Centre for Water Systems

COLLEGE OF ENGINEERING, MATHEMATICS AND PHYSICAL SCIENCES

A WATER CONSUMPTION QUESTIONNAIRE-BASED STUDY AND GROUNDWATER MODELLING INVESTIGATION: GROUNDWATER MANAGEMENT UNDER SEASONAL VARIABILITY IN FREETOWN SIERRA LEONE

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Signature ……………………

DEDICATION

“Dedicated to the memory of my father, Mr. Othman Bankole Ibrahim,
who always believed in my ability to be successful in the academic arena.
You are gone but your belief in me has made this journey possible.”

ABSTRACT

Adequate and sustainable water resources are fundamental for human life to promote economic and social growth. Since the start of industrialisation, the global water demand has been growing continuously. Access to sufficient domestic water supply is a very problematic experience for the urban population of low and middle-income countries. The leading factors behind water insufficiency are urbanisation, seasonal variability, economic growth, population growth, inadequate dam capacity, and lack of experts in the sector. Aside from these factors, behaviour, patterns and household characteristics have been identified as the most important influence governing water consumption.

Many Non-Governmental Organisations working in these low and middle-income countries have tried to salvage the problem by digging wells to support these communities. However, many of these dug wells have failed to supply the necessary daily volume because of unproductive siting, poor construction practices, and lowering of the water table due to seasonality. Little research has looked at any useful information on water consumption and evaluated groundwater storage of an aquifer as a solution for sustainable seasonal domestic water consumption.

Freetown, the capital city of Sierra Leone, is the case study because of the necessity to assess the problems of meeting water demands, initiated by variability in seasons, inadequate infrastructure, lack of expertise, and the intense migration from the rural areas to settle in the city. This has subjected surface water supplies to increasing pressure from growing demand. However, groundwater sources have not been sufficiently tapped. This research aims to develop a strategy to manage groundwater in a sustainable way under the influence of seasonal variability. To achieve this, two work elements were designed and implemented as part of this thesis.

The first work element gathered information using multiple-choice format questionnaires on the factors that influence seasonal water end-use consumption patterns at a per capita scale of 398 households. The key variables investigated were income, education, number of rooms, number of vehicles, family size, collection containers, and time to fetch and distance to source. The investigated households were categorized into four household income groups and were evaluated individually to determine their daily per capita water consumption in litres per day (l/p/d). Additionally, surveyed data was used to develop statistical regression models for estimating demand as a function of household characteristics using stepwise-multiple-linear regression techniques.

The second component of this research investigated groundwater interconnectivity with other surface water bodies for the assessment of the aquifer's suitability, pumping, recharge, and drawdown capacity for an increased abstraction of water supply. Consequently, related thematic maps have been created from digital elevation models and ASTER data downloaded from the USGS websites using a GIS format. The 3D numerical ModelMuse MODFLOW package, integrated with GIS techniques was used to understand the groundwater dynamics under varying scenarios of abstraction and wells performance for the next fifteen years.

The results of the water consumption questionnaire-based study provided quantitative evidence of daily per capita end-uses for the different household income groups. The modelled data indicated a significant variation in the volume of per capita water consumption (13 l/p/d to over 273 l/p/d). Also, the findings suggest that distance to a water source and queuing time to fetch water and return home impacts the volume of water collected. On the other hand, the groundwater simulations studies indicate managed groundwater abstraction to be the most efficient and sustainable strategy to increase daily per capita water end-use volume. Results revealed that the groundwater regional recharge rate (101 $x10^6$ m^3/year) is greater than the water supply from the service provider (12.4$x10^6$ m^3/year), thereby giving the possibility to increase yearly per capita water consumption. Further simulation results show water supply from infiltration galleries can produce a further 51.8×10^6 m^3/year.

A demand-supply analysis, taking into account population projections and per capita consumption estimates and groundwater supply simulations developed in this research, showed that the annual groundwater supply is sufficient to satisfy the domestic water supply needs without causing any water stress or shortage. Therefore, this research proposes the implementation of new boreholes for densely populated areas and infiltration galleries along simulated perennial rivers to address acute urban water shortage in Freetown, Sierra Leone.

LIST OF PUBLICATIONS

The key outputs from the work presented in this thesis are summarised as below and presented in Appendix G.

Journal paper

- Ibrahim A, Salmatta; Memon, Fayyaz Ali; Butler, David; 2021. Seasonal Variation of Rainy and Dry Season Per Capita Water Consumption in Freetown City Sierra Leone. MDPI *Water Demand Management* Water (20734441). Feb 2021, Vol. 13 Issue 4, p499. 1p. https://doi.org/10.3390/w13040499.

Conference paper

- Ibrahim A, Salmatta; Memon, Fayyaz Ali; Butler, David; Staddon, Chad, 2021. Seasonal Variation of Rainy and Dry Season Per Capita Water Consumption in Freetown City Sierra Leone. 5th Water Efficiency Conference, WatefCon2020 Online Conference: Moving towards Water Resilient Communities, University of the West of England, Bristol, UK. 3rd – 4th September 2020.

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Water Consumption Component

ASCII = American Standard Code for Information Interchange
A = average (or arithmetic mean)
AF = number of adult females in a household
AM = number of adult males in a household
A = total household floor area (m^2),
σ = standard deviation
Bt = bath
brt = bathroom taps

C = number of children in a household
d = day

dr, = duration of rainy season in year
dd = duration of dry season in year

$Deii$ = duration of water run during each event of water end-use ii

DEM = digital elevation model
DTM = digital terrain model
D_S = distance to water point

dws = dishwash

$E_{>76}$ = number of elders >76 years in the household,

$E_{66–75}$ = number of elders 66–75 years in the household

$x1$ = the value of each individual item in the list of numbers being averaged

$\sum x \ = \text{Sum of all the values of variables of x}$

F_V = flushing volume (L), m = middle-income

$Feii$= daily per capita average frequency of water end-use ii
FS = average family size
fl = flush

G = total garden area

HH = Households

h = high income households

I = per capita monthly income

L/l = litre,

l = low-income households,

lat = latrine

L/p/d = litre per person per day.

2M = surplus rainfall month

M = average monthly rainfall

m = middle income household

Min = minute

M/2 = month receiving less rainfall

N_{AF} = number of adult females in the household,

N_{AM} = number of adult males in the household,

N_{C} = number of children in the household,

N_{FL} = number of floors in the household,

N_{HS} = number of occupants in the household,

N_{RO} = number of rooms in the household,

No./d = number per day

p = person

PD_{W} - Protected dug well

pf = pour flush

PS = Public standpipe

Qe_{ii} = average flow rate of water end-use *ii* (l/min)

R = correlation coefficient

R^2 = coefficient of determination

R/S = River/Stream

R_O = number of rooms in the household
RW = Rainwater

s = slum-income, slum household

shw = shower

sec = second

S_H = shower volume

SSL = Statistics Sierra Leone

T_S = time spent to fetch water

TW = daily per capita water consumption

Ve_{ii} = quantity of water consumption during each event of water end-use

Vol = volume

VS_S = vendor pushcart
w = whole sample,

wsh= washes

WB = bowser
tf = toilet flushing

t = time,

X_2 = Normal rain month

Δh = the change in head from point 1 to point 2, [L]

ΔS_t = Change in storage

Δx = the distance between point 1 and point 2, [L]

Φ = streamfunction

Q'y = discharge per unit width (L^2/T) in the y direction

Q'_x = discharge per unit width (L^2/T) in the x direction

$S\gamma$ = specific yield

TWi = annual per capita total water consumption during year *i*

TWi = annual per capita total water consumption during year i

We_{ii} = daily per capita average consumption for water end-use *ii*

We_w = daily per capita average water consumption by each end-use during rainy season

We_d = daily per capita average water consumption by each end-use during dry season

WTW = Water Treatment Work

WW_{brt} = hand wash basin tap use wastewater

$WW_{b=}$ = bathing wastewater

WW_{black}= black wastewater

WW_{ck} = wastewater from cooking

WW_{cw} = wastewater from clothes washing

WW_{dw} = wastewater from dishwashing

WW_{grey}= grey wastewater

WW_{hw} = wastewater from house washing

WW_{shw} = wastewater from showering

WW_{tf} = wastewater from toilet flushing

WW_{vw} = wastewater from vehicle washing

A = average (or arithmetic mean)

n = the number of items being averaged

$x1$ = the value of each individual item in the list of numbers being averaged

$\sum x = \text{Sum of all the values of variables of x}$

Qe_{ii} = average flow rate of water end-use *ii* (l/min)

Ve_{ii} = quantity of water consumption during each event of water end-use *ii*

qx = specific discharge in the x-direction [L/T],

ψ = groundwater flowpath [L^3/T]

X_1 = scarce rain month

X_2 = surplus rain month

Y_R = average yearly rainfall

Groundwater Modelling Component

$\frac{\Delta h}{\Delta x}$ = hydraulic gradient in the x direction (dimensionless)

n_e = effective porosity.

v_x = actual fluid velocity, [LT^{-1}]

gpt = guid partition table

Δs = change in log cycle

b = aquifer thickness

B = baseflow

C = conductance, m^2/day

CHD = time-variant specified-head package

CHOB = specified-head flow observation package

CSV = comma-separated values

CV= coefficient of variation

dh = volumetric outflow rate, [L^3T^{-1}]

D_i = soil water deficit

dn = specified outflow volumetric flux rate, [L^3T^{-1}].

DRN = drain package

DROB = drain observation package

DRT = drain return package

E_A = actual evapotranspiration

E_p = potential evapotranspiration

ET = evapotranspiration

ETS = evapotranspiration segments package

EVT = evapotranspiration package

GBOB = general head-boundary observation package

GHB = general-head boundary package

h = hydraulic head
HFB = horizontal flow barrier package

HK = horizontal hydraulic conductivity in longitudinal/lateral direction
HOB = head observation package

I = infiltration

K x = saturated hydraulic conductivity in the x-direction, $[LT^{-1}]$
L = length of the river reach [m]
LAK = lake package

M = thickness of river bed [m]
MODFLOW = modular groundwater flow model

NM = normal rainfall

NT = normal temperature

NMA = national minerals agency
NP_R = percentage of normal rainfall
NP_T = percentage of normal temperature
NRMS = normalised root mean squared
NRMSE = normalised root mean square error
O = overflow

P = precipitation from rain or snow
PET = potential evapotranspiration
Q = discharge (m^3/s)
r = radius of the well (m)
R, Re, = recharge

RCH = recharge package

RES = reservoir package

RIV = river package

R_U/R_O = runoff

RVOB = river observation package

S = storage coefficient (--dimensionless)
s’ = residual drawdown (m)
s_1 = initial drawdown
SFR = stream-flow routing package

S_i = soil water surplus

Sp = drawdown when the pump is turned off (m)

S_R = standard deviation of yearly rainfall
SRTM = shuttle radar topography mission
Ss = subsurface flow or stormflow

S_t = storage amount of water in the soil.

S_T = standard deviation of yearly temperature
SWB = soil water budget

t = time/time taken since pump was stated
T = temperature
T = transmissibility (m^2/day)
t’ = time since pumping was stopped (min)
t_0 = initial time
t_1 = final time
Tp = time taken when the pump is turned off (minutes)

T_x = transmissivity in the x direction
T_y = transmissivity in the y direction
T_z = transmissivity in the z direction
u = parameter of the Theis (well) function
UZF = unsaturated zone flow package

VK = hydraulic conductivity in vertical direction
W = width of the river [m]

W(u) = well function
WEL = well package

X calc = calculated head for each observation
X obs = represents the observed head for each observation
X_1 = Mean/2

X_2 = 2*Mean

Δh = the change in head from point 1 to point 2, [L]
ΔS_t = change in storage

Δx = the distance between point 1 and point 2, [L]

Φ = streamfunction
$Q'y$ = discharge per unit width (L^2/T) in the y direction
Q'_x = discharge per unit width (L^2/T) in the x direction
$S\gamma$ = specific yield

Definition of Symbols

[L, length; T, time; --, dimensionless]

Symbol	Dimension	Definition
b	L	thickness of confined aquifer or saturated thickness of water table aquifer
d_s	L	thickness of the well-bore skin
F′	L	Modified Hvorslev (1951) observation well shape factor
h	L	head in aquifer
h_c	L	model calculated drawdown
h_D	--	dimensionless drawdown
hi	L	initial head (or potentiometric surface) in aquifer
h_m	L	measured drawdown

K_D	--	dimensionless ratio of vertical to horizontal hydraulic conductivity
K_s	L/T	Hydraulic conductivity of well-bore skin
K_r, K_z	L/T	Horizontal and vertical hydraulic conductivity of aquifer, respectively
L	L	Length of the screened interval of observation well
Q	L^3/T	Pumping rate of well
R	L	Radial distance from axis of pumped well
r_c	L	Inside radius of the pumped well in the interval where water levels are changing during pumping
r_D	--	Dimensionless radial distance to observation well or piezometer from axis of pumping well
r_p	L	Inside radius of the observation well in the interval where water levels are changing during pumping
r_w	L	Radius of the screened interval of the pumped well
S	--	Storativity (storage coefficient) of aquifer
S_s	1/L	Specific storage of aquifer
S_w	--	Well-bore skin
S_y	--	Specific yield of aquifer
t, t_0,t_1	T	Time
t_D	--	Dimensionless time
t_{Dy}	--	Dimensionless time with respect to specific yield
T	L^2/T	Transmissivity of aquifer
W_D	--	Dimensionless well-bore storage
W'_D	--	Dimensionless delayed response factor
z	L	Depth below top of aquifer or initial water table

z_1	L	Depth below top of aquifer or initial water table to the top of screened interval of observation well
z_2	L	Depth below top of aquifer or initial water table to the bottom of screened interval of observation well
z_p	L	Depth below top of aquifer or initial water table to centre of piezometer
z_{pd}	L	Depth below top of aquifer or initial water table to the top of screened interval of pumped well
z_{pl}	L	Depth below top of aquifer or initial water table to the bottom of screened interval of pumped well
α_i	1/T	ith empirical drainage constant
β	--	Dimensionless product of and the square of dimensionless radial distance to observation well or piezometer
β_w	--	Dimensionless product of anisotropic ratio of vertical to horizontal hydraulic conductivity and the square of dimensionless radius of screened interval of pumped well
γ_i	--	Ith dimensionless empirical drainage constant
∞	--	Infinity

UNITS

bt/p/d	number of baths per person per day
brt/p/d	number of bathroom tap use per person per day
cm	centimetre
cs/d	cooking sessions per day
d	day
dws	dishwash per day
fl/p/d	number of toilet flushes per person per day
fl/p/d	number of toilet flushes per person per day
g	gram
gal	gallon
hh	household
hr	hour
hr/d	hours per day
hr/min	hours per minutes
hr/hh/d	hours per household per day
hr/wtr	hours per watering session
km	kilometre
Km/hr	kilometre per hour
Km^2	Kilometre square
km^2/yr	kilometre square per year
Km^3/yr	cubic kilometre per year
L	litre
l	litre
L/bt	litre per bath
l/cs	litre per cooking session
l/d	litre per day
l/event	litre per tap use event
l/fl	litre per toilet flush
l/hh/d	litre per household per day
l/hh/w	litre per household per week
l/min	litre per minute
L/min	litre per minute

L/bt	litre per bath
L/p/d	litre per capita per day
l/p/d	litre per capita per day
L/tf	litres per toilet flush
L/wsl	litres per clothes washing load
l/wsl	litres per clothes washing load
L/wsh/d	litres per wash per day
L/pf/d	litres per pour flush per day
lat/p/d	latrine use per person per day
m	metre
m^2	square meter
m^2/hh	square meter per household
m^3/yr	cubic metre per year
m^3	cubic meter`
m^3/d	cubic meter per day
m^3/sec	cubic meter per second
m^3/hr	cubic meter per hour
m^3/yr	cubic meter per year
m^3/hh/yr	cubic meter per household per year
m^3/p/yr	cubic meter per person per year
min	minutes
min/d	minutes/day
min/shw	minutes per shower
min/p/shw	minutes per person per shower
min/p/w	minute per person per week
min/p/wsh	minutes per person per wash
min/wsh	minutes per wash
min/wtr	minutes per watering
^{O}C	Celsius (centigrade)
sec	second
sec/tpu	seconds per tap use
sec/brt	second per bathroom tap use
shw/d	number of showers per day

shw/p/d	number of showers per person per day
SLL	Sierra Leone Leones
SLL/mon	Sierra Leone Leones per month
tpu/p/d	number of tap uses per person per day
wsh/d	number of washes per day
wsh/w	number of washes per week
wtr/d	frequency of garden watering per day

ACRONYMS/ABBREVIATIONS

DFID	Department for International Development
FAO	Food and Agriculture Organisation
GCMs	Global Circulation Models
GoSL	Government of Sierra Leone
GVWC	Guma Valley Water Company
JMP	Joint Monitoring Programme
LGAM	Local Government Act Ministry
MDAs	Ministries Departments and Agencies
MDGs	Millennium Development Goals
MICS	Multiple Integrated Cluster Survey
MoE	Ministry of Energy
MoFED	Department for International Development
MoLGRD	Ministry of Local Government and Rural Development
MWR	Ministry of Water Resources
NASA	National Aeronautics and Space Administration
NMA	National Minerals Agency
NOAA	National Oceanic and Atmospheric Administration
NWP	National Water Policy
PRSP(s)	Poverty Reduction Strategy Paper (s)
RCMs	Regional Circulation Models
SALWACO	Sierra Leone Water Company
USEPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator system
WASH	Water, Sanitation and Hygiene Sector
WB	World Bank
WTW	Water Transmission Works

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND JUSTIFICATION

Water is the most valuable and essential natural resource to mankind as well as to the ecosystem (Mooney et al., 2005). It is a vital part of the human life. However, its availability varies with time and space as characterised by the hydrological cycle.

The effect of seasonal variability on water resources with reference to household characteristics (demographic, socio-economic and water-use) on end-uses scale has been widely addressed in the literature by Cosgrove and Loucks (2007); Klein et al. (2007); Arouna and Dabbert, (2010); Grafton et al. (2011); Ogunbode and Ifabiyi (2014); Hussien et al. (2016); Kumpel et al. (2017). However, the impact of seasonal variability and management strategies are very dismal to addressing per capita water needs. Additionally, water consumption is varied seasonally, predominantly in developing countries where water scarcity affects more than 40 percent of the global population (UNESCO, 2018). This figure is projected to rise to 3 billion people in water-stressed countries by 2025, UNDP (2018).

As population increases, freshwater demand increase, and supplies per capita also decreases. The rise in urban water demand has been supported by consistent research for evaluation and adjustment in planning purposes, designing and management of water supply systems to be sustainable in the developed world. However, water consumption patterns in the developing world have not been investigated widely. Studies reported in Calow *et al.* (1997); Atkins (2008); Gruber et al. (2009); Arouna and Dabbert (2010); Fielding *et al.* (2012); Akoteyon (2016); Lapworth *et al.* (2017) show that access to water supply in urban Sierra Leone like many other sub-Saharan countries is experiencing serious setbacks, many of which are socio-economic, political and climatic in nature. In past decades, concerns have been raised on the amount of water availability for domestic water supply in developing countries Goulden et al. (2009); Kundzewicz and Döll (2009); Taylor et al. (2009); Borg et al. (2012) asserted that groundwater may be the only sustained and logical option to support communities where surface waters are inadequate. Groundwater requires less treatment for access in terms of infrastructure requirement compared to surface water (Braune and Xu, 2010). However, the dearth of observational data and difficulty to access available ones in many African countries has given rise to uncertainty in groundwater development and abstraction.

Groundwater is the water occurring beneath the earth's surface that completely fills the void space of rocks or sediments. Globally, groundwater resources are under immense pressure caused by anthropogenic activities and other factors including seasonal variability and climate change (WWAP, 2017). The rapid population growth, especially in urban settlements could potentially exhaust the quantity and degrade the quality of water if not managed properly; and will admittedly generate considerable challenges to develop appropriate water supply strategies.

For many developing countries, groundwater is the main water source for more than two billion people (Seckler *et al.*, 2010). In Sierra Leone and most other developing countries in sub-Saharan Africa, groundwater is the main source of supply in some urban and most rural settlements because it is a cheaper option than harvesting surface water (Hiscock and Grischek, 2002). According to the United Nations (2013) groundwater's importance has not been thoroughly investigated and therefore there is a need for further research on the topic.

The rates of human usage generally outpace the natural rates of groundwater replenishment; as such, conservation measures must be put in place in every community (Alley et al., 1999). Groundwater resources need to be well protected, as reduction in its storage can lead to severe implications in the water cycle; its quantity and quality. In some situations, the use of groundwater is inadequate because of wrong wells siting, poor productivity of wells, drying of wells and poor water quality. Properly conserving groundwater requires careful analysis of where it is located, how it moves, and how it is recharged (Sophocleous, 2010). A sustainable development of groundwater resources will require quantitative estimates of its volumes in the aquifer zones.

Quantifying the dynamics of groundwater flow in different geological setting is still a challenge, because of the difficulties in determining hydrogeological parameters and the availability of the equipment to monitor and gather data from observations. Even when there were attempts to research seasonal variability water consumption and groundwater as a source of domestic water consumption, the focus was often to treat each study in isolation. The impetus for estimating per capita water consumption and groundwater recharge potential is to ensure sustainable abstraction during the rain and dry weather conditions as water consumption can vary greatly between these seasons (Taylor, 2013). An assessment tool like this study is required, to be able to quantify the impact of factors, such as household characteristics, seasonal variability and groundwater development.

This research will address relevant information lacking on what previous researchers have studied on household water consumption, seasonal variability impacts on groundwater resources. This is to support domestic water consumption and further design a simulation that will model the behaviours of per capita seasonal water consumption patterns for a densely populated urban city, that struggles with providing adequate water service and poor management strategies like in Freetown, Sierra Leone (Lapworth et al., 2017).

The methodology includes a three-part water consumption survey, well pumping tests, and an analysis of downloaded digital elevation data of the study area in a spatial process. This will identify and manage the potential risks and limitations applied to the field geology, geohydrology, geomorphology, geophysics, hydrology, drainage and land use properties for the hydrogeologist to understand the problems of groundwater exploration and abstraction. It will analyse different types of groundwater flow calibrated situations, with the use of a 3D simulation ModelMuse MODFLOW approach to iterate present and future scenarios of groundwater system to change in precipitation and abstraction. Furthermore, it will analyse the spatial variation of surface and subsurface properties looking at soil type, lineaments, aspect ratio, slope, and vegetation for water consumption and usage. The study aims to propose a strategy that will manage groundwater resources sustainably to households under future seasonal variability on groundwater recharge and abstraction. This will be done by determining the aquifer safe yield, to know how much water each well will pump in the rainy and dry seasons as well as how many wells are needed for a safe and sustainable exploitation. The predictions and results from the groundwater simulations will determine the suitable regions to site new artificial recharge and water abstraction points. GIS environment is used to analyse and prepare all the thematic maps from downloaded topographic information. The groundwater potential zone map is produced from the analysed thematic maps. Each component layout is discussed in the related chapters.

1.2 RESEARCH QUESTIONS

The research has been designed to investigate the following research questions:

1. What are the factors that affect access and availability to domestic water for consumption?
2. How does seasonal variability impact groundwater resource in Freetown?
3. How the groundwater in Freetown is influenced by different water needs and what is the safe aquifer safe yield between seasons?
4. What will be the hydrogeologic effect of abstraction as a result of seasonal variability?
5. What minimum water level is possible or needed to sustain the usage and demand in the dry periods?
6. What sites or locations can be selected for new construction of water points?
7. What are the key groundwater recharge sources?
8. What is the magnitude and direction of groundwater flow under natural and artificial recharge processes?
9. How to mitigate groundwater stresses caused by natural and artificial processes?
10. What will the average water consumption patterns and behaviours likely be?

1.3 AIM AND OBJECTIVES

The aim of this research is to develop a strategy to manage groundwater resources sustainably to households in Freetown, Sierra Leone under the influence of seasonal variability. To achieve this aim, the research will include the following objectives:

1. Review the literature on factors that affect groundwater resources as well as mitigation and adaptation strategies to manage them.
2. Conduct seasonal domestic water consumption questionnaire-based study and identify the factors between end-uses of water at per capita level for households in Freetown, Sierra Leone.

3. Develop hydrogeologic models for Freetown using numerical ModelMuse MODFLOW packages and GIS to delineate wells position and identify sources of recharge and response of the aquifer to abstraction.
4. Evaluate the developed numerical models using available topographic and wells data under specific hydrogeologic conditions.
5. Predict the groundwater quantity and assess the recharge capacity in the area over a period of next 15 years by using a numerical model under various scenarios.
6. Apply the groundwater simulation to investigate the impacts of climate and seasonal variability on Freetown groundwater resources.
7. Identify suitable sites for new wells / boreholes construction and artificial recharge structures for adequate groundwater management.

1.4 NOVELTY AND CONTRIBUTION TO KNOWLEDGE OF THE RESEARCH

Research conducted in this study can be considered as original and makes a contribution to knowledge in several ways:

- This research produces a number of datasets on per capita water consumption by urban households and neighbourhoods. In low and middle income countries, these variables may help to explain the impact of household characteristics (for example, the number of children, the number of males, number of females and the age of the elderly in the household, the number of rooms, the number of floors, and income), water use characteristics (for example, shower volume, number of water storage containers, time spent to fetch water, distance to water points), and seasonal variability on domestic water consumption at end-use scale.
- Data collected during the study was used to develop models based on multiple linear regression (STEPWISE). Using these statistical regression models, one can estimate future water consumption in relation to household and water use characteristics for low and middle income countries.
- A methodology has been developed to simulate groundwater recharge flow by integrating per capita water end use consumption data for different groundwater

abstraction scenarios. This can be used to design a sustainable water supply plan for future years.

- A methodology has been developed to assess and quantify the recharge capacity of the groundwater system under the impact of seasonal variability. This can be used to manage and design the safe yield abstraction strategy of the aquifers.
- In this study, digital groundwater maps were produced based on the geology of the area. The maps and this report provide useful baseline information for a variety of purposes, including groundwater investigation, groundwater development, groundwater management, and aquifer safety.

1.5 ORGANIZATION OF THE THESIS

The organization of the thesis consist of eight chapters covering all aspects of the work, carried out viz., seasonal water consumption survey and pumping wells tests field data analysis, preparation of geologic thematic maps, analysis of the results of the investigation for household water consumption, the assessment of groundwater resources, groundwater numerical models calibration, groundwater model validation, sensitivity analysis of groundwater parameters, groundwater quantification management application for sustainable abstraction under the impact of seasonal variability, design of infiltration galleries and siting of new wells/boreholes.

Chapter 1 will provide the background and justifications for the research. The chapter describes the research questions, aim and objectives, and details the contributions to the knowledge.

Chapter 2 on literature review presents a comprehensive evaluation on the previous studies conducted by other investigators relevant to this study. While reviewing the research papers, the following topics of interest were chosen for review, household/per capita water consumption, and seasonal variability impacts on groundwater resources, groundwater modelling and GIS, groundwater recharge, aquifer parameters, quantitative assessment of groundwater, statistical modelling and groundwater management.

Chapter 3 presents the generalised characteristics of Freetown, materials and methods used in preparing hydrogeologic and thematic maps as well as an overview of the climate and geomorphology in the capacity to support groundwater as a potential sustainable solution. The chapter will also describe the geology and hydrogeologic conditions of the study area.

Chapter 4 presents the methodologies employed for household water consumption data collection and analysis, development of water use models, model calibration and validation for household characteristics. It distinctly deals with the details of the regression models used to develop a relationship between per capita water consumption in the households. It also presents the methodology for the analysis of the observed groundwater field data consisting of topographical characteristics using GIS. The chapter will also presents the study of rainfall patterns, temperature analysis trend, assessment of groundwater scenarios, water budget study, estimation of aquifer parameters and groundwater management.

Chapter 5 is a presentation of the detailed statistical analysis for water consumption questionnaire-based study result. The relationship between household characteristics (socio-economic, demographic and water use) and the consumption for water is investigated. The chapter will focus on analysing the effect of income and seasonal variability on per capita water consumption. Additionally, it will present statistical regression models developed to estimate per capita water consumption as a function of household and water use characteristics.

Chapter 6 describes the entire groundwater model development and groundwater model application results. It will highlight the analytical and numerical details of the various methods used to develop the relationship between water consumption and groundwater recharge. The calibration and superposition modelling approach which are appropriate to adequately simulate scenarios of the objectives will be utilised. It also presents discussions for the analysis of the observed field data consisted of topographical characteristics study using GIS, study of rainfall and temperature analysis, estimation of aquifer parameters using pumping test data, estimation of volumetric budgets using water balance methods, assessment of groundwater quantity using ModelMuse MODFLOW and GIS. Additionally, it will present the sensitivity analysis to test the accuracy of the groundwater model results and overall responses of simulation changes in hydraulic conductivity and recharge.

Chapter 7 will present the strategies developed for groundwater management strategies and guidelines relating to planning, siting, projections of groundwater potential zones, annual aquifer safe yield exploitation and designing of artificial recharge structures like infiltration galleries.

Chapter 8 provides key conclusions and the recommendations that will summarise the findings of the research and proposed further research in this area of study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

There are many constraints and challenges in providing water for domestic consumption as well as agricultural use at all times of the year (Mancosu et al., 2015). Among the major problems in developing countries is the lack of qualified human resources (hydrogeologists), inadequate institutional capacity, inadequate water management strategies, lack of awareness on climate and seasonal change to recognize the vulnerability of water resources, lack of data, and financial challenges to engage in research. A combination of these problems compromises the incapability to provide enough water to meet daily per capita consumption. The stresses on water resources are a combination of population growth, urbanisation, and encroachment on the watershed, poor siting of wells/boreholes, poor skills and knowledge to locate sustainable water sources (Döll et al., 2015). As the population is increasing, so will the increase in threat to water subjected to continuous exploitation.

The water demand has been increased many folds and most of the areas dependent on surface water have struggled with infrastructural challenges and are looking at harnessing groundwater to meet this increasing need for water. However, the inadequate knowledge of water managers, water education on pollution, urbanization, lack of realistic technical information for successful wells siting has degraded both the quantity and quality of the resource. There is an urgent need for research on water consumption behaviours and patterns to design efficient and effective water use strategies being integrated into groundwater management procedures (Troy et al., 2008; Forster et al., 2009). Valuable information and a good understanding of the relationship between domestic water needs and groundwater development can help policymakers and water resource planners with better coordination in their efforts to ensure the sustainability of urban water resources (Gleick, 1996; Varis et al., 2014).

This chapter presents background information and reviews of literature relevant to impacts of seasonal variability on groundwater resources; and its effects on per capita water consumption for outdoor and indoor water end-uses in an urban setting. The causes, effects, and factors of seasonal variability on groundwater hydraulics and demand, as well as seasonal per capita water consumption patterns, will be explored in Section 2.2 to 2.6. Groundwater-surface water dynamics, governance, and management will be reviewed in Section 2.7 to 2.9.3. The quantification of water withdrawals for consumptive uses from the surface and subsurface environments will also be studied in Section 2.10. Additionally, the impact of seasonality on domestic water consumption patterns and household characteristics will be discussed in Section 2.10.1.

This chapter will also present literature on intensive groundwater abstraction and groundwater yield in an urban setting in Sections 2.9.2 to 2.9.3. And finally conclude by outlining the current deficiencies in the collection of knowledge and what measures need to be put in place to mitigate the impacts on groundwater availability for sustainable water consumption.

2.2 Water consumption at a per capita level

Per Capita water consumption is water used by each person per day. According to the WHO (2005), the volume per person varies between 50 and 100 litres (L) of water per day to take care of the most basic needs and health issues. These uses usually include drinking, cooking, food preparation, washing of clothes, sanitation, personal and household hygiene.

Per capita, water consumption is affected by several factors including water-utility tariffs, water availability, weather, and climate (Bates et al., 2008; UN-WWAP, 2015; Unesco World Water Assessment Programme, 2018)). Studies of per capita water use vary widely across the world (Whittington and Nauges, 2010). Analyses of residential per capita water consumption surveys conducted in industrialised and developed countries have highlighted that water consumption often varies across countries by quantity, availability, and access. The variability makes it difficult to effectively determine an inclusive per capita water usage globally. As such within the low and middle countries, there is a considerable heterogeneity among households and their water consumption patterns vary due to income and storage potential (Howard, 2003; Hussien et al., 2016).

Not all households are connected to a piped water network in low and middle-income countries, and even those that are connected experience intermittent water supply services and have relied on a variety of multiple water sources e.g. streams, rivers, dug wells, rainwater characterized with different levels of services including distance, queueing time, quality, price and reliability (Water, 2008; Whittington, 2010).

Availability of water is one of the biggest challenges facing the water sector in many low and middle-income cities and this is exacerbated by the increasing material comfort of the urban population and per capita water demand that stresses the limited water resources (Klein et al., 2007). According to the WHO/UNICEF (2015) and United Nations Children's Fund (2018) round trip access to basic drinking water service should take 30 minutes or less as defined by the Sustainable Development Goals (SDGs); and if access exceeds 30 minutes, the service is termed as limited. Many studies, Aitken et al. (1994); Borg et al. (2013); Basu et al. (2017) have analysed some of the factors impacting domestic water use in developed and developing countries. In Makurdi Nigeria, Aho et al. (2016) used multiple regression analysis to identify seven variables mainly; household size, gender, number of children in the household, kitchen type, and level of education as the significant factors influencing residential per capita water consumption. Some of these studies with their key findings are listed in Table 2.1.

The WHO has guaranteed that the minimum basic daily per capita water needs in an emergency or humanitarian situation is 20 litres per person per day. However, the FAO has established data for daily per capita water consumption (l/p/d) for some developed countries and middle and low income countries from early 2000 to date, example America as 185l/p/d, Ghana and Nigeria has been estimated as 36 l/p/d, Australia 338 l/p/d, England 148 l/p/d, China 230 l/p/d (FAO AQUASTAT, 2016).

Table 2. 1 Summary of factors affecting per capita water consumption

Factors	Reference	Key findings
Education level	Asthana (1997)	Higher literacy of women affects water consumption and determines the choice of safe water and willingness to pay for it.
Household size & household type	Domene and Sauri (2006)	They investigated whether housing types e.g. single houses, apartment blocks with garden space, swimming pool and household types lacking these amenities based on their size and consumption behaviour will impact domestic water consumption.
	Seyed et al. (2016)	That per capita water consumption varies considerable with household type and size.
Religious practice	Zaied (2016)	They studied five different types of taps flows consumed during ablution and used the analysis to develop better ablution strategies such as releasing water from the taps to wash the different body parts when needed.
Household income	Darr et al. (1975)	Income has been an important predictor of residential water use
	Dandy et al. (1977)	Water consumption is positively correlated with Income level of households.
Seasonal change	Grafton et al. (2011)	Price and non-price factors on residential water demand to respond to climate variability
Household makeup & property	Aho et al. (2016)	They used kitchen type, number of cars, different water sources, number of children <6 years and gender to study water consumption and noted these variables predict residential water demand.
Climatic condition	Balling et al. (2008)	Investigated the sensitivity of single-family residential water consumption to variations in climate in Phoenix, Arizona and found that residential water consumption is significantly related to variations in climate.
Attitude and Affluence	Harlan et al. (2009)	The study addresses how and why affluence affects household water consumption behaviour.
	Randolph and Troy (2008)	In Australia, they investigated the water use attitudes of households to reduce water demand.
Human behaviour	Jorgensen et al. (2009)	That Trust in water providers and in the different water using sector is an effective tool in water demand strategies.
	Fan et al. (2013)	In China, consumption behaviour is investigated to design efficient and effective water use strategies.
	Shan et al. (2015)	Investigated how end-uses behaviours, property characteristics attitudes and beliefs could be applied to domestic water consumption to promote water saving in Greece and Poland.
Age of household members	Ogunbode and Ifabiyi (2014)	Investigated consumption variations among households age group from 18 – 65 to derive relevant decision on domestic water use.
House ownership	IPART (2004)	Households living in houses to those living in flats consume more water because houses are much larger in terms of space.
Water Conservation	Borg et al. (2013)	In Davis, California, they investigated the use of low-flow devices to increase water efficiency and conservation.
	Willis et al. (2011)	Use of smart metering and household income to reduce water wastage and control water consumption.
	AWWARF and AWWA (1999)	Investigate water end-uses in single family households for conservation effectiveness
Household location and area	Viljoen (2015)	Researched different categories of housing locations and areas e.g. slums, low income groups with varying use to alternative water sources, water saving fixtures and toilet usage to establish guidelines for water efficiency.

	Purshouse et al. (2015)	In Accra, Ghana investigated improved water in Slum areas with regards to accessibility and reliability.
Water supply reliability and accessibility	Purshouse et al. (2015)	In Nairobi, Kenya they looked at water source locations inside the house, inside the yard or elsewhere and it reliability.
Water collectors	Graham et al. (2016)	Across all developing countries investigated, female children were more likely to be the water collectors than their male counterparts.
Piped water connection /non-connection	Basani et al. (2007)	They studied water connection from four different water providers and estimated water consumption for each household by dividing their monthly bills by unit tariff to delivery system
Water price	Khadam (1988)	Water price can be a tool to ration or discourage water consumption in piped households to increase consumption in informal settlements.

2.2.1 Indoor water requirements

According to Gato-trinidad et al. (2011), indoor water use is weather dependent. Water requirements for indoor water use activities comprise the following end-uses.

Showering and bathing

Several studies investigated the relationship between showering and household characteristics. Household water demand for showering is mostly the highest of all indoor water use in low and middle-income cities and it increases with increasing family size and the household income Troy et al. (2005). Household water use for showering and bathing may be influenced by climate conditions. Rathnayaka et al. (2015) observed that hot weather and dusty situation increases the number of showering/bathing times.

In terms of saving water, low flow showerheads can be installed in households to save up to 50% of indoor water use (McKenzie-Mohr and Associates, 2010). The most common method of bathing in many low and middle-income countries is by having water in a bucket bath. Beal et al. (2010) and De Buck et al. (2017) have estimated water usage for showering in developed countries (38 – 65l/p/d) and in low and middle countries with inadequate water distribution systems (15 – 25 l/p/d). Bartram and Howard (2003) and Stephens (1996) observed that the quantity of water required to maintain good hygiene may vary significantly depending on the water collection patterns. Gleick (1996) recommended that the water used for bathing is ranged between 5 and 70 l/p/d and mostly is 15 l/p/d. The volume of water used for bathing in developed countries is estimated at 27 – 99l and for developing countries between 5 – 25l (Inocencio et al., 1999).

Wash hand basin taps

Boone et al. (2011) examined how water supply choice and time are influenced by household characteristics in Madagascar. In Kenya and Ghana, Purshouse et al. (2015) investigated the accessibility and reliability of improved water supply to slum areas. Zaied (2017) studied water consumption, during ablution, from five different types of taps and used the analysis to develop better ablution strategies e.g. by releasing water from the taps only at moments of need or using a container to store the water for ablution. In China, Fan et al. (2013a) researched water consumption behaviours to design efficient and effective water use strategies. Fielding et al. (2012) identified and analysed the critical determinants of household water use, and how demographic, psychosocial, behavioural, and infrastructure variables all have a role to play in determining household water use. Hussein et al. (2016), predicted future per capita washbasin tap water use for the city of Duhok, to range from 10l/p/d to 11l/p/d. In many low and middle-income regions, low-volume taps are common because of limited water availability. The key message in all these studies is that from the analysis of water used to wash body parts during ablution, the feet, hands and face takes much longer time to wash. If the tap is left running during the wash period, unnecessary volume will be consumed. To save water consumed in ablution from taps, it is best to only release water at moments of need. Other ways to reduce water use is to have the push-type tap or to only use the required volume in a container.

