
Evaluation of water situation and development of drinking water management plan for Aba City Southeast Nigeria

A thesis approved by the Faculty of Environment and Natural Sciences at the Brandenburg University of Technology Cottbus–Senftenberg in partial fulfilment of the requirement for the award of the academic degree of Doctor of Philosophy (Ph.D.) in Environmental Sciences

By

(Master of Science)

Uche Dickson Ijioma

from Aba, Abia State, Nigeria

Supervisor: Prof Dr rer. Rainer Herd

Supervisor: Honprof. Dr. rer. Frank Wendland

Date of oral examination: 9 April 2021

Acknowledgement

I want to specially express my indebtedness to Prof. Dr Rainer Herd for accepting to supervise, guide and mentor me through this research as my primary supervisor. You have been like a father, your guidance, meticulous and constructive criticism has made me a lot better and I appreciate it. To my second reviewer, Prof. Dr Frank Wendland, you have shown interest in this work from the very start, and have consistently supported, contributed and guided me to the very last minute to ensure that this work meets the highest standard. I say a big thank you to you.

I want to take this opportunity to thank all colleagues and staff at the Department of Raw Material and Natural Resource Management, at the BTU Cottbus-Senftenberg, for creating an atmosphere of brotherhood in a workplace. Your support and contributions towards this research in different ways have been a source of inspiration and strength. Worthy mentioning is Ms Simone Lubrich, Antje Bohn, Bert Dörre, Martin Rangel, Wlad Schafrik and students at the department, I thank you all.

I want to appreciate all organizations that have supported me financially in this research. They include the Department Raw Material and Natural Resource Management, and the Graduate Research School (GRS), at the BTU Cottbus-Senftenberg for financing part of the data collection, research-stay abroad in Nigeria, and participation in an international conference in Liege, Belgium, where I presented some of the preliminary findings of this research. Others include the Young People's Ministries Global Scholarship of the United Methodist Church, GradV Post-graduate Scholarship (short-time) for doctoral candidates at the BTU Cottbus-Senftenberg from the Federal State of Brandenburg to finalize the drafting of this monogram.

I want to thank some individuals in the collaborating institutions in Nigeria that provided secondary data to support this scientific work in the study area. They include Agrometeorological station, National Root Crop Institute, Umuahia, Nigeria (Dr Amara Uzor Totty) for providing me with some of the climate-related data; Hydrological Department of Anambra-Imo River Basin Authorities (Mr Anieke) for providing supplementary hydrogeological and borehole data that was used to augment the results of the hydrogeological field investigation, Standards Organization of Nigeria Aba centre (Dr Ms Ojeh) for providing information on some of the industries operating the study area, Abia State Teaching Hospital (Dr Chappo and Dr Onyema) for providing some health-related information on water-borne diseases in the area.

My appreciation also goes to apl. Prof. Dr Thomas Fischer at the Central Analytical Laboratory at the BTU Cottbus-Senftenberg for his time, suggestion, advice and technical supports during the planning phase of the groundwater sampling and analyses in Nigeria; Dr Mrs Akuagwu N. Agbanyim and the

laboratory technician, (Mr Okoronkwo Christopher) at the Departments of Chemistry and Microbiology, Abia State Polytechnic Aba for granting me access to their laboratories to evaluate the bacteriological and some of the chemical indicators in the groundwater and alternative drinking water samples; Mr Paul Nwachukwu at the International Energy Services laboratories, Port Harcourt for assisting in the analysis of the samples. Other includes Prof. Michael Ijioma at the Department of Geography and Environmental Sciences, Abia State University Uturu for your fatherly advice and support, Mr Nkene Eukeme (Tonimas Nigeria Limited), Mr Chidozie Okoroama (DMD Korama Clover Industries) and Engr Polycarp at (AfroBeverages Industries Aba) for giving me access to your facilities. and the many more who I can not mention due to space. Your assistance and cooperation in different forms are acknowledged and I thank you all.

Special thank you to a great friend, Mr Okechukwu Njoku and his family, for having my back during the research stay and field campaigns in Nigeria. I acknowledge the tremendous support and roles you have played in making the logistics of my stay in Nigeria seamless. To Ms Heidi Weiss, thank you so much for finding time to proofread and translate the abstract of this research to German within a short time of notice. To all my colleagues, contemporaries, and friends in the ERM PhD programme, as well as the Nigerian students at the BTU Cottbus-Senftenberg, I want to thank you all for you who have encouraged, supported and contributed to this research. You have all made me a better person in one way or other. I say thank you

To my spouse, Dr Mary Nthambi, I appreciate you immensely for making out time to proofread this dissertation report, your contributions (emotional, financial and spiritual), as well as encouragement in my difficult moments. I cannot take it for granted, it means so much to me, and I appreciate it so much.

Finally, to my brother Dr Ekeoma Ijioma, you have been the pace-setter, pillar of support, and friend. Your academic achievement is a driving force and I have drawn a lot from you. Thank you for the advice and contributions to this research. To the rest of my siblings, friends and well-wishers, who have been part of this success story, I thank you for your contributions, encouragement, moral and emotional supports, they are invaluable and mean so much to me.

Dedication

To my mother, Mrs Ori Juliet Ijioma for your love, kindness and the gift of education, even when you had none and to the little woman in the house, Chimamanda. I am so proud of you for the patience and understanding you have shown me throughout the period I was writing.

Table of content

Acknowledgement	i
Dedication	iii
Table of content	iv
List of Figures	viii
List of Tables	xiii
List of Abbreviations and acronyms	xv
Abstract	xvii
Zusammenfassung	xviii
Chapter 1: Introduction	1
1.1 Background.....	1
1.2 Aims of the research.....	2
1.3 Research contributions, novelty, and scientific progress.....	3
1.4 Research design and approach.....	4
1.5 Structure and organization of the dissertation	5
Chapter 2: Access to drinking-water resource in sub-Saharan Africa: a case of Nigeria	7
2.1 Background.....	7
2.2 Overview and water resource potentiality of Nigeria	9
2.3 Water policy and institutional framework in Nigeria	13
2.4 Review of institutional management challenges in Nigeria	16
Chapter 3: Case study area: Aba City and its environs	18
3.1 Background.....	18
3.2 Physical and socio-economic description.....	19
3.3 Physiographical characterization of the area	21
3.3.1 Hydrometeorological evaluation.....	21
3.3.2 Climate-based water budget analysis	23
3.3.3 Water budget quantification	26
3.3.4 Estimation of net groundwater recharge	26
3.3.5 Geology and Hydrogeology	28
3.3.6 Soil characteristics.....	31
3.3.7 Source of water supply	32

Chapter 4: Empirical evaluation of the origin and access to drinking water in Aba, Nigeria	34
4.1 Background.....	34
4.2 Methodology	35
4.2.1 Procedure for the questionnaire administration	37
4.3 Results and discussion.....	38
4.3.1 Source and origin of water for drinking and domestic purposes.....	38
4.3.1 Quality awareness on the water sources for drinking purpose	42
4.3.2 Contamination sources to the main source of water.....	43
4.3.3 Socioeconomics factors influencing the choices of the respondents	44
4.3.4 Urban influence on the quality of other water sources	44
4.3.5 Households and industrial water consumption patterns.....	45
Chapter 5: Geomorphometry and land use derived information	48
5.1 Background.....	48
5.2 Methodology	49
5.2.1 Land surface analysis.....	50
5.2.2 Landcover dynamics and change detection	51
5.2.3 Groundwater contamination hotspot mapping	52
5.3 Results	52
5.3.1 Land surface analysis.....	52
5.3.2 Landcover change detection/Land use analysis.....	56
5.3.3 Groundwater potential contamination source (Hotspot) mapping	60
5.4 Discussions	60
Chapter 6: Evaluation of the chemical risk and hydrochemical investigations	66
6.1 Background.....	66
6.2 Methods	67
6.2.1 Procedure and experimental design	67
6.2.2 Groundwater quality evaluation	68
6.3 Results and discussion.....	71
6.3.1 Assessment of the physicochemical and general chemistry of the groundwater	71
6.3.2 Effects of seasonality on the groundwater quality	76
6.3.3 Influence of land use on the groundwater quality	78
6.3.4 Hydrochemical assessment	79

Chapter 7: Bacteriological risk assessment in different drinking water sources	88
7.1 Background.....	88
7.2 Methods	89
7.2.1 Evaluation of secondary health data.....	90
7.2.2 Bacteriological risk categorization based on <i>E. coli</i> count	91
7.3 Results	91
7.4 Discussion	94
Chapter 8: Development of decision support tools for groundwater management	99
8.1 GIS-based groundwater quality mapping: a water quality index (WQI) approach	100
8.1.1 Background.....	100
8.2 Methodology	102
8.2.1 Selection of water quality indicators.....	103
8.2.2 Transformation of the quality indicators	104
8.2.3 Assigning weights to indicators	105
8.2.4 Aggregation of the Sub-index [SI].....	105
8.2.5 Mapping the groundwater quality (WQI approach).....	106
8.3 Results and discussion.....	107
8.3.1 Water quality index calculations and mapping	110
8.3.2 Comparison of the impact of sub-index aggregation function	113
8.3.3 The implication of land use on water quality distribution	115
8.3.4 Influence of pumping on groundwater quality and evaluation of the WQI distribution maps	116
Chapter 9: Groundwater vulnerability assessment using a modified DRASTIC approach	121
9.1 Background.....	121
9.2 Methods	122
9.2.1 Implementation of the vulnerability assessment maps	125
9.3 Results and discussion.....	126
9.3.1 Thematic/rating maps	126
9.3.2 Groundwater vulnerability assessment map	136
9.4 Evaluation and limitations of the vulnerability models	140
Chapter 10: Implementation of thematic decision-support management tool	142
10.1 Background.....	142
10.2 Methods	143

10.3	Results and discussion.....	146
Chapter 11: Summary, recommendations and research outlook.....		149
11.1	Summary.....	149
11.2	Recommendations.....	152
11.2.1	Education and sensitization of people on the quality issues related to drinking water sources	152
11.2.2	Regulation and licensing for safe private supply activities	153
11.2.3	Ensuring safe private supply for drinking water sources	154
11.2.4	Enforcing safe separation distance between the origin of contaminants and water sources	155
11.2.5	Implementing zoning practices using the thematic decision support management tool	156
11.3	Limitations and research outlook.....	157
List of references		160
Appendix 1		181
Appendix 2		190
Appendix 3		191
Appendix 4		195
Appendix 5		196
Appendix 6		197
Appendix 7		197
Appendix 8		198

List of Figures

Fig 1-1: Flow chart of the research design of the dissertation adapted from the WHO water safety plan framework.	5
Fig 2-1: Water stress baseline map of sub-Saharan African countries.....	8
Fig 2-2: Comparison of the proportion of the national population that have access to piped water in some selected countries in sub-Sahara Africa.	8
Fig 2-3: Hydrological map of Nigeria showing the main drainage network and the hydrological divisions.	10
Fig 2-4: Map of agro-ecological and climate classification of Nigeria (Source: Papaioannou, 2016). ..	11
Fig 2-5: Map of Nigeria showing (a) average seasonal rainfall distribution between 1981 - 2015 and (b) annual rainfall distribution in Eastern region of Nigeria and the case study area (Modified from (a) FEWS NET, 2016; and (b) Lekwa & Whiteside, 1986) respectively.	12
Fig 2-6: Interaction of stakeholders in the institutional framework for water supply in Nigeria	16
Fig 3-1: The population growth time series from 1930 to 2019 based on the actual and estimated population.	19
Fig 3-2: Map of the study area showing maps of (a) Nigeria (b) the federal state of Abia (c) constituent local government areas of Aba	20
Fig 3-3: Illustrations showing time series of climate variabilities (a) monthly average of maximum temperatures between 1980-2008 and average monthly rainfall between (1994-2014) and (b) trend in the annual rainfall pattern between 1994 - 2014 with a 5-year moving average.	22
Fig 3-4: Climate-based qualitative hydrological balance showing the interaction of average monthly rainfall and the corresponding potential evapotranspiration (ET_o) between 1994-2016.....	24
Fig 3-5: Map of eastern Nigeria showing (a) the geology and location of Aba (Lekwa & Whiteside, 1986) (b) generalized dip section in the structural provinces of the Niger Delta with emphasis on the Benin formation, which make-up the aquifer of the study area.....	29
Fig 3-6: Hydrogeological investigations showing (a) the lithography of 3 sites at Osisioma, Osusu and Umule areas in Aba, (b) photos of some soil samples showing soil textures of different layers in the borehole log and (c) map showing the borehole logging sites and other tube wells distributed in both sparse built-up (LR) and densely built-up (HR) areas in the study area.....	30

Fig 3-7: Soil map of Nigeria showing the location and soil description of the study area.	32
Fig 3-8: Photo Illustration of typical stages in private tube well construction and installation of submersible motor (SUMO) pump in a private resident block in Aba.	33
Fig 4-1: Schematic diagram showing stages in the empirical study to understanding the water situation in the study area.....	36
Fig 4-2: Map of household distribution in the denseST residential areas in Aba.	38
Fig 4-3: A column plot showing the distribution of water providers in the area.	40
Fig 4-4: A pie chart showing the distribution of respondents with access to the main source of drinking water in the area.	41
Fig 4-5: A bar graph comparing quality awareness in water sources by households in the study area.	42
Fig 4-6: Pie chart of distribution of housing units types found in the study area.....	44
Fig 4-7: A pie chart of the percentage volume of water abstraction by industry.	47
Fig 5-1: Schematic diagram showing the methodological linking urban land use stress on the terrain derived properties and the groundwater quality.....	49
Fig 5-2: A schematic showing type of land surface parameters (morphometric variables) and data source for their derivative.....	50
Fig 5-3: Maps of different land surface properties in the area showing (a) Filled elevation [DEM] (b) slope, (c) flow accumulation (d) topographic index TI and (e) a 3D impression of upland depression extracted from the TI and overlaid on the DEM of the flow direction.	53
Fig 5-4: Column chart showing the slope analysis of the DEM in the study area.	54
Fig 5-5: Illustration of flow accumulation map showing hydrological features (stream and ponds) in the study area.....	55
Fig 5-6: Land use map of Aba illustrating changes in the land use classification from 1986 to 2017...	57
Fig 5-7: Bar chart comparing the change in the landcover detection for the 3 temporal boundaries; 1986, 2003 and 2017 respectively.	58
Fig 5-8: Map of Aba showing changes in the urban sprawl expansion map between 1986 to 2017. ..	59

Fig 5-9: Map of land use hotspot showing potential contamination sources overlaid on the urban built-up class and its interaction with some of the upland depression derived from the topographic index map.....	61
Fig 5-10: Map of groundwater contamination hotspots showing arbitrary coloured segmentation of groundwater reservoirs and direction of flow of the groundwater. The segmentation is not to scale.	64
Fig 6-1: Map of tube well distribution on the delineated urban land use map differentiating wells in the densely residential (HR) and sparsely residential (LR) areas.....	68
Fig 6-2: A scatter plot showing the relationship between pH and the sum of all major cations in the groundwater wells for the LR (green dots) and HR (red dot) areas of Aba.	73
Fig 6-3: Seasonal trends (wet season) and (dry season) in the groundwater quality indicators between (a) densely (HR) built-up and (b) sparse (LR) wells.	77
Fig 6-4: A trend illustration showing the spatial difference in the quality indicators in the dry seasons between LR and HR wells.	77
Fig 6-5: Boxplot diagrams showing the statistical distribution of major cations and anions for wells in (a) sparse (LR) and (b) wells in densely (HR) built-up areas.	79
Fig 6-6: Boxplot showing dominant major cations and anions for the grouped wells based on the statistical median for the normalized concentrations of the ions.	80
Fig 6-7: Piper diagrams illustrating hydrochemical facies of the groundwater wells in (a) sparse (LR) (b) densely (HR) built-up and (c) combined LR and HR wells in the study area.	81
Fig 6-8: Chadha's plot showing the dominant water types and geochemical processes in the sparse (LR) and densely (HR) built-up wells in Aba.....	82
Fig 6-9: Bivariate cross-plotting of major ions in the groundwater reservoirs in wells of sparse (LR) and densely (HR) built-up areas.	84
Fig 6-10: Bar graphs illustrating the index of base ion exchange for (a) CAI-1 and (b) CAI-2 against the wells in both the LR areas (green shaded bars) and HR areas (red shaded bars).	86
Figure 7-1: Some examples (a) water samples analysed and (b) set-up for the bacteriological evaluations.	90
Fig 7-2: Distribution of water sources and alternative drinking water sources for the bacteriological analysis in the study area.	91

Fig 7-3: Bar chart showing the average counts of colony-forming units in Total Coliforms and <i>E. coli</i> detected in the water and beverages samples.	92
Fig 7-4: Some results of the bacteriological tests showing detection of colony-forming units of indicator organisms (salmon-red coliform and purple-dark blue <i>E. coli</i> colonies) in (a) water sample from Aba River, (b) sample of groundwater from a borehole (c) non-alcoholic beverage sample.	93
Fig 7-5: illustrations showing (a) map of diarrhoeal cases incidence distribution and (b) a time series plot of diarrhoea disease for children under the age of 5 years in the study area.....	94
Fig 7-6: Images of active dumpsites locate close to a residential building with a tube well. (Photos taken by the author during the 2017 field campaign in the study area).	95
Fig 7-7: Some bacteriological contamination sources of water in the area (a) leaky septic tank (b) rearing of cattle close to domestic water sources (c) disposal of household waste into the watercourse (d) direct recharge of groundwater with wastewater from a fish farm.....	97
Fig 8-1: Mapping of groundwater risk evaluation tools to different categories of risk levels.	99
Fig 8-2: Schematic flow diagram for developing the GIS-based WQI quality mapping.	103
Fig 8-3: Quality indicator distribution maps of selected indicators showing (a) pH, (b) TDS, (c) chloride, (d) TPH, (e) nitrate, (f) Manganese, (g) Iron and (h) Lead in the groundwater.....	108
Fig 8-4: Water quality index maps showing surface interpolation estimated by (a) WLSA and (b) WGA sub-aggregation methods.	111
Fig 8-5: Comparison of water quality status between the “actual” and “estimated” per cent areas results of the WQI with the respect to the sub-index aggregation functions.....	112
Fig 8-6: WQI maps of (a) WLSA and (b) WGA overlaid with the bubbles of TPH concentrations of the wells.....	115
Fig 8-7: Illustration of the cone of depression and a pump’s zone of influence in a homogenous aquifer.	117
Fig 8-8: Illustrations of a contaminated site showing (a) hydrocarbon pipeline network map of Nigeria (modified from Ambituuni et al. (2015); (b) industrial zone in the northwestern part of the study area, and (c) satellite imagery of an identified contamination plum showing the zones of influence of three selected tube wells.....	119
Fig 9-1: A schematic diagram showing the weighted thematic layers of DRASTIC parameters and the proposed DRASTIC-P _a	125

Fig 9-2: The rating map of Depth to the water table [D].....	127
Fig 9-3: The rating map of net recharge rate [R].....	129
Fig 9-4: The rating map of aquifer media [A].	130
Fig 9-5: The rating map of soil media [S].....	130
Fig 9-6: The rating map of topography [T].	131
Fig 9-7: The rating map of the impact of vadose zone [I].	132
Figure 9-8: The rating map of hydraulic conductivity [C].....	133
Figure 9-9: Map illustration of (a) distribution of categorized active pumps and (b) rating map of the distribution of impact of active pumps [P _a].	135
Figure 9-11: Multiple bar chart comparing the vulnerability index classes area for the DRASTIC and DRASTIC-P _a methods.	136
Figure 9-10: The vulnerability assessment maps showing the results of (a) DRASTIC and (b) DRASTIC-P _a models for the area.	136
Figure 10-1: A schematic flow showing steps for developing and implementing a thematic decision-support tool for drinking water management in Aba, Nigeria.....	144
Figure 10-2: Schematic diagram showing a GIS-based assembling of components zones that constitute the thematic decision support tool. (a) homogenized zone with high aquifer vulnerability (b) extracted area where the water quality index is unsuitable, (c) homogenized zone with low vulnerability index, and (d) digitized industrial clusters overlaid on the delineated urban land use as the base map.	145
Figure 10-3: Map of Aba showing the thematic decision support management tool and important homogenized zones.....	147

List of Tables

Table 2-1: Agroecological zones classification based on climate data in Nigeria .	13
Table 2-2: Relevant colonial and post-colonial water policies and regulations in Nigeria.	14
Table 3-1: List of some commercial trading areas in Aba.	21
Table 3-2: Results of rainfall coefficient showing seasonality classes throughout the year.	23
Table 3-3: Results of annual average hydrologic cycle components from 1994 -2016.	27
Table 3-4: Summary of the results of net recharge rate by land use types in Aba	28
Table 4-1: Categorization of main sources of drinking and domestic water in Aba.	39
Table 4-2: A Summary of social statistics of households and water consumption pattern in Aba.	45
Table 5-1: Landcover classification according to FAO.	52
Table: 5-2: Land use classification analysis based on area covered by each class between 1986-2017.	56
Table 6-1: Selected quality indicators and the standard methods for the analyses.	69
Table 6-2: Descriptive statistics of some physicochemical and some chemical parameters measured in the groundwater wells in the area.	71
Table 6-3: Summary of WHO rating of TDS on drinking-water quality.	74
Table 6-4: Correlation analysis of some indicators influenced by land use in the area.	78
Table 6-5: Summary of water types in the groundwater wells for both the HR and LR areas.	81
Table 7-1: Classes of common pathogenic organisms found in drinking water.	89
Table 7-2: Summary of E.Coli risk assessment categorization according to the WHO.	91
Table 7-3: Summary of the bacteriological tests in the source water.	92
Table 8-1: Aspects and drivers of groundwater decision support system.	100
Table 8-2: List of selected water quality indicators for the WQI mapping.	104
Table 8-3: Interpretation of the water quality index status.	106
Table 8-4: Summary of the correlation coefficient matrix for WGA against the selected quality indicators.	109
Table 8-5: Summary of the correlation coefficient matrix for WLSA against the selected quality indicators.	109
Table 8-6: Summary of “actual calculated” and “estimated area” of the WQI classes based on the WLSA and the WGA methods.	112
Table 8-7: Results of some tube wells measurements and aquifer hydraulic characteristics.	118
Table 9-1: Datatypes of hydrogeological settings used for the groundwater vulnerability assessments.	124

Table 9-2 Designation of vulnerability classes for the DRASTIC and DRASTIC- P_a indices.....	124
Table 9-3: Summary of ratings for the DRASTIC and modified DRASTIC (DRASTIC- P_a) variables.....	126
Table 9-4: Summary of some important urban subclasses with the designated impact rating for active groundwater pumps.....	134
Table 9-5: Interpretation of ranges for the impact of active pumps and their ratings.....	135
Table 10-1: Analysis of the constituent zones in the thematic decision support management tool.	146
Table 11-1: Minimum siting distance of wells from potential contamination sources	155

List of Abbreviations and acronyms

AIRBA – Anambra Imo River Basin Authority

AVI – Aquifer Vulnerability Index

COP – Concentration of flow, Overlaying layer and Precipitation

DEM – Digital Elevation Model

DMZ – Delineated Monitoring Zone

DTM – Digital Terrain Model

DRASTIC – Depth to the water, net Recharge rate, Aquifer material, Soil type, Topography, Impact of vadose and hydraulic Conductivity

DRASTIC-P_a – Depth to the water, net Recharge rate, Aquifer material, Soil type, Topography, Impact of vadose, Hydraulic Conductivity and impact of active pumps

EPIK – Epikarst, Protective cover, Infiltration conditions, Karst network development

EC – Electrical conductivity

ET – Evapotranspiration

ET_(literature) – Actual Evapotranspiration based on literature

ET_o – Reference evapotranspiration

FAO – Food Agriculture Organization

GIS – Geographical information system

GLEAMS - Groundwater Loading Effects of Agricultural Management Systems

GOD – Groundwater Hydraulic confinement, aquifer Overlaying strata resistivity and Depth to the water table

H_o – Height of the water table before pumping

HSPF – Hydrological Simulation Program Fortran

HR – High (densely built-up) residential area

IWRM – Integrated Water Resource Management

JMP/ UNICEF – Joint Monitoring Program United Nation's International Children Emergency Fund

K_f = hydraulic conductivity

LR – Low (sparse built-up) residential area

LSP – Land Surface Parameter

MDG – Millennium Development Goal

MODFLOW – Modular groundwater Flow model

n – Effective porosity

N_r – Net recharge

NAFDAC – National agency for food and drug administration and control

NRCRI – National Root Crop Research Institute

NWS – New Water Scheme zone

OLI/TIRS - Operational Land Imager / Thermal Infrared Sensor

P – Precipitation

SEEPAGE – System for Early Evaluation of Pollution potential from Agricultural Groundwater Environments

SDG – Sustainable Development Goal

SINTACS – Soggienza-depth to groundwater (S); Infiltrazione - effective Infiltration (I); Non saturo - unsaturated zone attenuation capacity (N), Tipologia della copertura - Soil overburden attenuation capacity (T); Acquifero - Saturated zone features (A), Conducibilità - Hydraulic Conductivity (C), and Superficie topografica - Topographic surface slope (S).

SUMO pump – SUBmersible MOtor pump

R – Radius of influence

R_r – Runoff coefficient

SRTM – Shuttle Radar Topographic Mission

SWAT – Soil and Water Analysis Tool

TA – Total Alkalinity

TDS – Total Dissolved Solids

TIN – Triangulated Irregular Network

TPH – Total Petroleum Hydrocarbon

UN – United Nations

USGS – United States Geological Survey Agency

WGA – Weighted Geometric Average

WHO – World Health Organization

WLSA – Weighted Linear Sum Average

WQI – Water Quality Index

WRI – World Resource Institute

WSP – Water Safety Plan

Abstract

The impact of urbanization on the quality of drinking water sources is a challenge in many developing countries. In this research, the main source of drinking water was quantified, quality baseline defined, and a thematic decision support management tool developed to protect the quality using Aba, Nigeria. Data from primary and secondary sources were obtained from desktop search, empirical instruments, satellite data, hydrogeological investigations and water quality assessment. Geoscientific and statistical tools were used to analyse the landform, characterize the land use, and create management tools to protect the water source.

The results revealed that groundwater is the main source of water for both domestic and industrial uses. An average water consumption per capita rate of 35.9 l/day was estimated, which is low compared to the WHO recommendation. The landform and land-use analyses revealed that the area is low-lying, poorly drained, and the urban land-use is the fastest-growing class growing averagely at 0.6%/annum between 1986 to 2017. Some of the urban land-use practices that harm the quality of the groundwater were identified and mapped in a contamination hotspot map.

The results of the twenty-one quality indicators in the groundwater showed that the pH was acidic (3.7-5.6), total dissolved solids (TDS) ranged between 6.5 mg/l-364 mg/l. The mean concentrations of the remaining indicators were within the WHO limits for drinking water quality. But, the EC, TDS, chloride and nitrate revealed significant differences when tube-wells between densely and sparse built-up areas are compared. Again, four dominant water types were identified in groundwater. The Na-HCO₃ water type was dominant mostly in the sparse built-up area and it is assumed as the background groundwater facies in the area. Whereas Mg, Ca-Cl, Na-Cl and Ca-HCO₃ water types were predominant in the densely built-up area. The bacteriological assessments of drinking water from natural and alternative (i.e. beverages and packaged water) sources revealed the presence of *E. Coli* and *Coliform* bacteria in some samples of the natural water.

The groundwater quality distribution and vulnerability assessment maps were developed based on water quality index, and DRASTIC methodologies, respectively. The quality distribution map showed that > 98% of the area has a “suitable” rating. While the vulnerability assessment map found that the groundwater has a “medium” baseline vulnerability covering about 80%. The differences in the results were due to some observed poor urban land-use practices in the area. Finally, a thematic decision support tool that delineates priority monitoring zones and suggests possible source protected areas tailored for the area was developed. This tool is cost-effective in protecting the groundwater quality and can be applied to other developing urban areas with similar physiological conditions.

Zusammenfassung

Der Einfluss der Urbanisierung auf die Qualität der Trinkwasserquellen ist in vielen Entwicklungsländern eine Herausforderung. In dieser Studie wurde die Haupttrinkwasserquelle der Stadt Aba, Nigeria quantifiziert, die Qualität untersucht und ein thematisches Entscheidungshilfe-Management-Tool entwickelt, um die Wasserqualität zu schützen. Daten aus Primär- und Sekundärquellen, Satellitendaten, hydrogeologische Untersuchungen und Wasserqualitätsbewertungen wurden verwendet. Geowissenschaftliche und statistische Werkzeuge wurden eingesetzt, um die Landschaftsform zu analysieren, die Landnutzung zu charakterisieren und Managementinstrumente zum Schutz des Wassers zu entwickeln.

Die Ergebnisse zeigten, dass Grundwasser die Hauptwasserquelle sowohl für den häuslichen und industriellen Gebrauch ist. Es wurde ein durchschnittlicher Wasserverbrauch pro Kopf von 35,9 l/Tag bestimmt. Die Landform- und Landnutzungsanalysen ergaben, dass das Gebiet niedrig liegt, schlecht entwässert ist und die städtische Landnutzung die am schnellsten wachsende Klasse ist (durchschnittlich mit 0,6% / Jahr zwischen 1986 und 2017). Einige der städtischen Landnutzungspraktiken die die Qualität des Grundwassers beeinträchtigen, wurden identifiziert und in einer Kontaminations-Hotspot-Karte dargestellt.

Einundzwanzig Qualitätsindikatoren im Grundwasser wurden untersucht und zeigten u.a., dass der pH-Wert niedrig war (3,7-5,6), der Gesamtgehalt an gelösten Feststoffen (Total Dissolved Solids, TDS) lag zwischen 6,5 mg/l-364 mg/l. Die mittleren Konzentrationen der übrigen Indikatoren lagen innerhalb der WHO-Grenzwerte für die Trinkwasserqualität. Allerdings zeigten elektrische Leitfähigkeit, TDS, Chlorid und Nitrat Unterschiede, zwischen Brunnen in dicht bebauten und spärlich bebauten Gebieten. Vier dominante Grundwassertypen wurden identifiziert. Der Wassertyp Na-HCO₃ war überwiegend im dünn besiedelten Gebiet dominant und wird als Hintergrundgrundwasserfazies im Gebiet angenommen. Im dicht bebauten Gebiet dominierten hingegen die Wassertypen Mg, Ca-Cl, Na-Cl und Ca-HCO₃. Bakteriologische Bewertungen zeigten in einigen Proben E. Coli und coliforme Bakterien.

Die Karten zur Verteilung der Grundwasserqualität und zur Vulnerabilitätsbewertung wurden basierend auf dem Wasserqualitätsindex bzw. DRASTIC-Methoden entwickelt. Die Qualitätsverteilungskarte zeigte, dass > 98% der Fläche eine „geeignete“ Bewertung aufweist. Während die Karte zur Vulnerabilitätsbewertung ergab, dass das Grundwasser eine „mittlere“ Basisvulnerabilität von etwa 80 % aufweist. Die Unterschiede in den Ergebnissen waren auf Landnutzungspraktiken in dem Gebiet zurückzuführen. Schließlich wurde ein thematisches Entscheidungshilfemittel entwickelt, das vorrangige Überwachungszonen abgrenzt und mögliche Quellschutzgebiete vorschlägt. Dieses Instrument ist kostengünstig und kann auf andere sich entwickelnde städtische Gebiete mit ähnlichen Bedingungen angewendet werden.

Chapter One

1. Introduction

1.1 Background

Since the industrial revolution, and as the world's population continues to grow, the global fresh water resource has been under serious stress due to increasing demand. This is because most of the world's freshwater resources are finite (fixed in quantity), renewable (self-regenerating) and the availability in space are not uniformly distributed (FAO 2003). The local availability of this resource can be associated with the prevailing meteorological and physiographical conditions of the area. Besides the ice caps, glaciers and permanent snow, the groundwater is the most abundant freshwater source and represents 30.1% (23,400,000 cubic Kilometer) of the global water resource (Gleick 1996; PennState 2019). The groundwater is considered safer than the readily available surface water in many places because it is protected and less prone to pollution. It is naturally self-purifying and has a better microbiology quality (Thompson et al., 2007). It constitutes the largest reservoir of drinkable and safe freshwater serving many communities both in developed and developing countries. In 2010, over 2.5 billion of the world population depended directly on groundwater to meet their domestic needs (WWAP, 2015).

There is an increasing demand for groundwater resources especially in urban areas of developing countries due to the following factors: fast-growing population, agricultural production to feed the population, booming industrial and commercial activities, insufficient public supply, and even the changing climate. These factors limit the availability of the resource in many potential catchments due to mismanagement of the water resource (Şen, 2015) and can also have deteriorating impacts on the quality of the groundwater.

In many urban areas of developing countries, the interaction between land use practices and groundwater usually has a deteriorating effect on the quality of the groundwater (Mallin, 2009). The situation is not peculiar only to the sub-Saharan African countries, but to other poor developing economies in Asia, as well as South America. This is because these developing urban neighbourhoods are characterized by having a dysfunctional public water supply service, lack a central sewage system (Edet, 2014), use on-site sanitary facilities (Cissé Faye et al., 2004; Hassane et al., 2016) and indiscriminately discharge both domestic and industrial effluents directly into cesspits, sometimes into the groundwater aquifer and surface water bodies without treatment. Despite these poor environmental practices, people still depend on these water sources, especially groundwater, to meet their domestic water needs. In light of this, it means that as household effluents are discharged

underground, groundwater abstraction happens side by side in areas where groundwater is the main source. The mortality rate of children under five and elderly people are increasing, as a result of water-related diseases caused by drinking and/or using contaminated water in many developing countries (UNDP, 2018). The safety of drinking water directly from the groundwater without prior treatment is no longer guaranteed due to poor sanitation, inadequately enforced environmental and land use practices even in urban areas of developing countries, as well as weakness in the institutional framework that protects the resource, e.g. against over-exploitation. Sometimes, the relevant agencies that have the mandate to protect the groundwater lack the tools to make informed decisions or are incapacitated by existing policies, which were not tailored to the prevailing local situation (Ogunba, 2011). The poor urban plan implementations are causing pollution of the groundwater making it unsuitable for drinking and intensify the scarcity of the resource in the area (Saghir and Santoro, 2018). Lack of access to water aggravates poverty, degrades quality the life, makes food unaffordable, cause indignity in human and the environment is worse off (WWAP, 2015). Hence, there is a need to develop scientifically-based decision support management tools that will aid relevant authorities to carry out a risk assessment and manage the source water. Since the situation is common in many developing countries, this tool can be adapted regionally, to ensure the availability of the groundwater resource and safeguard the public health of the urban poor who are the most vulnerable.

1.2 Aims of the research

This research is focused on resolving some of the challenges facing access to safe drinking water sources in most developing urban areas typical in sub-Saharan Africa. In this research, Aba in the Southeastern part of Nigeria was used as the case study area. The selection of a humid part of Nigeria for the context of this study is to elucidate some factors that are continually depleting the access to safe drinking water both qualitatively and quantitatively in some areas with abundant water reserves. The main goals of this research can be summarized in the following headings to support relevant authorities to make a decision that can protect the water source and safeguard public health. This could be achieved by

1. Establishing a quality baseline status of the source water;
2. Develop a thematic decision support management tool that can be used to protect the quality and delineate priority monitoring parts in the study area to ensure sustainable use of the groundwater.

The quality baseline status of the main drinking water source (groundwater) entails general chemical, bacteriological and toxicological characterization and risk assessments. The bacteriological assessment goes beyond the main drinking water source (i.e groundwater), but other natural (rain

and surface water) and alternative drinkable sources (e.g. beverage drinks manufactured locally in the study area). On the other hand, the decision support risk management tool can be used to identify the suitability and susceptibility of the source water in different parts of the area. The risk management tools will delineate the highly susceptible zones and prioritize them for routine monitoring of the source water. This will reduce the cost and improve the efficiency of monitoring activities in the area. Based on these goals, this research will address the following specific objectives in the study area including:

- Evaluate the potentiality and factors influencing access to the main drinking water source
- Appraise the land use derived information, including identifying, collate, categorize and map hotspots that influence the groundwater quality
- Assess the bacteriological risk in different drinking water (natural and alternative sources), including beverage drinks produced in the area
- Evaluate the geochemical and toxicological risks associated with the main water source
- Delineate the influence of urbanization on the hydrochemistry and chemical quality of the groundwater
- Carry out a groundwater quality distribution and vulnerability assessment maps
- Create a thematic decision support tool for the protection and management of the water source in the study area

1.3 Research contributions, novelty, and scientific progress

The efficient use of the available water lies in the hands of all stakeholders in the water sector to ensure that access to the resource is continuous and the quality is adequately protected. The decision support tools are important instruments developed to guide relevant authorities to understand the status of both the quality and quantity of the water resource, as well as initiate protection strategies to manage and ensure the sustainable use of the resource.

Hence, the main contributions of this dissertation are threefold and can be summarized as follows:

- a) In this research, some existing methodological approaches have been adopted and developed for the groundwater quality distribution and vulnerability assessment mapping for the peculiarity of the study area and enhance the methodology. The use of the WQI approach implements a uniform scale, which transforms units and dimensions of different water quality indicators to create a GIS-based thematic map. This is novel and has been fully explored in many developing countries. Most water quality maps are usually derived and developed using

a proxy quality variable to indicate changes that will occur spatially and temporarily. This in many cases may not be a true reflection of the reality, and a combination of the indicators.

- b) For the first time, this study has conceptualized an approach that incorporates and evaluate the impact of active pumps into conventional indexing and overlay groundwater vulnerability assessment method such as the DRASTIC. The introduction of an urban feature such as the impact of the active submersible motor (SUMO) pumps for groundwater abstraction is a common feature in many urban communities within the region, where the public supply has been dysfunctional. This feature is mappable and can exert changes in the hydrogeologic setting of the area. This additional parameter was used to modify the conventional DRASTIC method and demonstrate the impact of active pumps on the hydrogeology as well as used as a screening tool for the vulnerability assessment of the groundwater in the area.

- c) This development of a methodological framework and implementation of a cost-effective thematic decision support tool derived by combining results of groundwater water quality index mapping and the modified DRASTIC vulnerability assessment in the case study area. This contribution is new and has never been implemented in the region. This approach can be transferred to other urban areas in sub-Saharan African countries with similar physiological features and hydrogeologic settings.

1.4 Research design and approach

The methodological design of this dissertation was adopted from the approach of the WHO's water safety plan. The conceptualization and assessment of risks associated with drinking water sources and the development of decision support for the study area are shown in the scheme (Fig (1-1)). The research design divides this dissertation into main two parts. The first segment deals with the risk assessment in the first part (Part I). This combines the "system assessment" and "Monitoring" of the water safety plan to holistically identify and evaluate the sources of risks, as well as the current quality status of the drinking water sources. The risk assessment of the water source involves desk-based reviews and intensive field campaigns involving empirical studies and hydrogeological investigations to identify risk sources and other factors influencing the quality of the water. On the other hand, the second segment deals with Part II which covers the "Management and communication" as well as "Feedback" of the water safety plan. In this part, the development of the decision support tools that will be used for risk screening and analytic tools to design the monitoring programs of the water source in the area is covered. This part is at the strategic level of risk management of the source water, thereby ensuring that public health is protected.

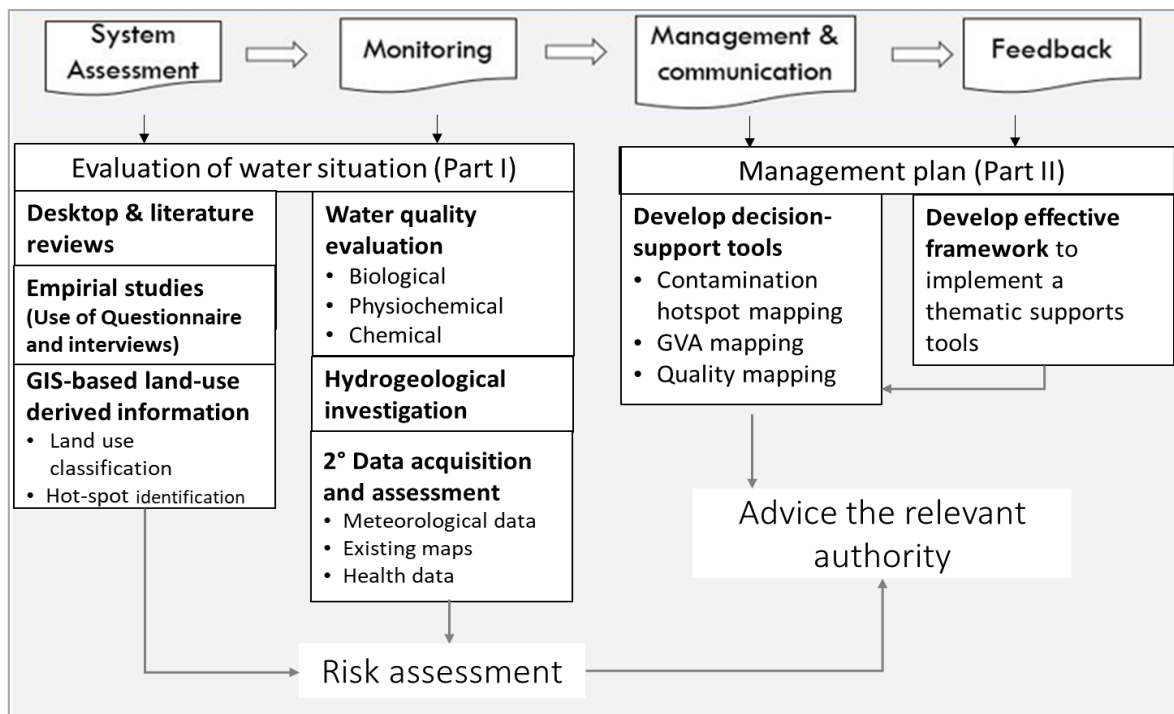


Fig 1-1: Flow chart of the research design of the dissertation adapted from the WHO water safety plan framework.

1.5 Structure and organization of the dissertation

The overall structure of this dissertation was grouped into three sections, constituting 11 chapters. Based on the broad spectrum of this research, these chapters are categorized into: Section A consists of Chapters 1-3. These chapters set the background describing the problem statement, the main goals of the research and present the selected study area used to demonstrate the ideas developed in this study. Section B dealt with the methods, results and discussion of the findings for each of the specific goals of the research in Chapters 4-10. Section C consists of only one chapter, i.e Chapter 11, which gave a general summary of all the previous chapters, and made some recommendations, as well as research outlooks, were drawn from the chapters. The appendices contain supplementary information that was used in the study. The writing style in each of the chapters start with a brief background into the topic, highlights the specific objectives that it aims to achieve, the methods and approach used to achieve the objectives, and discuss the important findings in the results. The highlights of each chapter are as follow:

Chapter 1 introduces the main problem, set the context of the water situation within the region, the main goals of the research, and highlighted the contributions of the research. Chapter 2 reviewed the access to water and the regional usage of water in sub-Sahara Africa. Then, the challenges faced by the water sector using Nigeria as a case in point for the region was covered. Chapter 3 explores the

case study area giving basic information about the population dynamics and some physiographic factors that influence water availability in the area.

Chapter 4 uses an empirical study to evaluate the main source of drinking water, household perception of water quality, sources of urban contamination to the water source and justify the choice of the study area for this research. Chapter 5 describes land use derived information that influenced both the potentiality, availability and quality of the source water using geoscientific tools (GIS and remote sensing). The chapter covers topics like geomorphology and landform analysis, landcover change detections analysis and mapping of hotspots, as well as associated risks area that can influence the water quality.

Chapters 6 holistically deal with the chemical risk assessment of the main water source, the influence of seasonality and urbanization on the quality of the groundwater, as well as delineation of urban impact on the hydrochemistry and characterization of the groundwater facies. The bacteriological risk evaluations of different natural drinking water and alternative sources such as packaged water and beverage drinks were investigated in Chapter 7.

Chapters 8, 9 and 10 bring together different parts required to develop the thematic decision support management tool to assist the relevant authorities to protect and manage the quality of the drinking water source (i.e. groundwater) in the study area. Chapter 8 utilizes some of the results of selected chemical quality indicators to create the groundwater quality distribution map of the area. The water quality index approach was used to enhance the concept of groundwater quality information mapping. On the other hand, Chapter 9 developed a GIS-based groundwater vulnerability assessment of the area based on the DRASTIC and modified DRASTIC- P_a methods. Both results from chapters 8 and 9, contributed to the methodological enhancement of groundwater quality distribution and vulnerability assessment mapping respectively. Chapter 10 is a synthesis of the methodological framework developed in this study. It combined the results of Chapters 5, 8 and 9 to create a thematic decision support tool. The thematic decision support management tool presents a cost-effective way developed for the management of the groundwater in the case study area.

Finally, Chapter 11 summarizes the main findings in each of the previous chapters and propose recommendations, which highlight the salient observations and contributions of this research. Also, it identified some knowledge gaps, which can be translated into windows of research opportunities for the scientific community.

SECTION A

Research background and review of literature

Chapter Two

2 Access to drinking-water resource in sub-Saharan Africa: a case of Nigeria

2.1 Background

The term “access to water” refers to water that is safe, readily available at any time within one kilometre and can be used for drinking, food production and recreation (Geere, 2016). Today, the global trend for water withdrawal revolves around these three main sectors including domestic, agriculture and industrial use, in which the domestic sector accounts for only 12 % of total withdrawals (FAO, 2016).

In many developing countries, the population and economic growth are happening faster compared to the rest of the world. Besides, the impact of the changing climate is evident, making it a challenge to keep up with the demands for renewable water resources leading to water scarcity¹ in these countries. Water scarcity endangers public health because it leads to poor sanitation, the prevalence of water-related diseases, reduces the quality of life, as well as increases the price of food (Hunter et al., 2010; FAO, 2016). The context of efficient use of freshwater resources in the African continent showed that all the countries in the Northern African region are water-stressed² due to the influence of the Sahara Desert. The analysis of water-stressed countries in Africa revealed that the most endowed freshwater resource countries are found within the central African region. The average water stress situation in the sub-Saharan African region is estimated at that only 3% of the countries are water-stressed. However, this proportion masks most countries in the region, which are already declared water-stressed (FAO, 2018). The water stress index map revealed that 20.5 % of the countries in the region lies between high to extremely high water-stressed countries. Examples of these countries include Botswana, Namibia, South Africa, Eritrea, Burkina Faso and Niger as shown in Fig (2-1) (FAO, 2018; World Resource Institute, 2019). The JMP WHO/UNICEF global reports showed that despite the 83% progress achieved in 2015 at the expiration of MDG, 2.2 billion people still do not have access to safely managed drinking water sources as of 2017. Most of these people live in the

¹ Water scarcity describes a situation arising due to deficit in a finite available resource “supply” over an ever increasing (excess) user “demand”. It can be used to portray a situation of physical shortage if the acceptability insufficient, even if it is available for a large population or there is inadequate infrastructure to supply water to the people irrespective of abundant water resource (Lawrence et al., 2002).

² Water stress is an indicator to efficiency of water use. It is calculated as the proportion of all freshwater withdrawn compared to the total available freshwater resource (FAO, 2018).

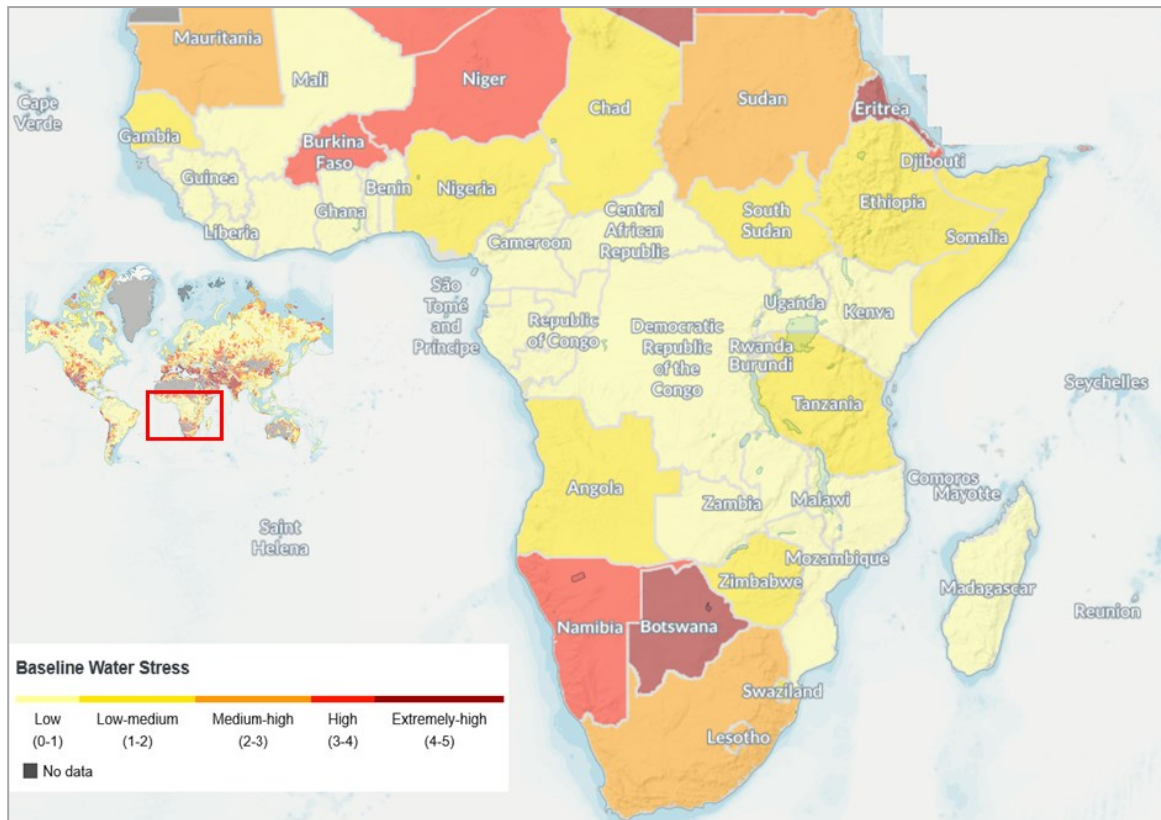


Fig 2-1: Water stress baseline map of sub-Saharan African countries (Modified from world resource institute, 2019).

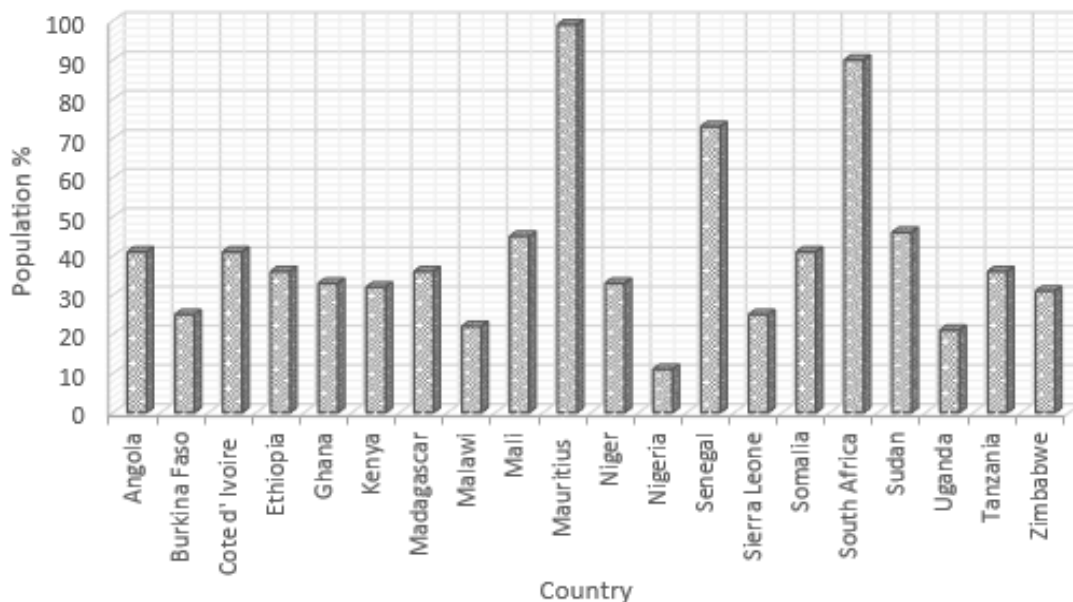


Fig 2-2: Comparison of the proportion of the national population that have access to piped water in some selected countries in sub-Sahara Africa (Data source: UNICEF, 2019).

least developing countries (WHO/UNICEF, 2019). The World Bank’s MDG scorecard of 2015 showed that the progress made in sub-Saharan Africa was slow and 319 million people in the region still do not have access to improve water in the region (WHO, 2019). In general, the water situation in sub-

Saharan Africa countries shows that much of the water withdrawn in these countries go into agricultural production, while only 16% (representing 19 Km³/year) of the total water withdrawn is used domestically (FAO 2016). Today, the concept of water availability can be used as an indicator for measuring the economic prosperity and social well-being of people (Lawrence et al., 2002; Hunter et al., 2010). In the sub-Saharan African region, Nigeria has the least proportion of people having access to piped water as shown in Fig (2-2). This indicator supports the poor economic and wellbeing progress made in Nigeria with about 46% of the population living in extreme poverty (Kazeem, 2018). The focus of this chapter is to review and evaluate the water resource potentiality of countries in sub-Saharan Africa and assess some factors influencing the water availability in the region. Nigeria has been selected as a case in point to carry out this assessment because it represents the biggest economic unit in this region and is home to one-fifth of the people living in the region (estimated population of SSA is 1.078 Billion people (World Bank, 2019). For this purpose, a synthesis of the physiological, regulatory policies and institutional factors that influences the water situation in Nigeria will be carried out. It will be concluded by summarizing some of the challenges faced in the water resource management of Nigeria.

2.2 Overview and water resource potentiality of Nigeria

Nigeria is found in the West African region and the most populous country in sub-Saharan Africa. The current population estimate is about 203 million people and the seventh most populous country in the world (US Census Bureau, 2019). Nigeria is ranked as a fast-growing and biggest economy in Africa, with a GDP worth of US\$ 397.3 billion as of December 2018 (Trading Economics, 2019), and it is rated as a lower middle-income country according to the World Bank classification (World Bank, 2018). The freshwater resource endowment in Nigeria is quite vast, but the distribution is spatially skewed to the southern part, leaving the highly populated Northern Nigeria water-stressed (FGN, 2004). The baseline water stress map for Africa suggests that Nigeria belongs to the low-medium water-stressed countries. Most literature available has estimated total freshwater reserves solely based on the surface water in Nigeria, with an estimation of groundwater resource grossly under-estimated. The total estimated freshwater reserve lies between 274-305 billion cubic meters (Oteze, 1981; FGN, 2004; Andres et al., 2018). The vast network of surface water bodies (rivers, streams, lakes, and estuaries), which drains the 924 000 Km² area of Nigeria. These surface water bodies only occupy 1.41% of the landmass, and they account for 267.3 billion m³ of the total volume (FGN, 2004). The three biggest surface water features are the Niger- Benue River system, and Lake Chad. The Lake Chad system drains internally. Fig (2-3) illustrates the hydrological map of Nigeria showing the divisions and the drainage network.

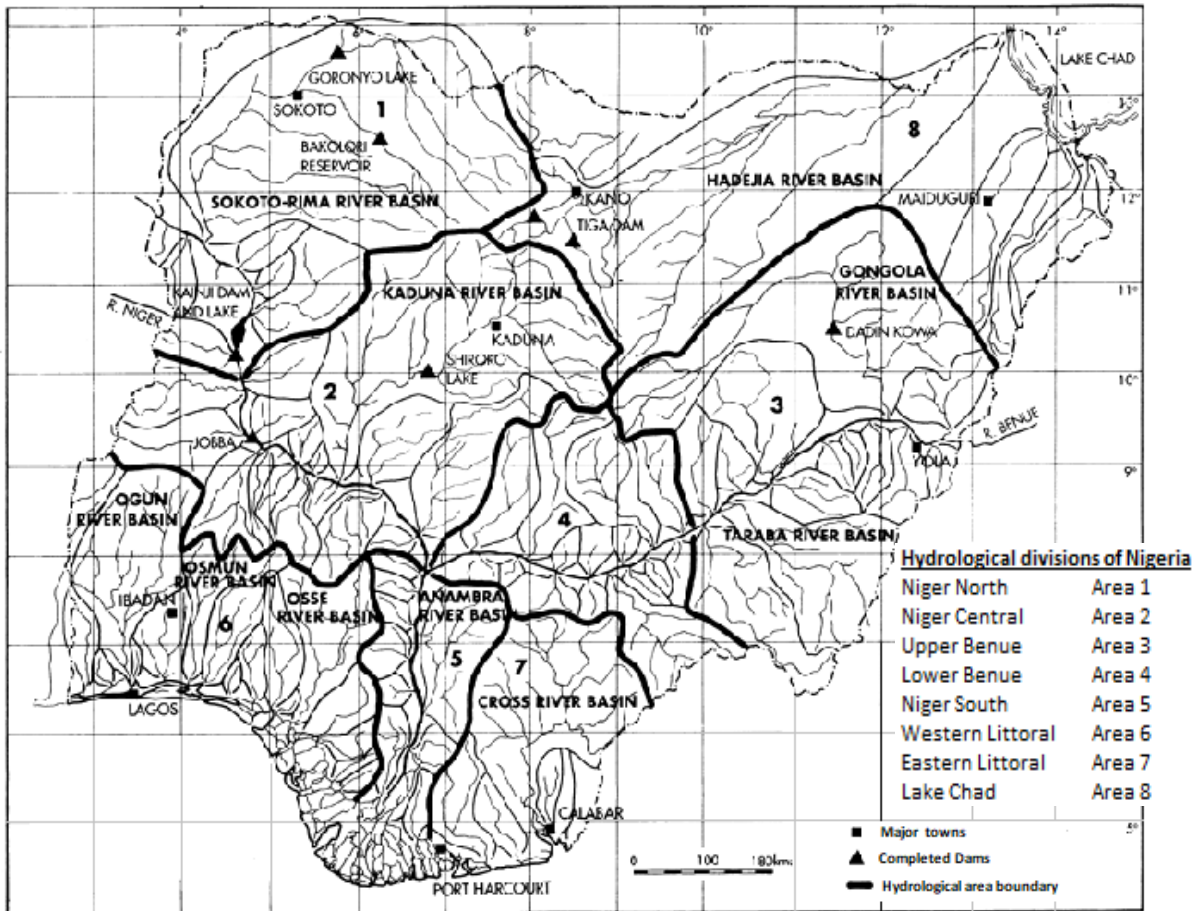


Fig 2-3: Hydrological map of Nigeria showing the main drainage network and the hydrological divisions (Modified from Ita, 1993).

The Niger River system is exogenous³ and the hydrological basin is shared with upstream countries including the Republic of Mali and the Niger Republic. Therefore interference from the upstream countries can lead to a water crisis in the country (Xercavins, 1999). Other important perennial rivers systems form tributaries to the Niger-Benue system, while some drain directly into the Atlantic Ocean through the deltas. (Ita, 1993). Based on the surface drainage networks, the country was divided into eight (8) hydrological zones or divisions as shown in (Error! Reference source not found.). The network densities in the different zones suggest that the southern parts (i.e. zones 4, 5, 6 and 7) are better drained than the northern parts (i.e. zones 1, 2, 3 and 8) respectively. On the other hand, groundwater reserve accounts for up to 52 billion m³ (FGN, 2004; Andres et al., 2018). Nwankwoala, (2015) reported that the groundwater reserves in the country might have been under-estimated and should equal or outweigh the surface freshwater reserves in the country. This is because the water-bearing sedimentary aquifers alone cover approximately 40% of the country's geology and groundwater

³ Exogenous water source implies that there is inflow of water from neighbouring upstream countries that shares the same basin.

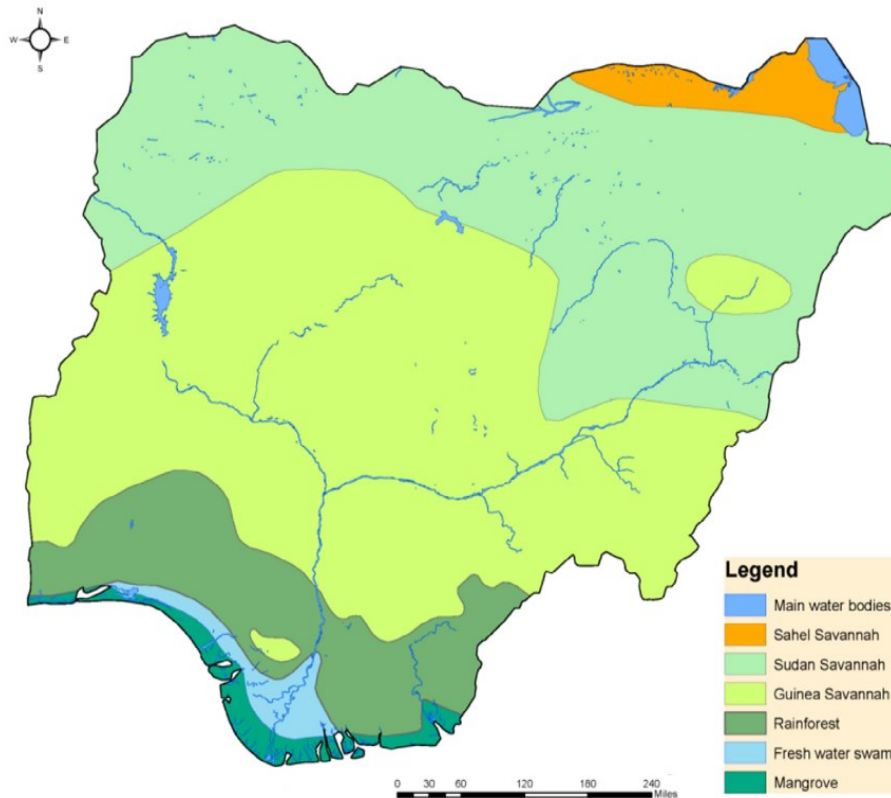


Fig 2-4: Map of agro-ecological and climate classification of Nigeria (Source: Papaioannou, 2016).

discovered in the crystalline basement complex of Nigeria. However, there are no authoritative estimations of the groundwater in the basements at the moment (Oteze, 1981).

The agro-ecological and vegetation analysis of Nigeria has been described in Fig (2-4). The map revealed that the mangrove swamps forest covers the entire low lying south coastlines. This is overlapped by the tropical rainforest area in the Southeast and Southwest regions. Moving to the Northcentral parts where there is an elevation rise to the plateau (average elevation of 600m and a maximum elevation of about 2 Km towards Shebshi Mountains along the northeastern corridor). The mountain areas are covered with thick forest and surrounded by savannah grass vegetation. The extreme northern part is toward the South of the Sahara and has arid vegetation (Nations Encyclopedia, 2019). As one moves from the South to the northern parts, the vegetation cover changes. Six climate and vegetation zones can be identified in the map of the agro-ecological zones of Nigeria (Papaioannou, 2016).

The climate conditions contribute significantly to water availability in different parts of Nigeria. The rainfall and temperature are the most common and frequently measured climate data, which serves as a pointer to the water situation of an area. These climate factors reflect the extent of the water availability in Nigeria since the distribution is not uniformly spread throughout the country.

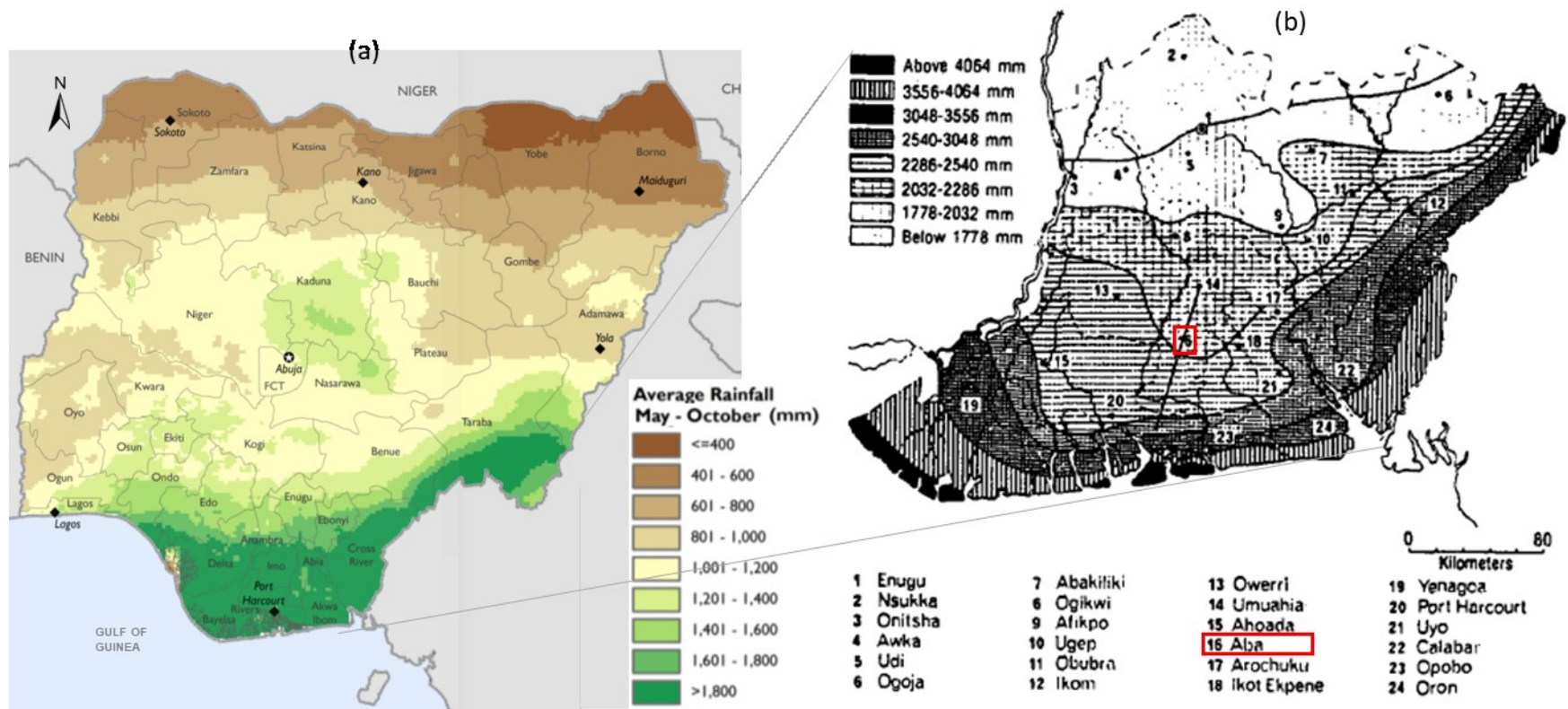


Fig 2-5: Map of Nigeria showing (a) average seasonal rainfall distribution between 1981 - 2015 and (b) annual rainfall distribution in eastern region of Nigeria and the case study area (Modified from (a) FEWS NET, 2016; and (b) Lekwa & Whiteside, 1986) respectively.

There are two main climate seasons in Nigeria, namely the wet and dry seasons. The wet or rainy season starts in March-April and ends in October. It is influenced by the southwesterly tropical maritime airmass. The airmass flows through the Atlantic ocean laden with moisture, giving rise to lots of rainfall in the southern parts of Nigeria. Whereas the northeasterly tropical continental airmass across the Sahara Desert cause the climate in most parts of northern Nigeria to be dry and leads to semi-arid to arid conditions (Eludoyin and Adelekan, 2013). The rainy season contributes about 84% of the annual rainfalls (Adejuwon, 2012). The precipitation map of Nigeria in Fig (2-5) describes the annual average rainfall distribution throughout the country. The extreme parts of northern Nigeria such as Maiduguri receive, as low as 400 mm/annum of rainfall, while it gets rainier in the southern part with some towns along the coastline receives more than 4000 mm/annum of rainfall (Eludoyin and Adelekan, 2013). The pouring rainfall in the south parts sometimes causes severe environmental havoc such as erosion, due to high run-off. Table 2-1 summarizes the relationship between some climate data (annual rainfall and prevailing surface temperatures) and the corresponding agro-ecological zones in different parts of Nigeria. Rainwater represents a major source of water for many

Table 2-1: Agroecological zones classification based on climate data in Nigeria (Source: Enyidi, 2017).

Climate	Annual rainfall (mm)	Normal monthly temperature (°C)	Min (°C)	Max (°C)
Semi -arid	400 – 600	32 – 33	13	40
Dry subhumid	600 – 1000	21 – 31	12	49
Subhumid	1000 – 1300	23 – 30	14	37
Humid	1100 – 1400	26 – 30	18	37
Very humid	1120 – 2000	24 – 28	21	37
Ultra-humid	>2000	25 – 28	23	33
Mountainous	1400 – 2000	14 – 29	5	32
Plateau	1400 – 1500	20 – 24	14	36

households living in many urban and rural communities alike. It is also the main source of groundwater recharge in Nigeria. A recent study between 1981-2015 suggests that the trend of rainfall pattern in Nigeria has increased in the northeastern parts and there has been some localized reduction in rainfall in the southern part of Nigeria such as Warri in Delta State (FEWS NET, 2016). However, this observation cannot be tied to the rhetoric of the anthropogenic changing climate in the country.

2.3 Water policy and institutional framework in Nigeria

Nigeria is a signatory to many international water conventions, policy initiatives and agreements that ensures the development of the water sector of the country and meet the water need of the people living in water shortage areas. The development and management of water resources in Nigeria is the

institutional responsibility of the three levels of government including the Federal, State and Local governments. At the Federal level, strategic issues related to water resource management are the responsibilities of the federal government agencies and ministries related to the water sector (FGN, 2004). These agencies include the Federal Ministries of Agriculture, Environment, Power and Steel, Federal Department of Inland Waterways Authority and Nigerian Meteorological Services Agency. The roles of these are to ensure that the following objectives are met:

- Manage and safeguard the water resource in the area
- Ensure all citizens get an adequate supply of safe water in both rural and urban
- Comply with all the international agreements and initiatives within the water sector that Nigeria is a signatory to.
- Regulate all activities related to the water sector

To strengthen the institutional framework in Nigeria, many laws, policies and regulatory instruments have been developed since colonial and post-colonial Nigeria to protect, guide, monitor and define the extent of government control over the resource to ensure prompt access to water. Table 2-2 summarizes some of the relevant legal instruments on water provisions modified from Akpabio, (2012).

Table 2-2: Relevant colonial and post-colonial water policies and regulations in Nigeria.

Water Acts, policies and regulations	Summary of targeted water provisions
The waterworks Act 1915	Protects water from being contaminated by harmful substance
The Minerals Act of 1917	Empowered the Head of Government to make policies that prevent pollution on any watercourse
The Public Health Act of 1917	Provide regulations that protect the water and the atmosphere by harmful human activities
The Petroleum Act, 1969	Provides guidelines that protect inland watercourses from pollution
The Oil in Navigable Waters Act, 1968	Prohibits water pollution by oil spillage
The Land use Act of 1978	link land ownership to ownership of groundwater resources
The River Basin Development (RBDA) decree /Act of 1976, 1987 & 2004	Provide a Pan-Nigerian programme for comprehensive and integrated water resources development and management
National Policy on Environment, 1989	Provide water quality regulation and standards as well as pollution control
National Guidelines and standards for Environmental pollution control (1991)	Provide control for pollution in water bodies as part of the environment
National Effluent Limitation Regulation 1991	Provides control on the direct discharge of industrial effluent into the water bodies

Nigerian Industrial Standards for potable Water and Natural Mineral Water, 1992	Provides standards for drinking-water quality to safeguard public health
The Environmental Impact Assessment (EIA) decree/Act 1992 & 2004	The Act protects both the physical environment and the water bodies
Water Resources decree/Act of 1993 & 2004	Gives the Federal government of Nigeria the exclusive right to control the water resources
National Rural Water Supply and Sanitation Policy, 2000	Deals with rural water and sanitation through community participation. The targets of the programme were to achieve UN MDGs on access to water and sanitation
National Water Resources Management Policy, 2003	This recognizes water as an economic good, opted for integrated and demand-driven services
National Economic Empowerment and Development Strategy-NEEDS (2003-2007)	Deals with water and sanitation challenges in urban areas, small towns, rural areas It prioritizes the development of adequate water supply and sanitation services as a way of reducing poverty and enhance socio-economic development
National Water and Sanitation Policy, 2004	This operated strictly in line with the demand-driven approach of the National Water Resources Policy
National Development Plan (NDP), 2007	Provides subsidies on water and sanitation facilities making them affordable for the poor
National Environmental Standards and Regulations Enforcement Agency Act, 2007	Stipulates a wide range of environmental protection, coordination and enforcement functions
Nigerian Standard for Drinking Water Quality, 2007	Provides standards for drinking-water quality to safeguard public health

Modified from Akpabio, (2012).

