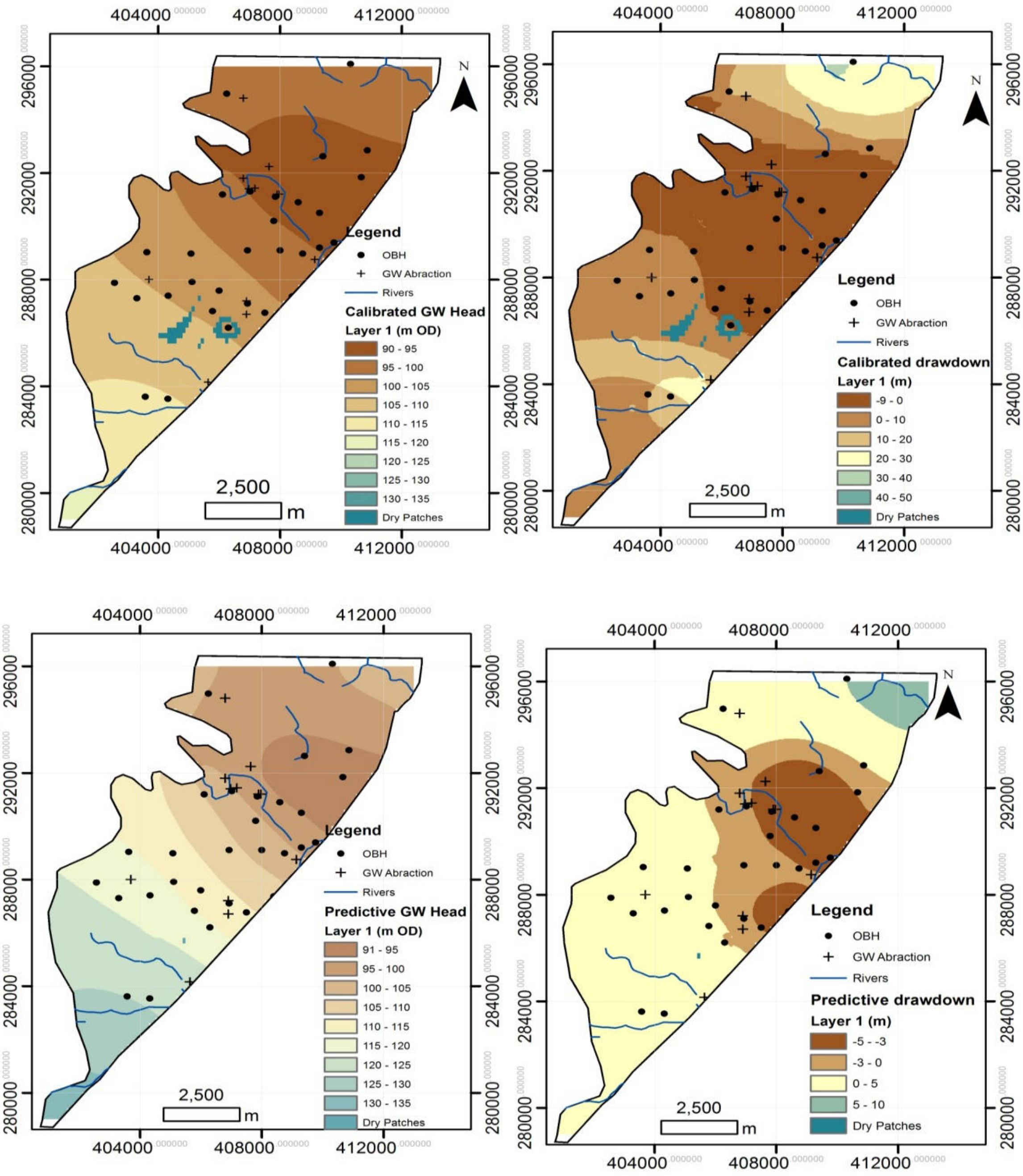

Figure 10: Simulated and predicted groundwater head values

3.2 Lagos Metropolis model

Also, for the Lagos metropolis model, the hydrostratigraphic model showed that the area is underlain by three major and laterally extensive alternating sequences of aquifer and aquiclude horizons, with a near horizontal water table. The thicknesses of the aquifers are irregular and widely varied. However, the model was setup for only the first layer because there were no sufficient data available to support a three-layer model. The ranges of values of transmissivity and storage coefficients for the first layer are $1.08\text{x}10^{-5}$ – $4.68\text{x}10^{-4}$ m^2/s and $1.90\text{x}10^{-4}$ – $2.87\text{x}10^{-3}$, respectively. The regional groundwater flow direction was towards the south both for the simulated and field conditions (Figure 11). The range of values of drawdown after 158 days of pumping is 2 m – 15 m (Figure 12). The coarse discretization, dearth of available initial data, non reliable borehole logs and lack of temporal water level data hindered efficient model calibration process and therefore limits predictive capability of the flow model.