Toilet flushing

The impact of various factors on water use for toilet flushing is investigated. Water availability, income, and cultural factors influence the choice of sanitation technology (White et al., 1972). The study conducted by Inocencio et al. (1999) shows that the daily per capita water requirement for toilet flushing depends on the type of technology and the source of water available. Another study observed that the required water used for toilet flushing depends on the type of sanitation technology, for example, pour-flush and pit latrine toilets require 2- 6 l/p/d and 1-2 l/p/d, respectively (Mara, 1985).

A considerable quantity of water can be used for toilet flushing. The UN (2003) report noted that a single flush of a western toilet uses as much water as the average person in low and middle-income countries uses for the entire activities of a single day of bathing, clothes washing, cleaning, drinking, and cooking. Per capita, water use for toilet flushing correlates positively with the number of family members staying at the house most of the day without full-time outside employment (Blokker *et al.*, 2009).

Dishwashing

Similar to toilet flushing, water use for dishwashing correlates positively with the number of family members in the house but decreases with an increase in the number of family members that have full-time employment outside the house (Mayer et al., 1999). Although using an electric dishwasher is seen to save a considerable amount of water, energy, time, and money (Berkholz and Stamminger, 2010), the use of a dishwasher is not common in low and middle-income countries due to lack of continuous energy and available water supply. Dishwashing is mainly done by hand in a bowl of water.

Richter (2011) observed that in his study comparing the use of an automatic dishwasher to a manual one, a saving of 50 – 80% amount of water and energy is conserved to only 6-40% when the process is done manually. In the UK, the daily per capita average consumption for manual dishwashing is 49 l of water and 1.7 kWh of energy (Berkholz et al., 2010). However, reduced consumption of water to wash a similar amount of dishes can vary from 15 to 23 litres per day in middle and low income countries (Schuetze and Santiago-Fanidino, 2013).

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Drinking and Cooking

Since the 1990s, the urban population in many developing countries without safe and improved access to drinking water has increased to 844 million people in 2015 (WHO/UNICEF, 2017). Water use for drinking and food preparation is a function of various factors. This amount varies depending on the climate conditions and human physiological characteristics but the variation is very slight (Gleick, 1996; Inocencio et al., 1999). Per capita, the average quantity of drinking water for survival is 2 l/p/d (Gleick, 1996).

The quantity of water used for cooking increases with the increase in household income (Blokker et al., 2009). Globally, per capita, minimum water usage is 10 l/p/d for food preparation in developing regions while it increases to up to 50 l/p/d in the developed regions (Gleick, 1996). Water requirement for food preparation is also affected by the type of water sources, such as standpipe (10.5 l/p/d), piped connection (7-15 l/p/d), and private well (15 l/p/d) (Inocencio et al., 1999).

Clothes washing

Water source type can be a major factor affecting the quantity of water used for clothes washing. In the low and middle-income countries, Inocencio et al. (1999) observed approximately 8–10 l/p/d for a private well, 5–38 l/p/d for piped connection, and 5 l/p/d for standpipe. Other parameters that can influence the number of clothes washing per household per day can be seasonal (temperature) variability and the number of occupants (Arouna and Dabbert, 2010). However, the required water for laundry can be much higher in some countries such as the United States, 29–71 l/p/d (Inocencio et al., 1999).

Intermittent energy and water supply is another significant factor for not operating water-saving appliances in developing countries. Schuetze and Santiago-Fandiño (2013) observed that the use of house saving water appliances could contribute to efficient water use. The main parameters to identify water consumption for clothes washing are the number of times clothes washing is done per day and the volume of water used per each wash. Household size, income, number of school-going persons, and the number of family members that work full time outside the house are some of the factors that are influencing and directly related to water use for clothes washing (Mayer et al., 1999). Moreover, the quantity of water required for clothes washing varies depending on whether it is manual washing or using a washing machine.

2.2.2 Outdoor water requirements

The outdoor water requirements for a household comprise water use for garden watering, swimming pool usage, and vehicle washing. Outdoor water use is more sensitive to the changes in water price and climate than indoor use. Garden watering is usually the main reason for increasing the quantity of household water consumption (Fan et al., 2013). Outdoor water use varies greatly depending upon geographic location, the climate of the region, and also the watering system. It might be higher in the dry and hot climate regions and also when using an inefficient watering method example in garden watering. In most developed countries, daily average water consumption for outdoor uses (water used mostly for garden watering) accounts for approximately 60% of the total household consumption in America (EPA, 2013).

A household swimming pool can also be an intensive outdoor water consumer. Mini et al. (2014) listed that the minimum quantity of water necessary for filling an average swimming pool is approximately 19000 gallons (86376 Litres). This volume of water is a challenge for many low and middle-income countries that struggle with providing an adequate daily per capita water supply of 50 l/p/d. In reality, a significant amount of water may evaporate from the swimming pool, mainly in dry and arid regions.

2.2.3 Estimation of household water demand

Nauges and Whittington (2010) observed in their study that one key challenge that water managers face in designing water distribution systems is data availability, which includes, for example, water price, cost of water collection, quality of water service, and socio-economic characteristics of a household.

Typically, water utility companies have no information on households' socio-economic and demographic characteristics, such as household size, income, household composition, age, gender, and education level. Water planners need information on the patterns of households and water characteristics to address the challenges to meet the water supply-demand. This is why household water consumption surveys can be conducted to provide these data. Most studies have identified two main methods to estimate or predict future water usage for a household (Nauges and Whittington, 2010; Hussein et. al., 2016). The simplest method is to estimate the daily water end uses with the predicted size of the population. In this method, the difficulty is integrating the changes in per capita water consumption as a result of seasonal weather variation, income/economic growth, change in water price, lifestyle, and technological development (Nieswiadomy, 1992). The second is the economics approach which uses a function of various factors (e.g., income, weather, water price, and other factors) to develop a water consumption estimation model (Gato et. al., 2013).

One of the efficient methods for understanding and estimating household water usage is to disaggregate water consumption to end-uses (Marinoski et al., 2014; Hussein et. al., 2016). The definition of end-use depends on the scale of the investigation. At a household level, it comprises cooking, showering, house washing, clothes washing, dishwashing, tap uses, toilet flushing, vehicle washing, and garden watering. The water end-use method can assist water managers to design effective supply management programs to ensure sustainable water consumption, such as using low flow plumbing fixtures appliances in flush toilets and showerheads and adopt efficient irrigation technologies (Millock and Nauges, 2010).

In the developing countries, fewer effort has been made for modelling household and domestic water usage compared to that in the developed countries (Nauges and Whittington, 2010). This may be due to the unreliable household water supply at public standpipes, intermittent water supply with private piped connections and the multiple household water sources accessed in developing countries.

Several studies have considered different household and water habit characteristics for water usage modelling and estimation in the developing countries, such as distance to a water source, queueing time to fetch water (Ogunbode and Ifayabi, 2014), Household size (Aho et al., 2006), an education level (Fan et. al., 2014), family income (Fan et. al., 2014) and reliability of water from other sources (Smiley, 2016). Consequently, the household physical characteristics (e.g., number of rooms, number of floors, total built-up area, and garden area), rainwater harvesting, and greywater recycling should also be considered to develop effective models to predict domestic consumption.

2.3 Groundwater Resource

Groundwater is the water occurring beneath the earth's surface that fills the void space of rocks or sediments; it is a highly valuable resource, clean and more abundant than surface water (UNESCO, 2015). It accounts for only 30% of Earth's freshwater and is the primary source of over 1.5 billion people worldwide. Groundwater has many advantages for water supply development. Water stored in aquifers is naturally protected from evaporation and has an excellent microbiological and organic quality, which requires minimal treatment as against surface water (Chilton and Foster, 1995). The capital cost of groundwater development is relatively modest and the land requirements are minimal (Chilton and Seiler, 2006). Globally, groundwater resources are under immense pressure caused by anthropogenic activities and other factors including climate variability which affects its availability seasonally (Christensen et al., 2007; IPCC, 2007). Groundwater resource provides the highest possibility of coping with and mitigating the impacts of climatic effects and water use demand compared to surface water, because of its location; as it responds more slowly to meteorological conditions and can provide a natural buffer against the effects of climate variability and droughts (Bates et al., 2008). Regardless of its location, rapid population growth especially in urban settlements could potentially exhaust the quantity and degrade the quality if not managed properly.

2.3.1 Gravity and molecular attraction on groundwater

In contrast to surface water, groundwater is subjected to gravity and molecular attractive forces in the subsurface. Gravity force causes water to infiltrate through the impermeable layers into the saturated zone. The molecular attraction allows the slow flow of the water through small pore spaces. Gravity and molecular attraction then translate the direction and rate of groundwater movement in the subsurface. Groundwater, unlike surface water, is not in direct contact with the atmosphere, and therefore in the subsurface, it is coupled with its gravitational potential energy under considerable atmospheric pressure, such that for groundwater in confined aquifers, the pressure is so high that it creates upward flow against gravity as characterised in Artesian wells (Thompson and Cairncross, 2002). Groundwater travels from a region of a high hydraulic gradient to one of a low hydraulic gradient. Pumping of groundwater from wells can have significant effects on the system as it always causes a decrease in groundwater levels at and near the well thereby creating pronounced depression cones.

2.3.2 Factors affecting groundwater resources

Apart from the geological problems (drought and pollution from commercial pesticides) faced by aquifers, groundwater resources in developing cities are stressed with the problems of poor planning, urbanization, population growth, and sanitation problems (Lapworth et al., 2015). An overview of studies discussing factors affecting groundwater is shown in Table 2.2. The main problems faced by wells construction include well siting where hydraulic properties can affect groundwater flow; recharge, exploitable storage for large-scale development in aquifers (Stuart et al., 2011). There is mounting evidence that variability in seasons is caused by increasing concentrations of greenhouse gases, that have occurred in the past, and is happening now and will continue to happen (IPCC, 2007; Dragoni and Sukhija, 2008). However, the effect on groundwater compared to surface water would not be too pronounced because of groundwater's location and its residence times. This further explains why groundwater is a preferred option under seasonal conditions to surface water that is subjected to excessive exploitation and climatic conditions. This will then affect the hydrogeologic cycle through the change in temperature and precipitation (Singh and Kumar, 2010).

Groundwater resources in developing cities are stressed with the problems of poor planning, migration (economic, cultural, and political such as civil disturbance), land use patterns, sea-level rise, and contamination (Lerner, 1990; Foster et al., 1999; Lapworth et al., 2015). The main factors that control groundwater development include vegetation, infiltration rate, surface runoff, and temperature (Xu and Beekman, 2003; Braune and Xu, 2010; MacDonald et al., 2013). The Commission and Environment (2012) has reported that the growing demand for freshwater has caused many countries to examine ways in which essential water can be provided while preserving supplies for future use. Urban settlements with accompanying deforestation and other adverse environmental effects has led to a much-reduced supply of water from surface water resources. This in turn has resulted in much reliance on groundwater as an alternative source.

Table 2. 2 Overview of Studies discussing Natural and Man-Made Stresses affecting Groundwater Development (Source authour's analysis)

No.	**Driving factors**		**Cited References**										
	Determinant	**Determinant analysis**	Gerla and Matheney (1996)	Xu and Beekman (2003)	Miyaoka (2007)	Bates et al. (2008)	Dragoni and Sukhija (2008)	Singh and Kumar (2010)	Döll et al. (2012)	Sekhar et al. (2013)	Grajewski et al. (2014)	Serdeczny et al. (2016)	Lapworth et al. (2017)
1.	***Natural***	Geological	✓		✓	✓							
		Land use / land cover	✓		✓	✓	✓		✓		✓		
		Sea level rise			✓	✓		✓		✓		✓	✓
		Temperature	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Infiltration	✓	✓	✓	✓		✓	✓	✓	✓	✓	
		Run-off	✓	✓		✓		✓	✓	✓	✓	✓	✓
2.	***Anthropogenic***	Over abstraction	✓	✓		✓			✓	✓		✓	✓
		Pollution	✓		✓	✓	✓	✓		✓		✓	✓
		Urbanization /poor planning				✓			✓	✓		✓	✓
		Migration				✓						✓	
		Population growth				✓			✓	✓		✓	✓
		Agriculture			✓	✓			✓			✓	
		Deforestation /Reforestation				✓	✓				✓	✓	

2.4 Climate and Seasonal Variability

From the 1970s to 1980, the Sahel, region in Africa, which borders the southern fringe of the Sahara has been experiencing a series of devastating droughts which are unparalleled to the wetter period in the 1950s (Bates et al., 2008). Sub-Saharan Africa has also been experiencing more frequent, intense, and extreme climatic conditions over the last decades (Elliot et al., 2011). Generally, rainfall variability has occurred across the African continent. Most areas have seen more frequent and longer hydrologic drought periods with impacts on water supply systems. According to the IPCC, areas located in the western Sahel have shown projections to experience the strongest and driest periods of hot climatic situations. They expect central Africa to experience a slight increase in flash floods and a decrease in wet periods. The West African region has been identified by the IPCC (2013) and Calow et al. (2010) as a climate-change hotspot, with adverse consequences that are likely to reduce water development and impact food security.

The study area, located in Sierra Leone West Africa has been designated as the third most vulnerable country after Bangladesh and Guinea Bissau to climate change. In the last decades, Freetown has faced an array of formidable environmental problems, including mudslides, land degradation, deforestation, loss of biological diversity, pollution of freshwater resources, and coastal area degradation which are a consequence of over-exploitation of the natural resources According to the UNFCCC (2007) and climate change science events, the impacts are expected to continue to affect Sierra Leone now and in the future.

Freetown is predominantly vulnerable to the increasing occurrence and severity of heavy rainfall, flash floods, and severe storms (thunder, lightning, violent winds, coastal erosion, and flooding) during the monsoonal period from June to October. In August of 2017, a mudslide occurred after three days of intense torrential rain, leading to over 1,000 people killed. Climate variability-related hazards are having increasingly adverse effects on Freetown’s catchment area and sustainable water resources throughout the seasons have been challenging.

In a study conducted in Calgary Alberta by Akuoko-Asibey et al. (1993), the effects of temperature and precipitation were observed in weekly per capita water consumption for a period of eight years. The analysis provides information that in the case of increasing precipitation, the water demand reduces and increases when temperature increases. The current study has investigated per capita water consumption for the rainy and dry seasons and will calibrate a hydrogeological model that would also monitor and estimate groundwater recharge levels. The results of the calibration will be used to develop a strategy for equitable distribution during fluctuations of weather variables.

In previous studies by the IPCC (2013) and the study by Zhang et al. (2000), it was also observed that the annual mean temperature has increased between 0.5 and 1.58°C, and the annual precipitation also increased from 5% to 35% in southern Canada over the same period. The pattern of temperature change was obvious warming in the southwest part whereas it was a cooling effect in the northeast but with similarities in magnitudes for both minimum and maximum observed temperatures. The IPCC since its Third Assessment Report has become reassured that for some parts of the world, the weather and extreme events will become more evident, frequent, widespread, and intense in the 21st century and beyond.

2.4.1 Threats and stresses leading to seasonal variability

In tropical Africa, a considerable amount of the seasonal rainfall originates from thunderstorms, and frequently these groups together, producing mesoscale convective systems (MCS). In modest terms, these are arches of enormous rainstorms that can conceal the region. African rainstorms are among the most intense on earth. The quantity of these storms has increased recently in sub-Saharan Africa, by a volume of three, since the early 1980s. It is variances in temperature that cause climate, which create a reason for air to move and form seasons (Jones and Briffa, 1992). The rise in the intensity of these major storm systems looks like a result of seasonal change.

Weather prediction in the Sahara sees increased warming leading directly to a future of additional intense rainfall events, particularly in the Sahel region (Tayanç et al., 1997). Subsequent devastating events like mudslides and flooding will become more frequent. The influence of this unfamiliar rainfall and temperature patterns on water resources, agriculture, food security, and hygiene are apparent in many parts of Africa and Freetown in particular (GoSL, 2015).

Seasonal and climate variation are a result of fluctuations in surface temperature which would be reflected in precipitation and evaporation rates. Taylor et al. (2009); Bonsor et al. (2010); ACPC (2011); and Elçi (2011) observed in their studies, slight warm temperatures in the early sixties over Africa, and a steady increase over the next decades at a rate of 0.5°C during each decade while precipitation declined in many parts of Africa. Parry et al. (2007) in their research concluded that the African continent has experienced an adverse change in climate in the last 40 years, and would require detailed studies to further predict future uncertainty of the impacts on groundwater resources. Accessing long term and high-quality climate records for analysis of extreme situations has been a challenge even for the developed world. The situation is even worse in the developing countries who find it hard to secure short-term or current data. Some areas that have been designated as vulnerable countries have been experiencing severe weather situations, while in other areas there has been no apparent evidence (Grajewski et al., 2014).

In the study conducted by Aitken et al. (1994) and Lapworth et al. (2015) they noted that the water sector faces constraints and growing pressures due to the continuous settlement on water catchment areas, increasing water demand, inadequate energy security to pump the water and change in weather patterns. Figure 2.1 presents the natural and anthropogenic threats and stresses that exacerbate the impacts seasonal variability would have on groundwater resources.

Groundwater reaction to changing climatic conditions is further threatened and subjected to several stress factors discussed in Figure 2.1, which would worsen future impacts of seasonal effect on groundwater sources (Li and Urban, 2016).

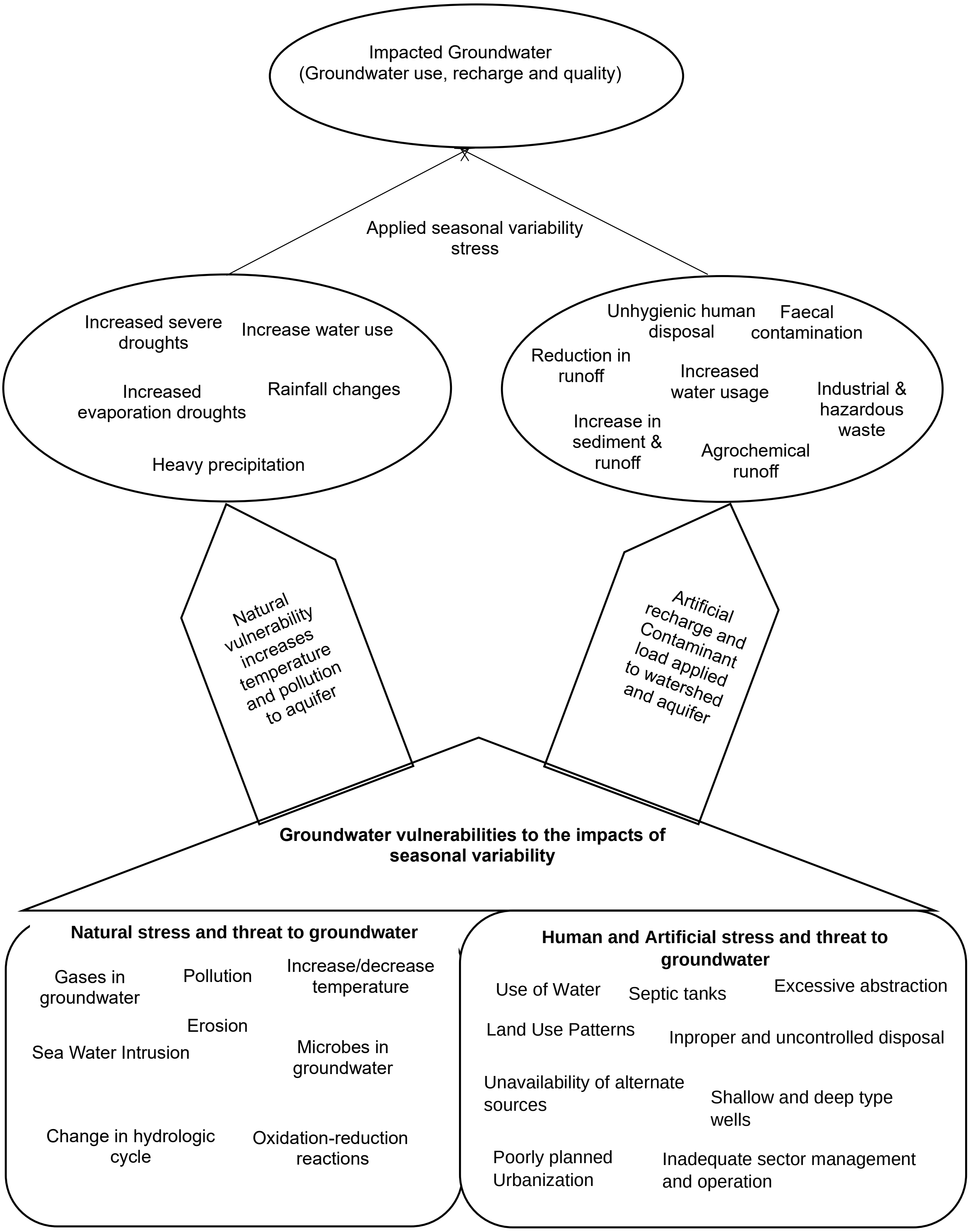


Figure 2. 1 Natural and Man-made threats and stresses leading to impacts of seasonal variability on groundwater sources (Source: authour’s construction)

2.4.2 Effects of seasonal variability

A change in Earth's temperature can cause an increase or decrease in precipitation or change the rate of rainfall intensity (Tindimugaya et al., 2010; Elçi, 2011). The effects of seasonal change pose more challenges on the hydrological cycle both in terms of quantity and quality (Kumar, 2012) and can arise from several scenarios that are likely to lead to hydrologic droughts and extremely dry periods (Oates et al., 2014). Christensen et al. (2007); IPCC (2007); Bonsor et al. (2010) and Calow et al. (2011) in their studies explained that the dependence on groundwater resources is expected to deepen especially with the uncertainties in climates around the world particularly for places characterized by the rapid increase in population and with already stressed meagre water resources.

Sykes (2006) and Thomas and Tellam (2006) noted that during groundwater recharge and discharge, the seasonal change will also compromise groundwater quality, especially during dry seasons because the water table levels are low and there is a high concentration of total dissolved solids (TDS) levels. Franssen (2009) and Brown (2012) identified severe high risks on water sustainability, rates of recharge, and quality problems. They observed that the effects will create more demand stress on groundwater systems. Arnbjerg-Nielsen (2008) also documented that urbanization, land-use patterns; intense industrialization has caused extensive pressure on the hydrological cycle and creates disastrous climatic events. Zektser et al. (2004) reiterated that aquifers are affected differently and that over-abstraction of groundwater can lead to stretched drawdown thereby reducing groundwater quantity, quality and eventually can cause land subsidence. In all the studies on impacts of groundwater resources, researchers have reiterated that a change in surface temperature and precipitation rate will affect aquifers water balances; and as depicted in Figure 2.1, it will affect the availability of water between seasons. The solution is to implement mitigation and adaptive strategies for sustainable management (Pitz, 2016).

2.5 Land Use Patterns

In assessing the problems of seasonal variability impacts on groundwater resources, it is important to understand what factors affect the process of adding water to the groundwater reservoir (Foster and Chilton, 2003). Lerner (1990); Allen et al. (2007) and Baker (2009) identified several of these factors; for example land use, land cover, topography, magnitude, intensity, and duration of precipitation which are discussed in this literature that affects natural recharge process. Major changes in land use and land cover caused by population growth, structures for habitation, food demand, fuel use, mining, irrigated agriculture, urbanization, and urban water supply are taking place which is detrimental to groundwater systems (Ramsar, 2006; Wang et al., 2015).

Some of these activities are man-made, irreversible, and have continued to impact groundwater systems globally in the last fifty or more years (Paul, 2006; FAO, 2016). These processes have resulted in immense exploitation and drastic changes in many watershed and recharge zones (Foster, 2013; FAO, 2016). Land use planning is a vital step to protect our ecosystems because any negative effect in the land use will impact the hydrology of the catchment area, which would in turn have an effect on groundwater recharge and discharge. The impacts of how land use and land cover would affect the water budget are the most widely researched topics and many of these studies have specified that large-scale land use and land cover are the determinant factors resulting in seasonal, climatic, and hydrologic changes. (Foster *et al.*, 2009) explained that the link between land use and groundwater has long been known and now needs to be integrated into policies to manage groundwater resources and protect aquifers against seasonal variability impacts. This will ensure groundwater quantity and quality (Dragoni and Sukhija, 2008; Foster, Tuinhof and van Steenbergen, 2012; Wang, Gao and Wang, 2015).

2.5.1 Deforestation

Vegetation is greatly influenced by local climate and soil conditions (Eden and Megdal, 2006). It affects the hydrologic cycle in many ways by influencing river flows and groundwater recharge (Taylor and Barrett, 1999; Gleick, 2000). In most parts of the world, the natural vegetation has been damaged through man-made activities (Walraevens *et al.*, 2009; MacDonald et al., 2013) as quarrying, forest fires, farming, construction, technology make way for urbanization. Dragoni and Sukhija (2008) in their research observed that deforestation in high altitudes would support warming because the presence of trees would decrease the albedo effects (snow areas would warm and melt) and evapotranspiration would increase. However, they noted that for the tropics, the trees would provide a cooling effect as trees will intercept the sunlight rays, making the soil much cooler than in an area where the vegetation cover is absent. Hlásny *et al.* (2015) explained that because the absence of trees will expose the soil to more heat, evaporation will increase, and as groundwater moves through the heated surface soil, it is depleted in quantity. The occurrence as explained by Dragoni and Sukhija (2008) of what happens in high altitude areas as against what happened in the tropics with the impact of deforestation on groundwater continues to put forth the argument amongst other researchers (Bates et al., 2008; GWP, 2014) that deforestation leads to an increased annual catchment yield and supports groundwater recharge and flow during the dry season. Under deforestation, water evaporates and moves faster and then settles on the impermeable surface until it slowly infiltrates back into the aquifer. In terms of quality under the influence of deforestation, GWP (2014) noted that quality is generally acceptable, but in arid climates, the salt concentration is increased from the sub-soil zone.

2.5.2 Agriculture

A more evident environmental concern is the scarcity of fresh water supply for agriculture (UNESCO, 2012; UN Water, 2018). Agriculture uses about 70% total of groundwater resources which has tripled more than 50 years ago. It is expected to increase by a further 19% as a result of irrigation activities by 2050. Agriculture is the largest consumer of Earth’s available freshwater competing with other water uses. As the population continues to increase especially in Southeast Asia, food demand will increase thereby increasing the threats to dry up the ecosystem coupled with effects from seasonal changes (UNESCO, 2012). Mekonnen and Hoekstra (2010) in their research observed that the increasing population and increase in per capita food consumption will stretch groundwater demand in the agriculture sector. Agriculture will affect groundwater quantity and quality due to excessive abstraction and also diffuse pollution from nutrients and pesticides depending on the kind of agro-husbandry practised (GWP, 2014; FAO AQUASTAT, 2016). The prolonged use of fertilizers in agriculture and irrigation activities can seep into groundwater and persist for several years thereby degrading the quality of groundwater (Gardner and McGlynn, 2009).

2.5.3 Settlements

Foster et al. (2012) noted that consideration must be drawn to the rapid increase in population and improved standards of living, which is mounting pressure on the already scarce water resources as this will further reduce the average daily per capita domestic water consumption available for use. The existence of residential and industrial areas in the urban settlement has generated a rapid population growth that is now looking for a supplementary water source to support intermittent or dwindling surface water supply that is adversely impacted by changes in temperature throughout the seasons. Taylor et al. (2010) and Taylor and Tindimugaya (2011) observed that intensive groundwater abstraction in Sub Saharan Africa is conducted in both urban and rural cities as the primary or secondary source, in areas where water supply networks are faced with challenges. With the growing urban population, the focus is now on groundwater.

However, the extensive abstraction of groundwater can lead to significant consequences like reduced flows to other surface water bodies, depletion of groundwater; saline intrusion, natural disasters e.g., landslides, and rockfalls arising from slope failure in water catchments zones (Holman and Trawick, 2011). Urbanization and population growth will increase the risk of groundwater to pollution and unmanageable withdrawals (Robertson *et al.*, 2003). Further impacts on groundwater quality are caused by leaking tanks from fuel stations, petrochemical production plants, and vehicle maintenance depots. In many poorly planned developing cities, with no proper sanitation structure, the most common source of groundwater pollution is poor sanitation systems which worsen groundwater quality (Ellis, 2008). Shallow aquifers are more susceptible to contamination. In Europe and the USA, diffuse nitrate concentration is the most prevalent pollutant. Overexploitation of groundwater pumping has led to unsustainable conditions leading to reduced water levels, degraded aquifers, and increased salinization (Mauclaire and Gibert, 1998).

2.6 Industries

The probable causes of pollution in groundwater from Industries can occur in varying forms from pharmaceutical factories, industries using hazardous chemicals, effluents from mining sites, lead batteries, pesticides, hydrocarbons compounds, to other landfill waste (Bloomfield *et al.*, 2006). These pollutants, if not properly dispose of can seep into the soil and contaminate groundwater with heavy metals and other hazardous compounds. In many developing cities e.g. Freetown in Sierra Leone, there are no regulations in place for disposal of toxic or domestic waste like acid lead batteries, either from the industries or households. However, in situations where such laws do exist, there are no enforcement procedures to ensure harmful and toxic wastes are disposed of properly. Residents and industries simply dump their waste at available dumpsites or in the ocean. It is worrying that pollutants can seep through the soil, mixing the groundwater with heavy metals. The situation is made worse because these factories and dumpsites are located in residential areas (Sophocleous, 2002; Bloomfield *et al.*, 2006; Li and Merchant, 2013). The main factor for determining the fate of these pollutants once they get into the soil onto groundwater is aided by rainfall intensity and duration (Dragoni and Sukhija 2008). Groundwater's vulnerability is also affected by seasonal variability and land-use change.

2.6.1 Pollution

Vrba (2002) in his research documented how groundwater can be contaminated in various populated urban cities from uncontrolled waste discharges, industries, and agrochemicals effluents. Lerner (1990) and Butler and McEntee (2007) noted that groundwater quality is subjected to long-term deterioration from diffuse pollutants from landfill sites etc. Groundwater is hydrologically linked to surface water bodies and they become susceptible to threats of improper disposal of pharmaceutical, liquid, and solid waste from landfill sites, and petroleum industries (Calow et al., 2011). The uncontrolled use of fertilizers from prolonged farming activities and leached chemicals from mining activities make their way into groundwater and contaminate its quality. Pollution can also occur naturally if there are concentrations of minor or unwanted impurity in the groundwater which can travel from a pollutant source to groundwater and contaminate it. The pollutants then form a contaminant plume in the aquifer (Goldberg, 1989; Gurdak et al., 2009; Bear and Verruijt, 1987; Sykes, 2006; Environment Protection Agency, 2013). Apart from the above-mentioned contaminant sources, groundwater quality is affected by major minerals from salt-bearing rock formations and over-extraction caused by seasonal variability (Baba and Tayfur, 2011; Wuana and Okieimen, 2011; Liu et al., 2014).

2.7 Groundwater-Surface Water Interactions

In the development of our water resources, it is the hydrological cycle that helps us to understand the continuous movement of water above and below the surface of the Earth (Winter et al., 1998). Groundwater and surface water are connected and interact with one another in all landscape (USGS, 2016). Winter et al. (1998); Rassam et al. (2013) and

Fleckenstein et al. (2010) emphasized the development of both groundwater and surface water impact on each other's quality and quantity. Jones et al. (2013) and Yang et al. (2015) supported the argument on the interaction between the two and noted that at a certain stage within the hydrological cycle especially during the wet seasons, surface waters e.g. a stream can discharge (supply) water to a groundwater source and at such instances, the stream is referred to as a losing stream (Xu and Beekman 2003; Zhou and Li 2011a). The reverse is also possible in the dry season, where the stream can be recharged by a groundwater source; known as gaining stream. Winter et al. (1998) and Döll *et al.* (2012) also explained that both surface water and groundwater depend on their location for development. In another study conducted by Ponce (2007) he argued that there is a great interaction between surface water and groundwater because surface water can become groundwater through infiltration, while groundwater can become surface water through exfiltration, and that one cannot be considered or evaluated without the other.

2.7.1. Groundwater discharge and recharge dynamics

Recharge largely depends on the permeability of the aquifer’s lithology (Myette and Simcox, 1992; Sheng, 2013). The consequences of the various changes and threats to freshwater resources are hard to predict in detail. It is therefore imperative that all key factors which affect the water balance are monitored to understand the trends in rainfall, surface water flow, groundwater levels, abstractions, soil moisture, and land use pattern (Sophocleous, 2002; Xu and Beekman, 2003). Recharge movement is generally in the direction where hydraulic conductivity is the least as against discharge which is moving in the direction where hydraulic conductivity is the highest and it involves a saturated movement (Dassargues, 1999; Wang et al., 2010). Determining the position of the water table and the groundwater flow path is important in designing a water safety and development framework (Rassam et al., 2004). Conversely, gravity which is a driving force in land topography also helps determine groundwater movement and recharge (Khadri and Pande, 2016a). The water table slopes from recharge areas to discharge areas as the flow is from a region of a high gradient to one of low gradient (Barackman and Brusseau, 2004; Sanford and Casile, 2015). Recharge expressed in volume per unit area is how groundwater is replenished mostly after precipitation followed by rainfall and it varies year to year depending on land use, air temperature and other factors discussed earlier (Heath, 1983). Groundwater flow in this research would be simulated using water balance methods and Model Muse MODFLOW packages designed by the United States Geological Surveys (USGS). The water balance equations and software package are capable of representing conditions related to groundwater flow such as evapotranspiration, recharge, drainage, stormflow, runoff, river interaction among others.

2.7.2 Rivers as boundary conditions in groundwater modelling

Surface waters are in constant interaction with groundwater systems and they are a fundamental component in nearly all landscapes ranging from small streams, lakes, wetlands to major river valleys and seacoasts (Xu and Beekman, 2003; Ramsar, 2006; Zeng and Cai, 2014; Qiu et al., 2015). The river boundary is the main link to groundwater and to evaluate groundwater resources and aquifers, the boundary needs to be established (Scibek and Allen, 2010; Zhou and Li, 2011a). The boundary between groundwater and rivers is mostly referred to as a Dirichlet boundary condition, this means that the two are in a constant and good relationship with each other (Landmeyer, 1994; Rassam et al. 2004; Qiu et al., 2015). Rivers are very important in the water cycle because they carry rainwater back into the sea. In a landscape where this connection is not established; the boundary is described as a 'no-flow zone' (Qiu *et al.*, 2015).

2.8 Groundwater Occurrence and Hydrogeological Environments

Groundwater occurrence is influenced by several factors namely the geology of the potential aquifer, topography, climate, permeability and porosity of the aquifer materials. According to Chilton and Seiler (2006) different geologic formations can form useful aquifers and all geological materials contain some water in them. Unconsolidated sedimentary deposits around the world form some of the most important aquifers which produce very large volumes of groundwater pumped for water supply and irrigation. Weathered basement complex aquifers are common in ancient crystalline rocks of the Precambrian or Lower Palaeozoic age, which covers about 40 percent of the total land area in Sub-Saharan Africa. Major cities including Freetown located on such formations may find it difficult to abstract the large quantities of water needed for urban supply and also be unable to dispose of wastewater to the subsurface in a sanitary manner (McFarlane, 1992). The process of weathering and disaggregation of rocks enhances the porosity and permeability which can be quite low, making it difficult to abstract and supply demanding communities (Chilton and Foster, 1995). Groundwater velocities and the hydraulic conductivities in weathered and fractured bedrock aquifers vary greatly, but borehole yield can then be sustained if the aquifer storage and recharge rates are adequate. Taylor and Barrett (1999) claimed that crystalline rocks do not make good yielding aquifers and are difficult to study, but because of the high dependence by inhabitants in the urban dwellings and potentially high risk to contamination, more research has been focused on fractured and crystalline aquifers. However, during these processes of recharge, there is a tendency for contamination through leaching into aquifers (Eiswirth and Hötzl, 1997). The process of weathering also increases the gas content in groundwater (Pitkanän and Partamies, 2007). Despite the high demand for groundwater and the many wells and borehole constructed in developing countries, very little knowledge is known about them, and therefore more research needs to be focused on them to support future per capita water use (Richey *et al.*, 2015).

2.9 Groundwater Management

In most developing countries, the water sector lacks the expertise and skills to manage its water resources. Groundwater is the main source of water for over two billion people globally (WWAP, 2015), but lacks proper management as with other forms of surface water supply in most parts of the world (Famiglietti, 2014). The Water Divisions in most African countries including Sierra Leone lack the capacity and regulatory framework for monitoring individual groundwater extraction. Added to this, the sanitation sector is usually poorly prioritized and grossly underfunded by governments (Prüss-Ustün et al., 2008). Therefore, seasonal variability impacts will intensify and lead to high levels of aquifer contamination and occurrence of waterborne diseases which can affect vulnerable and poor communities especially women and children in most developing African countries including Sierra Leone (Lapworth et al., 2017).

The Groundwater Governance (2012) report cautioned that improved groundwater governance can only be meaningful if policies are integrated into groundwater management and procedures. These policies must take into consideration mechanisms for extraction, water supply, and use, wastewater reuse, and payment for water and environmental services to promote aquifer protection (Defra, 2008; Water Resources Group, 2009). Society is largely unaware of the groundwater development in their locality

(Defra, 2008 and Groundwater Governance, 2012). Therefore, the majority of the public has no awareness and knowledge about groundwater occurrence below the Earth; its recharge process; flow and discharge patterns (Edition, 2013). Some water managers and the majority of groundwater users in developing countries are not conscious that their behaviours and practices may pollute the groundwater resources (Management, 2003). Similarly, users in the agricultural and mining sectors, who abstract and unknowingly dispose of harmful toxic chemicals in the form of fertilizers, pesticides, and heavy metals to the soil, usually do not know the consequences of their acts, and that it may lead to diminishing issues of groundwater, degrading its quality, declining surface water bodies, reduced base flows and deterioration of the ecosystem (Sophocleous, 2002; Bloomfield *et al.*, 2006; Shankar et al., 2008).

2.9.1 Groundwater Governance

Natural resource governance is inclusive of participation, accountability, transparency, information flow, and respect for formal laws (Foster et al., 2009a). The hydrological cycle is not visible and clear to users on how it is impacted. Groundwater governance is when authourities ensure the rule of law, by instituting policies that will protect aquifers, control exploitation, monitor users and polluters behaviours, and put in place mechanisms for adjustment to groundwater extraction. These policies or decisions would moderate groundwater use and promote aquifer protection. On the other hand, groundwater management is the set of actions to implement decisions and policy from governance.

The Environment Protection Agency (2013) report highlighted that in some developed countries, only surface water abstraction for public use is controlled and protected by an Act or by regulation. It noted that there is no license requirement or recognized Act that controls groundwater abstraction in many parts of the world. In a project supported by the World Bank and other partners, Hiller et al. (2012) conducted case studies on seven randomly selected countries; to identify water governance issues and develop policies to manage groundwater and adapt to future climate change impacts. South Africa is observed has a National Groundwater Strategy that addresses groundwater deficiency, and this policy has helped to maintain the minimum equitable water distribution in the drought season for all household income groups.