It is also the responsibility of the other tiers of the government (i.e. state and local governments) to construct, manage, distribute, monitor, and repair water infrastructural facilities in both urban and rural communities within their jurisdiction. The new sectoral policy reform in 1999/2000 stipulates the involvement of more actors in the water supply chain. The interactions and roles of some of the stakeholders are shown in Fig (2-6) as adopted from Obeta, (2019). At the top is the Federal Ministry of Water Resources as the head and coordinating agency of the government responsible for providing water in the country. The representative agencies for the State and local governments are the state water corporations and the zonal water units respectively. The other key stakeholders, who make policies and give technical supports to the state and organise financial assistance throughout the country. To ensure better efficiency in water delivery in the new policy reform, selected individuals, members of the community and NGOs are given mandates to ensure the continuous water supply at all times.

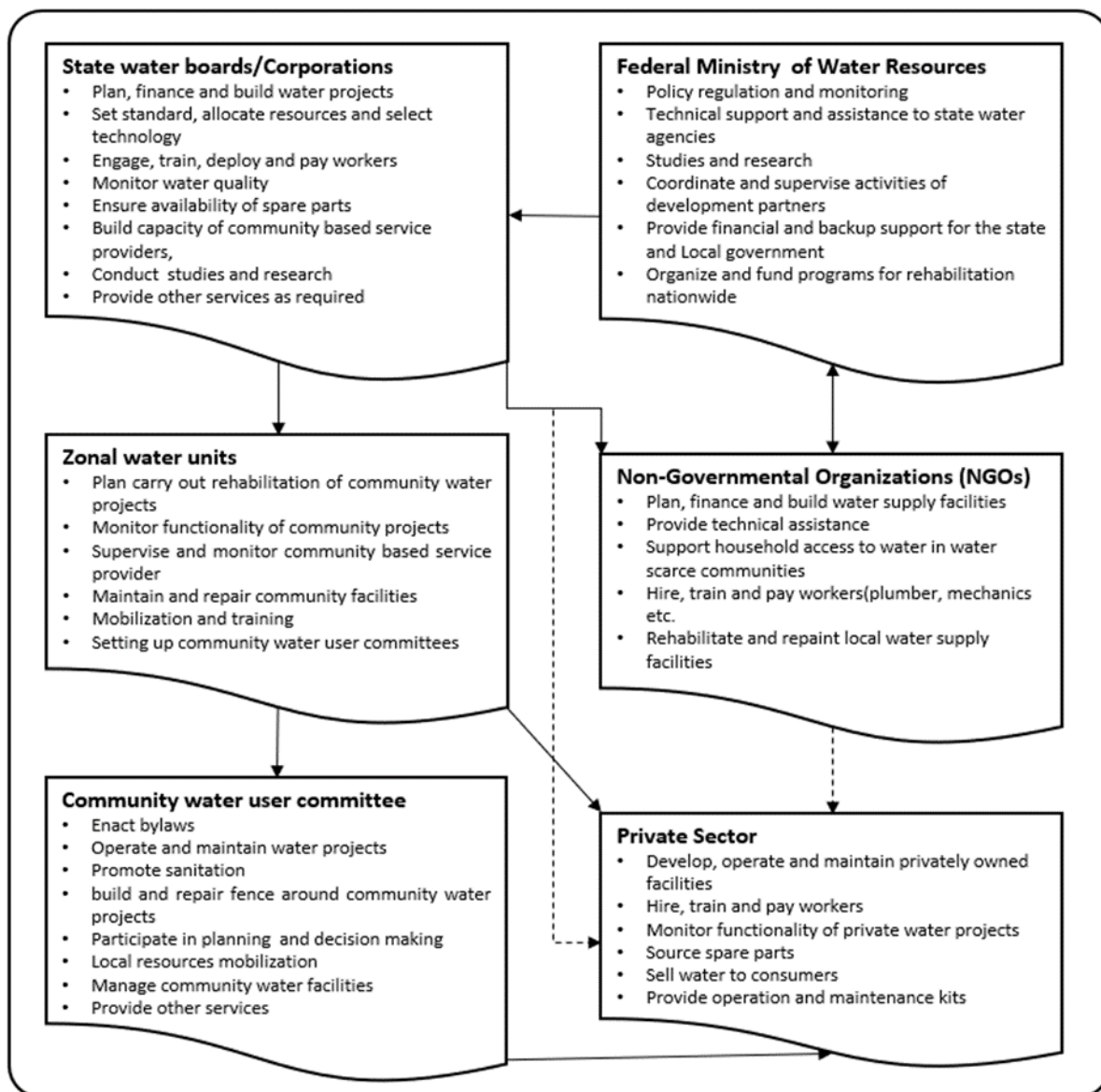


Fig 2-6: Interaction of stakeholders in the institutional framework for water supply in Nigeria (Source: Obeta, 2019).

2.4 Review of institutional management challenges in Nigeria

Despite the vast water resource endowment in Nigeria, there is still a high prevalence of water shortage among both urban and rural dwellers. At the end of the MDG, in 2015, it was reported that approximately 57 million people still do not have access to safe drinking water in Nigeria (World Bank 2017). The analysis of the report shows that there is a spatial disparity in the access to improved water sources between the urban dwellers who have better access compare to persons living in rural areas. In 2017, the breakdown of the proportion of the population that has access to improved water sources showed that 66.8 % of the population use non-piped, but improve sources. With this report, the

Nigerian government needs to invest more in the water sector to fulfil its commitment to meeting SDG 6a (UNICEF, 2019). Generally, the scarcity of water and the poor performance of the water sector has been linked to both natural catastrophes such as drought, flood, desertification, etc., and anthropogenic stress such as poor watershed management and pollution of the watercourse) leading to water unavailability in different parts of the country. Other issues responsible for the shortage of drinking water include the high population growth rate, rapid urbanization rate and the rising living standards of Nigeria (FGN, 2004). To adapt to these natural and man-made stresses in the water sector, sound management policies and other instruments need to be put in place to protect the resource and ensure sustainable use. Despite the numerous regulatory instruments put in place by the government, the water sector has remained under-developed and the shortage challenge lingers. The continuous creation of multiple autonomous agencies within the sector has led to the duplication of functions and conflicts of interest among these agencies (Ogunba, 2011; Enyidi, 2017). These weaken the institutional frameworks as the agencies lack coordination. The recent reforms in the policy amendment of 1999-2000 in the sector brought together the public-private partnership in the provision of water to the people. This may degenerate the continuity of the public water service delivery in Nigeria (Obeta, 2019), and present a short-run solution, which could be considered a “ticking-time-bomb”. Reports have shown that the private water supply has improved and guaranteed increased access to drinking water supply in most parts of urban and rural Nigeria (WaterAid, 2019). However, the engagement of private stakeholders in the domestic water supply services has been reported to have two main disadvantages: (a) they exploit poor consumers to maximize profit (Meagher, 2013), and (b) they can deliver unsafe water that has not been treated to the people (accepta, 2017).

To overcome these shortcomings, the government should control the pricing of water vending if privatization is a way to solve the problem of supply through programs that will set the price of water delivered to consumers. Palaniappan et al. (2004) support that water supply should be consumed at a price to serve as a control. The pricing ensures that the resource is efficiently used and the resource is better conserved.

However, privatization promotes availability and communal use, but the government should ensure that the water is seen as a “social good” rather than an “economic good” for-profit maximization. This can be achieved if the government play a strategic role in the sector by providing support by way of free training for private operators, all-round monitoring of the quality of the water, set performance criteria and subsidies in areas that ensure availability of water for domestic and drinking purposes.

Chapter Three

3 Case study area: Aba City and its environs

3.1 Background

The tale of challenging water situations in Nigeria is synonymous with the semi-arid Sahelian parts of Northern Nigeria. The scarcity of water in this region has led to several issues ranging from socio-economic and humanitarian hardship, as well as to health problems. However, little or nothing is said about the humid parts of the country with abundant water resources but access to water by the people is not adequate, even in urban areas. On the other hand, people living in urban areas are expected to depend on the public water supply for which the service is dysfunctional in almost all the major towns and cities across Nigeria. This raises the question about how do people meet their water needs, in the poorly regulated environmental condition that poses a threat to the quality of the water sources in different parts of the country?

The southern part of Nigeria is mostly humid and has an abundant reserve of freshwater resources, yet access to improved water sources is still a mirage in most urban areas. The groundwater is the major source of domestic supply and plays a very important role in meeting the water needs of people living in most urban areas. Therefore it is important to address the factors surrounding the resource potentiality and quality of the groundwater for the sustainable management of the resource in this part of the country. For this research, Aba, a typical and important commercial area in the Southeastern part of Nigeria was selected to demonstrate the water situation, factors influencing water availability and cost-effective management of the resource within the region. Some of the important characteristics that can influence resource use, general quality, and availability include population, socio-economic, and physiological factors in the area that will be highlighted. This is because these factors contribute to both anthropic and natural stress on the quantity and quality of water in the area. The chapter will be divided into two parts. The first part will deal holistically with the population and socioeconomic factors that influence the water consumption pattern. While the second part gives a detailed background of the physiological factors including the hydrometeorological conditions, geology, and hydrogeological situation for better understanding the factors influencing the natural water availability and quality in the selected study area.

3.2 Physical and socio-economic description

Since 1901, Aba was one of the regional outposts in southern Nigeria in the British colonial days. It is the commercial and economic hub of Abia State, as well serves other important towns in the South-east region of Nigeria. It is a densely populated area and has grown continually in population since the national population census of the 1930s. The rising population trend can be illustrated in Fig (3-1). The trend in the population time series demonstrates a steep rapid population growth starting from the mid-1970s to the present. It is currently densely inhabited with over one million people living in the area (translating to a population density of 4500 – 5000 persons/km²). The area spreads through five local government areas including Aba North and Aba South local government areas forming the core of the Aba urban centre. The urban periphery includes fast-growing settlement and commercial areas in Obingwa, Osisioma, and Ugwunagbo local government areas. It covers an estimated total area of 236.1 Km² (the Aba shapefile on ESRI world street base map in ArcGIS. See the map of the study area in Fig (3-2). The rapid population growth rate in the area puts pressure on the existing urban infrastructures, which are dilapidated at the moment due to poor maintenance and lack of expansion of the facilities to accommodate the fast-growing population. The area is famous for its artisanal craftsmanship, which has attracted medium-large-scale manufacturing industries including breweries (soft and alcoholic beverages), plastic-blowing manufacturing, soap and detergents, pharmaceutical products, textile, glass, as well as corrugating aluminium roofing sheets. Other products manufactured in the area are agricultural value-added products such as vegetable oil, palm oil, as well as palm kernel oil processing, petroleum products marketing; and other allied chemical products e.g. paints manufacturing etc. Commercial trading activities are found in different parts of the study area. These activities include small-medium scale artisanship in shoe-making, metal fabrication, carpentry, auto repairs, tailoring are some of the works that make Aba famous.

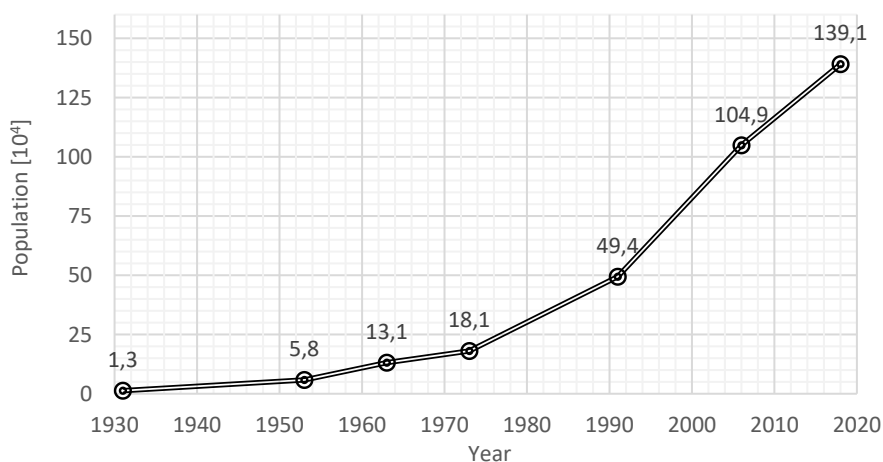


Fig 3-1: The population growth time-series from 1930 to 2019 based on the actual and estimated population (Population data gather from Nzeadibe & Anyadike, 2012 and NBS, 2012).

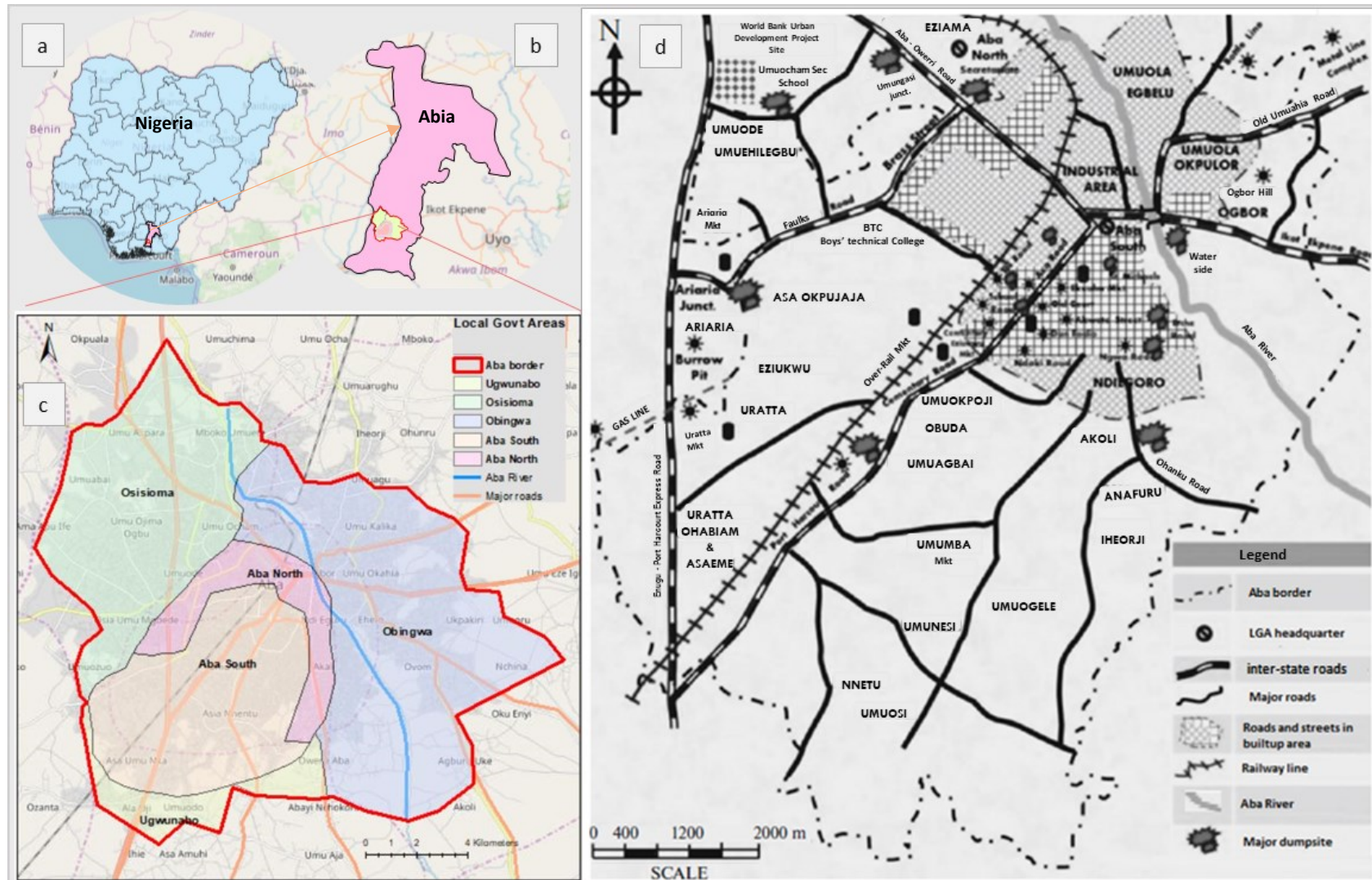


Fig 3-2: Map of the study area showing maps of (a) Nigeria (b) the federal state of Abia (c) constituent local government areas of Aba, and (d) some urban features in the core urbanize parts, which can influence the water quality in the study area.

((d) was modified from Agharanya & Dim, 2018)

The locally-made Aba products are sold in both formal and informal shopping/trading locations at small, medium and large scales. Table 3-1 shows a collection of some important commercial trading centres in Aba. These commercial centres in the study area serve many local and international markets distributed within Nigeria and some West, as well as Central African countries. There is also subsistence farming taking place around the peri-urban communities that flank the area, mostly for small-scale crop and livestock productions. Some of these activities require a large volume of water and they depend basically on the groundwater. The generated process effluents are poorly handled before release to the environment and this may contaminate the ground surface and ultimately the groundwater.

Table 3-1: List of some commercial trading areas in Aba.

Name of Shopping centres
Aba (Ekeoha) shopping centre
Amagbonna Market
Cemetery /Eziukwu Market
Pharmaceutical wholesale market
Enyimba Electronic market (street market)
Ngwa road new Market
Umungasi salat market
Waterside cattle market
Alaoji auto spare-parts market
Nsulu market (Slaughterhouse)
Ojike lane/Milverton cement and building material market

3.3 Physiographical characterization of the area

3.3.1 Hydrometeorological evaluation

The analysis of data for the climate variables such as temperature and monthly rainfall in the study area were obtained from the Agrometeorological station at the National Root Crop Research Institute (NRCRI) in Umudike (42 km N 25°E of Aba) for 30 years between 1980-2010. The arithmetic mean of the monthly rainfall⁴ for the period under consideration was used to calculate the annual rainfall. The results showed that the maximum and minimum annual rainfall recorded over this period ranged between 2070 – 2460 mm. The range of rainfall indicates that the area falls under the ultra humid agro-ecological zone as shown in Table 2-1. A five-year moving average of the annual rainfalls was performed on the data to smoothen the crest and troughs in the line plot of the time series from 1994-2014 and the trends in the annual rain pattern in Fig (3-3(b)). The rainy season months start around

⁴ Average rainfall estimation can be done using three methods. These methods include arithmetic mean, Thiessen polygon and Isohyetal method. The arithmetic mean method is used for flat and low-lying relief areas.

March / April and last until October, whereas the dry season begins in November and ends in March. For all the months, September was observed to be the month with the highest received rainfall and December is the driest month of the year according to the average monthly rainfall data in Fig (3-3(a)). The average monthly temperatures (minimum and maximum) were analysed starting between 1980 – 2010. The results of the analysis showed that the average annual minimum and maximum temperature over this period were 23°C and 33.1 °C respectively throughout the year. The data revealed that February is the warmest period of the year while July and August recorded the lowest average maximum temperature for the period covered. Generally, the rainy months have relatively lower average temperatures than the dry month (relate the line plot of the average monthly temperatures and the bar chart of average monthly rainfalls in Fig (3-3(a)).

In general, the coefficient of variation of the regression line for the average annual rainfall revealed a decreasing trend as shown by the slope of the equation of the straight line (See Fig (3-3(b))). Also, the overall decreasing trend in the illustration corroborates with the Mann-Kendall statistical analysis of the annual volume of rainfall received in the area as reported in Ogbonna et al. (2015). However, the degree of wetness of the months was evaluated based on the analysis of the average monthly rainfall

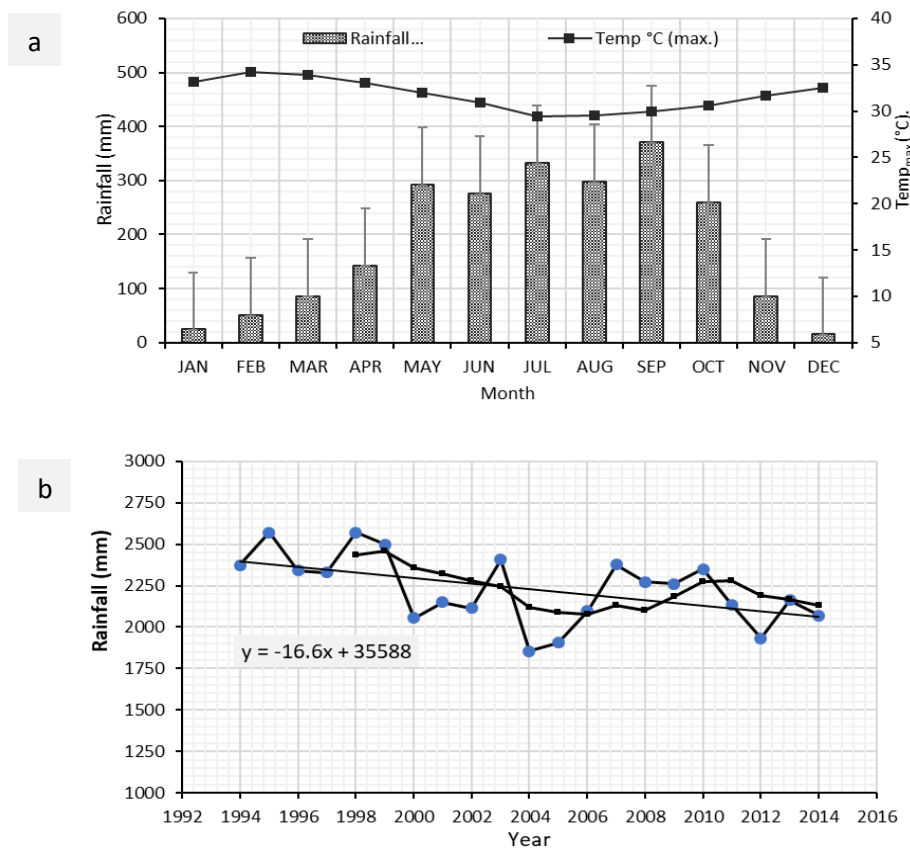


Fig 3-3: Illustrations showing time series of climate variabilities (a) monthly average of maximum temperatures between 1980-2008 and average monthly rainfall between (1994-2014) and (b) trend in the annual rainfall pattern between 1994 - 2014 with a 5-year moving average.

using the concept of the rainfall coefficient as described in Gemechu, (1977). The results of the rainfall coefficient calculations and the categorization of the rainfall seasonality (i.e. rainy and dry) months are summarized in Table 3-2 for the study area. The outcome of the analysis revealed that July and September were the rainiest months in a calendar year, while December and January were the driest months of the year.

Table 3-2: Results of rainfall coefficient showing seasonality classes throughout the year.

Month	Rainfall coefficient	Category	RC Interpretation ⁵	
January	0.1	Dry	< 0.6	Dry
February	0.3	Dry	0.6 - 0.9	Low wet
March	0.5	Dry	1 - 1.9	Moderate wet
April	0.8	Low wet	2 - 2.9	High wet
May	1.6	Moderate wet	>3	very High wet
June	1.5	Moderate wet		
July	1.8	Moderate wet		
August	1.6	Moderate wet		
September	2.0	High wet		
October	1.4	Moderate wet		
November	0.5	Dry		
December	0.1	Dry		

3.3.2 Climate-based water budget analysis

The water budget takes into account the estimations of components of the hydrologic cycle, primarily rainfall, evapotranspiration, storm-run-off, and changes in the stored groundwater. To qualitatively describe the water budget, a climate-based approach that describes the hydrological budget⁶ was followed. The choice of the qualitative evaluation of the water balance is because of the paucity of micro-level rainfall data to carry out a comprehensive model of the study area. A few climatological data such as monthly precipitation, temperature, evaporation rate and wind speeds were collected from the meteorological station close to the study area and used for the analysis of the water budget. The budget information represents the water resource potentiality in the study area.

The most important water balance components considered within the catchment of the area include rainfall [P], actual evapotranspiration ET_o , storm runoff (overland flow) R and the lump change in groundwater recharge represented by ΔS . The relationship between these components is summarized by the water balance equation given by the expression shown in equation 3-1:

$$P = ET_o + R + \Delta S \quad (3-1)$$

⁵ Interpretation and classification of rainfall coefficient follows the procedures in Gemechu, (1977).

⁶ Hydrological or water budget is a hydrologic concept that describes the water inflow – outflow in a watershed.

Of all the components, the actual evapotranspiration is the most difficult parameter to measure directly in the cycle. The most common methods directly use to obtain the actual evapotranspiration are achieved through experimental measurements. These include the use of the lysimeter, soil moisture depletion and water balance estimation methods. However, the water balance method is carried out based on the estimations of accurate measurements of components of the hydrologic balance. The estimation of storm runoff and net recharge or change in groundwater storage components is usually predicted from well established hydrological models (Combalicer et al., 2008), while the precipitation can be simply measured in the field using the rain gauge.

In contrast, estimating the potential evapotranspiration ET_o from climate data is easier from well established empirical methods. The ET_o can be calculated from two (2) approaches (a) Blaney-Criddle and (b) Modified Penman methods (Tukimat et al., 2012). The estimation takes into account climate parameters such as temperature, day length, humidity, wind speed and sunshine radiation. The equation of the Blaney-Criddle depends only on temperatures and it is most suitable for arid conditions than the latter, which can be modified for any climate condition (El-Wahed and El-Mageed, 2014). The ET_o expresses the upper limit for terrestrial water loss through the vaporization process via transpiration of plants, as well as evaporation of surface water and soil moisture respectively. The expression of reference evapotranspiration implies that there is a continuous loss of water even when there is no surface water available, whereas the actual evapotranspiration is obtained from field measurement and/or based on accurate hydrological models from the water balance components or the other methods.

The estimation of the potential evapotranspiration was calculated based on the FAO ET_o calculator (<http://www.fao.org/land-water/databases-and-software/eto-calculator/en/>), which is based on the reference evapotranspiration. Therefore, in this study, the ET_o refers to the reference evapotranspiration estimated with the FAO ET_o calculator. The basic principle used for the

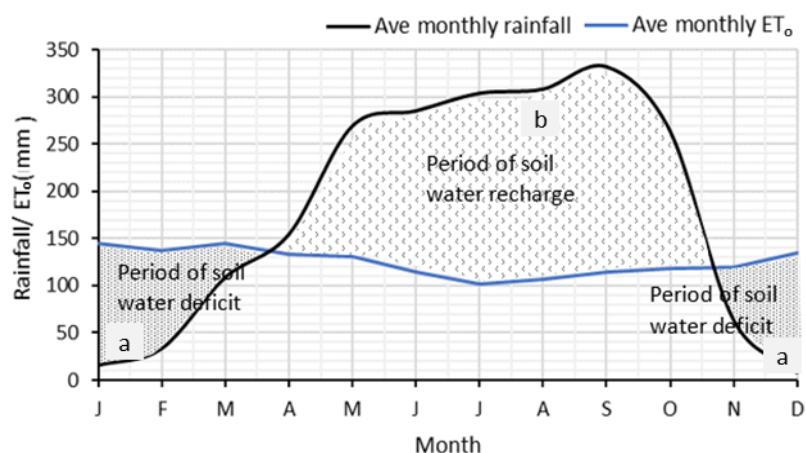


Fig 3-4: Climate-based qualitative hydrological balance showing the interaction of average monthly rainfall and the corresponding potential evapotranspiration (ET_o) between 1994-2016.

development of the calculator was derived from the Penman-Montheit equation. The calculator can use to estimate the ET_o even when some of the climate parameters are missing.

For this study, the monthly potential evapotranspiration for the period (1994 – 2016) was estimated from the corresponding averages of the monthly rainfall, maximum temperature and minimum temperatures. The remaining parameters indicated in the equation were augmented with constants built-in in the calculator. The climate-based qualitative hydrological balance of the study area was constructed as shown in Fig (3-4). The illustration represents an average water supply (rain) and demand (evapotranspiration) plots for the reference period. The interaction of the plots of the average monthly rainfall (P) and potential evapotranspiration (ET_o) show three important periods in Fig (3-4). These periods can be described as follows:

- i. Rainfall (P) < potential evapotranspiration (ET_o)
- ii. Rainfall (P) > potential evapotranspiration (ET_o)
- iii. Rainfall (P) = potential evapotranspiration (ET_o)

The first period represents the zone of water deficit, which is represented in the shaded segments (a) in the qualitative chart between the periods January – March and November – December respectively. There is less frequency of rainfall and the marginal temperature difference between the day and night temperatures are higher. During this period, there is an increase in the evaporation rates of open water bodies, as well as the transpiration for the plants. Overall, there is a deficit in the amount of rainfall received to compensate for the potential evapotranspiration. The depletion of soil water in the area occurs through different sources, including direct loss of water from surface water bodies, top-soil surface, more intense transpiration in the plants, required to cool them and loss of the groundwater through the increased capillary rise. This situation is typical during the dry months (November to March) of the dry season in the area.

The second period depicts the zone of water surplus represented in the shaded segment (b) of the chart. This zone represents the runoff components to the surface waters and increases in the groundwater storage (i.e. net rainwater infiltration and recharge) of the groundwater. This happens during the better part of the rainy months (i.e. mid-March and October) of the rainy season. During this period, there is a high volume and frequency of rainfall, which exceeds the amount of potential evapotranspiration rate. This period leads to the storage of the surplus rainwater in the aquifer, flooded ponds and surface water. The final period of equal rainfall and evapotranspiration corresponds to the beginning and end of the rainy season, which corresponds to mid-March and the end of October respectively. During this time, surplus rainfall ideally equals zero, as all rainfall were used to take care of evaporation and transpiration needs. Some of the infiltrating rainwater stay in the soil unsaturated zone and it is available for plant transpiration.

3.3.3 Water budget quantification

The water budget calculation in the study area was based on the data available from the meteorological station, so only a rough estimation of each of the components according to equation 3-1 was possible. The average monthly rainfall (P) data was used as the main source of water supply in the study area. The evapotranspiration process is the natural pump that takes away water and represents the most important natural form of water removal mechanism in the catchment. The estimation of reference evapotranspiration (ET_o) obtained from the FAO calculator and the regional evapotranspiration obtained from the literature ($ET_{(literature)}$) will be used as the maximum and minimum limits, respectively for the area. Other forms of water removing mechanism could be human-induced. These are direct or indirect water withdrawal systems for industrial, agricultural and domestic purposes. The surface runoff and net recharge (i.e change in groundwater storage) are renewable forms of storage mechanisms within the catchment. These are usually estimated with accurate hydrological models. The amount of rainwater stored in the aquifer depends on several factors such as the soil type as well as prevailing geological composition, topographic features, land cover/land use types, etc. in the area. Therefore, the rainwater infiltrating rate through the ground depends on the spatial surface sealing distribution in the area. These surface sealings could be natural or man-made induced by land use practices in the area.

3.3.4 Estimation of net groundwater recharge

The net infiltration rate of rainfall can be directly correlated to the net groundwater recharge in an area. This hydrological phenomenon comprises two main components. They include the net groundwater recharge and the baseflow discharge into the surface water body. Several methods can be used in the determination of net groundwater recharge rates in the area. Other than this method, the water-table fluctuation (WTF) method (Hassane et al., 2016), chloride mass balance (CMB) (Hamutoko et al., 2017), the use of environmental isotope (Adomako et al., 2010; Fareze et al., 2016) and the water balance method (Bazimenyera and Zhonghua, 2008) has been used to demonstrate the net groundwater recharge rates in these studies. The annual net groundwater infiltration rate in the study area was estimated using the water balance equation approach according to Bazimenyera & Zhonghua, 2008. The runoff coefficients for different land use classes were incorporated into the water balance equation and implemented spatially over different land use classes identified in the land use map as shown in Equation 3-2. The calculations show the distribution of the net-infiltration rate in different parts of the area.

$$N_r = (P_a - ET_o)(1 - R_r) \quad (3-2)$$

where N_r = Net infiltration rate;

P_a = Average rainfall (mm/annum);

ET_o = Average reference evapotranspiration (mm/annum);

R_r = Surface runoff coefficient for different ground surface.

The implementation of equation (3-2) was based on some factors which affect the net recharge rate and the following assumption were considered:

- 1 The geology and soil type prevailing over the entire study area are uniform
- 2 The topography of the area is more or less flat
- 3 The rainfall (P_a) and evapotranspiration (ET_o) are uniformly distributed throughout the area
- 4 The net recharge rate depends on the land use distribution
- 5 The net infiltration (recharge) rate N_r is inversely proportional to the runoff coefficient assigned to the land use class of the area.

6 The net infiltration rate comprises the change in groundwater storage, interflow, and baseflow
 Based on this premise, the average annual net recharge rates for the area were estimated for each land use type from Equation 3-2, by implementing the corresponding runoff coefficients on the appropriately identified land use classes in the land use map of the area for 2017. It is worthy of mention that both primary and secondary data were used for these calculations to obtain the average annual actual and potential evapotranspiration, as well as the distribution of the effective rainfall in the study area based on the GIS-based analysis of the land use map of the area in 2017. The results of the hydrologic cycle components are summarized in Tables 3-3.

Table 3-3: Results of annual average hydrologic cycle components from 1994 -2016

Average annual rainfall P	2143.0	
Annual Evapotranspiration ET	ET_o	$ET_{(literature)}$
	1499.8	900.0*
	Min	Max
(P – ET)	643.2	1243.0
Annual surface runoff	303.4	586.4
Annual infiltration rate	339.8	656.6

All the parameters in the water balance equation were measured in [mm]. * value represents the average regional actual evapotranspiration ($ET_{literature}$) obtained from Hayward and Oguntoyinbo, (1987) and Ophori (2007). The ET_o is the average reference evapotranspiration calculated with the FAO calculator based on the hydroclimatic parameter obtained from the NRCR weather station at Umudike for the study area.

The (P-ET) factor represents the effective rainfall derived from the corresponding average annual rainfall and the lower and upper limits of the evapotranspiration in the study area. Table 3-4 summarizes the results of the identified land use classes, the distribution ratio of the land use classes, annual runoff and infiltration coefficient, as well as the net recharge rate in each of the land use classes. The result of the net recharge distribution shows the range of volume of groundwater stored underground in the aquifer. This represents about 15.9 - 31.9 % of the average annual rainfall received.

If the study area - Aba City and its environs covers 236.1 sq Km, then this ratio will amount to an average of 80.5 -155.5 million cubic meters/annum of groundwater stored in the aquifer.

Table 3-4: Summary of the results of net recharge rate by land use types in Aba

Land use class	Area ratio	Runoff coefficient [R_r] ⁷	Infiltration coefficient	Net recharge rate (mm/annum)
Settlement	0.36	0.8	0.2	21.7 – 43.3
Barren land	0.09	0.6	0.4	46.9 - 83.8
Vegetation	0.38	0.15	0.85	138.9 – 268
Arableland	0.17	0.1	0.9	111.2- 215
Total				339.8 – 656.6

3.3.5 Geology and Hydrogeology

The groundwater availability depends on factors such as geology, soil morphology, topography and rainfall patterns, which describe the area. The geology of Nigeria comprises the basement complex and sedimentary rocks, with minor volcanic plateau rocks and the River alluvium (Nwankwoala 2015, Tijani et al., 2018). These sedimentary formations represent about half of the proportion of the geology of Nigeria and can serve as groundwater reserves. The geology of the study area (Aba) is typical of the eastern inland areas of the Niger Delta basin, which is composed of the continental coastal plain sand of the Benin formation as shown in Fig (3-5(a)). The Benin formation is one part of the three main litho-stratigraphic units in the Niger Delta basin as shown in the geological cross-section in Fig (3-5(b)) (Aminu & Olorunniwo, 2002). The Benin formation was formed during the Pleistocene – Oligocene in the tertiary-quaternary age (Shell-BP, 1957) and constituted the water-bearing unit in the depositional facies (Reijers, 2011). The Benin formation is made up of medium-coarse grain sand, very fine gravel and sometimes cross-bedded by localized clay lenses in the formation. The formation is one of the most important sedimentary aquifers in terms of groundwater reserves in southern Nigeria (Nwankwoala, 2015). The grains confer the aquifer excellent storage characteristics but the clay lenses make the aquifer sometimes locally confined in some places (Wright et al., 1985; Amadi et al., 2012; Tijani et al., 2015). The lithology of a self-conducted borehole logging in the area revealed the configurational layers of different soil textures in some private tube wells constructions shown in Figs (3-6(a) to (c)). The results of the lithograph revealed that the aquifer is unconfined. This corroborates with the strati-lithology reports in some parts of neighbouring cities like Umuahia (Ukandu et al., 2011) and the inland parts of Port Harcourt within the regional basin (Akpokodje and Etu-Efeotor, 1987).

⁷ The runoff coefficients is the fraction of the received rainfall which did not infiltrate into the groundwater. Due to paucity of data in this study area, the R_r were values estimated from the assigned runoff coefficient in Table 3-4 according to the report of Jinno et al. (2009) for different land use ground surface for different land use classes in to estimate the net recharge rate (change in groundwater storage).

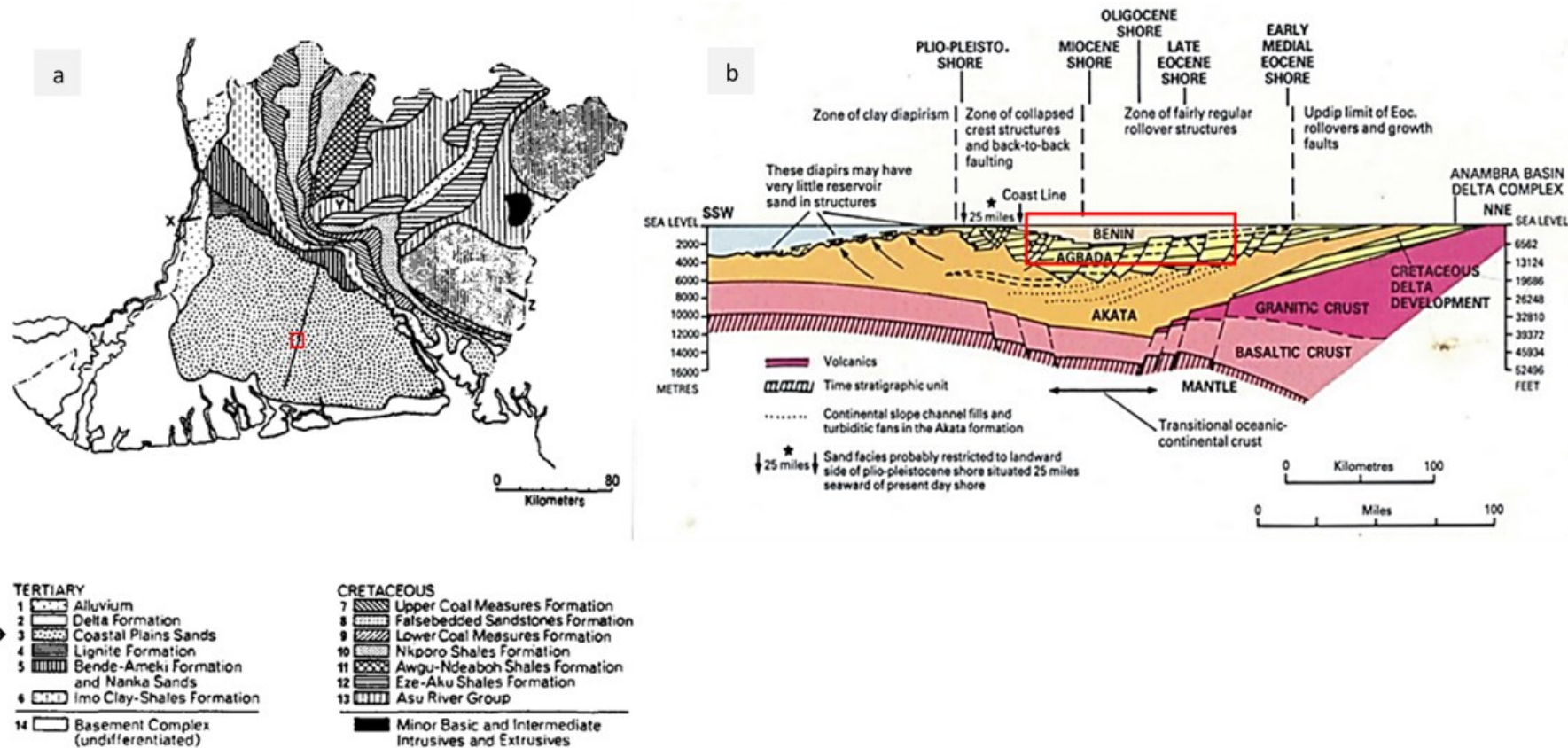


Fig 3-5: Map of eastern Nigeria showing (a) the geology and location of Aba (Lekwa & Whiteside, 1986) (b) generalized dip section in the structural provinces of the Niger Delta with emphasis on the Benin formation, which make-up the aquifer of the study area (Modified and adapted from Aminu & Olorunniwo, 2002).

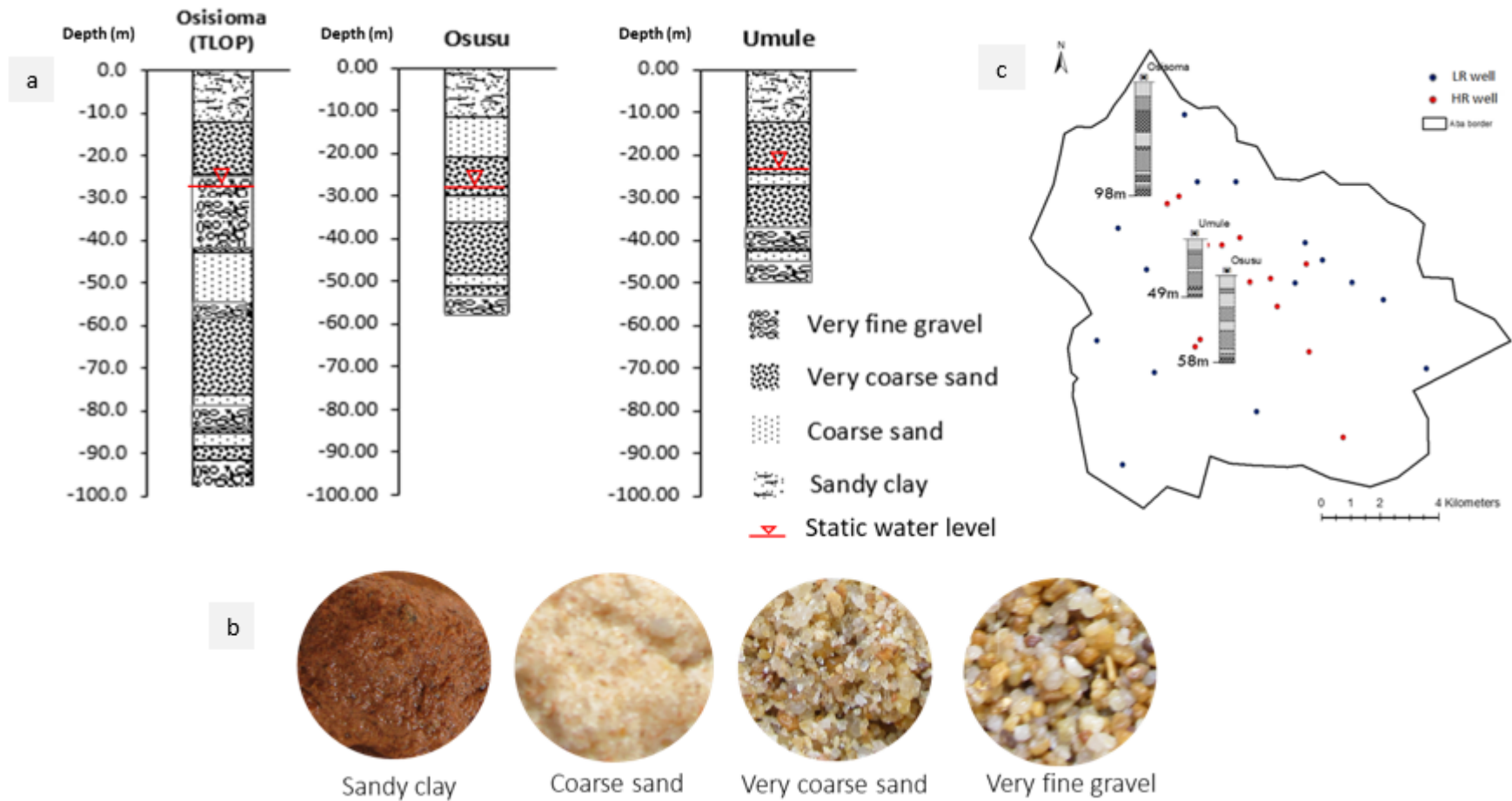


Fig 3-6: Hydrogeological investigations showing (a) the lithography of 3 sites at Osisioma, Osusu and Umule areas in Aba, (b) photos of some soil samples showing soil textures of different layers in the borehole log and (c) map showing the borehole logging sites and other tube wells distributed in both sparse built-up (LR) and densely built-up (HR) areas in the study area.

These borehole logs resembled those of the cities afore-mentioned, as they belong to the same geological formation as the study area. The water table elevations observed in different parts of the study area ranged between (21 – 33)m below ground level (field observation; Abaji and Nwankwoala, 2018). The tube wells at the trough areas close to the Aba River and wells at the south-western part of the study area have lower elevations. However, the average water table elevation was 27 m below ground level for the different dipped private tube wells during the hydrogeological investigations (See Table A-6.1 in Appendix 6). Other hydrogeological and hydraulic characterizations reported for the area include hydraulic conductivities K_f range from 0.13×10^{-4} to 5.70×10^{-3} m/s (Adamu et al., 2019; Agharanya and Dim, 2018) and an aquifer storativity of 3.53×10^{-4} (the coefficient dimensionless) has been documented for the area (Amajor, 1991). Based on the results of some pump test exercises carried out during the investigations an aquifer yield of 4.5 l/s was estimated for the area.

3.3.6 Soil characteristics

The soil is another physical aspect that influences both the quality and quantity of groundwater in an area. According to the reconnaissance soil map of Nigeria, the soil type is uniform and undifferentiated throughout the study area as shown in Fig (3-7). This soil type is described as the ferrallitic soil according to the FAO classification (ESDAC, 1990). The soil moisture properties are typical of the rainforest. The FAO classification describes the soil as red-yellow Ferralsol on loose sandy sediments, which is derived from the underlying unconsolidated sedimentary coastal plain sand of the Benin formation as the parent source of the mineral.

The morphological characterization showed that it is predominantly a medium grain sandy-clay soil type, and a reflection of the parent materials according to Adamu et al. (2019). This report corroborates with the results of the digital soil particle size fraction map of Nigeria (Akpa et al., 2014). The main mineral components of the soil type in the area are quartz, with little amounts of iron ore minerals (Chikezie et al., 2010). The petrographic microscopy of the parent minerals revealed that the sand compositions in the region comprise 95-99 % quartz, 1-2.5 % Na+K mica, 0.5-1% Feldspar and 2-3% coloured minerals (Ukandu et al., 2011).

The little fraction of the clay minerals present consists of kaolinite and other trace minerals (Lekwa and Whiteside, 1986; Chikezie et al., 2010). The soil pH is usually low. This is because of the wet and tropical rainforest conditions in the area. The acidity of the soil pH in the area influences the pH of the groundwater.

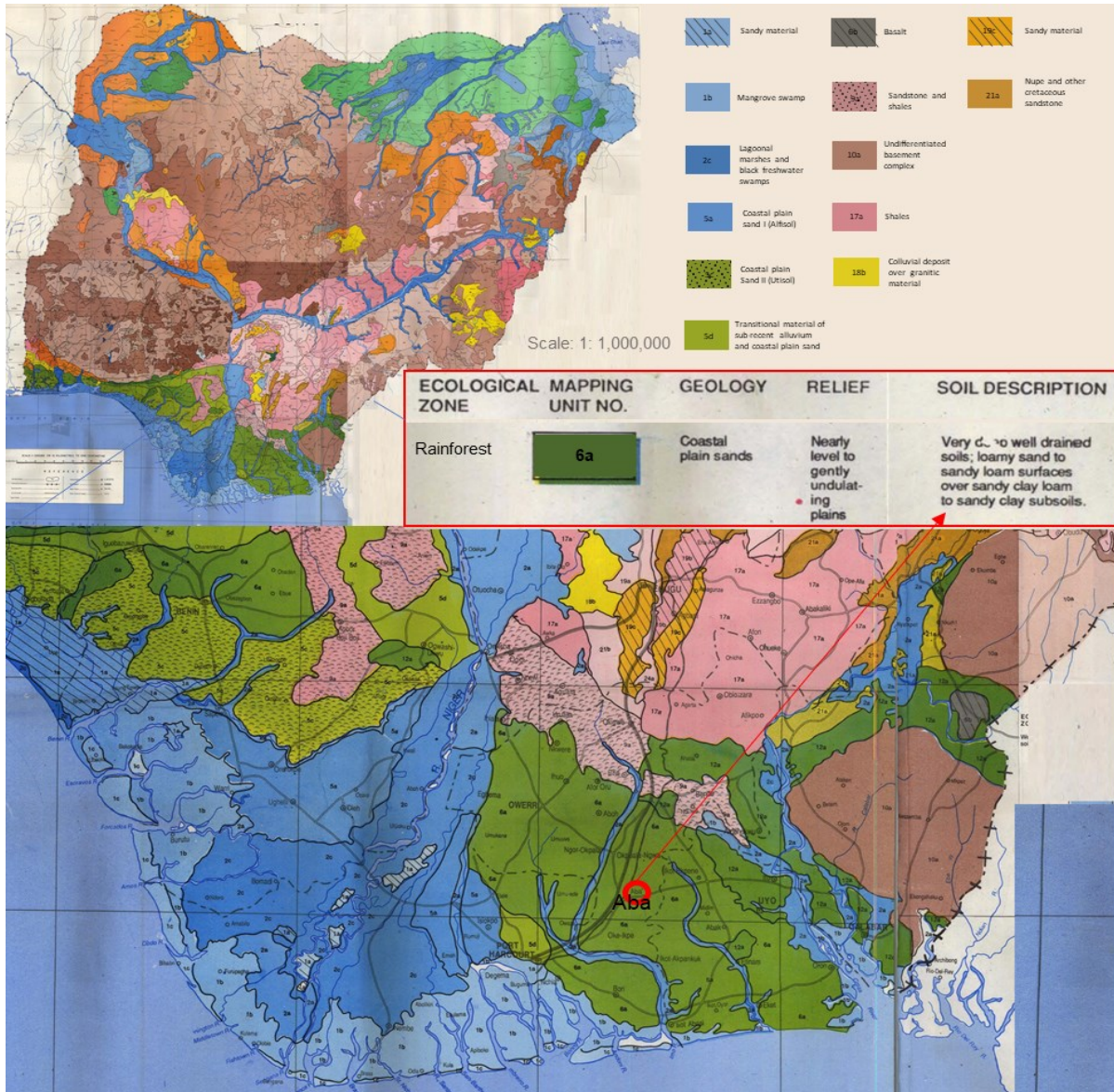


Fig 3-7: Soil map of Nigeria showing the location and soil description of the study area (Modified from ESDA, 1990).

3.3.7 Source of water supply

One of the distinct features that differentiate most urban settings from the rural ones is the availability of social and infrastructures integrated into the urban development architecture. These include amenities such as good road networks, hospitals, public water utility, central sewerage system, wastewater treatment facilities, amongst others for the people living in the urban area and provided by the municipality council. However, in many major towns in Nigeria and other sub-Saharan Africa urban areas, some of these amenities might be missing or some cases available, but in a deplorable state. Aba, Nigeria share this kind of situation. Historically, the area has three water schemes (waterworks) located at Industrial layout, CKC (Asa road) and the Ariaria schemes that supply different

parts of the area. Since 2002, these waterwork schemes have been dysfunctional. Currently, the main source of water supply for most households comes from groundwater tube wells. These wells are usually deep cased wells with submersible pumps, which are powered by an electric motor. The average well pump screen is positioned about 32m below ground level (private conversation with local drillers). The common drilling techniques used in the area are percussion and rotary drilling methods depending on the intended depth of the well. A typical tube well in the area is connected to an overhead tank(s) to provide pressure for the distribution of the water under gravity. Fig (3-8) shows photos of different stages in a typical tube well construction installed with a submersible motor (SUMO) pump used in private residential buildings. The stages include (a) the start of the drilling bit head (b) manual rotary drilling with the drilling technicians and roustabouts (c) end of tube well-casing with a plastic tube (d) installation of the SUMO pump (e) pumping of groundwater directly from the well and (f) overhead storage tanks for storing abstracted groundwater.



Fig 3-8: Photo Illustration of typical stages in private tube well construction and installation of submersible motor (SUMO) pump in a private resident block in Aba.

SECTION B

Methods, Results and discussion

Chapter Four

4 Empirical evaluation of the origin and access to drinking water in Aba, Nigeria

4.1 Background

One of the indicators for measuring the economic progress of a nation is the ability to meet the water needs of the people living in the country (SIWI, 2005). In many developed countries, running tap water in living and office spaces may be taken for granted, whereas it is a luxury in many countries sub-Saharan Africa, Nigeria inclusive. It is the statutory responsibility of the three levels of government in Nigeria to provide safe and potable water for her population. For instance, the federal states have the mandate through the States' water corporations to provide water needs for the people living in urban settlements. However, only 8.1% of the population is served by partially functional water corporations in Nigeria (NBS, 2009). This implies that most people in the urban parts of the country have to sort out their water needs through alternative sources that ensure healthy living and economic progress. Today, private water supply (PWS) is the most commonly practised system in both the urban and rural areas of Nigeria (Edet et al., 2011). This is not peculiar to Nigeria, but also in many other developing countries both in Africa and Asia, where PWS is practised in the urbanized areas (McIntosh, 2003). For instance, less than 30% of urban residents in Asia are connected to an uninterrupted water supply service in the urban areas and this service is mostly targeted to the urban rich who pay little relative to the urban poor (McIntosh, 2003). In most developed countries, PWS is most common only in rural areas. For example, 1% of the people living in England and Wales get their domestic water from boreholes and natural springs (DWI (Drinking water inspectorates) 2018) and only 0.8 % of the German population are served by hamlet wells (WHO, 2011). However, these types of small private water supplies serve people living in remote rural areas and these sources are subjected to less stringent regulations that might put public health safety in jeopardy.

On the one hand, public water supply⁸ has been argued to be a safer option for meeting the drinking and domestic water needs of many people than private water supply. This is because regulations bind public water suppliers unlike most private ones (DWI, 2018). Taking private water supply⁹ away from the hands of individuals and corporations, who sometimes can be exploitative and compromises the

⁸ Public water supply: this is a term used to describe water utility managed or licensed by the municipality to supply drinking water and water for other purposes to households and commercial businesses, especially in defined urban settings. They serve populations > 5000 people in a given area (McIntosh, 2003).

⁹ Private water supply (PWS): this is a water source provided by a non-licensed supplier. This type of water supply system according to the drinking water inspectorates has a capacity to supply < 10m³/day or < 50 people. They are not subject to strict monitoring and risk assessment by the state or national regulations (DWI, 2018).

quality of the service to maximize profits and ensures that water remains a social good. There are still health risks associated with the private water supply, for which not much is known about even in developed countries (Clapham, 2010). In Nigeria, over US\$60 – \$70 million are invested annually in the private water supply (Macheve et al., 2015). This includes the cost of installation and maintenance of private bore-wells, as well as contributions of households who obtain water from the commercial wells, especially in the urban areas.

An empirical field study is usually carried out to justify an observation or explain why a situation conforms to a certain pattern and based on that draw inference(s) on the subject. Sometimes the outcome of the empirical studies gives descriptives of the main subject, while others are explanatory depending if the design of the analysis is qualitative or quantitative. This approach has been widely explored in different branches of science and humanities. This research is aimed at taking a holistic approach that combines both scientific and perception-based techniques to come up with solutions that technically support the relevant authorities in solving the increasing problem of water inaccessibility in the area. In this chapter, questionnaires and semi-structured interviews will be used to explore the knowledge, behaviour and perception of the people, to identify and evaluate the current water issues facing the people of Aba. The goals are three-fold: first to determine the main and alternative sources of water for drinking, domestic and other purposes. Second, to understand the factors influencing the quality of the drinking water in the area. Third, to investigate the water consumption patterns of households. This will help in quantifying and understanding the current trends in the water withdrawal rates and usage in the study area. This information is important to fill in knowledge gaps, develop new literature for future studies and help local authorities to create campaign strategies that sensitize the local people on some of the bad environmental practices that harm the water resources in the area. It will also support the design of some policy recommendations and general outlooks on the appropriate ways in which safe drinking water can be managed and made available to households.

4.2 Methodology

The methodological approach used in this study is illustrated in Fig (4-1). The schematic flow chart highlights the different phases and actions that were identified for the understanding of the water situation in the area. This five-stage approach was developed and implemented by the author for this empirical study to meet the objectives of the research. This includes problem definition, data sources and collection process, data interpretation, main findings, and conclusion, as well as the recommendation phases.

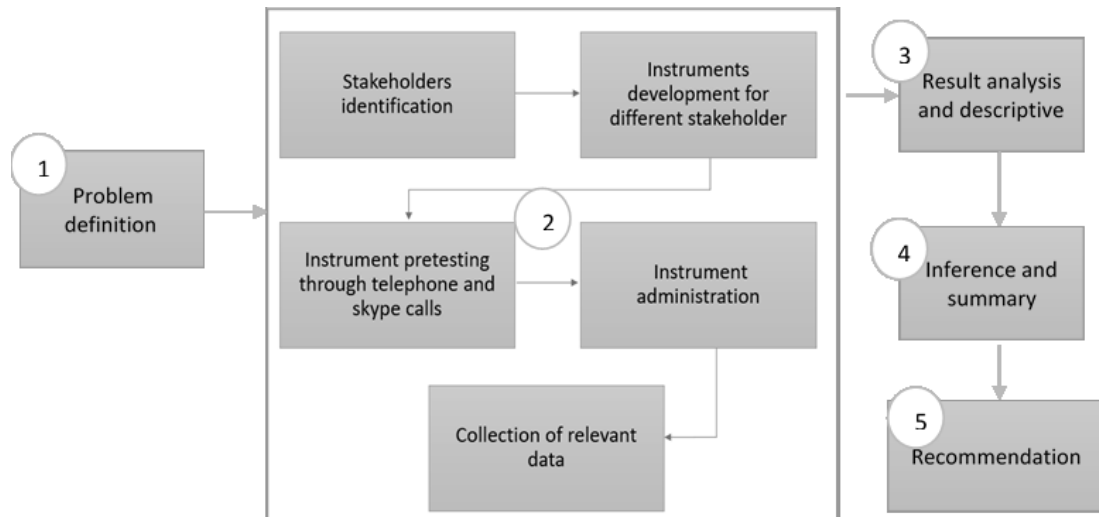


Fig 4-1: Schematic diagram showing stages in the empirical study to understanding the water situation in the study area.

Stakeholder identification: The stakeholders¹⁰ were randomly selected members of the case study area who responded to the survey. These included householders in the study area, members of any organization or representatives of relevant government agencies who use water directly or whose activities influence the use of water or affects the quality of water within the catchment of the study area.

The following stakeholders were identified and they responded in the surveys to:

- Household representative
- Experts from relevant industries
 - Borehole drillers,
 - Manufacturing industries and
 - Some fish farm owners
- Academia from institutions of higher learning who are teaching in relevant subjects
- Relevant personnel from the following government agencies
 - Local government authorities
 - Town planning authorities
 - Ministry of health and environment
 - Standards organization of Nigeria
 - State Waterboard authority

¹⁰ Stakeholder is a member of a group who can affect or be affected by the objectives, strategies or overall goals of the group. In our context, the stakeholders are the various component blocks that make use of or influence decisions on how water is supplied and withdrawn in the area.

Survey instruments: A set of questionnaires were designed by the author tailored to achieve the objectives set for the study. The survey tools were developed targeting different identified stakeholders to obtain the information (data) required to understand the problem of the water situation in the area. The administration of the survey questionnaires was a face to face chat guided by the questionnaire among randomly selected representatives stakeholders who were willing to participate in the research which cuts across the entire study area (a copy of the questionnaires' template is attached in Appendix 1).

Before the final data collection, the questionnaires were pre-tested with 10 respondents selected from the study area to ensure that the questions were properly formulated and suitable to meet the objectives of the research. During the interviews, voice recording and photos of the interviewee were avoided to encourage more people to participate, while retaining confidentiality in the exercise.

4.2.1 Procedure for the questionnaire administration

4.2.1.1 Household survey

The household survey was carried out in April 2016 in the study area. The sampling technique used for the administration was the multi-stage sampling procedure in which randomly selected respondents from households in 10 densely residential parts of the study area were targeted. For each of the areas, an average of 15 households was interviewed. The survey administration involved a face to face chat and the answers to the questions were recorded in the questionnaire for all the interviewees. The questionnaire has 3 parts namely: The first part contains questions on the origin of the main water source, who supplies the drinking water, and accessibility of the water source. In this section, different categories of the improved and unimproved water sources were listed based on the WHO/Joint Monitoring Programs classes for drinking-water sources and presented to the respondents to choose their main source of domestic and drinking water. The second part tests the respondents' level of awareness on the quality of the drinking water source and identifies some common contaminants sources to the water sources in the area. The third part estimates the domestic water consumption pattern of households in the area.

4.2.1.2 Industry and expert surveys, and informal chats

The participants in this part of the study include stakeholders from the industry, academia, government agencies and other stakeholders of interest as identified earlier. The snowball sampling techniques were mostly adopted for the stakeholder identification and selection in this case. The selected experts were consulted and required to complete the industry survey and participate in the semi-structured interview designed for this study through face-face interviews and in some cases, follow up chats using skypes and telephone. The main aim of the industry survey was to determine

the daily water extraction rates, categorize the industries based on the water needs, and assess their environmental performance in terms of effluent disposal options in the study area. Based on the water demand of the different industries, the daily abstraction rates of some of the industries were ranked and categorized to manage the quantity of the main water source in the study area.

4.3 Results and discussion

A total of 150 responses were obtained from the household questionnaires and the data were analyzed to describe the water situation in the study area. These respondents were selected from 10 densely residential parts of the study area and Fig (4-2) shows the household distribution map for the survey. The overall observations and descriptives for the different aspects of the household questionnaire are summarized and discussed under the following headings:

4.3.1 Source and origin of water for drinking and domestic purposes

The results of the main water source for drinking in the study area can be classified into 3 categories as summarized in Table 4-1. Half of the respondents chose that the source of water for drinking water or domestic use comes from the tube wells/borehole as the most used option in the area.

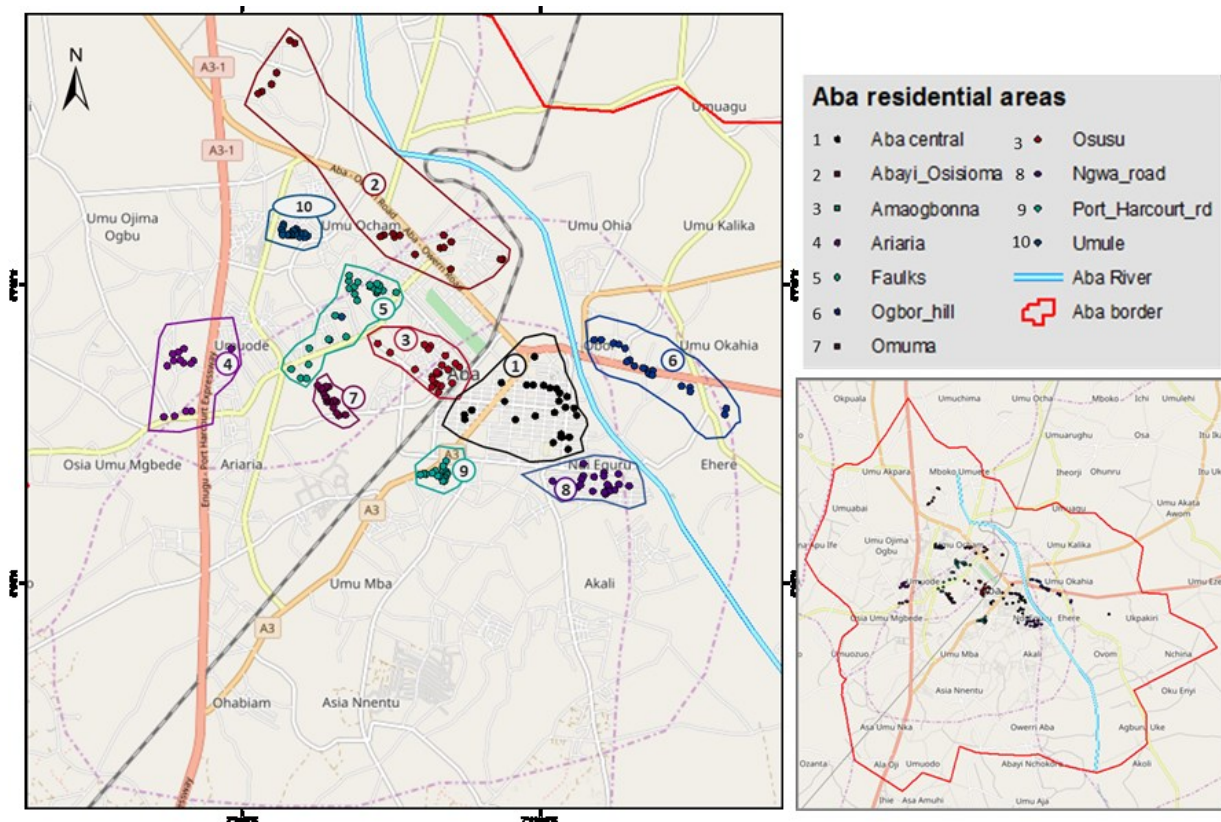


Fig 4-2: Map of household distribution in the densest residential areas in Aba.

This was followed by the alternative-drinking-water ¹¹ sources, i.e water in polythene sachet bags (a.k.a. pure water), as well as bottled water, and finally treated piped water. However, the treated water was identified as the least source of drinking water in the area. The use of water in sachet bags is very common and ubiquitous. This product is believed to have undergone at least some form of physical and microbial treatment. The industry has developed from manually sealed polythene sachets, now into a fully mechanized and automated hot-sealed water sachet industry. This represents the second most commonly used source of drinking water in the area and sometimes the most reliable source both in the urban and rural settings. This is because it is cheap and there are competitions among private vendors who produce them.

Table 4-1: Categorization of main sources of drinking and domestic water in Aba.

Drinking water sources	% of the respondent (N=150)	Categories of the drinking water sources
Treated piped water	2	Improved source
Tube well / Borehole ¹²	50	Unimproved source
Protected Springwater	0	Alternative sources
Protected hand-dug well	0	
Rainwater	0	
Unprotected hand-dug well	0	
Unprotected spring water	0	
Tankers / Vendors	0	
Streams/River water	0	
Bottled water	3	
Sachet water	45	

However, the litter coming from the packages of the packaged water is creating another environmental challenge due to the poor management of the waste that comes from these products. This product is not clear whether it belongs to the improved or unimproved water source type since the integrity of the water is not guaranteed. When the water is bottled, it forms another class of alternative drinking water sources. It is the most common source of drinking water among rich people because it is believed that quality is guaranteed. However, today the uncontrolled springing of unlicensed water bottling companies in the area has cast doubt on the quality of the water and some

¹¹ Alternative-drinking-water sources refer to commercially packaged drinking water sources that has supposedly undergone some form of physical or chemical treatment. These products are regulated by the national agency for food and drug administration and control (NAFDAC) but sometimes thses products do not conform to the local or international standards due to poor regulation. They include bottled water, water in sachet and ice blocks that can be served in drinks and used for cooling purposes to preserve food and keep drinks cool.

¹² Borehole water refer to water that is directly pumped from the underground and stored in an overhead tank without passing it through any form of treatment. The water in the overhead tank can be used through shared standalone pipe or distributed to the rooms within a residential property for drinking and domestic purposes.

of the bottled water products that might be treated as their “pure water” counterpart. It is difficult in this case to categorize them according to the water safety classes (i.e. improved or unimproved source). Therefore, packaged water - bottled water or water in sachet bags have been referred to as an alternative drinking-water source.

However, the treated piped water is the most reliable source of drinking water in terms of the quality of the drinking water, but the least in terms of accessibility. It is usually obtained from manufacturing industries, which are obligated by law to provide safe drinking water for their staff. This source of drinking water is extended to the general public through standalone pipes as a way of corporate social responsibility to the host community. They are mostly used by people living around the vicinity of the industries offering them because it is free. In most cases, the supply of the treated water is reliable. This confirmed the results of the quality indicators tested for in the treated piped water, which were found to conform to the standards of drinking water quality by the WHO. Sometimes, this water has been treated as part of the product line of the company. Examples of places where treated water can be found are some of the beverage and packaged water companies that offer free water to neighbouring households in the area.

The respondents identified three possible sources of drinking water in the area. These include rainwater, surface water (Aba River) and the groundwater from the tube wells. The results showed that 100% of respondents obtained the water from the groundwater. Against the surface water and rainwater sources; all the respondents said that the groundwater is the origin of drinking water across all households in the residential areas. This also applies to all the packaged water industries that abstract groundwater from tube wells for their product.

The questions of “who supplies water” to households were presented to the respondents to select against four main providers listed for them including “Government” (public), “Donor

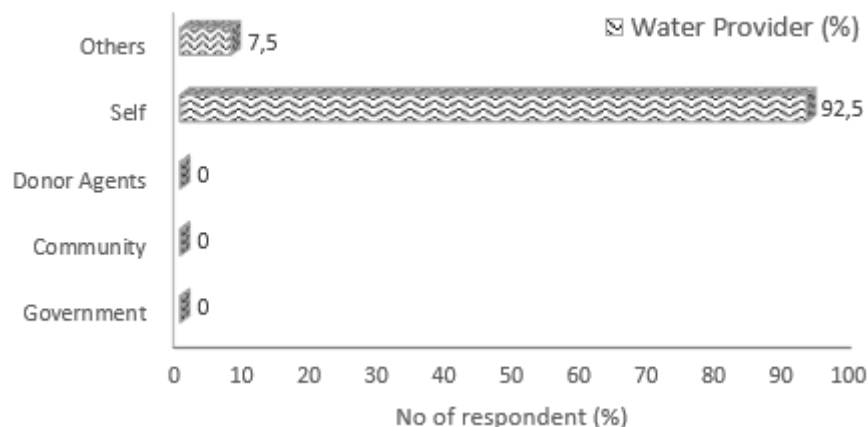


Fig 4-3: A column plot showing distribution of water providers in the area .

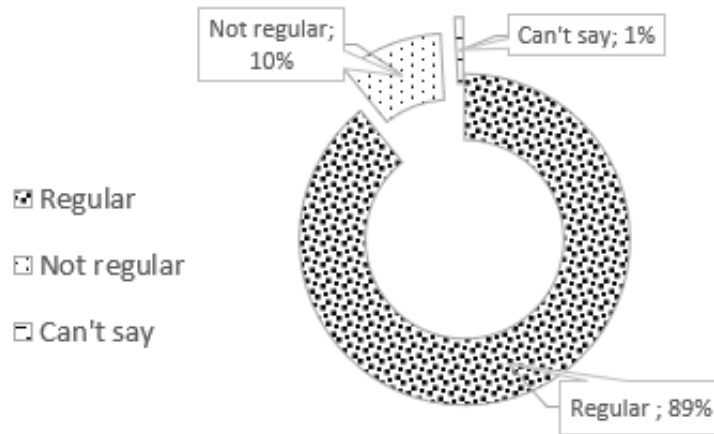


Fig 4-4: A pie chart showing distribution of respondents with access to the main source of drinking water in the area.

agencies/community-based services (public)", Self (private), and Others (private). The category "others" belong to households that obtain water from private organizations that supply the host community free water as shown in Fig (4-3). The results showed that respondents in all the residential areas get water from private sources (self or other sources).