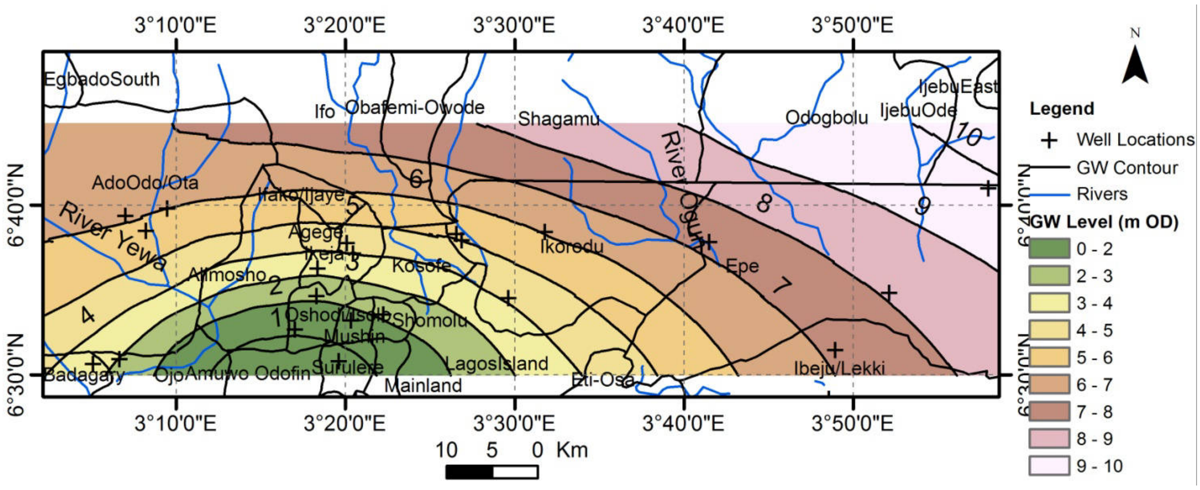

Figure 11: Simulated regional groundwater flow pattern

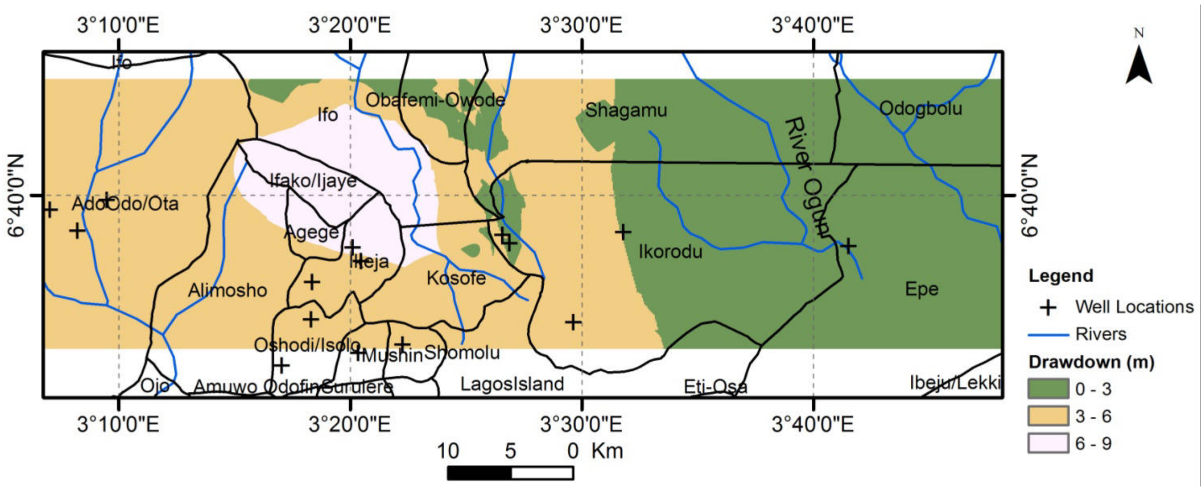

Figure 12: Simulated drawdown values

4 Conclusions

In this work, emphasis was laid on the availability of the required input data and the implications for the validity of the resultant solution of the models. Although flow models were developed for both the Birmingham and Lagos metropolis study areas, however the Lagos model was plagued with dearth of the required spatial and temporal geo-hydrological data and this greatly limited the reliability, possible applicability and the prediction capability of the model. Therefore, in order to ensure development of sustainable water resources framework for Nigeria, the following recommendations are made:

1. Wide availability of quality assured, retrievable and accessible data (Online access).
2. Effective coordination and interactions between the various relevant governmental agencies.
3. Water Resources Bill that will mandate professionals to surrender / submit all data acquire from government and private funded projects and researches.
4. Pro-active engagement between the professional associations and the relevant government agencies.
5. Effective implementation and enforcement of the existing and new regulations.

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