In Sierra Leone, like most developing countries, the Water Division lacks the capacity and regulatory framework for monitoring of individual groundwater extraction (Supply, 2008). There is no regulation for groundwater construction or exploitation.

The issue of paying for water plays an important role in determining the desirability of water (WHO and Unicef, 2000; Theesfeld, 2010; GEF, 2015; Governance, 2015). Most users believe that they should not pay for water because it is a ‘gift from God’; even people who have access to treated tap water are unwilling to pay the cost for water and this will affect its management and quality (Tuinhof et al., 2011; Famiglietti 2014).

2.9.2 Groundwater yield and extraction

Ponce (2007) argued that since groundwater is an essential resource in transit from the place of recharge to a place of discharge; an assessment of its sustainable yield should not only take into account the hydrogeological boundaries of the aquifer but must consider the socio-economic context as well, to incorporate all boundaries, including surface water hydrology, geology, ecology, climatology, and related fields. The sustainable yield was defined as the average rate of pumping that can be maintained without endangering either the quantity or quality of pumped water (Change and Basis, 2001). Groundwater velocities and the hydraulic conductivities in weathered and fractured bedrock aquifers vary greatly, but borehole yield can then be sustained if the aquifer storage and recharge rates are adequate.

Khater (2002), Llamas and Custodio (2003) and Llamas and Martínez-cortina (2009) observed in their studies that during the dry periods in the southern, central and coastal Sahel, groundwater is excessively exploited but with the dearth of information on groundwater use in Africa, there is very little documented statistics of groundwater use apart from the same use as that of Surface water sources. Howard and Gelo (2002) observed that with the intensive but beneficial use of groundwater in urban areas, its quantity and quality are compromised and that there is a need for operational groundwater supervision and designed protection approaches to prevent future challenges. The traditional law which operates in many regions in Europe, the USA, Africa, and other parts of the world that gives the landowner rights to exploit all underlying groundwater is the main drive for owners to extract unlimited quantities of groundwater with no regard for withdrawals for other users (Burchi and Nanni, 2003). In most developing countries in

Africa, people who own their land and can afford the cost of drilling a borehole or dig a well can do so without any restriction from the government or any authority (Famiglietti, 2014). Groundwater use must be monitored as an ultimate alternative source to regulate water supply during inadequate intermittent situations, water supply system breakdown, irrigation purposes, and industrial use as well as during hydrological drought periods (Orden, 2002; Haq, 2006; Cosgrove and Loucks, 2007). Naturally, groundwater abstraction should be proportional to its rate of recharge because, if groundwater is withdrawn from an aquifer at a rate more than how it is recharged, the water level would be low and this will affect its quantity, quality, and sustainability (Nyenje and Batelaan, 2009).

2.9.3 Impacts of intensive groundwater abstraction

The rapid increase in population greatly increases the risk to groundwater from pollution and unmanageable withdrawals (Robertson *et al.*, 2003). An increase in population provides the need for improving groundwater protection and designing strategies to sustain its high quality for consumption. Taylor et al. (2010) and Taylor and Tindimugaya (2011) noted that intensive groundwater abstraction in Sub-Saharan Africa is conducted in both urban and rural cities and is known as the primary or secondary source where water supply networks are faced with challenges. Overexploitation of groundwater pumping has led to unsustainable conditions leading to reduced water levels, degraded aquifers, and increased salinization (Mauclaire and Gibert, 1998; Falke et al., 2011).

2.10 Quantification of Water Withdrawals and Consumptive Uses from Groundwater and Surface Water

There is evidence that humans have adversely impacted the global hydrological cycle (Zektser et al., 2004; Zhou et al., 2016). Döll et al. (2012) analysed the impacts of freshwater withdrawal based on flow and storage variations, using the global water resources and water use model WaterGap (a tool for assessing the impact of global change and water security on freshwater resources). They observed that 35% of water withdrawn (4300 km^3/year) from 1998 to 2002 worldwide is groundwater and this is the source for five water use sectors mostly irrigation, households, and manufacturing. This data is in comparison to total withdrawals (1400 km^3/year) worldwide for surface water during the same period. The WaterGap model was able to calculate for the first time in global scale history, where and when human monitored water abstractions are taking place. This model was able to predict how storage in surface water and groundwater were increased or decreased. Because WaterGap had some limitations, Döll *et al.* (2012) also used a new sub-model of WaterGap called GWSWUSE, which is a more robust model to distinguish between the specific sector withdrawal and consumptive uses, from groundwater and the individual types of surface waters (rivers, lakes, streams, reservoirs). The computation was based on nine water use data sets. However, no information was available for a total of 55 countries, and in most countries, there were inconsistencies of total sectoral as well as groundwater uses from different data sources and some were not available at all. The benefit of the GWSWUSE sub-module is that it can distinguish the actual source of water (ground or surface) and can further compute net abstractions from groundwater (NAg) and net abstractions from surface water (NAs). However, MODFLOW, the widely improved modelling software application tool has improved packages to investigate both surface waters and groundwater sources, which this study will employ.

2.10.1 Water Consumption Challenges

Globally, the main contributing factors towards water problems for many regions that affect water consumption are accessibility, increasing population, urban development, seasonal and climatic variabilities (UNESCO, 2003). It has been observed by many researchers that the greatest challenge faced worldwide in the 21st century is securing adequate safe water for human consumption (Gleick, 2003; Harlan et al., 2009; WWAP, 2014; WHO/UNICEF, 2015; Sorensen et al., 2016).

Edgar et al. (2003) and IPCC (2013) observed that urbanization is putting pressure on already stressed surface water sources and that there is a need to tap other water sources; for example, rooftops for rainwater harvesting. Domene and Saurı (2006); Willis et al. (2013), and Tran et al. (2016) noted that global per capita water use is increasing much faster even as the world population is increasing due to huge consumption as a result to affordability. Research conducted by Hanak and Browne (2006) observed that households with high income spend more on water and are not conservation concern as long as they can afford it. De Oliver (1999), Randolph and Troy (2008) documented that the dwellings and property types, as well as the lifestyles consumers engage in, would determine their attitude towards water-saving measures.

As the world population is projected to increase to about 9.3 billion by 2050, freshwater demand would increase, and supplies for per capita would decrease also (UNDP, 2009; Commission for Africa, 2010; UNEP, 2010). The UNDP 2015 report has informed that if the current household consumption trends should continue, then about 25 countries in Africa will experience severe water stress and drought. The UNDP Human Development Index has also projected that by 2025, close to 1 billion people would be living in developing cities; mostly in African countries, and experiencing severe water supply shortages as well as degraded quality from overuse, since rapid urbanization would put increasing pressure on water resources and the environment. According to the Commission for Africa (2010)**,** there is little or no data on the distribution of water resources in Sub Saharan Africa. However, the little information available is inaccessible, inaccurate, and meaningless.

Research into household and per capita water consumption in African cities are few and there is a dearth of studies on seasonal per capita water dynamics. According to the United Nations (2013) and FAO AQUASTAT (2016) 10 – 12 % of worldwide water consumption goes to municipal and domestic use. FAO has further established the current per capita water consumption per litre per person per day (l/p/d) for some of the developed and developing countries globally and has indicated that industries consume over 50% of total water available for human use e.g. in Belgium; which uses 80% of the water in industry.

According to Schleich and Hillenbrand (2009) economic, social, and environmental factors will continue to create significant stress on freshwater demand and with the predicted change in climatic variables, this will extend the effect in the future. Therefore, with the influence of the climate variables, it will mean that rainfall patterns will affect water consumption rather than total rainfall experienced as the temperature is the dominant factor in this situation (Arbués et al., 2004; Hoffmann et al., 2006; Schleich and Hillenbrand, 2009).

In the case of developing countries, in particular, household sizes and use of white goods or water use appliances like dishwashers and washing machines would not present a challenge in improving or establishing strategies for efficient water use in the face of seasonal variability, because these goods are not common in use with most developing cities in Africa. In the households where these goods are present, the lack of continuous energy and water supply to power them for their operations is not feasible (Arbués et al., 2004; Hoffmann et al., 2006; Kenney et al., 2008). Hoffmann et al. (2006) argue that water consumption and water price are inelastic and so they cannot be used as an efficient strategy for regulating per capita water consumption. Measures such as sensitization and education campaigns to communities about seasonal impacts, water rationing, instituting fines for over-abstraction, fines for polluters, water restrictions, and subsidization of community programs should be considered as an adjustment strategy to mitigate seasonal variability.

Understanding per capita domestic water consumption patterns and its challenges is important in designing strategies for seasonal adaptation and water use. Having an exact estimate of per capita water consumption is difficult, and therefore, to categorize household water consumption would require an efficient water consumption model that will bring out the differences in per capita water use patterns (Hoffmann et al., 2006). In this study, the effects of seasonality on groundwater resources are integrated with the model simulation and watershed water balance methods.

2.11 Groundwater Quantity Modelling Study

Decision-makers require adequate information on groundwater interactions to formulate sustainable groundwater resource development strategies. Modelling of groundwater helps us to understand the water budget, its flow velocity, contaminant path, and estimate predictions for future scenarios (OhioEPA, 2007). Groundwater models are utilized to simulate and predict aquifer conditions (Döll *et al.*, 2012). Sindhuja et al. (2016) claimed that analytical and numerical models, for example, ModelMuse MODFLOW, Visual MODFLOW and Geographic Information Systems (GIS) mapping are tools for analysing groundwater quantity, especially where groundwater network is complex. Groundwater flow models are utilised to calculate the magnitude and direction of movement through aquifers. The use of numerical models to understand the quantification and movement of groundwater provides an effective approach to study complex hydrogeological systems (Takounjou et al., 2009; Hashemi et al., 2013; Kumar and Singh, 2015).

In groundwater modelling, the key components include data collection, model conceptualization, model development and calibration and confirmation of the results (Yang et al., 2010). The literature reviewed reveals that in the context of impacts of seasonality on water resources, very little research has been conducted on groundwater compared to surface water which has been a widely researched topic for different climatic regions because of its easy accessibility; as compared to groundwater which requires long historical data and complex techniques (Singh and Kumar, 2010).

This section highlights several types of research and case studies presented in tabular comparison; Table 2.3, in which impacts of seasonal variability on groundwater resources have been modelled globally with similar results for a situation where seasonal changes are affecting groundwater levels. These studies have indicated that a numerical model with surface and groundwater interaction is the best method to estimate groundwater levels and groundwater recharge under different climatic scenarios for the past, present, and future trends (Hashemi et al., 2015; Khadri and Pande, 2016). A study conducted by Weldemichael (2016), has established that the numerical hydrogeological model is more reliable when there are more Spatio-temporal data and that using a smaller grid size of fewer than 100 metres x 10 metres for the watershed object would give a better simulation result, and will help understand the movement in fractured crystalline aquifers much better. Weldemichael (2016) also noted that software adjustments would help create better model calibration and budget quantification to normalize the period for the simulation.

2.11.1 Groundwater quantity modelling study using ModelMuse MODFLOW and GIS

Parameters such as depth to groundwater, recharge, soil geology, conductivity, and topography need to be taken into consideration when designing water systems and water development models. Groundwater recharge expressed in volume per unit area is how groundwater is replenished mostly after precipitation followed by rainfall, and it varies from year to year depending on effect of land use, air temperature, and other factors shown in Figure 2.1 (Heath, 1983).

Gunawardhana et al. (2009) studied the responses of aquifers by investigating the effect of seasonal changes of temperature distribution patterns and heat flux in the Sendai plain in Japan; observing one hour of groundwater temperature up to a depth of 60 metres for three different aquifer levels. MODFLOW three-dimensional numerical codes were used to simulate the groundwater flows. They noted that aquifer temperature is sensitive to changes in groundwater flow patterns as heat is transported by both conduction and convection current of groundwater. Gunawardhana et al. (2009) concluded that thermal effects can cause significant changes in hydraulic conductivity as density and viscosity of water are temperature dependent.

Raposo et al. (2012) in their study assessed the problems that impact of climatic variability will have on the hydrological cycle to serve the growing population in Europe as temperature and precipitation change. Groundwater recharge largely depends on the permeability of the aquifer's lithology (Myette, 1992; Sheng, 2013). The consequences of the various changes and threats to freshwater resources are hard to predict in detail. It is therefore imperative that all key factors which affect the water balance are monitored to understand the trends in rainfall, surface water flow, groundwater levels, abstractions, soil moisture, and land use pattern.

Groundwater Information Systems (GIS) technology has been used in previous modelling studies to integrate topographic data into MODFLOW packages especially in areas with poor hydrogeologic information, to model groundwater potential for future consumption (Takounjou *et al.*, 2009; Sule and Ayenigba, 2017). With the support of ArcGIS and QGIS environments, the digital elevation model (DEM) of an area is extracted by a gridding data tool and converted into a surfer grid format to use in the MODFLOW interface as in the studies of Kirubakaran et al. (2018) and Akter and Ahmed (2021). Additionally, shapefiles of study areas and well locations have been prepared and incorporated into the GIS environment to simulate potential groundwater demand and use. In all these studies, there is evidence to demonstrate that the integration of GIS, local field data, and numerical models is a powerful tool in understanding the development and supply of groundwater. The MODFLOW software is capable of representing conditions related to groundwater flow such as evapotranspiration, recharge, drainage, drawdown, river interaction among others.

Groundwater quantity flow in this research, would be simulated using ModelMuse MODFLOW packages.

Table 2. 3 Natural and Man-made threats and stresses leading to impacts of seasonal variability on groundwater sources (Source: authour's construction)

Year	Authors	Study Site	Site description	Aquifer Description	Models	Seasonal Variability Scenarios	Variables Investigated	Groundwater Metrics and Results
1999	Chen et al.	Bie vre-Valloire, in the Rhoone Valley, France	Tectonic trench of crystalline Alps linked with several valleys & rivers to the Mediterranean Sea.	Crystalline with long history of human influence	Hydrogeological models including Monte-Carlo to conduct sensitivity analysis of the hydraulic parameters	Climate data combined with hydrologic model using spatial & temporal distribution of land cover to predict the impact of doubling of CO2 on groundwater recharge.	Rain, temperature & evapo-transpiration	Estimate the effect of climate change on groundwater recharge and soil moisture in the root zone
2002	Kirshen	Eastern Massachusetts, USA	The 'Ponds' covering an area of 28km^2	Highly permeable unconfined stratified aquifer	MODFLOW	2030, 2100	Temperature & Precipitation due to 20-year drought climate situations for 2030 and 2100.	Annual recharge shows slight and significant changes for both 2030 & 2100 under both scenarios or they stay the same.
2004	Ojo et al.	Several countries in West Africa	Several fresh water & stress points in West Africa	Sudano–Sahelian region		Water supply scenarios for future West African urban and rural communities	Rainfall, floods, river flows, discharges, acute shortage of freshwater	West Africa is projected to suffer extensive and severe climate change impacts on aquifers. Adaptation

							and water stress.	strategies proffered
2004	Allen et al.	Grand Forks Aquifer of south-central British Columbia, Canada	Located in the semi-arid climate & mountainous valley of KettleR	Highly productive alluvial aquifer dominantly used for irrigation and domestic purposes	MODFLOW, HELP	1961 – 2099 present; 2010 – 2039; 2040 – 2069; 2070 - 2099	Change in recharge, Change in river stage	Observed minimal water level changes with change in recharge & water table level were markedly influenced by changes in river stages.
2007	Toews	Okanagan region British Columbia	Semi-arid	Okanagan region of intense irrigation.	3D MODFLOW, HELP 3.80	Simulated rise of water Table for future time periods,	Stochastically-generated climate from three GCMs	Modelled the impacts of future predicted climate change effect on water levels
2011	Gao	North America in a complex situation	Complex Geologic and Hydrogeologic conditions	Multiple layered aquifer.	3D numerical MODFLOW	Dewatering complex hydrogeologic/ geologic situations	Multiple layers of simulation for complex hydrogeologic conditions	An efficient tool for modelling complex hydrogeologic conditions. The number of layers in the simulation has an impact on the result.
2011	Zume and Tarhule	Southern Great Plains, in the United States	Semi-arid Northwestern Oklahoma	Alluvial aquifers in semi-arid Northwestern Oklahoma	Visual MODFLOW	Simulate potential impacts of anthropogenic	Projected groundwater withdrawal, severe drought,	The combined impacts of anthropogenic pumping & droughts would

						pumping & recharge variability on an alluvial aquifers	prolonged wet period, & human adjustment scenario	create drawdown greater than 12 m in the aquifer.
2011	Mutasa	Sardon catchment, Spain	Semiarid area & climate prone region comprised of impermeable schist & massive granite	Catchment is part of the Rio Tormes river basin with fairly undulating topography	MODFLOW	Quantify impacts of groundwater in semi-arid area	Precipitation and temperature daily record	Groundwater resources are influenced by climate change.
2014	Kheder	West of AlKarj city, Saudi Arabia	flood-prone areas on the surface	Aquifer underlain by highly weathered, jointed & fractured limestone rock, fluvio alluvium sediments & sandstones where the isolated hills are clay composition	GIS and MODFLOW software	The utilization of geo-database to model flood disaster risk and wastewater pollution in valleys and basins.	Understanding the interconnections between the flood on the surface and seepage into the surrounding rocks and soil layers	Recharge of central AlKharj watershed is an interaction between geo-morphology, water level. Groundwater is mainly confined to secondary porosity i.e. fractured zone, fault, joint and weathered column.

2016	Sindhuja et al.	Urban India prone to contamination form	Groundwater of Bapatla mandal, coastal Andhra Pradesh in India	Open and bore wells with high concentrations of dissolved solids.	Water Quality Index (WQI), numerical and analytical model, Visual MODFLOW, GIS	Groundwater models are used to simulate and predict aquifer conditions	Physio-chemical parameters such as pH, Electrical Conductivity, Total Dissolved Solids, Total Hardness, Chloride are analysed using	Urbanization, Industrialization, Coastal region & sewage disposal add high concentrations of chemicals to groundwater causing pipe corrosion, scaling, palatability, incrustation, health effects.

Topographic and DEM data, integrated with the calibration and superposition modelling approaches, and concepts in hydrogeological modelling for alluvial and fractured aquifers were reviewed.

2.11.2 Techniques for Estimating Recharge

Groundwater discharge movement is generally in the direction where hydraulic gradient is the least as against recharge which is moving in the direction where hydraulic gradient is the highest and it involves a saturated movement. Determining the position of the water table and the groundwater flow direction is important in designing water abstraction points. However, gravity which is a driving force in land topography also helps determine groundwater movement (Pande, 2016). The water table slopes from recharge areas to discharge areas as the flow is from a region of a high gradient to one of a low gradient.

2.11.3 Status of Research and Case Studies on Impacts of Seasonal Variability on Groundwater Resources

Grajewski et al. (2014) analysed the sequence in changes of groundwater levels in the Puszcza Zielonka forest and observed that seasonal fluctuations are dependent on abiotic factors (e.g. air, temperature, soil, water, sunlight) that leads to the rise and depletion of groundwater tables). They noted that during the wet season in June and July there was a considerable increase in precipitation from heavy rainfall until September when the groundwater level starts to deplete. They also compared the results to the analyses conducted in previous years (2001–2009) that were similar to their collected data. It was observed that shallow wells, were replenished by precipitation, and the response by this process affected the groundwater levels.

Chen (1999) presented an approach where a simple disaggregation scheme was employed to investigate rain, temperature, and potential evapotranspiration in combination with a hydrological model for a hydrological site of Bie`vre-Valloire plain in the Rhoöne valley (France). The purpose of his study was to estimate the effect of climate change on groundwater recharge and soil moisture in the root zone. Kirshen (2002) using no general circulation models at all, simulated temperature and precipitation scenarios for 2030 and 2100 for a mean and 20-year drought climate scenarios in Massachusetts USA on highly permeable unconfined stratified aquifer with 3D-MODFLOW packages. The results of their analysis point out that the impact on groundwater, based on climate change could increase groundwater recharge see some negative impacts on groundwater recharge for both 2030 and 2100 under both scenarios.

This current research has first conducted a seasonal per capita water consumption survey to understand the individual water end-uses needs and the identified areas of high consumption rates. Secondly, based on the analysis of the water consumption survey, a three-dimensional groundwater quantity modelling was done to determine the aquifer safe yield and predict current and future water abstraction potential to support seasonal per capita consumption for the next fifteen years (2020 – 2035). The case studies discussed in this chapter have solely investigated climatic variability impacts on groundwater resources, which have led to some of the reasons why groundwater is a sustainable option for domestic consumption. This research has not only investigated the problem but has looked into the possible solution to solve inadequate, unreliable and stresses domestic water consumption.

Ojo et al. (2004) in their research examined climatic variability trends on several variables including rainfall, floods, river flows, discharge, acute shortage of freshwater, and water stress that would deteriorate with future impacts of climate change in several countries in West Africa by utilizing the climatic index model. The researchers then projected water supply scenarios for future urban and rural Nigeria which they claim gives a realistic figure for most of the other countries in West Africa and observed that impacts of climate variability on aquifers in West Africa such as Guinea, Ghana and Cameroon are expected to be severe and extensive, and this may depend on the region.

Allen et al. (2004) modelled climate-change-sensitivity analysis in the Grand Forks aquifer in south-central British Columbia Canada, by projecting changes in temperature and precipitation scenarios using MODFLOW – Visual HELP to estimate aquifer recharge. They calibrated a three-dimensional groundwater flow model for a sensitivity analysis where temperature and precipitation were projected in four climate scenarios to estimate the different recharge values for all scenarios. Toews (2007) utilised HELP 3.80 Hydro-model and obtained climate data to model spatial groundwater recharge for the semi-arid Okanagan region in British Columbia. The study employed a transient 3D-MODFLOW model to simulate the effects of water level rise for future scenarios of intense irrigation activities. Mutasa (2011) in his groundwater modelling study of the Sardon catchment area utilised MODFLOW to simulate future groundwater level changes and "*demonstrated that the quantification of impacts on groundwater*" can be determined by calibrating data with MODFLOW for historical, current, and future trends using the statistical downscaling model. He iterates the simulation in a transient state for over 60 stress periods and revealed that there is evidence of climate change in the catchment. The key message in these studies is that numerical modelling packages can address issues related to the sustainability of groundwater resources. Transient-flow groundwater modelling can accurately examine temporal variations in groundwater storage, which are considered a decisive parameter for representative climate-change impact modelling in aquifers.

Gao (2011) explained that for a 3D numerical MODFLOW where the geology of the aquifer is a complex formation, the number of layers in the simulation may have an impact on the result, and therefore, multiple lines in the calibration should be employed to iterate a representation of the groundwater conditions of the study area. Zume and Tarhule (2011) utilised Visual MODFLOW to simulate various stress situations in an alluvial aquifer in semi-arid northwestern Oklahoma by investigating projected groundwater abstraction, a case of a severe drought, prolonged wet period, and human adjustment variables to determine potential impacts of anthropogenic pumping and recharge variability. The important message is that groundwater numerical modelling is an integrated and robust tool used to investigate the operational control on groundwater flow in small and large aquifers. The investigated case studies have demonstrated that groundwater numerical models have been recognised as the appropriate tools which are frequently used in studying groundwater flow systems. Numerical models have been proven to be suitable tools over several decades for addressing a series of groundwater problems and supporting the decision-making process for water managers.

2.12 Research gaps

Before this study, no detailed investigation on per capita water consumption and application of 3D modelling to investigate groundwater development, occurrence and management has been undertaken in the study area. The first hydrogeology map prepared in Sierra Leone was a regional study of groundwater in north and west of Africa published in 1988 by Bank and Bank (1992) and UNEP/RIVM (1997)In 2009 the British Geological Survey (BGS) researched Sierra Leone. Groundwater quality data on Sierra Leone was updated by Lapworth et al. (2015) following the Ebola crisis, which highlighted some basic hydrogeologic parameters and groundwater quality issues.

In 2012, the Ministry of Energy and Water Resources with support from UNICEF (Danert, 2015) commenced a water data points analysis in the rural parts of the country. This study was updated in 2016 by HydroNova who analysed 28,850 water data points under the government's 2012 national survey of water points (Ministry of Energy and Water Resources, 2012). The survey included basic parameters of boreholes such as water level in the rain and dry season and location of hand-dug wells in the country, though basic hydrogeologic parameters such as static water levels were not measured in the survey (Fileccia et al., 2018 and van Steenbergen, 2018).

In the 2016 HydroNova country-wide hydrogeologic investigation, borehole drilling data, geophysical surveys, water quality analysis, and borehole drilling reports from EDAL drilling company and some Non-Governmental Organizations working in the country produced twenty hydrogeologic and thematic related maps that would serve as the baseline data for rural Sierra Leone where groundwater is used as main source of water supply, developed according to IAH standards and guidelines (Struckmeier, 1995).

The groundwater and aquifer systems of Freetown urban have not been researched. This study has conducted a detailed study of the hydrogeology components and properties of aquifer systems to close the gaps. Besides the hydrogeological data, other geodata, like topography, land use/land cover (LULC), soil, groundwater potential zone map, or climate data have never been investigated. These gaps have been closed by applying GIS environments, integrated with 3D-numerical modelling techniques to produce the groundwater potential zone map and other thematic maps as baseline data of the study area.

2.13 Summary

The significant highlights that can be drawn from the literature review are summarised as below:

- There is poor knowledge of how household characteristics (demographic, socio-economic, and water use) relate to a daily per capita water consumption. Additionally, statistical modelling for domestic per capita water consumption as a function of household characteristics has not been thoroughly investigated for the developing countries.

- Seasonal variability impacts on access to groundwater resources have been debated, analysed, and simulated using several groundwater software packages on various studies mostly from Europe, Asia and North America. However, very few studies have been conducted on how seasonal variability would impact the access of groundwater resources in Africa.

- The main challenge of seasonal variability impacts on groundwater resources is that many tropical regions mostly in Africa; lack the awareness of seasonal variability; they do not have the required human resource, there is inadequate institutional capacity and knowledge base to recognize the vulnerability of groundwater, water resource managers cannot design better adaptive strategies, that will mitigate adverse effects on groundwater.

- There is little or lack of data on the distribution of freshwater resources in Sub-Saharan Africa. However, the little information available is inaccessible, inaccurate, and meaningless and these necessitate the urgency for scientists to review the current studies and focus on designing adjustable strategies, for groundwater development and management.

- The impact of seasonal variability (dry and rainy season) on freshwater resources has a significant effect on per capita water consumption in developing countries, and this has not been addressed adequately. Therefore, it is extremely important to undertake studies that will quantify groundwater availability and recharge potential for sustainable use.

- There are numerous studies on groundwater development using analytical and 3D finite numerical models. These models provide the background for understanding the interaction between surface water and groundwater system. They also provide the context in determining the effects of human and environmental impacts for estimating future changes in the groundwater system.

- Despite the numerous studies conducted on groundwater quantity assessment globally, it is to be noted that no study to simulate groundwater quantity in the study area, that will proffer solutions to upgrade technical and institutional capacities at decision-making levels, has been conducted using analytical and 3D finite numerical models. The Soil Water Balance method and ModelMuse MODFLOW are established mathematical tools to simulate groundwater flow and recharge. They are used in this study to identify potential water catchment zones and estimate the groundwater recharge development to support an increase in daily per capita water consumption supply.

CHAPTER 3: GENERALISED CHARACTERISTICS OF FREETOWN (CASE STUDY)

3.1 General

Freetown, the national capital of Sierra Leone, covers an area of 73 km^2 shown in Figure 3.1, is located approximately on Latitude 8°29′02″ N and Longitude 13°13′47″ W. It is divided into four income groups and their locations as shown in Figure 3.1 (Supply and Framework, 2008). There are deprived densely populated informal slum settlements; concentrated mainly along the coastal plains and marginalised land in the city. These communities rarely have piped water to them; but have benefitted from other improved sources such as protected spring and gravity sources. There are also poor dense areas with less access to public standpipes. A cluster of poor households in better-off areas with limited or no piped water supply services; either because of low pressure or that the system is non-existent. The final group is the better-off neighbourhoods, with meter pipe connection. Data collected from the Sierra Leone Statistics Office indicate 229,951 households with a population of 1.055 million in the urban and sub-urban neighbourhoods. A description of the water consumption distribution network located in the study area; Western of Serra Leone is provided in Section 3.1.

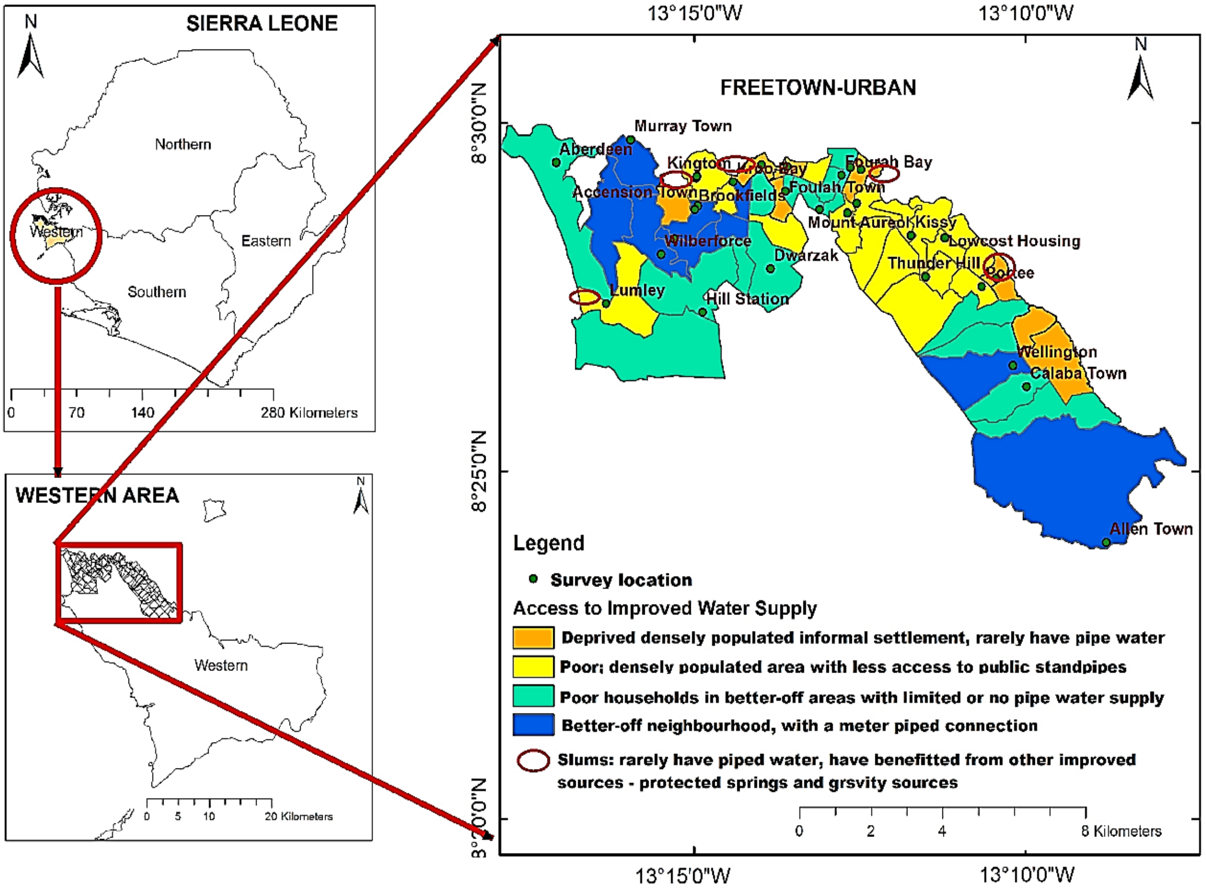


Figure 3. 1 Map of Study Area with access to GVWC piped and non-piped connection where research is conducted (Source: authour's construction)

3.1.1 Climate

By virtue of geographical location of Freetown, the climate is tropical and humid all year with mean lowest monthly temperatures of 16^{0}C in the night during the coldest month (August) to 31^{0}C in the hottest (April). The relative humidity ranges from an average of 80% during the rainy season to about 60% during the dry season (Lapworth et al., 2015; Meteorological dept, 2016). It has the African monsoonal rainfall type with average annual statistics recorded between 2500 to 4500 mm/year. Precipitation is mainly influenced by the weather with seven months of rainfall from May to November and five months of dry season from December to April. During December to early March, Freetown experiences a short spell of cool dry winds blown from the Sahara Desert referred to as Harmattan period, which brings the temperatures at night as low as 12^{0}C, while in the mountains, it can get even cooler. Table 3.1 presents the 2015 summary of climate data in the study area downloaded from the Meteorology Department.

Table 3. 1 Summary of climate data in Freetown (Meteorological Dept, 2015)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year total
Minimum temperature (°C)	24	24	24	25	24	24	23	23	23	23	24	24	
Maximum temperature (°C)	30.8	30.8	30.7	30.9	30.9	29.7	28.5	27.8	29.0	30.1	30.8	31.0	
Humidity (%)	86	86	88	88	88	86	84	82	84	86	86	86	
Precpi. (mm/month	8.6	6.8	5.4	55.3	203	460	1103	949	832	577	309	101	4519
Precpi. Days	0	0	1	4	15	22	27	27	24	21	9	2	152
Sea Temp (°C)	27	27	26	27	28	28	28	27	27	28	29	28	
Sunshine hours	7.3	8	7.5	6.9	6.1	5.1	3.3	2.8	4.2	6	6.6	7	
Daylight hours	11.7	11.9	12.1	12.3	12.5	12.6	12.6	12.4	12.2	11.9	11.7	11.6	
Wind speed (kph)	12.8	14.3	15.6	15.6	14.9	13.6	13.3	14.0	13.6	13.3	12.5	12.4	

3.1.2 Water Resources

Rainfall in Freetown, ranges from 1,900 to 5,000 mm annually. However, there is evidence of seasonality and water management issues. Despite the rich endowment of water in Sierra Leone, effective management of the resource is much needed in part because of the temporal variation in supply. Almost 90% of the annual discharge of all the rivers occurs from May to November. Sustainable social and economic growth are both intrinsically associated for an appropriate and proactive water resource management (Lapworth et al., 2015a).

The primary source of water supply in Freetown is pipe water from the Guma Valley Water Company (GVWC), which is the only service provider. GVWC is a parastatal institution that is 99% owned by the Government of Sierra Leone and 1% by the Freetown City Council (Williams, 2017). The main alternative sources in the dry and wet seasons for all household groups, are protected wells and rainwater, respectively. Sierra Leone has been promoting a free water policy since it gained independence in 1961. The average water tariff in Freetown is equal to US$0.22 per cubic meter.

Table 3.2 shows the percentage of main source of water for household use in the study and at country level during the dry season (Statistics Sierra Leone Household Report of 2018).

Table 3. 2 Percentage of main source of water for household use in the dry season in the study area and country scale (Source: 2018 SLIHS Report)

	Piped	**Tube well/ Borehole**	**Protected dug well**	**Unprotected dug well**	**Protected Spring**	**Unprotected Spring**	**Rainwater**	**Surface Water**	**Bottle/sachet water**	**River/ stream**	**Other**	**Total (%)**
Freetown (%)	32.8	7.5	38.8	5.8	6.3	2.0	0.0	0.7	0.3	5.6	0.2	100
Sierra Leone (%)	8.3	2.5	21.0	8.8	2.0	5.2	0.2	0.6	0.2	51.0	0.2	100

However, the most common choice during the dry season at country level is river/stream. Some of the main and alternate sources common in the study area are shown in Figure 3.2. The provision of improved source of domestic water is the responsibility of several authorities. Including the central government, local government, the community, Non-Governmental organisations, and donor agencies (Table 3.3). However, residents who can afford the cost drill/dug boreholes/wells, install water tanks on their houses. In the rainy season, people collected water in bucket under their roofs wherever they can or through structures that divert rainwater into large tanks and containers. Freetown experiences the African monsoonal rainfall type which can be very torrential and makes it difficult to collect rainwater.

Table 3. 3 Percentage of main source of water for household use in the dry season in the study area and country scale (Source: 2018 SLIHS Report)

Region	**Central Govt**	**Local Govt**	**Community**	**Donor Agency**	**NGO**	**Private Company**	**Private Self Supply**	**Religious Body**	**Natural Source**	**Other**
Freetown	53.2	5.8	11.0	0.6	1.9	61.1	13.8	0.0	2.5	24.1

Samples of bottled water

A private installed water tank at Kissy

A sample of packaged water

Community installed water tank at Wellington

A privately owned well that serves the Calaba Town community

A community standpipe at Fourah Bay

An unprotected well at Kissy

A spring at Foulah Town

A community spring at Congo Water

Figure 3. 2 Photos of varying primary and alternatives water sources in neighbourhoods of Freetown (Sources: authour's construction)

The water sector is facing serious challenges due to infrastructural disrepair, lack of maintenance, settlement on catchment areas, increasing water demand from population growth, poor energy supply, seasonal and climatic variability (Aitken et al., 1994; Lapworth et al., 2017). It is poorly prioritised and lacks the expertise and technical capacity to manage and supply water to households in Freetown on a

continuous daily basis (Lapworth et al., 2017). Moreover, the population of Freetown has been continuously increasing and the city has not seen adequate water storage capacity improvement to its only water reservoir built in 1960s. Report on the current operation, transmission and state of Guma Water Treatment Works (GUMA WTW) falls completely short of what is required to deliver a satisfactory and equitable water supply to the Freetown area (Atkins, 2008b). According to the Supply and Framework (2008) the current water supply requirement to serve Freetown is about 126 Megalitres per day (Mld), but the most reliable supply from Guma WTW is only 83.5 Mld and this includes domestic, commercial and industrial sectors. Therefore, this leads to rationing, as the service is concentrated more to the western part of Freetown from the Guma WTW with the central and eastern parts connected to smaller networks as shown in the GWTW transmission and distribution network diagram in Figure 3.3.
The provision and allocation of daily sustainable piped water supply has always been a significant constraint to Freetown's population which is less than 50% (Economides and Economides, 2009).