The government (public) and community-based water supply systems in the area, which used to exist are currently unavailable. The responses to the question of "accessibility of the water" again, revealed that the water supply from these private sources are readily available in most parts of the residential areas and throughout the main seasons in the study area as shown in Fig (4-4).

Access to water for both domestic and drinking water purposes has improved as there are many wells, both private and commercially available, which gives the respondents options to select where and how much they want in every part of the city. Today, the supply of water is more reliable in the hands of private individuals compared to the service of the State water boards whose services were "epileptic" due to several technical and financial challenges surrounding their operations (source: a private conversation with the staff member of the Aba waterworks). The poor services of the state water boards are not peculiar to the state and this has been reported in different parts of the country (Macheve et al., 2015). The situation degenerates as the city grows in population and there were no commensurate infrastructural upgrades to take care of the fast-increasing population in the area. The water rent charges are too low and many users are not willing to pay regularly to sustain the services of the public water supply in the area. This situation has been widely cited as one of the problems facing the public water supply sector in Nigeria (Macheve et al., 2015).

4.3.1 Quality awareness on the water sources for drinking purposes

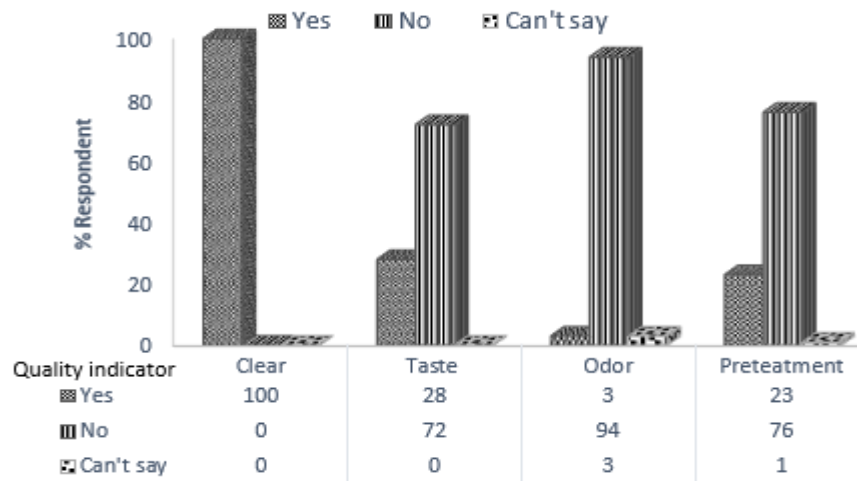


Fig 4-5: A bar graph comparing quality awareness in water sources by households in the study area.

The results of respondents' awareness of some physical quality indicators such as clarity, taste, odour, and if the drinking water is pretreated are summarized in the bar graph shown in Fig (4-5). The results revealed that drinking water (i.e. the groundwater) is generally clear for all the respondents. For results on the questions regarding if the drinking water has taste, showed that only 28% of the respondents said their drinking water source has an objectionable taste. Analytical tests on water samples showed that the total dissolved solids in the groundwater are higher in the densely residential areas and places where there has been confirmed sabotage or accidental spill affect the aesthetic groundwater quality. An example of this case is found in areas around the industrial estate in Osisioma. On the question, if the water sources have an odour. Three per cent of the respondents said that the water has objectionable odour. This response was observed among people living in the areas where the groundwater quality has been contaminated with petroleum hydrocarbon products due to pipeline sabotage. In this area, the groundwater is observed to have both odour and taste. In many parts of Nigeria with the right of way of the hydrocarbon pipelines, the occurrence of pipeline sabotage is a common phenomenon among communities. This has economic implications and degrades the environment (Ambituuni et al., 2015). Another source of odour and taste in drinking water identified comes from poor quality packaged water such as the commercial water in sachets. It is recommended that such packaged water, must be consumed within the recommended product shelf life. Olaniyan et al. (2016) reported a shelf-life of 12 weeks from the date of manufacture before the quality degenerates, developing an objectionable taste or/and odour. The objectionable quality in some of the packaged water products may occur due to poor handling of the products and the use of non-sterilized packaging materials. These encourage the growth of microbes in the water (Akinde et al., 2011; Omalu et al., 2010) and the conditions reduce the acceptability of the products, thereby making the water unfit for human consumption. The results of responses to the question if the

respondents pretreat their water before drinking showed that 23% of the respondents treat their water before drinking. This implies that the majority of the people in the study area drink untreated water coming directly from the source or have no idea if the water they drink was treated before they drink. Some of the common treatment options presented to the respondents include boiling, chemical treatment and allowing the water to stand so that suspended particles can settle. For the treatment options, respondents that boil their water represents 20%, while only 2.5% do some form of chemical treatment either to correct the pH of the water to the standard recommended limit or disinfect the water against microbial contamination. Further probes on the reason why the respondents pretreat their drinking water show that 94% of the treated water on health grounds to prevent illness, while the remaining 6% of the respondents “cannot say” why they pretreat their drinking water nor do not know the reason for treating their water.

4.3.2 Contamination sources to the main source of water

The outcome of the household survey suggests the groundwater is the principal source of water for households. Some potential sources of contamination in the area were identified and listed for respondents to choose and ranked on a scale of 1 – 5. The ranking was done in descending order in which contamination sources with low potentials are assigned the lowest scores. This was used to characterize the most potent of the contamination sources in the list so that the water quality indicator from these sources can be prioritized during the monitoring. The results of the ranking order are shown as Septic tank > industry > refuse dumpsite > auto-garage. Whereas contamination from underground storage and agrochemical were given the least priority in these residential areas but such activities are minimal or some cases non-existent in these parts of the study area. The result implies that the use of the septic tank is the most potential contamination source with the highest ranking in all the residential areas. In developed urban areas, household effluents, human solid waste and the urban storm are conveyed through a central sewerage system to the wastewater treatment plants. However, in developing urban areas such as Aba and many other cities in Nigeria, the use of septic tanks are used in the absence of the central sewerage to manage the household effluents in the area. Another environmental challenge arising from the lack of central sewerage is the way the sludge from the septic is managed when the tank is full. Most of the sludge evacuating agents do not have a treatment facility and discharge the biosolid sludge downstream into the Aba River (Source: a conversation with an operator). Other people in the very poor neighbourhoods, bury the sludge and discharge the liquid in the open drainage channel, leaving the area filthy and smelly. These practices further exacerbate the microbial integrity of the groundwater quality and increase the nutrient load of the surface water.

4.3.3 Socioeconomics factors influencing the choices of the respondents

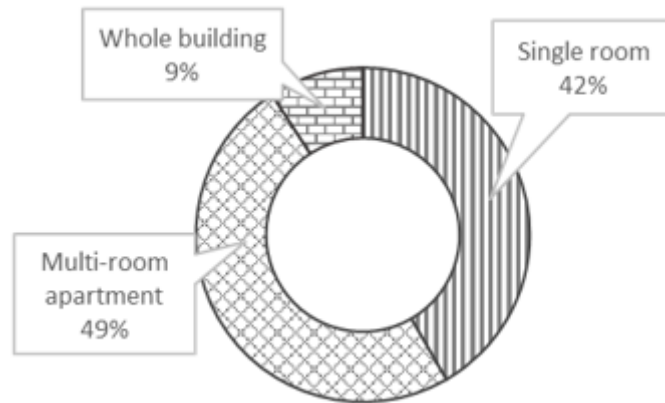


Fig 4-6: Pie chart of distribution of housing units types found in the study area.

The questionnaire captured some socioeconomic factors of respondents and these factors influence the water consumption patterns of the household. These factors include age, gender, family size, and type of housing unit occupied. The breakdown of the analysis showed that 54% of the respondents were male, 46 % female, the average size of the households lies between 4-5 members.

The distribution of different housing units lived by householders in the area is illustrated in Fig (4-6). The pie chart shows that the “multi-bedroom apartment” representing 49% of the householders is the dominant accommodation for most households, followed by the “single room” unit, which is 42 % and 9% of the respondents lived in the “whole building”. The housing unit and the household size can reflect the average income of the respondents. The respondents who live in single room accommodations are mostly found in informal settlement areas with very poor conditions. These households get their domestic water directly from the borehole in the neighbourhood which most often is fetched at a cost from these sources.

4.3.4 Urban influence on the quality of other water sources

The analysis of the hydrological conditions in the area in Chapter 3 showed that the area is endowed with a preponderance natural supply of freshwater resources. These sources include water from the Aba River (surface), an extensive rainy season supplying rainwater between seven to eight months a year, and groundwater. These sources can conveniently meet and sustain the water needs of the people in all the parts of the study area. However, the quality of the Aba River has been badly degraded due to the impact of some urban land use activities. These activities include the direct discharge of industrial effluents, release of municipal waste, the release of effluents from the abattoir, and channelling of the urban storm runoff into the river without any form of treatment etc. The lack of regulations on such practices that contaminate the water in the Aba River, making the source

almost unavailable for domestic use and may lead to serious ecological consequences such as eutrophication due to increase load of nutrients.

Rainwater is another important potential source of water for domestic use in the area. This source presents one of the purest forms of natural water and a lengthy rainy season for approximately eight months guarantees sufficient rainwater in the area. However, safe, hygienic or storage harvesting options of rainwater has not been exploited in the area. The commonest method of rainwater harvesting is through intercepting rain from rooftops to the water storage containers. However, there is little confidence in the integrity of the quality of the rainwater when it is collected. This is because the rooftops through which the rainwater was harvested were perceived to have been contaminated with droppings from birds, sometimes asbestos and corrosion particles from old roofing sheets in the rainwater. The contamination causes biological, chemical, and physical degradation of the rainwater coming from the roofing sheets. Again, the lack of space and storage containers sufficient to hold the rainwater for a long period makes the source unreliable for many households in the area

4.3.5 Households and industrial water consumption patterns

To estimate the households' water consumption power is not directly based on the available groundwater reserve in the area. The estimated population of the people in the area was acquired from the local municipal council for the different years and the households' survey data were used to supplement the demographic data in the case study area. The estimated population was based on the 2006 national population census of Nigeria with the current estimated population growth rate at 2.6%. Based on the population numbers, the estimated population for 2018 was calculated and compared with the figures obtained from the Ministry of health for the local Government Councils in Aba (population data based on the National Bureau of Statistics NBS, 2009). The estimated average number of households in the study area was calculated from the average size of the households and these were used to determine the average water consumption pattern. The results of the household consumption pattern are summarized as shown in Table 4-2.

Table 4-2: A Summary of social statistics of households and water consumption pattern in Aba

S/N	Water consumption estimations	Remark	Quantity
a	Estimated population of Aba	*	1 390 912
b	Estimated average household size	**	4.5
c	Estimated number of households in Aba	a/b	309 092
d	Estimated average household daily storage capacity (l/d)	**	161.4
e	Daily water consumption per capita (l/day)	d/b	35.9
f	Average total daily withdrawal rate by household (l/day)	c*d	49 887 449

*Sources of secondary data: Ministry of Health Aba North, Aba South and Osisioma Local Government Areas for the population in 2018. **derived from the survey as an average of the values collected.

The estimations are based on an average household size of 4.5 which was derived from the household survey in the area. The average household size corroborated with the size in the state of Abia, which averaged four persons per household (NBS, 2009). Despite the abundant freshwater reserve in the area, the result of the average daily water consumption per capita of 35.9 l/d in the study area was estimated. This rate was estimated on data obtained from the household survey, which take into account the average water storage capacity of the households and the duration it takes for the water to be used up.

Since there are no running taps inside the apartments in most houses, the use of water by members of the household are restricted by factors, including the water storage capacity of households, availability of space in house the storage containers, cost of buying water and the size of the household. These factors influenced the limited water sufficiency rates as estimated for the area, which is less than the daily water consumption per capita of 50 -100 l/d recommended by the WHO to meet the most basic daily water needs (UN, 2015). Based on these derived social statistics from the household survey, the average estimated daily groundwater withdrawal for domestic use is 49.9 million l/d in the area. In corroboration with these results, Macheve et al., (2015) in the performance assessment of the state water boards/agencies in Nigeria also found that the low consumption per capita rate of water in the households' of the study area, also tally with the reports for many states in Nigeria. This result applies to many of the Federal states, except that states in the North-central geo-political zones where the average daily water consumption per capita rate in the households are higher but still less than the lower limit of the WHO's recommended rate. The Asian Development Bank (ADB) reported similar results for some poor developing urban areas in the Southern Asian countries where the average water consumption per capita is < 40-50 l/d (McIntosh, 2003; Hunter et al., 2010).

4.3.5.1 Industry and expert survey

The set of questionnaires and semi-structured interviews were used to collate a list of industrial and commercial activities whose operations depend on the use of the groundwater and may have an impact on the hydrogeology or quality of the groundwater in the area. The surveys and interviews were administered on 20 experts drawn from the manufacturing industries such as beverages (3), packaged water (3), hospitality (3), agro-production (3), chemical industries (3), as well as other 5 relevant informants from government agencies and academia. The industries require water in varying amounts for different purposes related to production and process water, as well as products for which

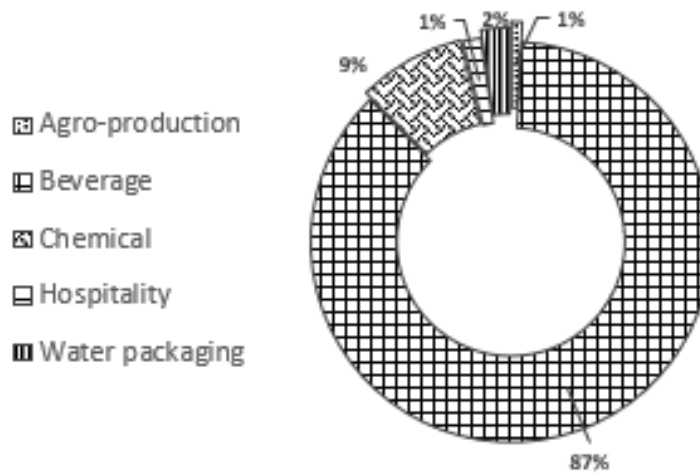


Fig 4-7: A pie chart of the percentage volume of water abstraction by industry.

water forms a large portion of the final product, e.g packaged water, and beverage drinks. The survey collected the storage capacity of each representative industry and the corresponding extraction frequency. The pie chart in Fig (4-7) represents the average distribution in volume per cent of the daily abstraction rate of the industries. The statistical ranking of the water needs for the industrial activities can be arranged in the following order: beverage > chemical > packaged water > hospitality > agro-production (Fish farm) in the area. This order represents the major industrial water abstracting activities in the area. But these categorizations do not depict all the industries operating in the area. The list represents the industries from which respondents were drawn during the field campaign. The main factors that determine the ranks for the different industries to their water demands are the scale of production at which the industry operates, the product and services they deliver, and the quantity of process water required for their operations. Currently, 297 manufacturing industries are operating in Aba (Source: a conversation with a staff of the Standards Organization of Nigeria (SON)). While some of the industry serves the local market, others produce for either the region, national or international markets. For instance, the beer and soda companies extract a huge quantity of water as part of their product and also produces a large volume of wastewater. The results of the industry surveys show that all the representative industries listed withdrew groundwater. Only 13% of the industries interviewed have a wastewater treatment facility in their plants. These plants are the large-scale manufacturing industries, such as the beer breweries and the soap manufacturing plants, which have the wastewater treatment plant within their plants. However, the discharged effluents of wastewater treatment plants were channelled directly to the Aba River, which made it the most vulnerable water source in the study area. The wastewater coming from most of the fish farms (representing 13%) are discharged directly into the aquifer. This can increase the nutrient and microbial load in the groundwater. The remaining industries discharge their effluent inside cesspits or direct to the open gutters (surface open channel) that empty inside the Aba River without any form of treatment.

Chapter Five

5 Geomorphometry and land use derived information

5.1 Background

The groundwater resource is an important source of water for domestic water supply in many developing countries. Globally, an estimated 1.5 billion peoples living in urban areas derive their domestic water supply from groundwater sources (Foster et al., 2010). Even in regions with abundant surface water reserves, groundwater is still preferred because it is considered bacteriologically safer than surface water. However, natural processes or human-induced activities can harm the quality of the groundwater. Natural processes influencing the quality of the groundwater are geogenic activities, and normally they cause gradual changes in the quality of the groundwater over an extended time. On the contrary, some anthropogenic activities have a significant impact on groundwater quality. In most cases, this is subject to the prevalent land use activities in the area. The interaction between groundwater and urban activities usually has a negative and rapid impact on groundwater quality (Anabella et al., 2014). These urban activities can lead to surface contamination due to poor environmental practices, which have been rampantly observed in many developing urban areas. Examples of urban land use practices that could harm the groundwater include inappropriate siting and management of municipal solid waste facilities, use of on-site sanitary facilities and defective septic tanks, excessive use of agricultural chemicals, as well as accidentally spilt industrial chemicals from manufacturing industries (Egboka et al., 1989). Other important sources include washed down atmospheric pollutants, such as inorganic sulfur (SO_x) and nitrogen (NO_x) compounds from smoke, flue dust, aerosols, and automobile emissions. These substances are most common in highly urbanized cities with large manufacturing industries and congested traffic situations. Some of these activities are the main sources of some emerging substances found in the groundwater for which their effects on both the humans and the ecosystem are not yet known (Stuart et al., 2011).

The prevailing indiscriminate and unregulated private withdraws groundwater for domestic, commercial and industrial purposes. This scenario characterizes many developing urban areas, and in the long run, the pumping activities harm the local hydrogeology and the consequence might affect the quality of the groundwater. The consequences of groundwater over-abstraction could cause land subsidence, pump failure, and poor groundwater quality.

The main goal of this chapter is to derive the impact of changing land use activities on the general quality and quantity of the main water source. In doing so, the following specific objectives will be achieved :

1. evaluate the land surface properties to understand the interaction between the hydrologic properties and the land use change;
2. detect the landcover/land use transitions over three spatial boundaries for 30 years;
3. identify, map and characterize the potential groundwater contamination sources

This will imply creating a hotspot map for the potential contamination sources within the study area. An inventory of some of the sources will be created to guide the relevant authority to carry out a risk assessment using some quality indicators variables identified. For each hotspot, the indicators will be used to evaluate the direct impact of land use activities on the quality and hydrochemistry of the groundwater.

5.2 Methodology

The schematic diagram in Fig (5-1) proposes a framework and methodological approach that systematically identify steps, as well as evaluate the interaction between the human stress to the landcover, land surface analysis and urban influence on the land surface. Some physical drivers influence the water flowing through the land surface as it interacts with human-induced land use. This joins the land surface flow and surface-derived contamination areas together through the geomorphometric properties and the groundwater contamination hotspots. The human-induced activities are directly connected to some of the urban-land use practices, which represents the human-induced stress on the physical arrangement. The landcover dynamics addresses the change detection in space and time based on activities taking place on the land surface, with special attention given to transitions in the urban land use class in the area.

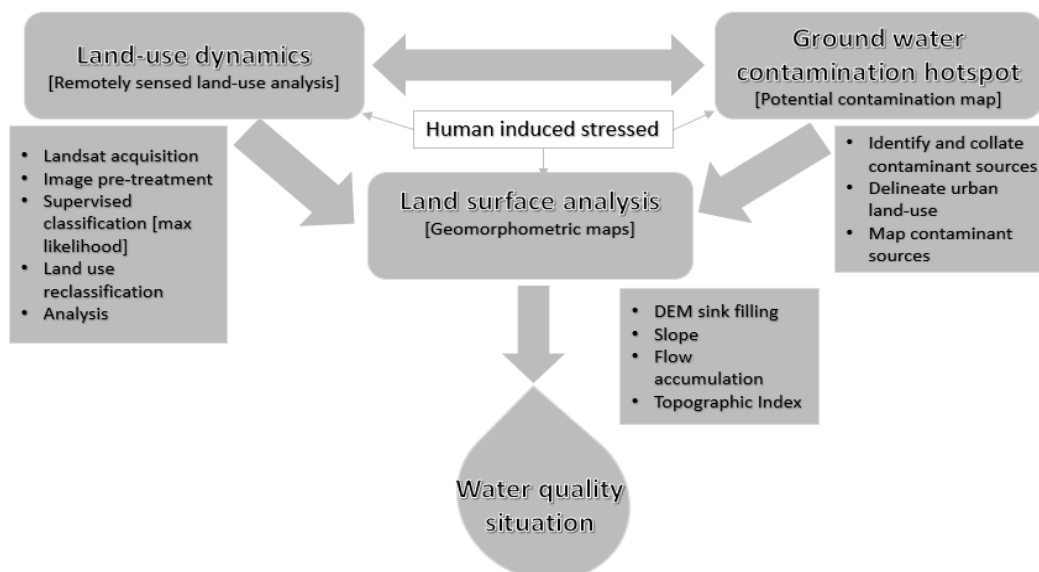


Fig 5-1: Schematic diagram showing the methodological linking urban land use stress on the terrain derived properties and the groundwater quality.

5.2.1 Land surface analysis

The land surface analysis takes into account land surface parameters (LSPs) derived from the Digital Elevation Module [DEM]. The concept of land surface analysis explores the topographic information, which can be directly derived from the digital elevation module (DEM). The DEM is a quantitative depiction of the earth's surface. These topographic properties in the area were evaluated using the free downloadable topographic data using the SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Module with a resolution $\approx 30\text{m}$, date of acquisition: 2014) acquired from the USGS EarthExplorer website applications (<https://earthexplorer.usgs.gov/>) or GloVis (<https://glovis.usgs.gov/app>). The visualization data for the DEM comes in three main formats and these formats include gridded DEM, triangulated irregular network (TIN) and digital contour (Mukherjee et al., 2013). The land surface parameters LSPs or morphometric properties inherent in the DEM can be derived through the application of surface analysis on the DEM/digital terrain model (DTM) on a GIS platform such as the ESRI ArcGIS. This was demonstrated for the study area following the flow schematic in Fig (5-2) differentiating variables that are obtained directly or derived from the DEM and considered for a better understanding of the water situation in the area.

The morphometric variables directly processed from the DEM are classified as primary terrain features. These include basic variables such as the elevation and slope, which gives information on the altitude and steepness of the surface respectively. Other primary terrain features considered gives regional information such as the surface catchment area, but was not considered at this time; and the hydrological features such as the upslope area properties including the flow direction, as well as, the flow accumulation. These properties describe the surface hydrological features considered in this

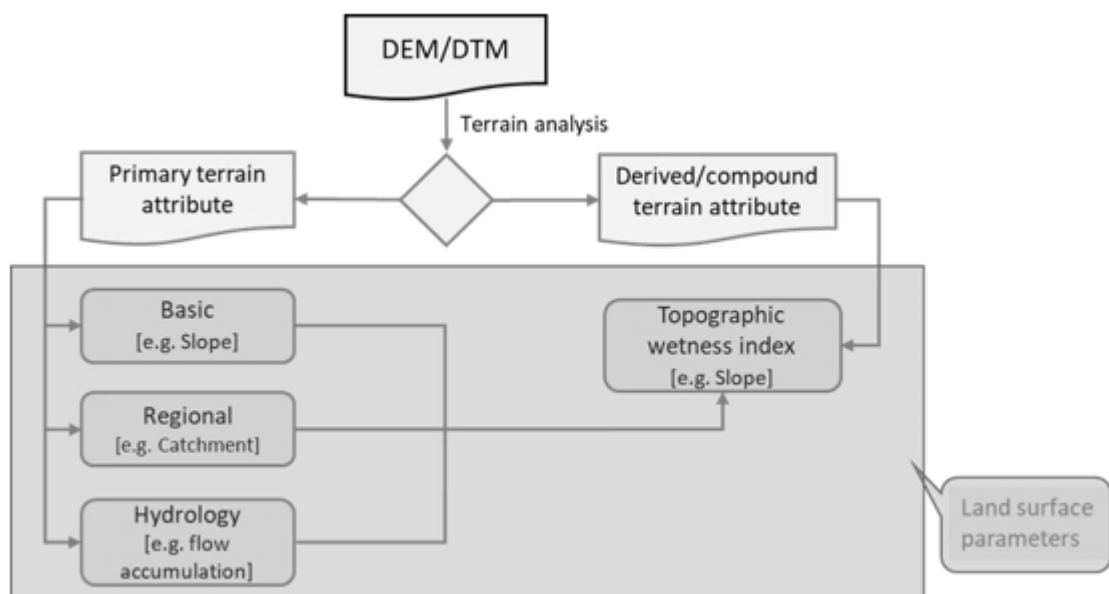


Fig 5-2: A schematic showing type of land surface parameters (morphometric variables) and data source for their derivative.

study. The derived or secondary terrain features are derived by combining the primary terrain attributes. One of the important secondary terrain features considered in surface evaluation in the area is based on the TOPMODEL (TOPographically-based hydrologic MODEL) (Beven et al., 1984). The model takes into account variables that contribute to the nature of the area and the hydrological response. It assumes that the topography drives the flow and can accurately predict areas where flow accumulates in the topographic low spots (Source: Lecture note: Soil and water research group, Cornell University). These spots can be depicted as streams, rivers, lakes, wetlands and upland depressions, which are groundwater recharge areas. The most important parameter of the TOPMODEL is the topographic index λ , also known as *Compound Topographic Index* (CTI) or *Topographic Wetness Index* (TWI) (Marthews et al., 2015). The index is calculated based on the equation 5-1:

$$\lambda = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (5-1)$$

where λ , α and β represents the topographic index, upslope area¹³ contributing area per unit length of the contour per unit length of the cells (i.e the hydrological flow accumulation) and the topographical slope respectively. The topographic index is a secondary terrain property because it is derived from other terrain properties. The implementation of these topographic parameters was carried out with the spatial analyst tool in ArcGIS 10.6 for the extracted DEM of the area.

5.2.2 Landcover dynamics and change detection

Remote sensing and GIS techniques were employed to characterize the prevalent land cover / land use. The remote sensing technique is one of the most common methods used in detecting changes in the landcover that have occurred in space and time on the earth's surface. It uses the electromagnetic reflectance of the landcover types (vegetated or non-vegetated) in detecting, identifying, and analyzing changes that have occurred in the area. It is an earth resource management tool (Zougrana et al., 2015). The landcover/land use analysis was done on the multispectral satellite imageries of the area obtained from the Landsat. A land use classification period of 30 years (a tri-temporal boundary) was adopted using Landsat imageries from 1986, 2003 and 2017 were used for the assessment. Good quality and free to download tiles of the Landsat multispectral imageries corresponding to the study area were obtained. The satellite data used include the Landsat 5 TM and Landsat 8 OLI/TIRS based on the suitability and availability of good satellite imagery for the area. Other ancillary information in the area about the land use classification was cross-referenced using satellite imageries from Google

¹³ Upslope area describes a contributing area above a contour, from which water flow get through the contour. It is a measure of the quantity of flow that run through the area

Earth and on-the-ground observations made (ground-truthing) during the field campaigns in 2016, 2017 and 2019. This was done to improve the accuracy of the land use classification and the class interchange analysis. The acquired Landsat imageries were pre-processed, trained and classified according to the supervised maximum likelihood algorithm in ESRI ArcGIS 10.6 program. The land use classes obtained can be described in Table 5-1 as modified from the FAO land use classifications.

Table 5-1: Landcover classification according to FAO.

	Land use class	Categories
Vegetated	Agriculture	Diminished forest, farms
	Vegetation	Evergreen forest, forest reserves, mixed grass, shrub, and tree
Non-vegetated	Built-up	Residential areas, tarred road, city centre, commercial & industrial areas
	Water	All the water bodies, e.g., streams, rivers, creeks, swamps, wetlands, mangroves, etc.

5.2.3 Groundwater contamination hotspot mapping

The mapping of the potential contamination sources was based on the identification and collation of different urban land use practices that can influence the quality and quantity of the groundwater. The resultant land use map of 2017 was delineated to isolated urban land use from the rest of the land cover types in the area. Some of the urban features were identified and digitized by tracing them out on the Google earth satellite at high resolution. The remaining were supplemented with objects after identifying them on the ground with their coordinates noted to enhance the accuracy of the mapping. The potential contamination hotspot map was developed by overlaying these features on the delineated urban land use and the topographic index maps. Through reviews and literature search, an inventory of some groundwater quality indicators was collated, which is linked to the identified urban land use practices for risk assessment in the area.

5.3 Results

5.3.1 Land surface analysis

The results of the land surface analysis derived from the SRTM DEM are shown in Figs (5-3 (a)-(e)). The illustrations include a) DEM with filled sinks, b) the slope, c) flow accumulation, d) the topographic index and e) the derived flow direction DEM with areas of upland depression respectively. These features control the degree of water flow and predict areas of flow accumulation, which are important for both the surface hydrology and groundwater recharging areas. The topographic map of the area is demonstrated with the gridded filled sink DEM showed in Fig (5-3(a)), which reveals the low and

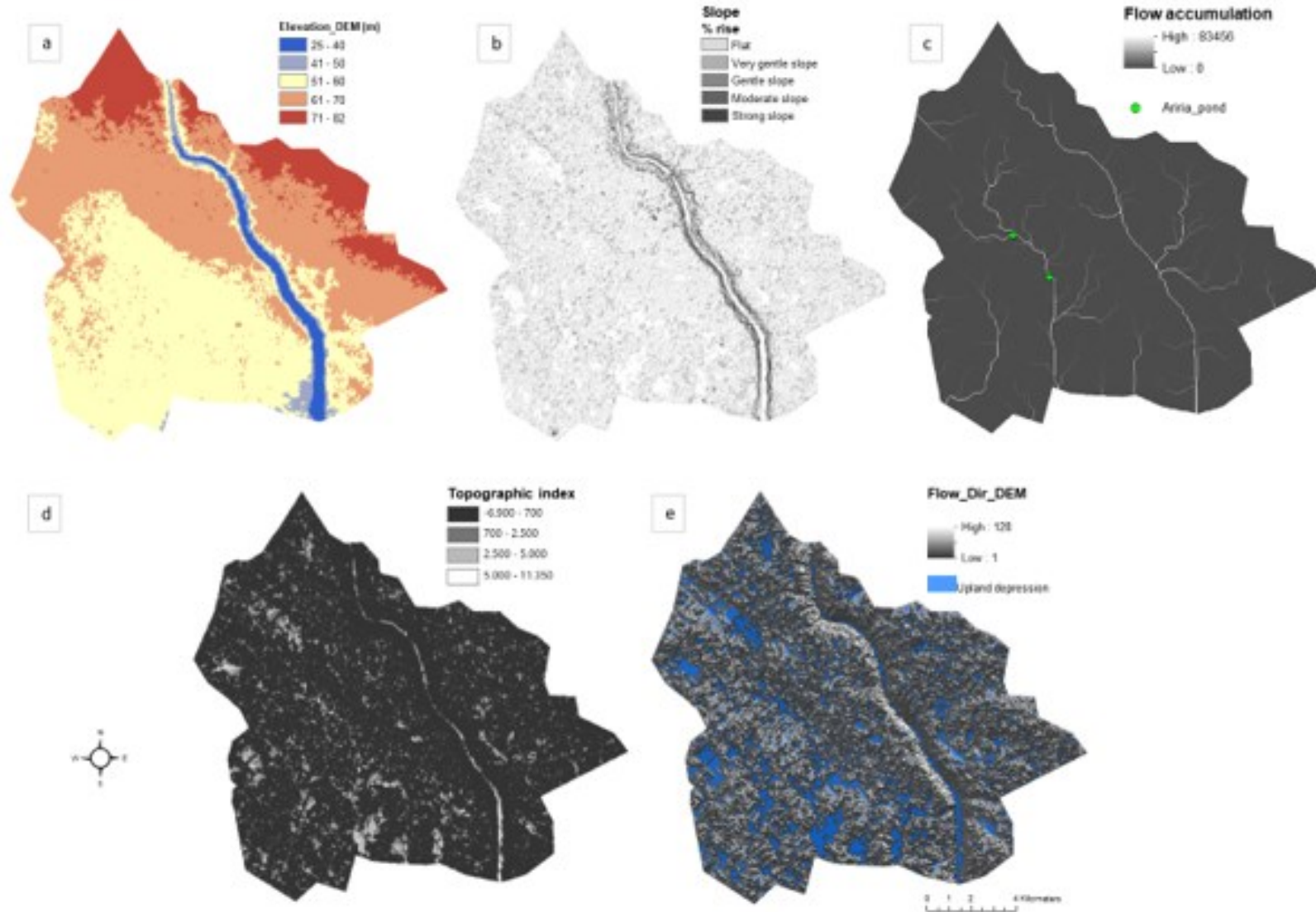


Fig 5-3: Maps of different land surface properties in the area showing (a) Filled elevation [DEM] (b) slope, (c) flow accumulation (d) topographic index TI and (e) a 3D impression of upland depression extracted from the TI and overlaid on the DEM of the flow direction.

high elevations in the map based on the classified colour ramp. The results showed that the minimum and maximum elevations in the area lies between 25m and 82m respectively, while the average elevation is 62 m above sea level. The lowest elevations are found along with the depression of the Aba River course, whereas the highest elevations are found around the N-NE corridors of the elevation map. The slope represents the change in the elevation of the area. It describes the downhill steepness in all eight directions.

Fig (5-3(b)) illustrates the slope map of the area which can be described by adopting the standard slope descriptor in (Barcelona Field Studies Centre, 2019). The evaluation of the slope descriptor in the map was summarized with a column chart as shown in Fig (5-4). The result showed that more than 85 % of the area is either flat or gently sloped which is typical of a floodplain. The steepest regions make up about 2.3% of the map, which is represented by a moderate–strong slope. This region constitutes the slope shoulders, especially along the Aba River axis. The remaining parts of the map are gently sloped areas. The maps of flow accumulation and direction models are shown in Figs (5-3(c) and (e)) respectively. These terrain properties characterize the flow and surface hydrology of the area. The development of the flow direction model was derived from the SRTM DEM after filling the sink to ensure that when water is dropped on the surface, it flows through along the stream path. The flow direction DEM suggest that the water flow in eight directions and the low-spot areas represent where the flow accumulates. These low spot areas in the map correspond to the upland depression derived from the topographic index map. The DEM of the flow direction and the upland depression has been illustrated in Fig (5-3(e)). Based on the DEM of the flow direction as the input grid DEM, the flow accumulation was derived using the spatial analyst tool in ArcGIS. The illustration in Fig (5-3(c)) shows the stream networks of the flow accumulation model generated in the area. The map suggests that the area is poorly drained since the stream network covering the area is not extensive.

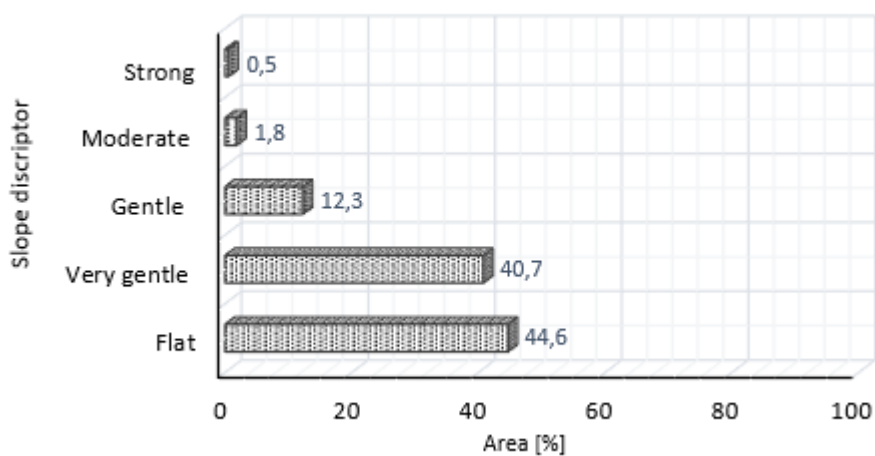


Fig 5-4: Column chart showing the slope analysis of the DEM in the study area.

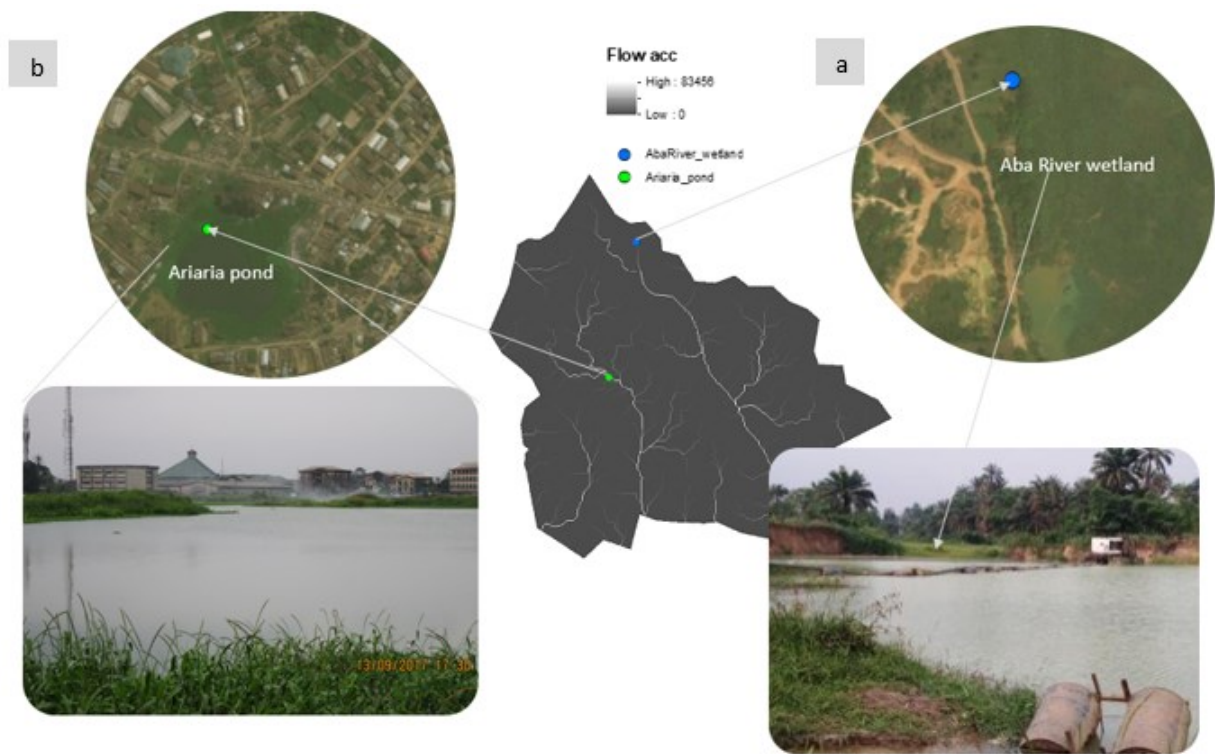


Fig 5-5: Illustration of flow accumulation map showing hydrological features (stream and ponds) in the study area.

The flow accumulation map shows two streams with tributaries which are represented by the light grey to white lines in Fig (5-5). These lines represent areas with high accumulation such as the Aba River and ponds or wetlands in the area. For example in the flow accumulation model, the main streamline in the area is on the hand right side and represents the perennial Aba River. This streamline was also seen as a conspicuous depression in the DEM grid. The Aba River flows from the NE to the South direction and it forms the main drain in the area. It discharges into the Imo River as one of its tributaries. On the other hand, the other stream networks at the middle and the left-hand side are not physical streams, rather along this streamline are pockets of ponds and wetlands on the land surface. The examples are illustrated with the photos and satellite imageries of the Aba River source head and the perennial Ariaria pond as shown in Fig (5-5(a) and (b)) respectively. The derived terrain property, topography index calculated from the flow accumulation and the topographic slope DEMs predict accurately the regions with the highest flow accumulation. These parts are important for both the surface flow and subsurface recharge of the groundwater system. But the topographic index does not consider some physical factors such as soil type, precipitation, vegetation types, etc. that could affect the results of its predictions. In Fig (5-3(d)), the regions of high flow accumulation are shown in the light grey–white patches in the topographic index map. The patches constitute the areas along the

Aba River and several other ponds, as well as wetlands. The analysis of the result of the TI map showed that 11.7 % is made up of upland depressions of the areas.

This is better depicted as the extracted blue patches which were overlaid on the DEM of the flow direction model in Fig (5-3(e)).

5.3.2 Landcover change detection/Land use analysis

The results of the analysis of the land use classification map over the selected time boundaries are shown in the maps in Fig (5-6). The landcover detection/land use classification maps identified four classes, which include urban land use, vegetated area, arable lands, and water. The components for each of the classes have already been described by the FAO land use classification in Table 5-1. A quick overview of the results of the land use classes in 1986 reveals that the vegetated areas were the dominant land cover class representing about half of the land use in the area. The vegetated areas consist of forest and palm plantations. This landcover type is the most being lost to urban land use. The arable land use is the second dominant landcover with a coverage of 30.3%, followed by urban built-up area 18.6% and the least landcover is the water land use class, which is 0.02%. The trend changes in the landcover between 1986 - 2017 suggest that the urban built-up class is changing rapidly. The concentration of the urban built-up land use is at the centre and it is a mixed built-up area consisting of residential, commercial, and industry built-up areas. The urban land use class has continued to increase and radially sprawl with a skew towards the North-eastern corridors. The results of the area and percentage covered by each of the land use classes between 1986 and 2017 in the study area are summarized in Table 5-2. The results showed that the urban sprawl in the area has almost doubled in size from 18.6 % to 36.1% between 1986 and 2017, while the vegetated areas continue to dwindle.

Table: 5-2: Land use classification analysis based on area covered by each class between 1986-2017

Class	Area (Km ²)			Area (%)		
	1986	2003	2017	1986	2003	2017
Urban	44.0	58.7	85.1	18.6	24.9	36.1
Vegetated	120.4	111.2	91.0	51.0	47.1	38.5
Arable land	71.6	66.1	60.1	30.3	28.0	25.4
Water	0.04	0.03	0.03	0.02	0.01	0.01

The trend array for the changes in the land use classes between 1986 – 2017 (31 years) revealed that the average annual growth rate are : Urban 1.33 Km² (0.6%) > Vegetated -0.95 Km² (-0.4%) > -0.34 Km² (-0.1 %) arable areas. The negative signs in the growth rates suggest annual losses in the land use class. It is worthy of note that the growth rate is a mean value, but the urban growth has doubled in size within this period.

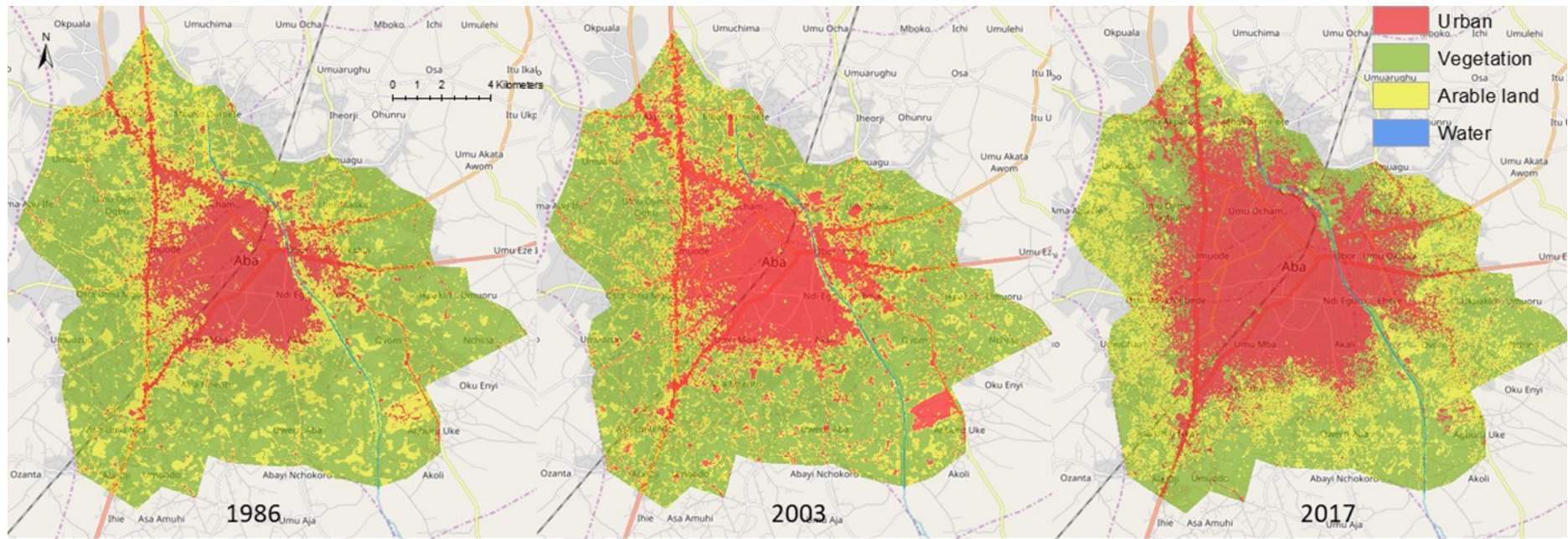


Fig 5-6: Land use map of Aba illustrating changes in the land use classification from 1986 to 2017.

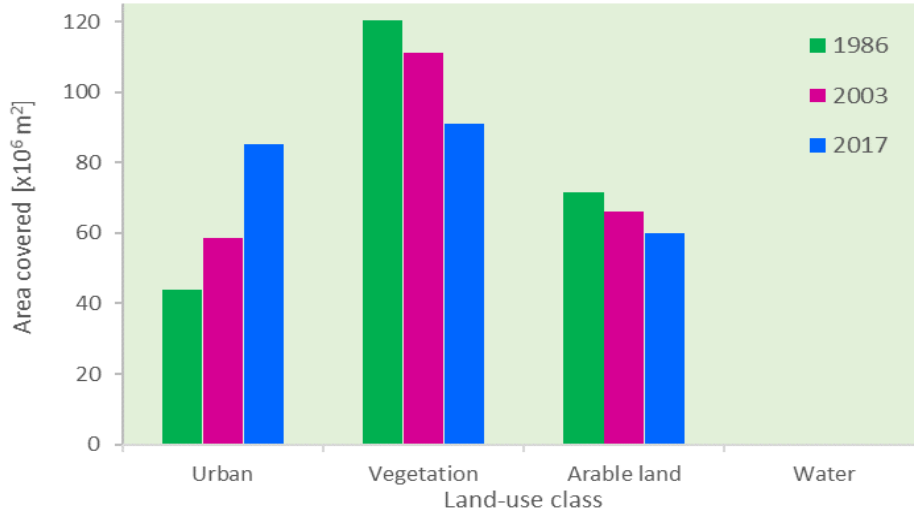


Fig 5-7: Bar chart comparing the change in the landcover detection for the 3 temporal boundaries; 1986, 2003 and 2017 respectively.

To appreciate the changes in the landcover conversion over the selected temporal boundaries, a multiple bar graph was used to compare changes in each of the classes as shown in Fig (5-7). The results of the analysis of the land use classification revealed that the broadleaf vegetated areas still have the highest share of the landcover in the area. However, the urban land use class show rapid changes whereas the changes in the arable land use are gradual. The gradual decrease in the arable land use is because most agricultural productions were done at the subsistence level. At the same time, the economic and commercial boom in the area encouraged rural-urban migration supporting the rapidly growing population and construction activities leading to the increasing built-up areas.

The urban sprawl expansion map was demonstrated to show the change detections in the urban land use from each of the time boundaries. This map was created by extracting the urban land use in each map, then obtaining the change by subtracting the urban land use of the previous spatial boundary from the later urban one as shown in the expression in equation 5-2.

$$\sum_{j=1}^2 \Delta U_j = \Delta U_1 + \Delta U_2 = (U_{n,j} - U_{n-1,j}) + (U_{n+1,j} - U_{n,j}) \quad (5-2)$$

$$n, j = 1, 2$$

Where ΔU = change in the urban sprawl the 2-temporary boundaries.

The change in the urban sprawl expansion map between 1986 and 2017 are shown in Fig (5-8). The results of the analysis of the change in the urban sprawl showed that between 1986 and 2003, the urban land use grew by 6.3 % of the area, whereas urban land use almost doubled to 11.2% between the period 2003 and 2017.

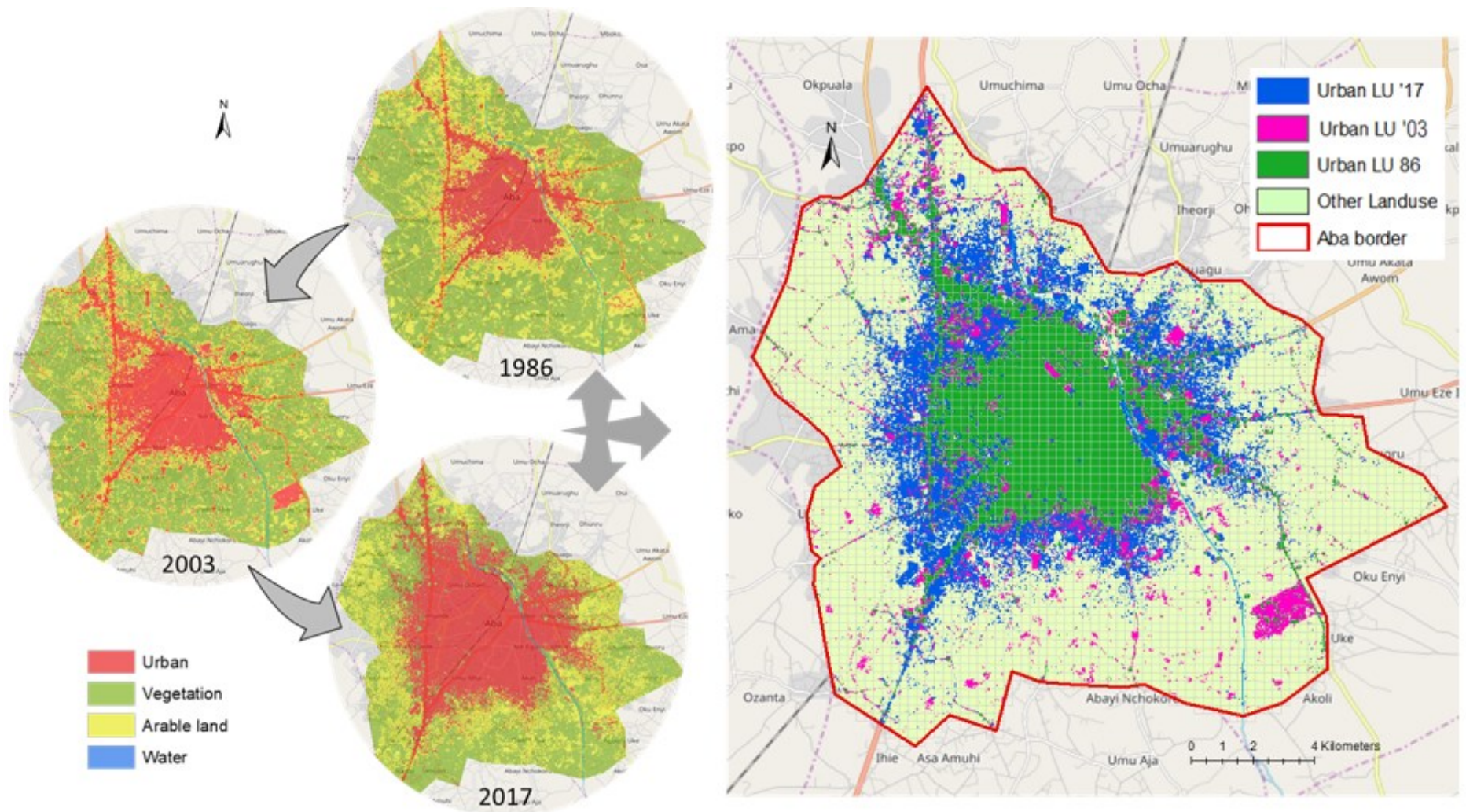


Fig 5-8: Map of Aba showing changes in the urban sprawl expansion map between 1986 to 2017.

This increase can be positively correlated to the steep increase in the population and economic progress in the area, in which a similar trend was reported in Emeribeole and Iheaturu, (2016). However, the consequence of such urban growth can weigh much on the limited space and available resources in the area, if proper plans are not put in place to check this expansion. The landcover detection for the water class was the smallest component in the land use map for the area. This component of land use classes represents about 0.02 % of the area in the 1986 map, subsequently decreased to 0.01% in 2003 and it remained constant in 2017. The decreasing trend in water class detection in the landcover can be associated with increasing water demand relative to the+ population, commercial, industrial activities and the influence of the changing climate.

5.3.3 Groundwater potential contamination source (Hotspot) mapping

From literature reviews, results of the field surveys and on the ground assessment of the area, we identified and collated a list of the potential urban contamination sources that can contaminate both the surface water and groundwater. Some urban classes identified are summarized in Appendix 2, Table A-2.1. The table shows different urban sub-classes that are potential sources of groundwater contamination, as well as some important water quality indicators that can be considered in the risk assessments of the groundwater. Some of these urban land use practices that interact directly or indirectly with the freshwater sources in the area were illustrated and mapped. This map can be referred to as a potential contamination hotspot map for the area as shown in Fig (5-9). The illustration on the map shows photos of some identified urban land use activities taken during the field campaign in the study area. These practices have a direct or indirect influence on the quality of the different freshwater (surface /ground-water) systems close to them in the area. When the hotspot map is overlaid on the delineated urban built-up area map from which roads and barren land surfaces have been subtracted. It is worth noting that the use of the septic drain which is the highest-ranked contamination source based on the results of the household survey, hence, the built-up class in the land use map was replaced by the septic tank in the legend. Overall, the hotspot map also revealed that some of these contamination sources are found in close interaction with the Aba River or near the groundwater recharge areas.

5.4 Discussions

The results of the topographic land surface model analyses presented offered very insightful details about the landforms, flowing streams, ponds, and wells as, detected rapid changes that occurred in the landcover of the area. The implications of the terrain models for this study area cannot be over-emphasized, rather they can offer some understanding into some current water-related issues and risk management of potential for freshwater contamination in the area.



Fig 5-9: Map of land use hotspot showing potential contamination sources overlaid on the urban built-up class and its interaction with some of the upland depression derived from the topographic index map.

The elevation map of the area shows that the Northeast corridors have high elevation and the altitude gradually decreases southwardly. The southern parts are mostly floodplain. It is also common knowledge that water flows in the direction of gravity, meaning that water moves from the high altitude area to the low flat regions in the low-level areas. In this regard, this assumes the direction of the surface streams and groundwater flow in the area as shown in the flow accumulation map in Fig (5-2(c)). This map agrees with the documentation in Agharanya and DIM, (2018), in which they established the direction of flow of the groundwater in a similar direction pattern as the surface flow in the area. The slope map describes the area as predominantly flat to gently sloped area and by implication, runoff is minimum, which is an advantage for recharge of the groundwater in this area. Adamu et al. (2019) described the main landforms in the area such as the valley areas of Aba River, marsh flood lands and the predominantly flat land. For these kinds of landforms, the flow accumulation pattern model does not show an extensive interlinking network of streams channels, causing a high volume of torrential rainfalls that the area received during the rainy days as they accumulate in the low-lying parts. The Aba River is the main controlling drainage system, making the area poorly drained since the River is not connected to all the stream networks in the area. This experience has also been reported in other urban areas in the Southwestern part of Nigeria (Ogunsanwo, 2002). However, with the increasing trend of urbanization, the extent of impervious surface simultaneously increases and has resulted in incessant urban flooding and notable ponds in several parts of the area. This observation has been reported in many works of literature linking the cause of urban flooding in many residential parts during the rainy season (Njoku et al., 2013; Ogbonna et al., 2015; Nwagbara and Okwuonu, 2016). Consequently, urban floods in some areas can deteriorate the quality of groundwater, when urban storm runoff collects surface contamination and deposit them in the ponds and groundwater recharge area where it infiltrates into the groundwater causing contamination (Nkwunonwo et al., 2016). The topographic index map predicts areas of high flow accumulation and it is an important tool that has been applied in different fields of natural resource studies. This tool has been applied to study, characterize, predict, plan and manage resources such as rainforest structures (Mackey, 1994), soil moisture (Western et al., 1999; Gómez-Plaza et al., 2001; Tombul, 2007), groundwater recharge influencers (Nolan et al., 2007), etc. For this study, the TI was developed to estimate the area of investigation where the urban land use interacts with areas with high flow accumulation. This specifically spots land use activities, which are directly in contact with groundwater recharge areas. These interactions are mapped in the hotspot map for both the surface and groundwater reservoirs. This approach is one step to highlight some of the current environmental issues influencing the availability of freshwater among households in the area. Based on the illustrations in Fig (5-9), the interaction between urban land use and some of the high flow

accumulation areas might harm the ecology, hydrogeology and the general quality of the water in the area. These observations are not peculiar to the study area but have been observed in many other developing urban that has been smeared by poor environmental practices or due to lack of strict adherence to the urban land use plans and implementation. These can lead to water insecurity due to contamination of the water sources for many households.

It has also been observed that there could be some ecological consequences due to the urban interaction with the natural water systems in the Aba River. The experience counting 25 years ago, the distribution of aquatic faunas in most parts of the Aba River was uniform distributed. But now, as has been observed by the author during the field visit, some parts of the Aba River close to areas with intensive urbanization have lost most of its fauna species. Some of the missing species include fishes and amphibians such as frogs and snakes that naturally breed in the river and along the banks are lost due to the impact of urbanization. Some factors which might be linked to the ecological losses in the River were highlighted in Hassall, (2014). These include over-exploitation of the resources, disturbances in the natural breeding cycle due to human activities, and pollution of the river water can be the causes of the disappearance of these species. Currently, fishes and frogs can still be seen in less disturbed sections of the river, in parts of the wetland ponds and river head from where the river stream is derived.

On the other hand, in sections of the river where effluents from industries and other activities such as car wash, commercial laundry, dry cleaning and carpet wash services, etc. are discharged into the river, can no longer sustain the aquatic faunas like the missing species. Other observed practices that contaminate the Aba River include nutrient and microbiological loads from animal slaughtering activities, siting of latrine along the river banks and household-refuse disposal by riverine shanty settlers, discharge of human excreta as and septic sludge in downstream parts of the river, as well as the canalization and channelling of urban surface storm runoff into the river. These kinds of practices have been reported in other developing urban areas in Nigeria (Fashae et al., 2019). The activities reduce the aesthetic value, degrade the quality, make them unsuitable for direct domestic consumption and reduce the availability of the resource.

Hydrogeologic concerns might arise with the changing landcover detections suggest increasing imperviousness of the land surface and increasing demand for water. As the urban land use sprawls, the demand for water increases both for domestics and industrial needs. In the dense residential and commercial parts, the land surface is sealed and this may impede the groundwater net recharge rates. Although, some studies have demonstrated that with diminishing vegetation cover (minimizes evapotranspiration), the water table rises in most urban parts. However, it has been reported that

another contributory factor responsible for rising water table elevation in many developing urban areas is the presence of artificial recharge systems such as cesspools, soakaway, as well as other on-site sanitary facilities. It has been reported that the use of septic drains represents a major source of groundwater recharge systems in many developing towns without a central sewer system (Hassane et al., 2016; Faye et al., 2019).

An arbitrary landcover segmentation of the groundwater reservoirs into 3 portions in the area namely, upstream, midstream and downstream reservoir can be created based on the urbanized landcover detection type has been illustrated in Fig (5-10). The anthropogenic activities have a varying degree of influence on the quality of groundwater and the surface water in different parts of the area. Of most significance is the western corner of the upstream reservoir, and the central midstream reservoirs, which have a quite conspicuous presence of urban land use activities that may have a direct impact on both the river and groundwater quality and more importantly the deteriorating groundwater quality in these parts. Some of the hotspot responsible for the degenerating poor quality has been illustrated in some pictures taken during the field investigation in Aba. The North-western corridor has the new industrial estate, including the petroleum product depot and the hydrocarbon pipeline network passing through this part. A probable incident of pollution from the hotspots in this part can be harmful to the groundwater and further transmitted along the direction of the groundwater flow downstream to the midstream segment of the reservoir. It is also worthy of mention that this study

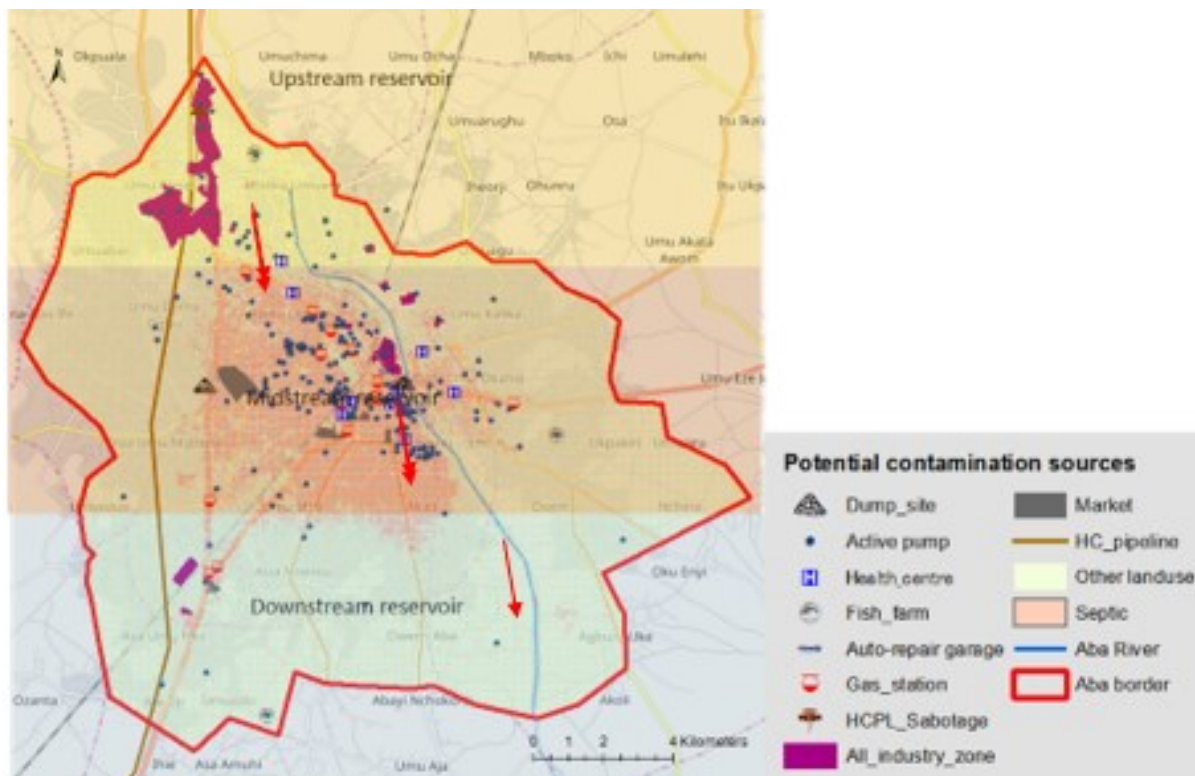


Fig 5-10: Map of groundwater contamination hotspots showing arbitrary coloured segmentation of groundwater reservoirs and direction of flow of the groundwater. The segmentation is not to scale.

did not cover the flow direction of the groundwater in this In the midstream segment, is the densely residential and commercial areas with the septic tanks being the most likely influencers of the groundwater quality. Here the TDS concentrations and chlorides are higher, compared to the other groundwater reservoir segments. Other urban land use practices observed that have been reported in other developing countries and can harm the quality of the groundwater include the use of open surface and borrow/mine-pits as dumpsites for municipal solid waste disposal (Nwachukwu & Nwachukwu, 2016; Ferronato & Torretta, 2019), the draining of industrial storm runoff and effluents in cesspools, direct discharge of fish farm effluents into the groundwater aquifer (UNwater, 2015). The inadequacy of the urban public water supply in many developing urban areas have perpetuated the use of septic and latrines for on-site sanitation (Lewis et al., 1980; Diaw et al., 2019).

The use of petroleum products has been part of the everyday lives of people in Nigeria. These products are used as fuel for cooking, transporting, generation of private power for domestic and industrial use indiscriminate siting of gas service stations, which hold underground storage tanks. Again, accidental failure of the underground storage tanks and the transfer networks can compromise the groundwater with the products. In the area, hydrocarbon spills from leaky private power generators, auto repair garages, industrial engines and vandalized pipelines conveying the products from the Depot have been observed.

Other urban practices, which affect the quality of the groundwater include management of waste from commercial activities such as hospitals (clinical and dental wastes), photo labs, private laboratories, etc., that do not have a proper waste management system for discharging their effluent have dedicated cesspools where they empty their waste have been observed. These sources and practices form the hotspots and are potential contamination sources of pollution to the groundwater. Therefore, relevant authorities in these developing urban areas must implement strategies to adapt to the challenges that come with the trend of urban sprawl and harmful environmental activities associated with them.

Chapter Six

6 Evaluation of the chemical risk and hydrochemical investigations

6.1 Background

The risks associated with water for drinking purposes is measured by the quality of the water source. However, water is a universal solvent and defining the quality is a complex topic. This is because the term water quality¹⁴ depends on the amount of everything that water carries along as it travels from the atmosphere or through the soil materials into different water bodies. The risk characteristics are related to the quality of a water source, which can be measured by different quality indicators grouped under physicochemical, biological, and chemical (i.e. general chemistry, radiological and toxicological) aspects when examining the acceptability of a drinking water source. The chemical risk assessment is given less priority than biological risk because the former arises due to long term exposure whereas the biological risk causes immediate public health problems for the source water (Thompson et al., 2007).

In many developing urban centres, the groundwater is the most reliable, improved decentralize source of freshwater (Barrett and Howard, 2002; Ocheri et al., 2014). Apart from natural factors, such as complexities in the lithology, the direction of flow of the groundwater, the quality of the recharging water etc., anthropogenic activities represents a major threat to the quality of the groundwater. These activities include inappropriate disposal of municipal solid and industrial wastes, accidental spills from manufacturing activities, the use of leaky septic tanks and on-site sanitary facilities, etc. have been reported as urban stressors to the quality of the groundwater (Egboka et al., 1989; Ocheri et al., 2014; Ukpong et al., 2015). Besides, urban land use have significant effects on the general hydrology of the area, as it decreases the permeability of the landcover, causing high urban storm runoff, and lowers the groundwater net recharge rate in the area (Howard, 2002; Mallin, 2009). Urban storm-runoff is regarded as a diffused source of contamination to the groundwater as the runoff water gather surface contaminations in recharging ponds. This affects the quality of the groundwater and can initiate changes in the hydrogeochemistry of the groundwater. Hence, when assessing the hydrochemistry of groundwater, it is important to examine the influence of anthropogenic pressure on the groundwater and may cause changes in the major chemistry of the groundwater. Therefore, it is important to unmask the impact of urban land use when characterizing the hydrochemistry of urban

¹⁴ The quality of water is acceptable if the maximum acceptable concentration (MAC) of anything (indicators) present in it does not exceed the standard limit recommended by competent relevant authorities (Misstear et al., 2006).

groundwater. Many studies characterizing the hydrochemistry of urban groundwater in the sub-Saharan African context have reported dynamic and complex hydrochemical facies for the water source in the region. For instance, the characterization of the groundwater in the Tema district of Upper Accra revealed that the predominant groundwater facies are Na-Cl type and Ca-Mg-SO₄ types (Fiango et al., 2010). The dominant water types reported for the groundwater in Lagos Nigeria also showed such variability in the hydrochemical characterization (Akoteyon et al., 2018).

In general, the dominant water type is influenced by geogenic factors such as the distribution of geological material, primary chemical processes and other anthropogenic factors taking place in the area. Previous studies on the hydrochemical assessments of the groundwater in Aba revealed that the groundwater has no dominant water type, although the geology of the area appears to be uniform. Independent studies from Amadi et al., 2009 and Agharanya and Dim, (2018) reported that the calcium-bicarbonate (Ca-HCO₃) type is the predominant water type in the area, but Aliche et al. (2010) found that the sodium-chloride (Na-Cl) type is the dominant water type in the area. Based on these studies, it is assumed that the urban land use have significant impacts leading to the contrasting water types already reported in the area. Therefore, the main goal of this chapter is to investigate the quality aspects of the groundwater with a focus on the influenced by urban land use, with the following specific objectives:

1. evaluate the general trends in the chemistry of the groundwater using descriptive statistics;
2. assess the seasonal and spatial trends in the quality of the groundwater;
3. characterize the hydrochemistry and delineate the impact of urbanization on the quality of groundwater.

6.2 Methods

6.2.1 Procedure and experimental design

Groundwater samples were collected from 61 randomly selected tube wells distributed in both densely and sparsely built-up areas. The wells were spatially defined on the remotely sensed land use map of the area shown in Fig (6-1. These wells are used for commercial, industrial and residential purposes. The sampling periods covered the two main seasons in southern Nigeria, (rainy season's samples obtain in July – August 2017 and dry season's samples in February-March 2019). The GPS coordinates of each tube well were recorded and the wells purged for 2 – 3 minutes before the samples were taken. The wells in the densely built-up area were designated as HR wells, whereas those in the sparse built-up areas were designated LR.

the hydrochemistry of the groundwater results were statistically analysed using boxplot and other hydrochemical evaluation methods.

Table 6-1: Selected quality indicators and the standard methods for the analyses.

Indicator variable	Method of Analysis	Method/regulation
Temperature (T)	Electrometry	
pH	Electrometry	
Oxidation-reduction potential (ORP)	Electrometry	
Electrical conductivity (EC)	Electrometry	
Total dissolved solids (TDS)	Electrometry	
Total alkalinity (TA)	Titrimetry	
Calcium (Ca)	AAS	ASTM D511
Magnesium (Mg)	AAS	ASTM D511
Sodium (Na)	AAS	ASTM D4191
Potassium (K)	AAS	ASTM D4191
Iron (II) (Fe ²⁺)	AAS	ASTM D4191
Manganese (Mn)	AAS	ASTM D4191
Lead (Pb)	AAS	ASTM D4191
Chromium (Cr ⁵⁺)	AAS	ASTM D4191
Cadmium (Cd)	AAS	ASTM D4191
Chloride (Cl)	Titrimetry	Mohr titration method
Bicarbonate (HCO ₃)	Titrimetry	P & M value titration
Sulphate (SO ₄)	UV-Spectrophotometry	APHA 4500 SO4 2- E
Nitrate (NO ₃)	UV-Spectrophotometry	APHA 4500 NO3
Orthophosphate (PO ₄)	UV-Spectrophotometry	APHA 4500PD
Total petroleum HC (TPH)	Gas chromatography	EPA 8015

6.2.2.1 Hydrochemical methods

The analyses of geochemical species in the groundwater were used to describe the hydrochemical behaviours of the groundwater chemistry. These methods use major ions present in the groundwater solution to visually describe the evolutionary trends and the mechanisms that influence the chemistry of the water. In this study, the following hydrochemical methods were employed to explain the hydrochemical characteristics of the groundwater in the area.

- Piper diagram according to Piper, (1944);
- Chadha plot according to Chadha, (1999);
- Bivariate scattered cross plots
- Ion exchange indexing according to Schoeller, (1965).

The piper diagram is one of the most frequently used hydrochemical methods for evaluating the hydrochemical composition of the groundwater using a trilinear triangular as described in Piper, (1944). The method offers the flexibility that several samples can be analyzed on a plot. Again, the water type classifications and the mixing propensity of waters in the plot is easy to visualize through

this method (Leis, 2018). However, the demerits of the diagram are that it requires a special program to plot the chart and the actual concentrations of the predetermined reacting ions are normalized before being implemented in the chart. This makes it difficult to account for other ions in cases where other ions are significant.

Chadha, (1999) proposed a less complicated hydrochemical scattered chart, which is comparable to the piper diagram. This chart is effective in interpreting the association of the major ions in the groundwater. It can be prepared from a simple spreadsheet scatter plot such as MS Excel. Chadha identified 8 positions (known as quadrants) and suggested four main geochemical fields defined by the quadrants. The quadrants are likened to the triangular segments of the piper's diamond shape, which represents the different hydrochemical facies in the groundwater. Chadha, (1999) described the basis for the plot construction, as well as the interpretation of each of the hydrochemical quadrants. The use of bivariate scatter plots demonstrate the association between the major ionic species in the groundwater. They help in the study of the stoichiometric relationship of the dissolved ions and their origin in the groundwater. Several combinations of such cross plots have been proposed in many published literature of hydrochemistry to illustrate the source mineral furnishing the major ions in the groundwater.

Schoeller (1965) first described the index of base ion exchange as the chloro-alkaline index (CAI). The concept explains the direction of movement of base cations between the groundwater and its host environment. The base cation exchange between the adsorption complexed and dissolved ions in solution. This involves the movement of the alkali metal ion group [Na + K] and alkaline earth metal group [Ca + Mg] between the rock and the groundwater (Hwang et al., 2017). Based on this concept, Schoeller 1965 proposed the chloro-alkaline indices CAI-1 and CAI-2 respectively to demonstrate the direction of movement of the base ions as expressed in equations (6-1) and (6-2).

$$CAI_1 = \frac{[Cl] - ([Na] + [K])}{[Cl]} \quad (6-1)$$

$$CAI_2 = \frac{[Cl] - ([Na] + [K])}{[HCO_3] + [CO_3] + [SO_4] + [NO_3]} \quad (6-2)$$

Each of the chemical symbols in equations (6-1) and (6-2), represents the reacting concentration of the ions in meq/L. When the sign of the value of the index is positive, it means that the [Na+K] ions in the groundwater can remove [Ca+Mg] ions in the solid aquifer materials. The reverse process occurs when the sign in the value of the index is negative. These indices can be used to explain if alkalinization or earth-metal alkalinization has occurred in the groundwater.

6.3 Results and discussion

6.3.1 Assessment of the physicochemical and general chemistry of the groundwater

The groundwater samples from the sparsely built-up (LR) area were collected from 33 tube wells, and 28 samples were taken from the densely built-up (HR) area for chemical analyses. The results of the selected physicochemical and chemical quality indicators in the wells were grouped according to the tube well locations as presented in Table 6-2. For the quality check on the results of the chemical analysis, the charge balance error (CBE) was determined. The result of the CBE lies within the range $10 < |x| < 15$ for the wells. However, the CBE results are higher than the $\pm 5-10\%$ recommended. This is because some of the analyses of the major ions were performed in a commercial laboratory facility. Most often, these commercial laboratories do not perform customized calibrations for some of the ions and this leads to the high CBE ranges as recorded in this study. In a case like this, a CBE range of $\pm 15\%$ is acceptable (Andersen, 2015).

The summary of important descriptive statistics of the indicators is shown in Table 6-2 and compared against the maximum acceptable concentrations set by the WHO for drinking water quality.

Table 6-2: Some descriptive statistics of physicochemical and chemical parameters measured in the groundwater wells.

Quality indicators	WHO (MAC)	Sparsely built-up (LR) wells (N=33)				Densely built-up (HR) wells (N=28)			
		Mean	Std dev	Min	Max	Mean	Std dev	Min	Max
Temp (°C)	Ambient	27.5	0.9	26.7	31.0	28.1	0.9	26.4	30.3
pH	6.5-8.5	4.9	0.3	4.2	5.6	4.2	0.4	3.7	4.9
ORP (meV)	-	132.4	23.1	82.0	189.0	174.1	31.4	81.0	207.0
EC ($\mu\text{S}/\text{cm}$)	1000	35.2	33.4	10.0	196.8	276.6	128.7	69.2	560.0
TDS (mg/l)	500	22.9	21.7	6.5	127.9	179.8	83.7	45.0	364.0
TA (mg/l)	-	18.0	3.0	11.6	24.0	17.1	5.6	9.0	30.5
HCO ₃ (mg/l)	-	22.0	3.7	14.1	29.3	20.8	6.8	11.5	37.1
Cl (mg/l)	250	7.9	8.0	1.0	37.0	61.1	23.9	5.1	101.7
SO ₄ (mg/l)	100	1.1	0.6	0.4	3.8	1.6	0.9	0.5	3.2
PO ₄ (mg/l)	0.54	0.5	0.2	0.0	1.0	0.8	0.3	0.3	1.4
NO ₃ (mg/l)	50	0.6	1.0	0.0	5.8	2.9	4.4	0.002	14.2
Na (mg/l)	200	2.4	2.0	0.1	6.5	3.7	1.0	0.9	6.0
K (mg/l)	10	1.3	1.1	0.0	5.2	3.9	5.0	0.7	19.3
Ca (mg/l)	75	0.6	0.9	0.0	3.4	5.0	4.2	0.4	19.3
Mg (mg/l)	20	0.3	0.5	0.0	3.0	2.0	2.0	0.02	6.6
Cd (mg/l)	0.003	0.002	0.001	0.001	0.003	0.001	0.0005	0.001	0.002
Pb (mg/l)	0.01	0.005	0.0005	0.005	0.008	0.001	0.0005	0.001	0.002
Fe (mg/l)	0.30	0.12	0.13	0.001	0.40	0.13	0.13	0.001	0.41
Cr (mg/l)	0.05	0.001	0.000	0.001	0.001	0.003	0.01	0.001	0.02
Mn (mg/l)	0.20	0.016	0.038	0.001	0.21	0.24	0.23	0.001	0.60
TPH (mg/l)	0.6	0.047	0.154	0.001	0.72	0.002	0.002	0.001	0.01

The abbreviations ORP, EC, TDS, TA and TPH means oxidation-reduction potential, electrical conductivity, total dissolved solids, total alkalinity and total petroleum hydrocarbon respectively.

(See full results of the physicochemical and chemical indicators for the 61 tube wells in Tables A-3.1 and A-3.2 enclosed in Appendix 3). These results of the indicators were grouped into different classes

for easy reporting and analysis. The classes include physicochemical (Temp, pH, ORP, EC, TDS and TA), nutrients (nitrates, and phosphate), minor constituents (Iron and Manganese), major constituents (Na, K, Ca, Mg, Cl, HCO₃, SO₄) and trace substances / heavy metals (Cd, Cr, Pb and TPH).

6.3.1.1 Physicochemical factors (Temp, pH, EC, and TDS)

6.3.1.2 Temperature:

Some studies have reported that warmer temperatures in groundwater can be referred to as a pollutant in the groundwater (Massmann et al., 2008; Saito et al., 2016). The groundwater temperature is an essential driver for quality assessment. This is because changes in the groundwater temperatures can influence some indicators that control both the chemistry (Menberg et al., 2014) and biochemical activities of the groundwater. This parameter depends on the prevalent ambient air temperature and the temperature gradient of the area. The average temperature in the LR and HR wells are 27.5 °C and 28.1°C respectively. Comparatively, the HR wells have higher temperatures than the wells in the LR areas. This result agrees with other studies which have found that groundwater temperatures are higher in densely built-up areas relative to green areas to support this observation (Gross, 1991; Berlin.de, 2011). The result shows that there is faster physical deterioration in the quality of the groundwater as we move from the LR wells to the HR wells, in the same direction as the temperature. However, seasonally the average groundwater temperatures in both the LR and HR wells were all lower than the average maximum monthly air temperature for the month of August-September (for the rainy season) and February (for the dry season), during which the samples were collected.

6.3.1.3 pH:

The pH values of all the wells were acidic and did not conform to the recommended WHO maximum acceptable limits for drinking water (6.5 – 8.5) in both the LR and HR wells (WHO, 2011). The pH range in the HR wells lies between 3.7 and 4.9, while in the LR area, it lies 4.5 and 5.6. The wells in the HR area showed more acidic groundwater pH than the LR wells based on this range. The acidic groundwater pH in the area supports the results of recent studies conducted in the area, as well as groundwater pH within the regional basin (Amadi et al., 2009; Aliche et al., 2010; Agharanya and Dim, 2018). The acidic groundwater pH value is typical of humid areas, where base cations in the groundwater have been washed away by rainwater (Knutsson, 1994; de Ridder, 1994). Drinking water with acidic pH has no direct health implications, however, groundwater with acidic pH can dissolve more substances in the surrounding, thereby increasing the concentration of such ions especially the

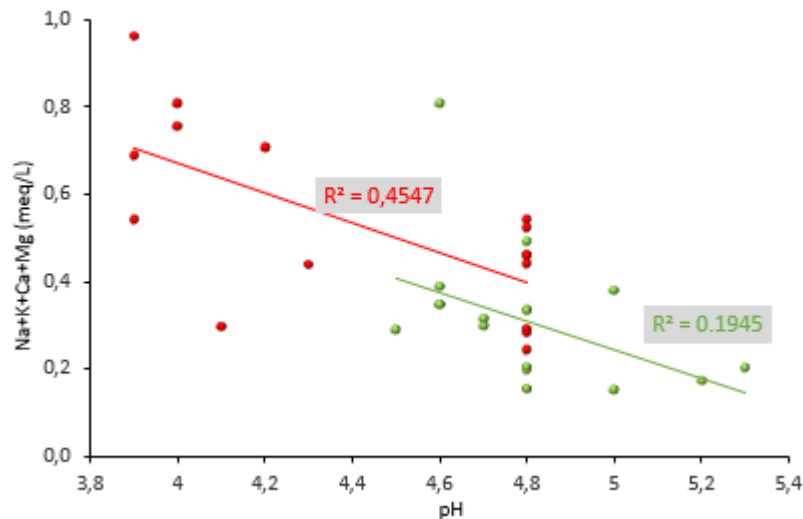


Fig 6-2: A scatter plot showing the relationship between pH and sum of all major cations in the groundwater wells for the LR (green dots) and HR (red dot) areas of Aba.

metal ions. This can affect the taste, appearance and acceptability of the groundwater for drinking purposes. A scattered plot illustrating the impact of the pH and total cations present in the groundwater samples from the LR and HR wells is shown in Fig (6-2). The illustration revealed that there is an inverse relationship between the groundwater pH and total concentrations of the major cations, meaning that wells with higher dissolved cations concentrations have lower pH values.

This result supports the findings of O’Driscoll et al. (2010). The wells with the higher total cations were found in the HR area for which 50% of the total wells in this area have pH values < 4.5 and these are predominantly in the HR wells. The more acidic groundwater reservoir suggests the presence of organic contaminations in the groundwater, which are capable of being degraded to carboxylic or phenolic anions (Hem, 1985). The characteristic use of septic tanks and soak-away pits for treating human bio-waste in the HR area and congested commercial areas contribute to the high amounts of dissolved organic and inorganic substances in the groundwater in this part. In contrast, the LR wells have slightly higher pH values, with an average greater than 4.5. These wells are relatively less mineralized than the wells in the HR areas. In general, the pH recorded for the HR wells is more acidic than the pH of wells in the LR area.

6.3.1.4 Electrical conductivity (EC) and total dissolved solids (TDS)

The EC simply describes how conductive the groundwater will be if an electric current is passed through it. The corrected EC values of the tube well samples correspond to the specific electrical conductivity @25°C. Generally, the descriptive statistics results in Table 6-2 shows that the EC in the HR wells is higher than those of the LR wells. On average, the EC in the HR wells were roughly 8 times more than those found in the LR area. The EC can be directly correlated to dissolved inorganic

substances that can conduct electric currents in the water. Sometimes, it can be a proxy indicator for monitoring the quality of the groundwater wells especially groundwater with the possibility of saline intrusion. The EC and total dissolved solids (TDS) are interconvertible and they are related by the expression as shown in equation 6-3 (van der Aa, 2003; Rusydi, 2018).

$$\text{TDS (mg/l)} = \text{EC}_{25} (\mu\text{S/cm}) * A \quad (6-3)$$

where EC_{25} = the specific electrical conductivity of the sample at 25°C; A = the ratio of TDS to EC_{25} .

This ratio of TDS to EC range between 0.55 - 0.75 for freshwater, but A = 0.65 was adopted for this study. This is according to the recommendations of Rusydi 2018. Based on this, the TDS was calculated from measured EC_{25} . This indicator can be used as a measure of the freshness of different natural water sources (Todd, 1980). TDS is strongly associated with the taste and acceptability of a drinking water source. This is true because dissolved inorganic and little amounts of organic substances can have an impact on the taste of the groundwater (WHO, 2003). Table 6-3 summarizes the rating of TDS based on the taste it gives the drinking water according to WHO Guidelines for drinking-water quality. Based on the TDS rating, the groundwater wells in all the LR areas fall under the “excellent” category. Though wells in the HR area have elevated TDS concentrations relative to the well in the LR area, the TDS values still lie between “excellent” to “good” ratings.

Table 6-3: Summary and categorization of TDS based on WHO ratings for drinking-water quality.

TDS class (mg/l)	Rating
< 300	Excellent
300-600	Good
600-900	Moderate
900-1200	Poor
>1200	Unacceptable

The low mineralization in the groundwater fact that the parent geology contains predominantly quartz with a very tiny portion of clay minerals (Onyeagocha, 1980; Lekwa and Whiteside, 1986). This sedimentary mineral yields only small amounts of mineral ions from trace impurity through chemical weathering. Again high volume of seasonal rainfall received in the area dilutes the concentrations of the dissolved mineral in the groundwater, keeping the level of mineralization low.

6.3.1.5 Nutrients (Nitrate and Phosphates)

The presence of nutrients in the groundwater is a signature of anthropogenic stress in the water source. The average nitrate concentrations for the LR and HR wells were 0.6 mg/l and 2.6 mg/l respectively. In the LR wells, nitrate concentrations were basically under 1 mg/l. However, in one of the wells in the HR area, the concentration of NO_3 as high as 14 mg/l was measured. In both cases, the concentrations levels are well below the MAC (maximum acceptable concentration) of 50mg/l for

nitrate in drinking water. This wide margin of nitrate concentrations in the groundwater between the LR and HR wells is an indication that the deteriorating nitrate concentration level in the groundwater comes from surface-derived contamination. This result supports the findings in Misstear et al. (2006), which revealed that rapid changes in the nitrate concentrations of natural water come from surface contamination. Some of the sources of nitrate in groundwater are from decomposed remains of plants and animals or waste from food and agricultural industries, as well as sewage from households and industries (Kot-Wasik, 2007). The same trend goes for the measured phosphate concentrations in the groundwater. The average concentration of phosphate in the LR and HR wells was 0.5mg/l and 0.8 mg/l respectively. These results suggest that some wells in the HR areas have exceeded the recommended MAC limits for drinking water quality. The increasing concentrations of phosphate, especially in the HR areas can be attributed to land use practices in which phosphates are derived from domestic and commercial cleaning products such as detergents. The use of fertilizers is not common in the area, which is another common source of diffuse phosphate in the groundwater. Phosphates are not toxic to people unless they are present in extreme concentrations leading to digestive problems.

6.3.1.6 Minor constituents (Iron and Manganese)

Iron and Manganese are among the most abundant elements on the earth crust and sometimes they occur together in most minerals. They are usually mobilized into the groundwater by the chemical weathering of parent materials. However, these elements are beneficial to the human at some concentrations but might some health challenges when the MAC is exceeded. The average concentration of the iron measured in the wells both in the LR and HR areas is 0.1 mg/l, which is below the MAC for Fe^{2+} in drinking water. However, a couple of wells in the HR area measure concentrations of Fe^{2+} up to 0.4 mg/l. When concentrations of iron in the drinking water > 0.3 mg/l, it confers bad taste, as well as the hardness of the groundwater. On the other hand, the average Mn recorded were 0.016 and 0.24 mg/l in the LR and HR areas respectively. In general, higher concentrations of Mn are released in the groundwater at lower pH (Amfo-Otu et al., 2014). This trend supports the finding in the area. The HR wells with more acidic groundwater recorded higher concentrations of Mn compared to the Mn concentration in the LR wells. It has been reported that Mn can impact taste and stain laundry at concentration > 0.1 mg/l. Epidemiological, oral exposure of Mn has been associated with some neurological effects but this data to qualitative and quantitatively back the claims (WHO, 2011b).

6.3.1.7 Heavy metals and trace substances (Cadmium, Chromium, Lead and TPH)

The reviews in the area revealed the possible presence of trace substances such as TPH from fuel products and other solvents from households and some commercial activities. The release of everyday

household items such as batteries, white product appliances, fluorescence, as well as energy-saving bulbs in the dumpsite and spilling of substances containing heavy metals in the environment are ways in which these ions are released. These substances are usually found in very small concentrations in the environment, but human exposure to these substances in concentrations above the MAC might be lethal. The concentrations of these substances in groundwater > MAC makes the water unsuitable for drinking. The heavy metals analysed in this study are based on the most commonly available ones in this study. Cadmium, Chromium and Lead were measured and none of these heavy metals exceeded the MAC for drinking water in both the LR and HR wells. The average recorded concentrations of Cd, Cr and Pb in the LR well were 0.002 mg/l, 0.001mg /l and 0.005 mg/l respectively. Whereas the average concentration in the HR wells recorded are 0.001 mg/L, 0.003mg /l and 0.01mg /l respectively. In most of the wells, these metals were not detected. The average lead concentrations detected in wells around the new industrial zone of the LR area is already on the threshold concentrations above, which can lead to cause health concerns. These results support the findings of Akakuru et al. (2017) for which the presence of lead and other heavy metals were found in groundwater wells near the NNPC depot in the area. The source of lead was suspected to have come from the anti-knocking agents in petroleum fuel in the groundwater. Lead has been described as a cumulative poison and it is associated with health problems such as anaemia and reproductive disorder in humans (Kumar and Puri, 2012). Petroleum hydrocarbons products are part of the everyday products in many households used for domestic cooking, private power generation and automobile fuels to commercial fuels for industries and big establishments. The average TPH concentrations detected were 0.005mg /l and 0.002 mg/l for the LR and HR wells respectively. However, there are complaints about some tube wells that have been polluted from a petroleum pipeline in the LR areas due to incessantly sabotage of the lines. This contamination resulted in odour, taste and visible traces of the product on the groundwater. In one of these tube wells, the TPH measuring up to 0.7 mg/l was recorded.

6.3.1.8 Major constituents (Na, K, Ca, Mg, Cl, HCO₃, SO₄)

The major ions in the groundwater are mostly derived from the chemistry of the host rock material which bears the groundwater. The results evaluation of the major constituents in this study will be discussed in detail in the hydrochemistry section of this chapter for both the LR and HR wells.

6.3.2 Effects of seasonality on the groundwater quality

The seasonal impact on groundwater quality can be best studied by differentiating the influence of urbanization between the groundwater well groups. To achieve this, average results for each of the selected indicators were compared between the two main climate seasons for the tube well groups,

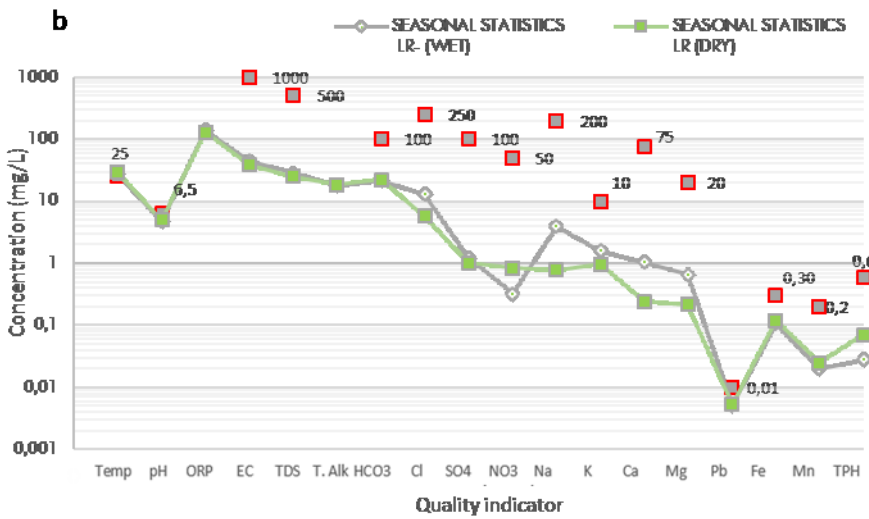
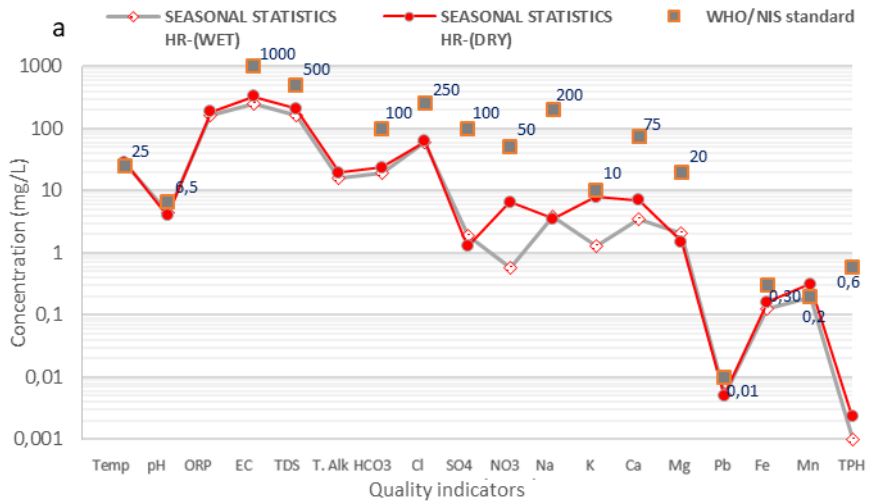


Fig 6-3: Seasonal trends (wet season) and (dry season) in the groundwater quality indicators between (a) densely (HR) built-up and (b) sparse (LR) wells.

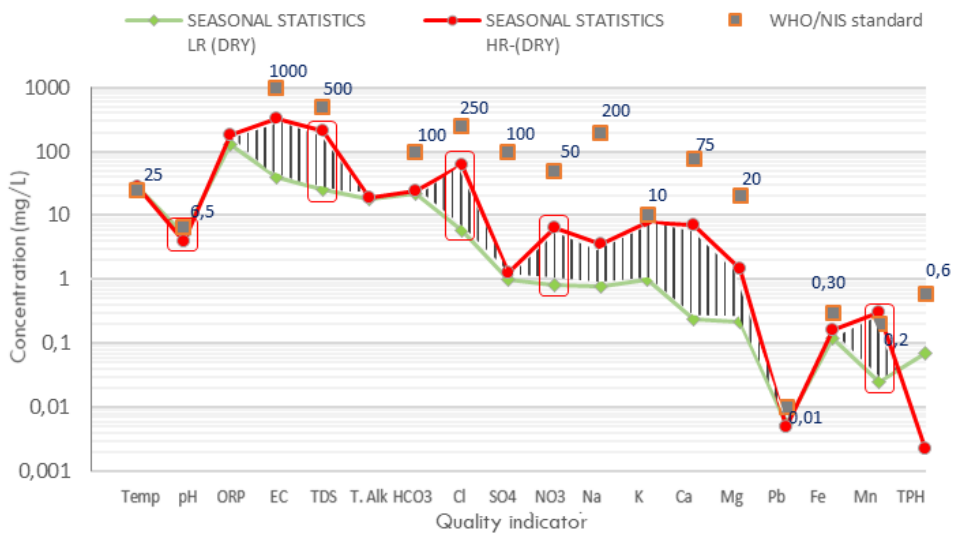


Fig 6-4: A trend illustration showing the spatial difference in the quality indicators in the dry seasons between LR and HR wells.

HR and LR, respectively and against the WHO's MAC for the indicators as represented in the semi-log plots (Fig (6-3a and b)). The seasonal quality of the groundwater in the LR wells shows that the average concentrations of most indicators are within the MAC. While the quality of some indicators in HR wells are approaching or have exceeded the WHO's MAC limits especially for a couple of indicators. However, the general trend patterns in both the HR and LR cases revealed that there is little or no impact of seasonality in the quality of the groundwater, switching between the two main seasons in the Aba.

6.3.3 Influence of land use on the groundwater quality

Here it is assumed that the results of the quality indicators in the LR wells serve as the background quality status for the area. The effect of the impact of urban land use on groundwater quality can be evaluated by comparing the results of some important contamination indicators between the HR and LR wells. The results are demonstrated in the semi-log plot trend line shown in Fig (6-4). Five urban contamination indicators such as pH, TDS, chloride, nitrate and manganese were selected for this purpose based on Nganje et al. (2017) and compared against the WHO MAC for drinking water.

The illustration showed that rapid changes in the average concentrations of the indicators in the HR wells, which are approaching the MAC limits relative to the average concentrations for indicators in the LR wells. The implication of the impact on the quality of groundwater by urban land use is highlighted with the shaded area between the trend-line of the HR and LR wells. The correlation analysis for the results between the LR and HR indicators is shown in Table 6-4. The results of the correlation suggest that the pH has strong linear relationships with the rest of the indicators. This suggests that as the groundwater pH becomes more acidic, the TDS, chloride, nitrate and Manganese concentrations in the groundwater are expected to increase. Other than the pH, the indicators show a strong linear relationship, which suggests the ions might have a common source from where they are derived.

Table 6-4: Correlation analysis of some quality indicators influenced by urban land use.

	pH	TDS	Cl	NO ₃	Mn
pH	1.00				
TDS	-0.71	1.00			
Cl	-0.66	0.95	1.00		
NO ₃	-0.53	0.59	0.43	1.00	
Mn	-0.72	0.73	0.70	0.50	1.00

6.3.4 Hydrochemical assessment

The hydrochemical assessment specifically deals with the evaluation of the major ions present in the groundwater. These ions determine the major chemistry of the groundwater and the evaluation are most often addressed with geochemical models to classify the water types and main geochemical processes taking place in the groundwater. In this section, different hydrochemical methods will be employed to analyse the results of the major constituents presented in Table 6-2 for wells in HR and LR areas.

6.3.4.1 Statistical evaluation of the major constituents ions

The results of the concentrations of the major ions in milliequivalent weights for the LR and HR wells are represented in the boxplot shown in Figs (6-5(a) and (b)) respectively. Each of these illustrations gives a quick overview of the statistical distribution for the major cations and anions dominance in the LR and HR areas. In Fig (6-5(a)), the predominant cations array can be expressed as $\text{Na}^+ > \text{Ca}^{2+} > \text{K}^+ > \text{Mg}^{2+}$, while for the anions is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$. On the other hand, the predominant cations' array follows $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ and the anions are $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-}$ for the HR area shown in Fig (6-5(b)). The dominance ions array, in this case, consider the position of the median equivalent weight concentration of the ions in the boxplot distribution. The results of the normalized equivalent weight of the major ions for the LR and HR wells are shown in Fig (6-6). In this case, the median value for each

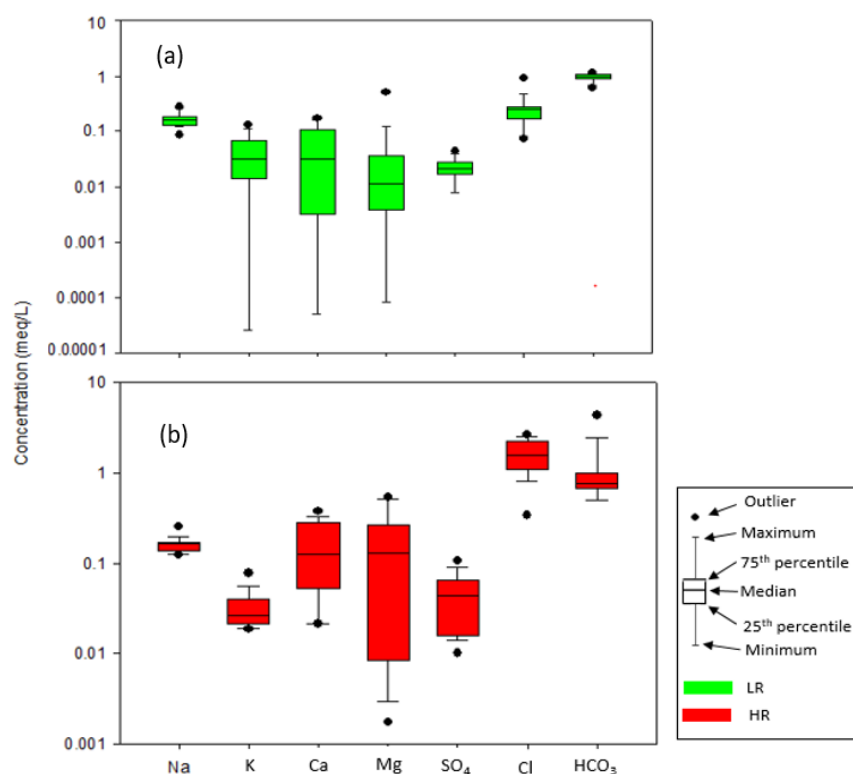


Fig 6-5: Boxplot diagrams showing the statistical distribution of major cations and anions for wells in (a) sparse (LR) and (b) wells in densely (HR) built-up areas.

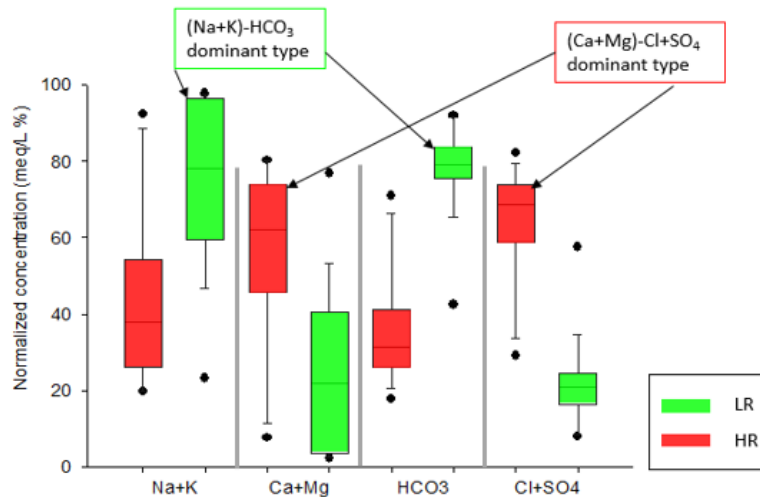


Fig 6-6: Boxplot showing dominant major cations and anions for the grouped wells based on the statistical median for the normalized concentrations of the ions.

indicator is taken as the representative concentration for the indicator. The implication of these results suggests the major ion with the highest median value in the boxplots of cations and anions are the dominant ions in the groundwater solution. Such a normalization approach forms the basis for popular hydrochemical methods such as the Chadha plot (Chadha, 1999) and the Piper trilinear plot (Piper, 1944). This statistical method also gives a quick hierarchical overview of the dominant ionic species in the groundwater solution. The results of the boxplot distribution array revealed that the LR wells were biased towards $[\text{Na} + \text{K}]\text{-HCO}_3$ water type. While the dominant water type in the HR wells skewed towards the $[\text{Ca} + \text{Mg}]\text{-}[\text{Cl} + \text{SO}_4]$ types. The Pearson coefficient of variation (CV) for the normalization results for the grouped major cations and anions concentrations of the HR wells gave $\text{CV} = 0.26$ and $p > 0.05$ between the alkaline earth metal ions $[\text{Ca} + \text{Mg}]$ and the strong acid anions $[\text{Cl} + \text{SO}_4]$. This shows that there is “no statistical significance” and no linear relationship between these ions and further suggests that the sources of these major ions may not be geochemically associated. It was found that the correlation coefficient between the alkali metal (Na+ K) and the weak acidic bicarbonate ions $[\text{HCO}_3]$ is $\text{CV} = 0.5$ and $p < 0.05$ for wells in the LR areas. This result revealed a moderate linear correlation and the relationship is statistically significant. The correlation coefficient gives a pointer that the ions may be derived from a common source.

6.3.4.2 Hydrochemical methods

The piper diagram has been widely applied in evaluating the hydrochemical facies of a groundwater system. The normalized results of the major ions (cations and anions) in milliequivalent/litre per cent (meq/l %) of the wells were plotted in the trilinear (piper) plotted for the LR and HR wells. Figs (6-7(a)-(c)) illustrating the piper plots of LR and HR wells respectively. The projection of the trilinear plots for the cations and the anions in each of the wells onto the diamond shape of the piper diagrams

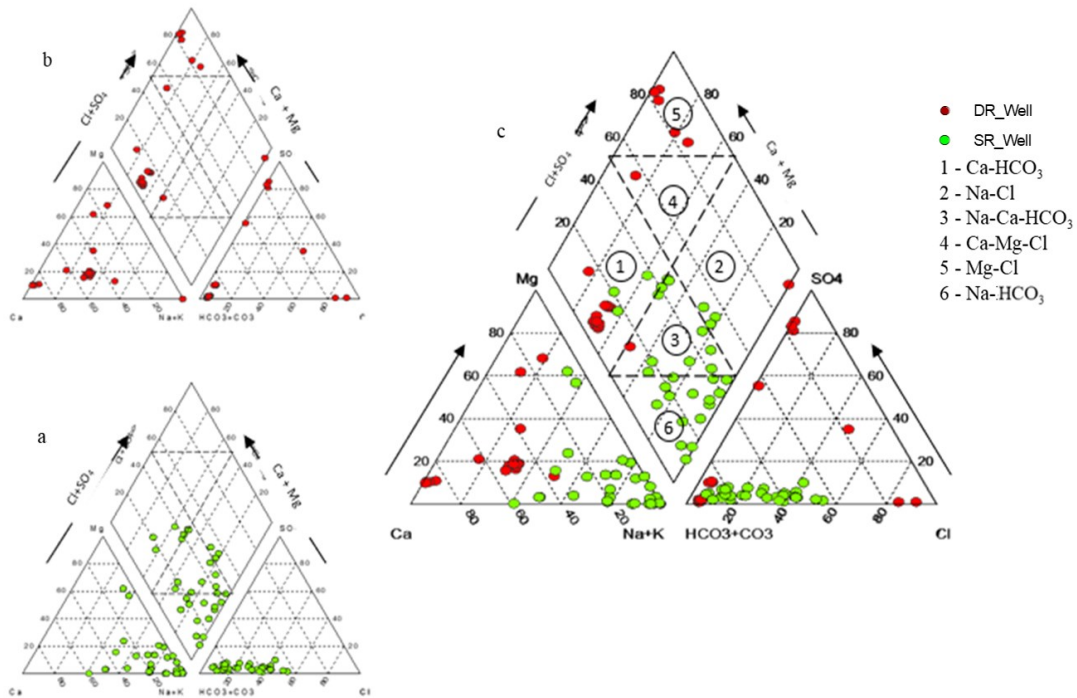


Fig 6-7: Piper diagrams illustrating hydrochemical facies of the groundwater wells in (a) sparse (LR) (b) densely (HR) built-up and (c) combined LR and HR wells in the study area.

define the region which represents the groundwater facies. The results for both the LR and the HR wells showed that most of the wells occur within the mixing zones of the diamond shape, which were represented by the dotted triangle at the centre of the diamond shape. The mixing propensity implies a dynamic environment as a result of the groundwater flow and other interactions arising from urban land use activities. However, the dominant water type in the LR area is the [Na+K]-HCO₃ type shown in Fig (6-7(a)). In addition to the dominant water type, there are other mixed water types as described in Table 6-5 for the LR wells. In Fig (6-7(b)), the predominant water type in the HR area is the [Ca, Mg]-Cl type.

Table 6-5: Summary of water types in the groundwater wells for both the HR and LR areas.

Water type	Percentage composition of water type (%)	Well location	Remarks
Mg-Cl-HCO ₃	11.8	HR	Mixed type
Ca-Cl-HCO ₃	11.8	HR	Mixed type
Ca-Mg-Cl-HCO ₃	5.9	HR	Mixed type
Mg-Cl	11.8	HR	Dominant type
Na-Cl-HCO ₃	5.9	HR	Mixed
Na-HCO ₃ -Cl	29.4	LR	Mixed type
Na-K-HCO ₃ -Cl	5.9	LR	Mixed type
Ca-Na-HCO ₃	5.9	LR	Mixed type
Na-Ca-HCO ₃	8.8	LR	Mixed type
Mg-Cl-HCO ₃	2.9	LR	Mixed type

The summary of percentages of mixed water types is shown in Table 6-5, however, details of all the tube wells and the water types are shown in Tables A-3.3 and A-3.4 enclosed in Appendix 3 for both the LR and HR wells respectively. The more simplified Chadha's plot also was used to support the results of the Piper charts as shown in Fig (6-8). Chadha's plot, besides identifying the dominant water type classes in the groundwater wells, also predicted important geochemical processes that control the chemistry of the groundwater. The dominant water type and the governing geochemical process in the groundwater wells depend on the position of wells across the eight (8) hydrochemical quadrants in the chart. The result showed that quadrants 5 and 8 represent the predominant hydrochemistry of the wells in the LR area. However, the dominant groundwater facies is the Na-HCO₃-type representing 78% of the wells, and the remaining Ca-HCO₃, Na-Cl and other mixed water types in the LR area. The dominant Na-HCO₃ water type is usually found in deep wells with a stable equilibrium between the groundwater and the rock (Chae et al., 2005). In such groundwater, the ion exchange process regulates the ions in the groundwater. Most of the HR wells occur in quadrant 6 and they represent 63% of the HR wells. The [Mg, Ca]-Cl water type is the dominant water type in the HR wells with the reverse ion exchange process as the main geochemical process controlling the

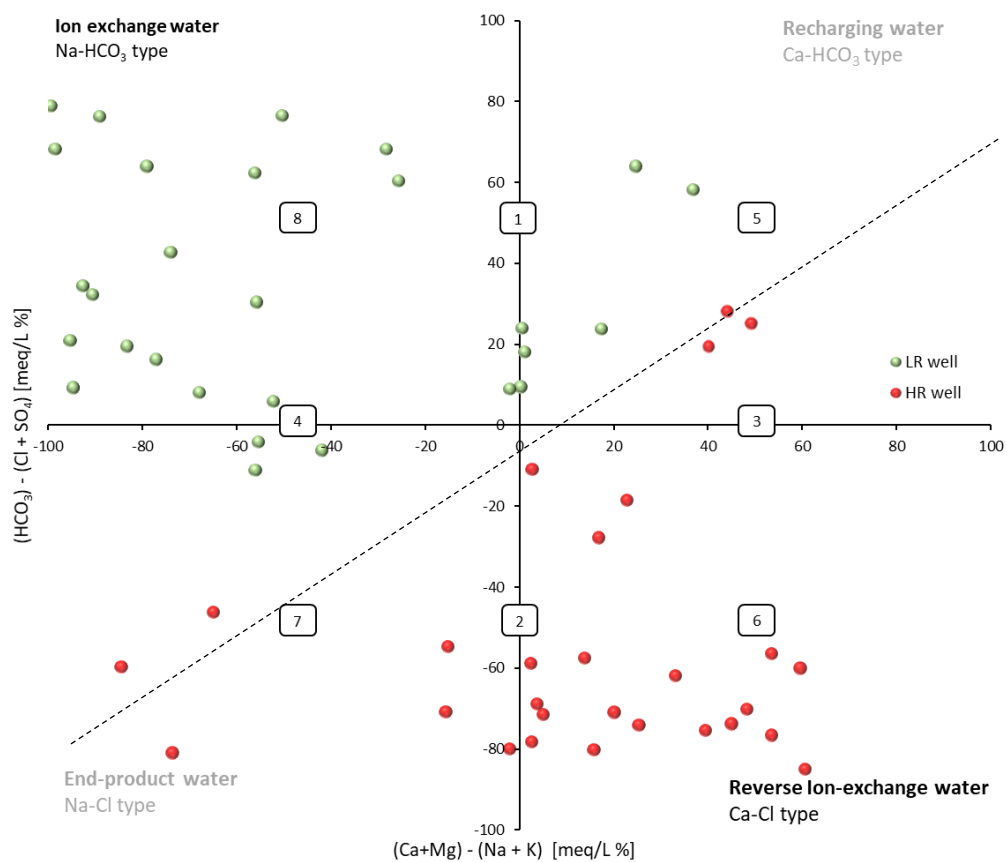


Fig 6-8: Chadha's plot showing the dominant water types and geochemical processes in the sparse (LR) and densely (HR) built-up wells in Aba.

chemistry of the groundwater. This water type is associated with the permanent hardness of the groundwater. The remaining water types found in the HR wells include the Na-Cl and Ca-HCO₃. However, one of the demerits of Chadha's plot is that the illustration does not clearly show the area within the quadrants where the mixed water types can be identified. In this case, a combination of the piper plot and Chadha's plot will suffice.

Generally, the soil and geology are assumed to be uniformly spread throughout the study area. Geogenic processes furnishing ions from natural sources are slow and take a very long period to effect noticeable changes in the hydrochemistry of the groundwater. However, the rapid urban and economic boom in the area has led to intense construction and infrastructural development, especially, within the HR areas. The population pressure and the use of septic tanks for sewage disposals within the HR area. These anthropic factors can be assumed to be contributors to the major ion chemistry of the groundwater. These localized land use practices in the HR area can responsible for the changes in the hydrochemistry of the groundwater since the rainwater continues to infiltrate into the groundwater over 7 months of the torrential rainfalls. Construction materials such as cement, gypsum and other clay materials used for concrete and building roads can be good sources of calcium and magnesium ions. On the other hand, chloride ions can be released to the groundwater from the direct draining of the septic tank and other on-site sanitation facilities form a reasonable part of the groundwater recharge system in the densely built-up HR area. This source can also be a major source of sodium and nitrate in the groundwater.

6.3.4.3 Bivariate cross plotting methods

To predict the major hydrogeochemical processes that furnish the major ionic constituents in the groundwater, it is important to express the concentrations of the ions either in milliequivalent weights or molar concentrations. These concentrations represent the reaction units of the reacting ions. Here different cross-plot combinations of the ions have been presented to demonstrate the geochemical process that governs the chemistry in the groundwater reservoirs as shown in Figs (6-9 (a)–(d)). The weathering of the parent materials and chemical weathering are the commonest way through which the major ions builds up in the groundwater (Berkowitz et al., 2014). To check between competing silicate and carbonate weathering processes, which one of the processes furnishes the groundwater with the major ions. A cross plot of [Ca+Mg] vs [HCO₃+SO₄] of the wells was performed as described in Kumar et al. (2009) shown in Fig (6-9(a)). The result of the plotting revealed that the majority of the

wells in the LR area are below the equiline¹⁵ of the scatter chart. The result confirms that silicate weathering is the main source of the major ionic species in the groundwater in this area against most HR wells which were found above the 1:1 line.

The background geology in the study area is predominantly quartz mineral with very little proportion of clay minerals such as kaolinite. The quartz mineral reacts slowly and comprises about 95% of SiO₄ in a tectosilicate arrangement in the crystalline lattice. The quartz mineral contains trace impurities of ions such as Na, K, Ca, Mg, Fe, and H (OH), which are more reactive and can influence the chemistry of groundwater (Berkowitz et al., 2014). Besides, the major ions are released from more reactive clay minerals in the host environment. The illustrations in Fig (6-9(b) and (c) describe the relationship between the alkaline earth ions [Ca+Mg] and the alkali metal ions [Na+K] to the total cations (TC) present in the groundwater wells in both the LR and HR wells. In Fig (6-9(b), the LR wells showed a weak association between the [Ca+Mg] ions to the TC in the groundwater, as most of the wells lie scattered below the 1:1 and 1:2 lines.

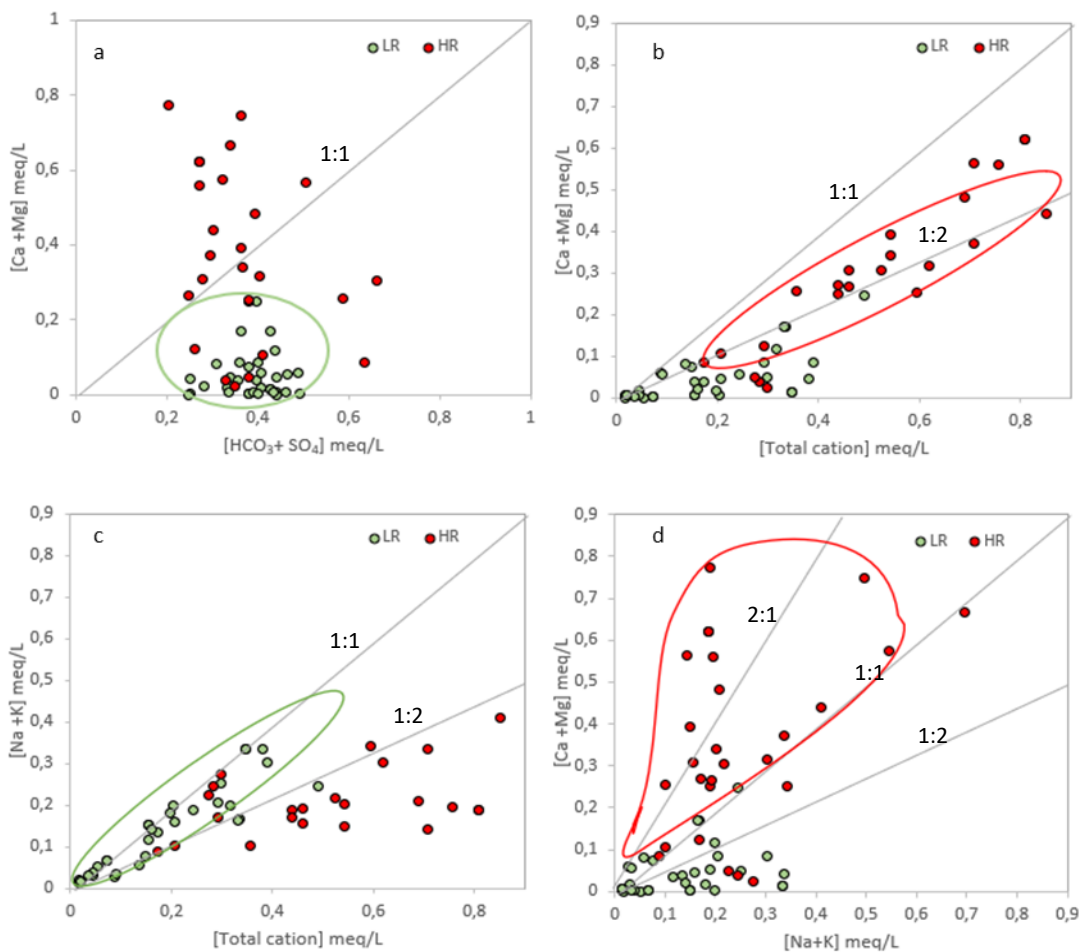


Fig 6-9: Bivariate cross-plotting of major ions in the groundwater reservoirs in wells of sparse (LR) and densely (HR) built-up areas.

¹⁵ The equiline represents the 1:1 line in a scatterplot.

However, the relationship between $[Ca+Mg]$ and TC for wells in HR areas look moderately strong, as most of the wells were aligned along the 1:2 line in the cross plot. On the other hand, we found in Fig (6-9 (c)) that the LR wells have a strong correlation between the $[Na+K]$ ions and TC where most of the wells aligned on the 1:1 equiline. This strong correlation suggests that $Na+K$ ions come from the silicate weathering and the HR wells lie along the 1:2 line for the $[Na+K]$ vs the TC suggesting a reversible ion exchange taking place in these areas. To check the direction of movement of the base cations between the groundwater and the host rocks minerals in Fig (6-9(d)), the ($[Ca+Mg]$ vs $[Na+K]$) test was performed, for both wells in the LR and HR areas. The results revealed that most of the HR wells were found around, and above the 2:1 line. This result implied that the $[Ca+Mg]$ ions in the groundwater come from the surrounding. This situation is not the same in the LR areas, where most of the wells lie under the 1:2 line, suggesting that the $[Na+K]$ ions were furnished from the rocks to the groundwater system. The different bivariate cross plotting arrangements suggest that silicate weathering must be the responsible for the low mineralization in the groundwater, as the quartz mineral is very unreactive. However, the base ion exchange processes can occur simultaneously in the wells of the HR area, introducing Ca and Mg ions in the groundwater.

6.3.4.4 Chlor-alkaline index (Index of base exchange)

To further understand the mixing and movement of the base ions within the groundwater, the concept of the ion exchange process was further investigated since it controls the chemistry of the groundwater both in the LR and HR areas. The index of base ion exchange suggests the direction of movement of the base (i.e. alkali metals and alkaline earth metal) ions between the groundwater and the clay minerals in the aquifer materials. The principle of ion exchange is a reversible process (Hölting and Coldewey, 2019). The ion exchange process governs the exchange of the main cations $[Na+K]$ and $[Ca+Mg]$ between groundwater and the host rock. The calculations of the chlor-alkaline index CAI-1 and CAI-2 were implemented based on the Equations (6-1) and (6-2) respectively. The results of the indices are summarized in the bar graphs shown in Fig (6-10 (a) and (b)) for the LR and HR wells. The bar graphs showed that the indices of the corresponding wells are not the same values for CAI-1 and CAI-2, but the signs are

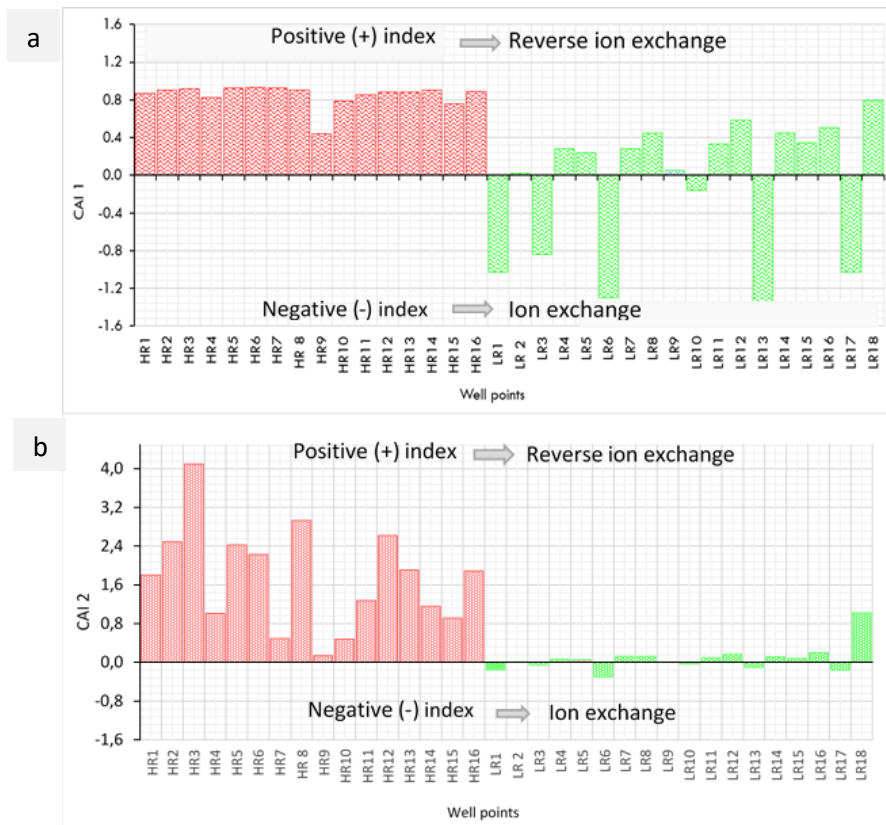
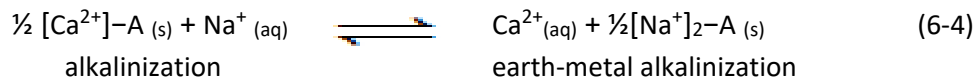


Fig 6-10: Bar graphs illustrating the index of base ion exchange for (a) CAI-1 and (b) CAI-2 against the wells in both the LR areas (green shaded bars) and HR areas (red shaded bars).

the same in both the LR and HR wells. The sign of the index suggests the direction of the movement of the base ions (i.e. whether the process will lead to ion exchange or reversed ion exchange) in the groundwater. The results of CAI-1 in Fig (6-10(a)) shows that all the HR wells, represented in the red shaded bars have positive CAI-1 indices. Whereas the green shaded bars refer to the LR wells, for which some have positive indices and some of the wells with negative indices. 83% of all the wells both from the HR and LR areas have positive indices. The results of the CAI-2 presented in Fig (6-10(b)) follows a similar trend as in Fig (6-10(a)) in terms of the signs, but the indices in the CAI-2 have much higher values than the CAI1 indices for most of the wells in the HR area.

In general, the index of base ion exchange is positive when the concentration of the chloride [Cl] is higher than the concentration of alkali metal [Na+K] ions, and this suggests that adsorbing [Ca+Mg] ions in the surrounding can be released into the groundwater to react with the excess [Cl] ions in the groundwater. However, if the reverse is the case, i.e. the index is negative, then there are more [Na+K] ions in the groundwater solution. Therefore, more [Na+K] ions from the surrounding will be released to exchange with [Ca+Mg] ions in the groundwater solution. This means that the movement of base ions could be in either direction, making the process a

reversible one. Therefore, wells with the positive CAI-1 index undergoes the reverse ions exchange while the wells with the negative CAI-1 index are ion-exchange controlled (Zaidi et al., 2016). It is worth mentioning that the movement of the Ca^{2+} in both directions can serve as a temporary pH buffering mechanism in the groundwater system (Toumi et al., 2015). Hence the concept of the base ion exchange process has been reported as the predominant geochemical process responsible for the mixing of the groundwater facies (Hamutoko et al., 2017). The mechanism of the reaction of the base ion exchange is demonstrated in Equation (6-4).



Where A = adsorbing (exchange) medium which could be a clay mineral

Equation (6-4) is a reversible chemical process leading to either the alkalinization process (i.e. the removal of Na and K ions in the groundwater) in the forward reaction or the earth metal alkalinization process (i.e. removal of the Ca and Mg ions) in the groundwater for the backward reaction. This equation was modified in Hölting and Coldewey, (2019, p. 144) to illustrate the base ion exchange taking place between the groundwater and the host surrounding. Another factor influencing changes in the index of base ion exchange and the hydrochemistry of groundwater is the direction of flow of the groundwater in the reservoirs (Hwang et al., 2017). This factor played an important role in explaining the mixing propensity in the groundwater reservoirs (Wallick and Toth, 1976) especially, in the LR areas. This can be confirmed with the mixed signs observed in the CAI-1 index of base exchange for wells in the LR wells. The direction of flow of the groundwater from more mineralized groundwater in the HR upstream to some less mineralized LR wells, the mixing of such groundwater reservoirs may give rise to rapid changes in the CAI indices as shown in Fig (6-10).

Chapter Seven

7 Bacteriological risk assessment in different drinking water sources

7.1 Background

Drinking water quality is guaranteed, if the physical, chemical, radiological and biological aspects are acceptable according to the set standards (WHO, 2011). Today, bacteriological risks are the most common causes of health problems associated with drinking water in many developing countries (Wright et al., 2004). In sub-Sahara Africa, microbial contamination in drinking water sources has been reported in many studies both in the surface and underground water sources (Banda et al., 2014; Sorensen et al., 2015; Nzung'aSilu, 2019; Gwimbi et al., 2019). The region accounts for most deaths in children under five globally due to preventable diarrhoeal cases transmitted through drinking water (Carvajal-Vélez et al., 2016). There are several other waterborne diseases such as cholera, hepatitis, typhoid fever, dysentery, guinea worm etc. prevalent in this region. The presence of these harmful microbial organisms in any source of water raises safety concerns for the people that consume it. However, governments in this region must ensure that people get microbial-free quality drinking water to guarantee public health.

The concept of indicator organisms in the assessment of the biological wholesomeness of the water has been used to monitor the presence of harmful pathogens in the source water. Coliform bacteria are the most frequently used indicator organisms. Most coliforms are known to be environmental bacteria; however, the presence of Coliform bacteria suggests that other harmful pathogens might be present in the sample. The advantage of using indicator organisms in the assessments for microbial wholesomeness in drinking water sources is because it gives a measure of the cleanliness of the distribution system (WHO, 2011), reliable means of assessing faecal contamination, saves time and reduces the cost of monitoring. It serves as a first check in the monitoring of microbial threats in drinking water sources. Some examples of other pathogenic microorganisms reported in drinking water sources are summarized in Table 7-1. *Escherichia coli* is also known as *E. Coli* is a gram-negative rod bacterium (Lohmann and Rauscher, 2019) and belong to the family of Coliforms. Many strains of *E. coli* have been identified which are harmless. These organisms grow in the lower intestines of humans and other domesticated animals especially cattle, goats and chickens etc. However, the pathogenic strains of *E. coli* known to be Shiga Toxin-producing *E. coli* (STEC) cause poisoning (diarrhoea) in infants and elderly adults (WHO, 2018). Other strains may cause urinary tract infections,

inflammation of intestinal walls, bloody watery diarrhoea. When detected in any drinking water, it can serve as a confirmation test for faecal contamination in the source water. This is because the *E. coli* bacteria can only exist in the intestine of animals.

Table 7-1: Some common pathogenic organisms found in different water sources (WHO, 2001).

Bacteria	Virus	Protozoa and Helminths
<i>Salmonella</i>	Picornaviruses (including Hep A)	<i>Giardia</i>
<i>Yersinia</i>	Adenoviruses	<i>Cryptosporidium</i>
<i>Campylobacter</i>	Parvoviruses	<i>Entamoeba histolytica</i>
<i>Vibrio cholera</i>	Small round structured viruses	<i>Balantidium coli</i>
<i>Shigella</i>	Hepatitis E virus	<i>Naegleria + Acanthamoeba</i>
<i>Legionella</i>	Papovaviruses	<i>Dracunculus medinensis</i>
<i>Aeromonas</i>		<i>Schistosoma</i>
<i>Ps. Aeruginosa</i>		<i>Cyclospora cayatenensis</i>
<i>Mycobacterium</i>		
Cyanobacterial toxins		

Some sources of *E. coli* contamination reported in urban groundwater in different parts of sub-Saharan Africa come from malfunctioning and leaky septic tanks, the use of on-site sanitation facilities (Barrett et al., 2000; Lapworth et al., 2017a), as well as manure stockpiles, stormwater runoff from animal dungs (humans and domesticated animals faeces) and open dumpsites causing biological contamination on both surface and groundwater (Lapworth et al., 2017b). The UN's sustainable development goals (SDG 6) target is to improve that people have access to safe drinking water and sanitation, especially in developing countries where the targets fall short. Nevertheless, epidemics from drinking water sources have continued. For instance, diarrhoea is the second leading cause of morbidity and mortality in an infant under 5 in many developing countries and must be checked. In this chapter, the goals are to investigate the bacteriological risks associated with drinking water both from natural and different alternative drinking sources in the study area. The presence of the indicator organisms in the samples of the water and alternative drinking water sources in the area can pose a health risk to the public since most people in the area do not treat their drinking water sources before consuming them. The results of the investigation will be correlated to secondary health data for diarrhoeal cases of children under five to have a better understanding of the water safety situation in the area.

7.2 Methods

Samples of natural source water (groundwater samples were taken directly from the tube wells and surface water from the Aba River [Water side] samples taken from different points between the stream-head area at Okpolumugbo and downstream along the Ngwa Road area in the



Fig 7-1: Some examples (a) water samples analysed and (b) set-up for the bacteriological evaluations.

densely residential areas) were collected with sterilized 50ml amber glass bottles for the bacteriological investigation. Other samples tested include alternative drinking water sources such as commercially packaged bottled water, water in sachet (also known as “pure water”) and beverage drinks (alcohol and non-alcohol) packaged in different materials such as aluminium, glass or PET that were produced only within the study area.

A total of 36 samples were bacteriologically tested according to the ISO 7704:1985 procedure as described in VWR [BDH] Chemical 2019 manual. This method is based on membrane filtration of inoculation of the microbes incubated in culture media which is a commercially prepared ready-to-use *coliforms chromogenic agar* (CCA) prepared on a 55 mm petri-dish and purchased from the VWR chemicals. The CCA media contain substrates, which selectively isolate coliforms and the *E. coli* bacteria in the samples. The isolations occur when the substrate in the culture medium cleave to the β -D-galactosidase enzyme in Coliform bacteria to give a salmon-red colouration to the coliform colonies and the β -D-glucuronidase enzyme of *E. coli* giving the colony a dark-violet colour. Some of the samples tested and the laboratory set-up for the bacteriological test on the water samples are shown in Fig (7-1(a) and (b)) respectively.

7.2.1 Evaluation of secondary health data

A secondary health data set related to the admittance of children under the age of five were collected from the Abia State University Teaching Hospital (ABSUTH) Aba. This data was evaluated to correlate the prevalence of diarrhoeal cases and the spatial distribution of the diarrhoeal incidence within the area for the period 2011 – 2015. A diarrhoea incidence map was created and laid over the delineated urban-land use map extracted from the 2017 land use map of the area. The size of the prevalence bubble in the distribution map describes the spatial severity of the disease and can be traced to the bacteriological quality of the drinking water

sources. A time series of incidence diarrhoea cases were plotted to show a trend of the prevalence over time.

7.2.2 Bacteriological risk categorization based on *E. coli* count

The microbial health risk associated with source water can be related to the quantity of *E. coli* colony forming units (CFU/100mL) present in the water sample. The risk category is divided into 4 classes as shown in Table 7-2, which describe the safety level on the source water for drinking purposes (WHO, 2011a). The incidence classification of *E. coli* present in the water can be likened to the range of diarrhoeal cases based on the risk category.

Table 7-2: Summary of E.Coli risk assessment categorization based on WHO recommendation.

Risk Category	E-coli (CFU /100mL)
Low	<1
Medium	1-10
High	11-100
Very high	>100

7.3 Results

One of the important findings of the household survey administration showed that about half the respondents in the study area drink untreated groundwater directly from the borehole wells, whereas the rest drink from the other alternative water sources. The result of the distribution of drinking water sources analysed is shown in the pie chart in Fig (7-2). A total of 36 samples were analysed for bacteriological contamination in the samples. The samples group breakdown is summarized in Table 7-3 shows the outcome of the bacteriological tests for the beverages and different water sources. The results of the analysis showed that about 37% of the total samples tested positive to either the *Coliform* and/or *E. coli* colony forming unit

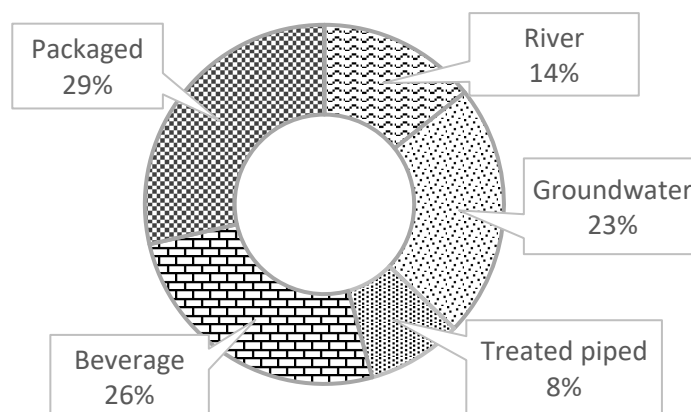


Fig 7-2: Distribution of water sources and alternative drinking water sources for the bacteriological analysis in the study area.

bacteria as detected in the samples. It was found that the samples of the Aba River and groundwater samples that contain both indicator organisms represent 16.7% of the total samples. The remaining alternative water sources such as the packaged water (i.e. bottled or water in sachets), and beverage drinks (non-alcoholic drinks) constituting 13.7% of the total samples were found positive for the indicator organisms. However, only coliform bacteria were detected in these samples.

Table 7-3: Summary of the bacteriological tests in the source water.

Water source	No of samples	Failed test?	E-coli?	Coliform?
Piped (treated)	4	0 (0%)	No	No
Beverages				
• Alum can	4	0 (0%)	No	No
• Glass bottle	4	2 (5.6%)	No	Yes
Tube well (GW)	8	2 (5.6%)	Yes	Yes
Packaged water				
• PET bottle	6	1(2.8%)	No	Yes
• PE sachet	5	2 (5.6%)	No	Yes
Aba River (SW)	5	4 (11.1%)	Yes	Yes

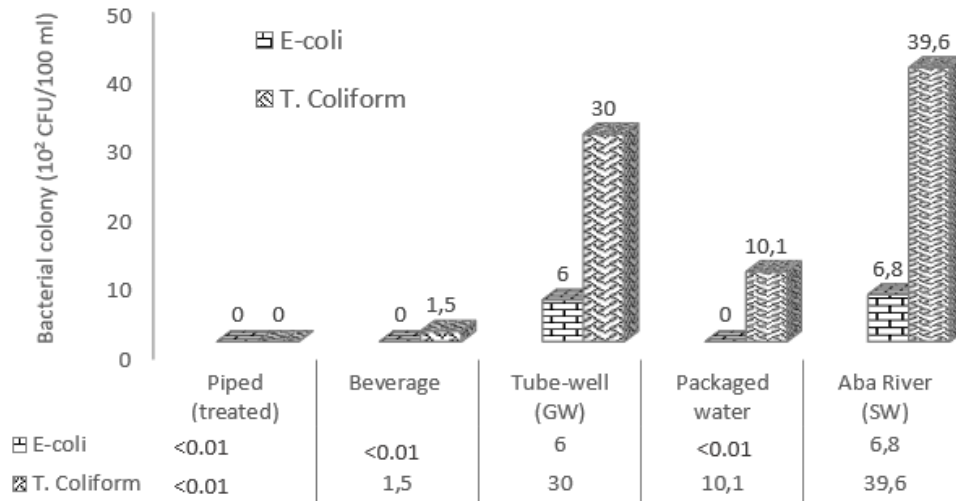


Fig 7-3: Bar chart showing the average counts of colony-forming units in Total Coliforms and *E. coli* detected in the water and beverages samples.

The bar graph in Fig (7-3) summarizes the bacterial risk categorization for the different samples using the averages of the colony counts of the detected indicator organisms in each sample group analyzed to determine the bacterial risk. Figs (7-4(a)-(c)) show some examples of the colony-forming unit growth of the indicator organisms in the source water and alternative drinking water samples.

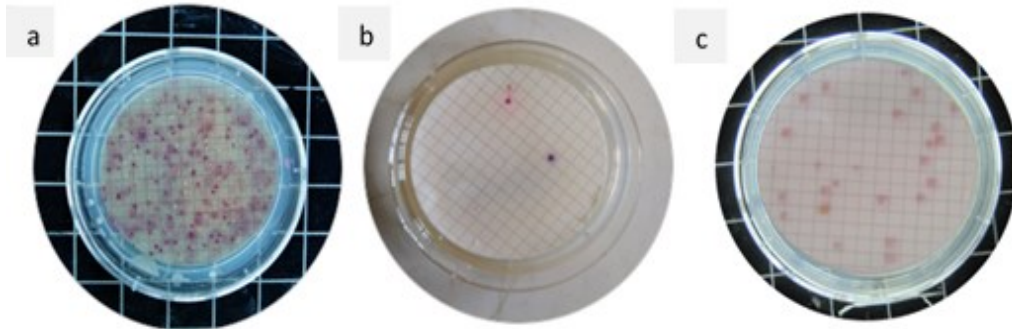


Fig 7-4: Some results of the bacteriological tests showing detection of colony-forming units of indicator organisms (salmon-red coliform and purple-dark blue *E. coli* colonies) in (a) water sample from Aba River, (b) sample of groundwater from a borehole (c) non-alcoholic beverage sample.

The results show that the piped treated water samples are the safest water source in terms of the bacteriological risk assessment in the area. It is worthy of note that the samples of the treated pipe water were obtained from the standalone tap outlets in one of the brewery plants in Aba. The results in Fig (7-3) showed the average *Coliform* bacteria and *E. coli* colony forming units present in some of the samples are 600 CFU/100 ml and 2400 CFU /100 ml for the groundwater and 680 CFU/100 ml and 3280 CFU/100 ml for the Aba River respectively. This suggests anthropic-derived microbial stress on the natural water sources in the area due to the presence of *E. coli* in the groundwater and the river. No *E. coli* colony forming units was detected in the samples of any of the alternative drinking water sources, but averages of 150 CFU/100 ml and 1001 CFU/100 ml were detected in the samples of beverage and packaged water respectively.

The health data obtained from the Abia State University Teaching Hospital captured 1761 cases of children under five that visited the hospital. This data covers the period 2011 – 2015 (5-year). However, the diarrhoeal cases recorded within this period represents 17.2% (303 cases) of the total, and the prognosis showed that about 10% (30 of the diarrhoeal cases) resulted in death for the period under review. The diarrhoea incidence map for the area in Fig (7-5(a)) shows the distribution of the cases in the main residential parts of the area. The map is divided into two zones, i.e. the densely built-up zone in the orange shade, and the sparsely built-up zone is in the light green shade. The densely built-up area is further divided into two subclasses, with areas for commercial activities and dense residential areas. The commercial parts make up the core of the city centre, while the residential part surrounds the commercial part with high population density. The sparse built-up area represents other forms of land use including peri-urban residential settlements. The bubbles sizes in the map correspond to the frequency of the distribution of the diarrhoeal cases in the different residential parts of the study area. The large

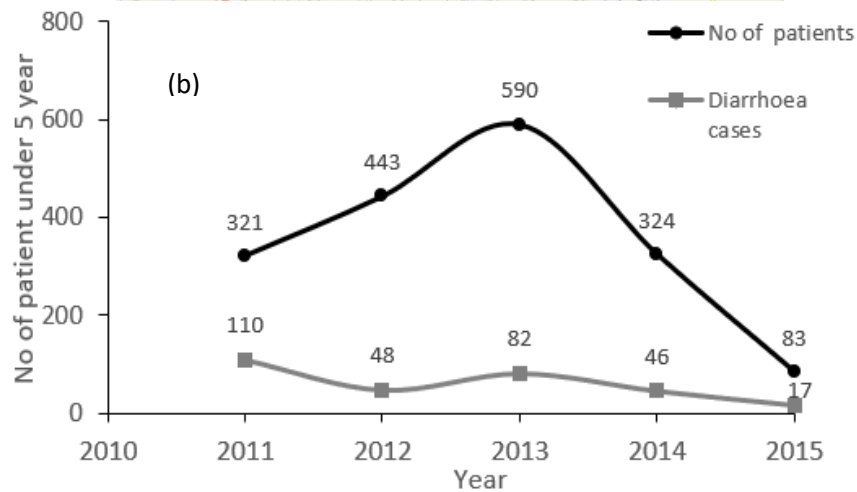
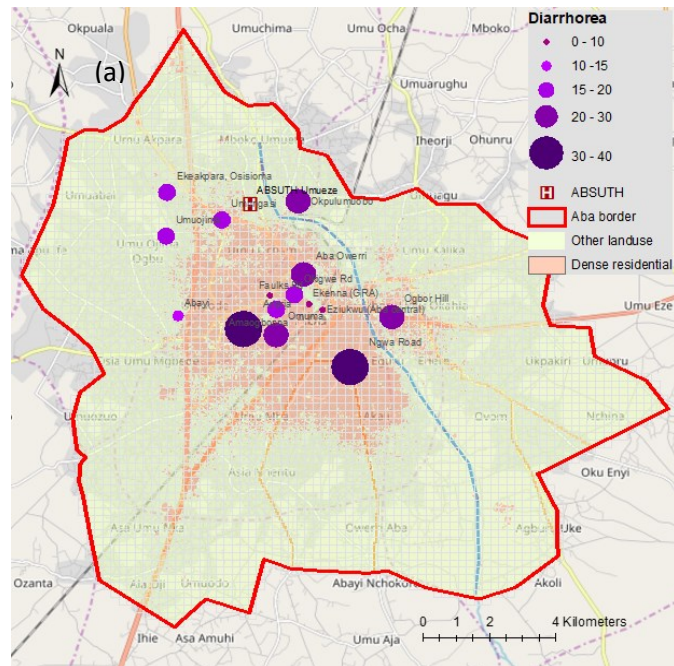


Fig 7-5: illustrations showing (a) map of diarrhoeal cases incidence distribution and (b) a time series plot of diarrhoea disease for children under the age of 5 years in the study area.

bubbles are found in the most congested parts of the residential area such as Ngwa road and Faulks road corridors. The result of the diarrhoea incidence time series plot for children under five years admitted at the Abia State University Teaching Hospital is summarized and shown in Fig (7-5(b)). The illustration suggests that the number of children admitted increased and peaked in 2013 with corresponding diarrhoeal cases. Then the trend indicates that the diarrhoeal cases rapidly decreased after the peak period as shown in the diagram.