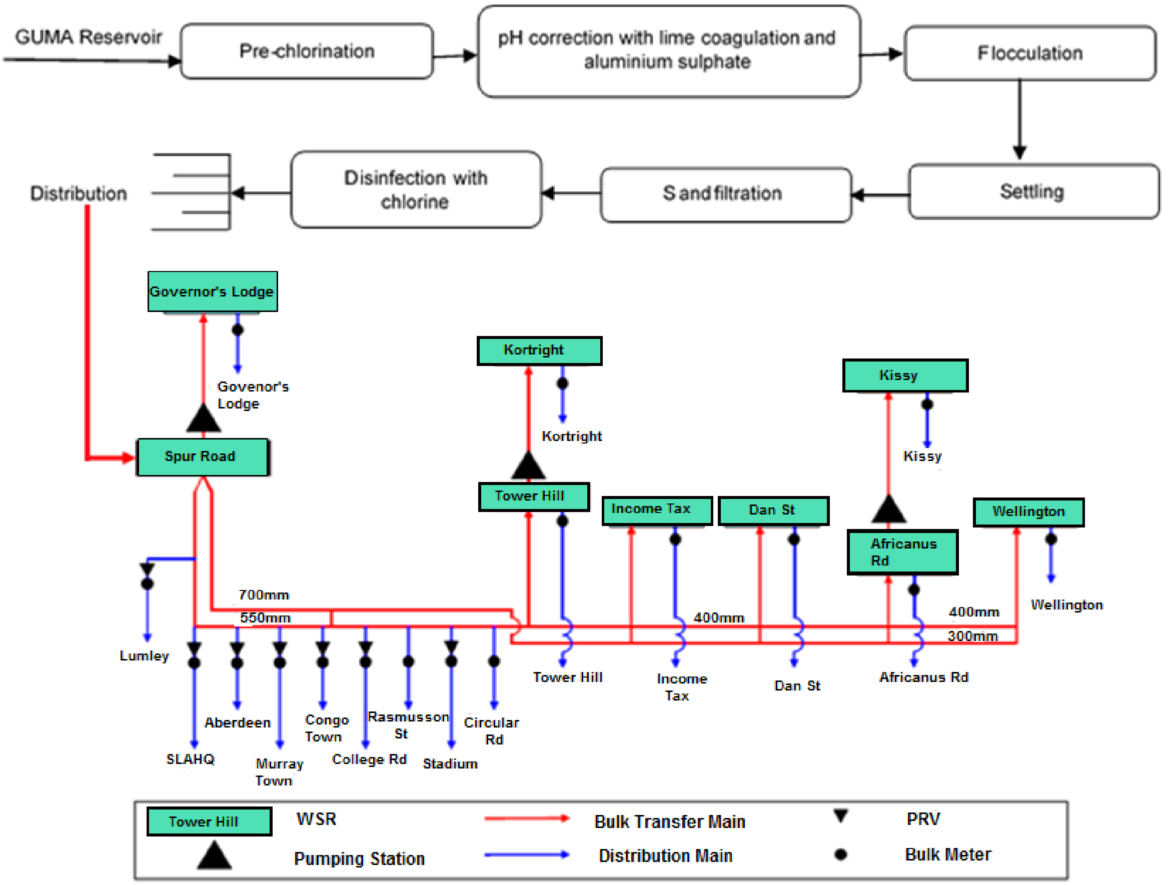


Figure 3. 3 Guma water treatment, transmission and distribution main system adapted from Leone, (2014)

Water Treatment, Transmission, and Distribution

To supply portable water to Freetown city, the treated water in the reservoir is pumped with a discharge of 2382 m^3/hr from the Mile 2 reservoir. The raw water is pre-chlorinated with the dose manually controlled. Lime and alum doses of 8kg/hr (2.2mgcl/l), which is the approximate measurement for the flow of 89 Mld is added to the raw water under closed manual control before passing to each of the three streams stretched up to 16 km. A turbine generator provides electrical power through routing to the dam. According to the Supply (2008b) report, the works has three stages, the stage 2 and 3 extensions both used degremont pulsators and Aquazur T filters and is combined with the Stage 1 filtered water flow with eight filters before being chlorinated and pumped to the treated water storage tank, from where it enters the gravity transmission system which conveys it to Freetown and its neighbourhoods as shown in Figure 3.3. The filters have an 800mm thick bed of 0.95mm sand on a 30mm layer of gravel. The total capacity of the dam is 89 Mld, but leakage leaves only 83.5 Mld for actual distribution. The reservoir has a plan area of 12.5 by 8m, 100m^2. Water is drawn from the dam through intakes at six levels.

Currently over 90% of the water supplied to Freetown, originates from Guma WTW in the western part of the city. This water is conveyed to Freetown through a low-level transmission and bulk transfer system from the clear water tank at Guma WTW to Wellington service reservoir in the east as shown in Figure 3.3.

There are various sources of water sought after by the households as pipe water supply is grossly inadequate in Freetown. Therefore, residents lose productive time by trekking and queuing for long hours at water points especially during the dry season.

Table 3.4 shows the approximate household percentage of distance in miles of the study area compared to the rest of the country that residents trek to their nearest main water source for drinking by the Statistics Sierra Leone 2018 Housing Report. The key message here is that though the survey conducted in Freetown present a difficult situation of longer time spent and far distances covered, the water access situation is better than the rest of the country.

Table 3. 4 Distance (Mile) to main source of drinking water in the dry season (SLHIS 2018 Report)

Region	less than 0.5 m	0.5 to 1 m	1 to 2 m	2 to 3 m	3 to 5 m	5 to 10 m	more than 10 m	Dwelling /compound
Freetown (%)	38.2	20.8	3.3	0.5	0.3	0.2	0.9	35.9
Sierra Leone (%)	50.4	24.7	7.6	1.6	0.7	0.4	0.8	13.9

Most people especially in the informal settlements and low-income household have settled themselves randomly in areas where there is no layout for piped connections or access to improve water supply. These settlements have been reporting high incidences of water related diseases such as diarrhoea and cholera (Nyenje et al., 2013; Carvajal-Vélez et al., 2016). Based on their vulnerability to water related diseases, Non-Governmental Organizations (NGOs) working in these communities have provided access to improved water supply sources; such as water stored in tanks, spring boxes, gravity piped water and dug wells. Household members trek long distances to access water points for their daily supply (Supply Plan, 2008).

Reliability of GVWC water supply varies between neighbourhoods, with those residents in the eastern parts of Freetown having less reliable service. Calaba Town and Old Wharf are areas that should be serviced by the GVWC but have no pipe water. Residents in these communities have been supported by charity organizations and more recently the WASH program with truck water and other alternatives sources such as spring boxes, wells, gravity pipes and rain harvesting. This has increased access to the number of improved water sources in these pipe water deprived households.

3.2 Geography of the study area

Freetown is a coastal city geographically located in the Western District of Sierra Leone. It lies between latitudes 8°20’38.04” N and 8°30’57.24” N and longitudes -13°1’46.56” W and -13°17’22.99” W and it forms the topographic sheet (61) on 1:50000 scale contoured plain metric map of Sierra Leone. The study area covers a total area of about 73 km^2 square kilometres with elevation varying from less than 1 m along the coast to about 510 m (inland) above mean sea level (MSL). The general trend is sloping from North East to South West. The population of Freetown is 1,055, 964 as per the Population and Housing Census PHC 2015 census with a male population of 513,199 and female population of 542,765**.** The study area has about 31 neighbourhoods. Figure, 3.4 shows the location map for Freetown and the study area details.

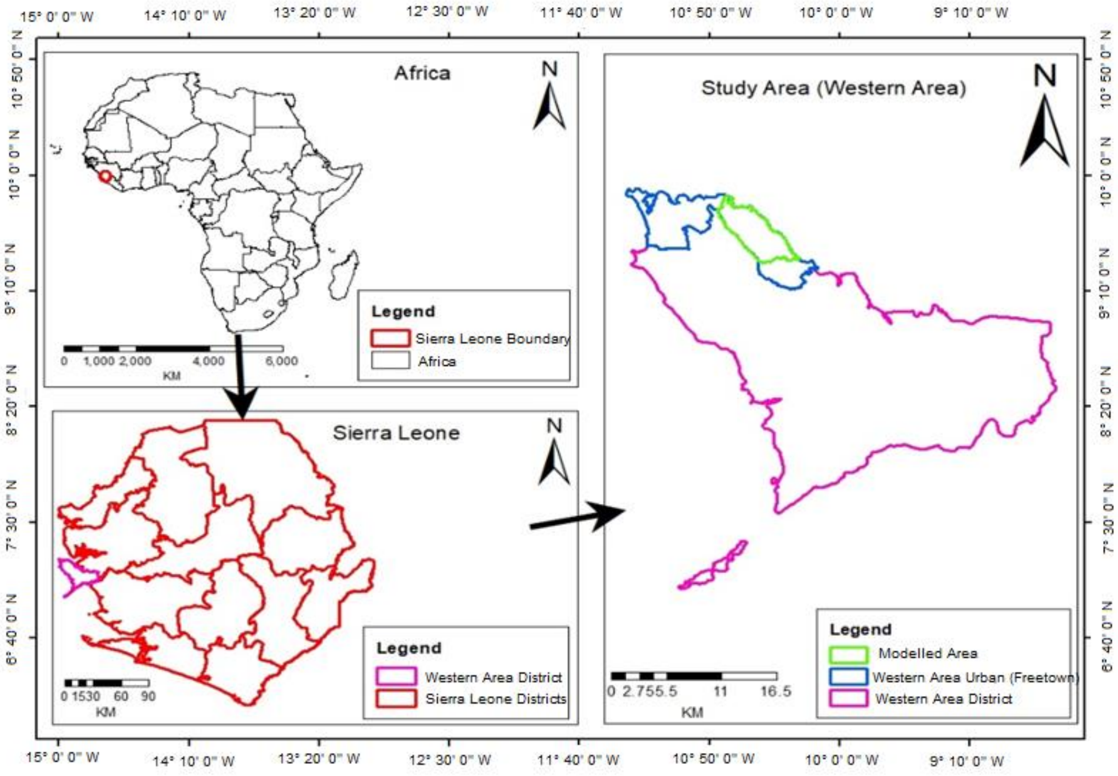
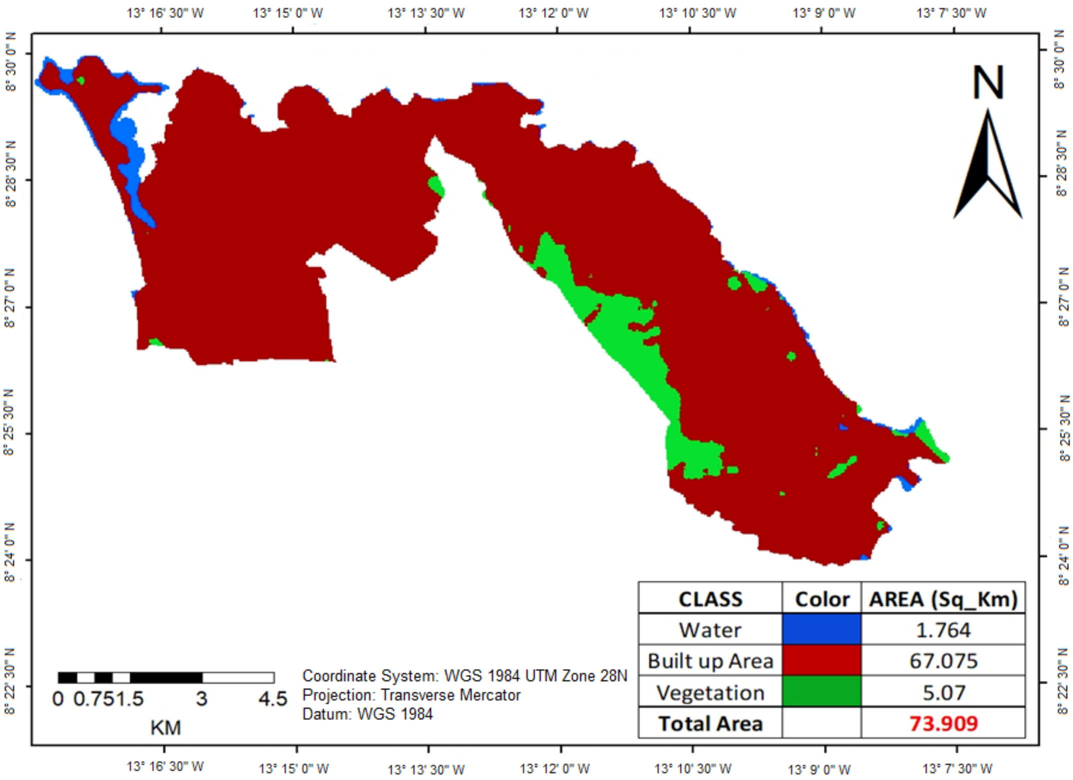


Figure 3. 4 Location map of Freetown (Source: authour's construction)

Out of the total geographical area of 73 square kilometres about 3.8 percent of the land is occupied by water, 85.7 percent of the area is covered by built-up area, and around 8.1 percent of the area is covered by vegetation (Figure 3.5). The soil ranges from weakly developed muds, hydromorphic clays to lateritic hills type. The climate is comparatively more pleasing with ambient temperatures averaging 23°C to 31.5°C. It becomes cooler and drier from December until mid-March during the Harmattan period (Lapworth et al., 2015).

During the dry season (December - April) the maximum temperature is about 32.5°C. There is a gradual decrease of both daylight and sunshine hours during the rainy season (June – October) shown from data by the Meteorological department. Petty trading and fishing are the major occupation in this region. The main crops grown in the area are maize, groundnut and millet with rich variety of fruits and vegetables. The administrative map of the study area of Freetown Western Urban is given in Figure 3.6.



CLASS	Color	AREA (Sq_Km)
Water	🟦	1.764
Built up Area	🟥	67.075
Vegetation	🟩	5.07
Total Area		**73.909**

Figure 3. 5 Land use and land cover distribution map of Freetown city (Source: authour's construction)

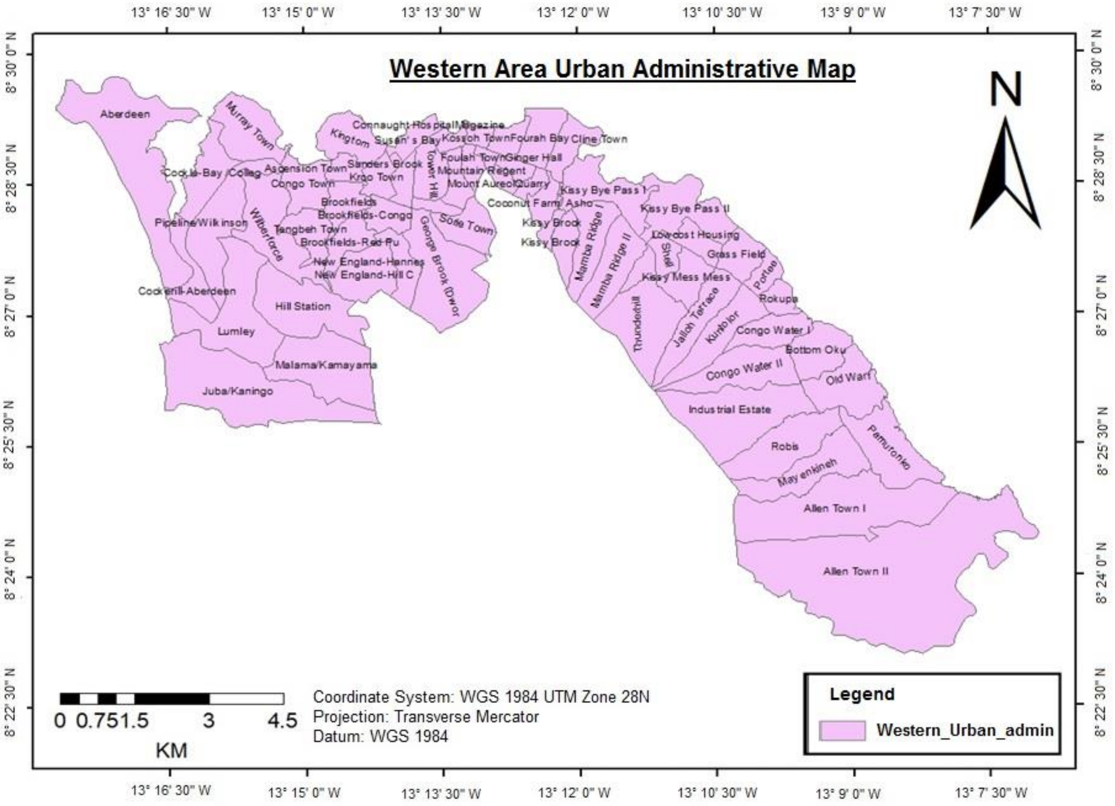


Figure 3. 6 Freetown City Administrative Map (Source: authour's construction)

3.2.1 Physiography

Freetown city a tropical landscape consists of an undulating mountainous peninsula which rises abruptly from the sea ward margin of the coastal plain inward. In general, due to erosion a few platforms have been formed in several mountain masses with varying altitudes from over 743 m to less than 396 m. It is geographically and geologically different from the rest of Sierra Leone. The mountains formed part of the funnel-shaped layered gabbroic intrusion known as the Freetown complex (Umeji, 1975). Several perennial streams and brooks have extended their courses from the hills across them to valleys. These hold water during the monsoon and for the dry season. The area has lost a high percentage of its forest reserve to urbanization and fuel-energy consumption.

3.2.2 Geology and geomorphology

Sierra Leone occupies the central portion of an Archean craton that was disrupted by the opening of the Atlantic Ocean. Freetown Peninsula; located in the extreme west of the country comprise mostly of mountainous ranges and valleys with elevations rising up to about 884m (2,900 ft) above sea level (Umeji, 1975; Hill, 2006).

The geology of the project area comprises the Freetown layered complex overlain by the recent Cenozoic Bullom Group formation (Figure 3.7). The Freetown layered complex is a rift-related tholeiitic intrusion associated with the Mesozoic Era (~193 Ma) opening of the Atlantic Ocean at midlatitude. The complex is ~ 60 km long, 14 km wide, and 7 km thick along a major E-W traverse trend. Chalokwu et al. (2010) observed that the exposed outcrops consist of a rhythmically layered sequence of dunite, troctolite, olivine gabbro, gabbro/norite, leucogabbro, and anorthosite. Mineral compositions in the complex range from An_{54} to An_{72} plagioclase series, Fo_{56} to Fo_{75} olivine (Fosterite), $En_{38.5}$ to $En_{44.8}$ augite, and $En_{54.9}$ to $En_{74.6}$ orthopyroxene.

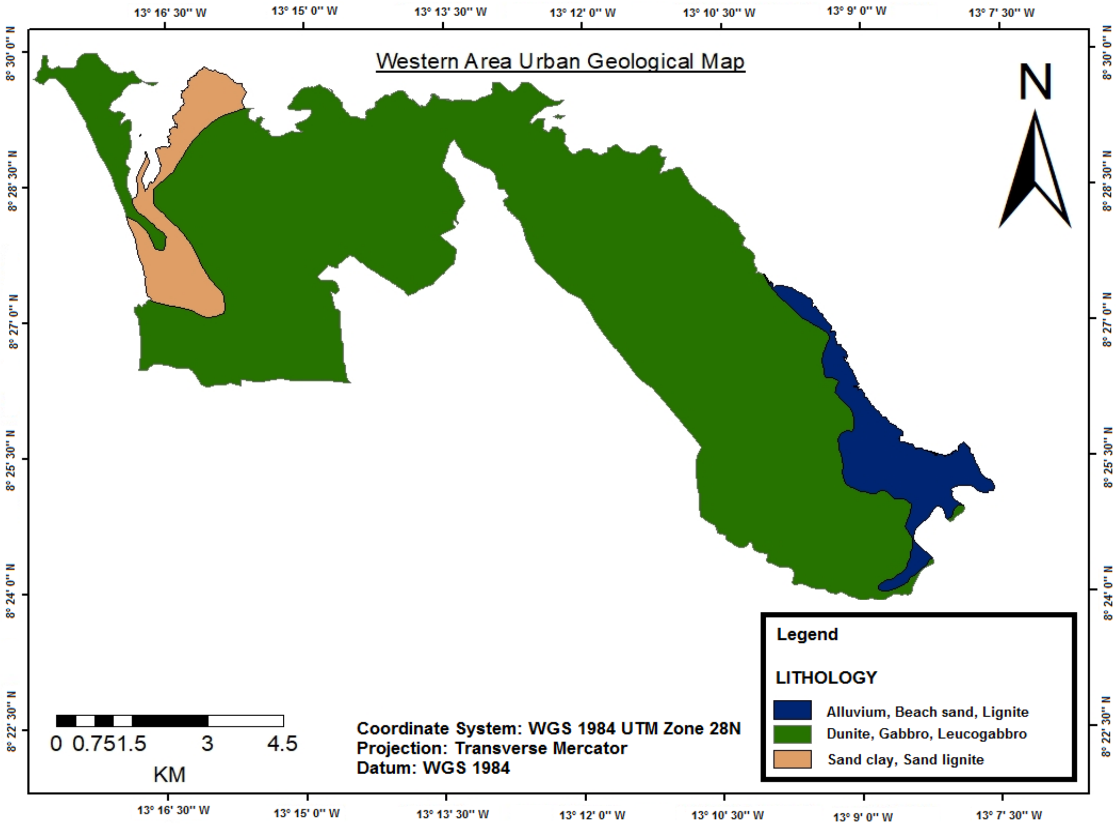


Figure 3. 7 Geological Map of study area (Source: authour's construction)

The tertiary to quaternary Bullom Group deposits, are nearly horizontal beds of marine, estuarine, and fluvial gravels, sands and kaolinitic clays with lignite. In the vicinity, laterites as a result of weathering of the Freetown layered complex occur within the relatively unconsolidated sediments and form resistant outcrops. Beside these, there also occurs basic dykes of dolerite composition that criss-cross the complex. These morphological features are grouped topographically into highlands (recharge zones) and lowlands (discharge zones) which are characterised by a downward and an upward flow of water respectively (Akiwumi, 1994; Chalokwu, 1995).

3.2.3 Groundwater State in the Study Area

Groundwater storage and flow is entirely intergranular in the coastal areas. However, there is limited data on borehole yields for the fractured gabbros with secondary porosity, and these have been tapped between 0.3 and 3 litres/second (l/s) in the weathered zone of the Freetown complex (Lapworth *et al.*, 2015a). Lapworth et al. (2015) had estimated that yields for boreholes in the Bullom Group sediments often abstract up to 6l/s. They also noted that the deeper, fractured bedrock is relatively the most stable groundwater source and serve as better aquifers with considerable improved hydraulic and storage properties than in the higher regolith zone.

Freetown experiences a rainy season due to the African monsoon which runs from May to November. Rainfall is the main source of groundwater recharge in the area. The depth of groundwater at static water level (swl) ranges from 30 m to 3 m during the pre and post monsoon periods and ranges from 18.2 m and 1.6 m (swl) during the monsoon (Hydronova, 2017). Precipitation ranges between 2,400 and 5,000 mm/year, with high infiltration rates. The shallow aquifer tends to dry up rapidly when the rains stop as groundwater drains rapidly away through the permeable material. The yields decline steadily in dry season or the well dries up. The wells and borehole stratigraphic profiling of the study area are presented in Figures 3.8 and Figure 3.9, drawn from data sourced from Baba Drilling Exploration Company and the EDAL Drilling Company LTD. The stratigraphic profiling presents the lithologic section of some wells and boreholes in the study area. Based on borehole lithologic logs, weathered and fractured aquifer units were delineated in the area. The first criterion influencing the depth of well development is the lithology and depth of the aquifer. The hydraulic properties estimated from the pumping tests of the aquifers indicate negligible to fairly high transmissivity and moderate specific capacity values as revealed by most boreholes. This suggests boreholes of good performance for urban water supply. Plans to develop groundwater in any area should be based on the stratigraphic profile and site investigation to assess the functionality of the proposed construction.

3.2.4 Aquifer Potential of Hard Rock Formation in the Study Area

An aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt). Groundwater can be extracted through a well and or borehole. Sierra Leone is divided into four hydrogeological units. (1) Unconsolidated sedimentary deposits, (2) Consolidated metamorphic, (3) Igneous/ultrabasic rocks and (4) Basement complex.

The entire study area is underlain by Triassic to Jurrasic crystalline ultrabasic igneous formations which have no primary porosity (Umeji, 1975) and overlain by the unconsolidated sediments of the Bullom Group formation which have primary porosity and higher permeability and therefore constitute the main aquifers with yields of up to 5 litres per second (l/s) (Lapworth et al., 2015b; Fileccia et al., 2018). Groundwater accumulation in the ultrabasic igneous rocks occurs in fractures, joints and fissures from thin weathered laterite zone (Taylor and Barrett, 1999). The prevalent aquifer types are unconfined.

In aquifers of igneous rocks, groundwater occurs under water table or phreatic conditions in weathered, fractured, and jointed formations. The Freetown complex are essentially, a series of cumulate rocks of gabbroic composition, containing layers of dunnite, troctolite, olivine-gabbro, gabbro, leucogabbro and anorthosite (Chalokwu et al., 1995). Sedimentation structures such as cross-bedding are common in the gabbro layers and some 6,000 m of thickness is exposed (Chalokwu et al., 2010). Parameters such as depth to groundwater, recharge, soil geology, media and conductivity, topography need to be taken into consideration when designing water development models, these have been discussed earlier in this chapter. The pore space or crevices/cracks/faults developed in the weathered mantle act as shallow granular aquifer and form the potential water bearing and yielding zone. There is dearth of information regarding results of drilled and hand dug wells, and on borehole yield in the Freetown complex.

Borehole lithology data from Baba & EDAL drilling companies indicate that the thickness of aquifer in the weathered and fractured gabbroic formation varies from 10 to 32 metres. Water table is highly seasonal and varies from shallow to deep, but the intensity of weathering joints, fractures and their development is much less when compared to the overlying poorly consolidated (laterite and alluvial) formations. As a result, they are termed as low aquifer productivity zones especially in a region where the intensity of weathering together with development of joints and fractures is greater. The maximum well/borehole depth recorded in these strata is 132 metres data from EDAL[1].

3.2.5 Sedimentary (alluvial) formation in the Study Area

In alluvial formations, groundwater occurs under water table conditions. These formations are highly porous, permeable and develop into good potential water bearing zones. Sedimentary formation (Bullom Group) is characterized as poorly consolidated marine and estuarine sediments, sands, gravels and kaolinitic clays with some lignite. Borehole lithology data from Baba & EDAL drilling companies indicate that there is considerable thickness of weathering range from 5 to 46 metres below ground level. Due to the fact that sandstone, gravel and sand possesses some inter-granular space, which may be available to the groundwater (provides storage), this type of aquifer is regarded as having a high groundwater potential. Unlike the hard rock aquifers which are localised and very sensitive to recharge, the sandstone aquifer, due to its primary porosity (inter-granular space filled with groundwater) may withstand long periods of drought and lack of recharge. Consequently, the sandstone aquifer is regarded as a more reliable and longer-lasting source of groundwater as compared with any other aquifer.

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[1] EDAL Drilling Company LTD and BABA Drilling & Exploration Company LTD

The groundwater potential of sedimentary (alluvial) rocks is higher than that of other types of rocks in the study area. Pumping test results illustrate the practical utility of a newly developed relationship for determining aquifer characteristics (specific storage coefficient and hydraulic conductivity) based on borehole/well hydraulics analysis. As a result of the analyses, the watershed shows excellent groundwater potential zones to improve the yield capacity of future wells and infiltration galleries (Ashraf et al., 2018).

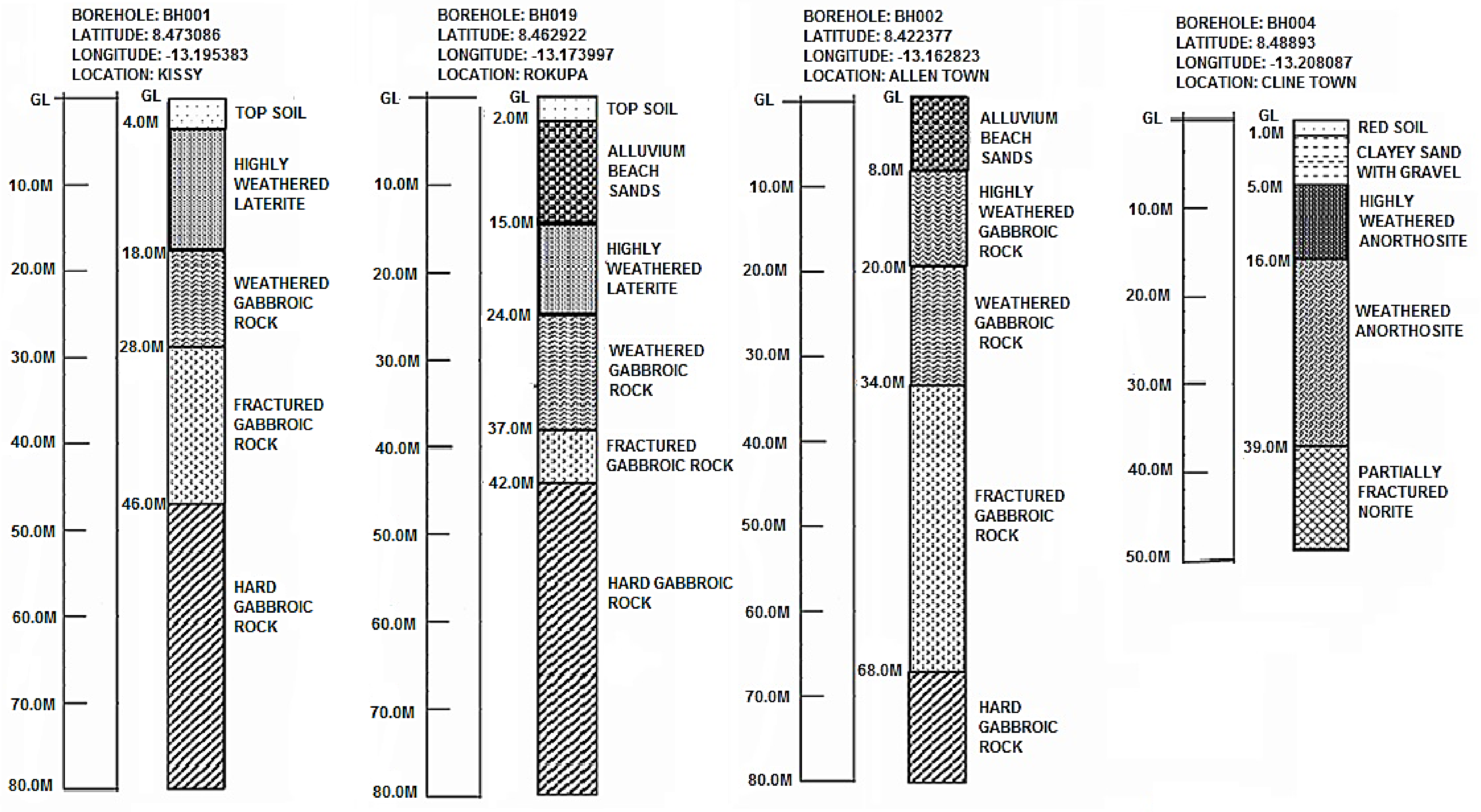

Figure 3. 8 Stratigraphic Profiling of Boreholes and Wells in the Study Area from data (Sources: authour's construction)

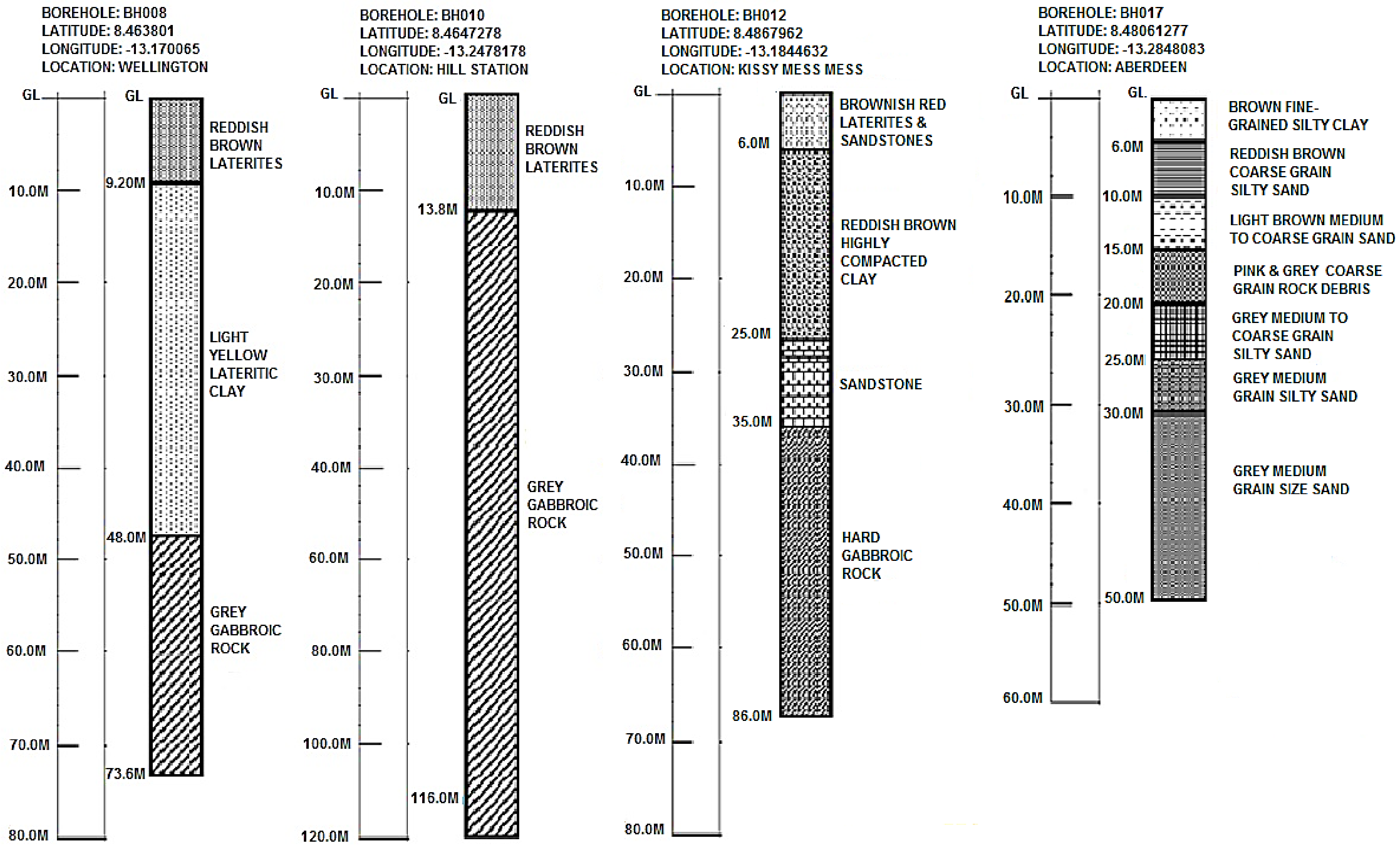

Figure 3. 9 Stratigraphic Profiling and Wells in the Study Area from data (Sources: authour's construction)

3.3 Summary of GIS application in Groundwater Development and Modelling Studies

GIS environment is used to produce the data in visually mapped format. To demarcate groundwater characteristics of the study area, a range of essential parameters and specialised maps were prepared due to the dearth of data in the study area. The various field data for the analysis were collected from different sources as listed in Section 3.4. The flow chart for the delineation of Land use and topographic patterns for the groundwater modelling component of the present study is shown in Figure F2.1 in Appendix F. GIS technique also extracts and digitised maps and water flow information from DEM into raster, surfer grid and ASCII files format for the groundwater simulation. The map preparation method integrates advanced modern mapping applied in the GIS environments (ArcGIS and QGIS). Actual coordinates systems were used in the prepared maps to locate and display data correctly on the earth's surface.

The hydrogeologic thematic maps of Freetown were developed to serve as baseline information for the area. Downloaded Radar Topography Mission (SRTM GL1) Global 30m resolution data with the help of ArcGIS 10.6.1 and QGIS 3.10.1, were prepared to simulate the data for the next fifteen years in ModelMuse MODFLOW 2005 and ModelMuse MODFLOW 6. The groundwater model setup done for the study area of approximately 25.5 km^2 was discretised with a finite-difference grid of cell size discussed in sections 4.13.1 and 4.13.2 (ModelMuse MODFLOW Input and Layer elevations). Digitised maps, processing geospatial files and interpolated aquifer parameters for ModelMuse MODFLOW as well as watershed delineation of the study area.

The model domain was divided into the required layers (1, 3, 4, and 5) parallel to the main geological surfaces in the different simulations. For example, in the simulation of infiltration galleries, the alluvial aquifer layer was used (1 layer), and this alluvial layer was further discretised into five vertical layers. In the unstructured grid simulation for regional groundwater flow, three layers were used (upper, middle, and lower aquifer layers). For the simulation using MODFLOW-NWT to compare the observed and simulated heads, four layers (alluvial, upper, middle, and lower fractured aquifer layers) were used. In the zone budget simulation to study the water balance of the entire model such as the pumping in certain areas or evapotranspiration of the area, five layers were used (aquifers 1 to 5). The boundary conditions and hydraulic properties used in the models are discussed in section 6.5 of chapter 6 groundwater development. GIS has been used to define spatial input for the models through inserting shapefiles and polygons on top, front, and side views of the model domain as discussed below.

3.4 Field data collection

3.4.1 Topographic, rainfall and groundwater analyses

The various field data used for groundwater analysis, rainfall and topographic studies were collected from different sources. To assess and evaluate groundwater development quantitatively the following data were used to facilitate the groundwater modelling process in this study.

- Borehole logs from drillings: These were received from EDAL Drilling Company LTD and BABA Drilling & Exploration Company LTD to understand the in situ (subsurface) conditions of the aquifer.
- Well pumping tests: These were gotten from EDAL Drilling Company LTD and BABA Drilling & Exploration Company LTD. The pumping well tests data received were conducted during the well drilling processes in January and February of 2016 and March to May of 2017. The data were used to estimate the hydraulic properties of the study area by Theis (1935), Cooper and Jacob (1946), and Chow (1951) methods. These are basic analyses for constant rate pumping tests and are frequently used. They are based on the same principle: pumping at different flow rates is carried out, and the drawdown or water level changes are observed. Estimation of aquifer parameters from the pumping tests data are shown in Table F1. 1 in Appendix F.
- Rainfall data: These were downloaded from World Bank Group Climate Change Knowledge Portal online historical and projections database (1901 – 2099) from the World Bank data site[2]. Local rainfall and temperature data for a period of 29

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[2] https://climateknowledgeportal.worldbank.org/download-data

years (1990 - 2018) was obtained from the Sierra Leone Meteorological Agency (SLMet, 2018). Weather data was also downloaded from the Weather Atlas site[3].

- Topographic data: Previous studies showed that topography contributes to groundwater movement across many spatial scales; steeper topography can be associated with deeper water table depths, more regional groundwater flow, and control of groundwater recharge and discharge (Maxwell et al., 2015). Likewise, studies have shown that geology and climate control groundwater development (Green, 2016). Topography influences groundwater fluxes and water table depths across the watershed. Hence, the topography is one of the main analyses carried out using GIS to study the topographic characteristics of the watershed. Digital Elevation Model (DEM) and ASTER data were obtained with the help of USGS NASA Earthdata download and OpenTopography Shuttle Radar Topography Mission (SRTM GL1) Global 30m resolution data downloaded from the USGS LPDAAC[4], BBBike[5] and Opentopography websites[6]
- Hydraulic parameters: The values of hydraulic conductivity, transmissivity, storativity, drawdown and specific yield for various geologic materials were calculated from pumping well data using Aqtesolv software package[7].
- Ground truth data: Direct observation and measurements of the wells were conducted. Due to difficulty in finding satisfactory observation wells, only 10 wells are tested during field work at Murray Town, Wilberforce, Kingtom, Kissy, Wellington, Calaba Town and Allen Town. Groundwater level measurement and pumping tests were conducted from 10 residential households and industries were analysed to calculate the hydraulic properties.

3.4.2 Water consumption analysis

- The field data for quantitative assessment of per capita water consumption was gathered using a questionnaire base study conducted in the two seasons.