7.4 Discussion

The results of the bacteriological investigation in the different drinking water sources show that water from untreated natural sources such as groundwater from some borehole wells or water from the downstream of the Aba River can be bacteriologically ranked “very high risk”. This is

judged by relating the amount of average colony forming units per 100ml of samples for *E. coli* risk categorization assessment in Table 7-2. The implication of having *E. coli* in the water sources indicate possible faecal contamination due to a direct human influence on the source water. In densely populated areas, there is no central sewer system. The use of cesspools, on-site sanitary facilities like pit-latrines or leaky septic tanks are prevalent, which are used for human disposing solid waste from water cisterns, as well as other household effluents, eventually, find their way into the groundwater. These sources have been widely reported and corroborate with the results of other researchers in the sub-Saharan African region as the source of bacteria in a natural water system. Diaw et al. (2019) in their investigation showed a strong positive correlation between *E. coli* contamination and septic tank drains in Dakar, Senegal. Another source linked bacteriological contamination in the groundwater to the use of on-site sanitation facilities found in most developing countries (Cissé Faye et al., 2004; Banda et al., 2014; Lapworth et al., 2017). There are other forms of land use practices that have been observed, which could compromise the bacteriological wholesomeness of the groundwater in the area. Examples of such practice include the use of a private residence as a burial ground for both dead humans and animals. This practice is culturally acceptable in many African communities as it is sometimes used to secure ancestral land for the future generation. Again, acquiring spaces for the burial of deceased ones at the cemeteries and churchyards in some cases may be very expensive and not affordable for the urban poor living in many developing urban areas.

Besides, leachates from municipal solid waste when not adequately managed can be a source of bacteriological contamination in the area. These sites are sometimes close to residential buildings (see photo illustration in Fig (7-6)). This exposes the quality of the groundwater to both biological and chemical contamination. Often, the dumpsites are borrow-pits or gully erosion sites, which have been converted to landfills. Such sites are liable to quick groundwater contamination as the attenuation time and capacity of the unsaturation zone has been reduced,



Fig 7-6: Images of active dumpsites locate close to a residential building with tube well. (Photos taken by the author during the 2017 field campaign in the study area).

therefore an attenuation process may no longer be effective in dealing with contaminants before they reach the groundwater. The municipal wastes collections are usually not sorted and therefore contains high organic waste from both households and waste from the food market. The composition of these wastes in the dumpsite may sometimes comprise dead infants, aborted foetus and animal carcasses, and sometimes waste from unlicensed medical centres. Such components in borrow-pit/ landfills can compromise the biological quality of the groundwater.

Also, It was observed that many fish farms in the area drill tube well to drain effluents of the fish farm directly into the aquifer without any form of treatment. Some of the local drilling companies, employ practices that may contaminate the groundwater during the drilling of the borehole wells. The use of contaminated drill fluid has been observed in the area. In the case, where the supply of groundwater from nearby boreholes well or storage tanks during the drilling of new tube wells, some uneducated local drillers use stagnate pond water or rainwater logged in the area as the source of recirculation fluid during drilling. These kinds of practices can introduce harmful organisms into the groundwater if such circulation fluids have been contaminated. Poor environmental practices which affect the microbial quality of the Aba River were also observed. In riverine neighbourhoods and shanties in the area, some households defaecate and channel their household effluents (solid and liquid) directly into the river. More so, there were other practices such as animal rearing and slaughtering activities next to the river, as well as the disposal of sewage sludge from on-site sanitation facilities directly inside the Aba River. These activities increase the microbial load and affect the bacteriological integrity of the water source as illustrated in the photos shown in Fig (7-7). Some of these practices are not peculiar to the study area but have been widely reported in many developing urban contexts (Barrett et al., 2000; Chukwu et al., 2011). It is assumed that the alternative drinking water sources have gone through some treatment processing: physical, chemical and/or bacteriology before being distributed to the general public for consumption. However, this is one of the reasons why the results do not show *E. coli* contamination in most of the alternative sources. But colonies of *Coliform* bacteria were formed in some of the samples. This form of bacteria is easily found in the environment. The use of non-sterilized packaging materials has been reported as a source of bacteriological contamination in the packaged water (Omalu et al., 2010), while poor handling and storage of these products are other sources through which these products can be infected with the bacteria (Akinde et al., 2011).



Fig 7-7: Some bacteriological contamination sources of water in the area (a) leaky septic tank (b) rearing of cattle close to domestic water sources (c) disposal of household waste into the watercourse (d) direct recharge of groundwater with wastewater from a fish farm.

The presence of total coliform bacteria in any water samples announces bad news for the drinking water distribution system. This simply means that the distribution system is not clean, or the disinfection process was not sufficiently done to secure the drinking water.

The health risk assessment of the area was related to the incidence of diarrhoeal cases in children under five. The result section showed that the trend of the diarrhoeal cases within the 5 years in the area. The declining trend in diarrhoea cases gives a positive indication that the biological quality of the water and sanitation which the people are using have improved in the area. Other than drinking water, the spread of the disease can be contracted through other means, such as ingesting contaminated foods or having contact with infected people. Therefore, maintaining a high level of hygiene is very important and handwashing practice with soap can help minimize the incidence of diarrhoea. In the incidence distribution map of diarrhoeal cases, there are two factors, which play out to account for the distribution of the disease within the study area: (1) population density and (2) income-class distribution of residents in the area. These factors can influence the frequency of the cases. The high population density areas are mostly in the shanties, places where people with low-income earners. In these areas, there is a high prevalence of diarrhoea cases which are represented with bigger diameter bubbles. The

buildings in this area are congested and sometimes do not follow the city master plan. Because of this, the tube wells installation in this area does not follow the stipulated separation distance from potential contamination sources such as septic tanks stipulated by the standards organization of Nigeria. Leaky septic tanks and drain fields are rampant in the area and can influence the bacteriological quality of the groundwater leading to faecal contamination. An example of a leaky septic drain observed in one of the main residential areas is shown in Fig (7-7(a)). It is a common scene among the poor income-earning neighbourhoods and most households living in this area cannot afford to buy at least the reliable alternative drinking water sources available, for which they have to pay more.

Chapter Eight

8 Development of decision support tools for groundwater management

Preamble

The contributions of groundwater to the domestic water supply both in the rural and urban sub-Saharan African communities cannot be over-emphasized. In many parts of the globe, environmental agencies responsible for the management of urban drinking water use tools such as frameworks, software, numerical analysis tools, and maps to fulfil this obligation. Some of the tools are specifically designed to evaluate and manage risk on the groundwater at different levels depending on the data demands (Environment Agency, accessed 31.10.2019). This is illustrated in Fig (8-1).

The most basic of the tools are the risk screening tools, which are presented in the form of maps. They are used to identify prevailing hazards that should be further investigated, by either employing a generic risk assessment tool or carry out a detailed investigation based on the amount of data available for use. In Nigeria, just like in many sub-Saharan African countries, data required for water resource management are scarce. This is known to be one of the major challenges facing the development of the water sector in the region, and the investment in data repositories and gathering are inadequate. The decision making is based on rash and unquantified uncertainties due to either lack of hydroclimatic data or unavailable water use information (Hughes, 2019). The short-run solutions often entail copying completely western solutions, which should have been adapted with the local knowledge. However, the lack of either know-how or inadequate data to modify this procedure often lead to their failure of the solution. Therefore, developing countries must invest in information gathering systems tailored

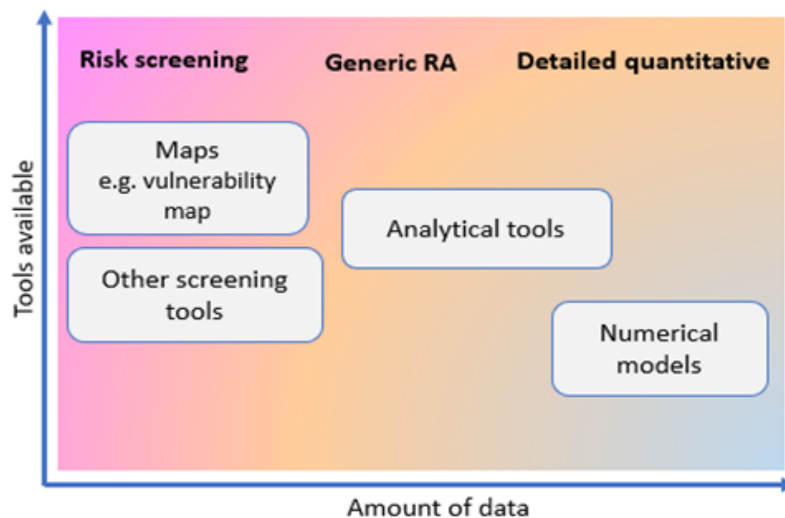


Fig 8-1: Mapping of groundwater risk evaluation tools to different categories of risk levels.

towards supporting decisions making processes by relevant water agencies to manage the threat of groundwater insecurity and contamination in their areas. A sound decision support system related to integrated groundwater management usually include aspects (i.e. unprocessed information), as well as drivers (stakeholder that influences decision making) to be considered (Pierce et al., 2016) as summarized in Table 8-1.

Table 8-1: Aspects and drivers of groundwater decision support system (Source: Pierce et al., 2016).

Aspects	Data and models	Drivers	Stakeholder perspective
Aquifer performance		Groundwater governance	
Biophysical systems	Issues of concern		
Human setting	Stakeholder engagement		
Spatial scale	Governance of other systems		
Temporal scale			

This chapter aims to propose novel approaches that can adapt common and widely used risk screening and risk assessment analytics developed for the area to deal with the local situation in the area. These tools can be used in combination to support decision making by relevant authorities in managing and protecting the groundwater quality, which is main the source of drinking water in most parts of the region. The proposed groundwater risk assessment tools considered include the groundwater vulnerability assessment and the groundwater quality distribution maps for the area.

8.1 GIS-based groundwater quality mapping: a water quality index (WQI) approach

8.1.1 Background

Besides the rising temperature and the uncertainty in rainfall variabilities (Hughes, 2019), fast-urban growth rates have been reported as another contributory factor to surface-water and groundwater unavailability (Tatlock, 2006) in many parts of sub-Saharan Africa leading to water stress in the region. Little wonder why many countries in the region, Nigeria inclusive, failed to meet the targets of the MDG 7c in 2015 (World Bank, 2015). To improve the availability of potable drinking water, there is a need to strengthen the capacity of decision-makers in the water sector with scientifically-based information to guide them in making policies that protect the source water in the area. The groundwater quality information map is one of the analytic tools that guide the relevant agencies and policymakers in their job of managing the source water. Often, this map is a spatial representation of the groundwater quality data and defines the suitability of the groundwater for different purposes. However, the water quality variables list is unexhaustive and the monitoring programs are only based on some routine indicators of

interest in certain areas due to the high cost of monitoring. The question is how then can we create a thematic water quality map that encompasses these quality indicators?

The concept of water quality index (WQI) is a set of mathematical equations that can be used to reduce the complexity of managing a large volume of data from several water quality variables. It transforms selected water quality variables with different dimensions and units into a single unitless number, which defines the quality of the water. The indices obtained are categorized into classes to represent the quality of the source water and its possible suitability for different purposes. Historically, WQI estimation was first credited in Horton, (1965), and the concept has continued to evolve over the years (Abbasi and Abbasi, 2012). This tool has been successfully used to evaluate the suitability of different water bodies, including surface and groundwater. Therefore, the indices can be handy for some decision-makers who might be technically unskilled in managing a large volume of different water quality data to support their decisions. The WQI has been widely applied in different parts of the world by government agencies, institutions, and research groups to monitor and validate the quality of different water bodies (Abbasi and Abbasi 2012). In Nigeria and other parts of sub-Saharan Africa, the water quality index has been used in several studies to evaluate the quality of different water sources, including, treated piped water, surface water, and groundwater in different parts of the country (Egborge and Benka-Coker, 1986; Akoteyon et al., 2011; Etim et al., 2013; Oni and Fasakin, 2016). However, several modifications and method enhancements have evolved in correcting some of the inherent problems associated with some of the methods of assessing the WQI. One such approach is in the aggregation step which might introduce “ambiguity”¹⁶ and “eclipsing”¹⁷ in the final indices. Abbasi and Abbasi, (2012) reported that fixing the mathematical functions aggregation step in the WQI estimators will enhance the performance of the estimation, thereby eliminating this inherent problem. The weighted linear summative averaging function that has been reported might introduce ambiguity in the aggregation steps, thus replacing the linear sum function with the weighted geometric averaging function can be used in eliminating this problem.

Several studies in the context of developing countries have implemented the water quality index using the weighted linear summative approach as the sub-index aggregation method despite

¹⁶ Ambiguity is an inherent problem in the SI aggregation function that arises when the final index becomes unacceptable, even when none of the sub-indices did not pass the critical level of water quality index.

¹⁷ Eclipsing occurs alongside ambiguity and it occur when index has not pass the unacceptable value, in spite one or more of the subindices exceeding the critical level.

being flawed to have an inherent problem. Some of the reasons why this method of water quality index estimation is used in research related to many developing countries' contexts are due to the following: 1.) scantiness of water quality data available for the assessment, 2.) easiness to apply and 3.) can be employed both for surface and groundwater evaluations (Yidana and Yidana, 2010; Oni and Fasakin, 2016; Kwani et al., 2018). The integration of the GIS platform in the management of data for water quality assessment has also been explored to spatially analyze and manage different water quality indicators (Nas and Berkday, 2010; Yidana and Yidana, 2010; Balakrishnan et al., 2011). However, the concept of WQI can be used to bring together water quality indicators and transform the different dimensions and units to create a thematic water quality map. This concept has been demonstrated in Ketata et al. (2012); Batabyal and Chakraborty (2015) and Kwani et al. (2018).

In this chapter, the importance of creating a groundwater quality index map using GIS as a tool to combine and visualize several water quality indicators while isolating factors that influence the acceptability of water in the thematic map will be explored. Through this the following specific objectives will be achieved:

- Address the problem of ambiguity inherent in the estimation methods. This will be illustrated by comparing the results of the WQI maps derived from commonly used sub-index aggregation methods from an empirical study.
- develop an analytic management tool that complements the groundwater vulnerability assessment tool developed to support water quality decision making in the area. This tool highlights the quality distribution and the suitability of the groundwater for drinking purposes in the area.

8.2 Methodology

The implementation of the groundwater quality mapping was done using data of some selected quality indicators from the groundwater samples of the 61 tubes-wells described in Chapter 6. To actualize the groundwater quality mapping in the area, the steps in the schematic flow were followed as shown in Fig (8-2. The scheme is an illustration of the methodological approach and the procedure starts with defining the spatial boundary covering all the tube wells used for the evaluation, as well as acquiring their spatial identity during the groundwater sampling. At the core, involves sampling and evaluation of water quality indicators in each of the tube wells. Then, the quality data are normalized in the form of the water quality indices (WQI) for each of the tube well and converted into point data on the GIS platform.

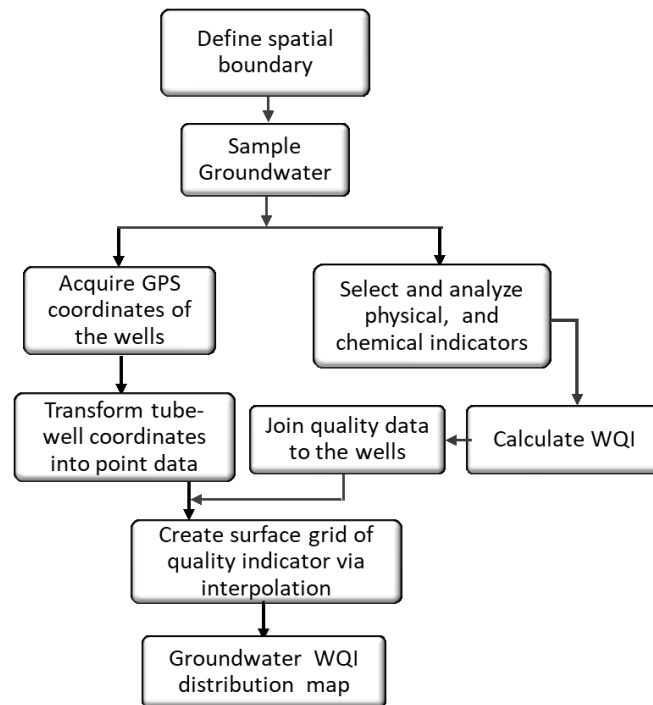


Fig 8-2: Schematic flow diagram for developing the GIS-based WQI quality mapping.

However, the WQI calculation follows four basic steps as described in its procedures. These include selecting the quality indicators, transforming the variables into a uniform scale, assigning weights to the indicators, and aggregating the sub-index to estimate the WQI for the wells (Abbasi and Abbasi, 2012). These steps will be detailed as follows.

8.2.1 Selection of water quality indicators

In most cases, the selection of quality indicators used for the WQI estimations are based on the professional judgment of experts of government institutions and other agencies responsible for the evaluation of water quality (Fernández, et al., 2004). There are many factors, which can influence the selectability of quality indicators in a study. These factors could range from the availability of finance to perform some techniques required to estimate the quality indicators to the ability to identify indicators, which may have an overall impact on the quality of the water. These factors may lead to the problem of subjectivity and lack of reproducibility of the final output. Kocer and Sevgili, (2014) suggested that a multivariate statistical approach can be used to reduce the redundancy in the indicator selection when several quality parameters are available for the WQI estimation.

In general, the quality indicators selected are usually routine water quality parameters. These include physicochemical, chemical and sometimes, microbial indicators that could influence the health or aesthetic acceptability of the water source. The results of the descriptive statistics for the quality indicators assessed in the tube wells revealed that the average values were less than

the MAC values for most of the indicators, but the pH. However, the standard deviation showed some tube wells strongly deviated from the average values of the measured indicators especially in many of the HR wells. In this case, there were cases where the values of the measured indicators either exceeded the MAC value or range or the measured values significantly deviated from the observed mean values for the indicators in a couple of the wells, especially in the HR wells.

Based on these criteria, eight quality indicators were identified and selected from the list of 21 indicators measured for the quality evaluation of the groundwater in the area. Table 8-2 gives a summary of the selected water quality indicators considered in this study and the WHO's MAC for the indicators.

Table 8-2: List of selected water quality indicators for the WQI mapping.

Quality indicator	Maximum acceptable concentration (MAC)	Remarks
pH	6.5 – 8.5	WHO/ NIS
Total dissolved solids	500	WHO/ NIS
Iron (II)	0.3	WHO/ NIS
Manganese	0.2	WHO/ NIS
Lead	0.01	WHO/ NIS
Chloride	250	WHO/ NIS
Nitrate	50	WHO/ NIS
Total petroleum hydrocarbon (TPH)	0.3/0.6 *	WHO; *DPR intervention limit

Sources of MAC for drinking water quality: SON, (2007); WHO, (2011)

8.2.2 Transformation of the quality indicators

This step deals with the mathematical function that transforms each indicator and brings them to a uniform scale. Some water quality indicators are unitless (e.g. pH), some have special units such as electrical conductivity ($\mu\text{S}/\text{cm}$), while others are measured in concentrations terms (e.g milligram per litre [mg/l]). It is important to transform all the units to a dimensionless scale by way of normalization. The WQI transformation process follows a sub-indexing approach, which creates a uniform scale for all the indicators selected for the estimation. The same expression for the quality rating function is used for all the selected indicators and the normalization process is achieved as shown in Equation (8-1). The value of the transformed and normalized sub-index is expressed as the quality rating of each indicator.

$$q_i = 100 * \left(\frac{C_i - C_0}{S_i - C_0} \right) \quad (8-1)$$

where q_i = the quality rating for the i th indicator,

C_i = the measured concentration of the i th indicator in the water sample for the well-point under consideration,

C_o = the concentration of the i th parameter in deionized water is assumed to equal zero for most of the parameters, but pH and DO.

S_i = maximum allowable concentration (MAC) set for the i th indicator by the relevant standard agency for drinking water.

The calculations of the quality ratings for indicators such as pH and DO follow special recommendations. For this study, the C_o for pH in pure water is set to be 7.0 which implies neutral water, hence the permissible S_i for the pH value was taken to be 6.5 since all the measured pH in the wells were all acidic and lower than the minimum limit for the WHO's pH of drinking water.

8.2.3 Assigning weights to indicators

The assignment of weights for all the selected indicators followed a systematic approach as shown in Equation (8-2). The expression in Equation (8-2) assumes that the assigned weight w_i for the i th indicator is a function of the WHO's MAC as summarized in Table 8-2. This means that $w_i = f(S_i)$ and K is the constant of proportionality. K is determined by the expression in Equation (8-3a), where n is the number of quality indicators selected for the WQI calculation. Based on these expressions in Equation (8-3b), W is the sum of all the assigned weights for the n parameters. The expression of W is the summation of the calculated weights w_i , where W equals 1. The expression of W is otherwise known as the unit weight.

$$w_i = \frac{K}{S_i} \quad (8-2)$$

$$(a) K = 1 / \sum_{i=1}^n \frac{1}{S_i}, \text{ and } (b) W = \sum_{i=1}^n w_i = 1 \quad (8-3)$$

8.2.4 Aggregation of the Sub-index [SI]

The aggregation of the sub-index SI_i is the sum of the products of the assigned weight of the i th indicator and the corresponding quality rating for the point of each tube well (i.e the product of (8-1) and (8-2)) as shown in Equation (8-4). However, the aggregation of the WQI takes into account the sum of the sub-indices of the n indicators selected for the WQI assessment. In this study, we explore two methods of sub-index aggregation approaches to investigate and visualize the main pitfalls associated with the methods. These include the weighted linear sum

average (WLSA) and weighted geometric average (WGA) sub-index methods as expressed in equations (8-5) and (8-9) respectively.

$$SI_i = w_i * q_i \quad (8-4)$$

The weighted linear sum aggregation method (WLSA) can be expressed as:

$$WQI = \frac{\sum_{i=1}^n (w_i * q_i)}{\sum_{i=1}^n w_i} \quad (8-5)$$

The weighted geometric water quality index is proposed to replace the summative aggregation in equation (8-5).

$$SI_i = q_i^{w_i} \quad (8-6)$$

$$WQI = \prod_{i=1}^n SI_i \quad (8-7)$$

$$\log SI_i = w_i \cdot \log q_i \quad (8-8)$$

$$WQI = \prod_{i=1}^n 10^{w_i \cdot \log q_i} \quad (8-9)$$

The water quality index, when estimated, can be used to express the degree of suitability of the wells for drinking in most parts of the area as shown in Table 8-3.

Table 8-3: Interpretation of the water quality index status.

Index scores	Index designation
0–25	Excellent
26-50	Good
51-75	Moderate
76-100	Poor
>100	Unsuitable

The interpretation of the index scores in Table 8-3 was adopted from Rawat and Singh 2018.

The table show the degree of suitability of the water for drinking purposes. The tube wells with quality index designated “poor” - “unsuitable” must be flagged, and monitored regularly.

Source: (Rawat and Singh 2018)

The implication of Table 8-3 means that a critical limit of 100 was set for index classes, above which the source water will be unsuitable for drinking. This means that wells with low index have good quality for drinking. However, it is assumed that the target set for the drinking-water suitability based on the quality index should be less than the moderate index class for the area.

8.2.5 Mapping the groundwater quality (WQI approach)

To understand the spatial distribution of the groundwater, the water quality index mapping approach was introduced. This begins with creating the spatial distribution of the component quality indicators in the area as described in the schematic flow chart of Fig (8-2). The quality

distribution surface for each indicator was created based on the results of the 61 tube wells. The quality surface for the eight selected indicators was created using the ordinary kriging (OK) interpolation method. This method was selected because the points were spread throughout the area and it is the most commonly used method in geosciences. The WQI calculation approach was used to combine and transform the units and dimensions of all the eight indicators to a common unitless scale based on the sets of mathematical expressions as described in Equations (8-5) and (8-9) respectively. The WQI for the 61 tube wells were calculated using both the weighted linear summative average (WLSA) and weighted geometric average (WGA) sub-indices aggregations methods. The final WQI distribution surfaces (thematic) maps were created by joining the WQI score with each tube well and create a quality gridded surface by OK interpolation. The results of implemented WQI quality distribution surface for both aggregation methods were analyzed and compared.

8.3 Results and discussion

The illustrations in Figs (8-3(a)-(h)) show the spatial quality distribution maps for the selected indicators including pH, total dissolved solids(TDS), Chloride, total petroleum hydrocarbon (TPH), nitrate, Manganese, Iron and lead respectively. The tube well information and the results of the selected indicators were extracted from Table A-4.1, detailed in Appendix 4. In general, the quality indicator maps represent the arbitrary weight of the concentrations reclassified using the second, third and fourth quartile of the concentrations recorded across the 61 tube wells for each of the indicators' distribution maps. This was done to regionalized the surface concentration (i.e. to show local differentiation) in each of the quality rating maps. For each of the rating maps the second, third and fourth quartile concentrations ranges were designated as L, M, and H representing low, moderate, and high concentrations respectively. A detailed evaluation of Figs (8-3 (a, d and f)) representing the distribution maps of pH, Manganese and TPH revealed that in some or all the wells (for the case of the pH), the measured concentrations exceed the recommended WHO's MAC for drinking water quality in the groundwater. For instance, the pH map in Figs (8-3(a)) was used to describe distribution maps. The pH of the groundwater is generally low and does not fall within the set pH range (6.5 - 8.5) for drinking water quality for all the well samples. However, the analysis of the pH data also revealed that the pH in the wells changed in space especially in the densely residential built-up areas at the centre with lower values in the range between 4.0 - 4.4. However, the pH in the wells of the sparse built-up area at the horn and north-western corner is higher and lies between 4.9-5.2. The pH range lies between 4.5 - 4.8 and represents a moderate pH weighting the remaining

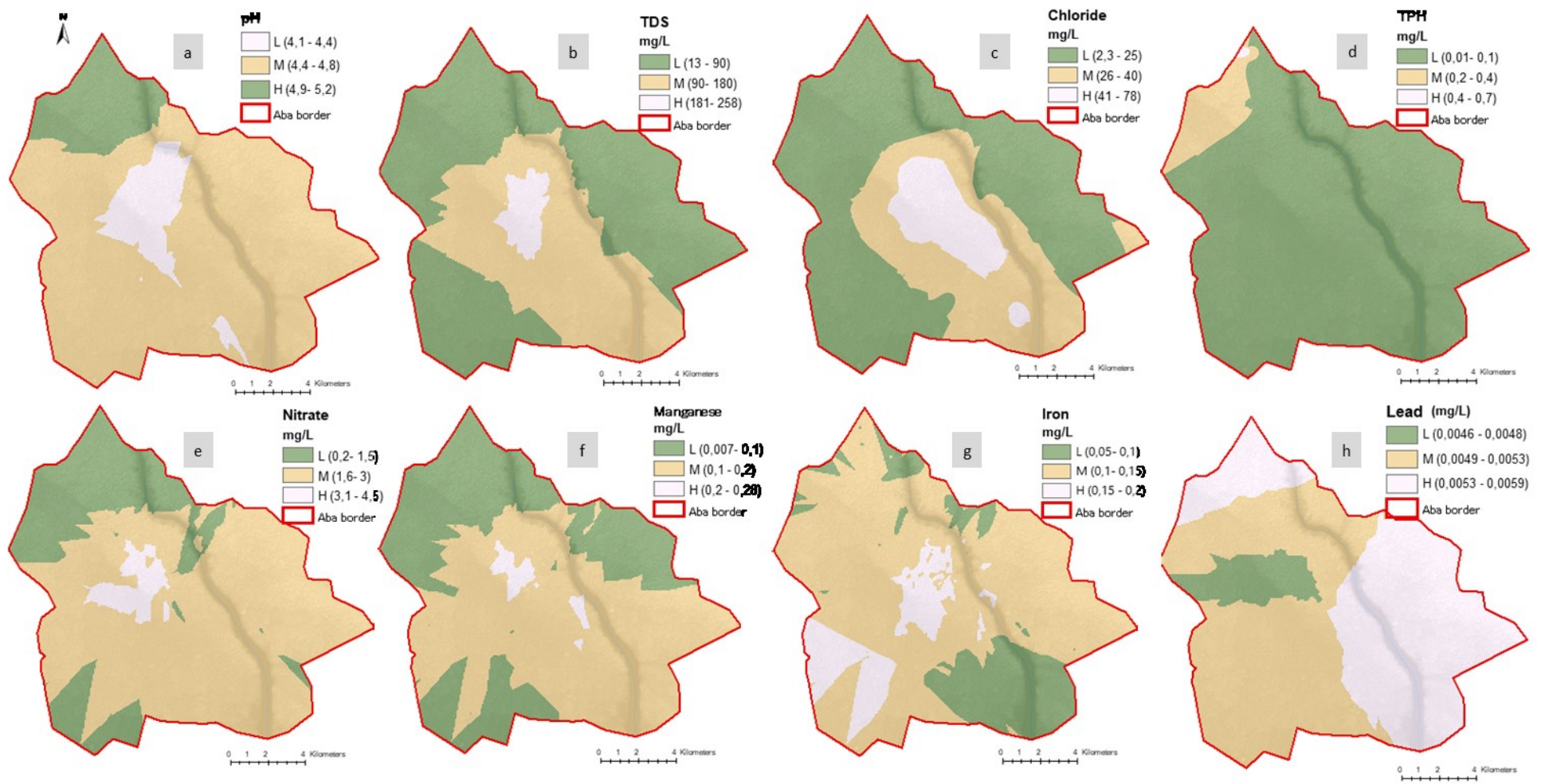


Fig 8-3: Quality indicator distribution maps of selected indicators showing (a) pH, (b) TDS, (c) chloride, (d) TPH, (e) nitrate, (f) Manganese, (g) Iron and (h) Lead in the groundwater.

parts of the study area. This same procedure applies in creating indicator quality distribution maps for the other selected parameters. For the remaining indicator distribution maps in Figs (8-3 (b, c, e, g and h)) describing TDS, chloride, nitrate, Iron, and Lead respectively, the analyses of the results showed that the maximum acceptable concentrations values were still within the WHO’s MAC recommendations for drinking water quality. But the trends in the results suggest that there is a spatial differentiation in the quality of groundwater in the wells, in which the indicators are showing deteriorations in some areas as can be seen in the indicator distribution maps. Overall, it has been observed that there is a significant influence of land use activities on the groundwater quality especially at the central built-up parts, which is predominantly residential and commercial land use. This contributes to the exacerbation of deteriorating groundwater quality in this area such as the further lowering of the pH.

Based on the WLSA and WGA sub-index aggregation methods, the water quality indices for each of the tube wells were computed as summarized in the tabular matrix of Table A-4.1 in Appendix 4. The influence of each indicator on the water quality index can be understood by looking at the correlational statistics of the matrix. The results of the correlation coefficient between the WQI for both aggregation methods and the selected indicators used for the calculations are summarized as

Table 8-4: Summary of the correlation coefficient matrix for WGA against the selected quality indicators.

	WGA	pH	TDS	Cl	NO ₃	PO ₄	Mn	Fe	Pb	TPH
WGA	1.0									
pH	0.11	1.0								
TDS	-0.16	-0.71	1.0							
Cl	-0.19	-0.66	0.95	1.0						
NO ₃	-0.06	-0.53	0.59	0.43	1.0					
PO ₄	0.04	-0.15	0.14	0.03	0.47	1.0				
Mn	-0.10	-0.72	0.73	0.70	0.50	0.14	1.0			
Fe	-0.12	-0.02	0.13	0.08	0.14	0.03	-0.04	1.0		
Pb	0.30	0.07	-0.17	-0.15	-0.15	0.05	-0.08	-0.18	1.0	
TPH	0.98	0.10	-0.16	-0.18	-0.06	0.03	-0.11	-0.11	0.33	1.0

Table 8-5: Summary of the correlation coefficient matrix for WLSA against the selected quality indicators.

	WLSA	pH	TDS	Cl	NO ₃	PO ₄	Mn	Fe	Pb	TPH
WLSA	1,0									
pH	0,10	1,0								
TDS	-0,16	-0,71	1,0							
Cl	-0,18	-0,66	0,95	1,0						
NO ₃	-0,07	-0,53	0,59	0,43	1,0					
PO ₄	0,02	-0,15	0,14	0,03	0,47	1,0				
Mn	-0,10	-0,72	0,73	0,70	0,50	0,14	1,0			
Fe	-0,12	-0,02	0,13	0,08	0,14	0,03	-0,04	1,0		
Pb	0,29	0,07	-0,17	-0,15	-0,15	0,05	-0,08	-0,18	1,0	
TPH	0,99	0,10	-0,16	-0,18	-0,06	0,03	-0,11	-0,11	0,33	1,0

shown in Table 8-4 and Table 8-5. The results of the statistical correlation revealed that the pH of the groundwater has a strong relationship with other indicators such as TDS, chloride, nitrate and Manganese at 0.71, 0.66, 0.53 and 0.72 respectively, but in the negative direction. This implies that the areas with more acidic groundwater will have higher concentrations of TDS, chloride, nitrate and manganese increase in the groundwater. However, this trend between pH, chloride and nitrate is rather moderate than strong. But the TPH concentration distribution does not show any statistical correlation with any of the other indicators. This is because the indicator does not exist naturally in the groundwater and the presence is a signature of direct human influence. Furthermore, it was observed that the distribution of iron and lead concentrations in the groundwater does not show a significant deviation in the average value, however, though there were cases where a couple of the tube wells especially in the densely residential area have concentrations of iron that were above the WHO's MAC. These wells are local and do not have a significant impact on the overall quality of the groundwater in the study area. Thus, the reason for the weak correlational coefficient for these indicators. Besides, the distribution of lead concentrations was still within the WHO's MAC recommendation for drinking water quality. But some parts of the sparse built-up areas around the north-western and the eastern parts have slightly higher concentrations as shown in Fig (8-3(h)). Based on the iron and lead distribution in the area, these concentrations have minimal impact on the water quality index calculation in the groundwater.

Again, the simple linear correlation analysis carried out on the WQI scores against the quality indicator matrix highlights the different degrees of influence the selected quality indicators have on the WQI scores. The results of the statistical correlations are shown in Tables 8-4 and 8-5 based on the WLSA and WGA sub-index aggregation methods respectively. In both cases, only the TPH happened to be the indicator that has the most impact on the calculated WQI with correlation coefficients of 99% and 98% for WLSA and WGA respectively for all the wells. The coefficient of correlation is positive between the TPH and WQI. This result suggests that increasing TPH concentrations in the groundwater degrade the WQI, while the rest of the indicators, which are mostly geogenic do not significantly harm the quality of the groundwater.

8.3.1 Water quality index calculations and mapping

The results of the WQI calculations shown in Table A- 4.1 of Appendix 4, were used to create the WQI distribution surface based on the OK interpolation with the index score of the wells. The resultant maps are shown for the WLSA and WGA sub-index aggregation functions in Fig (s 8-4(a) and (b) respectively. The summary and comparison of the analysed results of the actual WQI scores of the individual wells and the results of analyses of the predicted WQI surface maps for the sub-index

aggregation (WLSA and WGA) methods are illustrated with the bar charts and table shown in Fig (8-5(a) and (b)) respectively. According to the analysis of the results for the WLSA sub-index aggregation method in Fig (8-5(a)) showed that 88.5% of the wells designated “good quality” was calculated as the actual WQI, whereas wells with “excellent” and “poor” index qualities represent 1.6% each. The remaining wells representing the “unsuitable” quality category, make up 8.2%. In Fig (8-5(b)) on the other hand, the results of the actual well indices calculated with the WGA sub-index aggregation revealed that 90.2 % of wells have the “excellent” class as the dominant quality class. the WGA sub-aggregation method. This is followed by 4.9% of the wells, which belong to the “unsuitable” quality class, and the remaining 3.3 % and 1.6% of the wells fall under the “good” and “poor” quality classes respectively.

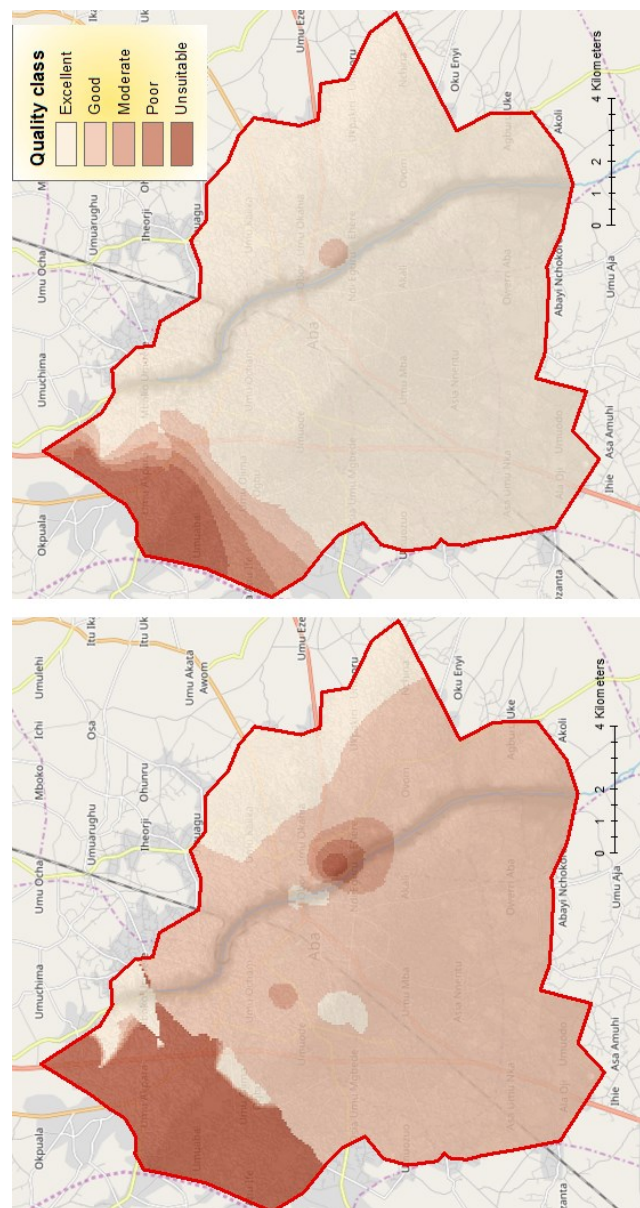


Fig 8-4: Water quality index maps showing surface interpolation estimated by (a) WLSA and (b) WGA sub-aggregation methods.

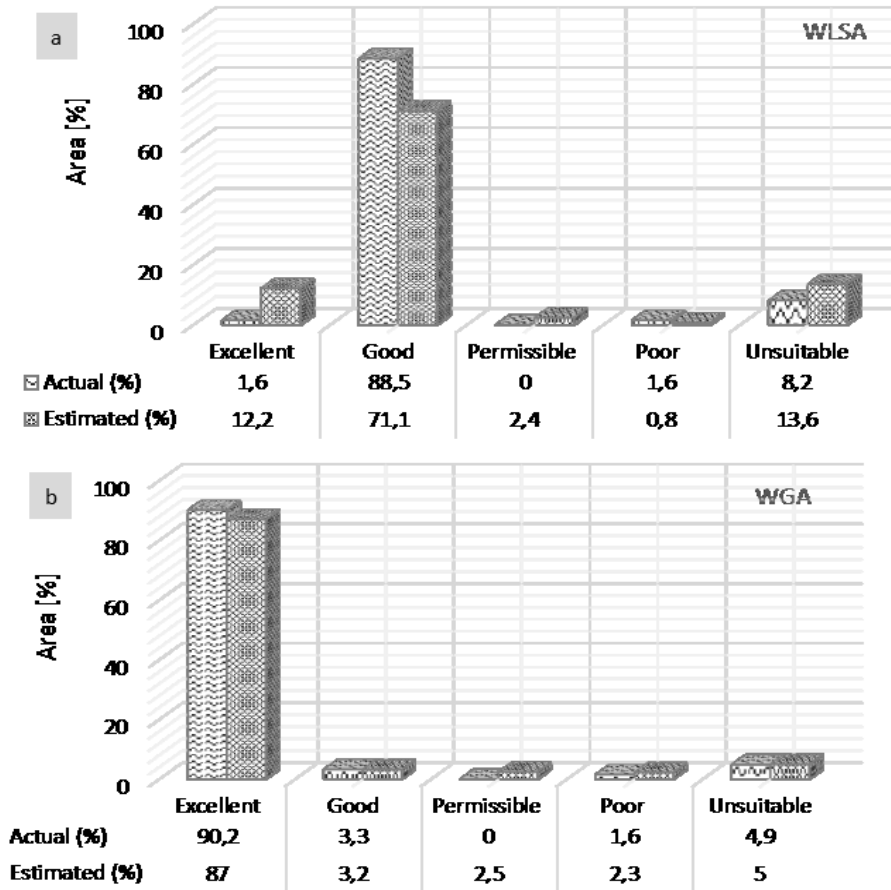


Fig 8-5: Comparison of water quality status between the “actual” and “estimated” percent areas results of the WQI with the respect to the sub-index aggregation functions.

When the analysis of the interpolated WQI surfaces for both aggregation functions shown in Figs (8-5(a) and (b)) are compared, the results of the maps showed different proportions of water quality distribution (excellent, good, permissible, poor and unsuitable) representing all the classes. The summary of these results can be seen in the estimated column of Table 8-6.

Table 8-6: Summary of “actual calculated” and “estimated area” of the WQI classes based on the WLSA and the WGA methods.

Status	Actual (%)		Estimated (%)	
	WLSA	WGA	WLSA	WGA
Excellent	1.6	90.2	12.2	87.0
Good	88.5	3.3	71.1	3.2
Permissible	0.0	0.0	2.4	2.5
Poor	1.6	1.6	0.8	2.3
Unsuitable	8.2	4.9	13.6	5.0

It was found that 71.1% of the area calculated with the WLSA sub-index aggregation method map were designated “good” and it is the dominant class. This was followed by “unsuitable” 13.6 %,

“excellent” 12.2%, “permissible” 2.4 %, and “poor” indexed area 0.8%. The results of the WGA sub-index aggregation map revealed that the predominant quality index represents the area with the “excellent” class, constituting 87%. This was followed by the “unsuitable” class 5%, “good” class 3.2% and the remaining area represent the “permissible” and “poor” class 2.5% and 2.3% respectively. The quality index class dominance array for the WLSA based WQI distribution can be reported as follows: good > unsuitable > excellent > permissible > poor, whereas the WGA based dominance distribution array can be expressed as excellent > unsuitable > good > permissible > poor.

The comparison of corresponding results of the analysis of the “actual %” indices of the tube wells and “estimated %” of the quality index surface for the WLSA and WGA sub-index aggregation methods were evaluated to deduce, which aggregation method fits better to reality. The results have already been summarized in Fig (8-5(a) and (b) and they show that the difference between the results of the “actual” indices in the wells and the “estimate” area in the map of WLSA based method is more significant than the WGA based approach. For instance, in the WLSA aggregation method, the difference between the classes in the “% actual” WQI calculation for the wells and “estimated” derived from the quality surface map is 17.4% apart for the dominant class “good”, while the differences for the “excellent” and “unsuitable” classes are 10.6 and 5.4 respectively. On the other hand, there is a little difference in the quality designation between the “actual” calculated and the “estimated” area classes for the WGA aggregated method. The results show that the dominant “excellent” class differ only by 2,3% and there is little or insignificant difference when the remaining classes were compared. It can be inferred that the WGA sub-index aggregation method has a better fitting to reality than the results of the WLSA sub-index aggregated function.

8.3.2 Comparison of the impact of sub-index aggregation function

One of the goals and contributions of this chapter is to use the effect of the aggregation function on the water quality distribution maps to elucidate the influence of the inherent ambiguity associated with the sub-index aggregation functions. First, the effect of the individual indicator (thematic) maps in a selected portion of the area where the WQI index is conspicuously unsuitable is x-rayed. The impact of deteriorating concentrations of TPH and Pb indicator maps around this area has a strong influence on the water quality index designation and causes the groundwater quality rating to be “unsuitable”. However, the combined effect of the patterns when overlaid revealed the overwhelming impact of these indicators, especially causing the critical limits of 100 in the sub-indices calculation to be exceeded. This leads to ambiguity of the final indices. This might be the reason why there are more areas with “unsuitable” quality classed areas for the WLSA based quality map than in the WGA quality map. This shortcoming in the WLSA sub-index aggregation function was also reported in Tyagi et al.

(2013). Further, more clarity can be observed in the distribution patterns of the groundwater quality index maps in this selected portion of the study area, if the water quality indices between WLSA and WGA methods are compared for the calculated and estimated.

In general, the water quality index of the wells suggests that the chemistry of the groundwater in most parts of the study area is quite acceptable other than the acidic groundwater pH which is typical for the region. This confirms why the dominant quality class represented in the WGA map belong to the “excellent” class. Hence, the dependence of many industrial activities on the groundwater such as the multi-national alcoholic and non-alcoholic breweries and other manufacturing industries that depend on the groundwater for both the process and product water needs. However, this study did not consider extensively the presence of other potential trace substances in the groundwater that might have a serious impact on the quality of groundwater at the time of the assessment due to financial and other technical limitations. However, the water quality index assessments and distribution map can help the responsible authorities to make decisions on the suitability of the groundwater as source water for drinking purposes (Abbasi and Abbasi, 2012; Ismail and Robescu, 2019).

Further, the selection criteria of indicators used for the WQI calculations can lead to criticisms of subjectivity in the index evaluation. However, care must be taken to ensure that the level of subjectivity could be reduced through some statistical assessments as suggested in Abbasi and Abbasi, (2012). The weights assigned to the indicators were established based on Equation (8-3), w_i is a function of the maximum acceptable concentration MAC (S_i) of the i th parameter. One will begin to wonder why the S_i should be the driving factor that influences the weight assignments to quality indicators as the driving force for the water quality index? Most trace pollutants at very small concentrations can be lethal and this poses serious health challenges for the people. Developing a system that assigns scores and ranges to the toxicity of the routine water quality indicators must be introduced to take care of this concern. Therefore, the concept of unit weight cannot be directly correlated to the dimensions of MAC of the indicator and its impact on the overall quality index of water. Also, the transformation scale should be designed in such a manner that relative weights should be assigned to indicators based on the impact it has on the water quality index estimation. In this case, indicators with high health risk potential or have significant impacts on the acceptability of the groundwater should be assigned high weights, such that the critical limits of the sub-index will be exceeded if the sample failed. The principle of unit weighting can be improved with the concept of relative weighting as demonstrated in Ketata et al. (2012) and Batabyal and Chakraborty, (2015). Although, the relative weight assignment can lead to the problem of subjectivity of the method.

8.3.3 The implication of land use on water quality distribution

The results of the WGA aggregated quality distribution map revealed that the predominant groundwater status in the area is the “excellent” class. Despite a little part in the area where the groundwater has been designated “unsuitable” as shown in Fig (8-4(b)). The area designated with the “unsuitable” class makes up only 5 % of the study area on the map. It will be observed that if the WQI distribution of the area is overlaid on the contamination hotspot map, the unsuitable class falls on the new industrial cluster in the sparse residential area on the top northwest corridor.

The results of the analysis of TPH in some groundwater wells revealed that TPH concentrations > 0.3 mg/l in this zone were recorded, and the direct consequence makes the groundwater unfit for drinking. The use of petroleum fuel products in Nigeria is part of the everyday lives of the people. These include the use as a domestic fuel for cooking, electricity generation, and automobile fuel, as well as industrial uses. This makes the parameter a necessary indicator to be considered for this study. If the concentration bubble of the TPH distribution is overlaid on the WQI map shown in Fig (8-6, the area with the biggest bubbles falls within the parts where the NNPC petroleum depot is located and the hydrocarbon products’ pipeline was laid along the expressway going to Enugu. The reported occurrence of petroleum product pipeline theft and sabotage leads to the frequent spill of petroleum products which contaminates the groundwater (Ambituuni et al., 2015; Ite et al., 2018). Besides, there could be some cases of accidental spills of petroleum hydrocarbons from industrial sources and this may contribute to the abnormally high TPH concentrations relative to other parts of the area. The result also confirmed the reports on the groundwater contamination with TPH in other independent

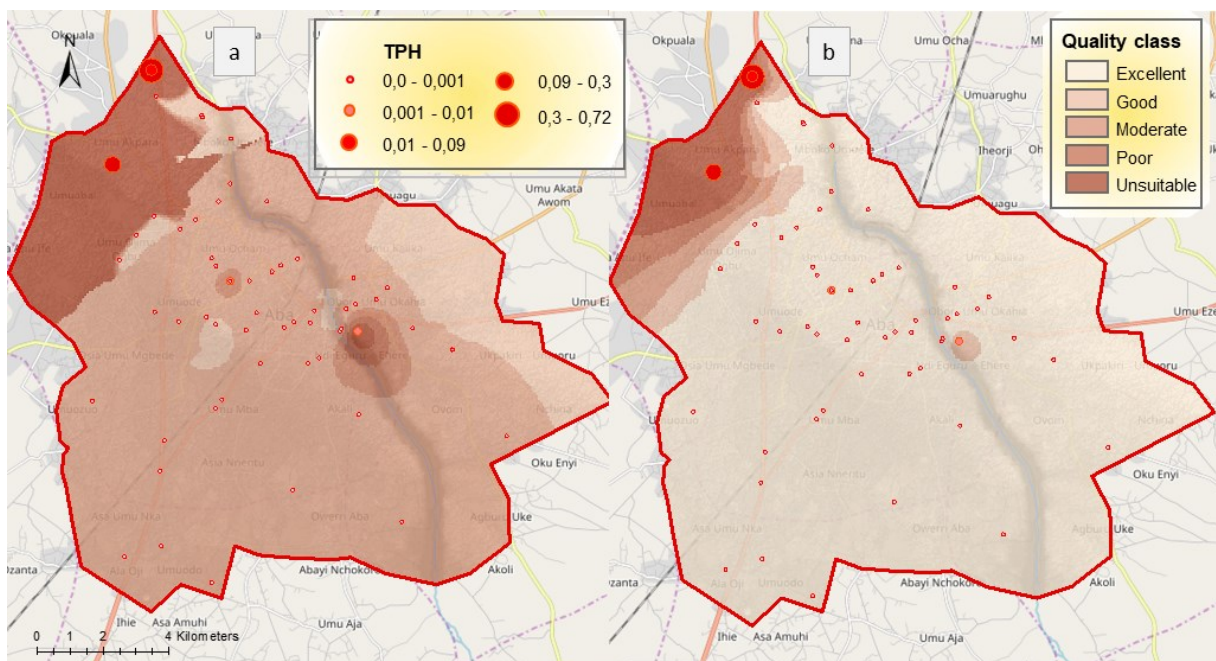


Fig 8-6: WQI maps of (a) WLSA and (b) WGA overlaid with the bubbles of TPH concentrations of the wells.

research evaluating the groundwater quality in this part of the area (Akakuru et al., 2017; Ighariemu et al., 2019). The thematic groundwater quality distribution map so far did not reveal an increasing impact of other human activities on the quality of the groundwater. This can also be confirmed by the observed differentiation in the selected individual quality distribution maps, especially in the densely high built-up area. For example, the statistics of indicators such as pH, TDS, chloride, nitrate, manganese, and iron does show a significant difference in the standard deviations between the densely built-up areas compared to the sparsely built-up areas. Also, the increasing accumulation of concentrations of lead around the new industrial zone can be correlated to the increasing TPH concentration in the groundwater. This observation supports the finding of Akakuru et al. (2017), who reported increased concentrations of lead in the groundwater. The source of lead can be linked to its use as an anti-knocking additive in the fuel of petroleum products, which can be traced to the NNPC depot that has operated in the area for several years.

8.3.4 Influence of pumping on groundwater quality and evaluation of the WQI distribution maps

Other than the acidic nature of the groundwater pH in the area, the results of the chemical quality of the groundwater were generally good and found to be within the recommended maximum acceptable concentrations for drinking water quality for most indicators. However, much of the observed spatial quality differentiation in the groundwater quality between wells in the sparsely built-up (LR) and densely built-up (HR) areas were not captured in the results of the WQI distribution maps because the concentrations of some quality indicators, which were degrading are still within the WHO recommendations. Hence, the WQI distribution maps predicted the groundwater to be “good” – “excellent” quality spread in almost all parts of the study area. In contrast, the groundwater quality of the North-western parts of the area was shown to have been polluted and unfit for drinking. This portion of the area can be used to validate and demonstrate the impact of pumping on the quality distribution of groundwater.

While abstracting groundwater from a tube well using a submersible pump, the pumping process creates 2-dimensional flow (i.e. movements in both lateral and perpendicular directions) of the groundwater. This action forces the piezometric well-head to drop and the formation of a cone of depression. The conical zone of influence and the direction of flow of the groundwater is illustrated in Fig (8-7). The illustration revealed how pumping activities can indirectly influence the quality of the groundwater especially in situations where the contamination hotspots are rampant and unregulated around pumping wells. Some research has shown that during pumping the base of the depression cone is elliptical and different empirical formulae have been proposed to estimate the radius of influence of wells based on the aquifer situations (Fileccia, 2015). The estimation of the radius of

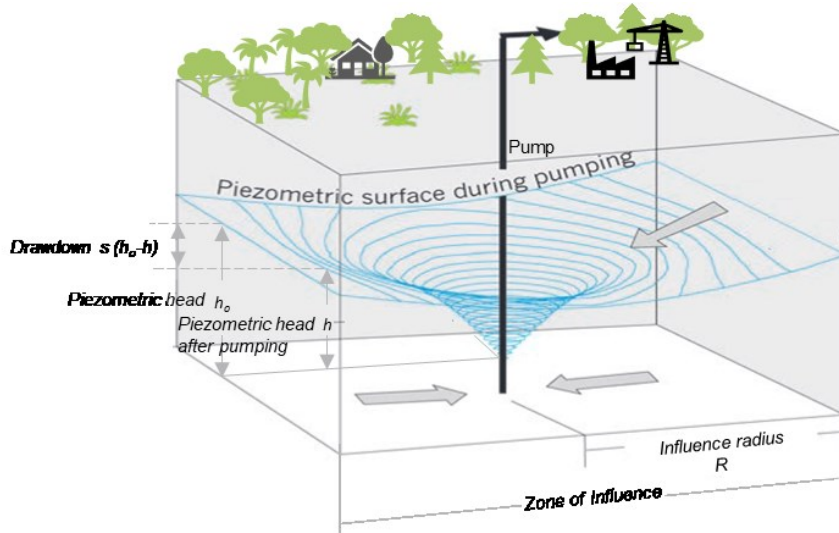


Fig 8-7: Illustration of the cone of depression and a pump's zone of influence in a homogenous aquifer (Modified from Fileccia, 2015).

influence R for an unconfined aquifer can be estimated using expression (8-10) according to Weber, (1928).

$$R = 3 \sqrt{K_f h_o \frac{t}{n}} \quad (8-10)$$

Where R = radius of influence (m)

K_f = hydraulic conductivity (m/s)

h_o = piezometric head before pumping began

t = pumping time (s)

n = effective porosity

Three tube well points were identified around the industrial estate in the north-western part of the study area where the groundwater has been contaminated with petroleum products. The evaluation of the radius of influence of these wells will be used to demonstrate how pumping exacerbate the quality of the groundwater in the face of poor environmental practices, as well as validate the accuracy of both WQI distribution maps models already described. For this exercise, three industrial tube wells around the affected area were identified BH_T3, BH_T5 and BH_AB. The water storage capacity for the wells (V) represents the volume of water extracted, (t) pumping time taken to fill the overhead reservoirs and (h_o) groundwater table elevation of the selected wells before pumping started were recorded (Table 8-7). The radius of influence R for each of the tube wells was calculated according to equation 8-10, and other hydraulic parameters necessary to estimate the zone of influence were adopted based on the report of Agharanya and Dim, (2018). The results of the estimations for each of the wells are summarized in Table 8-7.

Table 8-7: Summary of measurements from the tube wells for the estimation of radius of influence.

Hydraulic property	Borehole			Reference/remark
	BH _{T3}	BH _{T5}	BH _{AB}	
Storage capacity V (m ³)	190.0	380.0	60.0	Field measurement
Time t (s)	42222.2	84444.0	13333.3	Time to fill the storage tanks
Height h (m)	29.1	29.3	29.4	Field measurement
Radius of influence, R (m)	252.6	358.4	142.7	Calculated from equation 8-10
TPH in water sample (mg/l)	0.5	0.7	ND	Chem. analysis of samples
Pump rate (m ³ /s)	4.5 x 10 ⁻³			Field measurement
Hydraulic conductivity K_f (m/s)	1.5 x 10 ⁻³			Agharanya and Dim, (2018)
Effective porosity [n]	0.26			Agharanya and Dim, (2018)

ND = not detected.

The results of the calculations of the zone of influence of the pumps suggest that the tube wells with the highest radius of influence and drawdowns at the time of the pumping has the most influence and can change the direction of natural lateral flow of the groundwater during pumping towards the wells. The array of the pumps' influence on the lateral movement of the groundwater can be ordered as follow: BH_{T5} ($R_{T5} = 165.8$ m) > BH_{T3} ($R_{T3} = 117.5$ m) > BH_{AB} ($R_{T_{AB}} = 66.4$ m). This observation revealed the extent of the influence of the pumps on the distortion of the groundwater elevation is a reflection of the amount of water withdrawn and transferred to the storage tanks linked to the tube wells. Therefore, the closer a contamination hotspot is to a pump's zone of influence, the easier is it for the groundwater to be contaminated. The results show that the radius of influence of the BH_{T5} intersects with a hydrocarbon pollution plume, that has spread on the groundwater reservoir as shown in Fig (8-8). The TPH contaminations in the groundwater impacting both taste and odour on the groundwater as observed in the samples of BH_{T5} and BH_{T3} respectively. The presence of the TPH was confirmed in each groundwater wells through laboratory testing for TPH and the results are shown in Table 8-7.

The chemical analysis of TPH in the groundwater wells showed different concentrations of hydrocarbons in the wells. This further reiterates the effects of the zone of influence of the wells on the groundwater quality. The BH_{T5} well has the highest concentration of the TPH = 0.74 mg/l, which is by far greater than the maximum acceptable concentration (0.3 mg/l) of TPH in drinking water, followed by BH_{T3}, with TPH = 0.54 mg/l. These concentrations correlate with the corresponding individual radius of influence of the respective wells. Although the BH_{T3} well was farther away from the hydrocarbon plume, the radius of influence R_{T3} may have intersected with the R_{T5} , this interaction may be responsible for the contamination with the petroleum hydrocarbon product. However, the BH_{AB} well shows no trace of the TPH concentration in the groundwater and this well has the least zone and radius of influence and drawdown caused by the pumps.

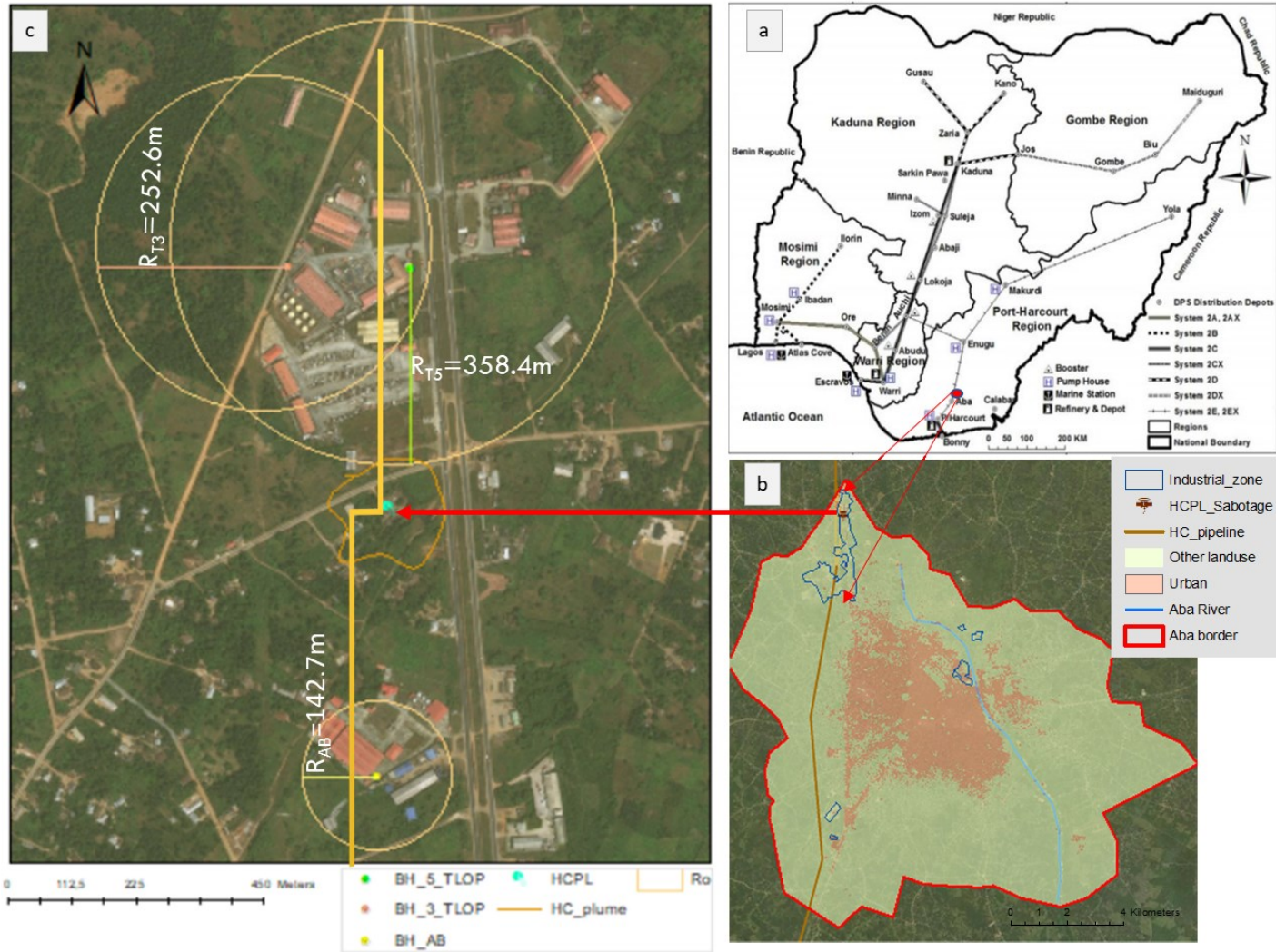


Fig 8-8: Illustrations of a contaminated site showing (a) hydrocarbon pipeline network map of Nigeria (modified from Ambituuni et al. (2015)); (b) industrial zone in the northwestern part of the study area, and (c) satellite imagery of an identified contamination plume showing the zones of influence of three selected tube wells.

The pumps with lower drawdowns have some things, which does not affect the flow natural flow of the groundwater. The relationship between the outcome of the TPH concentrations distribution and the WQI distribution map around the industrial zone showed that the groundwater quality index in the selected area was designated unsuitable for drinking. However, the pattern of the WQI distribution surface based on the WGA sub-index aggregated quality map appears to be more realistic to the effect of the pumps than the WLSA aggregated quality distribution map. As observed, the concentration of the WQI in the map fades away similarly in trend as the results of the analysis of the TPH concentrations in wells. As the wells are away from the centre of the hotspot, which is the vandalized pipeline, the more the concentrations of TPH diminishes in the groundwater. However, this type of distribution pattern was not found in the WLSA aggregated distribution map with the quality index designation of unsuitable class. In this case, the water quality index distribution pattern in this part was uniformly spread and does not represent the reality based on the impacts of the pumps.

Chapter Nine

9 Groundwater vulnerability assessment using a modified DRASTIC approach

9.1 Background

Fundamentally, the management of groundwater resources can be performed either by planned monitoring activities or computational modelling of the groundwater (Jang et al., 2017). The sampling and monitoring activities give the real-time situation of the groundwater quality, but the process consumes time and it is expensive to execute over a large area, unlike the computational modelling approach. The vulnerability assessment is one of the screening methods to ensure the sustainable management of groundwater. The concept of a groundwater vulnerability assessment was developed as a management tool to systematically identify and isolate contamination sensitivities in different parts of the aquifer. These sensitivities are a result of hydrogeological factors or surface contamination due to pollution sources in the catchment. This facilitate planning, prioritize monitoring, and protect the quality of the groundwater (Saatsaz et al., 2011; Jang et al., 2017).

Several methods of vulnerability assessment have already been explored to evaluate groundwater vulnerability in different parts of the world. The robustness of each approach depends on the amount of data, budget, and technical competence that goes into the methods. These methods include the process-based groundwater simulation models such as SWAT, GLEAMS, HSPF, MODFLOW, etc., statistical-based methods, and overlay/indexing-based methods. The indexing methods such as the DRASTIC (Aller et al., 1987), GOD (Foster, 1987), SEEPAGE (Moore and John, 1990), AVI (Van Stempvoort et al., 1993), SINTACS (Civita, 1994) EPIK (Dörfliger and Zwahlen 1998; Doerfliger et al., 1999), and COP (Vias et al., 2006) have evolved over the years.

The overlay and indexing methods are simpler and more straightforward compared to the process-based simulation methods that require technical and numerical analytical skills, as well as, special computer hardware and software to execute the program (Jang et al., 2017). The best groundwater risk management practices suggest identifying areas with a high vulnerability potential and prioritize them for regular monitoring to reduce the cost of monitoring. The DRASTIC method is the most popular overlay/indexing method and it was first reported by Aller et al. (1987) for the USGS EPA. The concept of DRASTIC and the other index-based groundwater vulnerability assessment tools utilizes meteorological and geologic data as the main hydrogeologic settings¹⁸ in determining the pollution potential risks within a catchment. Overall, the format of the output is in the form of a map. One of

¹⁸ A hydrogeologic setting represents a mappable unit, which in our context is a hydrogeologic factor that can influence direction of movement of surface contamination to the groundwater.

the main advantages of the DRASTIC method is its ability to precisely predict different degrees of vulnerabilities for complex geological features.

The concept of a modified DRASTIC is necessary to improve the predictive capability of the method. This can be done by introducing other hydrogeologic settings, which can lead to some form of regionalization in the area, especially in cases where the geology is simple. However, several scholars have argued that the DRASTIC method is subjective in its assignment of weights to the hydrogeologic settings (Mogaji et al., 2014), while others suggested more and better adaptability of the method, through the inclusion of anthropogenic parameters that influence the groundwater quality as part of the components of the DRASTIC method. These enhance the accuracy of the method's predictions (Amadi et al., 2014; Kumar and Krishna, 2019). The modified DRASTIC methods have been implemented in many studies (Jasem, 2010; Moustafa, 2019; Jhariya et al., 2019). In the context of this study, the idea of the modified DRASTIC explores the impact of a land use practice that influences both the quality and flow directions of the groundwater. This anthropogenic influence has a varying potential threat to the quality of the groundwater, the range and ratings are based on the amount of groundwater withdrawn from the aquifer, which is closely linked to the prevailing urban land use that it serves.

The goal of this chapter is to develop a methodology that will investigate, with an additional emphasis on the influence of abstraction pumps on the vulnerability of the aquifer using a modified DRASTIC approach. The outcome of this potential pollution assessment will compare the results of the conventional DRASTIC, and the proposed modified DRASTIC methods. This tool will form part of the decision support management tool that will be used to protect the groundwater quality in the study area.

9.2 Methods

The concept of aquifer vulnerability assessment assumes that the susceptibility of the aquifer depends on the extent of protection, which the groundwater gets from over-burdening geological materials. It also assumes that the contamination begins at the surface, and it is conveyed by rainwater through the unsaturated zone to the groundwater in the saturated zone. The indexing methods have been established and used to evaluate several physical mappable factors that influence the contamination of the groundwater. The DRASTIC is an acronym that represents seven hydrometeorological and geological parameters. These parameters include depth to the water table [D], net recharge rate [R], aquifer media [A], soil media [S], topography [T], the impact of the vadose zone [I] and hydraulic conductivity [C] which are believed to influence the quality of the groundwater. The method addresses generally two sets of potential contamination sources: general, and agriculture. However, this study

deals with the general contamination potential since the aquifer in the area is mostly influence by urban activities with minimal agricultural land use. The evaluation procedure assigns each parameter with a weight, range from 1–5 based on the comparative effect. it would have while influencing the movement of the surface contaminant to the groundwater. The parameters with higher contamination potentials are assigned higher values. Then each parameter has a range, which can be interpreted in terms of the extent of protection they offer to the groundwater. These ranges are assigned rating values from 1–10. These numerical weights and ratings for the DRASTIC overlay and indexing vulnerability assessment method were developed by Aller et al. (1987) (Table A-5.1 in Appendix 5 shows the ranges and ratings of the parameters). The DRASTIC index [DVI] can be calculated as the linear sum of the product of the weight and rating for each of the DRASTIC hydrogeologic parameters as expressed in Equation 9-1.

$$DVI = \sum_{i=1}^n w_i * r_i \quad (9-1)$$

Equation 9-1 can be rewritten in a simpler algebra expression as shown in equation 9-2

$$DVI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \quad (9-2)$$

where n = total number of hydrogeologic setting (parameter) considered,
 l = ith parameter,
 w = Weight assigned to ith parameter,
 r = rating of the ith parameter.

The modified DRASTIC vulnerability assessment in this study was used to evaluate the impact of the active pump [P_a] as a mappable unit with influence from different urban land use practices on the groundwater vulnerability. With this modification, Equation 9-2 can be expressed as Equation 9-3.

$$DVI_m = DVI + ([P_a]_w * [P_a]_r) \quad (9-3)$$

where DVI_m = proposed modified DRASTIC index (DRASTIC- P_a)

Table 9-1 summarizes the data types and their sources from which the different hydrogeologic components were derived. The processing of some of these data have been described in the previous chapters and here they will be used for the implementation of the DRASTIC and modified DRASTIC (DRASTIC- P_a) methods. The vulnerability class analysis of the DRASTIC and DRASTIC- P_a are grouped into five vulnerability classes designates as: “very low”, “low”, “moderate”, “high”, and “very high”. The minimum and maximum values of the indices lie between 24-220 and 32-270, for the conventional DRASTIC and DRASTIC- P_a methods respectively. The index is dimensionless and the categorization of the indices into classes is summarized in Table 9-2 for both methods. Each vulnerability class describes

the degree of susceptibility of the groundwater to surface contamination. The higher the index, the more vulnerable the area is to contamination risk.

Table 9-1: Datatypes of hydrogeological settings used for the groundwater vulnerability assessments.

Data output layer	Data type	Source/reference	Format
Depth to the water table	Borehole log, 30m - SRTM DEM	Field measurement, reports from AIRBA*, USGS Earth Explorer (https://earthexplorer.usgs.gov/)	Raster
Net recharge rate	Land use map, meteorological data, runoff coefficient	NRCRI meteorological station Umudike, Jinno, et al., 2009. Already described in Chapter 3	Raster
Aquifer media	Shapefile, Borehole Lithograph	Field measurements already described in Chapter 3	Vector
Soil media	Shapefile	Chapter 3 with data from Adamu et al., 2019; Adindu, et al., 2013	Vector
Topography (Slope)	30m-SRTM DEM	USGSA Earth explorer (https://earthexplorer.usgs.gov/)	Raster
Impact of vadose	Shapefile, Borehole Lithograph	Field observation/Chapter 3	Vector
Hydraulic conductivity	Shapefile, point data pump test data, sieve analysis	Adamu et al., 2019; Agharanya and DIM, 2015	Vector
Impact of active pump surface	Shapefile, well abstraction rates (point data)	Field measurement, household survey	Raster
Land use map	Landsat 8 OLI/TIR imagery	USGSA GloVis (https://glovis.usgs.gov/)	Raster

Table 9-2 Designation of vulnerability classes for the DRASTIC and DRASTIC- P_a indices.

<u>Designation</u>	<u>Vulnerability indices</u>	
	<u>Conventional</u>	<u>Modified</u>
Very low	24 – 60	32 - 80
Low	61 – 120	81 - 130
Medium	121 – 160	131 - 180
High	161 – 200	181 - 230
Very High	200 – 220	230 -270

9.2.1 Implementation of the vulnerability assessment maps

The concept of the groundwater vulnerability assessment is based on the multi-criteria weighted overlay and indexing approach. The implementation approach is GIS-based and follows a multi-criteria weighted overlay and executed with the raster calculator function of the spatial analyst tool in ArcGIS 10.6. The first steps in the implementation of the DRASTIC and the DRASTIC- P_a vulnerability maps start with creating the thematic rating maps for the hydrogeologic settings. The data used to create the rating maps are summarized in Table 9-1. All the vector maps produced have to be converted into raster maps, and the raster grid sizes resampled to be equal for all the maps. The significance of each of the thematic maps is discussed as follows and the map keys showing the resultant rating for each of the parameters. In general, the ranges, rating, and weights for each parameter have been predefined according to the documentation of Aller et al. (1987) as shown in Table A-5.1. The units of the hydrologic settings from Aller et al. (1987) were converted into the S.I unit in Appendix 5. The ranges for each of the hydrogeologic settings have been predefined for different situations. The numeric values (rates) between 1-10 are assigned to hydrogeologic situations, for which the higher the rate, suggests that the range make the aquifer worse off or more vulnerable. This makes the method adaptable since it is easy to identify the predefined ranges in your hydrogeologic and the results can be easily reproducible.

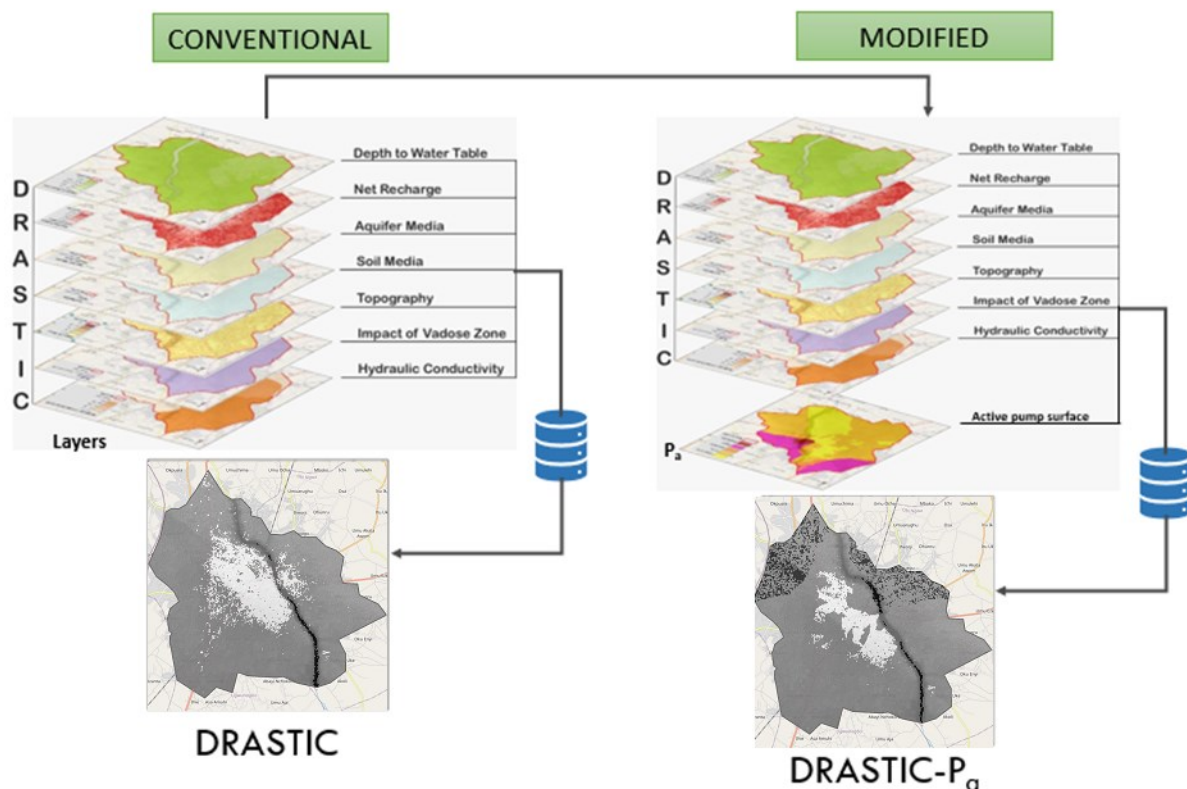


Fig 9-1: A schematic diagram showing the weighted thematic layers of DRASTIC parameters and the proposed DRASTIC- P_a .

9.3 Results and discussion

9.3.1 Thematic/rating maps

Each of the DRASTIC parameters is unique and contribute a significant impact on the vulnerability of the aquifer depending on the range and the ratings. The range and rating map for each of the DRASTIC parameters were adapted from Aller et al. (1987) to the local situation in the study area. The results of the ranges and corresponding ratings derived for each of the hydrogeologic components of the DRASTIC and DRASTIC-P_a are summarized as shown in Table 9-3. The results of each component are discussed in detail in the sub-section.

Table 9-3: Summary of ratings for the DRASTIC and modified DRASTIC (DRASTIC-P_a) variables.

Depth to water-table (m)	Rating	Net recharge rate (mm)	Rating	Aquifer media	Rating	Soil media	Rating
6.0-9.1	7	21-43.3	1	Sand & gravel	8	Sandy loam	6
9.2-15.2	5	46.9-83.8	3				
15.2-22.9	3	112.2-214	8				
23.0-30.5	2	138.9-268	9				
>30.5	1						
Topography (%)	Rating	Impact of vadose	Rating	Hydraulic conductivity (m/s)	Rating	Impact of pump (m ³)	Rating
0-2	10	Sand & gravel with silt	6	> 10 ⁻³	10	1-10	2
3-6	9					11-50	5
7-12	5					51-100	6
13-18	3					101-400	8
>18	1					>400	10

9.3.1.1 Depth to the water table [D]

The depth to the water table is the distance between the ground surface and the static groundwater level. This depth fluctuates depending on the seasons, wet or dry. Other factors influencing the groundwater recharge and the depth to the water table includes septic tank drain in the area. The implication of this parameter to the vulnerability assessment assumes that the deeper the water table, the lower the chances of the groundwater being contaminated or vice versa. The concept of depth to the water table was derived by subtracting the water-table elevation surface (data obtained from the borehole logging between 2017 and 2018 were obtained from AIRBA archives to augment the data from the field measurements (See Table A-6 in Appendix 6). The measurement points were rasterized via the geostatistical Kriging interpolation tool to create the estimated water-table elevation surface map for the area. However, the water-table elevation surface was corrected with standard reference above sea level (Adams, 2013).

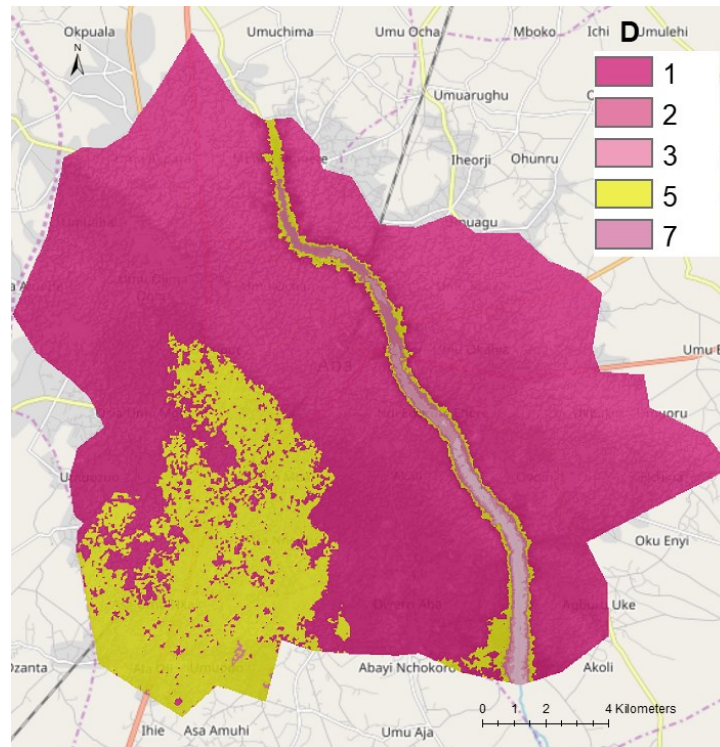


Fig 9-2: The rating map of Depth to the water table [D].

The depth to the water table map was created from the derived water-table elevation surface subtracted from the SRTM DEM of the area as shown in Fig (9-2). The result of the depth to the water table map shows the minimum and maximum depths of the water elevation lie between 6.8 - 62.3m. One of the distinct features in the landform is the trough of the River streamline in the slope of the DEM. The depth to the water table in the Aba river represents the groundwater level since the river is a receiving stream and drains both the groundwater and the surface run-off in the watershed of the area. The result of the depths to the water table rating map revealed that the elevation of the groundwater in Aba River, which represents the lowest point is at 6.8 m from the ground level. Hydrologically speaking, the elevation of water level in the trough of the Aba River should equal zero. Since the map of the static elevation level of the groundwater and a reference satellite elevation model was used to derive the depth to the water table. The coarseness of the DEM (resolution of about 30m) might be responsible for the anomaly or better said “inconsistency” as expected. Due to the ultra-high humid nature of the area, there may be varying seasonal vulnerability of the groundwater especially along the shoreline of the Aba River. During the dry seasons, the elevation of the water table is the same and the quality of the river water can be taken as a proxy for the groundwater. However, at the peak of the rainy season, the volume of surface runoff and groundwater discharge into the river will cause the elevation of the Aba River to rise above the level of the groundwater. During this period, the groundwater in the area around the Aba River will become

vulnerable if the river water has been polluted from man-made activities. This is not usually the case, since there is a sufficient dilution effect from the rainwater.

In general, the rating map revealed that the average depth to the water table in most other parts of the area are observed to be around 32 m, other than the southwestern corridor where the depth to the water table lies between 23 - 30 m. This means that groundwater vulnerability is low in most parts of the study area.

9.3.1.2 Net recharge rate [R]

The net recharge rate indicates the easiness at which contaminants can be transported vertically from the surface to the groundwater by infiltration. It assumes that the higher the net recharge rate, the greater the chances of contaminants reaching the groundwater table faster. The data used to create the net recharge rating map include average annual rainfall data for 22 years (1992-2014), the land use distribution map, and run-off coefficients of identified land use classes in the area as described in Chapter 3. The land use map identified four classes of land use excluding the water class in the area. These include the built-up area, barren-land, arable-land, and broadleaf vegetated land classes. The following assumptions were made in the creation of the net recharge rating map include:

1. The average rainfall was uniformly distributed over the land use
2. Groundwater recharge is rainfed and only infiltrated rainfall constitute recharge
3. the imperviousness of the land surface is inversely related to the net recharge rate;
4. Other factors that can influence the net recharge in the area were factored in the run-off coefficient assigned to the land use class as a constant.

The estimation of the net recharge rates was calculated using the hydrological water balance equation expressed in equation 3-2 distributed according to the identified land use classes in the area. The equation incorporates the surface run-off coefficients of identified land use classes adapted from Jinno et al. (2009) to spatially demonstrates the average infiltration rates in the corresponding land use class. Due to the paucity of data, these coefficients were used in this study, and it was not possible to compare the results of the estimations with other classical methods specific for the study area for accuracy evaluation. The result of the net recharge rating map is shown in Fig (9-3). It revealed that the average net recharge rate distribution range up to 44 mm/annum in the built-up areas, followed by 45 - 84 mm/annum for barren land, while arable 112 - 215, and the broadleaf vegetated land use areas have average net recharge rating up to 268 mm/annum. This implies that most of the groundwater recharge in the study area occurs at the arable and vegetated land use classes, which constitute more than half of the total land cover. Hence, the groundwater reservoir in the arable land and vegetated classes have a higher risk of contamination when there are hotspots around them.

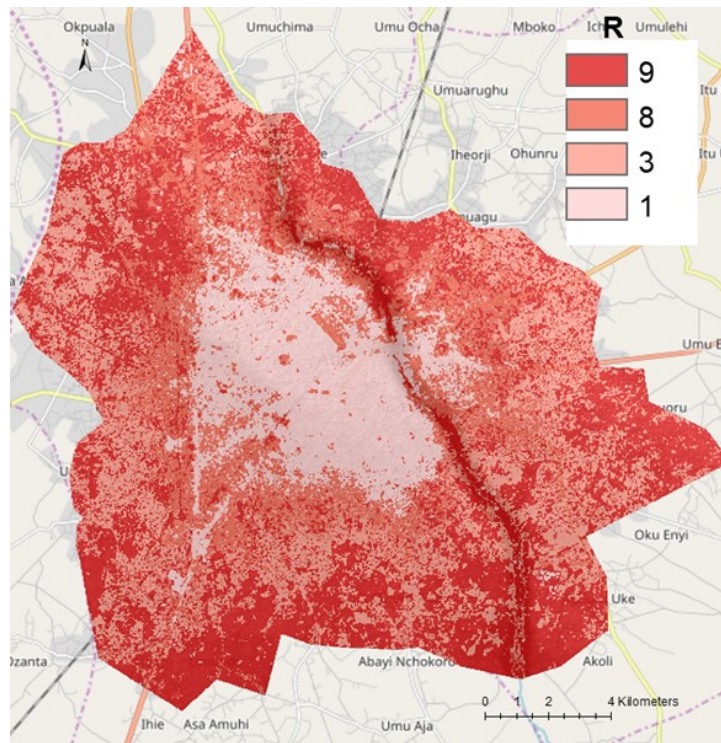


Fig 9-3: The rating map of net recharge rate [R].

On the other hand, the groundwater overburdened by the built-up and the barren land use classes has a lower contamination risk. This is because the land use classes have reduced the average net recharge rate due to the high degree of imperviousness of the surface. The land use change analysis of three spatial boundaries over a 30-years timeline in the area revealed a rapid increase in the urban built-up class. These classes introduce artificial surface sealing due to intensive construction and other structural-developmental activities taking place in this area.

9.3.1.3 Aquifer media [A]

The aquifer media describes the type of geological material that stores the groundwater in the saturated zone. If the aquifer materials are unconsolidated and porous, the groundwater flows through it faster and contamination can be transmitted from one point to the other. The data for the interpretation of the aquifer media was based on the results of the 5 hydrogeological investigations at Osisioma, Osusu, Umule, Umujima, and Asannetu during the field campaigns in 2017 and 2019. For all the sites, the borehole-well logs data showed that the aquifer materials in the saturated zone constitute medium-grained sand – coarse – very fine pebbles. The rating map for the aquifer media was created as shown in Fig (9-4). The results of the aquifer media rating map show that the area has layers of porous material uniformly distributed in the area with a range rating of 8.

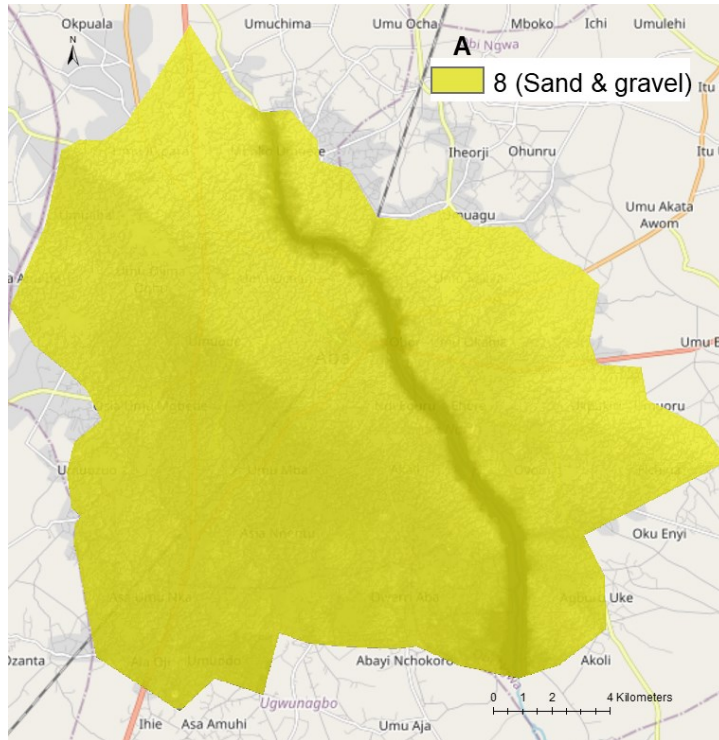


Fig 9-4: The rating map of aquifer media [A].

9.3.1.4 Soil media [S]

The soil media is the topmost part of the vadose zone. The texture of different soil types determine the water holding capacity, and in turn, this reflects on the rate at which water carrying contaminants infiltrates through the unsaturated zone to the aquifer. The soil media made up of clayey and silty

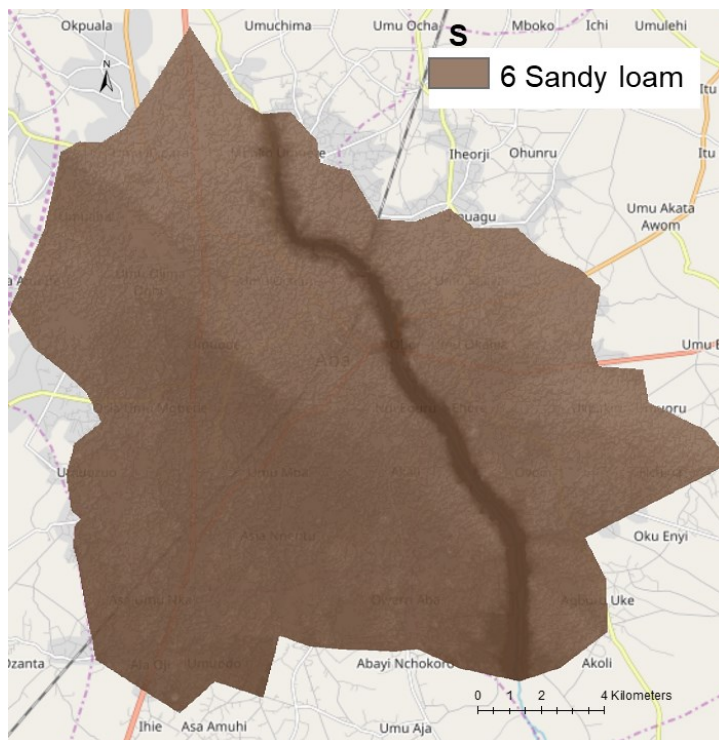


Fig 9-5: The rating map of soil media [S].

materials have a higher water holding capacity and it takes a long time to transmit surface contamination to the saturated zone and vice versa for soil with a sandy texture. The rating maps for the soil media was based on data obtained from documented field investigations relating to soil characterization in the area (Adamu et al., 2019; Adindu et al., 2013). The typical soil texture classes found at the sites in the area have been identified as sandy-silt-clay (sandy loam) according to the USDA classification. The soil media rating map was gridded with the kriging interpolation method and reclassified as shown in Fig (9-5). These soil textures are moderately permeable according to the USDA trilinear plot for soil texture classification. This implies that the rate of vertical transmission of surface contamination is moderated and controlled by the contribution of the clay-silt proportion in the soil.

9.3.1.5 Topography/Slope [T]

The topography describes the steepness of the land surface and characterizes the landform in an area. If the landform is flat, there will be little or no storm runoffs. This means that surface contaminants have more time to percolate faster through the unsaturated into the saturated zone, compared to a steep slopy landform in which rapid run-off reduces the risk of groundwater contamination. The results of the topographic map were derived from the slope map extracted from the USGS SRTM DEM (the grid resolution is 30m). The resultant slope was reclassified to match the recommended slope rating in Aller et al. (1987). However, the results show that the area is predominantly flat and this suggests that most parts of the area have a high susceptibility to groundwater contamination. The result of the topography rating map is shown in Fig (9-6).

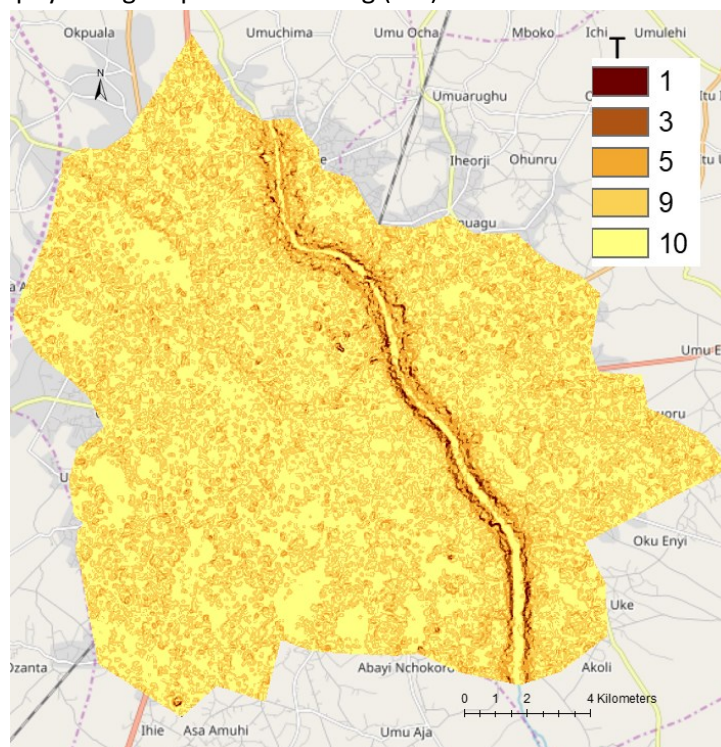


Fig 9-6: The rating map of topography [T].

9.3.1.6 Impact of the vadose zone [I]

The vadose zone is defined as the geological overburden above the saturated zone. The type of rock material above the saturated zone determines the extent to which contaminant attenuation occur before they reach the aquifer. For instance, a groundwater reservoir overlaid by a vadose zone composed of silty and clayey material requires more time for rainwater to travel through it to the aquifer. Therefore, there is a time for attenuation to take place through this media. The data used to describe the impact of the vadose zone rating map was based on the interpretation of the lithology of the borehole log wells from the hydrogeological investigations in Chapter 3. The results of the borehole log/lithograph analysis show that the vadose zone consists of about 10m of sandy clay overburden strata in the area. This top layer of sandy clay slows down the quick transfer of surface contamination to the groundwater. Other geological materials found in the vadose zone include - medium grain sand, very fine gravel and some silty facies in all the sites. The result of the vadose zone can be represented with a uniform unsaturated soil as shown in Fig (9-7).

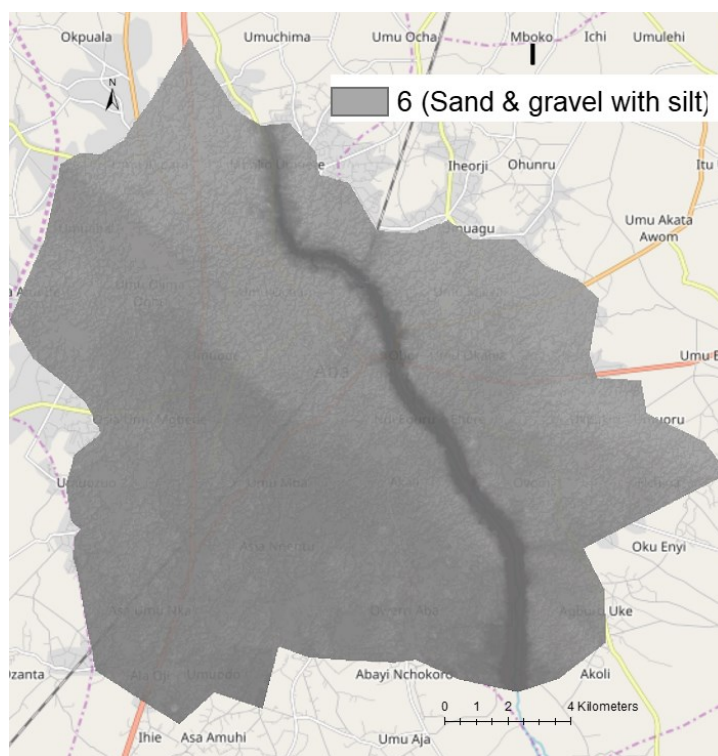


Fig 9-7: The rating map of the impact of vadose zone [I].

9.3.1.7 Hydraulic conductivity [C]

The hydraulic conductivity describes the ease with which water moves through geological porous materials to transmit water laterally in the aquifer. This property depends on the porosity in the aquifer material, and it is a function of time. It is assumed when the hydraulic conductivity is high, there is a greater chance of transfer of contaminants within the saturated zone. The data used for the hydraulic conductivity rating map was obtained by collating documented field experiments based on laboratory methods - sieve analysis (Agharanya and Dim, 2018), analysis of soil grain texture of borehole logs, and the use of pump test (Adamu et al., 2019) at different sites in the local government areas that make up the study area (See Table A-7 in Appendix 7). The hydraulic conductivity rating map was produced according to Kriging interpolation based on the distribution of these data. The hydraulic conductivity K_f values collated range from 1×10^{-3} m/s to 9.6×10^{-2} m/s, with an average of 1.52×10^{-3} m/s for the area. The results of the average K_f values alone implies that most parts of the area will have a high risk of contamination. See the hydraulic conductivity rating map (Fig (9-8)).



Fig 9-8: The rating map of hydraulic conductivity [C].

9.3.1.8 Impact of active pumps [P_a]

While the rest of the hydrogeologic factors already discussed, offer some degree of protection to the groundwater, and assumes that the transmission of surface contaminants occurs vertically. The impact of active pumps on the hydrogeologic settings influences both lateral and vertical movements of the groundwater. These movements can change the quality of the groundwater if there is localized

contamination in an area close to a pump. The impact of the active pump rating map was created based on the data gathered on the water consumption patterns section of the household survey, and interviews from relevant stakeholders. In a random survey targeting private borehole owners living in residential blocks, who abstract groundwater either for their domestic needs, or supplying other neighbouring residential blocks for commercial purposes. A typical residential block (i.e a plot), measures 100 x 50 square meters, but in this study, a residential block is made up of 4 plots and can accommodate an average of 120 persons in densely residential areas. This translates to an average of six households per plot. If the water consumption per capita in the study area is 35.9 l/d, the estimation of the water consumption rate for a residential block can be based on this premise. The low water consumption per capita in the study area can be limited by the storage capacities of private extraction pumps in each block and how long it takes for this water withdrawn to be used up. The withdrawal rates for the industrial and commercial extraction pumps in some urban sub-classes were calculated based on the data obtained from interviews with industry experts or supplemented with some published daily production capacity plus 20% processing water needs of the plants. The designation of the impact of some active pumps was categorized based on the groundwater daily withdrawal rates estimated for each urban sub-class shown and summarized in Table 9-4.

Table 9-4: Summary of some important urban subclasses with the designated impact rating for active groundwater pumps.

Urban land subclass	Daily withdrawal (m³)	Impact designation
Large scale breweries and manufacturing industries	> 400	Extreme
Medium-scale manufacturing industry	100 – 400	High
Hotels with swimming pool	100 – 300	High
Hotels and restaurants	15 – 100	Medium
Water bottling	50 -100	Medium
Pump in blocks of residential building	1 – 9	Low

The distribution of bubbles and colours represent the active pumps mapped in the area. The size of the bubbles indicates the range of magnitude of groundwater withdrawal rate categorized into sub-classes as shown in Fig (9-9(a)). These bubble points were overlaid on the delineated landcover base map of the area, and this gives an impression of the prevailing land use activity, which influence the wells, as well as the pumps. A total of 234 pumps were identified and categorized according to the

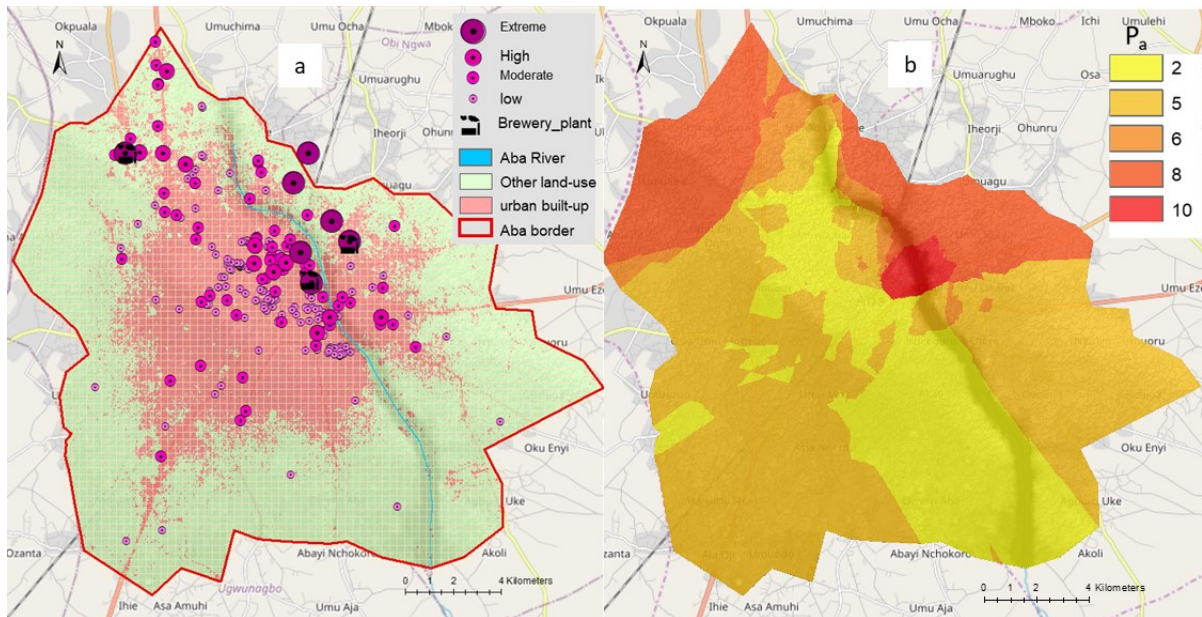


Fig 9-9: Map illustration of (a) distribution of categorized active pumps and (b) rating map of the distribution of impact of active pumps [P_a].

average daily withdrawal rates assigned to the sub-class pumps (See Tables A-8.1, A-8.2 and A-8.3 in Appendix 8 for the categories, range and rating of some active pumps in the area). Based on the pumps categorization, the ordinary kriging method was used to create the rating map for the impact of active pumps as shown in Fig (9-9(b)). The interpretation of the rating scheme is given in Table 9-5 and it describes the ranges for a daily volume of groundwater withdrawn by the pumps and the corresponding ratings. For this assessment

Table 9-5: Interpretation of ranges for the impact of active pumps and their ratings.

Impact of pumps (m^3)	Rating
1-10	2
11-50	5
51-100	6
101-400	8
>400	10

In the illustration, the impact of active pumps depends on the volume of groundwater abstracted. However, the uneven distribution of the active pump points throughout the area as shown in the map may have led to some skewness as seen in the impact of some powerful pumps in proximity in areas where there are little or no pumps.

In general, the result implies that the areas with a low rating of the pumps give a minimum impact on the hydrogeology. Whereas, the areas with a high rating are influenced by the impact of pumps belonging to large-scale manufacturing activities such as the beer breweries and beverage industries. These pumps have a conspicuous impact on the hydrogeology of the area.

9.3.2 Groundwater vulnerability assessment map

The results of implementations for both the conventional DRASTIC and the proposed DRASTIC-P_a indexing methods are shown in Figs (9-10(a) and (b)) respectively. The analyses of the results of the indices revealed that the vulnerability classes for the DRASTIC map lie between 107 and 171, whereas the vulnerability indices of the DRASTIC-P_a map range between 117 and 211. This range of indices for each method represents a set of vulnerability classes when categorized. The identified classes in the model fall only within low, moderate (medium) and high classes out of the five possible vulnerability classes shown in Fig (9-11). The results of the vulnerability class distribution analysis in percentages

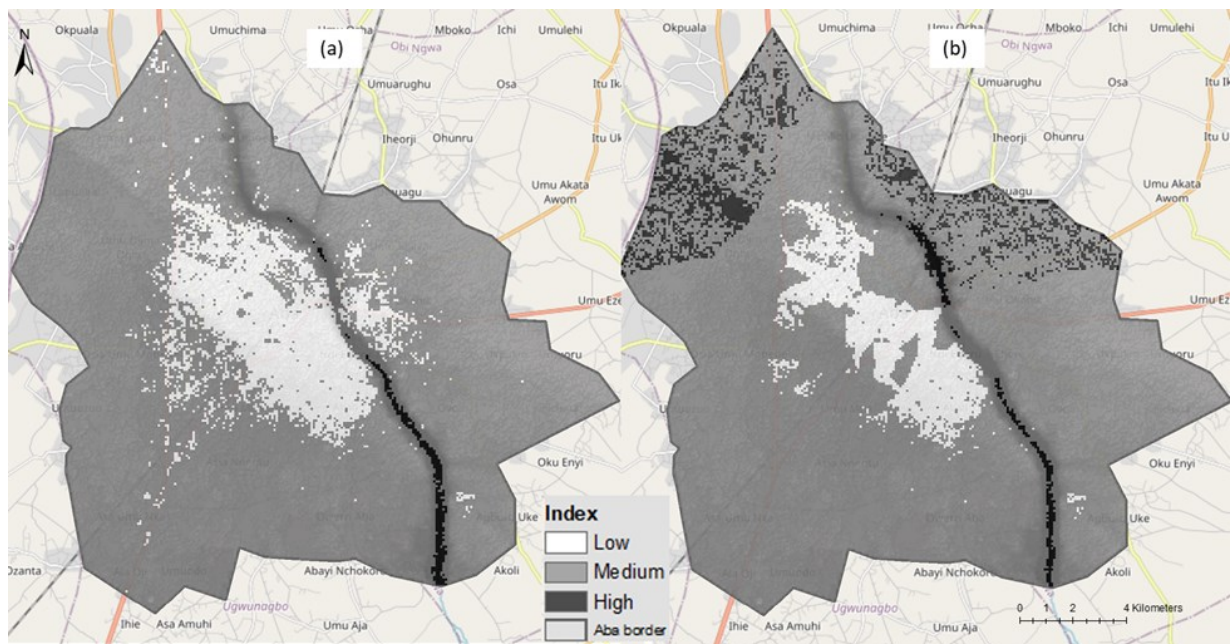


Fig 9-10: Vulnerability assessment maps showing the results of (a) DRASTIC and (b) DRASTIC-P_a models for the area.

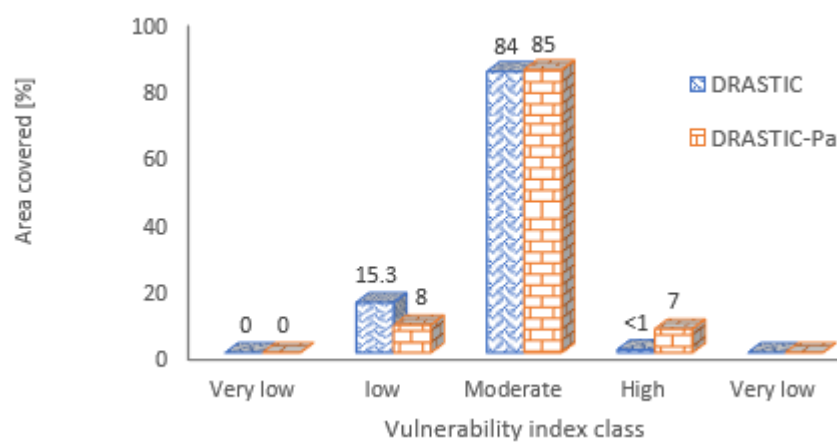


Fig 9-11: Multiple bar chart comparing the vulnerability index classes area for the DRASTIC and DRASTIC-P_a methods.

are presented and compared for both DRASTIC and the DRASTIC-P_a methods as summarized in the table of the illustration (multiple bar chart) shown in Fig (9-11). The results of the analysis revealed that the vulnerabilities in the DRASTIC method include 15.3%, 84%, and 0.7 % of the area represent low, moderate (medium), and high vulnerability classes respectively. These results of the DRASTIC map in Fig (9-10(a)), suggests that most parts in the densely urban area have low groundwater vulnerability. Whereas the vulnerability designation of the groundwater in the peri-urban area is mostly the moderate class. Some parts of the Aba River were found to be represented with high vulnerability. In the predictions of the vulnerability models, it is expected that the entire course of the Aba River and shoreline should be designated with the high vulnerability Very high ss, because of lack of physical protection over the groundwater.

The results of the DRASTIC-P_a method in Fig (9-10(b)) illustrates the spatial distribution of the vulnerability classes and the summary of the analysis of classes are shown in Fig (9-11). The results revealed that the low vulnerable part found in the densely built-up area based on the DRASTIC model was reduced from 15.3 % to 8 % and the high vulnerable areas increased from < 0.7 % to 7 %. The proportion of the areas with the moderate (medium) class remains predominant at 85% in the DRASTIC-P_a method just like in the DRASTIC method.

Generally, the different hydrogeologic parameters in both assessment methods have varying degrees of physical protection they offer to the aquifer in preventing surface contaminations from reaching the groundwater table. In the study area, Fig (9-10(a)) revealed that the net recharge rating map is the most sensitive parameter that influences the outcome of the models. This is a reflection of the local differentiation patterns seen in the DRASTIC vulnerability map. The low vulnerability index portions in the DRASTIC map were mostly influenced by the low net recharge rate of groundwater in the areas as shown in the rating map due to impervious surface sealing found in the densely built-up central parts.

For the DRASTIC-P_a method, the net recharge rate, as well as the impact of the active pump map have the most significant and localized differentiation effects on the assessment model. The introduction of an additional layer (impact of the active pump), led to further changes in the results of the DRASTIC method. These impacts influenced the vulnerability classes at the northern part and the central parts in the densely residential area as shown in Fig (9-10(b)). The clusters of pumps abstracting high volumes of the groundwater used as both product and process water by industrial activities influenced the outcome of the model. Also, arable and vegetated land covered classes at the northern parts enhances further the vulnerability of this part, as a large volume of the rainwater can to easily infiltrated through the geological overburden.

The compared result of the DRASTIC and the DRASTIC P_a methods revealed the additional impact of the active pump layer on the DRASTIC method. This impact led to transitions of some vulnerability classes especially movement from low vulnerability class to moderate vulnerability class. This mostly occurred in the densely built-up parts. Again, some parts of the moderate vulnerability areas were converted to high vulnerability groundwater at the sparse built-up area in the northern part in Fig (9-10(b)). This explains how the impact of the additional hydrogeologic layer in the DRASTIC- P_a method can significantly influence the quality of the groundwater. Evaluating quantitatively the changes between groundwater vulnerability between DRASTIC and DRASTIC- P_a methods, revealed that the active pump surface caused at least 7.3 % of the low vulnerable areas in the DRASTIC to shift to the moderate vulnerable class, as well as some moderate vulnerable class in the DRASTIC were converted to the high vulnerability class in the DRASTIC- P_a by additional 6.3%.

In both methods of assessment, the moderate vulnerability class remains the dominant class in both cases. Removing the effects of the net recharge rate and the impact of active pumps, the combined effect of the remaining hydrogeologic factors (low-lying topographic nature, sandy loam top-soil and the sandy-clay unsaturated zone and the rapid hydraulic conductivities) gave the area a moderate (or medium) aquifer protection. This makes the background vulnerability class of the area medium risk, which is observable in most parts of the study area. This result of the vulnerability assessment of the area corroborates with the outcomes of aquifer vulnerability assessment studies, performed with the DRASTIC method in some parts of the regional basin (Ibe et al., 2003; Ijeh 2013; Edet 2014; Amadi et al., 2014; Mgbolu et al., 2019).

Ibe et al., 2003 also highlighted that the porosity, the depth to the groundwater table, topography are the most important contributors to the aquifer vulnerability in the area. However, in the context of this study, the impact of permeability only can be distinguished from the rest of the other factors, which is influenced by the surface sealing mostly in the densely built-up parts. The vegetated arable agricultural and broadleaf classes with high net rainwater infiltration rates make the aquifer under them more vulnerable to surface contamination if exposed to a hotspot in proximity. Nevertheless, it was observed that some parts of the widely vegetated southwestern area are usually flooded. This part is topographically flat with a low lying slope, but the flooding situation would be significantly contributed by the lenses of silt and clay materials that hinder the infiltration of the water in this part.

Again, the transitional changes from one vulnerability class to another, between the DRASTIC and DRASTIC- P_a models demonstrate the effect of the impact of active pumps rating map in the assessment methods. Generally, the abstraction of groundwater through pumps influences the lateral flow of the groundwater. The pumps do not necessarily form any protection or directly contaminate

the groundwater. However, during pumping, the movement of the groundwater towards the wells may increase the possibility of the well being polluted if there is a contamination hotspot close by and hence the high vulnerability designation with increased pumping as demonstrated in the DRASTIC-P_a. This shows that the abstraction of a copious volume of groundwater can harm the quality of the groundwater if source protection is not implemented. The higher the volume of the groundwater abstracted, the greater the chance of harming the groundwater quality in this kind of environment as pumping continues. This is because the high prevalence of hotspots is high, and there is poor regulation of urban land use practices around the pumps which are sources of contamination to the groundwater. If the pumping leads to drawdowns, then the well's piezometric head is lowered and the groundwater flow will be directed to the pump, which may force cause polluted water around the hotspot area to flow towards the well. These urban contamination sources have already been identified in the area. The ubiquitous presence of these hotspots threatens the quality of the groundwater and the observation agrees with the reports of Edet, (2014) and Ibe et al. (2003), which show that this kind of practice is widespread in many parts of developing countries.

Most other studies which have demonstrated the concept of modified DRASTIC methods took into account urban land use sub-classes as the additional thematic rating unit into the DRASTIC method (Secunda et al., 1998; Ijeh, 2013; Amadi et al., 2014; Singh et al., 2015; Kumar and Krishna 2019). These urban land use sub-classes are usually seen as hotspots or sources of surface contamination that can expose the aquifer to harmful contaminants. The demerit of these hotspots is that they do not influence the movement of the water, nor offer any degree of protection to the groundwater. However, the impact of the active pump layer, as a substitute for the other anthropic hydrogeologic settings, is more appropriate because it influences the groundwater movement and can create hydrogeologic differentiation in the aquifer. This land use feature can influence the direction of the movement of surface contaminants in the unsaturated zone and the groundwater as well as in both the lateral and horizontal directions. In many developing urban areas, where there is a high dependence on the groundwater, the active pump layer can be implemented, as a hydrogeologic mappable unit to substitute other urban land use surfaces used in other studies.

The accuracy of the vulnerability assessment methods to the susceptibility of groundwater can be validated using the actual groundwater quality measurements in different parts of the area. In many studies where the DRASTIC method have been applied, the use of nitrate concentration distribution over the area is employed to validate the accuracy of the results of the DRASTIC model. This is usually common when it is applied in areas where agricultural land use prevailed and tons of fertilizers have been applied in such places. Agricultural practices are supposedly believed to elevate concentrations of nitrate in the groundwater, as a result of the use of fertilizers, and as such the use of measured

nitrate concentrations in different parts of the area are employed to validate the accuracy of the DRASTIC predictions. In a non-agricultural area, like in this study, the distribution of TDS concentrations can be used instead to validate the accuracy of the method. However, this could apply to areas that have sufficient monitoring wells to create a TDS quality surface, which can be overlaid against the vulnerability map to compare the accuracy of the model (Saatsaz et al., 2011).

However, adopting this approach to validate the predictions of the DRASTIC and DRASTIC-P_a methods may not be most appropriate considering the results of the groundwater quality distribution in the study area. For instance, the general mineralization and the total dissolved solids in the groundwater were low (i.e., lie between 6 mg/l - 365 mg/l) for all the wells analyzed throughout the study area relative to the maximum acceptable concentration (1000 mg/l) set by the WHO. The lowest TDS concentration was observed in a borehole very close to the Aba River where there was little influence of human activities and the highest TDS concentration was observed in a tubewell in one of the densest residential parts, that was sited close to a septic drain. These results by implication showed how land use activities contributed to the changes in the quality distribution of the groundwater. However, the dilution due to the effect of the large volume of rainwater usually received in the area, and the lack of urban hotspot information in the model made the outcome of the model unrealistic as would be expected for a developing area. Therefore, it will be difficult to integrate this type of validation approach using the actual concentration of dissolved substances in the groundwater to test the accuracy of the models. Such an approach alone might not be sufficient and should be exempted.

9.4 Evaluation and limitations of the vulnerability models

The results of the vulnerability assessment models (i.e. DRASTIC and DRASTIC-P_a methods) already discussed revealed that the sensitivity of the models depends principally on two out of the eight hydrogeologic settings. This is because the remaining six parameters are more or less identically spread throughout the area.

However, the concept of DRASTIC is best suited as a screening management tool, since it takes into account, only factors that offer physical protection to the aquifer or influence the movement of the groundwater. The results of both models revealed that the intensive urban activities taking place in the central parts of the study area have caused an anthropic impervious surface sealing and therefore protects the groundwater. The observed sealing confers the aquifer low vulnerability class in this densely populated urban built-up part of the study area. However, the lack of a central sewer system in most developing urban areas have made alternative methods such as the use of the septic tank, on-site sanitary facilities and cesspools inevitable in the management of residential effluents. These practices form important groundwater contamination hotspots, which can harm the quality of the

groundwater. Again, these practices directly recharge the groundwater and are unaccounted for in the assessment models. Based on these observations, the absolute transferability of both models in the context of developing countries might be misleading. This is because the extent of the surface sealing (imperviousness) in many parts of the urban settings of developing countries are limited to assume that dense urban built-up can represent low aquifer vulnerability. Further research is needed to factor in these lapses in the model to reflect the reality in this area.

Again, the issue of data paucity in many developing countries has been seen as one of the challenges facing research in the region. Some of the inconsistencies in the results of the models can be traced to poor quality data used in the models. For instance, the coarse resolutions of the DEM and the Landsat satellite imageries (approximate 30m resolution), as well as the uneven distribution of the pumps are some examples. These factors influenced some of the results of the hydrogeologic layers such as the depths to the water table, net recharge rate and impact of active pumps that were fed into the models.

The influence of the impact of the active pumps setting in the DRASTIC-P_a model cannot be over-emphasized. Currently, there are no monitoring wells throughout the study area. However, some lapses in the model were developed because of the uneven distribution of the active pump points throughout the entire study area as illustrated in Figs (9-9(b) and 9-10(b)). This uneven spread showed that some areas with clusters of pumps and others where there is little or no pump. The effect of the pump distribution is conspicuous in the central-eastern and central-western parts of the area of the DRASTIC-P_a model where there are no pumps, and the model showed higher vulnerability classes.

Chapter Ten

10 Implementation of thematic decision-support management tool

10.1 Background

The concept of groundwater management starts with a monitoring program that ensures ultimately resource availability, control pollution, reduces mitigation cost, as well as guarantee the safety of the product derived from the resource (AGW-Net 2015, pp. 100). However, this process is considered expensive in the context of most developing countries situations. There are two types of groundwater monitoring strategies: (a) external (i.e extending transboundary) monitoring and (b) internal monitoring strategies. The difference between the two is that the former covers international borders, while the latter deals with the impact of localized anthropogenic activities, especially in urban areas on the quality of groundwater.

In many developing countries there is a dearth of custom-developed decision support tools, available to relevant authorities to manage the groundwater under prevailing local situations, especially in the urban areas. One of the reasons being the implicating high cost of monitoring, as well as building an effective system to acquire and maintain a quality, and quantity database. These factors among other things hamper such development tools and consequently, contribute to mediocre decision making in the management practices by those saddled with this responsibility with the resources. Therefore, it is important to come up with tailor-made and scientifically-based strategies, using the available information to support and overcome these shortcomings and promotes manage the problems of water resource management in the global South.

Since data gathering is uncoordinated, scarce, or most times inexistent in this part of the world, it will be difficult to carry out a customized and efficient modelling that will support decision making for better water resource management in the area. In addition to the cost and data scarcity aspects, poor environmental practices and lack of strict implementation of urban practices in the developing urban areas lead to some weakness in existing models and methodologies because some of the peculiar features of the areas were not taken into account.

In this chapter, a thematic decision support tool for the management of drinking water was synthesized for Aba City, to protect the main source of water in the area. It describes a simple derivative procedure that uses different decision support tools, which were created after evaluating the water situation and physiological characterization of the area. In this study, the thematic decision support tool integrates systematically different groundwater management tools that have been previously derived:

- a. potential contamination hotspot map (Chapter 5, which identify important hotspots that can harm the quality of the groundwater),
- b. water quality index distribution map (Chapter 8, which analyzed the baseline chemical risk and quality distribution of in the groundwater), and
- c. DRASTIC-P_a groundwater vulnerability maps (Chapter 9, which screen and characterized the physical vulnerability of the aquifer).

The developed thematic decision support management framework and the tool marked overarching scientific contributions of this research in the study area. The implementation to a large extent can be extended to other developing urban settings in the global south region where conditions are similar and scarcity of data impedes implementation of more detailed decision support tools to protect and manage sustainably the available water resource. The framework should be tailored-made for the available data and the peculiarity of the developing urban situation, making the method transferrable and easily reproducible for areas with similar physiological settings.

10.2 Methods

The framework for the development of a thematic decision-support tool was built on the backbone of data obtained during the assessment. The methodology brings together the outcomes of the different decision tools developed (screening and analytic tools) to build a simple thematic decision support tool to manage the groundwater in the study area. The output of the management tool comes in the format of a map, which was built in a GIS environment. The schematic flow in Fig (10-1) summarized step by step the processes for the development of the framework and implementation of the tool. The flow diagram consists of four main stages (Evaluate – Create – Combine – Build & Validate). The system evaluation assesses the amount of hydrological (quality and quantity) data available in the area to understand the local situation. The available quality and hydrological data can be transformed into their spatial dimensions to create different decision support tools (both screening and analytic) for the area. Based on the tools, important features were defined to be captured in the thematic management tool and has to be delineated. In the case of this study, quality monitoring of the groundwater and selection of source protected areas were important in the area. For the delineation process, it is important to identify, extract and homogenized certain features in the different decision tools to create priority monitoring zones in the area. The criteria for the selection of the priority monitoring areas in the composite management tools were drawn from:

- (1) the compactness of the hotspots
- (2) suitability of the groundwater as a drinking water source, and;
- (3) distribution of the physical vulnerability of the aquifer in the area.

One of these criteria must meet in the management tools to be considered. Firstly in the analytic tools: (a) the derived industrial zones and use of septic tank and on-site effluent disposal facilities captured from the potential contamination hotspot and delineated urban land use maps respectively, to suffice contamination sources that directly harm the quality of groundwater through artificial recharge, (b) water quality index distribution map based on WGA sub-index aggregation method, which directly defines areas where the groundwater has been polluted and unsuitable for drinking. Secondly, the screening tool (e.g. DRASTIC-P_a groundwater vulnerability assessment tool) complemented the analytic tools, that defined the extent of physical vulnerability of the aquifer with a focus on the developing urban situation.

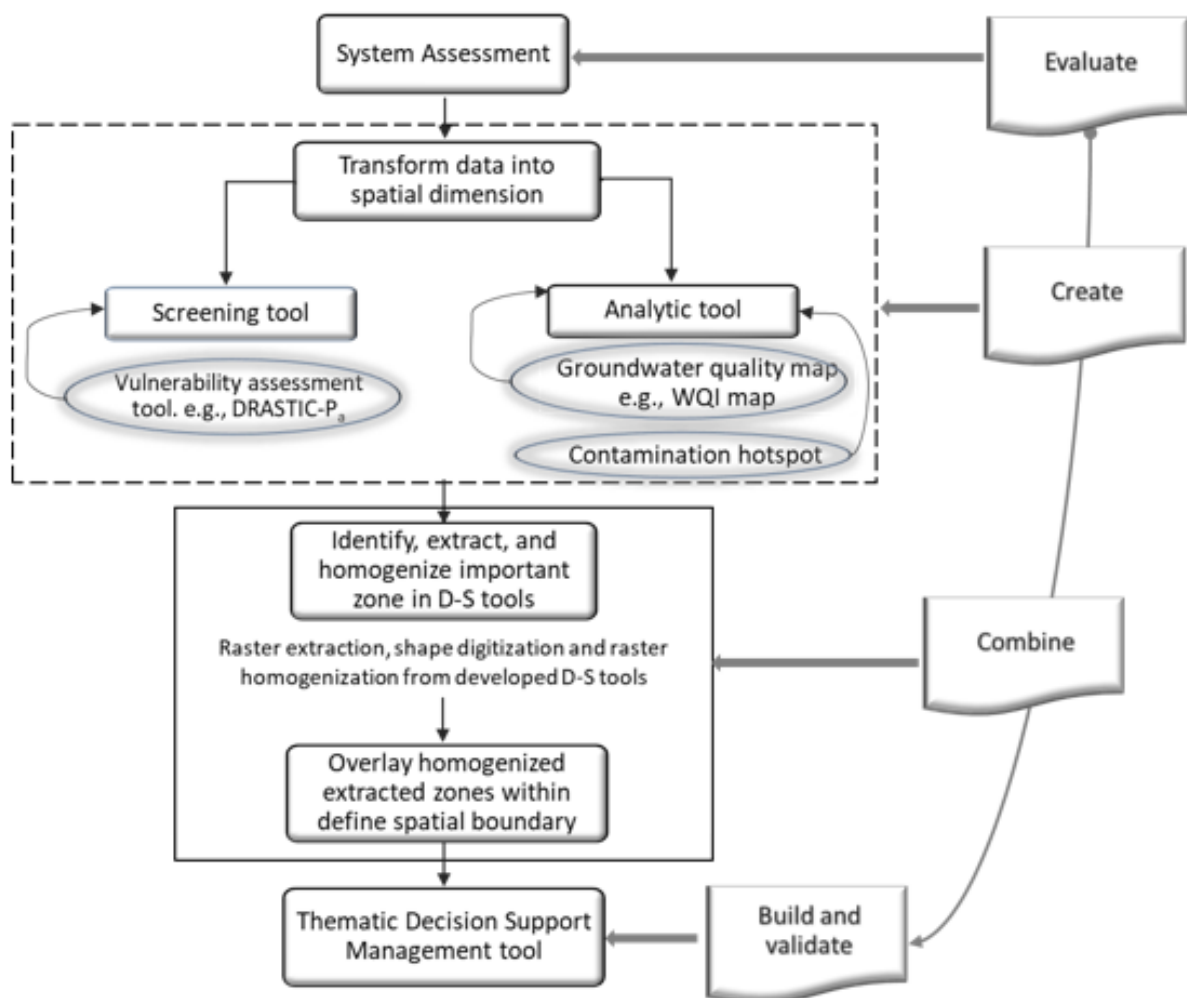


Fig 10-1: A schematic flow showing steps for developing and implementing a thematic decision-support tool for drinking water management in Aba, Nigeria.

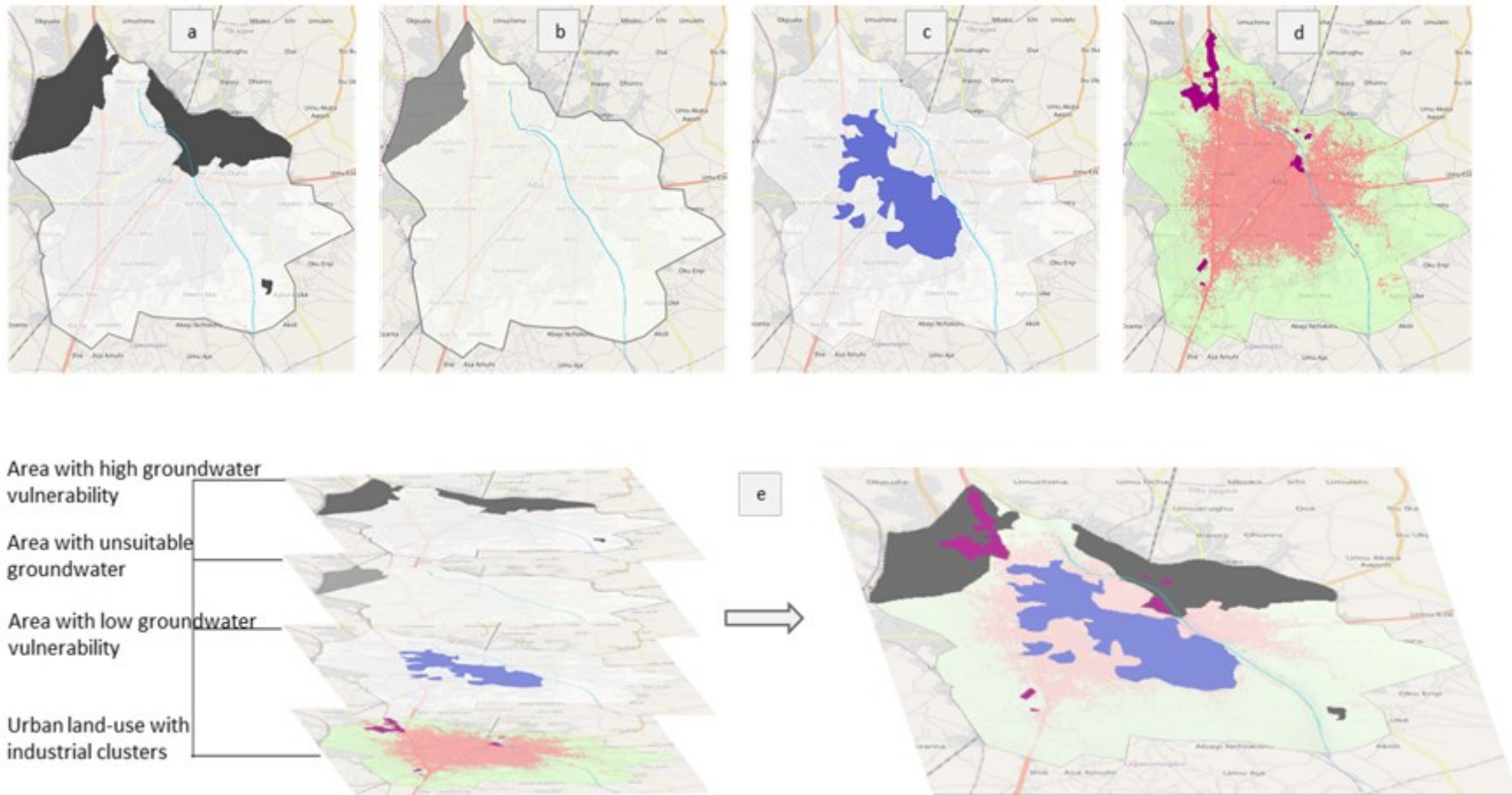


Fig 10-2: Schematic diagram showing a GIS-based assembling of components zones that constitute the thematic decision support tool. (a) homogenized zone with high aquifer vulnerability (b) extracted area where the water quality index is unsuitable, (c) homogenized zone with low vulnerability index, and (d) digitized industrial clusters overlaid on the delineated urban land use as the base map.

These conditions were identified and extracted from the tools to create the priority zones depending on the properties of the tools. When the features are sporadically scattered in space, first the raster is extracted and the areas covered were manually digitized to create polygon(s). Then, the polygon is reconverted into raster patch(es) and homogenized into identifiable units (Dawoud, 2004). These units are reclassified to create the delineated priority monitoring zones (DMZs) for the different management tools. The homogenized patches from the difference are represented in Figs (10-2 (a) – (d)).

The “combine-stage” involves overlaying and assembling all the homogenized zones onto the extracted urban land use map as the base map, which defines the spatial extent in the area. Then, this completes the process for building a thematic management tool. Since the models that gave rise to the homogenised zone in the case of this study has been validated, this part of the framework can be ignored. The component analysis of the zones was performed using the zonal statistics tool in ArcGIS to describe the extent of coverage.

10.3 Results and discussion

Fig (10-3) gives the illustration of the thematic decision-support management tool. It revealed different homogenized priority zones, which comprised areas with high aquifer vulnerability, areas where the groundwater is currently unsuitable for drinking and polygons of industrial clusters, all overlaid on the delineated urban land use map. Another important part at the core of the management tool, which serves as the source protected zone derived from DRASTIC-P_a is the homogenized area with low aquifer vulnerability.

Table 10-1 summarized the results of the area covered by each zone in the thematic management tool. In addition to the delineated urban parts, the breakdown of the tool revealed the main constituent homogenized units in the map, namely: the delineated monitoring zones (DMZs), and the source protected area for the proposed construction of the new water schemes (NWS) in the study area. The results of the decision management tools showed dominant parts of the DMZs are found in the northern parts of the study area.

Table 10-1: Analysis of the constituent zones in the thematic decision support management tool.

Constituent zone	Area	
	(km ²)	(%)
Delineated monitoring zones (DMZ)	45.4	19.2
▪ High-Vulnerability zone	40.8	17.3
▪ Unsuitable WQI zone	17.2	7.3
▪ Industrial cluster	4.6	1.9
New water scheme patch (NWS)	30.2	12.8
Urban land use	85.0	36.0

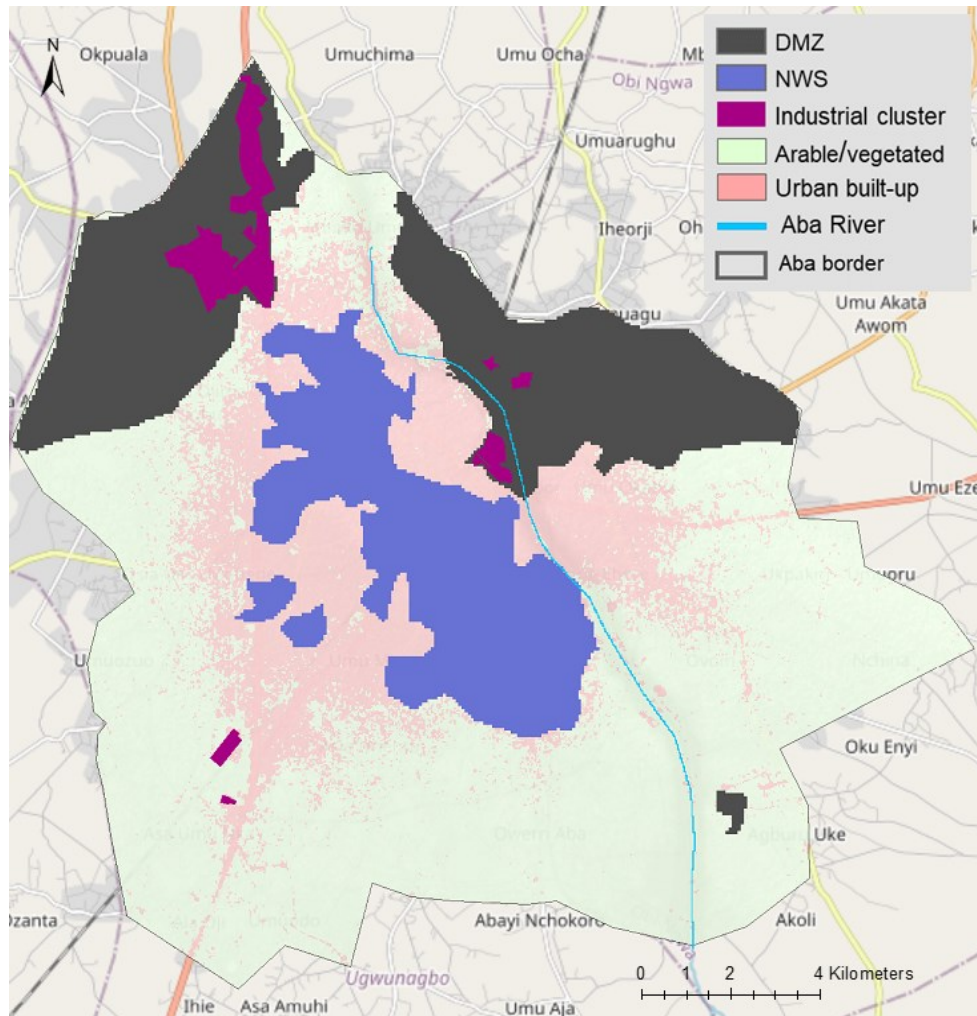


Fig 10-3: Map of Aba showing the thematic decision support management tool and important homogenized zones.

The analysis of the zones showed that the areas where the aquifer is most vulnerable to contamination make up 17.3% (i.e 40.8 Km²), whereas the area where the groundwater quality index is unsuitable for drinking constitute 7.3% (17.2 Km²) of the study area. Some parts of the digitized industrial clusters are embedded in both DMZ patches on the map. These clusters cover 1.94 % of the study area representing 4.6 Km². It has been observed that hydrocarbon that the pipelines running along this part are continually get vandalized, leading to hydrocarbon contamination in the groundwater. Again, most of the industrial facilities in this area do not have wastewater treatment units to process their effluents before they are discharged to the environment. The commonest effluent disposal methods are the use of cesspool drains and direct discharge into the aquifer through tube wells or the Aba River without any form of treatment. Hence, the monitoring activities within the DMZs must encompass qualitative and quantitative evaluations since these practices have a direct impact on groundwater quality.

The identification and selection of the proposed construction location for the new water scheme (NWS) were based on the results of the DRASTIC- P_a vulnerability assessment tool. The area where the aquifer showed the least physical vulnerability according to the model was taken into account, homogenized and delineated for this purpose. The area covered by the NWS is 12.8% and it is located at the core of the study area, which coincides with some parts of the densest residential and commercial area. However, the results of the model have not been conclusive because the input data such as impacts of groundwater contamination hotspots in the area were not integrated into the model, it was found that part of the zone completely intersects with the densely built-up area where poor land use and environmental practices have been observed. This part of the DRASTIC- P_a results suggests a weakness in this modified DRASTIC method in characterizing the aquifer of the area. This is because the method did not take into account the main contamination hotspots that have been observed in the area. In this part of the area, urban land use represents an important hotspot for groundwater contamination, especially in the densest residential parts due to the lack of central sewerage and the congested use of septic drains, cesspools and on-site sanitation facilities for household effluent disposal. The average water quality results of the indicators are deteriorating (i.e. there is increasing concentrations in the HR wells relative to the observed concentrations in the LR wells). Despite the poor environmental practices around the HR wells, the results of the quality indicators still lie within the maximum acceptable concentrations for drinking water quality, due to the dilution effect of the high volume of rainwater received contributing to this in the study area. Therefore, capturing the contamination of hotspots into the DRASTIC- P_a in characterizing the vulnerability of the groundwater will improve the outcome of the model and reflect the current reality in the baseline quality status of the groundwater as observed in the NSW area. Again, when this adjustment is done, a better delineation process and assignment of a suitable site(s) can be suggested for the construction of the waterworks in the area outside the densely residential parts due to the prevalence of the potential contamination hotspots.

The illustration of the thematic decision-support management tool highlighted important zones in the study area that can assist the local authorities in zoning and managing some of the unregulated urban practices, particularly activities that directly harm the quality of the groundwater and/or regulate the over-abstraction of groundwater in these areas.

The local town planning authorities in the area must reconsider a stricter implementation of urban land use activities such as licensing of direct discharge of effluents into natural watercourses. For example, criminal punishment should be handed to individuals or organisations that drilling boreholes to discharging effluents into the aquifer or Aba River must be considered. Land use activities already identified in the contamination hotspot map must be taken into account and appropriately zoned,

especially now that it has been established that the abstraction of a large volume of groundwater has a hydrogeological consequence in the vulnerability assessment of the groundwater.

In fast-growing developing urban areas such as Aba City, it is important to centralize pumping activities to areas where the aquifer is least vulnerable to surface contamination. This is because the cost of monitoring the groundwater quality in the study area is minimized as it will be easier to control zoning of different land use practices, especially around the pump fields. Therefore, this approach guarantees the water safety of the people living in the area. It is an important step to check and control the deteriorating influence of urban land use practices on the quality of groundwater as the source of drinking water in the study area.

SECTION C

Summary and Appendices

Chapter Eleven

11 Summary, recommendations and research outlook

11.1 Summary

This section summarizes the important observations and results obtained in this research. The access to drinking water resources and the development of an effective water resource management system in most parts of the sub-Sahara African (SSA) countries have been slow and grossly insufficient, to meet the water demands in many parts of the region. Despite the vast freshwater resources available in many parts of the SSA countries, some sections of the region are still water-stressed and have failed to meet the MDG 7 targets in 2015. In Nigeria, the estimated water resource potentiality is sufficient to meet the water needs of the people. But in reality, millions of Nigerians are still without access to potable water, both in the rural and urban areas. The following factors were identified to be responsible for this situation, such as the skewed spatial distribution of freshwater resources, rapid population growth, quick-rising urbanization trends without plans, as well as weakness in the institutional capacity and mismanaged investments in the water sector etc. These culminate in the shortage of water supplies both for domestic and other purposes. Therefore, more efforts, investment strategies, and control by all the relevant authorities must be committed to developing a water management system that guarantees the supply of safe and affordable water to many people in every part of the region.

The City of Aba and its environs were selected as a typical representative of a commercial urban area in Southeast Nigeria. The climatic conditions are tropical humid and the geology is made up of the coastal plain sand. The hydrogeological borehole logging of the area revealed that the aquifer is deep, predominantly unconfined, and covered with a layer of sandy-clay aquitard, which moderately protect the saturated zones. The climate-based evaluation of the hydrological balance in the area suggested that the aquifer stores sufficient groundwater, which currently served the domestic and industrial water needs of the people, obtained through tube wells.

The empirical study revealed that the predominant sources of drinking water come from boreholes (tube wells) and packaged water products, all originating from groundwater sources. The supply of the water is private and most people living in the area drink the water without treatment. The practice of private supply in the area guaranteed better access to water but has led to the proliferation of domestic and industrial pumps in the area. The current practice suggests that the abstraction of groundwater is unregulated, which might have negative hydrogeological consequences, as well as harm the quality of the groundwater. Despite the increased access to water to the people, the

estimated average daily water consumption per capita in the area was found to be below the recommended daily consumption rate by the WHO. This means that the basic domestic water and sanitation needs of most households in the area are compromised, and this could endanger public health.

The evaluation of the terrain and the dynamics in the landcover changes were used to derive information on some of the factors that influence the availability of water in the area. The terrain analysis showed that the area is predominantly flat land, with poor drainage networks. The results also predicted areas of high water accumulation, including the Aba River, existing ponds and marshy areas in the study area. The land cover change detection identified four main land use classes. These include arable, urban, vegetated and water classes. The analyses of the land use changes over 31 years showed that the urban land use has the most rapid growth, followed by the vegetated and arable land use types, which are currently being depleted. Further, some potential hotspots (urban practices which directly harm the quality of the water sources) were identified, collated and mapped. The quality risk indicators associated with the contamination sources were identified and targeted while performing the chemical and biological risk assessments in the water sources.

The physicochemical and chemical risk evaluation of the groundwater was conducted for wells in both sparse (LR) and densely (HR) built-up areas. It was found that the groundwater pH is generally acidic, has low mineralization, and seasonal changes have little or no influence on the quality when compared with the average results of the wells in the LR and HR wells respectively. However, the comparison of some selected indicators in the grouped wells suggest that the impact of urban land use is causing the deterioration of groundwater quality. The groundwater showed four (4) dominant water types, with spatial differentiation between the wells in the HR and LR built-up areas based on the hydrochemical assessments. The dominant water type in the sparse built-up areas is the Na-HCO₃ type, whereas the Ca-HCO₃, [Mg, Ca]-Cl and Na-Cl types were prevalent water types in the densely built-up area. The compositional changes in the major ion chemistry of the groundwater suggest the influence of some urban land use activities that introduce additional major ions in the groundwater and mixing propensity between the groundwater reservoirs. This explains the different water types found in both the LR and HR areas. Besides, the direction of flow of the groundwater enhances the mixing propensity of the groundwater reservoirs and helps to distribute between the HR and LR areas. The index of base ion exchange also helps to explain the buffering in the groundwater, thereby controlling the chemistry of the groundwater.

The bacteriological evaluation of drinking water from different (natural and selected alternative) sources showed that the treated piped water is the safest source. However, some samples were taken

from the Aba River and groundwater wells showed the presence of both *coliform* and *E. coli* bacteria. This suggests faecal contamination from anthropic sources in the water. Also, colonies of *coliform* bacteria were found in some of the alternative drinking water sources like the packaged water and the non-alcoholic beverage produced in the area. Also, it was found that the trend in the prevalence of diarrhoea cases in children under 5 years is decreasing. This result suggests a probable improvement in the microbial quality of the water and sanitation for the period under consideration in the area. It further identified and discussed some anthropogenic sources of bacteriological contamination in natural water sources.

A GIS-based water quality index (WQI) approach was used to develop the groundwater quality distribution maps. Two sub-index aggregation (i.e weighted linear summative averaging (WLSA) and weighted geometric averaging (WGA)) functions were used to evaluate the WQI of the groundwater in the wells to improve the methodological discrepancy in the estimation. The spatial distribution of the groundwater quality index was created using the WQI of the wells, and the predominant index classes in most parts of the area lie between “good” and “excellent”. However, the maps revealed that the groundwater quality around the industrial clusters in the north-western part of the study area has been contaminated, making the groundwater unfit for drinking. The correlation between the groundwater quality indices in the wells and the corresponding selected quality indicators suggest that the change in the quality index is mostly influenced by the change in the TPH. The TPH is not a normal constituent of the groundwater, therefore, this result suggests that the change in the quality indices is a human signature in the groundwater quality. The comparison between the “actual” of the wells indices and the “estimated” indices in the map suggests that the WGA sub-index aggregation function have better fitting than the WLSA sub-index aggregation function. This observation was further strengthened following the distribution patterns created by the estimation methods under the influence zone of pumps in the area, where the water quality is unfit and have shown some differentiation.