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[3] https://www.weather-atlas.com/en/sierra-leone/freetown-climate
[4] https://lpdaac.usgs.gov/tools/earthdata-search/
[5] https://extract.bbbike.org
[6] https://portal.opentopography.org/raster?opentopoID

[7] https://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm

CHAPTER 4: METHODOLOGY

4.1 Introduction

Groundwater is essential for the survival of mankind. Over the years, the demand for water has been rising (Rastogi, 2007). The increase in population created the need for improving groundwater development and strategic designs to sustain the high abstraction rate for consumption (Robertson *et al.*, 2003). The rapid exploitation of groundwater resources has resulted in the decline of the groundwater table. Sustainable per capita water consumption depends mostly on the amount of available water supply for access and the size of the population UN WWAP (2003). In this study, the occurrence of variable patterns of rainfall, the amount of available water and population size are the major factors that impact equitable per capita water distribution.

Most researchers solving the problem of water insecurity, have carried out investigations that have not integrated water consumption surveys and groundwater quantity flow simulations that define a solution for seasonal water availability. Literature reviewed have shown that research conducted on per capita, or household water consumption surveys have been done independently. Similarly, studies on groundwater and surface water as potential water sources for communities have been carried out alone.

This study is novel for its parallel quantitative investigations, integrating per capita water uncertainty, groundwater development, abstraction, and management. It quantifies the per capita water consumption of the study area, and models the groundwater development, impacts of future groundwater abstractions and design implementation. The water consumption data derived from the household survey will be the guide to develop management strategies for domestic abstraction as a reliable source throughout the different seasons.

This chapter has two distinct parts. Part A (Section 4.2 to Section 4.4) is focused on water consumption questionnaire based related aspects. Part B (Section 4.5 to Section 4.16) gives the methodology details for aspects related to the groundwater simulation.

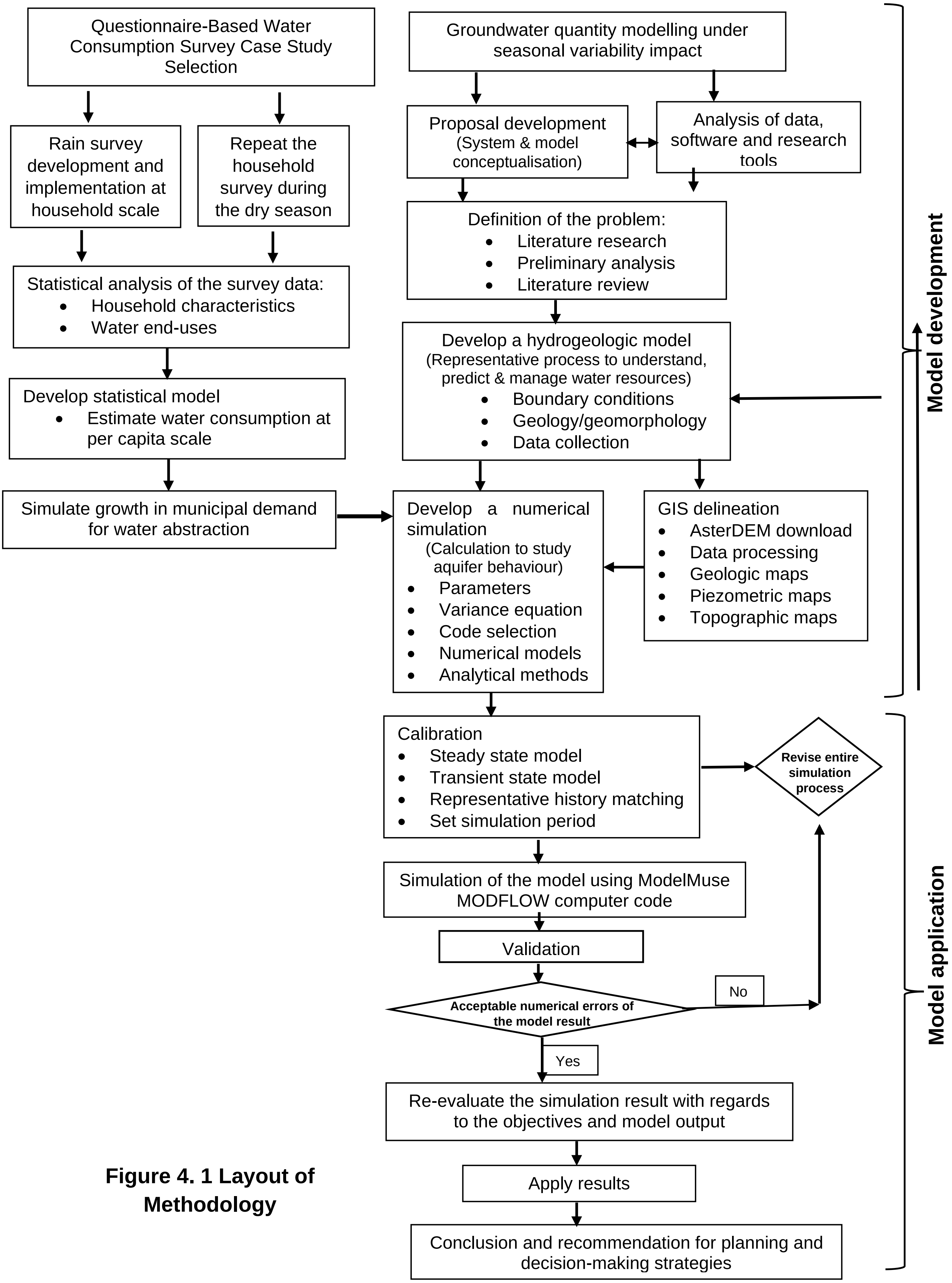

Figure 4. 1 Layout of Methodology

The questionnaire-based study aimed to collect quantitative information on water consumption during the rainy and dry seasons. The statistical modelling techniques used to analyse the survey data and the comparison between both seasonal studies are presented in Section 4.3.

This chapter also deals with materials and methods adopted in the groundwater modelling process to estimate the quantitative potential of the watershed. The objective of the 3D numerical modelling is to carry out an assessment on groundwater quantity and flow of the Freetown watershed. Model Muse MODFLOW simulation and Geographic Information Systems (GIS) are used for this study. The groundwater model is calibrated and validated. The validated model is used to estimate the recharge capacity of the watershed over a period of 15 years by using a 3D finite numerical model technique under various scenarios. It is also used to determine the appropriate planning and decision-making strategies for sustainable groundwater consumption and management.

4.2 Data Collection of Water Consumption Questionnaire-Based Study

4.2.1 Questionnaire-based Study Dissemination

This study has adopted a quantitative method for data collection aiming to gather information on the key variables that affect water consumption as presented in Figure 4.1. A detailed multiple-choice format questionnaire having over 80 standard and follow-up questions was developed to gather information. Data for the rainy season was collected in August 2017 and the questionnaires were completed by students at the University of Sierra Leone on behalf of their households. Data for the dry season was collected in April 2018 mainly from some of the previous respondents in 2017 and other new households. 245 and 153 households in the rainy and dry seasons were collected respectively making 398 households. University students were identified to complete the questionnaires on behalf of their households because they were in English and too detailed for the average inhabitants to complete with little supervision. Students were provided with a brief demonstration of how to respond to the questions; to minimise bias and address any issues related to the maintenance, integrity and quality of the collected data. Ethical approval for the study was obtained from the University of Exeter Research Ethics Committee. The researcher informed respondents that participation in the survey was entirely voluntary and intended for research purposes only. Respondents were assured of confidentiality of data recorded and that they were free to deny the information at any time without providing justification. Consent for data collection was granted by the Academic Approval Committee in the College of Engineering, Mathematics and Physical Sciences before the questionnaire was administered. The survey questionnaire comprised of five sections. The key variable quantity includes the seasonal variants of the:

- Socio-demographic characteristics (e.g., age range, gender, family income, gender, religion, education level, per capita income, household size, etc.).
- Household characteristics affecting water consumption (e.g., number of rooms, total built up area of the house, number of vehicles, number of bathrooms, number of toilets, etc.).
- Primary, secondary, and tertiary available sources of water for domestic and drinking household uses.
- Water use habits and ease of access (e.g., average daily water consumption, cooking, drinking, bathing, toilet flushing, house cleaning, washing vehicles), water collection containers, time taken, and distance travelled to collect water; means of transporting the collected water (e.g. on head, pushcart, etc.), water storage available within the household.
- Household water perception (e.g., water fees, willingness to pay to conserve water), education program (knowledge about water shortage) and household environmental attitudes (e.g. water shortage, quality, water pollution, environmental protection, air pollution).

The full questionnaire is shown in Appendix A.

Water Consumption of a Household

In addition to the household characteristics, the questionnaire-based study included over 30 questions regarding the frequency, duration of use, flow rate and volume of each water-end-use (e.g., showering, bathing, hand wash basin tap usage, toilet flushing, dishwashing, clothes washing, cooking, garden watering, house washing and vehicle washing).

4.2.2 Participants/Stakeholders Selection

The target participants were inhabitants of Freetown and it's neighbourhood. The questionnaires were distributed to a total 550 selected households in Freetown for both seasons in August 2017 and April 2018 for the rainy and dry season respectively (Figure 4.2). University students were identified to complete the questionnaires on behalf of their households because they were in English and complicated for illiterate respondents. The replies were received from 398 households. The investigated households were categorised into four household income groups and were analysed separately to determine their daily per capita water consumption in litres per day.

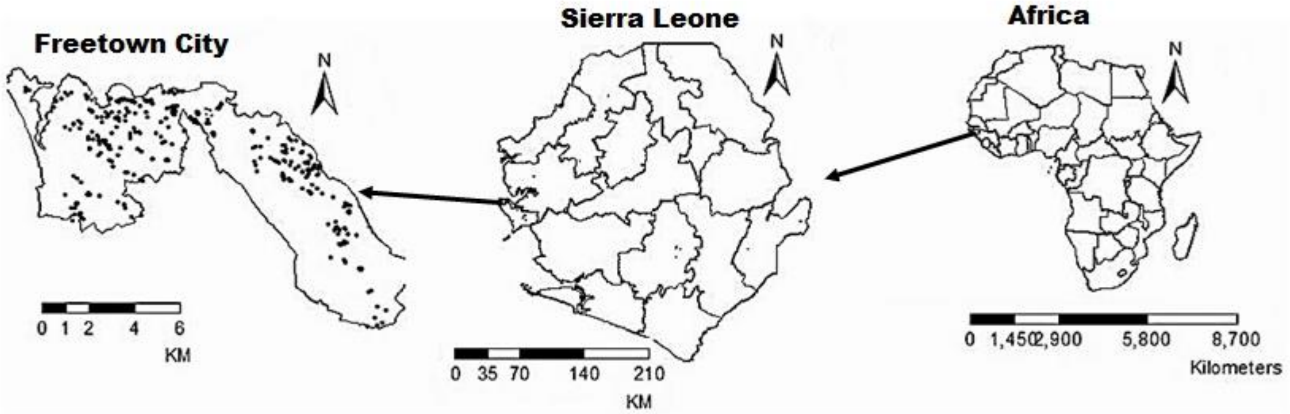

Figure 4. 2The distribution of Surveyed Households in the Neighbourhoods of Freetown city (Source: authour's construction)

To capture the seasonal variability of water consumption, the full survey explained earlier was conducted in the rainy season of August 2017 and repeated in dry season in April 2018; after a review of the questions to suit the dry season available alternative water sources such as rainwater and non-perennial streams that do not exist in the during this season.

The dry season survey was conducted in some of the same sample of households selected for rainy season survey and some new households. The limitations faced in the survey, was accessing the same number of households which were selected for the rainy season survey, as some of the students had gone for fieldwork during the dry season. Data gathered was used to compare and contrast average overall per capita water usage in the city to see how water use varies between the different households. The dry season survey was distributed to 160 households and the answers received from 153 households. Information were collected on the frequency, duration of use, flow rate where applicable and volume of each water end-use.

4.3 Questionnaire-Based Study Analysis

4.3.1 Materials and methods used in questionnaire-based study

In the water consumption study, 398 questionnaires were received, coded and imported into IBM SPSS statistics V25 for analysis of the statistical parameters (i.e., average, median, standard deviation, minimum, maximum and distribution shape identification through kurtosis and skewness). MS Excel was used to present the results in charts and table format. Using the dataset, 20 statistical models were developed using multiple regression (stepwise) technique to select the best combination of household, socio-economic and water use characteristics to construct the best fit model based on strong statistical foundations.

4.3.2 Impact of Income on Water Consumption

In Sierra Leone, there are four main income groups: the informal slum dwellers, low-income group, middle income group and high income group. The classification for the different income groups was based mainly on their settlement across Freetown city. The Statistics Sierra Leone Office (SSL) conducted an integrated socio-economic household survey in 2015. A household was defined as a person or group of persons related or unrelated who live together under the same roof and make common cooking arrangements. In the questionnaire analysis the actual frequency distribution of household income in Sierra Leone in shown in Table 4.1. This category was based on the average national household size of 5.6 persons. Table 4.1 shows that on a national scale, about 16 percent of households income level is lesser than Le1,000,000 whereas in the Western area region which includes Freetown city the percentage frequency is 18 percent. About 48 percent and 42 percent of households income level lie between Le1,000,000 and Le10,000,000 per month at national and in the western area respectively. This implies that about 60 percent of households' income level in the western region lies below Le10, 000,000 (About US$1000). The remaining 40 percent of households' income in the western area and 37 percent at national scale is greater than Le10, 000,000. This brings out the low-level income in Sierra Leone, and when high inflation hits, there are implications that affects the quality of life.

Table 4. 1 Percentage distribution of Average Monthly Household Income by Income Category based on the Integrated Household Survey of 2015 by Statistics Sierra Leone

Region	**Average Monthly Income in Sierra Leone Leones (SLL)**											
Total household income (SLL)	**< 5X10^6**	**5X10^5 -9.9X10^5**	**1.0X10^6 - 4.9X10^6**	**5X10^6 - 9.9X10^6**	**10X10^6 - 14.9X10^6**	**15X10^6- 19.9X10^6**	**20X10^6 - 24.9X10^6**	**25X10^6 - 29.9X10^6**	**30X10^6 - 34.9X10^6**	**35X10^6 - 39.9X10^6**	**40X10^6 - 49.9X10^6**	**> 50X10^6**
Sierra Leone (%)	7.97	7.69	28.68	18.89	10.48	6.48	4.49	2.9	2.66	1.82	1.39	6.57
Western (%) incl. Freetown	6.96	11.17	24.14	18.18	10.41	7	3.07	2.54	2.6	1.55	1.13	11.28

*1SLL 69 ×10^{-6} = £1

Income and affluence can be a key factor shaping per capita water consumption. Jorgensen et al. (2009), in their study noted that income is the main factor influencing household water consumption, indicating increased lifestyle and affordability for water needs as income increases. Per capita water consumption is a function of socio-economic factor and varies with people's behaviour, habit and income level. It increases with the increase in family income (Headley, 1963). Although, other factors, such as water storage containers, education level, age category and water points can have a minimal impact on water resource consumption. The major consumption influencing factors are household income, seasonal variability, weather, household size, hydrological characterization, distance to water points and time spent to fetch water (Inocencio et al., 1998; Ayanshola et al., 2012; Tshikolomo et al., 2012;

Rathnayaka et al., 2015). Therefore, the developed model investigates the influence of per capita income on water consumption based on the listed factors.

In the current study the household and per capita income levels are shown in Table 4.2. Statistical models will be generated for the various income level groups, which are the significant variables that impact access to water for consumption.

Table 4. 2 Income Groups Classification for the Current Study (Source: authour's analysis)

Income group	**Income range in Sierra Leone Leones (SLL)**	
	Per household	**Per capita**
Informal slum	$< 1.4X10^6$	$< 2.3X10^5$
Low	$<1.5X10^6 – 2X10^6$	$<3X10^5 – 4X10^5$
Middle	$2X10^6 – 6X10^6$	$4X10^5 – 1.5X10^6$
High	$>6X10^6$	$>1.5X10^6$

The per capita income for respective household groups has been obtained by dividing the household income by the average family size of each income group in column two. The surveyed 398 households were divided into four income groups (Table 4.3).

Table 4. 3 Number of Surveyed Households at different Income Groups (Source: authour's analysis)

Income group	Informal slum settlement	Low	Middle	High
Number of households	31	97	203	67

The variation in the household family income was significant, and ranges from 9×10^5 Sierra Leonean Leones (SLL) /month (≈£85) to Le 17×10^6 SLL/month (≈£1600), with an average household income equivalent to 5×10^6 SLL/month (≈£442). This monthly average family income is broadly consistent with the Civil Service Code (2009) and United Nations (2018) salary scale. Each income group was analysed individually to recognize the impact of variation in income on the per capita water consumption. The frequency distributions and detailed statistical analysis for all household characteristics are shown in Appendix B1 and B2, respectively.

4.3.3 Analysing the Seasonal Variability of Water

To study the seasonal variability of water end-uses, the frequency distribution and cumulative frequency of per capita average consumption are estimated for the rain and dry questionnaire surveys. Additionally, a two-tailed t-test is used at 95% confidence interval. This test shows that there is no statistically significant difference between the consumption in rainy and dry season when p value is higher than 0.05. In contrast, the difference is statistically significant if p value is less than 0.05. The detailed discussion on the seasonal variability impact on water end-uses between the seasons is presented in Chapter 5 and in Ibrahim et al. (2021).

4.3.4 Statistical Modelling of per capita Water Consumption with Household Characteristics

The water consumption data from the full 398 households was divided into calibration and validation sets. 70% of the data was used for calibration (i.e., training), while the remaining 30% was spared for validation (i.e., testing) purposes. Studies indicate that using 20/30% of the data for testing, but 70/80% for training can produce the best results (Gholamy et al., 2018). The calibration data set was used to develop statistical models to predict per capita consumption as a function of household socio-economic characteristics. The household socio-economic characteristics were divided into three groups, that is:

1. Socio-demographic characteristics: e.g., number of children, adult females, adult males, elders 66 – 75 years and elders over 76 years.
2. Physical characteristics: e.g., the number of rooms, household size, the total area of floors and house type.
3. Water use characteristics: e.g., shower volume, toilet flushing volume, time spent to fetch water and distance to water source.

Multiple Linear Regression (STEPWISE) Base Models

The STEPWISE multiple regression approach was used to predict water demand, this method has been previously used successfully (Hussien et al., 2016). The technique readily selects the combination of relevant independent variables to develop the best fit model based on strong statistical foundations and saves on the intense computational effort required by some other methods (e.g., evolutionary polynomial regression). It is a potential approach for selecting the best predictor variable from many variables.

Using the *STEPWISE* approach with the calibration set of data of whole investigated households, four models were developed based on demographic, physical, water use and whole characteristics were investigated further, and the values of correlation coefficient (R) were calculated. The acceptance or deletion of an independent variable for the regression model is based on the strength of relationship (i.e., the strength of the correlation) and also its contribution to the decrease of the residual sum of squares (Hussien et al., 2016). The regression coefficients and model are then statistically verified at every iteration to select or delete an independent variable.

The statistical tests performed include*:*

- The t-test (two-tailed) used at 95% confidence interval to examine the statistically significant if $p<0.05$ (Yasar et al., 2012).
- The analysis of variance (ANOVA) test (F-ratio) examines the significance of the regression. The model is statistically significant at $p<0.05$, which means that the overall regression model is a good fit for the data. That is whether the socio-economic, demographic and water use factors significantly influence the primary determinant of per capita water consumption (Aho et al., 2016; Hussien et al., 2016)

Correlation Analysis

The correlation coefficient R can be used to evaluate the strength of relationship between variables (De Lourdes Fernandes Neto *et al.*, 2005; Grafton *et al.*, 2011b). To understand the relationship between per capita water consumption and the variables affecting water consumption, a correlation matrix is constructed. The analysis of the data will suggest the type of relationship between dependent and independent variables.

4.4 Modelling Water at Per Capita Scale

Modelling of water and environmental systems using system dynamics has been carried out at various scales (Khan et al., 2009; Qi and Chang, 2011; Mereu et al., 2016). The system dynamic modelling (SDM) software in Figure 4.3 is used to capture the changes in behaviour in a water system over time by modelling the interactions between different end-use components. Based on a model, consumption of individual end-uses of water was calculated as well as the possible wastewater generated by the household and the potential reuse of wastewater.

This approach used helps to understand the contribution of each water end-use in a total per capita consumption. The individual end-use based on the model (Figure 4.3) can identify the end-use with highest water resource consumption. This approach has become very common for modelling Water Energy and Food (WEF nexus) sustainable livelihoods at per capita, a household, city and national scales (Chen and Chen, 2016; Hussien et al., 2016; Artioli et al., 2017). The key variables of this model are population increase, impact of seasonal variability (duration and volume in rain and dry season), household size, water points, distance to water points, and time spent on collection.

Another key variable is the influence of household income (i.e., slum settlement, low, middle, and high) and water storage containers on consumption. The model also calculates the consumption of individual end-use of water. The model components have over 100 variables in total and the structure is presented in Figure 4.3. The values of the input variables and parameters into the water consumption model depend on the pattern of water end-uses, factors that affect consumption and availability for the specific area. The full explanation of these variables and the mathematical expressions which describe the relationships between water consumption and household characteristics are explained in Sections 4.4.1 to 4.4.3.

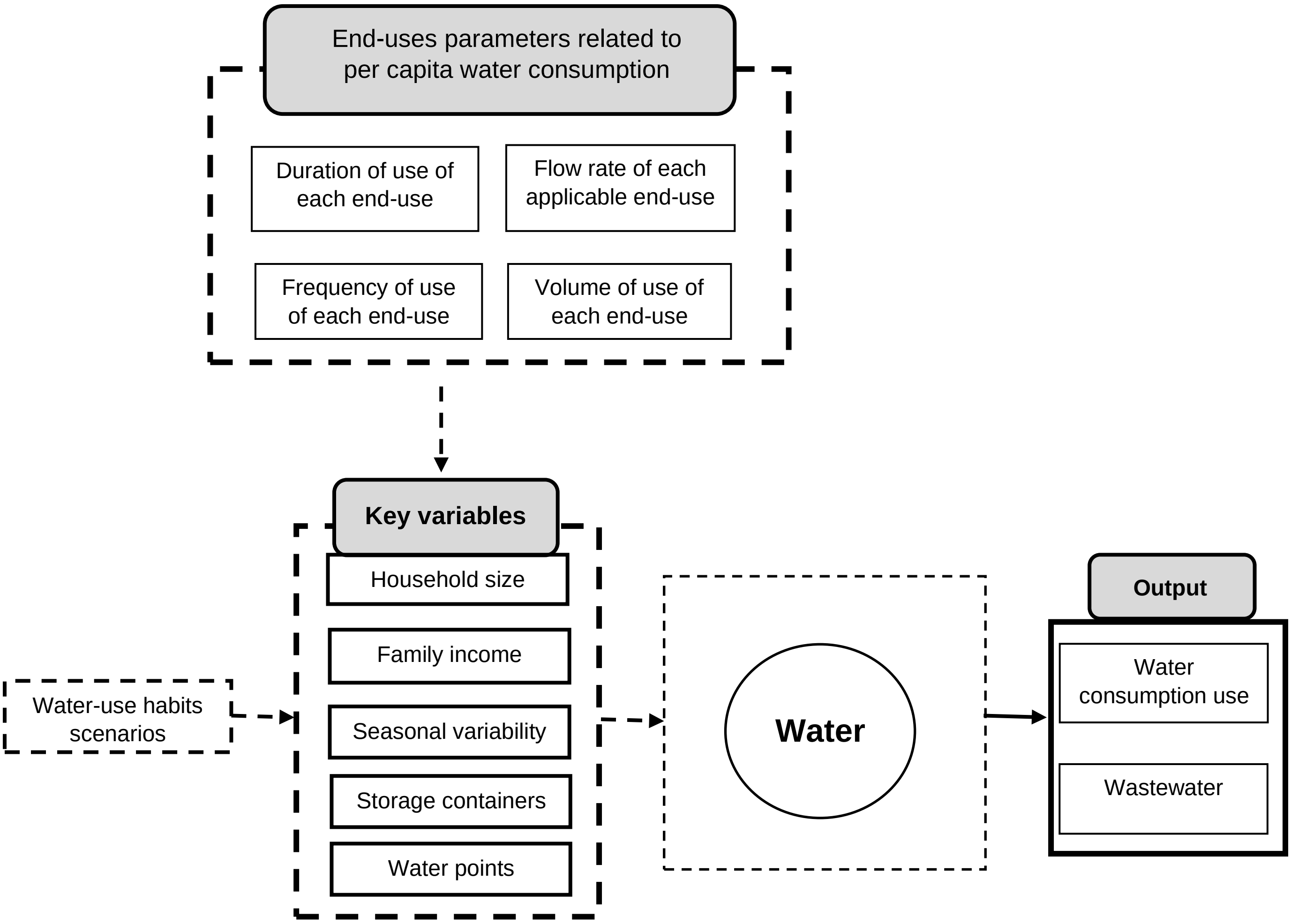

Figure 4. 3 The structure of water consumption model at a per capita scale (Source: authour's construction)

4.4.1 Modelling of per capita water consumption

In the water consumption model, per water capita consumption is divided into several micro-components (end-uses): showering, bucket bath, toilet flushing, house washing, cooking, dish washing, drinking, clothes washing, wash hand basin and vehicle washing. The model illustrates the influence of human behaviour for water end-uses, through including the parameters of water end-use into the model. For example, the frequency of use and the duration of water run during each event of water use are included. The model also includes the flow rate and volume of water end-use for households with and without piped water connection. However, pipe systems' leakages have not been considered in demand calculations.

The purpose of the equations is to calculate an accurate volume of the daily per capita average water consumption by each end-use and the annual per capita total water consumption during the year. This data will feed and guide water service providers about the required groundwater quantity for abstraction.

Using these parameters in Equation 4.1 it can be used to estimate the quantity of water consumption of each water end-use for showering and hand wash basin tap use. The quantity of water consumption of each water end-use (bucket bathing, toilet flushing, pour flush use, latrine use, drinking, dishwashing, cooking, clothes washing, house cleaning, vehicle washing and garden watering) can be calculated from Equation 4.2. These water end-uses have been calculated (Equation 4.2) based on frequency and required volume. The model also calculates black and grey water collected from a household as shown in Figure 4.4 from equations 4.3 and 4.4. Pipe system leakages have not been considered in the demand calculations.

$$We_{ii} = Fe_{ii} \times De_{ii} \times Qe_{ii} \qquad \text{(Eq 4.1)}$$

$$We_{ii} = Fe_{ii} \times Ve_{ii} \qquad \text{(Eq 4.2)}$$

Where:

We_{ii} = daily per capita average consumption for water end-use *ii* (l/p/d),
Fe_{ii} = daily per capita average frequency of water end-use *ii* (number of occurrences/p/d),
De_{ii} = duration of water run during each occurrence of water end-use *ii* (min/occurrence),
Qe_{ii} = average flow rate of water end-use *ii* (l/min), and
Ve_{ii} = quantity of water consumption during each occurrence of water end-use *ii* (l/occurrence).

Grey water is the wastewater drained from bathrooms and toilets including bathing water, shower water, handwash basins and clothes washing. Black water is the wastewater produced by dishwashing (in bowls), cooking, toilet flushing, washing vehicles, and cleaning houses. In the study area where water is scarce, greywater is valuable. Recycled greywater is commonly used for garden watering, house washing and toilet flushing.

$$WW_{grey} = WW_b + WW_{shw} + WW_{brt} + WW_{cw} \qquad \text{(Eq 4.3)}$$

$$WW_{black} = WW_{dw} + WW_{ck} + WW_{tf} + WW_{hw} + WW_{vw} \qquad \text{(Eq 4.4)}$$

where: WW=wastewater, b=bathing, shw=showering, brt=hand wash basin tap use, cw= clothes washing, dw=dishwashing, ck=cooking, tf=toilet flushing, hw=house washing, vw=vehicle washing, l=litre, d=day, min=minute.

Figure 4.4 shows the interactions between water end-uses at a per capita scale. The direction of an arrow shows water consumption correlated with each end-use. These interactions are directed in the developed model.

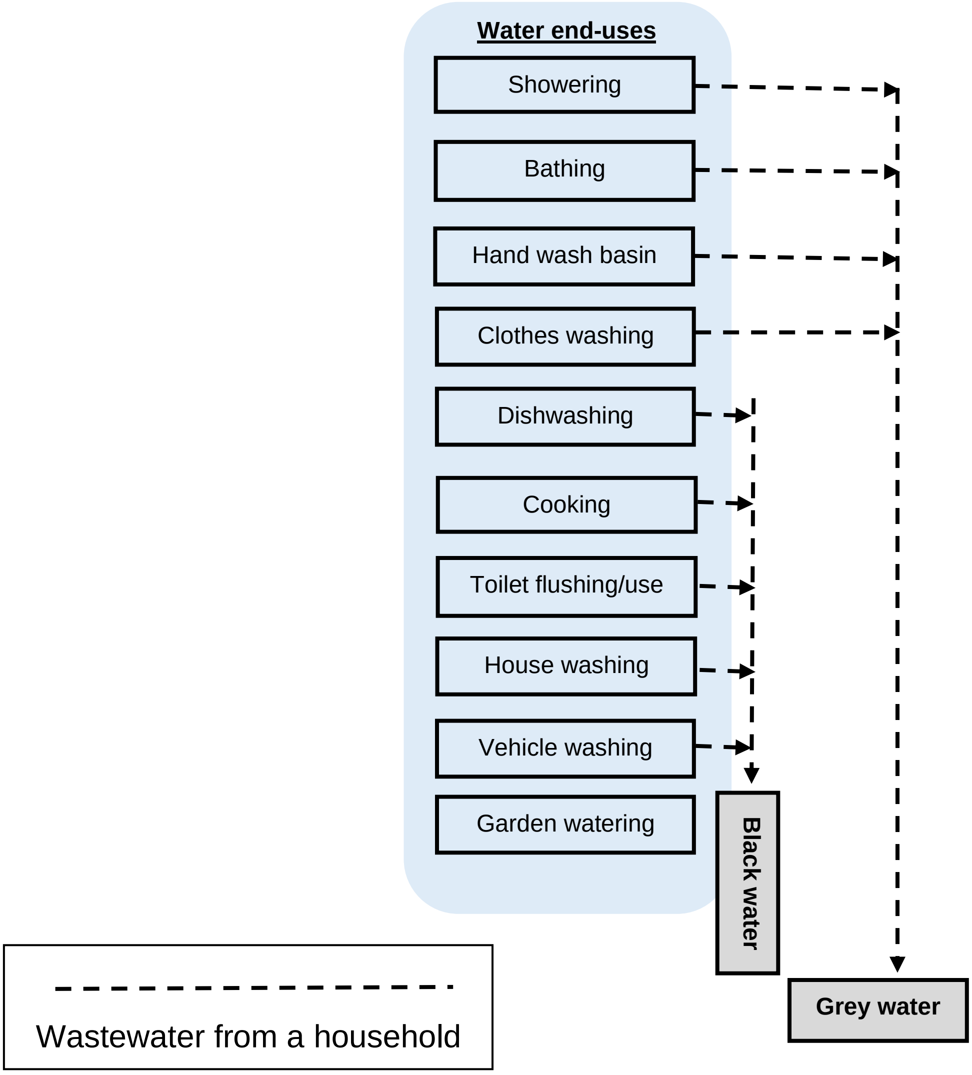

Figure 4. 4 Schematic of the interactions between water end-uses at a per capita Scale (Source: authour's construction)

4.4.2 Impact of seasonal variability of water availability

The per capita water consumption varies seasonally due to changes in the weather and the availability of water source (Zhou *et al.*, 2000; Polebitski and Palmer, 2010). The seasonal variability of domestic water consumption in many tropical countries is mainly affected by climate, seasonal and hydrological conditions (Inocencio and Largo 1998;Tshikolomo et al., 2012; Ayanshola et al., 2012; Rathnayaka et al., 2014).

Furthermore, the majority of water consumption is lower in the dry season because of the water scarcity and limited alternative water sources (Scarascia-mugnozza, 2003; Domènech and Saurí, 2010). Per capita water consumption is a function of socio-economic, weather, season, hydrological characterization, lifestyle and technical factors. Therefore, per capita water use varies from one region to another region. Households access water based on their income levels, patterns and culture (Fan *et al.*, 2013). Many developing countries experience intermittent piped water supply to households, and they receive water for a short period of time on some days of the week (Aho et al., 2016). The reliability of piped water and alternate water sources deteriorates in the dry season and this increases the distance trekked and time covered by households to collect their daily water supply (Arouna and Dabbert, 2010). Hence, households have responded by storing water in large containers in the home as well as using all available alternative sources which can be an improved private wells/boreholes and other unprotected sources (springs, stream).

The model shows the impact of seasonal variability on water consumption at a per capita scale for different water end-uses. The annual per capita consumption can be calculated by considering the daily per capita average consumption and total duration of rainy season and dry season separately. Using the water end-uses presented in section 4.4.1, the total water consumption during the seasons can be determined. Equation 4.5 aims to calculate the annual per capita average water consumption.

$$TW_i = dw_{,i} \times \sum We_w + dd_{,i} \times \sum We_d \qquad \text{(Eq 4.5)}$$

where: TW_i = annual per capita total water consumption during year *i* (l/p/y),
We_w = daily per capita average water consumption by each end-use (Figure 4.4)

during rainy season (l/p/d),

We_d = daily per capita average water consumption by each end-use (Figure 4.4) during dry season (l/p/d),

$dw_{,i}$ = duration of rainy season in year *i* (d), and

$dd_{,i}$ =duration of dry season in year *i* (=365− $dw_{,i}$) (d).

The parameters influencing water consumption for the different seasons and income groups are available in Table 5.8.

4.4.3 Impact of Income on per capita water consumption

Income and affluence can be a key factor shaping per capita water consumption. Jorgensen et al. (2009), in their study noted that income is the main factor influencing household water consumption, indicating increased lifestyle and affordability for water needs as income increases. Per capita water consumption is a function of socio-economic factor and varies with people's behaviour, habit and income level. It increases with the increase in family income (Headley, 1963). Although, other factors, such as water storage containers, education level, age category and water points can have a minimal impact on water resource consumption. The major consumption influencing factors are household income, seasonal variability, weather, household size, hydrological characterization, distance to water points and time spent to fetch water (Inocencio et al., 1998; Ayanshola et al., 2012; Tshikolomo et al., 2012; Rathnayaka et al., 2015). Therefore, the developed model investigates the influence of per capita income on water consumption based on the listed factors.

4.5 Materials and methods for groundwater modelling

GIS was used for analysing geographic information while conceptualising hydrogeological systems. All GIS data required for conceptual modelling were converted to the appropriate formats for numerical modelling using ArcGIS 10.6.1 and QGIS 3.10.1. The database and groundwater modelling include some stages, which are shown in the flow chart showing the detailed modelling schematic in Figure 4.5.

In the present study, the various analysis carried out were study of topographical characteristics using GIS, rainfall characteristics, temperature characteristics, estimation of the aquifer parameters by basic analytical methods using Theis, Cooper Jacob and Chow, Thornthwaite soil water balancing modelling approach to model soil water into evaporation and assessment of groundwater development by the U.S. Geological Survey 3D ModelMuse MODFLOW GUI numerical method to estimate groundwater recharge and groundwater quantity analysis as per numerical procedure to determine the maximum sustainable extraction from an aquifer (Winston, 2015).

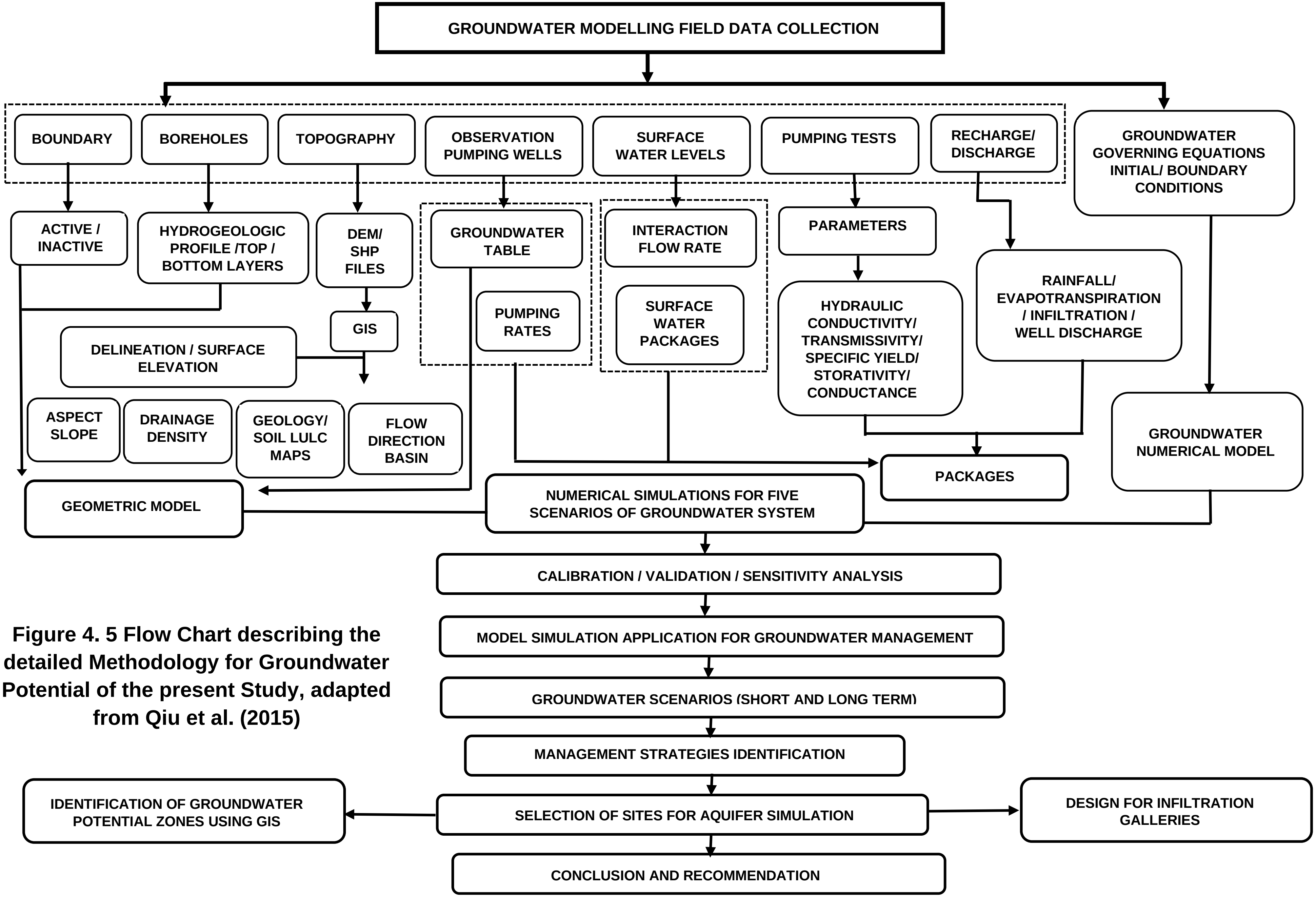

Figure 4. 5 Flow Chart describing the detailed Methodology for Groundwater Potential of the present Study, adapted from Qiu et al. (2015)

Legend

⬚ Related groundwater parameters and analysis of field data

4.6 Study of topographical characteristics

The presence and productivity of groundwater development in an aquifer depends on three broad factors, topographic, geological and hydrogeological. Topographical environment presents the degree of slope and profile curvature for the water infiltration rates while the geological and hydrogeological environments stimulate the transmissibility of water resources and the interaction between water and residential development in the watershed respectively.