The physical susceptibility of the aquifer to contamination was evaluated based on the indexing, and overlay method of eight hydrometeorological and geological parameters. The multi-criteria vulnerability assessment method was based on the DRASTIC, and the method was modified to DRASTIC-P_a to enhance the methodology according to the peculiarity of the study area. The outcome of the two assessment methods revealed that the predominant vulnerability class of the groundwater is the medium (moderate) class. The combined effect of the hydrogeological settings in the area suggests that these features offer moderate protection to the groundwater. However, the differentiation in the vulnerability assessment of the groundwater arises due to the localized changes in the net recharge areas, and the depth to the groundwater. When the DRASTIC method is compared

to the modified DRASTIC-P_a method, revealed the effect of the additional impact of the active pumps on the vulnerability assessment. This anthropogenic hydrogeological factor was responsible for the transitions of some areas from “low” to “moderate” vulnerability classes and others from “moderate” to “high” vulnerability classes in the groundwater of the study area. However, the validation of the models obtained from these methods was exempted since the spatial distribution of the groundwater chemistry was almost uniform and still within the MAC values of drinking water. Therefore, applying such a method of validation might be misleading.

Finally, a methodological framework was developed from existing management tools created for the study area. These tools include the potential contamination hotspot map, WQI distribution map and DRASTIC-P_a vulnerability assessment map. The thematic decision support management tool forms one of the most important contributions of this research, and the approach can be adopted as a cost-effective way of delineating the most vulnerable areas in the catchment for monitoring purposes, especially in data-scarce regions where investment in data gathering and management is not efficient. This framework can be reproduced and transferred to other regional commercial settings in the southeastern, and southwestern parts of Nigeria where similar physiological and urban conditions prevail. Also, the approach can be extended to other developing urban regions in the world to promote easy monitoring and management of the quality of the groundwater as source water for drinking.

11.2 Recommendations

The reduced availability of safe drinking water sources and the sustainable use of groundwater resources by millions of people living in the region can not be over-emphasized. In this study, some of the chapters made some interesting observations and findings on some factors that influence the accessibility of drinking water, or some problems(i.e quantity and quality), which exacerbate the supply challenges. It is important to make some recommendations that can improve the safety and guarantee the sustainable use and management of the groundwater resource within the region.

11.2.1 Education and sensitization of people on the quality issues related to drinking water sources

The quality distribution map developed for the area identified some parts of the study area for which the groundwater is unfit for drinking, due to pollution. The local authority must communicate to the people living around this area about the quality state of their water source and the health implications of drinking this type of water. To drive this message, different modes of communication can be used to advise the residents of the study area about the quality status of the drinking water sources. These

modes of sensitization will include the use of billboards, campaigns at churches and mosques, the teaching of nursing mothers at local health centres by mid-wives, and the use of radio jingles etc.

Further, it has been observed that one of the ways through which the groundwater get contaminated is through the activities of the local borehole technicians, who construct the tube wells. These technicians sometimes, amidst difficult situations come up with improvisation that leaves the groundwater worse off out of ignorance. For instance, some of the artisan drillers, use the possibly contaminated standing pond as recirculation water during drilling of wells, while others recommend the direct discharge of effluents in wells to some of their clients, as a solution to their effluent management problem. These types of sharp practices can be eradicated if these technicians are fully aware of the implications of their actions. Therefore, local drilling operators should be formally educated in this trade and licenced to ensure that they are not ignorant of some practice that compromises the environment and the health of the public. This will include organizing workshops that will teach technicians working codes and ethics in drilling and construction of tube wells. Therefore, formal training will help improve professionalism in the trade, developing a standard procedure for tube well construction for licensed borehole drilling practitioners from time to time, create a platform that connects the drillers and local authorities. This will help discourage drillers, who engage in sharp practices that are currently taking place during tube well drilling operations for the fear of loss of licence if found wanting.

11.2.2 Regulation and licensing for safe private supply activities

One of the consequences ensuing from the dysfunctional state of the public water supply in the study area is the proliferation of groundwater pumps used in private boreholes to meet both domestic and industrial water needs. Currently, the extraction of groundwater from private pumps are not regulated. Based on the results of the vulnerability assessment, over-abstraction of groundwater may have already been taking place and this exacerbates the local hydrogeological conditions, leaving the groundwater quality worse off. Therefore, the local authority must enforce strict licensing of land use activities that require or extract at least 15 m³/day of groundwater. Hence, a system of inventory that takes a record of groundwater withdrawal can be created. This type of programme will set withdrawal limits for different active pumps and mandate individual users of the groundwater to keep records of daily withdrawals, which they will submit to the local authority to create a withdrawal inventory. This could serve as a database to be used to audit and manage the quantity of groundwater in the area. Also, the database can be used for integrated water resource management.

To improve and manage the progress made by increased access to water through private supply. The private-sector involvement in providing improved potable water in the area should be encouraged

and regulated through public-private partnerships (PPP). The partnership agreement can be such that the private investors must be licensed and can serve as social enterprises in the water supply value chain, and be monitored to guarantee safety in the drinking water they supply. The private businesses can invest in the decentralized water treatment infrastructure that can treat, and distribute the abstracted groundwater in the neighbourhoods, where the groundwater vulnerability is high as shown in the map e.g the DMZs. The authorities can be involved by providing or improving the existing water distribution infrastructure to transfer metered-treated water to nearby households at a regulated and subsidized fee. This can reduce government spending in the sector and encourage competition in the water supply business in the area. This will safeguard the public health of the people living around the DMZs in the short run.

11.2.3 Ensuring safe private supply for drinking water sources

The groundwater pH (3.7 – 5.6) is acidic and this means that the groundwater is soft, and has a high tendency to mobilize metal ions such as Mn, Zn, Pb, Cu, Fe, and other toxic substances from the environment, as well as plumbing fittings into the drinking water. Further, the pH range can impact a taste or cause the water to lose its aesthetic value or cause health concerns through toxic metal poisoning in the drinking water source. Therefore, the groundwater pH must be corrected to the pH range recommended by the WHO and/or the NIS standard for drinking water quality with the use of neutralizers. Appropriate doses of soda-lime (sodium bicarbonate) or caustic soda solutions or tablets. The neutralizers can be installed through an inline system between the pump, and the storage tank inlet point to correct the pH of the groundwater as soon as it is pumped out of the underground.

Naturally, bacterial microorganisms are not found in the groundwater unless there is a direct human influence that affects the natural background conditions. The results of the bacteriological assessment of drinking water sources revealed that some samples of the natural (groundwater and the Aba River) source water contain indicator organisms, including *E. coli*. To ensure the biological wholesomeness in drinking water sources, it is important to put some measures in place to stop the microbial contamination of the water sources meant for drinking. Therefore, microbiological treatment of natural water sources must be disinfected if it will be used for drinking, and/or other domestic uses such as handwashing and cooking. The following disinfection methods can be used to kill harmful micro-organisms in the drinking water:

- roll-boiling of the water at least for one minute is the simplest way to ensure that the microorganisms in the water are killed. Sometimes this method can be time-consuming, and comes with extra cost for the energy required to heat the water, or acquiring special heating and cooling equipment to actualize microbiologically free, safe and palatable drinking water.

- The use of chlorine tablets is one of the quickest, and effective ways of disinfecting the drinking water from bacterial, and/or viral contamination. Chlorine tablets can be used to disinfect the natural water both from surface and underground sources. However, high concentrations of chlorine residue in water have been linked to some health complications such as irritation of the oesophagus, burning sensation in the throat and can cause cancer of the bladder. In addition, it can also cause the corrosion of the plumb fitting in water infrastructures.
- Other easier and safer methods to disinfect the water source include passing the drinking water through a permanent point-of-entry disinfection unit installed on the line such as ozone or ultraviolet light for bacteriological treatment.

11.2.4 Enforcing safe separation distance between the origin of contaminants and water sources

The bacteriological evaluation of drinking water sources revealed that some groundwater samples taken from wells closed to septic tank drains were found to contain *E-coli* bacteria. This means that the proximity of wells meant for domestic, and drinking purposes has a direct relationship with the probability of being contaminated. Therefore, siting of wells for domestic water supply must always be supervised by the accredited agencies from the ministries of health and environment. The code of practice for water well construction recommended in SON 2010 define the safe separation distances between the proposed site for the drilling of tube wells and the possible contamination sources, which translates to the minimum source protection zone SPZ I¹⁹ radius. The separation distances between contamination sources and water wells in Nigeria are summarized in Table 11-1.

Table 11-1: Minimum siting distance of wells from potential contamination sources (modified from SON, 2010)

Contamination sources	Minimum separation distance (m)
Septic drain field	35
Septic tanks	20
Drain field system with more than 10,000 L/day of sewage inflow	100
Permanent building or structure	3
Livestock pen	75
Approved solid waste dump including the burial ground	1000

A re-evaluation and enforcement of these separation distances should apply to all the domestic wells in the densely residential areas. This is because the groundwater reservoirs within the residential

¹⁹ Source protection zone SPZ I otherwise known as the inner zone is defined as the distance or time demarcating a groundwater abstraction equipment from animals and human activities to prevent pollution of the aquifer. Borrow-pits

blocks are strongly influenced by septic tank drain fields, and maintaining such separation distances might be impossible in some cases. Therefore, wells that do not meet this minimum condition might be required to be re-installed into safer areas for the interest of public health.

Another setback in the implementation of the safe separation distance between domestic wells, and contamination sources is the abuse, and lack of strict compliance to the city master plan around the densely, and commercial built-up areas. For instance, the “sanitary lane” is a uniformly earmarked area within residential blocks for the construction of septic tanks in the main town area. But, it has been observed that some corrupt city town planning officials approve the construction of illegal structures in this zone, or property-owners do not adhere to the proper siting of septic drain construction in the area. Currently, this is why septic tanks arrangement in most parts of the area are haphazard, and in some cases, the construction of both septic tanks and borehole wells lying side by side has been observed. In such a situation, there is no guarantee to public health, and drinking water safety is compromised. Emphasis should be placed on restoring and enforcing the sanitary lanes in the densest residential area. Hence, local authorities and local drillers must cooperate to ensure tube wells construction will happen only in safe and approved zones within the residential areas.

11.2.5 Implementing zoning practices using the thematic decision support management tool

The zoning of land use activities is one way to protect different environmental aspects, especially groundwater. Since groundwater is the main source of drinking water, the quality must remain potable and safe for public consumption in the area. To achieve this, the local authority must construct monitoring wells, equally distributed throughout the priority DMZs, and routinely test the water quality to control pollution in the zone. Besides, monitoring of quality indicators and other forms of quality surveillance activities should be integrated into the program. The monitoring of the depths to water-table elevation can be included as part of taking stock of the groundwater usage in the controlled zone. These practices will help to check both the quality and quantity of the groundwater in the area and guarantee the safety of the source water to the general public, who depends on it for drinking and domestic purposes.

The average water consumption per capita of households in the study area was estimated to be relatively low compared to the UN’s recommendation for water sufficiency limit as shown in Aba. Therefore, the Federal state of Abia in Nigeria has proposed investments in new water schemes to upgrade, and expand the existing water utility infrastructure. When the project is implemented, this will improve the availability of potable water supplies for domestic use to the growing population in the study area. The thematic management tool developed in this study proposed a possible location (i.e., the NWS zone) where the construction of waterworks projects can be situated.

Other poor environmental practices of interest observed in the area that required proper include the use of borrow-pit as refuse dumpsites for municipal solid waste management has been observed and identified in the potential contamination hotspot map. This practice is a matter of environmental convenience and mediocrity in the management of solid wastes in the study area. Currently, there is no sanitary landfill, refuse separation and other waste management facilities in the area to adequately manage municipal solid waste. Therefore, the local authority may consider siting, and constructing a sanitary landfill, in the area where the aquifer vulnerability is suitable. This could be areas in the moderate aquifer zones outside the DMZs and the NWS source protected areas. The construction should be located in the appropriate zone based on the decision-support management tool and must follow the separation distance recommendation from any producing wells as listed in Table 11-1. The site location must also be far away from the densely built-up areas, as such to avoid interfering with the aquifers of the residential wells.

Again, the use of the septic tank in the area is another important land use practice that has a direct impact on the quality of the groundwater. Septic drains form part of the recharge system for the groundwater in the densely built-up residential parts of the study area and the hydrochemical and microbial results revealed that it contributes to the composition changes in the hydrochemistry of the groundwater and bacteriological integrity. Therefore, the municipal council should consider upgrading the existing sewerage infrastructure in the area. The construction of decentralized wastewater treatment units must be considered to handle the domestic effluents sewerage system in densely residential areas. All industrial activities which will pose threats to the water resource should be zoned outside the source protected area. All large-scale industrial manufacturing activities must be mandated as part of the licencing criteria to have a wastewater/effluent treatment unit in their master plan. This is to ensure that process effluents, including stormwater runoff from the facilities, are properly treated before they are discharged to the environment.

11.3 Limitations and research outlook

Despite the limitations observed in this research, for which some have been highlighted in the previous chapters. It is, therefore, necessary to see these limitations as gains because they have opened windows of research opportunities for further investigations in the study area. Some of these opportunities are knowledge gaps yet to be filled and needed for better understanding, as well as management of the water resource in the area. If this knowledge is developed, it can be transferred to other developing countries where similar hydrogeological and urban settings prevail.

One of the limitations can be narrowed down to the choice of the study area. The study area for this research has been considered a political boundary, and this can be seen as a limitation. Rather, a

hydrological catchment of the area should be delineated and considered in future. Because of the constraint financial budget, the political boundary of Aba was considered as the study area. This is due to prior knowledge and other affiliations to the area. However, the concepts and frameworks developed in this research can be replicated for the regional catchment as the boundary. This is important since the regional basin host other major urban areas such as economic capitals like Port Harcourt, Uyo and Owerri, with high population densities, similar urbanization trends and physiological features like Aba. Further studies on the catchment delineation and implementation of the decision support management tools can be pursued to effectively managed and protect the groundwater resources in the region.

To effectively understand and evaluate the water resource potentiality within the region, a detailed investigation of the different hydrologic components for the study area must be carried out. This will involve the accurate modelling of the storm run-off and the net groundwater recharge rate. The results can be compared with other classical approaches. Further estimations of other components of the hydrologic balance within the region can be performed. The knowledge of the water potentiality in the area will assist the relevant authorities to have a better understanding of the water situation to support a regional integrated water resource management.

It is important to develop a comprehensive drinking water management plan that ensures the sustainable use of the groundwater. The context of this study has set a backdrop, which needs to be followed to guarantee proper groundwater management strategies and protects the groundwater from contamination hotspots, as well as regulate the abstraction demands in the area. This means defining source protection zones for water extraction activities and implement appropriate zoning of urban land use around a defined pump field. The regulation will imply that only harmless activities to the groundwater must be allowed to take place within the correct number-of-days-line protection (in Germany 50 days-line source protection) around the zone of influence of the pumps, which will be estimated. To achieve this, extended hydrogeological investigations must be performed to estimate important aquifer features (hydrogeological and hydraulic parameters) specific to the area. These features include the geometry of the aquifer boundaries, groundwater flow regime, recharge and other social features etc, which must be established. With such information, it will be easy to calculate and define the zones of influence of the pumps using simple empirical hydrogeological equations. This approach will support the relevant authority to protect the pump fields from hotspot contaminations.

To completely comprehend the origin and evolutionary trends in the hydrochemistry of the urban groundwater system in the area, and correlate the discrepancy in the water types reported in this study, it is important to differentiate the proportion of the major ions stemming from the host

minerals and the surrounding. To achieve this will require a detailed geochemical investigation r using the stable isotope tracers to explore the influence of urban land use on the chemistry of the groundwater. The investigation will also consider the different artificial groundwater recharging sources in the area such as the use of the septic tanks and cesspools for managing residential effluents especially in the densely built-up parts of the study area.

Finally, the suitability of the NWS zone in the current thematic decision support management tool might be misleading since the selection criteria were primarily based on the DRASTIC-P_a model. Currently, the poor environmental practices in the area around this zone revealed activities that can directly harm the quality of the groundwater, as has been observed in the chemical and bacteriological investigations. Therefore, further investigations are required to improve and revise the DRASTIC-P_a model. When this is realized, the delineated NWS zone can be finalized, and this will help redefine the source protected area that will be used as a pump field to abstract groundwater to be used in the proposed waterworks project for the area.

List of references

- Abaji, F. A., & Nwankwoala, H. O. (2018). Characterization of Aquifer in parts of Abia State Southeastern Nigeria. *Earth Sci Pakistan*. doi:10.26480/esp.01.2018.18.22
- Abbasi, T., & Abbasi, S. (2012). *Water Quality Indices*. Amsterdam: Elsevier B.V.
- accepta. (2017). *Private water supplies- wells, springs, boreholes*. Retrieved December 12, 2019, from <https://accepta.com/environmental-water-wastewater-knowledge/water-treatment-knowledge/280-private-water-supplies-wells-springs-boreholes>
- Adams, R. (2013). *Water-table elevation and depth to the water table*. Minnesota: Minnesota Department of Natural Resources.
- Adamu, N., Ezeribe, I. E., & Oyediji, O. A. (2019). *Engineering properties of the soils around Aba, Southeast Nigeria*. Retrieved Nov 11, 2019, from Academia: https://www.academia.edu/8259145/Engineering_properties_of_the_Soils_around_Aba_South_East_Nigeria
- Adejuwon, J. O. (2012). Rainfall seasonality in the Niger Delta belt, Nigeria. *J. Geo. regional planning*. doi:10.5897/JGRP11.096
- Adelana, S. (2006). Nitrate pollution of groundwater in Nigeria. In Y. Xu, & B. Usher, *Groundwater Pollution in Africa* (pp. 37- 46). London: CRC Press.
- Adimalla, N., & Li, P. (2018). Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. *Human and Ecological Risk Assessment: An International Journal*. doi:10.1080/10807039.2018.1480353
- Adindu, R. U., Onyekachi, C. T., Kalu, E. T., & Amos, U. (2013). Infiltration characteristics of soils of some selected schools in Aba, Nigeria. *Appl Sci Res*, 11-15.
- Adomako, D., Maloszewski, P., Stumpp, C., Osae, S., & Akiti, T. T. (2010). Estimating groundwater recharge from water isotope ($\delta^2\text{H}$, $\delta^{18}\text{O}$) depth profiles in the Densu River basin, Ghana. *Hydrol Sci J.*, 1405-1416. doi:10.1080/02626667.2010.5
- Agharanya, U. P., & Dim, C. I. (2018). Water quality assessment and resource potentials: the case of Aba–urban and its environs, Niger Delta Basin. *Wat Res J.*, 250-267.
- AGW-Net. (2015). Module 5: Groundwater monitoring and information management. In V. Vaessen, & R. Brentführer (Eds.), *Integration of groundwater management into transboundary basin*

- organizations in Africa* (pp. 100-114). AGW-Net. Retrieved March 30, 2020, from https://www.bgr.bund.de/EN/Themen/Wasser/Politikberatung_GW/Downloads/Module_5.pdf?__blob=publicationFile&v=5
- Agwu, A., Avoaja, A. G., & Kalu, A. U. (2013). The Assessment of drinking water sources in Aba metropolis, Abia State, Nigeria. *Res Environ J.*, 72-76.
- Akakuru, O., Akudinobi, B. E., & Usman, A. O. (2017). Organic and heavy metal assessment of groundwater sources around Nigeria National Petroleum Cooperation Oil Depot Aba, Southeast Nigeria. *J Nat Sci Res.*
- Akinde, S. B., Nwachukwu, M. I., & Ogamba, A. S. (2011). Storage effects on the quality of sachet water produced within Port Harcourt metropolis, Nigeria. *Jordan J. Biol Sci*, 157 - 164.
- Akoteyon, I. S., Balogun, I. I., & Soneye, A. S. (2018). Integrated approaches to groundwater quality assessment and hydrochemical processes in Lagos, Nigeria. *Appl wat sci*, 1-19. doi:10.1007/s13201-018-0847-y
- Akoteyon, I. S., Omotayo, A. O., Soladoye, O., & Olaoye, H. O. (2011). Determination of water quality index and suitability of urban river for municipal water supply in Lagos Nigeria. *European J. Sci Res*, 54(2), 263-271.
- Akpa, S. I., Odeh, I. O., Bishop, T. F., & Hartemink, A. E. (2014). Digital mapping of soil particle-size fraction. *Soil Sci. Soc. Am. J*, 1953–1966. doi:10.2136/sssaj2014.05.0202
- Akpabio, E. M. (2012, July). Water supply and sanitation service sector in Nigeria: the policy trend and practice constraints. (M. D.-K. Joachim von Braun, Ed.) *working Paper Series 96*.
- Akpokodje, E. G., & Etu-Efeotor, J. O. (1987). The occurrence and economic potential of clean sand deposit of the Niger Delta. *J. African Earth Sci*, 61-65.
- Alich, A., Asana, I., Aghomishe, M. O., & Aiyegbusi, S. (2010). Hydrogeochemical characteristics and groundwater quality assessment in Aba metropolis, Southeastern Nigeria. *Annual Conference of the Nigerian Association of Hydrogeologists on water resources development and climate change*, (p. 30).
- Aller, L., Bennett, T., Lehr, J. H., Petty, R., & Hackett, G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. *Res Dev*.
- Amadi, A. N. (2012). Quality assessment of Aba River using heavy metal pollution index. *American J Environ Eng*, 45-49.

- Amadi, A. N., Olasehinde, P. I., Nwankwoala, H. O., Dan-Hassan, M. A., & Okoye, N. O. (2014). Aquifer vulnerability studies using the DRASTICA model. *Int J. eng sci invention*, 2319 – 6726.
- Amadi, A. N., Olasehinde, P. I., Yisa, J., Okosun, E. A., Nwankwoala, H., & Alkali, Y. B. (2012). Geostatistical assessment of groundwater quality from coastal aquifers of eastern Niger Delta, Nigeria. *Geosci*, 2(3), 51-59.
- Amadi, A., Olasehinde, P., & Yisa, J. (2009). Evaluation of groundwater quality in Aba metropolis Southeastern Nigeria using factor analysis. *Chemclass Journal*, 80-89.
- Amajor, L. (1991). Aquifers in the Benin formation (Miocene-Recent) eastern Niger Delta, Nigeria: lithostratigraphy, hydraulics, and water quality. *Environ Geol Wat Sci*, 85-101.
- Ambituuni, A., Hopkins, P., Amezaga, M., Werner, J., & Wood, J. (2015). Risk assessment of petroleum product pipeline in Nigeria: the realities of managing problems of theft/sabotage. Retrieved 07 24, 2019, from https://www.researchgate.net/publication/276058686_Risk_Assessment_Of_A_Petroleum_Product_Pipeline_In_Nigeria_The_Realities_Of_Managing_Problems_Of_Theftsabotage
- Amfo-Otu, R., Agyenim, J. B., & Nimba-Bumah, G. B. (2014). Correlational analysis of groundwater colouration from mountainous areas, Ghana. *Environ Res Eng Manag*, 16–24 .
- Aminu, M., & Olorunniwo, M. (2002). Seismic paleo-geomorphic system of the extensional province of the Niger Delta: an example of the Okari field. InTECH. doi:10.5772/48197
- Anabella, F., Martin, S. T., Eugenia, A., & Alberto, F. (2014). Assessment, monitoring and protection of groundwater pollution in urban areas - Cordoba City - Argentina. *European Sci J*. Retrieved December 27, 2019, from <https://paperity.org/p/59153437/assessment-monitoring-and-protection-of-groundwater-pollution-in-urban-areas-cordoba-city>
- Andersen, B. C. (2015). *Re: Can anyone tell me how to do ionic balance for water samples?* Retrieved from https://www.researchgate.net/post/Can_anyone_tell_how_to_do_ionic_balance_for_water_samples/559cdc246225ffc6e08b45fb/citation/download
- Andres, L., Chellaraj, G., Gupta, B. D., Grabinsky, J., & Joseph, G. (2018). *An evaluation of the contributing factors of water scheme failures in Nigeria*. World Bank Group.
- Aravin, V., & Numerov, S. (1953). *Theory of motion of liquids and gases in undeformable porous media*. Moscow: Gostekhizdat.

- Back, W. (1966). Hydrochemical facies and ground-water flow patterns in the northern parts of the Atlantic coastal plain. *Geological Survey Professional Paper*, 498-A. Retrieved from <https://pubs.usgs.gov/pp/0498a/report.pdf>
- Balakrishnan, P., Saleem, A., & Mallikarjun, N. D. (2011, December). Groundwater quality mapping using geographic information system (GIS): A case study of Gulbarga City, Karnataka, India. *African J. environ sci and tech*, 5(12), 1069-1084. doi:10.5897/AJEST11.134
- Banda, L. J., Mbewe, A. R., Nzala, S. H., & Halwindi, H. (2014). Effect of siting boreholes and septic tanks on groundwater quality in St. Bonaventure township of Lusaka district, Zambia. *Intl J. Env. Sci. Tox.*
- Barcelona Field Studies Centre. (2019, November). *Measuring Slope Steepness*. Retrieved April 15, 2020, from GeographyFieldwork.com: <https://geographyfieldwork.com/SlopeSteepnessIndex.htm>
- Barrett, M. H., & Howard, A. G. (2002). Urban groundwater and sanitation - developed and developing countries. In K. Howard, & R. Israfilov, *Current problems of hydrogeology in urban areas, urban agglomerates and industrial centre* (pp. 39 - 56). Dordrecht: Springer.
- Barrett, M. H., Johal, K., Howard, G., Pedley, S., & Nalubega, M. I. (2000). Sources of faecal contamination of shallow groundwaters in Kampala. *XXXth International-Association-of-Hydrogeologists Congress on Groundwater: Past Achievements and Future Challenges*. Cape Town.
- Bartram, J., Corrales, L., Davison, A., Deere, D., Drury D, G. B., . . . Steven, M. (2009). *Water safety plan manual: step-by-step risk management for drinking water suppliers*. Geneva: WHO.
- Batabyal, A. K., & Chakraborty, S. (2015, July). Hydrogeochemistry and water quality index in the assessment of groundwater quality for drinking use. *Wat Environ Res*, 87(7), 607-617. doi:10.2175/106143015X14212658613956
- Bazimenyera, J., & Zhonghua, T. (2008). A GIS-based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Hangzhou–Jiaxing–Huzhou Plain, China. *Res J. Appl Sci*, 550–559.
- Berkowitz, B., Dror, I., & Yaron, B. (2014). Characterization of the subsurface environment. In *Contaminant geochemistry* (pp. 3-28). Berlin Heidelberg: Springer-Verlag.
- Berlin.de. (2011). *Groundwater temperature*. Retrieved August 09, 2018, from https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/e_text/eka214.pdf

- Beven, K. J., Kirkby, M. J., Schofield, N., & Tagg, A. F. (1984). A physically based flood forecasting model (TOPMODEL) for three UK catchments. *J Hydrol*, 119-143.
- Brassington, R. (2017). *Field hydrogeology*, Chichester: Wiley.
- Carvajal-Vélez, L., Amouzou, A., Perin, J., Maïga, A., Tarekegn, H., Akinyemi, A., . . . Newby, H. (2016). Diarrhoea management in children under five in sub-Saharan Africa: does the source of care matter? a countdown analysis. *BMC Public Health*. doi:10.1186/s12889-016-3475-1
- Chadha, D. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. *Hydrogeol J.*, 7, 431– 439.
- Chae, G.-T., Yun, S.-T., Kim, K., & Mayer, B. (2005). Hydrogeochemistry of sodium-bicarbonate type bedrock groundwater in the Pocheon spa area, South Korea: water-rock interaction and hydrologic mixing. *J. Hydrol*, 326-343. doi:10.1016/j.jhydrol.2005.08.006
- Chandra, D. S., Asadi, S. S., & Raju, M. V. (2017, April). Estimation of water quality index by weighted arithmetic water quality index method: a model study. *Int J. Civil Eng Tech*, 8(4), 1215-1222.
- Chikezie, I. A., Eswaran, H., Asawalam, D. O., & Ano, A. O. (2010). Characterization of two benchmark soil of contrasting parent material in Abia State, Southeastern Nigeria. *Global J Pure Appl Sci*, 16(1), 23-29. Retrieved from www.library.wur.nl/WebQuery/file/isric/fulltext/isricu_t4d550810_001.pdf
- Chukwu, O., Adeoye, P. ., & Chidiebere, I. (2011). Abattoir wastes generation, management and the environment: a case of Minna, North-central Nigeria. *Int J Biosci*, 100 - 109.
- Cissé Faye, S., Faye, S., Wohnlich, S., & Gaye, C. (2004). An assessment of the risk associated with urban development in the Thiaroye area, Senegal. *Environ Geol*, 312–322.
- Civita, M. (1994). *Contamination vulnerability mapping of the aquifer: theory and practice*. Pitagora: Quaderni di Tecniche di Protezione Ambientale.
- Clapham, D. (2010, May). *Householders' guide to private water supplies*. Bucks: Foundation for water research. Retrieved from <http://www.fwr.org/waterq/frg0007.pdf>
- Combalicer, E. A., Lee, S. H., Ahn, S., Kim, D. Y., & Im, S. (2008). Comparing groundwater recharge and base flow in the Bukmoongol small-forested watershed, Korea. *J. Earth Syst. Sci.*, 553–566.
- Dawoud, M. A. (2004). Design of national groundwater quality monitoring network in Egypt. *Environ Monit Assess*, 99–118. DOI: <https://doi.org/10.1023/B:EMAS.0000031718.98107.eb>

- de Ridder, N. A. (1994). Groundwater investigation. In H. Ritzema (Ed.), *Drainage Principles and Applications* (2nd ed., pp. 33-74). Wageningen: International institute for land reclamation and improvement (ILRI).
- Diaw, M. T., Cisse, S., Taylor, R., Gaye, C. B., Niang, S., & Campos, L. C. (2019). The relationship between on-site sanitation density and shallow groundwater quality: evidence from remote sensing and in situ observations In Dakar, Senegal. *Groundwater quality conference*. Liege.
- Doerfliger, N., Jeannin, P. Y., & Zwahlen, F. (1999). Water vulnerability assessment in Karstic environment: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Env Geol*, 165-176.
- Dörfliger, N., & Zwahlen, F. (1998). *Practical guide: Groundwater vulnerability mapping in Karstic Regions (EPIK)*. Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL).
- Drinking water inspectorates (d.w.i). (2018, November). *Private water supply in England and Wales*. Retrieved from <http://www.dwi.gov.uk/private-water-supply/>
- DWI. (2016, Aug). *Keeping your private water supply safe*. Retrieved Dec 1, 2016, from dwi.defra.gov.uk/consumers/advice-leaflets/pws.pdf
- Edet, A. (2014). An aquifer vulnerability assessment of the Benin Formation aquifer, Calabar, southeastern Nigeria, using DRASTIC and GIS approach. *Environ Earth Sci*, 1747–1765.
- Edet, A., Nganje, T. N., Ukpong, A. J., & Ekwere, A. S. (2011). Groundwater chemistry and quality of Nigeria. *African J Environ Sci-Tech*, 1152-1169.
- Egboka, B. C., Nwankwor, G. I., Orajaka, I. P., & Ejiofor, A. O. (1989). Principles and problems of environmental pollution of groundwater resources with case examples from developing countries. *Environ Health Perspectives*, 39-68.
- Egborge, A. B., & Benka-Coker, J. (1986). Water quality index: application in the Warri River, Nigeria. *Environ Pol Series*, 12(1), 27 - 40. doi:10.1016/0143-148X(86)90004-2
- Eludoyin, O., & Adelekan, I. (2013). The physiologic climate of Nigeria. *Int J Biometeorol*, 241–264. doi:<https://doi.org/10.1007/s00484-012-0549-3>
- El-Wahed, M. H., & El-Mageed, T. A. (2014). Estimating reference evapotranspiration using modified Blaney-Criddle equation in an arid region. *Bothalia Journal*, 183-195.
- Emeribeole, A. C., & Iheaturu, C. J. (2016). Land use/ Landcover detection dynamics in urban sprawl movement (A case study of Owerri, Imo State Nigeria). *Int J. Res Emerging Sci. Tech*, 54 - 60.

- Environment Agency. (2019). *Groundwater protection: policy and practice, Part 3 - tools*. Retrieved 10 30, 2019, from www.environment-agency.gov.uk:
<https://www.croydon.gov.uk/sites/default/files/articles/downloads/part3gp3.pdf>
- Enyidi, U. D. (2017). Potable water and national water policy in Nigeria (A historical synthesis, pitfalls and the way forward). *J. Agr Econ Rural Dev*, 190-202.
- ESDAC (European Soil Data Centre). (1990). *Soils map of Nigeria*. Retrieved from European Commission Joint Research Centre:
https://esdac.jrc.ec.europa.eu/images/Eudasm/Africa/images/maps/download/afr_ngsms1.jpg
- Etim, E. E., Odoh, R., Itodo, A. U., Umoh, S. D., & Lawal, U. (2013). Water quality index for the assessment of water quality from different sources in the Niger Delta region of Nigeria. *Frontiers in Sci*, 3(3), 89-95. doi:10.5923/j.fs.20130303.02
- European Economic Community. (1980). *Council Directive Relating to the Quality of Water Intended for Human Consumption (80/778/EEC)*. European Union.
- FAO. (2003). *Review of world water resources by country*. Rome: FAO. Retrieved from Review of world water resources by country: <http://www.fao.org/3/y4473e/y4473e08.htm#TopOfPage>
- FAO. (2016). *AQUASTAT - FAO's Global Information System on water and agriculture*. Retrieved December 8, 2019, from <http://www.fao.org/aquastat/en/overview/methodology/water-use>
- FAO. (2018). *Progress on level of water stress - Global baseline for SDG 6 indicator 6.4.2 2018*. Rome: FAO/UN-Water.
- Fareze, L., Rajaobelison, J., Ramaroson, V., & Vallet-Coulomb, C. (2016). Origin and recharge estimation of groundwater using chemistry and environmental isotopes in the Mahafaly sedimentary aquifer District of Betioky Southwestern Madagascar. *Res J, Earth Sci*, 19 - 27.
- Fashae, O. A., Ayorinde, H. A., Olusola, A. O., & Obateru, R. O. (2019). Land use and surface water quality in an emerging urban city. *Appl Wat Sci*, 9-25.
- Faye, S. C., Pouye, A., Diaw, M. T., Diedhiou, M., Gaye, C. B., & Taylor, R. G. (2019). The Impacts of on-site sanitation on groundwater quality In the unconfined Thiaroye aquifer of Dakar, Senegal. *Groundwater Quality Conference*. Liege.
- Fernández, N., Ramírez, A., & Solano, F. (2004). Physicochemical water quality indices - a comparative review. *Geo J*. doi:10.24054/01204211.v1.n1.2004.9

- Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: a review of global issues. *Int. J. Environ. Res. Public Health*. doi:10.3390/ijerph16061060
- FEWS NET. (2016, 06 01). *Nigeria special report: visualizing trend in 1981 to 2015 rainfall in Nigeria*. Retrieved 03 03, 2020, from https://fews.net/sites/default/files/documents/reports/FEWS%20NET_Nigeria%20Rainfall%20Trends%20Map%20Book_20160601.pdf
- FGN. (2004). *National water policy*. Retrieved August 12, 2019, from <http://extwprlegs1.fao.org/docs/pdf/nig158231.pdf>
- FGN. (2011, May 24). National environmental (Surface and Groundwater quality control) regulations. *Federal Republic of Nigeria official gazette, 98(49)*, pp. 693-727.
- Fianko, J. R., Nartey, V. K., & Donkor, A. (2010). The hydrochemistry of groundwater in rural communities within the Tema District, Ghana. *Environ Monit Assess*(168), 441–449. doi:10.1007/s10661-009-1125-0
- Foster, S. (1987). Fundamental concept in aquifer vulnerability, pollution risk and protection strategy. In V. Duijvenbooden, & H. G. Waegeningh, *Vulnerability of soil and groundwater to pollutions* (pp. 69-86). Hague: Committee on Hydrogeological Research.
- Foster, S., Hirata, R., Misra, S., & Garduño, H. (2010). *Urban water use policy: balancing the benefits and risks in developing nations*. Worldbank.
- Geere, J. (2016, Mar 12). *Access to safe drinking water: challenges and opportunities for improving global health*. Retrieved from Fair Observer: https://www.fairobserver.com/more/global_change/access-safe-drinking-water-challenges-opportunities-improving-global-health-32394/
- Gemechu, D. (1977). *Aspects of climate and water budget in Ethiopia*. Addis Ababa: Addis Ababa University Press.
- GeographyFieldwork.com. (2019). *Measuring slope steepness*. Retrieved September 30, 2019, from Barcelona field study centre: <https://geographyfieldwork.com/SlopeSteepnessIndex.htm>
- Gibbs, R. J. (1970, December 4). Mechanisms controlling world water chemistry. *Sci*, 170, 1088 - 1090.
- Gleick, P. H. (1996). Water resources. In S. H. Schneider, *Encyclopedia of climate and weather* (pp. 817-823). New York: Oxford University Press.
- Gomez-Plaza, A., Martinez-Mena, M., Albaladejo, J., & Castillo, V. M. (2001). Factors regulating the spatial distribution of soil water content in small semiarid catchments. *J. Hydrol.*, 211–226.

- Gross, G. (1991). Das Klima der Stadt. In K. Hutter (Ed.), *Dynamik Umweltrelevanter Systeme* (pp. 271 - 289). Berlin: Springer.
- Gwimbi, P., George, M., & Ramphalile, M. (2019). Bacterial contamination of drinking water sources in rural villages of Mohale Basin, Lesotho: exposures through neighbourhood sanitation and hygiene practices. *Environ Health Prev Med*. doi:10.1186/s12119
- Hamutoko, J. T., Wanke, H., Koeniger, P., Beyer, M., & Gaj, M. (2017). Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etосha Basin, Namibia. *Isotopes in Environ and health studies*, 53(4), 382–399. doi:10.1080/10256016.2016.1273913
- Hassall, C. (2014). The ecology of urban ponds. *WIREs Water*, 187-206.
- Hassane, A. B., Leduc, C., Favreau, G., Bekins, B. A., & Margueron, T. (2016). Impacts of a large Sahelian city on groundwater hydrodynamics and quality: example of Niamey (Niger). *Hydrogeol J.*, 407–423.
- Hayward, D., & Oguntoyinbo, J. S. (1987). *Climatology of West Africa*. New Jersey: Barnes & Nobles Books.
- Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed.). United States Government printing office.
- Hölting, B., & Coldewey, W. G. (2019). *Hydrogeology*. Berlin: Springer Nature. doi:https://doi.org/10.1007/978-3-662-56375-5
- Horton, R. (1965). An index number system for rating water quality. *J Wat Poll Control Federation*, 37 (3), 300-306.
- Howard, K. (2002). Urban groundwater issues- An introduction. In K. W. Howard, & R. G. Israfilov, *Current problems of hydrogeology in urban areas, urban agglomerates and industrial centre* (pp. 1-12). Dordrecht: Springer Science+Business Media B.V.
- Hughes, D. A. (2019). Facing a future water resources management crisis in sub-Saharan Africa. *J. Hydrol: regional studies*. doi:10.1016/j.ejrh.2019.100600
- Hunter, P. R., MacDonald, A. M., & Carter, R. C. (2010). Water supply and health. *PLoS Med* . doi:10.1371
- Hwang, J. Y., Park, S., Kim, M.-S., J, H.-J., G.–M. L., Jeon, S. H., . . . Kim, H.-K. (2017). Applications of hydrochemical models for groundwater in Korea. *Environ Nat Resources Res*, 7(3), 51-69.

- lasija, M. (2012). What are the main causes of groundwater pollution? Retrieved February 8, 2018, from www.preservearticles.com/201101072821/causes-of-groundwater-pollution.html
- Ibe, K. M., Nwankwo, G. I., & Onyekuru, S. O. (2003). Groundwater pollution vulnerability and groundwater protection strategy for the Owerri area, Southeastern Nigeria. *Water Resources Systems—Water Availability and Global Change*. Sapporo: IAHS Publ.
- Ighariemu, V., Belonwu, D. C., & Wegwu, M. O. (2019). Level of petroleum hydrocarbons in water and sediments of Ikoli creek Bayelsa State Nigeria. *Toxicol Environ Health Sci.*, 114-119.
- Ijeh, I. B. (2013). Determination of the vulnerability of water supply aquifers in parts of Imo River Basin, South-eastern Nigeria: The case of Benin formation. *Int J. Modern Eng Res*, 291-295.
- Ismail, A. H., & Robescu, D. (2019). Assessment of water quality of the Danube River using water quality indices technique. *Env Eng Mgt J.*, 1727- 1737.
- Ita, E. (1993). Inland fishery resources of Nigeria. *CIFA Occasional Paper No. 20*. Rome: FAO. Retrieved from <http://www.fao.org/docrep/005/T1230E/T1230E02.htm#ch2>
- Ite, A. E., Harry, T. A., Obadimu, C. O., Asuaiko, E. R., & Inim, I. J. (2018). Petroleum hydrocarbons contamination of surface water and groundwater in the Niger Delta Region of Nigeria. *J. Environ Pollution and Human Health*, 51-61.
- Jang, W. S., Engel, B., Harbor, J., & Theller, L. (2017). Aquifer vulnerability assessment for sustainable groundwater management using DRASTIC. *Water*. doi:10.3390/w9100792
- Jasem, A. H. (2010). Assessing groundwater vulnerability in the Azraq basin area by a modified DRASTIC index. *J Wat Res and Protection*.
- Jhariya, D. C., Kumar, T., Pandey, H. K., Kumar, S., Kumar, D., Gautam, A. K., . . . Kishore, N. (2019). Assessment of groundwater vulnerability to pollution by modified DRASTIC model and analytic hierarchy process. *Environ Earth Sci*. doi:10.1007/s12665
- Jinno, K., Tsutsumi, A., Alkaeed, O., Saita, S., & Berndtsson, R. (2009). Effects of land use change on groundwater recharge model parameters. *Hydrol. Sci. J.*, 300-315. doi:10.1623/hysj.54.2.300
- Kazeem, Y. (2018, June 25). *Nigeria has become the poverty capital of the world*. Retrieved December 14, 2019, from Quartz: <https://qz.com/africa/1313380/nigerias-has-the-highest-rate-of-extreme-poverty-globally/>
- Ketata, M., Gueddari, M., & Bouhlila, R. (2012). Use of geographical information system and water quality index to assess groundwater quality in El Khairat deep aquifer (Enfidha, Central East Tunisia). *Arab J Geosci*, 1379–1390.

- Knutsson, G. (1994). Acidification effects on groundwater - prognosis of the risks for the future. *Future groundwater resources at risk (Proceedings of the Helsinki conference, June 1994)*. 222. Helsinki: IAHS.
- Koc,er, M. A., & Sevgili, H. (2014). Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. *Ecol Indicators*, 672– 681.
- Kot-Wasik, A. (2007). *Parameters of natural water*. Retrieved from Water quality control: Part 2: www.pg.gda.pl/chem/Dydaktyta/Analityczna/WQC/wqc_p2.pdf
- Kumar, A., & Krishna, A. P. (2019). Groundwater vulnerability and contamination risk assessment using GIS-based modified DRASTIC-LU model in hard rock aquifer system in India. *Geocarto International*. doi:10.1080/10106049.2018.1557259
- Kumar, M., & Puri, A. (2012). A review of permissible limits of drinking water. *Indian J Occup Environ Med*, 40-44. doi:10.4103/0019-5278.99696
- Kumar, N., Reddy, A., Reddy, R. M., & Srinivas, V. K. (2009). Preliminary investigation of groundwater quality in Hyderabad City Andhra Pradesh India. *Int J Chem Sci*, 59-70.
- Kwani, I., Ishaku, J. M., Bello, A. M., Yusuf, A., Abubakar, U., & Mukkafa, S. (2018). Assessment of water quality index for groundwater in Gombe and environs, North-east Nigeria. *IOSR J. Appl Geo & Geophysics*, 29 -37.
- Lapworth, D. J., Nkhuwa, D. C., Okotto-Okotto, J., Pedley, S., Stuart, M. E., Tijani, M. N., & Wright, J. (2017b). Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. *Hydrogeol J*. doi:10.1007/s10040-016-1516-6
- Lapworth, D. J., Stuart, M. E., Pedley, S., Nkhuwa, D. C., & Tajani, M. N. (2017a). *A review of urban groundwater use and water quality challenges in Sub-Saharan Africa*. Nottingham: British Geological Survey Open Report.
- Lawrence, P., Meigh, J., & Sullivan, C. (2002). The water poverty index: an international comparison. *Keele Econ Res papers*. Staffordshire: Keele University. Retrieved Dec 9, 2018, from www.keele.ac.uk/depts/ec/web/wpapers/kerp0219.pdf
- Leis, A. (2018, June 25). *Introduction to hydrogeochemical data evaluation and modelling (AquaChem, Phreeqc) - Part 1*. Retrieved from http://www.hwe.org.ps/Projects/Training/Groundwater%20Wells/presentations/Introduction%20to%20hydrochemical%20data%20evaluation_01.pdf

- Lekwa, G., & Whiteside, E. (1986). Coastal plain soil of south-eastern Nigeria: I. morphological classification and genetic relationships. *Soil Sci. Am. J.*, 154-160.
- Lerner, D. N., & Harris, B. (2009). The relationship between land use and groundwater resources and quality. *Landuse policy*, 265–273.
- Lewis, W. J., Foster, S. S., & Drasar, B. S. (1980). *The risk of groundwater pollution by on-site sanitation in developing countries: a literature review*. Dübendorf: International reference centre for wastes disposal.
- Linglu Qu, H. X., Nengjian Zheng, Z., & Zhang, Y. X. (2017, January). Comparison of four methods for spatial interpolation of estimated atmospheric nitrogen deposition in South China. *Environ Sci Poll Res*, 24(3), 2578–2588.
- Lohmann and Rauscher. (2019). *Escherichia coli*. Retrieved July 16, 2019, from hygiene in practice: <https://www.hygiene-in-practice.com/pathogen/escherichia-coli-en/>
- Macheve, B., Danilenko, A., Abdullah, R., Bove, A., & Moffitt, L. J. (2015). *State water agencies in Nigeria: a performance assessment*. Washington, DC: World bank. doi:10.1596/978-1-4648-0657-5
- Mackey, B. G. (1994). Predicting the potential distribution of rainforest structural characteristics. *J. Vegetation Sci.*, 43–54.
- Mallin, M. A. (2009). Effect of human development on water quality. In S. Ahuja (Ed.), *Handbook of water purity and quality* (pp. 67-94). IWA Publishing.
- Marthews, T. R., Dadson, S. J., Lehner, B., Abele, S., & Gedney, N. (2015). High-resolution global topographic index values for use in large-scale hydrological modelling. *Hydrol. Earth Syst. Sci.*, 91–104.
- Massmann, G., Nogeitzig, A., Taute, T., & Pekdeger, A. (2008). Seasonal and spatial distribution of redox zones during lake bank filtration in Berlin, Germany. *Environ. Geol*, 53-65.
- McCauley, A., Jones, C., & Olson-Rutz, K. (2017, March). *Nutrient management modules*. Retrieved from Montana State University: <http://landresources.montana.edu/nm/documents/NM8.pdf>
- McIntosh, A. C. (2003). *Asian water supplies: reaching the urban poor*. London: IWA.
- Meagher, K. (2013, June 28). *Water privatization: risks and benefits*. Retrieved December 12, 2019, from The systems of exchange: www.systemsofexchange.org/casestudies/effective-water-privatization

- Menberg, K., Blum, P., Kurylyk, B. L., & Bayer, P. (2014). Observed groundwater temperature response to recent climate change. *Hydrol. Earth Syst. Sci*, 18, 4453–4466.
- Mgbolu, C. C., Obiadi, I. I., Obiadi, C. M., Okolo, C. M., & Rumhe, P. E. (2019). Integrated groundwater potentials studies, aquifer hydraulic characterisation and vulnerability investigations of parts of Ndokwa, Niger Delta basin, Nigeria. *Solid Earth Sci*, 102-112.
- Misstear, B., Banks, D., & Clark, L. (2006). *Water wells and boreholes*. West Sussex: John Wiley & Sons.
- Mogaji, K. A., Lim, H. S., & Abdullar, K. (2014). Modelling groundwater vulnerability to pollution using Optimized DRASTIC model. *Earth Environ Sci*. doi:10.1088/1755-1315/20/1/012002
- Moore, P., & John, S. X. (1990). *SEEPAGE: A System for Early Evaluation of the Pollution Potential of Agricultural Groundwater Environments*. Chester, USA: Geol Tech; USDA, SCS, Northeast Technical Center.
- Moustafa, M. (2019). Assessing perch aquifer vulnerability using modified DRASTIC: a case study of colliery waste in North-east England (UK). *Hydrogeol. J*, 1837 - 1850.
- Mukherjee, S., Mukherjee, S., Garg, R. D., Bhardwaj, A., & Raju, P. L. (2013). Evaluation of topographic index in relation to terrain roughness and DEM grid spacing. *J. Earth Syst. Sci*, 869 - 886.
- Nas, B., & Berktaş, A. (2010). Groundwater quality mapping in urban groundwater using GIS. *Environ Monit Assess*, 160, 215–227. doi:10.1007/s10661-008-0689-4
- Nations Encyclopedia. (2019). *Nigeria-Topography*. Retrieved December 10, 2019, from <https://www.nationsencyclopedia.com/Africa/Nigeria-TOPOGRAPHY.html>
- NBS. (2009). Social statistics of Nigeria. *Part III: Health, employment, public safety, population and vital registration*.
- NBS. (2012). Social statistics in Nigeria. *Part III: Health, employment, public safety, population and vital registration*.
- Nganje, T. N., Hursthouse, A. S., Edet, A., Stirling, D., & Adamu, C. I. (2017). Hydrochemistry of surface water and groundwater in the shale bedrock, Cross River basin and Niger Delta region, Nigeria. *Appl Wat Sci*, 961–985. doi:10.1007/s13201-015-0308-9
- Njoku, J. D., Amangabara, G. T., & Duru, P. N. (2013). Spatial assessment of urban flood risks in Aba Metropolis, using geographical information systems technique. *Global Advanced Res J Env Sci Tox.*, 86-92.

- Nkemdirim, V. U., Alozie, G. C., & Ike, F. (2016). Spatial analysis of the quality of groundwater supply: evidence from Abia State. *Am J Wat Resources*, 83-90.
- Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2016). A review and critical analysis of the efforts towards urban flood risk management in the Lagos region of Nigeria. *Nat. Hazards Earth Syst. Sci*, 349–369.
- Nolan, B. T., Healy, R. W., Taber, P. E., Perkins, K., Hitt, K. J., & Wolock, D. M. (2007). Factors influencing groundwater recharge in the Eastern United States. *J. Hydrol.*, 187–205.
- Nwachukwu, M. A., & Nwachukwu, M. I. (2016). Model of a secure landfill using abandoned mine pit - technical and economic imperatives. *J Solid Waste Tech Manag*, 173-183.
- Nwagbara, M. O., & Okwuonu, I. E. (2016). Mapping of flood-prone areas in parts of Osisioma Ngwa local government area of Abia State, Southeast Nigeria. *J Sustainable Dev in Africa*, 64-76.
- Nwankwoala, H. (2015). Hydrogeology and groundwater resources of Nigeria. *New York Sci J*, 89 -100.
- Nwankwoala, H., & Warmate. (2014). Geotechnical evaluation of subsoil for foundation design considerations in Okochiri, Okrika Island, Rivers State, Nigeria. *Int. J. Curr. Res. Aca.Review*, 16-25.
- Nzeadibe, T. C., & Anyadike, R. N. (2012). Social participation in city governance and urban livelihoods: constraints to the informal recycling economy in Aba, Nigeria. *City, Culture and Society*, 313–325.
- Nzung'aSila, O. (2019). Physico-chemical and bacteriological quality of water sources in rural settings, a case study of Kenya, Africa. *Sci African*. doi:10.1016/j.sciaf.2018.e00018
- O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., & McMillan, S. (2010). Urbanization effects on watershed hydrology and in-stream processes in the Southern United States. *Water*, 2(3), 605–648. doi:10.3390/w2030605
- Obeta, M. C. (2019). Private for-profit rural water supply in Nigeria: policy constraints and options for improved performance. *J Wat Land Dev*, 101–110. doi:10.2478/jwld-2019-0033
- Ocheri, M. I., Odoma, L. A., & Umar, N. D. (2014). Groundwater quality in Nigerian urban areas: a review. *Global J Sci Frontier Res*, 35-45.
- Ogbonna, C., Ike, F., & Okwu-Delunzu, V. (2015). Spatial assessment of flood vulnerability in Aba Urban using Geographic Information System technology and rainfall information. *Int. J. Geosci*, 191-200. doi:10.4236/ijg.2015.63013

- Ogbonna, C., Ike, F., & Okwu-Delunzu, V. (2015). Spatial assessment of flood vulnerability in Aba urban using geographic information technology system and rainfall information. *Int J Geosci*, 191-200.
- Ogunba, A. (2011). *Nigeria's new environmental laws: what is the implications for groundwater protection and sustainability*. IUCNAEL. Ottawa: University of Ottawa. Retrieved from www.iucnael.org/en/documents/1009-adebola/file
- Ogunsanwo, O. (2002). Effect of inundation on the geotechnical properties of some Soils from parts of Southwestern Nigeria. *J. Min Geol.*, 38(1), 57-63.
- Olaniyan, S. O., Adeyemi, A. S., & Adeleke, W. O. (2016). Determination of shelf-life of selected sachet water in Ogbomosho, Oyo State Nigeria. *FUOYE J. Eng Tech.*
- Omalu, I. C., Eze, G. C., Olayemi, I. K., Gbesi, S., Adeniran, L. A., Ayanwale, A. V., . . . Chukwuemeka, V. (2010). Contamination of sachet water in Nigeria: assessment and health impact. *Online J Health & Allied Sci*, 1 - 3.
- Oni, O., & Fasakin, O. (2016). The use of water quality index method to determine the potability of surface water and groundwater in the vicinity of a municipal solid waste dumpsite in Nigeria. *Am J Eng Res*, 5 (10), 96-101.
- Onyeagocha, A. (1980). Petrography and depositional environment of the Benin Formation, Nigeria. *Journ. Min. Geol.*, 17, 147-151.
- Ophori, D. U. (2007). A simulation of large-scale groundwater flows in the Niger Delta, Nigeria. *Environ Geosci*, 181–195. doi:10.1306/eg.05240707001
- Oteze, G. (1981). Water resources in Nigeria. *Environ Geol*, 177 - 184.
- Owoyemi, A. O. (2005, November 01). *Sequence stratigraphy of Niger Delta, Delta field, offshore Nigeria*. Retrieved from Texas A&M Libraries: <https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/2768/etd-tamu-2004B-GEOL-Owoyemi.pdf?sequence=1&isAllowed=y>
- Palaniappan, M., Gleick, P. H., Hunt, C., & Srinivasan, V. (2004). Water privatization principles and practices. In P. Gleick, N. L. Cain, D. Haasz, C. Henges-Jeck, C. Hunt, M. Kiparsky, & M. P. Marcus Moench, *The world's water 2004-2005*. Washington: Island Press.
- Panagos, P., Jones, A., Bosco, C., & Senthil, K. P. (2011). Soil map of Nigeria based on C.C.T.A, in European digital archive on soil maps (EuDASM): Preserving important soil data for public free

- access. *International Journal of Digital Earth*, 434 - 443. Retrieved from https://esdac.jrc.ec.europa.eu/ESDB_Archive/EuDASM/Africa/lists/s1_cng.htm
- Papaioannou, K. J. (2016). Climate shocks and conflict: evidence from colonial Nigeria. *Political Geography*, 33–47.
- PennState. (2019). *Distribution of water on the earth's surface*. Retrieved December 15, 2019, from Earth in the future: <https://www.e-education.psu.edu/earth103/node/701>
- Pierce, S. A., Sharp, J. M., & Eaton, D. J. (2016). Decision support systems and processes for groundwater. In A. J. Jakeman, O. Barreteau, H. R. J., J. D. Rinaudo, & A. Ross, *Integrated groundwater management*. Cham: Springer.
- Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water analyses. *Trans A. M Geophys Union*, 25, 914 – 923.
- Popescu, I., Brouyère, S., & Dassargues, A. (2019). The APSÛ method for process-based groundwater vulnerability assessment. *Hydrogeol J*. doi:10.1007/s10040-019-02013-z
- PopulationLabs. (2011). *Nigerian population map*. Retrieved from Experimenting with Population Data: www.populationlabs.com/nigeria_population.asp
- Rawat, K. S., & Singh, S. K. (2018). Water quality indices and GIS-based evaluation of decadal groundwater quality. *Geol Ecol Landscapes*, 240 - 255. doi:10.1080/24749508.2018.1452462
- Reijers, T. J. (2011). Stratigraphy and sedimentology of the Niger Delta. *Geologos*, DOI: 10.2478/v10118-011-0008-3.
- Ridder, N. A. (1994). Groundwater investigation. In H. P. Ritzema, *Drainage principles and applications* (2 ed.). Wageningen: International institute for land reclamation and improvement (ILRI).
- Rusydi, A. F. (2018). Correlation between conductivity and total dissolved solids in various types of water: a review. *IOP Conf Ser.: Earth Environ Sci*. IOP Publishing. doi:10.1088/1755-1315/118/1/012019
- Saatsaz, M., Sulaiman, W. N., Eslamian, S., & Mohammadi, K. (2011). GIS DRASTIC model for groundwater vulnerability estimation for groundwater of Astaneh-Kouchesfahan Plain, Northern Iran. *Int. J. Wat*.
- Saghir, J., & Santoro, J. (2018, April). *Urbanization in sub-Saharan Africa: meeting challenges by bridging stakeholders*. Retrieved from https://csis-prod.s3.amazonaws.com/s3fs-public/publication/180411_Saghir_UrbanizationAfrica_Web.pdf?o02HMOFqh99KtXG6ObTacIKKmRvk0Owd

- Saito, T., Hamamoto, S., Ueki, T., Ohkubo, S., Moldrup, P., & Kawamoto, K. (2016). Temperature change affected groundwater quality in a confined marine aquifer during long-term heating and cooling. *Wat Res*, 120–127.
- Schoeller, H. (1965). Qualitative evaluation of groundwater resources. In *methods and techniques of ground-water investigations and development*. UNESCO, 54-83.
- Secunda, S., M. L. Collin, & Mellou, A. J. (1998). Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region. *J Environ Manag*, 39–57.
- Şen, Z. (2015). Groundwater management. In Z. Sen, *Practical and applied hydrogeology*. Amsterdam: Elsevier. doi:10.1016/B978-0-120800075-5.01001-3
- Shell-BP. (1957). Nigerian Geological Series: Umuahia Sheet 79. *Nigeria geological map 250000*. Geological Survey of Nigeria.
- Shirazi, S., H. M. Imran, & Akib, S. (2012). GIS-based DRASTIC method for groundwater vulnerability assessment: a review. *J. risk res*, 991-1011. doi:10.1080/13669877.2012.686053
- Singh, A., Srivastav, S. K., Kumar, S., & Chakrapani, G. J. (2015.). A modified-DRASTIC model (DRASTICA) for assessment of groundwater vulnerability to pollution in an urbanized environment in Lucknow, India. *Environ Earth Sci*, 5475–5490.
- SIWI. (2005). *Making water a part of economic development: The economic benefits of improved water management and services*. Retrieved July 25, 2020, from https://www.who.int/water_sanitation_health/waterandmacroecon.pdf
- Smedley, P. (2003). Groundwater quality: Nigeria. 1-9. Retrieved from <http://nora.nerc.ac.uk/516320/1/Nigeria.pdf>
- SON. (2007). *Nigerian standard for drinking water quality, NIS 554:2007*. Lagos: Standard Organization of Nigeria.
- SON. (2010). *Code of practice for water well construction (NCP 027: 2010)*. Lagos: Standard Organization of Nigeria.
- Sorensen, J. P., Lapworth, D. J., Read, D. S., Nkhuwa, D. C., Bell, R. A., Chibesa, M., . . . Pedleye, S. (2015). Tracing enteric pathogen contamination in sub-Saharan African groundwater. *Sci Total Environ*, 888- 895.
- Stuart, M. E., Manamsa, K., Talbot, J. C., & Crane, E. J. (2011). *Emerging contaminants in groundwater*. Nottingham: British Geological Survey.

- Tatlock, C. W. (2006). *Water stress in sub-Saharan Africa*. Retrieved from <https://www.cfr.org/backgrounder/water-stress-sub-saharan-africa>
- Thompson, T., Fawell, J., Kunikane, S., Jackson, D., Appleyard, S., Callan, P., . . . Kingston, P. (2007). *Chemical safety of drinking water: assessing priorities for risk management*. Geneva: WHO Press.
- Tijani, M. N., Crane, E., Upton, K., & Dochartaigh, B. (2015, 09 22). *Hydrogeology of Nigeria*. Retrieved from Earthwise: http://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Nigeria#Soil
- Tijani, M., Crane, E., Upton, K., Ó Dochartaigh, B., & Bellwood-Howard, I. (2018). *Africa groundwater atlas: hydrogeology of Nigeria*. Retrieved January 14, 2020, from British Geological Survey: <http://earthwise.bgs.ac.uk/index.php/Hydrogeology>
- Tiwari, T., & Mishra, M. (1985). A preliminary assignment of water quality index to major Indian Rivers. *Indian J Environ Protection*, 276 - 279.
- Todd, D. K. (1980). *Groundwater hydrology*. New York: Wiley.
- Tombul, M. (2007). Mapping field surface soil moisture for hydrological modelling. *Wat Resource Manag*, 1865–1880.
- Toumi, N., Hussein, B. H., Rafrafi, S., & Kassas, N. E. (2015). Groundwater quality and hydrochemical properties of Al-Ula region, Saudi Arabia. *Environ Monit Assess*, 187(84), 1-16. doi:10.1007/s10661-014-4241-4
- Trading Economics. (2019). *GDP Africa*. Retrieved December 9, 2019, from <https://tradingeconomics.com/country-list/gdp?continent=africa>
- Tukimat, N. N., Harun, S., & Shahid, S. (2012). Comparison of different methods in estimating potential evapotranspiration at Muda Irrigation Scheme of Malaysia. *J. Agri. and Rural Dev in the Tropics and Subtropics*, 77-85.
- Tyagi, S., Sharma, B., Singh, P., & Dobhal, R. (2013, August). Water quality assessment in terms of water quality index. *Am J Wat Resources*, 1(3), 34-38. doi:10.12691/ajwr-1-3-3
- Ukandu, J. S., Udom, G. J., & Nwankwoala, H. O. (2011). Hydrochemistry of groundwater in Umuahia South Local Government Area, Abia State, Nigeria. *British J. Appl Sci & Tech*, 141-151.
- Ukpong, E. C., Udo, E. A., & Umoh, I. C. (2015). Characterization of material from Aba waste dumpsites. *Int J Eng and Appl Sci*, 1-10.

- UN. (2015). *Human rights to water and sanitation media brief*. Retrieved July 28, 2019, from https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf
- UN. (2018, June 4). *Making water a human right*. Retrieved from United Nations Regional Information Centre for Western Europe: <https://www.unric.org/en/water/27360-making-water-a-human-right>
- UNDP. (2018, 09). *Sustainable development goals Goal 6: clean water and sanitation*. Retrieved from <http://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-6-clean-water-and-sanitation.html>
- UNICEF. (2019, June). *Drinking water*. Retrieved Dec 10, 2019, from UNICEF Data: <https://data.unicef.org/topic/water-and-sanitation/drinking-water/>
- UNICEF. (2019, June). *Drinking water*. Retrieved from UNICEF Data: Monitoring situation of children and women: <https://data.unicef.org/topic/water-and-sanitation/drinking-water/>
- UNwater. (2015). *Wastewater management – an UN-Water analytical brief*. Retrieved from <https://www.unwater.org>: <https://www.unwater.org/publications/wastewater-management-un-water-analytical-brief/>
- UNwater. (2018). *Water, Sanitation and Hygiene*. Retrieved August 07, 2018, from <http://www.unwater.org/water-facts/water-sanitation-and-hygiene/>
- US Census Bureau. (2019, December 9). *U.S. Census bureau current population*. Retrieved December 9, 2019, from <https://www.census.gov/popclock/print.php?component=counter>
- van der Aa, N. G. (2003). Classification of mineral water types and comparison with drinking water standards. *Environ Geol*, 44, 554–563.
- Van Stempvoort, D., Evert, L., & Wassenaar, L. (1993). Aquifer vulnerability index: a GIS compactable method for groundwater vulnerability mapping. *Can Water Res J*, 25–37.
- Vias, J. M., Andrco, B., Perles, M., Carrasco, F., Vadillo, I., & Jimenez, P. (2006). Proposed method of groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Applications in two pilot sites in southern Spain. *Hydrogeol J*, 912–925.
- VWR (BDH) Chemical. (2019, June 18). *CCA Coliforms chromogenic agar (ISO)*. Retrieved from https://www.reactivosparadiagnostico.com/customers/viewTDS.php?file=175452ZA_EN.pdf&id=a9ad911cf8515a6601994ef63d09fe13278bf66011372e2

- Wallick, E., & Toth, J. (1976). Methods of regional groundwater flow analysis with suggestions for the use of environmental isotopes. In *Interpretation of environmental isotope and hydrochemical data in groundwater hydrology* (pp. 37-64). Vienna: International Atomic Energy Agency (IAEA).
- WaterAid. (2019). *Nigeria*. Retrieved December 2019, 2019, from <https://www.wateraid.org/uk/where-we-work/nigeria>
- Weber, H. (1928). *Die Reichweite von Grundwasserabsenkungen mittels Rohrbrunnen*. Berlin: Julius Springer.
- Western, A., Grayson, R. B., Blöschl, G., Willgoose, G. R., & McMahon, T. A. (1999). Observed spatial organization of soil moisture and its relation to terrain indices. *Wat Resour Res.*, 797–810.
- Wheaton, R. M., & Lefevre, L. J. (2018). *Dowex Ion exchange resins: fundamentals of ion exchange*. Retrieved from http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0032/0901b803800326ca.pdf?filepath=liquidseps/pdfs/noreg/177-01837.pdf&fromPage=GetDoc
- WHO. (2001). Guidelines: the current position. In L. Fewtrell, & J. Bartram, *Water Quality: Guidelines, Standards and Health* (pp. 18 - 42). London: IWA Publishing.
- WHO. (2003). *Total dissolved solids in drinking-water: background document for development of WHO guidelines for drinking-water quality*. Retrieved August 2018, from http://www.who.int/water_sanitation_health/dwq/chemicals/tds.pdf
- WHO. (2011a). *Guidelines for drinking-water quality*. Geneva, Switzerland: WHO Press.
- WHO. (2011b). *Manganese in drinking water*. Geneva: WHO Press.
- WHO. (2018, November 18). *E. Coli*. Retrieved December 2, 2019, from <https://www.who.int/news-room/fact-sheets/detail/e-coli>
- WHO. (2019). *Water sanitation hygiene: key facts from JMP 2015 reports*. Retrieved December 12, 2019, from https://www.who.int/water_sanitation_health/monitoring/jmp-2015-key-facts/en/
- WHO/UNICEF. (2017). *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. (A. Grojec, Ed.) Geneva: World Health Organization. Retrieved from <http://apps.who.int/iris/bitstream/handle/10665/258617/9789241512893-eng.pdf?sequence=1>

- WHO/UNICEF. (2019). *Progress on household drinking water, sanitation and hygiene 2000-2017: special focus on inequalities*. Retrieved from https://www.who.int/water_sanitation_health/monitoring/jmp04_2.pdf
- World Bank. (2017). *A wake-up call: Nigeria water supply, sanitation, and hygiene poverty diagnostic. WASH Poverty Diagnostic*. Washington, DC: World Bank.
- World Bank. (2018, Dec 18). *Nigeria*. Retrieved from The World Bank Data: <https://data.worldbank.org/country/nigeria>
- World Bank. (2019). *Sub-Saharan Africa*. Retrieved December 10, 2019, from <https://data.worldbank.org/region/sub-saharan-africa>
- World Resource Institute. (2019). *Aqueduct country rankings*. Retrieved December 9, 2019, from <https://www.wri.org/resources/websites/aqueduct-country-rankings>
- Worldbank. (2015). *Improved water source (Percentage population with access)*. Retrieved November 16, 2015, from The World Bank - IBDR.IDA: <http://data.worldbank.org/indicator/SH.H2O.SAFE.ZS>
- Wright, J. B., Hastings, D. A., Jones, W. B., & Williams, H. R. (1985). *Geology and mineral resources of West Africa*. London: George Allen and Unwin.
- Wright, J., Gundry, S., & Conroy, R. (2004). Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Tropical Med Int Health*, 106-117.
- WWAP (United Nations World Water Assessment Programme). (2015). *The United Nation world water sustainable development report 2015: Water for a sustainable world*. Paris: UNESCO.
- Xercavins, J. (1999, Dec 14). Carrying capacity in East Sub-Saharan Africa: a multilevel integrated assessment and a sustainable development approach. *Doctoral thesis*. Catalunya, Spain: Universitat Politècnica de Catalunya. Retrieved Dec 14, 2018, from <https://www.tesisenred.net/handle/10803/6987?show=full&locale-attribute=en>
- Yidana, S. M., & Yidana, A. (2010). Assessing water quality using water quality index and multivariate analysis. *Environ Earth Sci*, 1461-1473.
- Zaidi, F. K., Mogren, S., Mukhopadhyay, M., & Ibrahim, E. (2016). Evaluation of groundwater chemistry and its impact on drinking and irrigation water quality in the eastern part of the Central Arabian graben and trough system, Saudi Arabia. *J. Afr Earth Sci*, 120, 208-219.
- Zoungrana, B.-B., Conrad, C., Amekudzi, L., Thiel, M., Da, E., Forkuor, G., & Löw, F. (2015). Multi-temporal Landsat images and ancillary data for land use/cover change (LULCC) detection in the Southwest of Burkina Faso, West Africa. *Remote Sensing*, 12076-12102.

Appendix 1

Survey instrument template for different stakeholders

Household Questionnaire

Part A

Preamble

This household questionnaire is designed to collect primary data on some information related to the current state of drinking water delivery in Aba city Nigeria. It seeks to investigate some factors affecting the quality of the main drinking water source and particularly, develop strategies that will help to protect and manage the groundwater as a drinking water source.

You have been selected randomly as one of the persons to participate in this survey. All information received from you in this exercise will be used for academic purposes and the findings of this research will be used to develop decision support tools to help create groundwater protection and management policies in Aba. This will help in ensuring drinking-water safety and improve sustainable development in Aba.

Do you consent to participate in this research? [_____] [YES = 1, NO = 0]. If NO, move to the next household

Location ID		
GPS Coordinate		
Latitude	Longitude	Accuracy (m)

Enumerator ID	
Date (DD/MM/YY):	Sign

Household profile

Household size		Age distribution		Employment Status		Education level	
2-3	<input type="checkbox"/>	18– 25	<input type="checkbox"/>	Employed	<input type="checkbox"/>	No education	<input type="checkbox"/>
3-4	<input type="checkbox"/>	26- 30	<input type="checkbox"/>	Unemployed	<input type="checkbox"/>	Primary	<input type="checkbox"/>
5-6	<input type="checkbox"/>	31– 40	<input type="checkbox"/>	Gender		Secondary	<input type="checkbox"/>
>6	<input type="checkbox"/>	41– 50	<input type="checkbox"/>	Male <input type="checkbox"/>	Female <input type="checkbox"/>	Tertiary	<input type="checkbox"/>
		>50	<input type="checkbox"/>				

Section A1

Main Sources of Drinking water

In this part of the survey, a classified list of possible drinking water sources will be presented to respondents to select. The perception of respondents will be used to evaluate their choice of water source and the quality of the water source that they have chosen. The questionnaire queries awareness of some physical quality indicators of the water sources, as well as identify some activities including land use types that could be a source of potential contamination to the main water source in the area. Furthermore, the questionnaire will answer the question of whom the main providers of water services are and the availability of the chosen water source in the area.

Check the appropriate box, which represents your main source of drinking water from the table below. On the comment column, rank the water sources in the order of priority should more than one choice applies using numerals starting with the main source and followed by the alternative source

Q1.1. How do you get your drinking water?					
Source (Improved)	Code	Comment	Source (Unimproved)	Code	Comment
Piped water <input type="checkbox"/>	PW		Unprotected dug well <input type="checkbox"/>	DW (U)	
Tube well/Borehole <input type="checkbox"/>	TW/B		Unprotected spring <input type="checkbox"/>	SprgW(U)	
Protected spring <input type="checkbox"/>	SpgW(P)		Water from vendors in tankers/cart with drums <input type="checkbox"/>	V_W	
Rainwater <input type="checkbox"/>	RW		Surface water (River, Dam, Lake, Pond, stream, canal) <input type="checkbox"/>	SW	
Bottled water <input type="checkbox"/>	BW		Sachet water <input type="checkbox"/>	PkgW	
Others, please mention					

Q1.2. Are there times in the year when you cannot access the drinking water for the above choice?		
NO, I have regular access <input type="checkbox"/>	YES, I have access seasonally <input type="checkbox"/>	NO, I do not have access <input type="checkbox"/>

Q1.3. Who provides your main source of drinking water.				
Government <input type="checkbox"/>	Community <input type="checkbox"/>	Donor agents <input type="checkbox"/>	Self <input type="checkbox"/>	Others <input type="checkbox"/>

Please mention, if others..... Go to Q1.4 if the Government

Q1.4. How will you score the government supply services in your area?		
Good <input type="checkbox"/>	Fair <input type="checkbox"/>	Poor <input type="checkbox"/>

If poor go to Q1.5, otherwise move to the next section.

Q1.5. Do you know the reason(s) why the public water supply in your area is no longer operational?			
Government decision <input type="checkbox"/>	Infrastructural inadequacy <input type="checkbox"/>	Bad management/ lack of maintenance of the facility <input type="checkbox"/>	Others <input type="checkbox"/>

Section A2

Quality Awareness

The respondents were asked questions to find out their perception of the quality of their drinking water sources. Later in this investigation, ground-water samples will be taken for analysis to draw the quality baseline, as well as correlate the quality to land use activities that can influence negatively on the quality.

Q2.1. Main water source code [_____]									
PW	TW/B	SprgW(P)	RW	BW	DW (U)	SprgW(U)	V_W	SW	PkgW

Q2.2. Do you treat your water source before use? YES <input type="checkbox"/> NO <input type="checkbox"/> I can't say <input type="checkbox"/>

Q2.3. If YES, who provides the treatment?			
Responsible authority <input type="checkbox"/>	Water vendor (provider) <input type="checkbox"/>	Self <input type="checkbox"/>	I cannot say <input type="checkbox"/>

Q2.3.1. If self? Why do you pre-treat before use?		
Improve appearance (clarity) <input type="checkbox"/>	Health reasons <input type="checkbox"/>	Others <input type="checkbox"/>

Q2.4. Do you perform any treatment on your water before drinking? Yes <input type="checkbox"/> No <input type="checkbox"/>

Q2.4.1. If YES, what type of pre-treatment do you use?	Remark
Sieving or filtration	<input type="checkbox"/>
Boiling	<input type="checkbox"/>
Addition of chemical substance (alum / Disinfectants) before use	<input type="checkbox"/>
Others, please mention.....	<input type="checkbox"/>

Q2.5. Please select appropriately the quality, which describes your drinking water source.				
Parameter				
Turbidity (Clarity)	Q2.5.1. Does the water look clear?			
	Colourless <input checked="" type="checkbox"/>	Rusty <input type="checkbox"/>	Milky <input type="checkbox"/>	Others <input type="checkbox"/>
Taste	Q2.5.2. Does the water have a taste?			
	Tasteless <input type="checkbox"/>	Salty <input type="checkbox"/>	Chalky <input type="checkbox"/>	Others <input type="checkbox"/>
Odour	Q2.5.3. Does the water have an odour?			
	Yes <input type="checkbox"/>		No <input type="checkbox"/>	
Hardness	Q2.5.4. If you use the water for bathing or washing, do you require plenty of soap?			
	Yes <input type="checkbox"/>		No <input type="checkbox"/>	
pH	Q2.5.5. When you store the water in a metallic container, does the container corrode easily?			
	Yes <input type="checkbox"/>		No <input type="checkbox"/>	

Section A3

Contamination Sources

The table below provides a list of some land use types that can be a potential source of contamination, particularly to groundwater. Please, check any land use type(s) that can be found close to your drinking water source selected in QA1.

Q3.1. Is anyone of the following land use activities situated close to your main water source?		
Contamination sources	Tick selection	Remark
Dumpsite / solid waste leachate	<input type="checkbox"/>	
Underground storage (fuel storage tanks, etc.)	<input type="checkbox"/>	
Inefficient discharge of domestic wastewater with cesspits	<input type="checkbox"/>	
Use of unsealed septic tanks/ pit latrine close to the drinking water source	<input type="checkbox"/>	
Manufacturing factory/warehouse close to the residential area	<input type="checkbox"/>	
Use of Agrochemicals e.g. Fertilizers/pesticides, or effluents from fish farms/ compost and animal dungs	<input checked="" type="checkbox"/>	
Auto- garage and repair centres	<input type="checkbox"/>	
Others, please mention.....	<input type="checkbox"/>	

Do have worries about the state of the drinking water situation in Aba? Please comment on them

Section A4

Household water consumption pattern

What is the total water storage capacity in your household (litres)?				
20L <input type="checkbox"/>	50L <input type="checkbox"/>	200L (1Drum) <input type="checkbox"/>	400L (Drum x 2) <input type="checkbox"/>	> 2 Drums <input type="checkbox"/>

How many days do the water in your household storage last?				
1 <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	>4 <input type="checkbox"/>

How much do you pay to meet the domestic water needs of your household?

How much do you pay to meet the domestic water needs of your household?				
₦20 <input type="checkbox"/>	₦40 <input type="checkbox"/>	₦60 <input type="checkbox"/>	₦80 <input type="checkbox"/>	>₦80 <input type="checkbox"/>

Conversion rate: 1 Euro = 411.78 NGN (Nigerian Naira). Rate as of February 2019

When do you consume most water in your household?		
Rainy season <input type="checkbox"/>	Dry season <input type="checkbox"/>	The same both seasons <input type="checkbox"/>

Part B

Industry questionnaire

Scope

One of the objectives of this research is to identify some of the land use types that potentially harm groundwater quality. Consequently, industrial activities are one of such land use types and they are commonly found near Aba. In this section, the main source of water for the operations of the selected industrial, as well as their environmental performance to the groundwater shall be ascertained.

Respondent ID	
Name of Organization	Position held

Location ID		
GPS coordinate		
Latitude	Longitude	Accuracy (m)

Enumerator ID	
Date (DD/MM/YY)	Signature

Q1. What is the main source of water for your operations?

Surface water <input type="checkbox"/>	Groundwater <input type="checkbox"/>	Public water supply <input type="checkbox"/>	Others <input type="checkbox"/>
--	--------------------------------------	--	---------------------------------

Q1.1. If others, please mention.....

Please identify your main source of water by assigning numbers (1-4) in the order of ascending priority in the box provided, if more than one source prevails

Q2. If groundwater, how much water do you require for your daily operations?
Comments/ Remarks

Q3. Do you treat your effluents?	Yes <input type="checkbox"/>	No <input type="checkbox"/>	I cannot say <input type="checkbox"/>
Comments/ Remarks			

If YES, continue with the Q4, otherwise, go to Q5

Q4. Where do you discharge your effluents?			
Surface water <input type="checkbox"/>	Cesspit / underground <input type="checkbox"/>	Public sewerage <input type="checkbox"/>	Others <input type="checkbox"/>
If others, please mention.....			
Comments/ Remarks			

Q5. What do you produce in your facility?
Comments / Remarks

Q6. Where do you store your raw materials and the produced good (s)?				
Surface (protection barrier) <input type="checkbox"/>	Surface (without barrier) <input type="checkbox"/>	Underground (protection barrier) <input type="checkbox"/>	Underground (without barrier) <input type="checkbox"/>	Others <input type="checkbox"/>
If others, please mention.....				
Comments / Remarks				

Q7. How frequent, do you experience substance spillage in your facility that might leach underground?	Often <input type="checkbox"/>	Rarely <input type="checkbox"/>	N/A <input type="checkbox"/>
Comments / Remarks			

(Often = >1x per annum, rarely = 1x per 3year, N/A = Not applicable or never happened)

Q8. Do you control what you produce in the laboratory?	Yes <input type="checkbox"/>	No <input type="checkbox"/>	I cannot say <input type="checkbox"/>
Comments / Remarks			

If YES, proceed to Q9, else end the survey and thank the respondent for his/ her participation

Q9. How do you manage your laboratory effluents?
Comments / Remarks

Other relevant stakeholder interview template

Part C

Scope

In this part of the survey, respondents/interviewees were drawn from relevant organisations in Abia State, including government ministries and parastatals, Aba city authority, town planners, other private stakeholders and NGOs, to answer some of the following questions relating to the roles of the government to ensure that safe drinking water reaches the residents of Aba city. More so, to ascertain how potential contaminants capable of reaching the groundwater can be averted from prevailing land use activities.

Respondent ID:

Occupation / Position:

Industry type:

Enumerator ID	
Date (DD/MM/YY)	Signature

Q1. How do you rate your knowledge of this subject?			
Professional <input type="checkbox"/>	Intermediate <input type="checkbox"/>	Low <input type="checkbox"/>	I cannot say <input type="checkbox"/>

Q2. Which of the listed sources below is/are the main source(s) of drinking water in Aba? *Please prioritize the portability and availability of the source using numbers (1-10) in ascending order of priority*

Source (Improved)	Code	Comment	Source (Unimproved)	Code	Comment
Piped water (public/private) <input type="checkbox"/>	PW		Unprotected dug well <input type="checkbox"/>	DW (U)	
Tube well/Borehole <input type="checkbox"/>	TW/B		Unprotected spring <input type="checkbox"/>	SprgW(U)	
Protected spring <input type="checkbox"/>	SpgW(P)		Water from vendors in tankers/cart with drums <input type="checkbox"/>	V_W	
Rainwater <input type="checkbox"/>	RW		Surface water (River, Dam, Lake, Pond, stream, canal) <input type="checkbox"/>	SW	
Bottled water <input type="checkbox"/>	BW		Package water (a.k.a. pure water) <input type="checkbox"/>	PkgW	

Please mention any other source.....

Q3. What is the present state of the government / public water supply in Aba?
<u>Comment (s) / Remarks</u>

Q4. Can you comment on the state of distribution of the various water sources in different sections of Aba?
<u>Comment (s) / Remarks</u>

An Arial map / Street map of the Aba was provided for illustration during the interview

Q5. Do you know areas in Aba that are most challenged with drinking water supply? Can you indicate the problem areas using the map provided?
<u>Comment (s) / Remarks</u>

Please use the Arial map / Street map provided for this demonstration. If the respondent is not familiar with the situation proceed to Q6, else go to Q7

Q6. In your own opinion what may be the reason for the problem associated with water supply in the area?
<u>Comment(s) / Remarks</u>

Q7. Do you know how residents or industries in Aba discharge their effluent (household or trade)?	Yes <input type="checkbox"/>	No <input type="checkbox"/>	I cannot say <input type="checkbox"/>
---	------------------------------	-----------------------------	---------------------------------------

If YES, go to Q8, else proceed to Q9

Q8. If Yes, where do residents and/or industries in Aba discharge their effluents?				
Surface water <input type="checkbox"/>	Open surface drainage <input type="checkbox"/>	Cesspits / Underground <input type="checkbox"/>	Others <input type="checkbox"/>	I cannot say <input type="checkbox"/>
<i>If others, please mention.....</i>				
<u>Comment(s) / Remarks</u>				

Q9. In your own opinion, which of the following land use types pose the most threat to groundwater?
Comment (s) / Remarks

Support your comments in Q9 using the table provided below

Table: List of some identified land use types that can contaminate the groundwater

<i>Contamination sources</i>	<i>Tick selection</i>	<i>Comment</i>
Dumpsite / solid waste leachate	<input type="checkbox"/>	
Underground storage tank (fuel storage tanks, etc.)	<input type="checkbox"/>	
Inefficient discharge of domestic wastewater using cesspits	<input type="checkbox"/>	
Use of unsealed septic tanks/ pit latrine / Cesspit close to the drinking water source	<input type="checkbox"/>	
Manufacturing factory/chemical warehouse close to residential areas	<input type="checkbox"/>	
Use of Agrochemicals e.g. Fertilizers/pesticides, or effluents from fish farms/ compost and animal dungs	<input type="checkbox"/>	
Auto-garage and repair centres	<input type="checkbox"/>	
Please mention others	<input type="checkbox"/>	

In the comment column, rank the land use types with the number from 1 – 8 according to the weight of impact it has on the groundwater, with the one having the most impact assigned the least number (e.g. Dumpsite – 2, UST - 5, Domestic wastewater – 3)

Q 10. Are there complaints related to water-borne diseases prevalence in the area?
Comment (s) / Remarks

Thank you for your participation and we appreciate the time you invested in this survey

Appendix 2

Table A-2.1: Inventory of some urban land use contamination sources and some identified water quality indicators derived from the sources

Category	Urban sub-class	Source/product(s)	Potential contaminants
Petroleum (oil and gas) down-stream products, glass, personal care and cleansing, textile	Industrial	Fuel and mineral oil products, detergents and soaps, dye, glass bottles, food products, beverages, resins	pH, total petroleum HC (TPH), heavy metal (As, Cr, Cd, Pb, Zn, Fe, Sn), SO ₄ , NO ₃ , PO ₄ , BOD, organic solvents
Allied chemical, manufacturing and commercial	Industrial	Paints sludge and synthetic resins for paints, furniture finishing, leatherwork, paper, foam	Heavy metals (such as Cr, Cu, Cd, Ni, Pb, and Zn), halogenated solvents, styrene, ethylbenzene
Automobile sales, repair and services	Industrial/Residential	Fuel products and additives, mineral oil, paints, halogenated solvents, accumulator battery	pH, TPH, heavy metal (Pb, Cd, Zn) solvents (VOC)- BTEX
Medical health centres	Residential	Disinfection and preservation products, dental amalgam, general medical waste, radioactive waste from X-ray	Halogenated solvents, Formaldehyde and phenol expired medicine-steroids and hormones, photographic chemical and radionuclides, and soiled biological contaminants, Hg
Commercial/warehousing	Industrial	Chalk, gypsum, cement, Al/Zn sheets, Soda	pH, Ca, Mg, SO ₄ , Fe
White products and repairs	Residential	e-waste – CRT and fluorescent powder	Heavy metal – (Pb, Cd, Ba Al, Fe, Ni, Sn, Mn)
Gastronomy and fresh organic food market	Residential	Restaurants, food markets	Nitrogen (NO ₃ ⁻ , NH ₄ ⁺), Cl, BOD
Dumpsite	Residential	Municipal	Nutrient (NO ₃ , NH ₄), -PO ₄ , heavy metals (Zn, Pb, Ni, Cd, Hg etc.), microbial contamination,
Households	Residential	Leaky septic tanks, personal care products, medicines and fuel products,	Microbial - total coliform, Faecal Coli, E-Coli, nutrient – NO ₃ , Cl, PO ₄ , solvent, expired pharmaceuticals, TPH etc.

Appendix 3

Table A-3.1: Seasonal physicochemical and chemical quality data from laboratory test during rainy season (August-September 2017)

Loc ID	Well location description	Long DD	Lat DD	Temp (°C)	pH	ORP (meV)	EC (µS/cm)	TDS (mg/l)	T. Alk (mg/l)	HCO ₃ (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	PO ₄ (mg/l)	NO ₃ (mg/l)
LR	Umunkama Ovom Ogor-hill	7,41826	5,10175	27,2	4,6	147	20,9	13,6	20,0	24,3	5,9	1,4	-	0,01
LR	Umuchichi- Okpulumogbo	7,36045	5,14799	26,8	4,7	142	28,7	18,7	16,1	19,6	9,1	0,9	-	0,011
HR	Keystone1 - Umungasi	7,36204	5,12611	27,6	4	189	202,8	131,8	12,8	15,6	51,5	0,8	-	0,008
HR	Ukadike - Akoli	7,38908	5,08149	28,2	4	183	265,7	172,7	12,8	15,6	68,1	0,8	-	0,002
HR	Easy On filling station- Ngwa Road	7,37672	5,09912	27,8	3,9	187	310,3	201,7	9,5	11,5	81,8	0,8	-	0,006
LR	Pepples Road	7,38367	5,10826	27	5,2	113	27,6	18,0	17,5	21,3	2,6	0,4	-	0,015
LR	Alaoma Osisioma	7,32527	5,1434	27,4	5,3	101	28,3	18,4	21,6	26,4	9,8	0,4	-	0,011
LR	TLOP- Osisioma	7,32438	5,18881	27,4	4,8	133	28,3	18,4	19,3	23,5	8,5	1,0	-	0,008
LR	Ehere Ogor Off Ikot Ekpen Rd	7,40591	5,10849	26,7	5	128	32,6	21,2	11,6	14,1	5,2	1,0	-	0,004
HR	Ukata- Ukegbu	7,38806	5,11586	26,7	4,3	168	110,3	71,7	15,8	19,2	39,0	3,2	-	0,006
LR	Abayi Egbulegba	7,32549	5,11355	27,2	4,6	150	51,2	33,3	17,3	21,1	15,0	0,6	-	0,008
LR	LPG Plant - Alaoji	7,32843	5,07338	27,6	4,8	133	31,0	20,1	17,9	21,8	9,8	1,0	-	0,004
HR	Nwala - Faulks Road	7,34902	5,12313	26,8	3,9	188	400,0	260,0	18,9	23,0	95,0	0,8	-	0,01
LR	ABSUTH	7,34535	5,14801	27,6	4,8	125	29,1	18,9	20,0	24,3	6,0	2,1	-	0,09
HR	Azikiwe	7,36583	5,10868	28,2	4,8	186	291,7	189,6	16,8	20,5	78,0	1,4	-	0,079
HR	Osusu Road	7,35722	5,11324	28	4,8	96	397,2	258,2	18,0	22,1	84,0	1,9	-	0,051
HR	Omuma Road	7,35391	5,10786	28	4,8	155	342,3	222,5	13,7	16,6	90,0	2,7	-	0,076
LR	Okpulegbu- Okpulumogbo	7,34041	5,17421	27,1	4,8	151	20,9	13,6	18,9	23,0	7,5	1,0	-	0,097
LR	Mbutu Isiahia, Umuojima	7,31438	5,12972	27,2	4,8	134	24,6	16,0	16,8	20,5	8,9	1,3	-	0,009
LR	Umungasi Road II off MCC	7,33822	5,14235	27,9	4,8	127	29,8	19,4	20,0	23,5	12,0	3,8	-	0,012
HR	Umule Umuehilegbu	7,34459	5,12784	27,3	4,8	81	145,6	94,7	30,5	37,1	36,3	2,6	-	0,04
LR	Chima Nwafor off MCC (Umuojima)	7,33346	5,13935	28,3	4,8	164	93,3	60,6	12,6	15,4	37,0	1,3	-	0,035
HR	Udenwanyi (PH Road)	7,34641	5,08615	28,3	4,8	180	170,9	111,1	9,0	11,5	59,0	2,8	-	0,083
HR	St Michael (Aba central)	7,37394	5,1102	28,8	4,8	181	162,6	105,7	13,0	15,4	52,0	0,5	-	0,029
LR	New Umuahia Road, Ogor Hill	7,38749	5,124175	28,1	5	124	30,6	19,9	18,0	21,9	10,0	1,8	-	0,035
HR	Gasline off 175 Faulks Road	7,34157	5,11953	27,8	4,2	166	110,3	71,7	20,0	24,4	5,1	3,1	-	0,091
LR	Umuola Aba	7,39449	5,117414	28,4	4,7	130	25,8	16,8	21,0	25,6	3,0	0,9	-	5,84
HR	Amankalu St off PH Road	7,34447	5,083444	27,9	4,1	187	227,5	147,9	15,0	18,3	40,5	2,3	-	6,5
HR	7 Faulks Road	7,355	5,12316	26,4	3,9	185	271,5	176,5	14,0	17,1	63,8	2,1	-	1,055
LR	Owerri Aba	7,4026	5,048	28,2	4,5	183	265,7	172,7	12,8	15,6	68,1	0,8	-	0,2
LR	Alaoji	7,3161	5,0372	27,6	4,8	133	31,0	20,1	17,9	21,8	9,8	1,0	-	0,004
LR	Umuozuo	7,306	5,0858	27,2	4,8	134	24,6	16,0	19,8	24,4	8,9	1,3	-	0,009
LR	Asa Nnentu	7,3685	5,058	28,4	4,5	149	33,2	21,6	19,2	23,4	14,8	0,8	-	0,089
LR	Ovom	7,4352	5,0748	27,2	4,6	149	20,9	13,6	18,0	24,3	5,9	1,4	-	0,01

Loc ID	Well location description	Long DD	Lat DD	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Cd (mg/l)	Pb (mg/l)	Fe (mg/l)	Cr (mg/l)	Mn (mg/L)	TPH (mg/L)
LR	Umunkama Ovom Ogor-hill	7,41826	5,10175	6,23	2,717	0,019	0,1	-	0,0	0,0	-	0,0	0,001
LR	Umuchichi- Okpulumogbo	7,36045	5,14799	3,317	4,288	0,241	0,4	-	0,0	0,0	-	0,0	0,001
HR	Keystone1 - Umungasi	7,36204	5,12611	3,821	1,289	5,876	3,2	-	0,0	0,0	-	0,2	0,001
HR	Ukadike - Akoli	7,38908	5,08149	3,965	0,751	2,151	6,2	-	0,0	0,1	-	0,6	0,001
HR	Easy On filling station- Ngwa Road	7,37672	5,09912	3,96	0,813	4,657	6,6	-	0,0	0,0	-	0,6	0,001
LR	Pepples Road	7,38367	5,10826	2,963	0,332	0,725	0,0	-	0,0	0,0	-	0,0	0,001
LR	Alaoma Osisioma	7,32527	5,1434	3,894	1,266	0,001	0,1	-	0,0	0,0	-	0,0	0,001
LR	TLOP- Osisioma	7,32438	5,18881	4,054	0,366	0,001	0,2	-	0,0	0,0	-	0,0	0,54
LR	Ehere Ogor Off Ikot Ekpen Rd	7,40591	5,10849	6,524	2,299	0,87	0,0	-	0,0	0,4	-	0,0	0,001
HR	Ukata- Ukegbu	7,38806	5,11586	3,822	1,043	0,871	2,5	-	0,0	0,0	-	0,2	0,001
LR	Abayi Egbulegba	7,32549	5,11355	4,023	5,195	0,195	0,9	-	0,0	0,0	-	0,0	0,001
LR	LPG Plant - Alaoji	7,32843	5,07338	3,551	0,001	0,08	0,0	-	0,0	0,0	-	0,0	0,001
HR	Nwala - Faulks Road	7,34902	5,12313	3,932	1,619	2,672	4,2	-	0,0	0,0	-	0,5	0,001
LR	ABSUTH	7,34535	5,14801	3,392	0,624	0,78	0,1	-	0,0	0,4	-	0,0	0,001
HR	Azikiwe	7,36583	5,10868	2,897	1,015	7,6	0,2	-	0,0	0,3	-	0,0	0,001
HR	Osusu Road	7,35722	5,11324	3,458	0,891	5,2	0,1	-	0,0	0,2	-	0,0	0,001
HR	Omuma Road	7,35391	5,10786	3,954	3,028	0,432	0,2	-	0,0	0,1	-	0,0	0,001
LR	Okpulegbu- Okpulumogbo	7,34041	5,17421	5,087	1,097	3,4	0,9	-	0,0	0,4	-	0,0	0,001
LR	Mbutu Isiahia, Umuojima	7,31438	5,12972	2,978	1,594	3,16	0,1	-	0,0	0,0	-	0,0	0,001
LR	Umungasi Road II off MCC	7,33822	5,14235	3,847	1,008	1,02	0,0	-	0,0	0,0	-	0,0	0,001
HR	Umule Umuehilegbu	7,34459	5,12784	4,012	1,834	6,02	0,1	-	0,0	0,3	-	0,0	0,001
LR	Chima Nwafor off MCC (Umuojima)	7,33346	5,13935	3,124	0,837	1,186	3,0	-	0,0	0,0	-	0,0	0,001
HR	Udenwanyi (PH Road)	7,34641	5,08615	3,984	0,927	1,714	2,2	-	0,0	0,0	-	0,0	0,001
HR	St Michael (Aba central)	7,37394	5,1102	2,985	1,618	2,305	0,1	-	0,0	0,4	-	0,0	0,001
LR	New Umuahia Road, Ogor Hill	7,38748611	5,124175	2,016	1,208	0,52	0,1	-	0,0	0,0	-	0,0	0,001
HR	Gasline off 175 Faulks Road	7,34156667	5,11953	2,924	0,731	6,1	3,2	-	0,0	0,1	-	0,0	0,001
LR	Umuola Aba	7,39448611	5,117414	4,083	0,951	2,1	0,1	-	0,0	0,2	-	0,0	0,001
HR	Amankalu St off PH Road	7,34446667	5,083444	6,004	0,739	0,426	0,0	-	0,0	0,1	-	0,0	0,001
HR	7 Faulks Road	7,355	5,12316	3,861	1,498	5,198	1,0	-	0,0	0,0	-	0,4	0,001
LR	Owerri Aba	7,4026	5,048	3,965	0,751	2,151	6,2	-	0,0	0,0	-	0,3	0,001
LR	Alaoji	7,3161	5,0372	3,551	0,001	0,08	0,0	-	0,0	0,4	-	0,0	0,001
LR	Umuozuo	7,306	5,0858	2,978	1,485	3,16	0,1	-	0,0	0,3	-	0,0	0,001
LR	Asa Nnentu	7,3685	5,058	3,082	2,942	0,892	0,5	-	0,0	0,0	-	0,0	0,001
LR	Ovom	7,4352	5,0748	6,23	2,717	0,019	0,1	-	0,0	0,0	-	0,0	0,001

Table A-3.2: Seasonal physicochemical and chemical quality data from laboratory test during dry season (February-March 2019)

Loc ID	Well location description	Long DD	Lat DD	Temp (°C)	pH	ORP (meV)	EC (µS/cm)	TDS (mg/l)	T. Alk (mg/l)	HCO ₃ (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	PO ₄ (mg/l)	NO ₃ (mg/l)
HR	Terminus Hotel Azikiwe Rd	7,38879	5,1075	27	3,7	207	286,7	186,3	14	17,1	53,2	1,05	0,73	10,2
HR	Keystone Bank, Aba Owerri	7,362	5,12601	27,8	3,8	198	226,2	147,0	18	21,9	42,8	0,96	0,95	6,1
LR	TLOP 4 PH Enugu expressway	7,32445	5,18895	28,2	5,2	118	12,0	7,8	18,5	22,6	1,0	1,01	0,55	0,7
LR	TLOP 3 PH Enugu expressway	7,32438	5,18881	28,6	4,8	189	33,9	22,1	13	15,6	2,7	1,31	0,43	0,9
LR	AfroBev PH-Enugu expressway	7,3258	5,18077	29,2	4,8	143	22,6	14,7	18,5	22,6	2,2	1,76	0,61	0,9
HR	Nwala Faulks Road	7,34902	5,12313	28	3,8	198	560,0	364,0	16	19,5	101,7	1,01	0,80	14,2
LR	Asa-Umunka	7,32744	5,04046	27,6	4,7	144	18,8	12,2	16	19,5	1,7	0,60	0,67	0,8
LR	Umunkama Ovom	7,41825	5,10173	28,3	4,8	139	22,2	14,4	22,6	27,5	2,2	1,79	0,92	0,8
LR	Ikonne Str New Umuahia Road	7,39803	5,12103	28,1	4,3	163	60,3	39,2	18	21,9	10,0	0,93	0,09	1,00
LR	Hollywood PH Road Aba	7,3584	5,09739	28,1	4,4	156	196,8	127,9	18,2	22,2	34,5	0,73	0,61	1,1
LR	MCC Umuocham	7,34326	5,13033	29	4,2	173	94,5	61,5	19,2	23,4	16,0	1,26	0,55	1,0
HR	Powerline Faulks Road	7,34452	5,10962	28,9	3,8	197	472,9	307,4	15	18,3	86,3	1,10	0,36	12,5
HR	73 Hospital Road	7,36885	5,11035	27,6	3,9	190	519,2	337,5	24	29,3	88,5	1,70	0,56	4,8
HR	Agharandu Ngwa Road	7,37328	5,09748	29	3,9	191	389,1	252,9	17	20,7	70,0	1,16	0,92	9,8
HR	Lokota Ebemma O-H	7,38521	5,11451	27,8	5,1	116	35,5	23,1	12	14,6	4,0	0,49	0,43	1,0
LR	Okpulumuogbo	7,34899	5,1535	31	5,4	102	15,7	10,2	21	25,6	1,0	1,02	0,37	1,2
HR	Umuode Road Faulks Road	7,33293	5,11049	30,3	3,8	197	309,1	200,9	14	17,1	59,2	0,78	0,64	4,4
LR	Waterside Market Road	7,38337	5,10746	29,2	5,3	105	40,7	26,5	15	18,3	6,3	0,35	0,40	0,52
LR	Waterside Okpulumuogbo (Source)	7,34923	5,1676	29,1	5,3	104	10,0	6,5	12	14,6	1,3	0,38	0,34	0,02
LR	Clover paint Ekeakpara	7,31236	5,15951	27,9	4,9	127	21,4	13,9	22	26,8	2,6	1,12	0,43	0,8
LR	Ikenga Oil Asa Nnetu	7,3432	5,0291	28,1	4,7	138	13,9	9,0	24	29,3	1,9	0,53	0,55	0,91
LR	Umuojima	7,31973	5,13752	28	5,6	82	13,0	8,5	20,1	24,5	2,2	1,63	0,64	1,2
HR	Aba North Local Govt Hqt	7,3648	5,12802	28,8	3,9	186	274,0	178,1	19	23,2	51,2	1,12	0,28	0,8
HR	PZ Cussons Mageret Ave	7,37001	5,1301	28,9	4,5	150	69,2	45,0	29	35,4	42,0	2,65	1,38	1,4
LR	MEFCO Asannetu	7,32713	5,0639	29	5,2	111	12,7	8,3	16	19,5	3,1	0,82	0,03	0,5
LR	Amaekpu Okpulumugbo	7,34012	5,17485	28,9	5,6	88	31,9	20,7	19	23,2	4,0	0,95	0,43	1,0
HR	Constitution crescent	7,3752	5,11391	29,1	4,9	123	133,3	86,7	28	34,1	21	1,31	0,58	1,1

Loc ID	Well location description	Long DD	Lat DD	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Cd (mg/l)	Pb (mg/l)	Fe (mg/l)	Cr (mg/l)	Mn (mg/L)	TPH (mg/l)
HR	Terminus Hotel Azikiwe Rd	7,38879	5,1075	3,217	10,5	5,374	2,1	0,0	0,009	0,0	nd	0,49	0,01
HR	Keystone Bank, Aba Owerri	7,362	5,12601	3,575	7,273	2,985	1,2	nd	0,00425	0,0	nd	0,31	0,001
LR	TLOP 4 PH Enugu expressway	7,32445	5,18895	0,102	0,359	0,04	0,0	0,0	0,0052	0,0	nd	0,01	0,09
LR	TLOP 3 PH Enugu expressway	7,32438	5,18881	2,98	0,41	0,001	0,3	0,0	0,008	0,1	nd	0,00	0,72
LR	AfroBev PH-Enugu expressway	7,3258	5,18077	0,194	0,745	0,109	0,7	nd	0,00478	0,1	nd	0,09	0,001
HR	Nwala Faulks Road	7,34902	5,12313	4,632	19,281	9,545	2,3	0,0	0,0052	0,1	nd	0,60	0,005
LR	Asa-Umunka	7,32744	5,04046	0,095	0,972	0,208	0,1	nd	0,0052	0,1	nd	0,00	0,001
LR	Umunkama Ovom	7,41825	5,10173	0,181	1,014	0,099	0,6	nd	0,0052	0,1	nd	0,00	0,001
LR	Ikonne Str New Umuahia Road	7,39803	5,12103	0,798	1,593	0,742	0,4	nd	0,0052	0,3	nd	0,03	0,001
LR	Hollywood PH Road Aba	7,3584	5,09739	4,192	1,669	0,219	0,4	0,0	0,0052	0,1	0,0	0,00	0,001
LR	MCC Umuocham	7,34326	5,13033	1,527	1,349	0,615	0,9	0,0	0,00464	0,2	0,0	0,02	0,001
HR	Powerline Faulks Road	7,34452	5,10962	4,631	13,447	8,121	2,0	0,0	0,00045	0,3	nd	0,48	0,001
HR	73 Hospital Road	7,36885	5,11035	4,029	2,363	19,299	1,2	0,0	0,0052	0,4	0,0	0,52	0,001
HR	Agharandu Ngwa Road	7,37328	5,09748	3,909	12,773	11,312	2,2	0,0	0,0052	0,3	nd	0,07	0,001
HR	Lokota Ebemma O-H	7,38521	5,11451	0,565	1,685	0,065	0,0	0,0	0,0052	0,1	nd	0,02	0,001
LR	Okpulumuogbo	7,34899	5,1535	0,114	1,834	0,001	0,0	0,0	0,0052	0,1	nd	0,02	0,001
HR	Umuode Road Faulks Road	7,33293	5,11049	3,909	6,477	6,291	0,7	0,0	0,0052	0,2	nd	0,52	0,001
LR	Waterside Market Road	7,38337	5,10746	0,873	0,732	1,607	0,0	0,0	0,0052	0,1	nd	0,00	0,001
LR	Waterside Okpulumuogbo (Source)	7,34923	5,1676	0,214	0,347	0,001	0,0	nd	0,0052	0,0	nd	0,00	0,001
LR	Clover paint Ekeakpara	7,31236	5,15951	0,19	1,21	0,09	0,0	0,0	0,0052	0,2	nd	0,01	0,3
LR	Ikenga Oil Asa Nnetu	7,3432	5,0291	0,2	0,91	0,02	0,0	0,0	0,0052	0,2	nd	0,01	0,001
LR	Umuojima	7,31973	5,13752	0,11	0,4	0,02	0,1	0,0	0,0052	0,2	nd	0,00	0,001
HR	Aba North Local Govt Hqt	7,3648	5,12802	5,01	3,27	4,98	0,8	0,0	0,0052	0,2	nd	0,08	0,001
HR	PZ Cussons Mageret Ave	7,37001	5,1301	0,94	1,9	0,87	0,5	0,0	0,0052	0,2	nd	0,03	0,001
LR	MEFCO Asannetu	7,32713	5,0639	0,11	0,39	0,043	0,0	0,0	0,0052	0,3	nd	0,21	0,001
LR	Amaekpu Okpulumugbo	7,34012	5,17485	0,565	1,685	0,054	0,0	0,0	0,0052	0,0	nd	0,00	0,001
HR	Constitution crescent	7,3752	5,11391	1,527	1,349	1,615	2,1	0,0	0,0052	0,0	0,0	0,00	0,001

Table A-3.3: Water type in wells in densely built-up (HR) residential area (N =28)

S/N	Location	Well ID	Water type
1	Keystone Bank - Umungasi	HR1	Ca-Mg-Cl
2	Ukadike – Ngwa Road	HR2	Mg-Cl
3	Easy On filling station- Ngwa Road	HR3	Mg-Cl
4	Ukata- Ukegbu	HR4	Mg-Na-Cl-HCO ₃
5	Nwala - Faulks Road	HR5	Ca-Cl
6	Azikiwe	HR6	Ca-Cl
7	Osusu Road	HR7	Ca-Cl-HCO ₃
8	Omuma Road	HR8	Na-Cl
9	Owerri-Aba (Ngwa Road)	HR9	Mg-Cl-HCO ₃
10	Umule Umuehilegbu	HR10	Ca-Na-HCO ₃
11	Chima Nwafor off MCC (Umuojima)	HR11	Mg-Na-HCO ₃ -Cl
12	Udenwanyi (PH Road)	HR12	Ca-Na-Cl
13	St Michael (Aba central)	HR13	Na-Ca-Cl-HCO ₃
14	Gasline off 175 Faulks Road	HR14	Ca-Cl-HCO ₃
15	Amankalu St off PH Road	HR15	Na-Cl-HCO ₃
16	7 Faulks Road	HR16	Ca-Cl-HCO ₃
17	Terminus Hotel Azikiwe Rd	HR17	Ca-K-Cl
18	Keystone Bank, Aba Owerri	HR18	Na-Ca-Cl
19	Nwala Faulks Road	HR19	K-Ca-Cl
20	Hollywood, PH Road	HR20	Na-Cl
21	MCC Umuocham	HR21	Ca-Na-Cl-HCO ₃
22	Powerline Faulks Road	HR22	Ca-Na-Cl
23	73 Hospital Road	HR23	Mg-Cl
24	Agharandu Ngwa Road	HR24	Mg-Cl
25	Umuode Road Faulks Road	HR25	Ca-Na-Cl
26	Aba North Local Govt Hqt	HR26	Ca-Cl-HCO ₃
27	PZ Cussons Mageret Ave	HR27	Na- Ca-Cl-HCO ₃
28	Constitution crescent	HR28	Mg-Cl-HCO ₃

Table A-3.4: Water type in wells in the sparsely built-up residential area (N = 33)

S/N	Location	Well ID	Water type
1	Umunkama Ovom (Starline) O-H	LR1	Na-HCO ₃
2	Umuchichi- Okpulumogbo	LR2	Na-K-HCO ₃
3	Pepples Road	LR3	Na-HCO ₃
4	Alaoma Osisioma	LR4	Na-HCO ₃
5	TLOP- Osisioma	LR5	Na-HCO ₃ -Cl
6	Ehere Ogbor Off Ikot Ekpene Rd	LR6	Na-HCO ₃ -Cl
7	Abayi Egbulegba	LR7	Na-HCO ₃ -Cl
8	LPG Plant - Alaoji	LR8	Na-HCO ₃ -Cl
9	ABSUTH	LR9	Na-HCO ₃
10	Okpulegbu- Okpulumogbo	LR10	Ca-Na-HCO ₃
11	Mbutu Isiahia, Umuojima	LR11	Ca-Na-HCO ₃
12	New Umuahia Road, Ogbor Hill	LR12	Na-HCO ₃ -Cl
13	Umuola Aba	LR13	Na-HCO ₃ -Cl
14	Alaoji	LR14	Na-HCO ₃ -Cl
15	Umuozuo	LR15	Ca-Na-HCO ₃
16	Asa Nnetu	LR16	Na-HCO ₃ -Cl
17	Ovom	LR17	Na-HCO ₃ -Cl
18	Owerri Aba	LR18	Na-HCO ₃ -Cl
19	TLOP 4 PH Enugu expressway	LR19	Na-HCO ₃
20	TLOP 3 PH Enugu expressway	LR20	Na-HCO ₃
21	AfroBev PH-Enugu expressway	LR21	Na-HCO ₃
22	Asa-Umunka	LR22	Na-HCO ₃
23	Umunkama Ovom	LR23	Ca-HCO ₃
24	Ikonne Str New Umuahia Road	LR24	Na-Ca-HCO ₃ -Cl
25	Lokota Ebemma O-H	LR25	Na-HCO ₃ -Cl
26	Okpulumuogbo	LR26	Na-HCO ₃
27	Waterside Market Road	LR27	Ca-HCO ₃ -Cl
28	Waterside Okpulumuogbo	LR28	Na-HCO ₃
29	Clover paint Ekeakpara	LR29	Na-HCO ₃
30	Ikenga Oil Asa Nnetu	LR30	Na-HCO ₃
31	Umuojima	LR31	Na-HCO ₃ -Cl
32	MEFCO Asannetu	LR32	Na-HCO ₃ -Cl
33	Amaekpu Okpolumugbo	LR33	Na-HCO ₃ -Cl

Appendix 4

Table A-4.1: Results of selected of quality indicators and the calculated water quality indices for each well using WLSA (WQI+) and WGA (WQI*) subindex aggregation function

Well ID	Well location description	Long DD	Lat DD	pH	TDS (mg/l)	Cl (mg/l)	NO3- (mg/l)	Pb (mg/l)	Fe (mg/l)	TPH (mg/l)	Mn (mg/L)	WQI+	WQI*
CB1	Terminus Hotel Azikiwe Rd	7,38879	5,1075	3,7	186,3	53,2	10,2	0,009	0,30	0,01	0,49	137,7	33,8
CB2	Keystone Bank, Aba Owerri	7,362	5,12601	3,8	147,0	42,8	6,1	0,0043	0,01	0,001	0,31	26,4	14,7
IB1	TLOP 4 PH Enugu expressway	7,32445	5,18895	5,2	7,8	1,0	0,7	0,0052	0,01	0,09	0,008	944,8	100,4
IB1.1	TLOP 3 PH Enugu expressway	7,32438	5,18881	4,8	22,1	2,7	0,9	0,0080	0,03	0,72	0,002	7432,5	338,4
IB2	AfroBev PH-Enugu expressway	7,3258	5,18077	4,8	14,7	2,2	0,9	0,0048	0,07	0,001	0,09	28,5	14,9
RB1	Nwala Faulks Road	7,34902	5,12313	3,8	364,0	101,7	14,2	0,0052	0,05	0,005	0,6	71,2	24,7
RB2	Asa-Umunka	7,32744	5,04046	4,7	12,2	1,7	0,8	0,0052	0,11	0,001	0,001	30,3	15,0
RB3	Umunkama Ovom	7,41825	5,10173	4,8	14,4	2,2	0,8	0,0052	0,15	0,001	0,002	30,4	15,0
RB4	Ikonne Str New Umuhia Road	7,39803	5,12103	4,3	39,2	10,0	1,00	0,0052	0,12	0,001	0,03	30,3	15,0
RB5	Hollywood PH Road Aba	7,3584	5,09739	4,4	127,9	34,5	1,1	0,0052	0,30	0,001	0,09	31,1	15,1
RB6	MCC Umuocham	7,34326	5,13033	4,2	61,5	16,0	1,0	0,005	0,07	0,001	0,021	28,1	14,9
RB7	Powerline Faulks Road	7,34452	5,10962	3,8	307,4	86,3	12,5	0,0005	0,17	0,001	0,48	13,0	12,5
CB3	73 Hospital Road	7,36885	5,11035	3,9	337,5	88,5	4,8	0,0052	0,29	0,001	0,52	31,1	15,1
RB8	Agharandu Ngwa Road	7,37328	5,09748	3,9	252,9	70,0	9,8	0,0052	0,41	0,001	0,071	31,6	15,1
CB4	Lokota Ebemma O-H	7,38521	5,11451	5,1	23,1	4,0	1,0	0,0052	0,28	0,001	0,019	30,9	15,0
RB9	Okpulumuogbo	7,34899	5,1535	5,4	10,2	1,0	1,2	0,0052	0,14	0,001	0,016	30,3	15,0
RB10	Umuode Road Faulks Road	7,33293	5,11049	3,8	200,9	59,2	4,4	0,0052	0,10	0,001	0,52	30,3	15,0
RW1	Waterside Market Road	7,38337	5,10746	5,3	26,5	6,3	0,52	0,0052	0,19	0,001	0,001	30,5	15,0
RW2	Waterside Okpulumuogbo (Source)	7,34923	5,1676	5,3	6,5	1,3	0,02	0,0052	0,06	0,001	0,001	30,0	15,0
IB3	Clover paint Ekeakpara	7,31236	5,15951	4,9	13,9	2,6	0,8	0,0052	0,02	0,3	0,012	3103,9	200,7
FB1	Ikenga Oil Asa Nnetu	7,3432	5,0291	4,7	9,0	1,9	0,91	0,0052	0,15	0,001	0,005	30,4	15,0
RB11	Umuojima	7,31973	5,13752	5,6	8,5	2,2	1,2	0,0052	0,15	0,001	0,001	30,3	15,0
CB5	Aba North Local Govt Hqt	7,3648	5,12802	3,9	178,1	51,2	0,8	0,0052	0,15	0,001	0,08	30,5	15,0
IB4	PZ Cussons Mageret Ave	7,37001	5,1301	4,5	45,0	42,0	1,4	0,0052	0,15	0,001	0,028	30,4	15,0
CB5	MEFCO Asanetu	7,32713	5,0639	5,2	8,3	3,1	0,5	0,0052	0,15	0,001	0,21	30,3	15,0
FB3	Amaekpu Okpulumugbo	7,34012	5,17485	5,6	20,7	4,0	1,0	0,0052	0,283	0,001	0,001	30,9	15,0
CB6	Constitution crescent	7,3752	5,11391	4,9	86,7	21	1,1	0,0052	0,001	0,001	0,003	29,8	15,0
CB7	Umunkama Ovom Ogbor-hill	7,41826	5,10175	4,6	13,6	5,9	0,01	0,0052	0,001	0,001	0,001	29,8	15,0
RB 12	Umuchichi - Okpulumugbo	7,36045	5,14799	4,7	18,7	9,1	0,011	0,0052	0,001	0,001	0,001	29,8	15,0
CB8	Keystone1 - Umungasi	7,36204	5,12611	4	131,8	51,5	0,008	0,0052	0,001	0,001	0,225	29,9	15,0
RB13	Ukadike - Akoli	7,38908	5,08149	4	172,7	68,1	0,002	0,0052	0,001	0,001	0,567	29,9	15,0
CB9	Easy On filling station- Ngwa Road	7,37672	5,09912	3,9	201,7	81,8	0,006	0,0052	0,079	0,001	0,586	30,2	15,0
RB14	Pepples Road	7,38367	5,10826	5,2	18,0	2,6	0,015	0,0052	0,001	0,001	0,001	29,7	15,0
RB15	Alaoma Osioma	7,32527	5,1434	5,3	18,4	9,8	0,011	0,0052	0,021	0,001	0,016	29,8	15,0
IB1	TLOP - Osioma	7,32438	5,18881	4,8	18,4	8,5	0,008	0,0052	0,001	0,54	0,039	5571,4	284,3
RB16	Ehere Ogbor Off Ikot Ekpen Road	7,40591	5,10849	5	21,2	5,2	0,004	0,0052	0,001	0,001	0,001	29,8	15,0
RB17	Ukata - Ukegbu	7,38806	5,11586	4,3	71,7	39,0	0,006	0,0052	0,434	0,001	0,239	31,6	15,1
RB18	Abayi Egbulegba	7,32549	5,11355	4,6	33,3	15,0	0,008	0,0052	0,001	0,001	0,043	29,8	15,0
CB10	LPG Plant - Alaoji	7,32843	5,07338	4,8	20,1	9,8	0,004	0,0052	0,001	0,001	0,001	29,8	15,0
RB19	Nwala - Faulks Road	7,34902	5,12313	3,9	260,0	95,0	0,01	0,0052	0,001	0,001	0,521	29,9	15,0
CB11	ABSUTH	7,34535	5,14801	4,8	18,9	6,0	0,09	0,0052	0,03	0,001	0,001	29,9	15,0
CB12	Azikiwe	7,36583	5,10868	4,8	189,6	78,0	0,079	0,0052	0,36	0,001	0,001	31,3	15,1
RB20	Osusu Road	7,35722	5,11324	4,8	258,2	84,0	0,051	0,0052	0,28	0,001	0,01	30,9	15,0
RB21	Omuma Road	7,35391	5,10786	4,8	222,5	90,0	0,076	0,0052	0,18	0,001	0,028	30,5	15,0
RB22	Okpulegba - Okpulumugbo	7,34041	5,17421	4,8	13,6	7,5	0,097	0,0052	0,08	0,001	0,004	30,1	15,0
RB23	Mbutu Isahia, Umuojima	7,31438	5,12972	4,8	16,0	8,9	0,009	0,0052	0,38	0,001	0,001	31,3	15,1
RB24	Umungasi Road II off MCC	7,33822	5,14235	4,8	19,4	12,0	0,012	0,0052	0,018	0,001	0,016	29,9	15,0
RB25	Umuale Umuehiegbo	7,34459	5,12784	4,8	94,7	36,3	0,04	0,0052	0,008	0,001	0,019	29,8	15,0
RB26	Chima Nwafor off MCC (Umuojima)	7,33346	5,13935	4,8	60,6	37,0	0,035	0,0052	0,34	0,001	0,001	31,2	15,1
RB27	Udenwany (PH Road)	7,34641	5,08615	4,8	111,1	59,0	0,083	0,0052	0,009	0,001	0,013	29,8	15,0
CB13	St Michael (Aba central)	7,37394	5,1102	4,8	105,7	52,0	0,029	0,0052	0,039	0,001	0,008	29,9	15,0
RB28	New Umuhia Road, Ogbor Hill	7,38749	5,124175	5	19,9	10,0	0,035	0,0052	0,39	0,001	0,001	31,4	15,1
CB14	Gasline off 175 Faulks Road	7,34157	5,111953	4,2	71,7	5,1	0,091	0,0052	0,048	0,001	0,018	30,0	15,0
RB29	Umuola Aba	7,39449	5,117414	4,7	16,8	3,0	5,84	0,0052	0,09	0,001	0,003	30,2	15,0
RB30	Amankalu St off PH Road	7,34447	5,083444	4,1	147,9	40,5	6,5	0,0052	0,17	0,001	0,019	30,6	15,0
CB15	7 Faulks Road	7,355	5,12316	3,9	176,5	63,8	1,055	0,0052	0,069	0,001	0,411	30,2	15,0
RB31	Owerri Aba	7,4026	5,048	4,5	172,7	68,1	0,2	0,0052	0,017	0,001	0,267	29,9	15,0
CB15	Alaoji	7,3161	5,0372	4,8	20,1	9,8	0,004	0,0052	0,001	0,001	0,001	29,8	15,0
RB32	Umuozuo	7,306	5,0858	4,8	16,0	8,9	0,009	0,0052	0,38	0,001	0,001	31,3	15,1
RB33	Asa Nnetu	7,3685	5,058	4,5	21,6	14,8	0,089	0,0052	0,293	0,001	0,009	31,0	15,0
RB34	Ovom	7,4352	5,0748	4,6	13,6	5,9	0,01	0,0052	0,001	0,001	0,001	29,8	15,0

Parameter	pH	TDS	Cl ⁻	NO ₃ ⁻	Pb	Fe	TPH	Mn
S _i	6,5	500	250	50	0,01	0,3	0,3	0,2
1/S _o	0,154	0,002	0,004	0,02	100	3,3	3,3	5,0
Σ(1/S _o)	111,8							
K	1/(Σ(1/S _o))	0,0089						
w _i	K/S _o	0,0014	1,78816E-05	3,58E-05	0,000179	0,8940824	0,0298027	0,044704
Σw _i	1							

Appendix 5

Table A-5.1: Assigned numerical range, rating and weight for each hydrogeologic setting in the DRASTIC method according to Aller et al., 1987.

Parameter ranges	Rating	Parameter	Rating
DEPTH TO WATER TABLE (m)		IMPACT OF VADOSE ZONE	
0.0 – 1.5	10	Karst limestone	10
1.5 – 4.6	9	Basalt	9
4.6 – 9.1	7	Sand and Gravel	8
9.1 – 15.2	5	Metamorphic/Igneous	4
15.2 – 22.9	3	Sand and Gravel with significant silt and clay	6
22.9 – 30.5	2	Bedded limestone, sandstone, shale	6
>30.5	1	Sandstone	6
NET RECHARGE RATE (mm)		Limestone	6
>254	9	Shale	3
177.8 – 254	8	Silt/clay	3
101.6 – 177.8	6	Confining layer	1
50.8 – 101.6	3		
0.0 – 50.8	1		
AQUIFER MEDIA		SOIL MEDIA	
Karst limestone	10	Thin or absent	10
Basalt	9	Gravel	10
Sand and gravel	8	Sand	9
Massive limestone	6	Peat	8
Massive sandstone	6	Shrinking and/or aggregated clay	7
Bedded sandstone, limestone & shale	6	Sandy loam	6
Glacial till	5	Loam	5
Weathered metamorphic / igneous	4	Silty loam	6
Metamorphic /Igneous	3	Clay loam	3
Massive shale	2	Muck	2
TOPOGRAPHY (% rise of the slope)		Nonshrinking and non-aggregated clay	1
0-2	10	IMPACT OF ACTIVE PUMP (m³)	
2-6	9	>400	10
6-12	5	100 - 400	8
12-18	3	50 -100	6
>18	1	15 - 50	5
HYDRAULIC CONDUCTIVITY (m/day)		0 – 15	2
>86	10	ASSIGNED WEIGHT	
45 - 85	8	Depth to water-table [<i>D</i>]	5
30 – 45	6	Net recharge rate [<i>R</i>]	4
13 - 30	4	Aquifer media [<i>A</i>]	3
4.5 - 13	2	Soil Media [<i>S</i>]	2
0 – 4.5	1	Topography [<i>T</i>]	1
		Impact of vadose [<i>I</i>]	5
		Hydraulic Conductivity [<i>C</i>]	3
		Impact of pumps [<i>P_a</i>]	5

The units of some of the hydrogeologic setting, such as *D*, *R*, *C* and *P_a* are expressed in SI units

Appendix 6

Table A-6.1: Static water level (water table elevation) of some tube wells used to estimate the depth to the water level rating map and reference with the extracted SRTM DEM of the study area

S/N	Well location description	Long (DD)	Lat (DD)	Elev. (m)	GW Elev. (m)
1	Aba Main Park	7,3717	5,1138	62	19.8
2	Osusu Sec School Aba	7,3525	5,1169	64	27.4
3	Asa Nnetu	7,3120	5,0561	-	36.6
4	Mbutu Isiahia Umuojima	7,3144	5,1297	64	22.8
5	Umule Umuehilegbu	7,3446	5,1278	58	26.3
6	TLOP 1	7,3244	5,1888	74	29.6
7	TLOP 2	7,3245	5,1890	75	29.8
8	TLOP 3	7,3247	5,1875	75	29.5
9	Ukwuakpu Umule	7,3436	5,1261	67	29.3
10	Koroma Clover	7,3125	5,1593	67	27.8
11	Umuojima	7,3197	5,1375	61	19.7
12	Ohanku village (Ngwa Road)	7,3950	5,0610	52	25.2
13	New Umuahia area	7,3910	5,1330	70	28.8
14	Akalanna Str.	7,3575	5,1155	-	27.2
15	Aba Sport Stadium	7,3753	5,1012	-	25.8
16	Ojike lane	7,3714	5,1149	-	20.1
17	Aja Road (Ngwa road)	7,3795	5,0948	-	27.2
18	Azuka avenue	7,3936	5,1114	-	28.4
19	Waterside Market Road	7,3834	5,1075	22,5	0.0
20	Waterside (Springhead)	7,3492	5,1676	36	0.0
21	Waterside (Under the bridge)	7,3807	5,1141	29	0.0
22	Waterside (Owerri Aba)	7,4122	5,0473	23	0.0
23	Water side (Alozie (PZ))	7,3740	5,1349	36	0.0
24	Water side (Owerri Aba)	7,3982	5,0848	30	0.0
25	62 Omuma Road	7,3539	5,1079	58	26.7
26	mpt1	7,3370	5,0770	-	28.2
27	mpt2	7,3250	5,0280	-	28.6
28	mpt3	7,4250	5,0870	-	27.1
29	mpt4	7,3140	5,0940	-	27.8

Appendix 7

Table A-7: Distribution of hydraulic conductivity K_f of some boreholes used of hydraulic conductivity [C] rating map

S/N	Well ID	Borehole location	Long (DD)	Lat (DD)	K (m/s)	K (m/day)
1	BH 1	Umunkama_Ovom	7,418	5,102	0.0041	357.7
2	BH 2	Aba Post Office	7,371	5,112	0.006	494.2
3	BH 3	Itungwa Aba	7,471	5,192	0.009	812.2
4	BH 4	Osisioma L.G.	7,324	5,158	0.0057	494.2
5	BH 5	Abayi P.S Aba	7,351	5,137	0.0091	786.2
6	BH6	AbiaPoly Umungasi	7,362	5,126	0.0036	307.6
7	BH 7	Umukalika Ogbor Hill	7,403	5,144	0.0085	734.4
8	BH 8	Ovom P.S Aba	7,387	5,110	0.0057	490.8
9	BH 9	Obingwa L.G secretariat, Mgboko	7,415	5,061	0.0044	381.9
10	BH 10	Umuosi	7,308	5,051	0.0083	713.7
11	BH11	TLOP Osisioma	7,324	5,189	0.0057	492.5
12	BH12	Ngwa road	7,389	5,081	0.0006	55.0
13	BH 13	Umuchichi Okpulumugbo	7,338	5,142	0.0004	33.0

Appendix 8

Table A-8.1: Range and rating of some low impact active pumps used to

S/N	Well location description	Long (DD)	Lat (DD)	Pump Category	Avg. pump rate (m ³ /day)	W	R
1		7,3778	5,1099	1	2.0	5	2
2		7,3741	5,1110	1	2.5	5	2
3		7,3780	5,1042	1	1.5	5	2
4		7,3791	5,1037	1	2.0	5	2
5		7,3780	5,1038	1	3.0	5	2
6		7,3801	5,1068	1	3.0	5	2
7		7,3798	5,1078	1	3.0	5	2
8		7,3788	5,1094	1	3.0	5	2
9		7,3742	5,1150	1	1.0	5	2
10		7,3755	5,1110	1	1.2	5	2
11		7,3773	5,1105	1	1.5	5	2
12		7,3764	5,1106	1	1.5	5	2
13		7,3696	5,1113	1	3.0	5	2
14		7,3790	5,1020	1	3.0	5	2
15		7,3732	5,1110	1	2.0	5	2
16		7,3701	5,1087	1	1.5	5	2
17		7,3781	5,1037	1	3.0	5	2
18		7,3777	5,1088	1	1.5	5	2
19		7,3786	5,1079	1	1.5	5	2
20		7,3771	5,1072	1	3.0	5	2
21		7,3744	5,1067	1	3.0	5	2
22		7,3655	5,1075	1	4.0	5	2
23		7,3644	5,1068	1	2.5	5	2
24		7,3716	5,1062	1	1.5	5	2
25		7,3645	5,1062	1	2.0	5	2
26		7,3607	5,1102	1	2.5	5	2
27		7,3575	5,1293	1	3.0	5	2
28		7,3611	5,1301	1	1.5	5	2
29		7,3626	5,1310	1	3.0	5	2
30		7,3616	5,1302	1	1.5	5	2
31		7,3616	5,1319	1	1.5	5	2
32		7,3695	5,1286	1	1.5	5	2
33		7,3547	5,1317	1	3.0	5	2
34		7,3554	5,1319	1	1.5	5	2
35		7,3545	5,1322	1	1.5	5	2
36		7,3532	5,1319	1	1.5	5	2
37		7,3527	5,1317	1	3.0	5	2
38		7,3361	5,1520	1	1.5	5	2
39		7,3356	5,1517	1	1.5	5	2
40		7,3375	5,1530	1	1.5	5	2
41		7,3407	5,1587	1	3.0	5	2
42		7,3400	5,1591	1	1.5	5	2
43		7,3382	5,1546	1	1.5	5	2
44		7,3541	5,1155	1	3.0	5	2
45		7,3523	5,1168	1	1.5	5	2
46		7,3575	5,1132	1	1.5	5	2
47		7,3600	5,1122	1	1.5	5	2
48		7,3637	5,1135	1	3.0	5	2
49		7,3632	5,1140	1	1.5	5	2
50		7,3618	5,1151	1	1.5	5	2
51		7,3627	5,1113	1	1.5	5	2
52		7,3622	5,1132	1	3.0	5	2
53		7,3609	5,1126	1	1.5	5	2
54		7,3607	5,1125	1	1.5	5	2
55		7,3606	5,1128	1	1.5	5	2
56		7,3613	5,1138	1	3.0	5	2
57		7,3612	5,1109	1	1.5	5	2
58		7,3606	5,1111	1	1.5	5	2
59		7,3602	5,1113	1	1.5	5	2
60		7,3600	5,1117	1	3.0	5	2
61		7,3597	5,1165	1	1.5	5	2
62		7,3594	5,1160	1	1.5	5	2
63		7,3588	5,1166	1	1.5	5	2
64		7,3608	5,1100	1	3.0	5	2

65		7,3599	5,1107	1	1.5	5	2
66		7,3464	5,1207	1	1.5	5	2
67		7,3522	5,1239	1	3.0	5	2
68		7,3522	5,1241	1	1.5	5	2
69		7,3513	5,1248	1	1.5	5	2
70		7,3518	5,1245	1	1.5	5	2
71		7,3530	5,1242	1	3.0	5	2
72		7,3524	5,1243	1	1.5	5	2
73		7,3549	5,1239	1	1.5	5	2
74		7,3526	5,1249	1	1.5	5	2
75		7,3522	5,1252	1	3.0	5	2
76		7,3512	5,1250	1	1.5	5	2
77		7,3491	5,1237	1	1.5	5	2
78		7,3483	5,1245	1	1.5	5	2
79		7,3491	5,1248	1	3.0	5	2
80		7,3495	5,1254	1	1.5	5	2
81		7,3483	5,1256	1	1.5	5	2
82		7,3483	5,1263	1	1.5	5	2
83		7,3456	5,1173	1	3.0	5	2
84		7,3454	5,1174	1	1.5	5	2
85		7,3479	5,1177	1	1.5	5	2
86		7,3402	5,1132	1	1.5	5	2
87		7,3416	5,1120	1	3.0	5	2
88		7,3428	5,1161	1	1.5	5	2
89		7,3495	5,1228	1	1.5	5	2
90		7,3427	5,1139	1	1.5	5	2
91		7,3424	5,1119	1	3.0	5	2
92		7,3473	5,1205	1	1.5	5	2
93		7,3768	5,0976	1	1.5	5	2
94		7,3810	5,0982	1	3.0	5	2
95		7,3803	5,0967	1	1.5	5	2
96		7,3875	5,0969	1	1.5	5	2
97		7,3860	5,0971	1	1.5	5	2
98		7,3854	5,0963	1	3.0	5	2
99		7,3860	5,0986	1	1.5	5	2
100		7,3840	5,0987	1	1.5	5	2
101		7,3839	5,0983	1	1.5	5	2
102		7,3826	5,0982	1	3.0	5	2
103		7,3811	5,0983	1	1.5	5	2
104		7,3808	5,0978	1	1.5	5	2
105		7,3846	5,0968	1	1.5	5	2
106		7,3844	5,0971	1	3.0	5	2
107		7,3847	5,0962	1	1.5	5	2
108		7,3841	5,0958	1	1.5	5	2
109		7,3840	5,0960	1	1.5	5	2
110		7,3824	5,0962	1	3.0	5	2
111		7,3807	5,0970	1	1.5	5	2
112	Starline Ogbor-hill	7,4183	5,1018	1	1.5	5	2
113	Umuchichi- Okpulumugbo	7,3605	5,1480	1	1.5	5	2
114	Ukadike - Akoli	7,3891	5,0815	1	1.5	5	2
115	Pepples Road	7,3837	5,1083	1	1.5	5	2
116	Alaoma Osisoma	7,3253	5,1434	1	3.0	5	2
117	Ehere Ogbor Off Ikot Ekpene Rd	7,4059	5,1085	1	1.5	5	2
118	Ukata- Ukegbu	7,3881	5,1159	1	1.5	5	2
119	Abayi Egbulegba	7,3255	5,1136	1	1.5	5	2
120	LPG Plant - Alaoji	7,3284	5,0734	1	3.0	5	2
121	Nwala - Faulks Road	7,3490	5,1231	1	1.5	5	2
122	ABSUTH	7,3454	5,1480	2	1.5	5	2
123	Azikiwe	7,3658	5,1087	1	1.5	5	2
124	Osusu Road	7,3572	5,1132	1	3.0	5	2
125	Omuma Road	7,3539	5,1079	1	1.5	5	2
126	Okpulegbu- Okpulumugbo	7,3404	5,1742	1	1.5	5	2
127	Mbutu Isiahia, Umuojima	7,3144	5,1297	1	1.5	5	2
128	Umungasi Road II off MCC	7,3382	5,1424	1	3.0	5	2
129	Umule Umuehilegbu	7,3446	5,1278	1	1.5	5	2

130	Chima Nwafor off MCC (Umuojima)	7,3335	5,1394	1	1.5	5	2
131	Udenwanyi (PH Road)	7,3464	5,0862	1	1.5	5	2
132	St. Michael (Aba central)	7,3739	5,1102	1	3.0	5	2
133	New Umuahia Road, Ogbor Hill	7,3875	5,1242	1	1.5	5	2
134	Gasline off 175 Faulks Road	7,3416	5,1120	1	1.5	5	2
135	Umuola Aba	7,3945	5,1174	1	1.5	5	2
136	Amankalu St off PH Road	7,3445	5,0834	1	3.0	5	2
137	7 Faulks Road	7,3550	5,1232	1	1.5	5	2
138	Owerri Aba	7,4026	5,0480	1	1.5	5	2
139	Asa Nnetu market	7,3161	5,0372	1	1.5	5	2
140	Umuozuo	7,3060	5,0858	1	3.0	5	2
141	Asa Nnetu	7,3685	5,0580	1	1.5	5	2
142	Ovom	7,4352	5,0748	1	1.5	5	2
143	Asa-Umunka	7,3274	5,0405	1	1.5	5	2
144	Ikonne Str New Umuahia Road	7,3980	5,1210	1	1.5	5	2
145	Hollywood PH Road Aba	7,3584	5,0974	1	3.0	5	2
146	MCC Umuocham	7,3433	5,1303	1	1.5	5	2
147	Powerline Faulks Road	7,3445	5,1096	1	1.5	5	2
148	73 Hospital Road	7,3689	5,1104	1	1.5	5	2
149	Agharandu Ngwa Road	7,3733	5,0975	1	1.5	5	2
150	Okpulumugbo	7,3490	5,1535	1	3.0	5	2
151	Umuode Road Faulks Road	7,3329	5,1105	1	1.5	5	2
152	Umuojima	7,3197	5,1375	1	3.0	5	2
153	Aba North L GA Hqt	7,3648	5,1280	1	3.0	5	2
154	Amaekpu Okpulumugbo	7,3401	5,1749	1	1.5	5	2
155	Constitution Crescent	7,3752	5,1139	1	5.0	5	2

Table A-8.2: Range and rating for medium-impact pumps

S/N	Well location description	Long (DD)	Lat (DD)	Pump Category	Avg. pump rate (m3/day)	W	R
1	Valluembra flour mill	7,3263	5,1686	3	100	5	5
2	Zandob Ind. Ltd	7,3149	5,1265	3	90	5	5
3	Nason Global concept Ltd	7,3254	5,1953	3	100	5	5
4	Nneoma table water	7,3979	5,1175	3	55	5	5
5	Grupo Industrial Trixi	7,3675	5,1306	3	65	5	5
6	Masters Energy Commodities	7,3658	5,1064	3	100	5	5
7	Novikov Venture	7,3513	5,1088	3	75	5	5
8	Eagle Best Table Water	7,3876	5,1126	3	100	5	5
9	Neu-Life Goodies limited	7,3634	5,1354	3	80	5	5
10	Lupal Pharmaceutical Ltd	7,3428	5,1150	3	54	5	5
11	Dechuss water	7,3401	5,1129	3	100	5	5
12	Achita Water	7,3484	5,1135	3	80	5	5
13	Koolis Water	7,4085	5,0987	3	55	5	5
14	Stan Table Water	7,4011	5,1056	3	100	5	5
15	Abia Poly Table water	7,3625	5,1272	3	80	5	5
16	Ultima	7,3282	5,1473	3	50	5	5
17	Afro- Breweries and distilleries	7,3264	5,1818	3	100	5	5
18	Koroma Clover Paints	7,3125	5,1593	3	100	5	5
19	Vitafoam Nigeria	7,3737	5,1223	3	190	5	7
20	Aba textile mill	7,3733	5,1244	3	89	5	5
21	Unilever	7,3731	5,1219	3	75	5	5
22	Top-tree	7,3262	5,1816	3	80	5	5
23	Unknown	7,3739	5,1403	3	230	5	7
24	IEA	7,3628	5,1302	3	100	5	5
25	Pfizer Poultry feeds	7,3746	5,1245	3	120	5	7

26	A-Z Premium Oil	7,3175	5,1646	3	100	5	5
27	Alba Soap	7,3258	5,1878	3	100	5	5
28	Hotel Great worth	7,3582	5,1570	3	45	5	5
29	City Discovery Hotel and Towers	7,3526	5,0754	3	48	5	5
30	Kenfield Multihotel	7,3543	5,0783	3	30	5	5
31	Las Palmas Holiday Inn	7,4017	5,1369	3	20	5	5
32	Capeville Hotel	7,3789	5,1144	3	35	5	5
33	Marrox Garden,	7,3839	5,1117	3	40	5	5
34	Firapur Hotel	7,3382	5,1505	3	35	5	5
35	Lucas Hotel	7,3321	5,1402	3	20	5	5
36	Crystal Park Hotel	7,3532	5,0890	3	16	5	5
37	Hopelin Hotel & Tower	7,3556	5,1455	3	18	5	5
38	Classic Hotel, Aba	7,3284	5,1413	3	20	5	5
39	Lokota Hotel	7,3852	5,1145	3	20	5	5
40	City Global Hotels	7,3608	5,1204	3	25	5	5
41	Galaxy Guest House	7,3592	5,1540	3	20	5	5
42	Hotel Great Worth	7,3582	5,1576	3	20	5	5
43	South Asia Hotels	7,3974	5,1057	3	18	5	5
44	Crest Hotel Ltd	7,3639	5,1232	3	32	5	5
45	Luxury City Royale	7,3578	5,1331	3	20	5	5
46	Donesto Grand Hotels	7,3391	5,1363	3	20	5	5
47	Uche's Garden Hotel	7,3812	5,1056	3	40	5	5
48	Pilot Hotel	7,3302	5,0879	3	25	5	5
49	Olive Hotel & Suites	7,3399	5,0926	3	35	5	5
50	Hotel De Ville	7,3636	5,1160	3	42	5	5
51	Palacio Guest House	7,3594	5,1201	3	45	5	5
52	El-Dorado Hotels	7,3633	5,1260	3	30	5	5
53	Abia Hotels Ltd.	7,3663	5,1231	3	26	5	5
54	Oomne Guest House	7,3657	5,1268	3	28	5	5
55	Evergreen Hotel Aba	7,3684	5,1328	3	36	5	5
56	Firapur Hotel	7,3382	5,1506	3	15	5	5
57	Diannex Guest House	7,3383	5,1328	3	30	5	5
58	Luxury City Hotels	7,3575	5,1326	3	25	5	5
59	Keystone1 - Umungasi	7,3620	5,1261	3	15	5	5
60	Easy On filling station- Ngwa Road	7,3767	5,0991	3	15	5	5
61	MEFCO Asa Nnetu	7,3271	5,0639	3	35	5	5

Table A-8.3: Range and rating for high impact pumps

S/N	Well location description	Long (DD)	Lat (DD)	Pump Category	Avg. pump rate (m ³ /day)	W	R
1	Enyimba International Stadium Aba	7,376867	5,10295	3	120	5	7
2	Tonimas Lube Oil plant	7,328896	5,185606	3	300	5	7
3	Planet Oil	7,327644	5,159642	3	200	5	7
4	J. Udeagbara holdings Limited	7,33484	5,156348	3	300	5	7
5	NNPC / PPMC	7,320327	5,159979	3	200	5	7
6	Enitona Hotels	7,366927	5,125223	3	55	5	7
7	Addrax Hotel & Suites	7,397272	5,108021	3	220	5	7
8	Hotel Du Golf	7,362969	5,122146	3	120	5	7
9	Terminus Hotel	7,380785	5,107797	3	210	5	7
10	Hotel De La Paix	7,356783	5,124868	3	200	5	7
11	Binez Hotel	7,357042	5,13052	3	40	5	7
12	NB Plc	7,375118	5,118856	4	6000	5	10
13	Guinness Brewery	7,315758	5,159885	4	2100	5	10
14	7-up Industries	7,387396	5,131945	4	1250	5	10
15	PZ Cusson Industries	7,371575	5,128589	4	520	5	10
16	International Glass Industries Aba.	7,3817	5,138452	4	500	5	10
17	GZ Industries Aba	7,374222	5,159985	4	600	5	10
18	Glass Force Ltd	7,369561	5,150443	4	580	5	10