To study the topographical characteristics of the study area, the topographical details were analysed using GIS. The flow chart for delineation of the maps is shown in Figure F2.1 in Appendix F. The different thematic maps were prepared using GIS methods, elevation data provided by SRTM (Shuttle Radar Topography Mission) Digital Elevation Model, at 30-metre resolution, made available by Open Topography and U.S. Geological Survey LPDAAC Earthdata for the LandUse/LandCover map, Contour map, Curvature map, Geology map, Drainage Basin map, Soil map, Aspect map, Slope map, Drainage Density map, Drainage Waterways map, Flow Direction map and Hillshade map. The thematic raster maps of the study area were prepared using satellite image visually interpreted, georeferenced with minor format changes to improve the appearance based on image characteristics, identified around the study area. The 14 prepared hydrogeological thematic maps, including LandUse/LandCover and administrative maps as shown in Figure D9.1 to D9. 11 in Appendix D, served as the major tool in the assessment of groundwater development and management for this research.

4.6.1 Geology

The geology map of the study area was analysed based on the stratigraphy of the geologic materials and structures modified by Keyser and Mansaray (2004). The different geologic formations were marked into a different colour unit based on composition, age and environment visible across the study area. Geology describes the hydrodynamic functioning and properties of the aquifer. The entire area can be classified into hard, fractured crystalline gabbroic rock and sedimentary formations shown in Figure 3.7. Quaternary and recent alluvial deposits such as gravels, sand, lignite, silt, clay etc., which are transported as river sediments superimposed the hard-gabbroic formation. Borehole logs with geological information are not readily available in the country.

Thematic maps, shown in appendix D, depicts the land surface features and provide a range of landscape reference including elevation, topography, hydrology and urban area demarcation. The maps are based on data collected from Shuttle radar topographic mission data LPDAAC USGS website[8] with 30 m resolution (SRTM) analysed from the 3-D coordinates (x, y, and z) with projection attribute, latitude and longitude geodetic data. The prepared maps have served as the baseline information for the overall assessment of the groundwater potential of the watershed.

4.6.2 Slope Map

The Slope map was prepared from the DEM layer by selecting the output of the Topo to Raster Tool and using the Slope Tool found in ArcToolBox in ArcGIS 10.6.1. Slope gives an indication of infiltration rate. In place where the slope is more, contact period of water with the surface is less and the rate of infiltration will be less. Likewise, in places where slope is relatively less, the contact of water with the surface will be high and the infiltration rate will also be high which gives an indication of good potential for groundwater. Figure F2.1 in Appendix F illustrates how the slope map was generated step by step using ArcMap and Slope details are given in Figure D9.1 in Appendix D. The hillshade map is a 3D representation of the terrain surface, which uses the altitude and azimuth properties to specify the sun's position. It gives an indication of the slope and aspect of the elevation surface. These effects can impact infiltration and evapotranspiration rates in the watershed. Further United States Geological Survey (USGS) graded classification system was used to delineate the downloaded data,

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[8] https://lpdaac.usgs.gov/tools/earthdata-search/

digitize, filtering with image interpretation to improve the shade, texture, pattern, colour, shape, size and location.

4.6.3 Soils Map

Soils of Sierra Leone belong to five orders[9] that is Inceptisols, Spodosols, Oxisols, Ultisol and Entisols (Royal et al., 1962). The soils of Freetown are described as indurated plinthite abundantly in gravels and boulders belong to the Inceptisols. The soil map was prepared and digitized using Arc GIS 10.6.1. Figure D9.2 in Appendix D defines the soil map of the study region. Soil is the upper weathered part of the Earth's surface formed due to combined action of rocks, topography and climate. Major part of the study area is having gravely ferralitic soils with shallow soils on moderate to high relief hills formed from basic and ultrabasic rocks. There are shallow soils on plateau mountains and lateritic hills and terraces. The western part of the area has undeveloped to weakly developed sand on coastal beach plains and with weakly developed muds and hydromorphic clays along coastal river estuaries on the downstream area. Soils types are the main criteria for recharge of groundwater.

4.6.4 Aspect

Aspect indicates directions the physical slopes face and relates to the solar exposure of the surface. The steps taken to create the aspect map of the watershed from DEM file in ArcMap 10.6.1 software is shown in Figure F2.1 in Appendix F. Aspect categories are symbolised using different colours and directions indicated as flat, north, northeast, east, southeast, south, southwest, west and northwest in Figure D9.3 in Appendix D.

4.6.5 Contour

Contour map shows the imaginary lines from connecting equal points having same elevations called contour lines. DEM file was used to produce the watershed contour map for the study area. A complete contour map having normal contour lines spaced at 20 m vertical interval was prepared designated by corresponding elevations in the

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[9] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/maps/?cid=nrcs142p2_053596

map. The actions followed in ArcMap 10.6.1 software to create the contour map are shown in Figure F2.1 in Appendix F. A contour map is very useful in determining nature of the terrain and they can appear in an upstream direction. The contour map generated is shown in Figure D9.4 in Appendix D.

4.6.6 Drainage

The study area watershed was having 7th order basin as can be seen from drainage waterways map created. Total catchment area was 73 km^2, Number of streams were increasing as stream order was increased, which is clearly visible in Figure D9.7 in Appendix D. Drainage plays an important role in surface-runoff processes, influencing the intensity of torrential floods, sediment load and even the water balance in a drainage basin. Flat area below 1 m mean sea level (msl) was found along the coastal plains from the aspect map which again corresponds to the undulated topography of the region.

Denser contours were concentrated in upstream side of the catchment where the topography is characterised with steeper slopes, while in downstream side along the coastal plains, contours were widely spaced because of relatively flat topography. GIS offers valuable techniques for developing thematic maps in watersheds where data is non-existent. Flowchart showing procedure to prepare drainage maps can be seen in Figure F2.1 in Appendix F. DEM file was used to prepare all drainage maps of the study region. Using ‘Fill’ function in ‘Hydrology’ tools of ArcMap 10.6.1, a depression less DEM file was used to make the flow-direction map and to correct the errors. Spatial Analyst Hydrology tool of Stream Order function in ArcMap, was used to prepare the Flow direction map. The direction in which water is flowing from each pixel to each of the eight surrounding pixels was calculated using the filled DEM. The eight-direction (D8) method of calculating pour points is commonly known as the pour point approach (Fairfield and Leymarie, 1991; Tarboron, 1997). A simple model of water movement chain within ArcGIS allows water to flow into the next cell in a direction where the descent is shallowest. The resulting flow direction is encoded between 1 and 128 in various directions (Figure 4.6). The accumulation of flow was calculated using a grid that indicated flow direction. A value was assigned to pixels in the flow accumulation based on the number of pixels that passed through them. For flow in the east direction, the value is 1. The value of water flowing west is 16. The eight-direction pour point model can be used to describe all 8 adjacent directions at a given point.

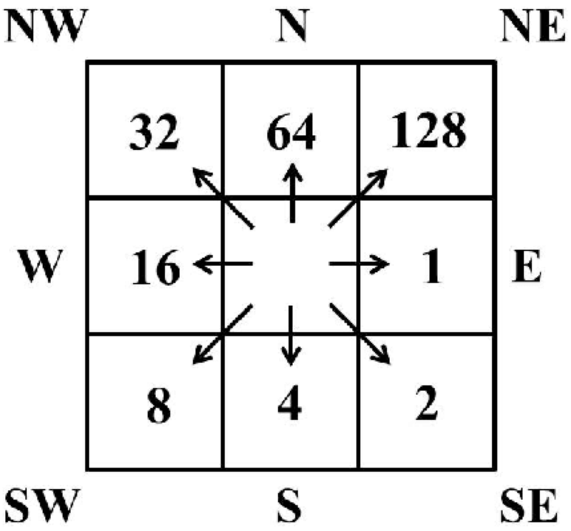

Figure 4. 6 Flow Direction in the Eight-direction Pour Point Model downloaded from ESRI website

The drainage pattern is dendritic in nature and controlled structurally. These thematic maps will be useful resource in many watershed management studies as essential inputs since access data of the area is limited or non-existent. Flow Direction and the Drainage maps are shown in Figures D9.5 to D9.8 in Appendix D.

4.6.7 Curvature

Curvature mainly affects flow acceleration and deceleration, as well as flow convergence and divergence. A negative value shows that the surface is upward convex and will cause flow to decelerate, while a positive value shows that the surface is upwardly concave, and this causes flow to accelerate. The study area has undulating topography and presents a situation of negative and positive values indicating a gaining (divergent) or losing (convergent) water at the soil surface. The curvature tool in the spatial analyst toolbox was used to create the curvature file shown in Figure D9.9 in Appendix D.

4.6.8 Elevation

Elevation map shows the different height and physical parts of the Earth relative to sea level. This is shown using contour lines. The elevation map is prepared from the SRTM DEM data. Figure D9.10 in Appendix D shows the elevation map of the study area; and would help the city to obtain flood and discharge maps for future adverse events management.

4.7 Study of rainfall and temperature characteristics

Rainfall is the main factor in the replenishment of water resources for both the surface and subsurface systems. Rainfall plays an important role in sustaining the groundwater system. Ogunbode and Ifayibi (2019) observed in the recent past, that rainfall occurrence has been impacted by its duration, intensity and frequency which has altered the rainfall patterns causing deficit or flooding thereby influencing the quantity and quality of the water management. In addition to their observation, Bonsor et al. (2010) have indicated that the inconsistent rainfall pattern is due to natural and manmade events.

Studies on global climate change (Major, 1997; Arnell, 1999) has shown that fluctuation in temperature is linked to climate change and this affects the proportion of precipitation in many parts of the world. In view of these observations, a systematic analysis of rainfall and temperature characteristic trends may help to understand the patterns of occurrence and would solve many water availability and management problems.

4.7.1 Rainfall and temperature analysis

To study the rainfall and temperature characteristics, the monthly rainfall data of 6 rain gauge stations for the period of 29 years (1990 - 2018) were collected from the Sierra Leone Meteorological Agency in Freetown. The average annual rainfall was determined by the arithmetic average method[10]. In this study, the rainfall months were classified as scarce, normal and surplus rainfall months. If M is the average monthly

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[10] https://www.geographynotes.com/rainfall-2/measuring-the-average-depth-of-rainfall-3-methods-atmosphere-geography/4715

rainfall, then a month receiving less than M/2 is defined as scarce month which is represented by X_1, 2M is the surplus month represented as X_2 and a value between X_1 and X_2 is considered as normal month. The yearly temperature was classified as cold, hot, and normal when a particular year receives temperature less than T- S_T, T + S_T and between T- S_T, and T + S_T respectively, where T is average temperature, S_T is the standard deviation of yearly temperature.

In this study, the average yearly rainfall is calculated and represented as $Y_{R.}$ The standard deviation of the yearly rainfall is represented as S_R. The yearly rainfall was classified as scarce, normal and surplus when a particular year receives rainfall less than Y_R - S_R, Y_R + S_R, and between Y_R - S_R and Y_R + S_R respectively. A low coefficient of variation (CV) value represents a more accurate estimate while a higher value has greater distribution around the average. The coefficient of variation (CV) is a statistical measure developed by Karl Pearson, used to determine the relative dispersion of data points around the mean. It is used in situations where we need to make a comparison of two or more variables in a sequence of events.

Rainfall and Temperature Trend Analysis

The rainfall and temperature trends of the study area were analysed from time series curve using linear regression least squares method, in line of best fit equation (Mudelsee, 2019). Trend refers to the low, medium and high frequency variations, characterised in a sequence of observed data plots with changes over time shown on a scatter plot. Hence, trend indicates a long-term increase or decrease in time sequence due to factors such as settlement, deforestation, or urbanisation of the watershed. The sequence value ‘M’ is plotted on the vertical axis and time ‘t’ on the horizontal axis. From the observed rainfall and temperature data, monthly yearly and seasonal trends were analysed and results are discussed in Sections 6.9.

4.8 Assessment of Groundwater Potential

Groundwater recharge, the most critical component in water balance of any watershed has been determined by employing the key water budget methods to estimate recharge. These are specifically, water balance (WB) and groundwater flow modelling using ModelMuse MODFLOW. The results of each method have allowed comparisons to be made as they relate to the groundwater recharge in an alluvial and fractured crystalline aquifer (Scanlon et al., 2002; Loáiciga, 2017).

The first step of a groundwater recharge study in an area that has not previously been studied and lacks groundwater monitoring information, should include collecting data on potential factors that impact on groundwater recharge, such as climate, abstraction rate, water consumption, pumping test, drawdown capacity, hydrology, geology and topography (Scanlon and Healy, 2001). These data are used to develop the conceptual model of recharge in the watershed. The conceptual model is spatio-temporal bias (space and time) and would provide the potential estimates and rates of recharge and drawdown.

4.9 Aquifer Parameter Studies

The groundwater investigation and monitoring has brought about the need for calculation of the aquifer parameters for the resource assessment and this is essential for the design of wells and boreholes. For the estimation of aquifers parameter, one needs to evaluate well performance and identify aquifer boundaries viz., hydraulic conductivity (horizontal K_r and vertical K_z), Transmissivity (T), Storage Coefficient (S) and Specific yield (S_y) from pumping tests are used to estimate the hydraulic properties of aquifers by conventional method as given in aqtesolv technique[11]. For this study, long duration pumping and recovery tests data of observation wells were considered. Theis, Cooper Jacob's and Chow tests analyses methods by fitting mathematical models to drawdown response data (water-level changes or pumping rates), using the procedure known as curve matching (Figures 4.7 to 4.11) are employed**.** The assumptions and data requirements for the different test analysis solutions are presented in D2.1 in Appendix D.

4.9.1 Estimation of Aquifer Parameters using Pumping Test Data

To estimate the aquifer parameters, an analytical approach was employed. Pumping test data collected from EDAL Drilling Company LTD, BABA Drilling & Exploration

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[11] http://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm

Company LTD and ground truth data conducted on community wells were analysed. The time drawdown data and recovery test data are shown in Table 4.4 and Table 4.5. These data had been interpreted using matching curve techniques viz., Theis curve method, Cooper-Jacobs method and Chow's method. These combined pumping test analyses are the most comprehensive set of solution methods for confined, leaky confined, unconfined and fractured aquifers that should help the hydrogeologist match the results and decide between different possible alternatives during the interpretation process.

a. Theis Curve Method

The drawdown data from pumping test shown in Table 4.4 are plotted on a log-log and semi-log plots (data curve) and the type of curve which has the plotted values of W(u) and u on a log-log sheet as shown in Figure 4.7 to 4.9. The graphs are used to identify the flow regime based on their shapes (Kruseman and de Ridder, 2000). Data curve is matched with the method-type curve keeping the axis of curves in best fit position as shown in Figure 4.10. The matched point is selected from the matched position. The values of W(u) and u are chosen from the type of curve and the values of s and t are chosen from the data curve. Substituting these values of W(u), u, s and t in the given equation, Transmissibility (T), Storage Coefficient (S) and Well Efficiency are determined.

$$T = \frac{Q}{4\,x\,\pi\,\mathrm{x}\ \mathrm{S}}\,x\,W(u) \qquad \text{(Eq 4.6)}$$

$$S = \frac{4\,x\,\pi\,\mathrm{x}\ \mathrm{T}}{\frac{r2}{t}} \qquad \text{(Eq 4.7)}$$

where, T = Transmissibility S = Storage coefficient t = time r = observation distance, W(u) = Well function, s = drawdown

Table 4. 4 Pumping Test for Time Drawdown Data

Time in minutes (t)	Water Level below datum (m)	Drawdown (m)	Discharge in m^3/hr	Observation distance at particular time r^2/t m/sec
0	15.96	0	Constant Discharge rate 3.9m^3/hr.	
1	17.90	1.94		1225.00
2	18.50	2.54		612.50
3	18.74	2.91		408.33
4	19.25	3.71		306.25
5	19.45	4.02		245.00
10	20.55	4.82		122.50
15	21.58	5.62		81.67
20	22.53	6.57		61.25
25	23.40	7.30		49.00
30	23.52	7.86		40.83
35	23.80	8.72		35.00
40	25.57	9.61		30.63
45	26.46	10.70		27.22
50	28.39	12.43		24.50
60	29.31	13.35		20.42
70	31.90	15.94		17.50
80	33.90	17.94		15.31
90	34.70	18.74		13.61
100	36.10	20.14		12.25
110	37.28	21.32		11.14
120	38.34	22.38		10.21
140	40.33	24.26		8.75
160	41.70	25.74		7.66
180	42.80	26.84		6.81
210	43.15	27.19		5.83
240	44.10	28.14		5.10
270	44.30	28.34		4.54
300	44.48	28.52		4.08
330	44.72	28.76		3.71
360	44.92	28.96		3.40

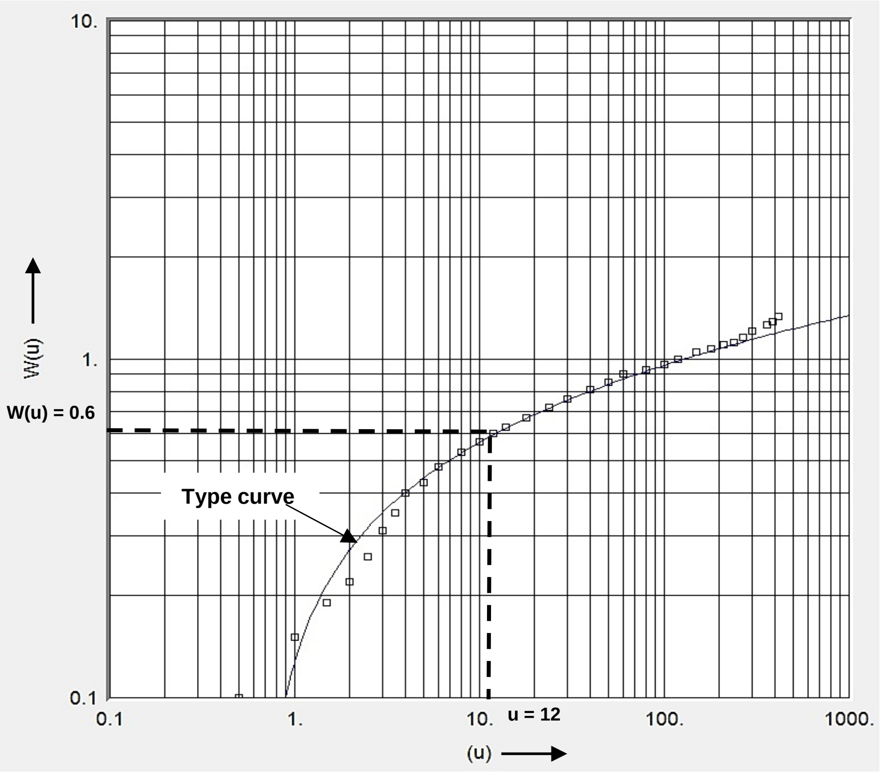

Figure 4. 7 Type of Curve generated from Aqtesolv analysis

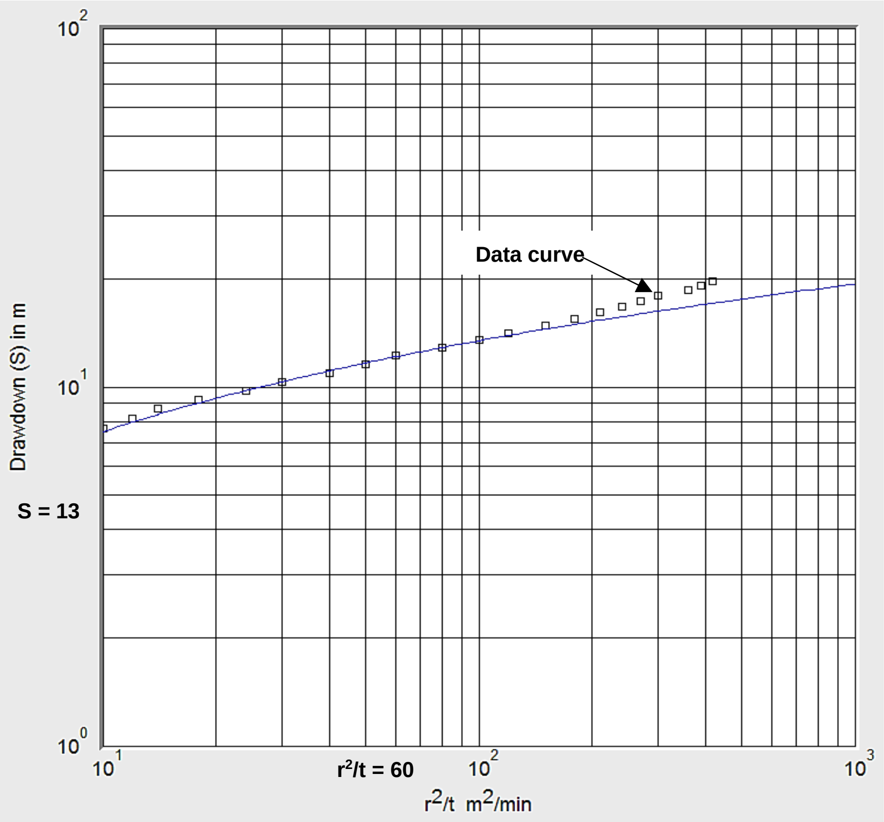

Figure 4. 8 Data Curve generated from Aqtesolv analysis

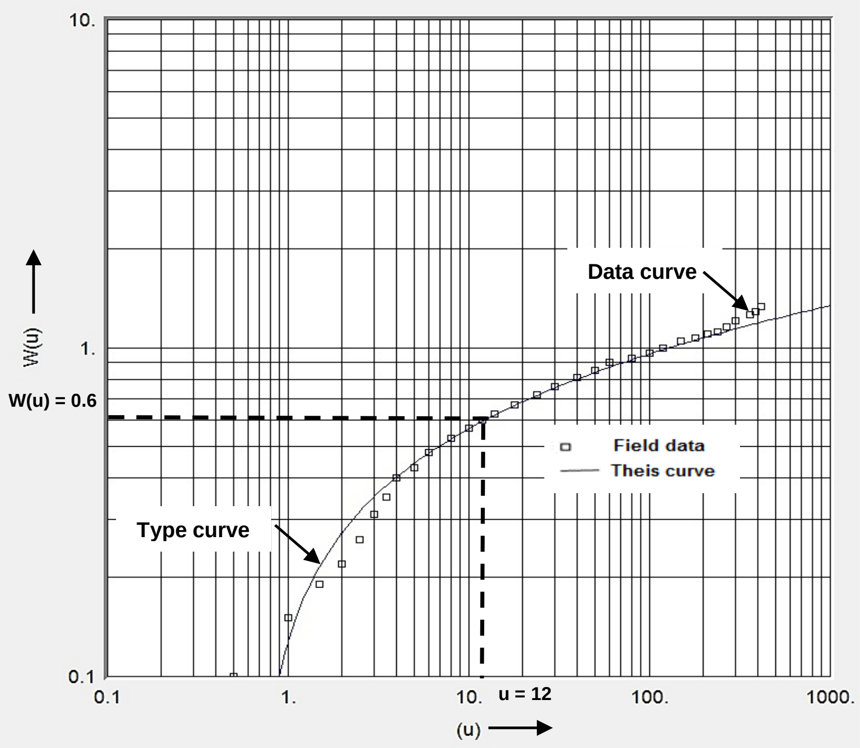

Figure 4. 9 Matching Data and Type curve generated from Aqtesolv analysis

b. Cooper Jacob’s Method

The pumping test data of drawdown and time are plotted on a semi log graph sheet as shown in the Figure 4.10. A standard procedure as out lined in Khadri and Moharir (2016) was employed. A straight line is drawn to the data point and the slope ∆s of straight line is determined. The time t_0 is noted where the straight line intersects the time axis and T and S value are calculated from the following equations.

$$T = \frac{2.3\ x\ Q}{4\ x\ \pi\ \mathrm{x}\ \Delta\mathbf{s}} \qquad \text{(Eq 4.8)}$$

$$S = \frac{2.25\ x\ \mathrm{T}x\ t0}{r^2} \qquad \text{(Eq 4.9)}$$

where, T = Transmissibility S = Storage coefficient $t0$ = time r^2 = observation distance, $\Delta\mathbf{s}$ = slope drawdown, Q = well discharge rate

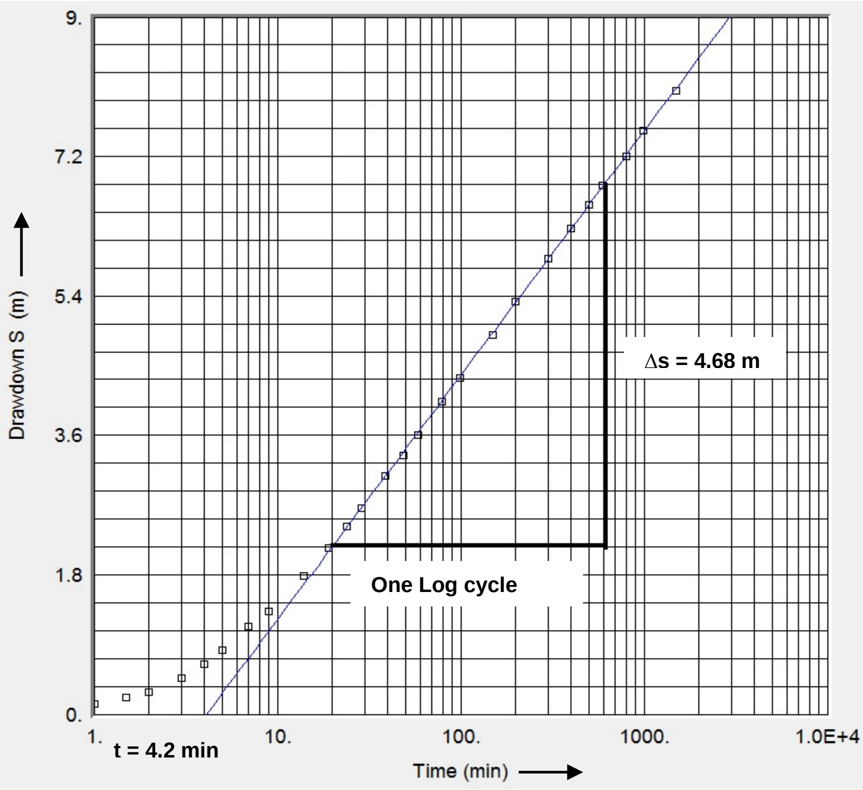

Figure 4. 10 Time-Drawdown straight line method curve generated from Aqtesolv analysis

c. Chow's Method

The pumping test data of drawdown and time are plotted on a semi-log graph sheet as shown in the Figure 4.11. From the graph a tangent was drawn on curve and the point of tangency was located and the values of s_1, t_1, Δs were selected. The values of W (u) and u were obtained from the relation graph and values of T and S were calculated from the equations as follows

$$T = \frac{Q}{4\ x\ \pi\ x\ S1}\ x\ W(u) \qquad \text{(Eq 4.10)}$$

$$S = \frac{4\ x\ \mathrm{T\ x\ u\ x}\ t1}{r^2} \qquad \text{(Eq 4.11)}$$

where, T = Transmissibility S = Storage coefficient $t1$ = time r^2 = observation distance, $S1$ = drawdown, W(u) = Well function, Q = well discharge rate

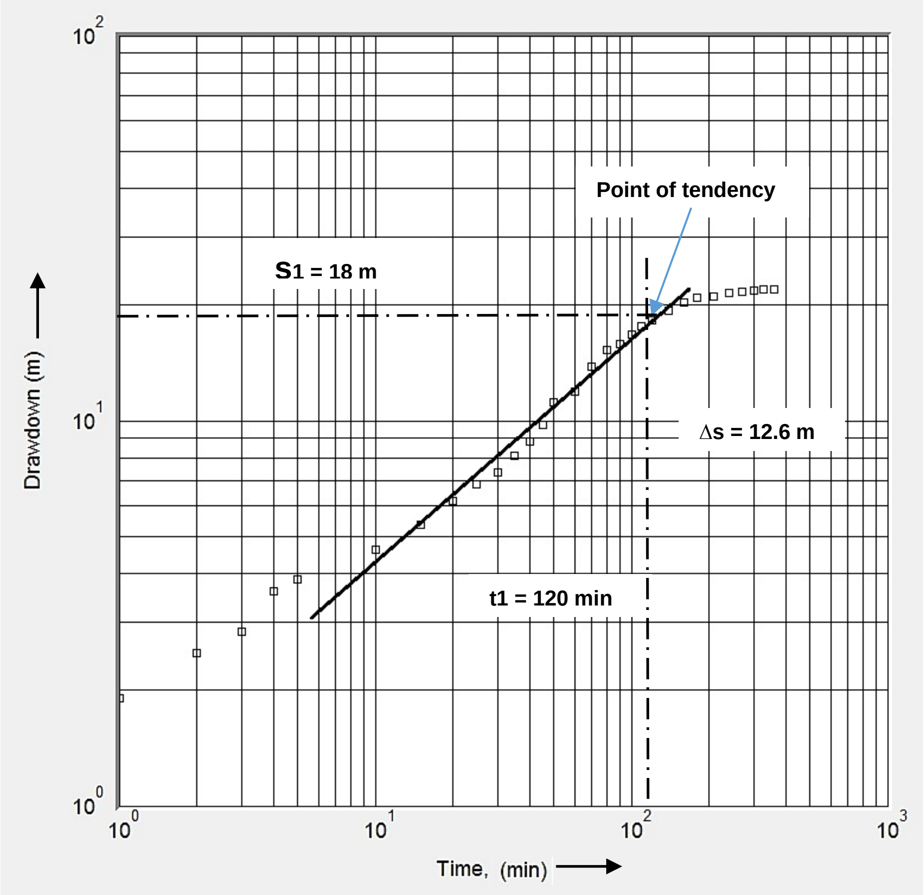

Figure 4. 11 Time-Drawdown curve 2 generated from Aqtesolv analysis

4.9.2 Estimation of aquifer parameters using recovery test data

The field data of residual drawdown s_1 as shown in Table 4.5 vs time are plotted on a semi-log graph sheet as shown in Figure 4.12. Two points are chosen from the graph and the value of Δs for one log cycle apart is obtained from the graph and the T and S values are obtained as follows.

$$s' = \frac{2.303\,Q}{4\pi T}\log\ \left(\frac{t}{t'}\right) \qquad \text{(Eq 4.12)}$$

$$T = \frac{2.303\,Q}{4\pi \Delta s\prime} \qquad \text{(Eq 4.13)}$$

$$Sp = \frac{2.3Q}{4\pi T}\log\left(\frac{2.25Ttp}{r^2 S}\right) \qquad \text{(Eq 4.14)}$$

$$S = \log\left(\frac{2.25Ttp}{r^2}\right)10\frac{4\pi TSp}{2.3Q} \qquad \text{(Eq 4.15)}$$

Where,

s' - Residual drawdown (m)

Q - Discharge (m^3/s)

t - Time taken since pump was stated (t = t + t')

t' - Time since pumping was stopped (min)

r^2 - Radius of the well (m)

Sp - Drawdown when the pump is turned off (m)

tp - Time taken when the pump is turned off (minutes)

Δs - one log cycle

S - Storage coefficient (--dimensionless)

T - Transmissibility (m^2/day)

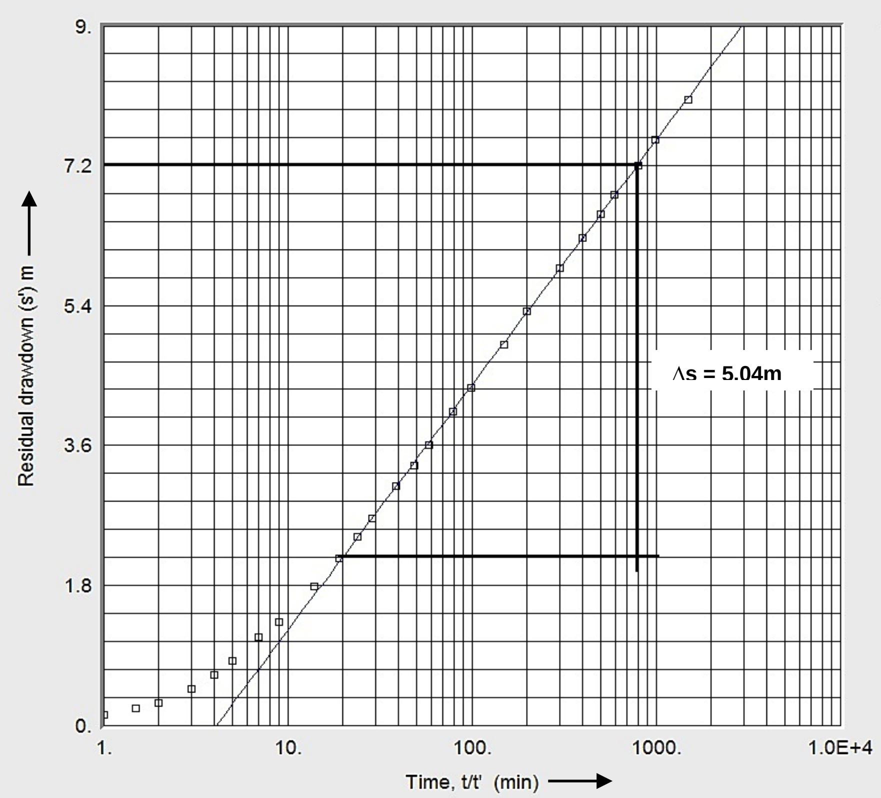

Figure 4. 12 Time t/t1 vs Residual drawdown curve generated from Aqtesolv analysis

Table 4. 5 Recovery Test Data

Time t^1 (minutes)	Time t/t^1	Depth below datum (m)	Residual drawdown (m)
0	0.0	44.92	28.96
0.5	242.0	44.61	21.9
1	132.0	44.53	19.15
2	71.0	43.30	16.65
3	50.7	42.32	14.56
4	40.5	41.22	12.75
5	34.4	40.06	11.15
10	17.8	38.52	9.65
15	12.0	38.02	8.64
20	9.1	37.84	7.19
25	7.3	37.63	5.89
30	6.1	36.69	4.67
35	5.3	36.00	3.47
40	4.6	35.13	2.57
45	4.1	34.39	2.48
50	3.7	32.48	1.53
55	3.4	32.35	0.63
60	3.1	31.35	0.59
70	2.7	30.84	0.53
80	2.4	29.86	0.5
90	2.1	28.71	0.44
100	2.0	27.28	0.41
110	1.8	26.31	0.38
120	1.7	25.08	0.33
140	1.5	24.56	0.29
160	1.3	23.13	0.26
180	1.3	22.32	0.24
210	1.1	21.32	0.22
240	1.1	20.12	0.19
270	1.1	19.34	0.17
300	1.1	18.63	0.13
360	1.0	17.24	0.11
390	1.0	16.05	0.08
420	1.0	15.98	0.06
450	1.0	15.38	0.02

4.10 Water Balance Study

Water balancing method also called conservation of mass (inflow – outflow) method has been widely used to make quantitative estimate of water development for large watersheds over long periods that impact the hydrological cycle (Thompson, 1967; Kumar, 2002; Fletcher et al., 2013). The study of water balance is characterized as a systematic interactions of surface water and groundwater data in any gain or loss of supply or change in properties between the two components that can be identified and calculated within a geographic area for a specified time. The method determines unknown fluxes and check measurements for errors of individual contribution of water sources into and out of the system over a specified period to establish level of variation in water due to changes in the components of the system. Basic concept of water balance is given as below:

Input to the system - Outflow from the system = Change in storage of the system

Three situations exist from this concept. If input is greater than output, then the change is storage is greater than zero. If input is less than output, change in storage is less than zero. If input is equal to output, change in storage is equal to zero.

4.10.1 Water balance on and within watersheds (Equations)

Reliable calculations of groundwater system behaviour depend on the capacity to develop models that precisely represent field conditions based on available data. There is a wide variety of data that can be used to develop our understanding of the hydrologic process extending from direct approximating of hydrologic parameters to unplanned information from geologic maps.

With limited data, the problem of model choice, model identification, and confidence in results is generally constrained. As additional data types are considered, estimates of parameters and rates of processes in the field improved. Coping with limited or very scarce available data is essential to making better predictions in managed watersheds. Hydrological modelling of watersheds is dependent on the available data sets, the lack of data often presents problems for accurate modelling and in turn, sustainable management of the water resources of these watersheds.

a. Watershed Water Balance

Considering the fluxes in a cross-section in the watershed shown in Figure 4.13 within an aquifer. The basic approach is three steps. 1. To define the control volume, 2. To define the flux that crosses the boundary of the control volume, 3. What is causing storage within the control volume, and these are used to write the water balance. Everything coming into the system is on the left side and everything going out is on the right side and there are changes in storage.

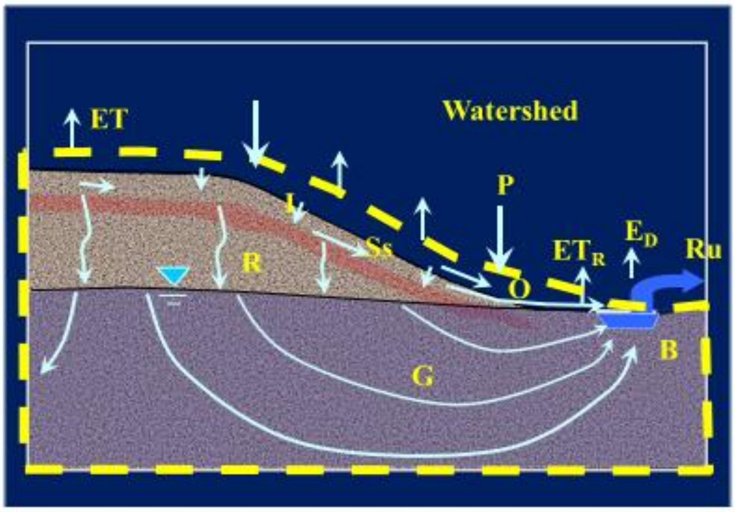

Figure 4. 13 Water balance entire Watershed courtesy Clemson Hydro

P = Precipitation
I = Infiltration
ET = Evapotranspiration
ET_R = Riparian Evapotranspiration
E_D = Evapotranspiration
R_U = Runoff
O = Overflow
R= Recharge
B = Baseflow
S_s = Subsurface flow
R = Recharge
G = Groundwater

To apply the water balance principle to the scale of the watershed, the control volume at the scale of the watershed is the cross-section within the yellow dash portion. The major fluxes that are crossing the boundary are precipitation (P) inflow, evapotranspiration (ET, riparian evapotranspiration ET_R, direct evapotranspiration E_D) outflow, and groundwater flow (G) outflow.

Recharge (R) does not count because it is a flux within the region, not crossing the boundary and does not represent storage. There is also storage of water within the vadose zone, and the water content of the vadose zone could change, and it is possible to have water stored in the saturated zone which could also change. The water table could also change and if it rises, then more water could be stored in the control volume. This can be represented together in Equation 4.16, and since the fluxes are precipitation and evaporation, then the area stored is that of the area of the land surface.

$$P = ET + Ru \qquad \text{(Eq 4.16)}$$

where, P = Precipitation ET = Evapotranspiration Ru = Runoff

However, the water level in the aquifer, the water content in the vadose, water level in surface water are expected to vary seasonally. So the change in the volume stored within the watershed vary seasonally (rain and dry seasons). To simplify this situation, a seasonal average can be considered where the volume is not changing in a long-term situation of steady-state condition and it will be equal to zero. Then the water balance equation (4.16) is for the entire watershed.

b. Vadose Zone Water Balance Approach A

The situation can be applied in the vadose zone. The approach is to draw the control volume, and there are a couple of ways to draw it, for example, one in which the balance goes as in Figure 4.14 across the water table and is slightly above the ground surface where precipitation is coming in and evaporation is going out. The subsurface stormflow (Ss) is going out, overland flow and recharge are the major fluxes that are crossing the boundary.

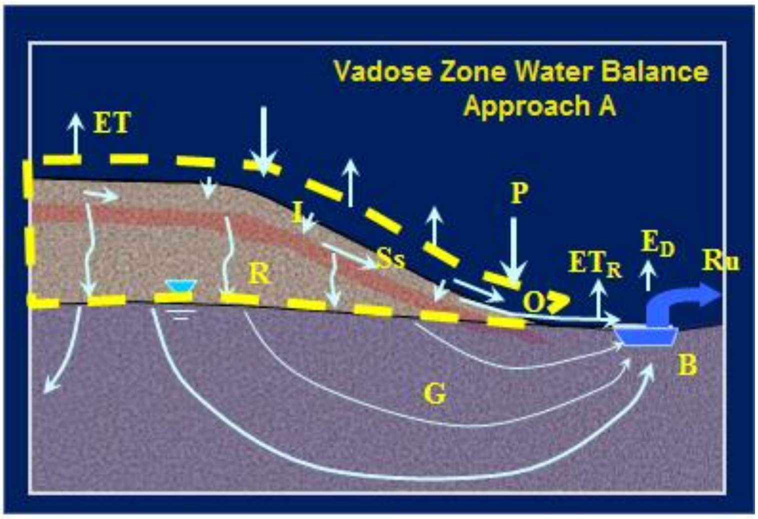

Figure 4. 14 Water balance Vadose Zone Approach A, courtesy Clemson Hydro

The storage will be the water content within the control volume. Changes in the water content will be influenced by how the storage in the soil moisture is changed. And this is represented for the long-term average as in equation (4.17) when storage is set at zero.

$$P = ET + S\mathrm{t} + R \qquad \text{(Eq 4.17)}$$

where, P = Precipitation ET = Evapotranspiration $S\mathrm{t} = \mathrm{stormflow},\ R$ = Recharge

Overland flow and subsurface runoff can be lumped together to give stormflow (this is water that sheds off quickly during rainfall), to give the water balance of the vadose zone as equation (4.17). This is different for the balance of the entire watershed. This proportion is dependent on the geology because if the area is underlain by crystalline rocks with very thin soils, then when precipitation occurs a high fraction of the rainfall will be shed off as stormflow. In areas where the watershed is paved, there will be a very high fraction of stormflow and very little recharge around the cracks of the pavement. For a watershed underlain by Beach sand, then when it rains a high fraction of the rain will soak the ground and infiltrate laterally as recharge, in this case, the proportion of evaporation will be smaller and there will be a higher fraction of recharge than stormflow.

c. Vadose Zone Water Balance Approach B

Another possibility in the vadose zone is to move the control volume (within yellow dash lines) so that the top boundary is down on the land surface.

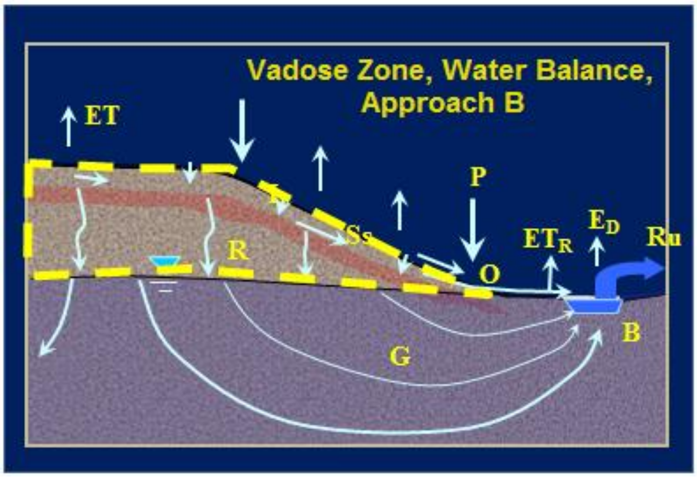

Figure 4. 15 Water balance Vadose Zone Approach B courtesy Clemson Hydro

In this case, the fluxes that cross the boundary are infiltration (inflow) evapotranspiration, stormflow, and recharge (outflow), so for long term consideration similar to the previous situation, storage can be ignored especially if the watershed is a flat area with permeable soils, then the stormflow will be small. The water balance is shown in Equation (4.18)

$$I = Ss + R \qquad \text{(Eq 4.18)}$$

where, I = Infiltration, Ss = Subsurface flow, R = Recharge

The rate of change of the water content can be expressed as a change in water content at a certain time minus a change in the time between the readings. As long as water content can be measured, then this gives an indication to assess the change of the volume stored.

d. Aquifer Water Balance

The aquifer water balance occurs when the water balance principle is applied to the aquifer itself. The control volume is indicated in Figure 4.16 at one possibility that goes to the water table, and down below similar to a confining unit at the water divide, presumably with some flow going in from one side and no flow going in from the other side.

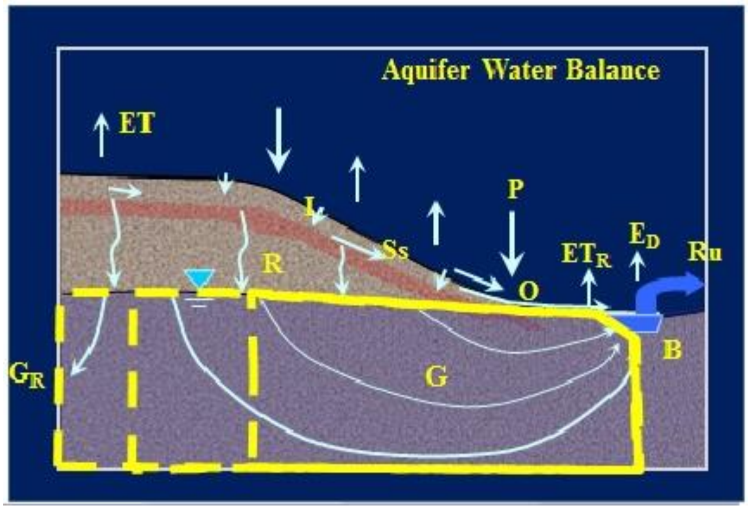

Figure 4. 16 Aquifer Water balance courtesy Clemson Hydro

Groundwater flowing out of the control volume (G_R) is an outflow, recharge (R) is inflow, and baseflow (B) is outflow to stream. Ignoring the riparian evapotranspiration (ET_R), and the simplest balance on the water table is seen in equation (4.19) and storage within the aquifer may change.

$$R = B \qquad \text{(Eq 4.19)}$$

where, B = Baseflow, R = Recharge

The boundary can be changed, and depending on where the control volume boundary is drawn, groundwater can flow in, stop recharge going in and baseflow going out of the watershed.

4.10.2 Modelling of Soil Water Budget (SWB) into Evaporation and Groundwater recharge

SWB is based on a modified Thornthwaite-Mather soil-water-balance technique, with components of the soil-water balance calculated at a daily time step Thornthwaite (1948) and Westenbroek *et al.* (2018). In a situation where water stored in the soil exceeds its storage capacity, it is believed that the excess water seeps into downward movement of the ground. This water is allocated to groundwater recharge, even though it may take a long time to reach the water table. The Thornthwaite technique[12] in soil water budget, uses a table with information of precipitation (P) and potential evapotranspiration (E_p) from a reference source and get a total column. Using an accounting procedure, an estimation of the recharge is done to analyse the allocation of the various water components in the hydrologic cycle. A water budget graph is then used to describe the climate of the area. Equation 4.20 is used to calculate the change in soil moisture which contribute to groundwater recharge. Soil moisture is the amount of water held in the soil storage for a give grid cell.

Change in soil moisture: $\Delta s_t = P - E_A$ (Eq 4.20)

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[12] https://www.usgs.gov/centers/umid-water/science/swb-modified-thornthwaite-mather-soil-water-balance?qt-science_center_objects=0#qt-science_center_objects

Equation 4.21 is used to calculate the deficit when there is not enough storage to meet the needs of potential evapotranspiration (E_P). The daily soil moisture deficit is the amount by which the actual evapotranspiration differs from the potential evapotranspiration

Deficit: $$D_i = E_P - E_A \qquad \text{(Eq 4.21)}$$

Where $E_P =$ potential evapotranspiration, E_A = actual evapotranspiration

Surplus moisture is the excess precipitation added to the daily soil moisture when it reaches it maximum soi moisture capacity. This is equivalent to the groundwater recharge value. Equation 4.22 is used to calculate the surplus moisture content. The surplus and deficit values have no direct effect on the calculation of groundwater recharge.

Surplus: $$S_i = P - E_P - \Delta s_t \qquad \text{(Eq 4.22)}$$

Where P = precipitation, $E_P =$ potential evapotranspiration, ΔS_t = change in storage When precipitation minus potential evapotranspiration is positive, the actual evapotranspiration equals the potential evapotranspiration. When precipitation minus potential evapotranspiration is negative, then actual evapotranspiration is equal only to the amount of water that can be extracted from the soil (change in soil moisture). Equations 4.23 and 4.24 are used to calculate the potential and actual evapotranspiration respectively.

Potential evaporation: $E_P = P + S_i$ (when storage is zero) (Eq 4.23)

Actual evapotranspiration: $E_A = E_P$ (unless storage goes to zero) (Eq 4.24)

Where,

P = Precipitation is the amount of water added to the soil in each month measured in millimetres (mm).

E_P = Potential evapotranspiration is the amount of water that could be available for evaporation (from the sun) and transpiration (from plants). It is different from actual evapotranspiration (mm).

S_t = Storage is the volume of water in the soil. It cannot go above 100 mm or below 0mm.

ΔS_t = Change in storage is the volume of change in the water held in the soil.

E_A= Actual evapotranspiration (mm) is the amount of water that is used. It is different from E_P when there is not enough water.

D_i= Deficit is when there is not enough storage to meet the needs of E_P (when storage is zero)

S_i = Surplus is when there is more water than the soil can hold, water runs off and is lost to the system. Storage cannot be greater than 100mm.

R_O = Runoff

4.11Three Dimensional (3D) Numerical Model to Simulate Groundwater Flow

3D numerical groundwater modelling approach has served as an effective decision-making tool for evaluating management measures of future groundwater abstraction and monitoring. It is an important activity in strategic water management which can be used to assess the current groundwater situation and to predict future hydrological environments. Groundwater modelling is also commonly used to quantifying groundwater recharge, discharge and to evaluate aquifer parameters. Numerical modelling represent the process of a real groundwater system with application by a computer program to solve the mathematical equations (Reilly and Harbaugh, 2004).

Groundwater mathematical models are the tools used to simulate (or to predict) the groundwater system using mathematical equations based on certain simplified assumptions (Kumar, 2014). These assumptions usually involve the heterogeneity of the geologic layers within the aquifer, the direction of flow and the geometry of the aquifer.

In this study, a groundwater flow model (GFM) is used to simulate appropriate groundwater abstraction under different scenarios. The developed simulation has been applied with an objective to understand the groundwater system, predict artificial and natural changes in response to stress, evaluate the aquifer hydraulic properties, determine the groundwater recharge, determine the performance of the wells/boreholes for future suitability and design artificial recharge zones such as infiltration galleries to provide realistic technical information for planning and adaptive strategies to water managers. Because models are not perfect for all situations, it is impossible to design one that will fulfil all purposes. MODFLOW can be used to address the types of problems to understand the history and future response of an aquifer through various modelling application. Table 4.6 is showing the aquifer related problems and the numerical modelling approaches that is used to address the problems identified the Freetown watershed.

Table 4. 6 Types of Groundwater flow problems in Freetown Watershed and Numerical approaches to Simulate them adapted from Reilly and Harbaugh (2004)

Problem Type	**Reason for undertaking Study**	**Approach to Model the Problem**
Understanding of Groundwater System	Investigation of hydrogeologic process and relationship with surface water	• Freetown Watershed Model Superposition (evaluate changes in stress & responses) • Sensitivity analysis (evaluate input parameters to see how they affect the model output parameters)
Estimation of Aquifer properties	• Aquifer test analysis • Determination of aquifer properties and system changes to external and manmade changes	• Calibrated model (matching observed heads) and Superposition
Understanding the Present system	• Determination of the effect of groundwater pumpage on surface water bodies. • Determination of sources of water to wells • Determination of responsible parties causing impacts on the system	• Calibrated model and superposition • Calibrated model • Calibrated model
Predicting the Future	• Management strategies to monitor abstraction • Simulate the behaviour of the system and evaluate water balance • Management and planning tool for decision making	• Calibrated and superposition models

Based on the problems listed in Table 4.6, certain approaches are used to address a specific problem. The calibration approach uses the closeness of fit between the simulated and observed conditions. The superposition model approach evaluates changes in stress and responses. Sensitivity analysis is integrally part of model calibration and it evaluate the model parameters to see how much they affect the outputs, which are hydraulic head and flow. The relative effect of the parameters helps to provide fundamental understanding of the simulated system.

In a numerical modelling, defining the actual boundary conditions and other parameters in the model is important. The model should include a detailed description of sensitivity analysis and documented justification for specific assumptions in varying certain aquifer parameters to see how they affect the model results other than the model defaults. The model should be calibrated to existing site environments. After calibrated, the model can be simulated in the predictive, interpretative or generic modes to generate results for a range of sensitive parameters (Anderson et al., 2015). The model is also validated. The model results should be analysed, evaluated and summarised. Conclusions and recommendations should be made from the entire simulation process.

In this research ModelMuse groundwater modelling software version 4 (MODFLOW 6) as well as MODFLOW–2005, MODFLOW-NWT and ZONEBUDGET developed by the United States Geological Science is used to model the specific related groundwater problem.

4.11.1 Groundwater Flow Models

The simulation of groundwater flow requires a thorough understanding of the hydrogeologic characteristics of the environment. The hydrogeologic analysis should include a comprehensive information of the following:

- Hydraulic properties of the aquifer system and confining layers.
- The thickness and subsurface extent of the aquifer system and confining layers (hydrogeologic framework).
- Hydrologic boundaries (also referred to as boundary conditions), which control groundwater movement, direction and flow rate.
- A description of the horizontal and vertical distribution of hydraulic heads throughout the modelled area for beginning (initial conditions), equilibrium

(steady-state conditions) and transitional conditions when hydraulic head may vary with time (transient conditions).

- Distribution and magnitude of groundwater recharge, pumping or injection of groundwater, leakage to or from surface-water bodies, etc. (sources or sinks, also referred to as stresses).

These stresses (pumping and discharge) may be constant (unvarying with time) or may change with time (transient). The outputs from the model simulations are the hydraulic heads and groundwater flow rates which are in equilibrium with the hydrogeologic conditions (hydrogeologic framework, hydrologic boundaries, initial and transient conditions, hydraulic properties, and sources or sinks) defined for the modelled area.

After defining the problem in Table 4.6, a connection is made to translate the real-world groundwater flow system (including the problem) into numerical ones, taking into account that the natural components, geometry, and aquifer characteristics are interpreted as accurately as possible into the real-world groundwater flow system.

The first step in constructing the groundwater flow conceptual model is defining the geological framework of the study area, including the number of stratigraphic layers, the thickness of each layer, lithology, and structure of the aquifers and confining units. The nature of the conceptual model will determine the dimensions and spatial distribution of the numerical model.

Water level depths (pumping tests data) and the thematic maps prepared are used to estimate the dominant directions of groundwater flow, the hydraulic gradient, locations of recharge areas, location of discharge areas, and the connections between groundwater aquifers and surface water systems to quantify recharge and baseflow.

For accuracy and simplicity, the GIS technique has used the natural geologic boundaries to construct the different numerical flow models (developed in Chapter 6). This allows the hydrological framework (hydrological boundaries, hydrostratigraphic units, water budget, and flow system) to be defined. The calculation of hydraulic parameters from the pumping tests has been useful to identify and distinguish the different hydrostratigraphic units. The hydrostratigraphic unit is crucial in determining the number of layers controlling groundwater flow within the system.

Model calibration is the process of adjusting one or more aquifer parameters until the results of the simulation match the measured data. It is also the procedure in which the groundwater flow system estimates the hydraulic parameters of an aquifer. A steady state calibration was performed to the pumping tests data that represent the steady state conditions of the aquifer behaviour over the long term at a given point in time under certain stresses (withdrawal) applicable at that time. Transient calibration is performed to pumping tests data that represent the aquifer's response to stresses such as withdrawal (Woessner and Anderson, 1992) over time, for the duration of the modelling period to achieve accurate calibration.

4.11.2 Governing Equations for Groundwater flow

Mathematical representation of hydrogeologic processes requires simplifying assumptions, which are integrated in the governing equations. Henry Darcy, a French Hydraulic Engineer, developed an empirical relationship for flow through porous media. He established that the specific discharge in Equation 4.25 was directly proportional to the energy driving force (the hydraulic gradient) according to the following relationship:

$$qx \; \alpha \frac{\Delta h}{\Delta x} \qquad \text{(Eq 4.25)}$$

Where, qx = specific discharge in the x-direction [LT^{-1}],

Δh = the change in head from point 1 to point 2, L

Δx = the distance between point 1 and point 2, L

$\frac{\Delta \mathrm{h}}{\Delta \mathrm{x}}$ = the hydraulic gradient in the x-direction, dimensionless

The specific discharge qx is defined as the flow volume per time per unit area and is the most often used in groundwater flow modelling (Equation 4.26). It represents flow of a single phase fluid (water) at constant density in a continuous porous medium under Darcy's law. It is sometimes referred to as the superficial velocity or the Darcy's velocity.

$$qx = -Kx\frac{\partial h}{\partial x} \qquad \text{(Eq 4.26)}$$

where K x = saturated hydraulic conductivity in the x-direction, LT^{-1}.

The negative sign indicates water flows from an area of a high head to a low head (a negative hydraulic gradient).

A combination of Darcy's flow equation with conservation of mass equation to give the following partial differential equations for the 3D movement of groundwater through a porous media for the steady and transient states is used in the groundwater flow modelling process. The mass balance principle requires that the rate of change in mass storage of an elemental volume with time be equal to the mass inflow rate minus the mass outflow rate.

Features of the governing equations and boundary conditions (e.g., aquifer geometry, hydrogeological properties and pumping rates) can be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a groundwater system than could be achieved with an analytical model. Equation (4.27) is the mathematical relationship representing three-dimensional (3D) transient groundwater saturated flow through an aquifer for heterogeneous and anisotropic conditions (Heights, 1971; Woessner and Anderson, 1992; Vázquez-Báez *et al.*, 2019).

$$\frac{\partial d}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial \gamma}\left(K\gamma\frac{\partial h}{\partial \gamma}\right) + \frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right) = \ Ss\frac{\partial h}{\partial t} \pm W^{*} \qquad \text{(Eq 4.27)}$$

where,

the variable of interest h, is the dependent variable, while x, γ, z, and t are the independent variables.

Kx, Ky and Kz = represent the hydraulic conductivities along the x, y and z coordinate axes, which are assumed to be parallel to major axes of hydraulic conductivity [LT^{-1}] h = the potentiometric or hydraulic head, [L]

h = change in hydraulic head [L]

W = volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the ground-water system, and W>0.0 for flow into the system (T^{-1});

Ss = volumetric specific storage of the porous material [L^{-1}]

t = time [T].

The subscripts on K denote anisotropic conditions, meaning that hydraulic conductivity can vary with direction x, γ, and z. The placement of K within the differential signs allows for spatial variation (heterogeneity) in hydraulic conductivity. There is no change in head with time in steady state conditions, so time is not one of the independent variables. The steady state equation is shown in Equation (4.28).

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial \gamma}\left(K\gamma\frac{\partial h}{\partial \gamma}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)= \ 0 \qquad \text{(Eq 4.28)}$$

Equation (4.27) simplifies when the problem is steady state (dh/dt=0) and/ or when two-dimensional (2D) (Craig, 2015). For 2D horizontal flow through a confined aquifer, vertically integrated parameters, i.e., transmissivity (T) and storativity (S), can be defined. Then the components of transmissivity in the x-, y- and z-directions are

$T_x = K_x b$, $T_y = K_y b$, and $T_z = K_z b$ respectively,
Where,
b = aquifer thickness [L]
S = Ss*b [dimensionless]
W*, the source/sink term, in Equation (4.27) becomes a flux, expressed as volume of water per area of aquifer per time, R (L/T). Under these conditions Equation (4.27) becomes:

$$\frac{\partial}{\partial x}\left(Tx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial \gamma}\left(T\gamma\frac{\partial h}{\partial \gamma}\right)+\frac{\partial}{\partial z}\left(Tz\frac{\partial h}{\partial z}\right)= \ S\frac{\partial h}{\partial t}-R \qquad \text{(Eq 4.29)}$$

For 2D horizontal flow in an unconfined, heterogeneous, anisotropic aquifer, the differential equation is:

$$\frac{\partial}{\partial x}\left(Kxh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial \gamma}\left(K\gamma h\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzh\frac{\partial h}{\partial z}\right)= \ S\gamma\frac{\partial h}{\partial t}-R \qquad \text{(Eq 4.30)}$$

Where
$S\gamma$ = specific yield and R is recharge rate.
Here, head (h) is equal to the elevation of the water table measured from the base of the aquifer. For a steady-state flow with no recharge (R = 0) in a homogenous and isotropic aquifer, equations 4.29 and 4.30 simplify to the Laplace equation for discharge potential (4.31).

$$\frac{\partial^2\Phi}{\partial \mathrm{x}^2} + \frac{\partial^2\Phi}{\partial \gamma^2} = 0 \qquad \text{(Eq 4.31)}$$

When the Laplace equation (4.31) applies, the discharge potential has the valuable feature that the derivative of Φ defines the streamfunction, ψ (L^3/T), which can be used to calculate groundwater flowpaths without particle tracking. The streamfunction is defined from the discharge potential as follows:

$$\frac{\partial\psi}{\partial\gamma} = +\frac{\partial\Phi}{\partial \mathrm{x}} = -Q'_x$$

(Eq 4.32)

$$\frac{\partial\psi}{\partial \mathrm{x}} = +\frac{\partial\Phi}{\partial\gamma} = Q'\gamma$$

where,

Q'_x and $Q'\gamma$ = discharge per unit width [L^2/T] in the x- and y-directions, respectively. ψ = streamfunction [L^3/T]

The discharge, Q, between streamlines is the change in the streamfunction:

$$\Delta Q = \psi_1 - \psi_2 \qquad \text{(Eq 4.33)}$$

For the above presented equations to be solved, initial, boundary, and constraint conditions must be met. The nonlinear continuity equation, in most cases, cannot be solved analytically and numerical approaches must be used to solve the equation. For nonlinear problems, it is necessary to iterate various boundary conditions so that the head value fulfils the head-dependent boundary condition and the unconfined head, resulting in the flow within the aquifer (Dettinger and Wilson, 1981). The solution of an equation can be more flexible with numerical results. Numerical results involves discretising the domain into a number of points (nodes) where the equation will be solved (Huyakorn et al., 1983).

4.12 Overview of ModelMuse MODFLOW

This research builds an interconnected simulation mimicking the characteristics of the chosen case study area as outlined in Section 4.12.1. ModelMuse MODFLOW has been employed to develop the simulations.

ModelMuse MODFLOW is the most widely used open access professional 3D numerical groundwater flow modelling software package. It combines the most powerful and intuitive interface with numerous facilities for data preparation and development using the latest model versions of MODFLOW 6, MODFLOW–2005, and MODFLOW-NWT.

ModelMuse can be applied to: a). Simulate systems for water supply, b). Evaluate contaminant remediation and mine dewatering, c). Delineate well capture zones, d). conduct an assessment for wells/boreholes future suitability, e). Simulate recharge, pumping and drawdown capacity, f). Identify and design sites for artificial recharge such as infiltration galleries. The ModelMuse GUI has been specifically designed to increase modelling productivity and reduce the complexities normally associated with building a three-dimensional groundwater flow model. The interface is divided into three separate segments viz.., Input Segment, Run Module and Output Module.

ModelMuse is simulated using a three-dimensional block-centred finite-difference approach for creating groundwater flow and transport input file for the U.S. Geological Survey (USGS) models MODFLOW–2005 and PHAST(Harbaugh, 2005; Winston, 2009). MODFLOW-2005 is written in standard Fortran 90 (American National Standards Institute, 1992) programming languages, which are highly portable (Harbaugh, 2005). The package has carefully avoided the use of non-standard features so that MODFLOW-2005 will run, without modification, on most computers.

The groundwater flow (GWF) process of ModelMuse MODFLOW has been divided into "packages." A package is the specific portion of the program that deals with a single aspect of simulation. An example is the Well Package, which simulates the effect of wells, and the River Package that simulates the effect of rivers. The Strongly Implicit Procedure Package solves the system of simultaneous finite-difference equations. The Fortran method divides the program into pieces or subroutines, so that each package consists of multiple subroutines.

The MODFLOW program is based on finite difference approach. Figures 4.17a and 4.17 b show the discretisation of continuous medium into finite difference cells of an aquifer system. Discretisation of a domain uses a grid system to divide a region of interest into rectangular blocks. Typically, these blocks are organized into rows, columns, and layers. Since finite difference methods are not intended to handle discontinuities in coefficients, one of the greatest limitations is their inflexibility when representing subsurface heterogeneity. However, ModelMuse MODFLOW is regarded as the leading groundwater modelling program in the world that can handle the limitations of the finite difference approach, such as the lack of flexibility in representing subsurface heterogeneity, of the equation being approximated ("jumps" in K, for example) (Kumar, 2019).

MODFLOW calculates finite-difference equations using equivalent conductances between adjacent nodes, termed "branch conductances", rather than conductances defined within individual cells. A horizontal conductance term between adjacent horizontal nodes is used instead of a node-specific conductance value. Conductance between nodes is often indicated by a '1/2' subscript. A conductance, Ki,j*1/2,k, for example, can be described as the difference between nodes i,j,k and i,j-1,k (4.17b). A cell is considered uniform within MODFLOW if two nodes within the cell have the same hydraulic conductivity (as the program allows for differing step sizes).

The parameter K can be discreetly changed between two cells with this method. Calculations of hydraulic conductivity at material interfaces are challenging due to the incapability of finite difference methods to handle discontinuities in coefficient K. A common way ModelMuse MODFLOW does this, is to average hydraulic conductivity across the interface and define it as shown in Figure 4.17b.

ModelMuse MODFLOW layers can be simulated as confined, unconfined, or a combination of both. It can simulate flows from external stresses such as flow to wells, recharge, evapotranspiration, flow to drains, and flow through riverbeds. The mathematical representation must be accurate, therefore models must be built around the characteristics of hydraulic parameters (hydraulic conductivity, transmissivity, specific storage, specific yield etc.), boundary conditions (constant heads and locations of impermeable boundaries) and stress (pumping rates, recharge from precipitation, evapotranspiration, drains, rivers etc.) (Reilly and Harbaugh, 2004; Harbaugh, 2005).

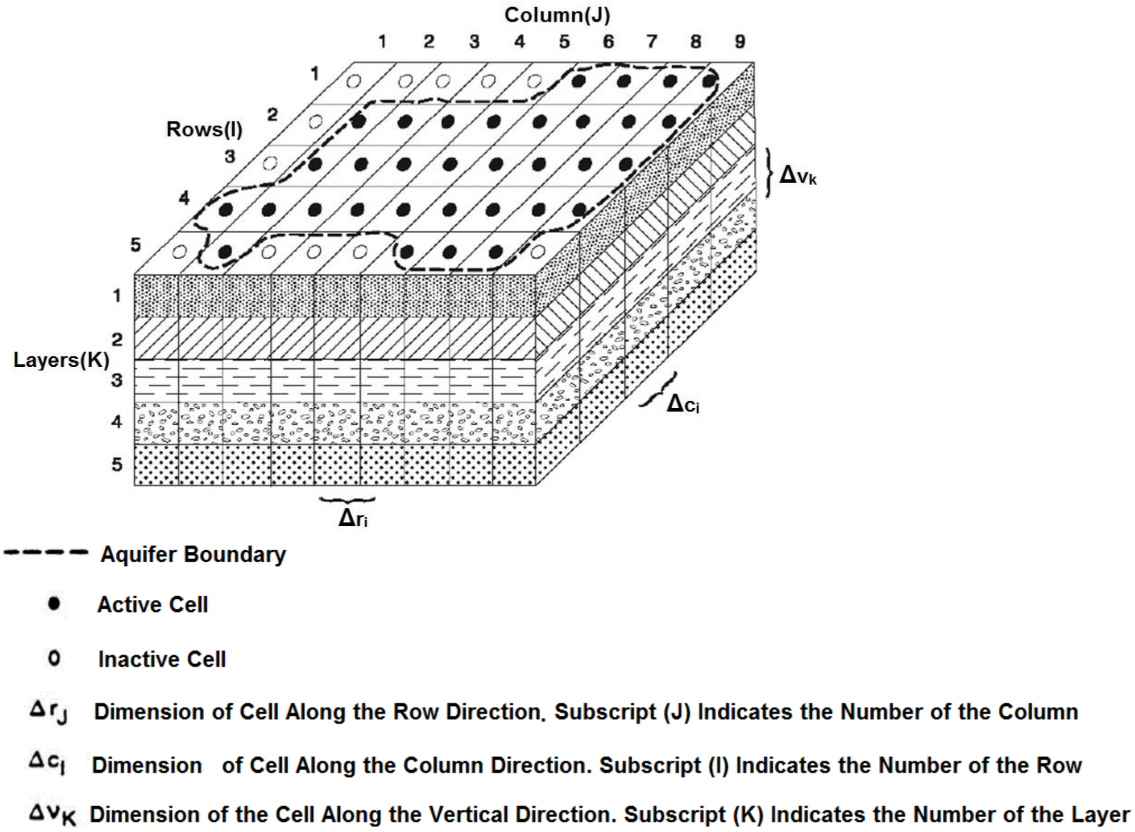


Figure 4.17a An illustration of a finite difference discretisation of an aquifer system in R3, with rows, columns, and layers representing the i, j, and k from directions source: (Harbaugh et al., 2000)

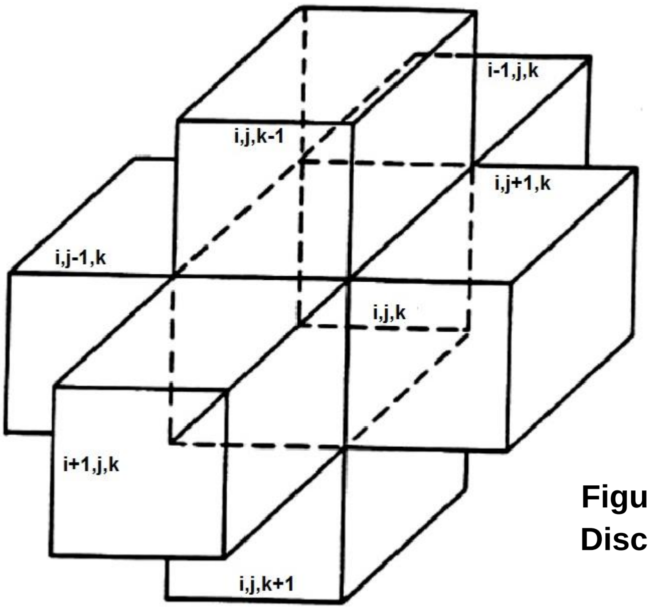


Figure 4. 17 MODFLOW Finite Discretization Representation

Figure 4.17b MODFLOW representation of the flow into cell i, j, k from cell i, j – 1, k

4.12.1 ModelMuse MODFLOW Version Codes used to Simulate Specific Aspects of the Groundwater System

a. MODFLOW-2005 – the previous version code used to solve groundwater equations. It simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (Harbaugh, 2005; Winston, 2009). In MODFLOW – 2005 all three boundaries head dependent flux, specified head and specified flux can be simulated as can flow and advanced external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds. Hydraulic conductivities or transmissivities for any layer in this model may differ spatially and be anisotropic and the storage coefficient may be heterogeneous (Harbaugh, 2005).

b. MODFLOW 6 is an object-oriented program and framework developed to provide a platform for supporting multiple models and multiple types of models within the same simulation. It is the current core version of MODFLOW released by the USGS and presently contains two types of hydrologic models, the Groundwater Flow (GWF) Model and the Groundwater Transport (GWT) Model**.** The GWF Model is based on a generalized control-volume finite-difference (CVFD) approach in which a cell can be hydraulically connected to any number of surrounding cells. Modellers can define the model grid using
    - A regular MODFLOW grid consisting of layers, rows, and columns,
    - A layered grid defined by (x, y) vertex pairs, or
    - A general unstructured grid based on concepts developed for MODFLOW-USGS.

c. MODFLOW-NWT is a Newton formulation of MODFLOW-2005 that provides an alternate method for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater flow equation. It is used with the Upstream-Weighting (UPW) Package for calculating inter-cell conductance in a different manner than is done in the Block-Centred Flow (BCF), Layer Property Flow (LPF), or Hydrogeologic-Unit Flow (Niswonger et al., 2011).

This study used the hydraulically connected control-volume finite-difference (CVFD) approach, the flow property input for the UPW package based on the LPF package used for solving problems involving drying and rewetting nonlinearities of groundwater flow equations, taking into account all three boundaries (head dependent flux, specified head and specified flux in Table 4.9) to simulate specific aspects of steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (Harbaugh, 2005; Winston, 2009).

4.13 Model Development Process

A general simulation flow chart of modelling methodologies of a groundwater system is given in the block diagram (Figure 4.18). Proper characterisation of the hydrogeological conditions at a watershed is necessary in order to design the relevant flow processes. Steps 1, 2, 3 and 4 are combined to produce the heads (drawdown) and water level at flow velocity.

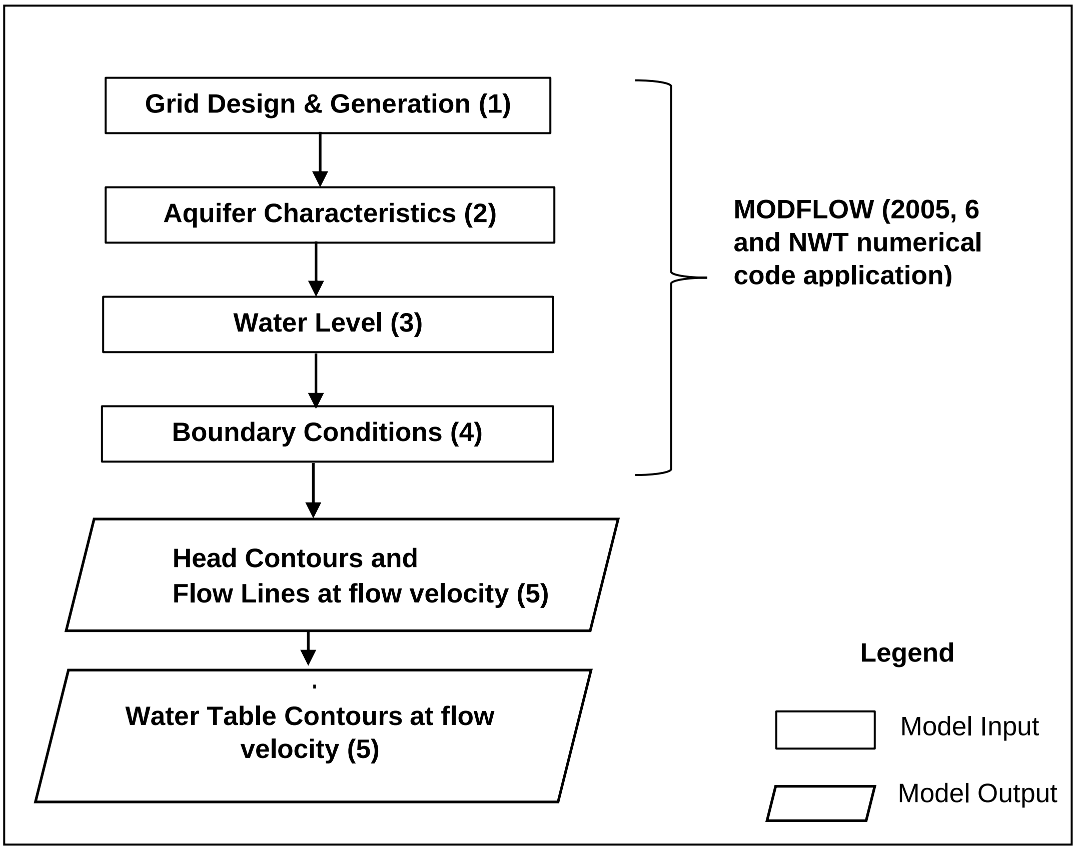


Figure 4. 18 Flow chart of modelling methodologies of a MODFLOW quantity system (Source: authour's construction)

In this study, ModelMuse MODFLOW models for the case study were developed, calibrated and validated with the primary data collected from the borehole drilling companies in the years 2016 and 2017. The observed and simulated heads was compared with the model predicted values. Then the models were used to generate predictions as per the objective of studies for different scenarios.

This level of hydrogeological characterisation (water interaction with the surface and subsurface environment) requires an assessment of the appropriate data, including monitoring wells and field parameters. Without proper representation of watershed characterisation, an appropriate or reliable model will not be calibrated. At the least, the following hydrogeological and geographic information must be available for this characterisation:

1. Topographic data (including 3D digital elevation model (DEM) and Digital Terrain Model (DTM) representation of the Area.)
2. Area geologic data integrating sub-surface geology.
3. Presence of surface-water bodies, measured stream-discharge (baseflow), flow direction data
4. Geologic cross sections drawn from borehole/well logs and soil borings.
5. Well construction diagrams.
6. Measured hydraulic head and elevation head data.
7. Estimates of hydraulic conductivity, transmissivity and other parameters derived from aquifer, pumping and/or slug tests data.
8. Location and estimated flow rate of groundwater sources and sinks.

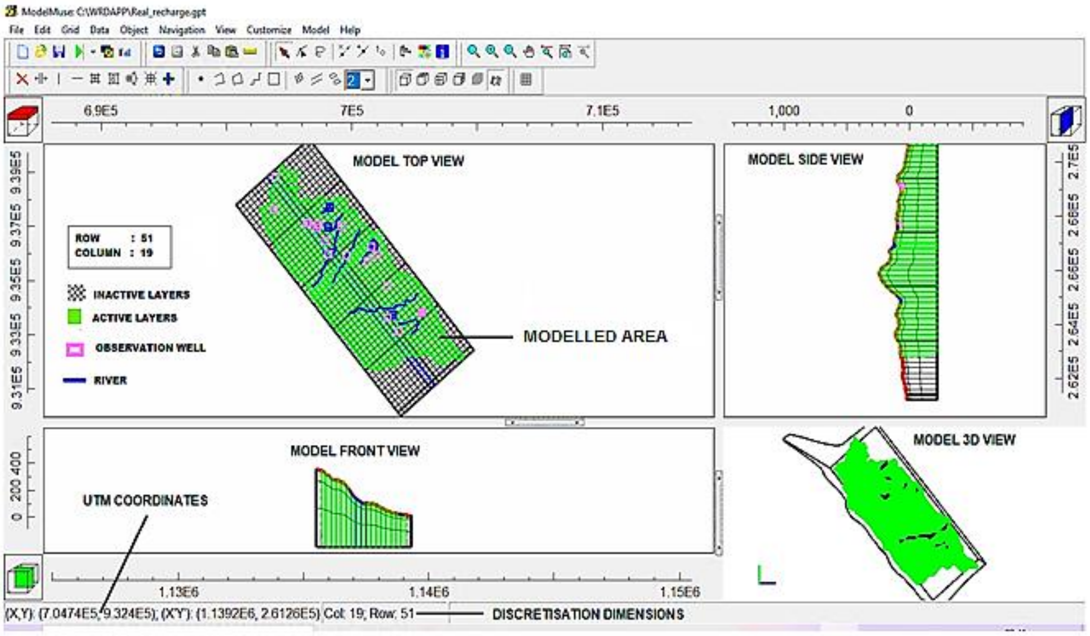
These data should be presented in map, graph or table format in a report documenting model development. In this study the required data for groundwater modelling was obtained from various sources as explained in Section 3.4.1.

4.13.1 ModelMuse MODFLOW Input

a. Base map

The boundary (base map) of Freetown Urban District area is obtained from toposheet 61 issued by the National Minerals Agency (NMA) and Sierra Leone Geological Surveys. It is scanned and saved as raster format (.jpg). Base map is imported into ArcMap. SRTM DEM (90 m resolution) was downloaded from USGS web archives and resampled into 500 m resolution thematic maps, hydrology DEMs/DTMs, ASCII raster formats, Shapefiles using ArcGIS and QGIS environments. In raster format, they can be easily georeferenced to the real-world coordinates. Geographic Information Systems (GISs) have the capability to manage, analyse, visualise and store huge spatial, non-spatial and temporal dataset and are the most efficient tools to manage complex modelling environments (Kushwaha et al., 2009; Haque *et al.*, 2012).

The modelled area lies between UTM Eastings northern latitudes 696381 and 704481 and UTM Northings 931888 and 939088 with a spatial extent of 25.5Km^2. The river flow is from north east to south west correlated mainly by the topography. The study area is discretised into upper left corner: (696381.37202078, 939088.938284549), lower left corner: (696381.37202078, 931888.938284549), upper right corner: (704481.37202078, 939088.938284549), and lower right corner: (704481.37202078, 931888.938284549) respectively. The discretisation dimensions have 51 Rows and 19 Columns. The cells of the remaining area (i.e.) outside the boundary of the modelled area is made as inactive. The grid formation of the study area is given in Figure 4.19.



```
(X,Y): (7.0474E5, 9.324E5); (X'Y'): (1.1392E6, 2.6126E5) Col: 19; Row: 51
```

Figure 4. 19 Grid Formation and Discretisation of the Study Area (Source: authour's construction)

4.13.2 Layer elevations

MODFLOW allows the input of GIS spatial and temporal data for accurate real-world conditions in developing the conceptual models. ArcGIS and QGIS environments were used to resample the input maps (ASCII raster and Shapefiles) so that groundwater resources can be visualised and interpolated.

For the modelling purpose, various layers from one to five were considered along the entire region of the study area based on the identified objective of the simulation. The top layer is named as Layer 1 and the bottom layer is named as Layer 5. The top layer is the alluvial formation of thickness 5 to 20 metres. The middle layers consist of weathered to fractured formations of thickness 30 to 80 metres. Using the GIS sampled data downloaded from the USGS website as input information, accurate real-world conditions of groundwater resources were simulated to explore the complexities of the basin with high difference on elevation and the use of text defined parameters. The discretisation tab is on the MODFLOW Layer Groups dialogue box to specify the positions of the boundaries between layers in a layer group. Data (layer type, vertical discretisation and layer boundary) can be entered directly in the table or they can be specified graphically as illustrated in Figure D10.1 in appendix D

4.13.3 Wells

ModelMuse MODFLOW 2005 uses an advanced option to insert multiple wells with different pumping rates at different depths by the use of some special features, with long and varied pumping schedules by altering the *.gpt file. It imports the wells for each stress period separately as a separate object with multiple point sections. The limitation is that it cannot set the well name, and in situation of wells with multiple pumping records, a group of superposed wells were inserted, one for each pumping rate record.

a. Pumping wells

Pumping well data obtained from the drilling companies were inputted into GIS environments to create new map layers in Aster DEM, ASCII and Shapefile formats to serve as topography and source into the simulation packages. The datasets were added to the study area (25 Km^2) in the different simulation development (discussed in Chapter 6, Section 6.5) and their pumping rate and their usage were calculated using the analytical methods of Theis, Cooper Jacob and Chow in Equations 4.6 to 4.15. The drawdown capacity, head distribution and flow rate of water sources were also calculated using equations given in Section 4.11 (Equations 4.27 to 4.30). By conducting the field study and using the available Baba and EDAL data, the groundwater available for abstraction in the study area was simulated. The pumping wells were located in the grid and the pumping rate (L^3T^{-1}) is entered.

Positive rates were used for injection. Negative rates were used for withdrawal. In the study area there is no injection wells. When MODFLOW 2005 develops a model, it imports the wells for each stress period separately as a separate object with multiple point sections. MODFLOW 6 imports wells in *.SHP format. The first pumping rate in the pumping schedule was used as the pumping rate for steady-state simulations. The pumping rate must be specified continuously for all stress periods. In a transient simulation, the pumping wells are turned off if the pumping rate is not specified for the later stress periods. If a well cell goes dry during a simulation, the pumping rate of the well at that location will automatically be reduced. Using the copying option in MS Excel, the multiple wells data from a *.CSV (Comma delimited) file were positioned in the grid using version code MODFLOW 2005. The pumping well edit screen for MODFLOW 2005 is shown in Figure D10.2 in Appendix D.

b. Head observation wells

The Head Observation package (HOB) is used to compare observed heads with simulated heads computed by MODFLOW. The aim is to reduce the discrepancies between observed and model generated values. The pane for the HOB package is on the MODFLOW Features tab of the Object Properties dialogue box. The simulated heads are computed by interpolating from the nearest cell centres to the position of the observation. Head observations can extend over several model layers in which case, cells from all the layers that are part of the observation were used in calculating the simulated head. MODFLOW 2005 package saves the calculated heads at the locations of specified observation wells for every time step in a *.HOB_OUT (Head versus Time) file. This allows the user to compare simulated heads with observed heads, produce

calibration statistics, and produce hydrographs at observation wells without saving the entire MODFLOW solution at every time step.
ModelMuse completes a process to insert piezometers as a HOB package into a regional groundwater flow in MODFLOW 6. Surface and screen elevations in *CSV format was converted to geodatabase feature class (shapefile) using ArcMap in order to be imported by ModelMuse 4, It does not use discretised vertex, the geographic coordinate position of a piezometer (borehole) is inserted and the solver gives the simulated head, unlike in MODFLOW 2005, the values of the observed head is inserted as shown in Figure D10.2 in Appendix D, and the simulation gives you the result heads and residuals. The HOB piezometer insert/edit screens are shown in Figure D10.3 in Appendix D. Python script was used to generate the plot of calculated-observed heads with the normalized root-mean-squared error (NRMSE) value as a header.

Neither the Ministry of Water Resources, nor the Guma Valley Water Company has any guidelines in place for groundwater abstraction and do not monitor groundwater levels in the study area. 19 wells are falling within the modelled area (Table 4.7). A general observation of water level data at some of the wells, suggest that water table tends to rise during July to November to reach the highest peak and start declining from January onwards to end of April yearly. The rise and fall depend upon the amount, duration and intensity of rainfall, soil texture, thickness of top layers, specific yield of the formation and general slope of the aquifer bottom towards the drainage channel.

Table 4. 7 Pumping Test Data of Wells used in the Modelled Area (Source: authour's data analysis)

Well_ID	Well Location	Easting	Northing	Well Depth (m)	S. W. L. (m)	Final Drawdown (m)
PW001	Adolphus St. Kissy	698663	937060	104	13.2	20.8
PW002	Orogu Bridge	702275	931468	80	17.28	32.4
PW003	Approved Sch. Portee	700620	935723	58	15.3	30.3
PW005	Blackhall Rd	696893	937651	63	12.05	21.8
PW006	Arshobie Corner	696895	937643	68	10	19.3
PW007	Carsel Farm 1 Kissy	698188	937091	65	15.5	28.8
PW009	Carsel Farm 2 Kissy	698274	937147	48	13.09	20.6
PW004	Cline Town	696970	938854	40	23.22	27.3
PW014	E. E.M. Sch Fourah Bay	698621	936939	70	13.9	28.5
PW015	Thunder Hill	699070	935974	78	18.5	33.2
PW016	Lowcost Housing	699584	937012	126	6.97	30.7
PW018	Portee	700801	936248	36	16.1	28.4
PW019	Rokupa	701023	935947	80	11.5	24.2
PW020	Thunder Hill	699767	935920	74	17	30.4
PW021	Calaba Town	701876	933117	70	23.2	40.2
PW022	Congo Water	701414	934797	43	10.21	28.2
PW023	Industrial Area	701414	933636	60	7.75	29.4
PW024	Old Wharf, Wellington	702797	933818	60	29.4	35.4
PW025	Davies Street sch	698939	936480	70	16.2	29.8

4.14 Hydrological Properties

ModelMuse MODFLOW packages allows the input and editing of hydrological properties, which include hydraulic conductivity, specific storage, initial heads and specific yield. These properties were used to define the aquifer properties in the Layer Property Flow package dialog box.

4.14.1 Hydraulic conductivity

Hydraulic conductivity (how well a porous medium can transmit water) controls the average behaviour of groundwater within the aquifer system. Three related concepts are defined: effective hydraulic conductivity, which relates the ensemble averages of flux and head gradient; equivalent conductivity, which relates the spatial averages of flux and head gradient within a given volume of an aquifer; and interpreted conductivity.

With the available pumping well data, an analytical numerical modelling was conducted to estimate the aquifer properties assigned in the simulations (Table 4.8). In the model development stage, two parameters are used to define the hydraulic conductivity ("HK_Par1" and HK_Par2 set as a value of 0) under the Layer Property Flow Package as shown in Figure D10.4 in Appendix D. The values of the aquifer properties are assigned in the model Data Sets as in Table 4.8.

Table 4. 8 Aquifer Properties Used In the Simulations (Source: authour's estimation of hydraulic parameters)

No.	**Aquifer Properties**	**Aquifer Parameter symbol**	**Upper layer Alluvial and Weathered Formations**	**Bottom/Lower layer Hard Rock**
1.	Horizontal hydraulic conductivity in longitudinal direction K_x, (m/sec)	HK	2×10^{-4}	4.0×10^{-5} - $1.21 \text{ x } 10^{-6}$
2.	Hydraulic conductivity in lateral direction K_y, (m/sec)	HK	2×10^{-4}	4.0×10^{-5} - $1.21 \text{ x } 10^{-6}$
3.	Hydraulic conductivity in vertical direction K_z, (m/sec)	VK (K_x/10)	2.0×10^{-5}	4.0×10^{-6} - 1.21×10^{-7}
4.	Horizontal anisotropy	HANI	((Kx =0), 1., (Ky/ Kx))	((Kx =0), 1., (Ky/ Kx))
5.	Transmissivity, m^2/sec	T	1×10^{-3}	1.0×10^{-4} - $4.0 \text{ x } 10^{-5}$
6.	Specific storage Ss (1/m)	SS	$1.3 \text{ x } 10^{-4}$	$1.20 \text{ x } 10^{-5}$
7.	Specific Yield Sy	SY	0.12	0.12
8.	River conductance m^2/sec	RIV	0.01	0.001 - 0.0005
9.	Drain conductance m^2/ sec	DRN	0.01	0.001 - 0.0005

4.14.2 Storage

The Storage package (STO) is used to specify the storage properties of cells in MODFLOW transient models. The modeller must specify whether the confined storage properties will be specified using specific storage or the storage coefficient. Three parameters are given as input in the storage menu. i). S - Storativity (dimensionless): The volume of water that will be released from storage per unit surface area of the aquifer per unit decline in hydraulic head. ii). Ss - Specific Storage (m^{-1}): The volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. Using specific storage, the model determines the primary storage coefficient by multiplying Ss with the layer thickness. iii). Sy - Specific Yield: The storage term in unconfined aquifers is known as the specific yield. It is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area per unit decline in the water table. Storativity and specific storage are storage properties in a confined aquifer system. The storage edit button is in the LPF and dialog box is shown in Figure D10.5 in Appendix D.

4.14.3 Initial heads

For a steady state simulation, MODFLOW needs an initial estimate for the head distribution and for a transient simulation it needs a starting head distribution. Data sets for the elevations of the top of the model and the bottom of each layer group must be created. The MODFLOW_Initial_Head data set is set at Model_Top and can be found under the Data Set dialog box dialogue. The drawdown is also calculated from the initial head. The initial head is assigned based on the water level (Shenga et al., 2018). Figure D10.6 in Appendix D shows the Initial Head edit dialogue box.

4.15. Boundary Conditions

Boundary conditions represent locations in the model where water flows into or out of the model region due to external factors. It facilitates the editing of various boundary conditions in the simulation model. These include head cells, general head cells,

drains, rivers, streams, walls (horizontal flow boundaries), recharge, lakes, evapotranspiration and wells.
ModelMuse MODFLOW mathematical problems are referred to as boundary-value problems and a requirement is that boundary conditions must be prescribed over the boundary of the domain. There are three types of boundary conditions in ModelMuse MODFLOW, (1) specified heads, (2) specified fluxes, and (3) head dependant fluxes (Table 4.9). In specified head boundaries, the head remains constant for the rest of the simulation. Fluid is simulated as moving in or out of the groundwater at a rate sufficient to maintain the specified head. In specified flux boundaries, the rate of fluid moving into or out of the groundwater is specified. The head at the specified flux cell changes in response to the flux. In head dependant flux boundaries, the rate of flow from the boundary into or out of the groundwater varies in response to changes in head in the boundary cell. Polygons are used to specify the specified-head boundary condition.

To obtain a solution to the groundwater flow equation, boundary conditions must be specified along the entire boundary of the three-dimensional flow domain. Boundary conditions generally represent the sources and sinks of water within the system and their selection is critical to the development of an accurate model (Reilly, 2001).

Table 4. 9 Essential designations for the three common mathematical boundary conditions specified in the analyses of groundwater flow systems modified from Franke et al, (1987) [h is head (L), n is directional coordinate normal to the boundary (L)]

Boundary condition type and name	Boundary name	Mathematical designation
Type 1 Specified head	Dirichlet	$h(x,y,z,t) = \text{constant}$ where h(x,y,z,t) is the specified value of hydraulic head at the boundary
Type 2 Specified flux	Neumann	$\frac{dh(x,y,z,t)}{dn} = \text{constant}$ where n is an outward direction normal to the boundary, dh is the volumetric outflow rate, $[L^3T^{-1}]$; and dn is the specified outflow volumetric flux rate, $[L^3T^{-1}]$.
Type 3 Head-dependent flux	Cauchy	$\frac{dh}{dn} + ch = \text{constant}$ (where c is also a constant)

Boundary conditions refer to hydraulic conditions along the perimeter of the problem domain. Dirichlet, Neumann, and Cauchy boundary conditions can be applied to both perimeter and interior boundaries. All the three types of boundary conditions can be time-dependent if boundary heads and/or flows are updated as the simulation progresses.

In the present study, different MODFLOW packages were tested to represent water exchange between the aquifer and the surface water under intensive abstraction for sustainable water consumption. Based on this application, the various simulations developed in Chapter 6 investigated the advantages of different packages under all three boundary conditions. The first was the recharge (RCH) package which is active at the top of the model. Along with the RCH package, an EVT package boundary condition for evapotranspiration was added, which covers the entire peripheral zone of the watershed. One of the main boundary conditions affecting the surrounding watershed areas was constant head in the Sierra Leone River. MODFLOW also evaluated the RIVER package, which simulates surface water/groundwater interaction through a riverbed separating the surface water body from the groundwater system. The parameters for the RIVER package include the bottom of the riverbed, as well as the head on the river. Other boundary conditions assessed include the DRAIN (which remove water from the aquifer) and the general head boundary (GHB) condition where flux is proportional to head difference.

4.15.1 Minimum boundary specification

For a steady-state simulation, at least one head boundary must be specified. The head boundary acts as a reference head for all calculations. The head boundary can be a constant head, river, drain, or general head boundary. For the transient simulation, conditions remain constant over a stress period and change abruptly, between stress periods. A stress period is defined as a time period in which all the stress (boundary conditions, pumping rates, etc.) on the system are constant. In reality, the constant heads are never constant unless the heads at the beginning and at the end of the stress periods, they change within stress periods. ModelMuse only defines specified-head boundaries using the CHD package to represent the head boundary of the area. The CHD Time Variant Specified Head used for the well interference simulation is from the Model_Top to the Alluvial_Aquifer_Bottom. The water table is assumed to be at 8 metres below the surface. Aquifer thickness is 80 metres. The constant head was taken as the Model_Top – 8. The CHD Time Variant Specified Head assign screen is shown in Figure D10.7 in Appendix D.

4.15.2 River head

The River Package (RIV) uses geospatial data to analyse the river budget, to know how much water the river is pouring into the aquifer, and to know the inflow from the aquifer to the river. It also specifies the difference between the river package and other package e.g. the drain package. In order to set up the RIV package, the boundary conditions must be activated under the head dependent flux. ModelMuse allows the full implementation of the RIV package through the attribute of a shapefile, this was imported as a single, multipart object with set values of intersected cells to prevent many river reaches. It has one number of Z formula and defined on Model_Top. The river is activated in MODFLOW Features, at a steady state of minus one (-1) and end time of 0. In the case of a river boundary condition, MODFLOW defines the conductance of a river as the hydraulic conductivity that measures the resistance to flow between the surface water body and the groundwater. River conductance is calculated as

$$\boldsymbol{C} = \frac{\mathbf{KLW}}{\mathbf{M}} \qquad \text{(Eq 4.34)}$$

Where

C = conductance, m^2/day [L^2/T]

K = Hydraulic conductivity of the river bed material, m/day

L = Length of the river reach, m

W = Width of the river, m

M = Thickness of river bed, m.

The RIV values are entered into the numerical version code as shown in Figure D10.8 in Appendix D

In developing the simulation for the infiltration galleries along a river, the following data was used in the RIV package. Granville brook has a length of 3.77 kilometres with mean above sea level elevation (amsl) of 63 m. It enters into the Sierra Leone River estuary where Granville brook bed elevation is 10 m (amsl) at the confluence point. The depth of water flow is about 2 metres at the entering point and 0.5 m at the confluence point. The brook bed is gravel and the hydraulic conductivity is taken as 4.57m/day. The bed thickness is considered as 2 m at the starting and 5 m at the confluence point. The width of the river at the entry point is taken as 20 metres and at confluence point it is taken as 150 metres.

4.15.3 Drains

The Drain package (DRN) pane is on the MODFLOW Features tab of the Object Properties dialog box. The data that can be specified for the Drain package are the Starting time, Ending time, Elevation and Conductance. The Elevation is the elevation of the drain. The DRN package is designed to simulate the effects of groundwater from the aquifer through the drain boundary when the head is higher than the elevation, and then the rate of flow will be proportional to the difference between the head and the elevation. Flow is always out of the model at the location of the lowest head in the grid cell. The DRN values entered in the model are shown in Table 4.8 and the DRN package edit screen is shown in Figure D10.9 in Appendix D.

4.15.4 Recharge

One of the significant boundary conditions of the groundwater flow systems is the recharge. This is a process where water is added to the aquifer from the surface through the unsaturated zone after infiltration and percolation due to a rainfall event. The rate of recharge can be influenced by several factors like water content of surface materials, type of soil, slope, plants cover and precipitation rate. The Recharge (RCH) package is designed to simulate recharge that occurs as a result of precipitation that percolate into the groundwater system. RCH can also be used to simulate recharge from sources other than precipitation like artificial recharge (flooding, irrigation, infiltration galleries etc.).

ModelMuse allows the modeller to specify a recharge rate over an area or where it will be applied. The RCH package pane is in the Object Properties dialog box from the MODFLOW Features tab (Figure D10.10 in Appendix D). Three possible choices can be applied, (1) the **Top layer**, (2) a **Specified layer** and (3) the **Top active cell**. In this study, 'Top active cell' is used so that the location of recharge can move up or down to allow dry cells at the surface convert to wet cells. In this study, recharge numerical simulation was specified using elevation and recharge rate data in Excel *CSV format, imported into a shapefile of the modelled area in ModelMuse. Both values are considered to have a linear relation, as the elevation increases, the recharge rate is also increasing. Negative recharge rates are allowed. A negative recharge rate might be used to simulate a constant evapotranspiration rate. The recharge model development process is discussed in Section 6.5.1. The recharge modelling result is presented in Section 6.12.1 of Chapter 6.

4.16 ModelMuse MODFLOW Run

After completing the input parameters, Run model is selected from the screen, by clicking the [Run] MODFLOW version code button and the Save dialog box, allows the modeller to update the model description. When the description is updated, the *.Nam file is then written to the MODFLOW input and output files. Steady state and transient state run types are available in the model. First, the model was run for steady state condition. After that the model was run under transient condition. If all goes well, ModelMonitor will run the model and will terminate without any errors. It verifies that the boundary conditions are working as specified. After the ModelMonitor is closed, the MODFLOW listing file *LST will be opened in a text editor. The overall volumetric water budget is listed at the end of each time step. ModelMonitor displays the percentage discrepancies from the budget. The budgets of all packages in the model are included in the results. A percentage discrepancy of not more than 0.1 is accepted. MODFLOW output provides contours of head equipotential, head difference, drawdown, elevation, net recharge, and water table. It also provides graphs of calculated vs. observed heads, calibration of residual histogram, head vs. time, normalized RMS vs. time, and drawdown vs. time. The model output also provides a cross section of the water table. The output result is imported using the

File|Import|Model results button. It is not advisable to use the watershed boundary as a no-flow zone, because the highest heads from a simulation are not located in the area where the ground elevation is the highest.

4.16.1 Steady State calibration

All the models in this study are calibrated for steady state runs. The simulation to compare the observed and calibrated heads, using MODFLOW 2005 was designed in steady-state with the acceptance criteria of NRMSE. The models are calibrated on steady-state because of the dearth in data for a more advance performance and because the transient state calibration can be very complex. The data for the transient state calibration depends on the comparison of the observed and simulated data for a single observation point without acceptance criteria. When using MODFLOW 2005 (HOB package), observed heads are inserted, and the Iterative Model Solution (IMS) solver will produce the simulated heads and residual. The details of the model configuration steps and result are presented in Section 6.5.2 of Chapter 6. The modelling procedure can be conducted using both the MODFLOW-2005 and MODFLOW 6 numerical codes.

In MODFLOW 6 version numerical code (also called ModelMuse 4), the observation utility (OBS package) is used to specify location where hydraulic heads and flows for use in the observation process are simulated. No observed heads or data are imported into MODFLOW 6 as was done in MODFLOW-2005; and it does not make any comparison between the observed and simulated heads. Surface elevation and well bottom elevation data in *CSV format are converted into a shapefile to be inserted into ModelMuse 4. The Newton option is turned on in MODFLOW Options, Wetting, with ‘Use Newton formulation’ checked. The wetting of a cell is controlled by either the head in the cell directly beneath or by the heads in the adjacent horizontal cells, plus the one beneath. Rewetting help make a model more realistic although less stable. In a convertible layer, rewetting can make dry cells become active again if neighbouring cells have heads higher than the base of the dry cell. The OBS is a regular regional model with no discretisation vertex, IMS solver is used, and the position of the piezometer is inserted to produce the simulated heads. Unlike in MODFLOW 2005, the observed values are inserted and the result produce the simulated heads and residual (difference between observed and simulated heads), which could be positive when the simulated heads are low or negative when the simulated heads are high against the observed heads.

Horizontal anisotropy is the ratio of transmissivity or hydraulic conductivity along a column to its component value along each row. The anisotropy factor can be assigned by a layer or remain as specified in the hydraulic conductivity. The models are run with all the above inputs for steady state using Iterative Model Solution (IMS) solver. The aquifer condition of the year 2017 is assumed to be the initial condition for the steady state model calibration.

In the Wells Interference numerical model simulation setup, the hydraulic conductivity values, boundary conditions and the water head levels through the steady state model calibration is then used as the initial condition in the transient model calibration. The above are used along with the specific storage and specific yield calculated values of the hydraulic parameters in Table 4.8. The transient (dynamic) calibration is carried out for the time period of fifteen years (473364000 seconds). The wells are activated on the transient state model. Each well was set to pump at a different pumping rate under direct pumping interpretation, to reflect the seasonal recharge variation of the aquifer set at Model_Top – 40 metres depth. The computed well parameters are in agreement with field characteristics based on the outcome of the simulation presented in Sections 6.5.3 and 6.12.3 of this thesis.

4.17 Summary

This chapter has discussed the detailed methodologies of the two components. These include firstly, details on the per capita water consumption questionnaire-based studies at end-used level conducted in the city of Freetown and the estimation of per capita water end-use volume. Secondly quantitative assessment of groundwater resources. The inferences drawn are discussed in chapter 5 and Chapter 6.

CHAPTER 5: WATER CONSUMPTION QUESTIONNAIRE-BASED STUDIES – RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter examines water consumption for 398 households of different income groups, with data collected through a questionnaire-based study (as described in Section 4.2), to develop statistical models to quantify water end uses and identify the factors influencing per capita water consumption for the City of Freetown, Sierra Leone. Lastly, the chapter investigates the impact of seasonal variability on per capita water consumption, using the collected data of water consumption questionnaire-based study during the rain and dry season.

5.2 Household socio-economic characteristics

The analyses of household characteristics of 398 residential units revealed 60% of houses, 30% apartments and 10% of compound houses (Separate rooms shared by several households on one property). The results show that 51% of the households (HHs) surveyed are middle-income, while the remaining 24%, 17% and 8% are low-income, high-income and informal slum settlements, respectively.

A summary of the analyses of household and socio-economic characteristics of the 398 household units surveyed is shown in Table 5.1 revealed that the average family size of all surveyed households was found to be 4.69 persons, approximately equivalent to the average household size (4.60 persons) as reported by the Sierra Leone Population and Housing Census conducted in 2015 for Freetown (Weekes and Bah, 2017). In terms of family composition, the average number of adult males and adult females from 15–65 years were 1.35 and 2.06 per household, respectively. The average number of young (both male and female under 14 years), elders (65–75 years) and the aged (>76 years) were 0.97, 0.21 and 0.13 per household, respectively, showing great variation between the young and the old population.

Table 5. 1Summary of statistical parameters of household characteristics for the whole survey (Source: 398 households' analyses)

Household Characteristics	Unit	Mean (Variance)	Sierra Leone Statistics Survey (2015)
Household size (occupancy)	No./hh	4.69 (2.51)	4.60
Number of children (<14 years)	No./hh	0.97 (0.84)	0.90
Number of adult male members (15–65 years)	No./hh	1.35 (0.83)	1.21
Number of adult female members (15–65 years)	No./hh	2.06 (1.14)	2.00
Number of elders (66–75 years)	No./hh	0.21 (0.18)	0.32
Number of elders (>76 years)	No./hh	0.13 (0.11)	0.20
Number of rooms in the household	No./hh	3.31 (1.44)	3.00
Number of floors in the household	No./hh	1.17 (0.93)	1.00
Total built-up area of floors	m^2/hh	311.36 (4377.1)	280.00
Garden area per household		32.03 (160.38)	28.00
Monthly per capita income	SLL/mon ($\times 10^6$)	1.35 (1.43×10^6)	0.90
Household type	%	Houses (60.6%) Apartment (29.9%) Compound houses—rooms (9.5%)	Houses (54.4%) Apartment (20.2%) Compound houses—rooms (9.9%)
No. of houses, apartments and compound houses	No.	Houses (241) Apartment (119) Compound houses—rooms (38)	-

Note: hh = household, SLL = Sierra Leone Leones (1000 SLL = £0.081)

The overall socio-economic characteristics of the surveyed households indicated an average floor area of 311 m^2 with a garden space of 32 m^2 for most of the surveyed households. In the surveyed households, 53% was a single storey, 30% were 2-storey, 8% were 3-storey, 5% were 4-storey and 4% were 5-storey. The average number of rooms was three. The variation in the household family income was significant and ranged from 9×10^5 Sierra Leonean Leones (SLL)/month (≈ £85) to Le 17×10^6 SLL/month (≈ £1600), with an average household income equivalent to 5×10^6 SLL/month (≈ £442). The monthly average family income is broadly consistent with the Government of Sierra Leone Civil Service Code: Regulations and Rules governing income and salary scales and the UN Salary scales for staff in the General Service and related categories (Carpenter, 2004). The frequency distributions and detailed statistical analysis for all household characteristics are shown in Appendix B1 and B2 respectively.

The questionnaire-based study revealed that only 33% of households have private connections to a pipe water supply. The pipe water supply is rationed on alternate days during both seasons throughout the study area and supplied for less than twenty-four hours. It is the primary source for households where it exists. Table 5.2 presents the households' percentage access to the different Multiple Household Water Sources (MHWS) in the rainy and dry seasons. The rainy season has far more water sources than in the dry season. Therefore, when the rainy season ends, household percentage access for water sources in the dry season will either increase as the available water source (replacement source) or decrease for that source because it is not available in the dry season. Hence the percentage increase or decrease in household access (+ve and -ve signs) shown in Table 5.2. These sources include small-scale water sellers using pushcart to sell water in 22 litre jerry-can containers referred to in this research as vendor water, and water sold by tanker truck bowsers referred to here as tanker bowser water sold to households (Elliott *et al.*, 2019; Multiple, 2019).

The pattern by which the households access their water sources showed that the middle- and high-income groups have the highest access to pipe water and other water sources like bowser and bottled. Rainwater, gravity/spring and surface water are the prominent improved and unimproved sources for the lower-income households in the area, as well as for all households during the dry season when taps are dry for longer periods (Thomson *et al.*, 2001). Water stored in tanks is provided and paid by Nongovernmental Organisations (NGOs) for communities' use and distributed to ten-thousand-litre containers stationed at certain deprived standpipe points in the study area. An example of this is shown in Figures 5.1 and 5.2. Packaged water is water sold in sachets, purported to be of better quality from water cottage industries mainly for drinking purpose. Some households reported saving rainwater in containers for use in the dry season, as well as households using packaged water for cooking light meals. At every improved and unimproved communal water point, households maintain a system to distribute equitable fetching and water collection time.

Table 5. 2 Household Percentage use of Multiple Water Sources in the Rain and Dry Season for different Water End-uses

Service facility types	Multiple water use type	Rainy season					Dry season increased or decreased change access				
		Drink	Cook	Bath /Hand washing	Clothes wash	Toilet use, House cleaning & others	Drink	Cook	Bathe /Hand washing	Clothes wash	Toilet use, House cleaning & others
Un-improved	Unprotected springs	9%	15%	21%	17%	30%	+13%	+13%	+12%	+18%	+8%
	Unprotected dug wells	20%	5%	13%	13%	28%	+3%	+8%	+10%	+15%	+14%
No service	Surface water (dam, streams, rivers, brook, pumping station)	7%	8%	13%	33%	37%	+14%	+7%	+25%	+23%	+26%
Improved	Pipe water	45%	89%	88%	86%	82%	+26%	-3%	-6%	-8%	-12%
	Protected dug wells	23%	14%	25%	22%	17%	+4%	+13%	+10%	+12%	+18%
	Boreholes	16%	20%	22%	24%	33%	+3%	+13%	+16%	+16%	+16%
	Protected springs	9%	14%	16%	13%	6%	+10%	+13%	+9%	+12%	+18%
	Rainwater	38%	93%	96%	95%	96%	0	-2%	-3%	-3%	-3%
	Packaged water	78%	6%	0	0	0	+15%	+5%	-	-	-
	Bottled water	25%	0	0	0	0	+5%	-	-	-	-
	Vendor water	3%	6%	10%	21%	13%	+7%	+17%	+8%	+4%	+13%
	Tanker bowser	2%	42%	55%	32%	45%	+11%	+6%	-2%	+6%	+6%
	Water stored in tanks	15%	32%	38%	34%	40%	+9%	+2%	+6%	+2%	-5%

Figure 5. 2 Water provided in 10,000 L tank at Kissy Brook

Figure 5. 1 A 10,000 L tank located next to a pubic standpipe point at Wellington

5.2.1 The effect of household socio-economic characteristics on the average total water consumption

The relationship between household socio-economic characteristics and total per capita water consumption is investigated.The correlation coefficient R can be used to evaluate the strength of the relationship between variables (De Lourdes Fernandes Neto *et al.*, 2005; Grafton *et al.*, 2011a). The analyses of the data suggest a strong relationship between household size (i.e., the number of people in the household) and total water consumption (R = 0.64), whilst there is a negative relationship between household total per capita consumption and household size (R = −0.728). The plots showing relationship between household total water and household characteristics are shown in Appendix C1 and C2. The study revealed that family income has a positive correlation (R= 0.70, $p < 0.05$). This relationship implies that there is an increase in per capita water consumption with the monthly income. Total water consumption increases with the number of containers (R = 0.61) used by households but is negatively affected by the distance to water points (R = −0.53) and the time spent to fetch water and return back (R = −0.71). This finding is consistent with those of (Howard and Bartram, 2003) who found that collection time and distance to water points are constraints to water access, because poorer households use less water as they have fewer storage containers and transport assets.

In this study, variables such as education level and employment status provide some indications of the socio-economic status of the households in each income group. Generally, according to (UNESCO World Water Assessment Programme, 2018), the adult literacy rate in Sierra Leone is 32%. The high proportion of households with tertiary certificate holders (42%) is because the surveys targeted university students to respond on behalf of their households, who have the requisite knowledge to understand and give reasonably accurate answers on access to their water supply. The results on occupation revealed that 31% were in trading and business, 29% civil servants, 24% Artisans/craftsmen, and 16% were engineers, technicians, and surgeons. Total water consumption is higher for the high-income group regardless of occupation.

a. Distance to the Sources of Water

Although multiple water sources are available to the households, the surveyed households have preferences for particular sources for specific water end use either because of availability or ease of access. The analysis of the full sample revealed that approximately 33%, 16% and 7% of the households have access to a household pipe connection, protected dug well and a borehole, respectively, within their households in the study area. Table 5.3 presents the percentages of the household’s distance to access the multiple water sources in their neighbourhoods. Only 46% of the households obtained their water from a distance of 0–100 metres (m) to their homes. A total of 90% of the surveyed households fall within the UN stipulated distance of within 1000 m to their homes (Houngbo, 2018; WHO/UNICEF/JMP, 2018) while the remaining 10% of the households cover more than 1000 m in search of their water source. In such a situation, productive time is lost to trekking and queuing for long hours.

Table 5. 3 Percentages of households with multiple water sources at various distances

Distance of water source to homes (m)	HPC	BH	WST	PDW	WB	VSS	PS	R/S	S/G	RW	Total (% distance)
0-100	33	22	39	25	40	45	63	28	20	96	46
101-500	-	18	54	35	-	-	68	16	32	-	26
501-1000	-	10	39	23	-	-	50	14	13	-	18
>1000	-	13	16	15	-	-	23	12	9	-	10

Note: PS - Public standpipe, WST - Water stored in tank, BH - Borehole, PDW - Protected dug well, WB - Bowser, HPC - household piped connection, RW- Rainwater, VSS- Vendor pushcart, R/S - River/Stream, S/G - gravity/spring.

b. Time Spent to Water Sources and Return Home

Figure 5.3 presents the percentages of households' distance and time spent to access their daily water use. For households a longer distance away from a water source, this affects the quantity of water collected for household use. From the figure, only 21%, which is less than a third of the surveyed households, spend 30 min or less to access their water supply. The remaining 79% of households fall beyond the UN's recommended baseline time, which should not exceed 30 min to fetch water and return home (Ki-moon, 2015). The analysis revealed that productive time is lost to trekking and queuing for long hours to collect daily water use.

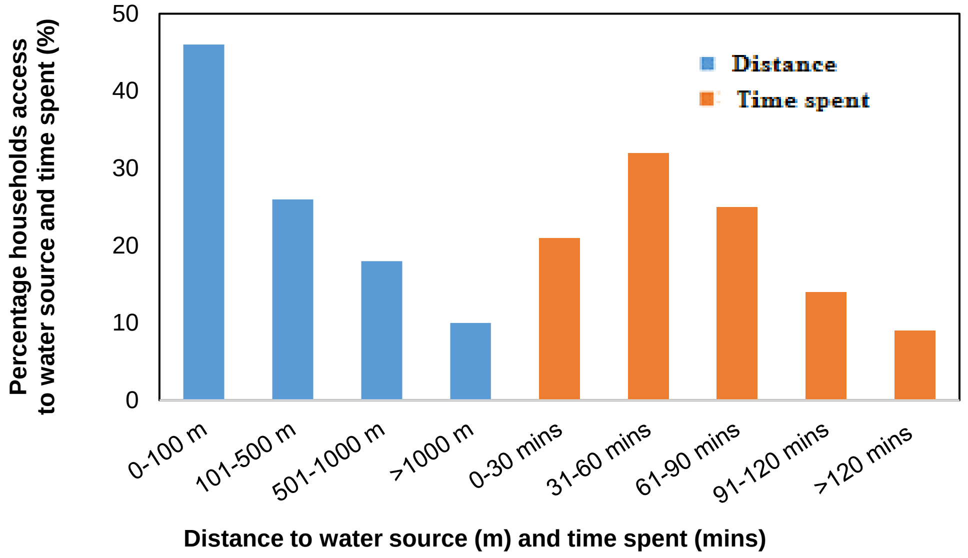


Figure 5. 3 Percentages of Households with respect to distance and time spent to access their daily water supply (Source: authour's analysis)

5.2.2. The effect of household socio-economic characteristics on per capita average water consumption

The frequency distribution of the daily per capita average water consumption for the whole sample is shown in Figure 5.4, signifying that the average is about 93 litres per capita per day (l/p/d). The daily per capita average water consumption for households with a pipe connection is 112 l/p/d. These amounts are higher than the nationwide estimated per capita volume set at 40 l/p/d for households with pipe connection by the WHO and UNICEF (2017). This average daily per capita water consumption is the volume of water obtained via the various multiple sources, as indicated in Table 5.2. Per capita consumption varies from 73 to 112 (l/p/d) for households without water supply pipe connections where showering, toilet flushing and hand wash basin use are absent, and from 91 to 133 l/p/d where showering, toilet flushing and hand wash basin tap use are common. The increase in male members and children in the household decreases per capita consumption. This decrease in per capita consumption for males seems to be because a high percentage of men are engaged in daily employment and use water for personal hygiene, probably washing clothes more than other members of the family daily. The high consumption for children is because they need to be cleaned more often than adults or elders in the household.

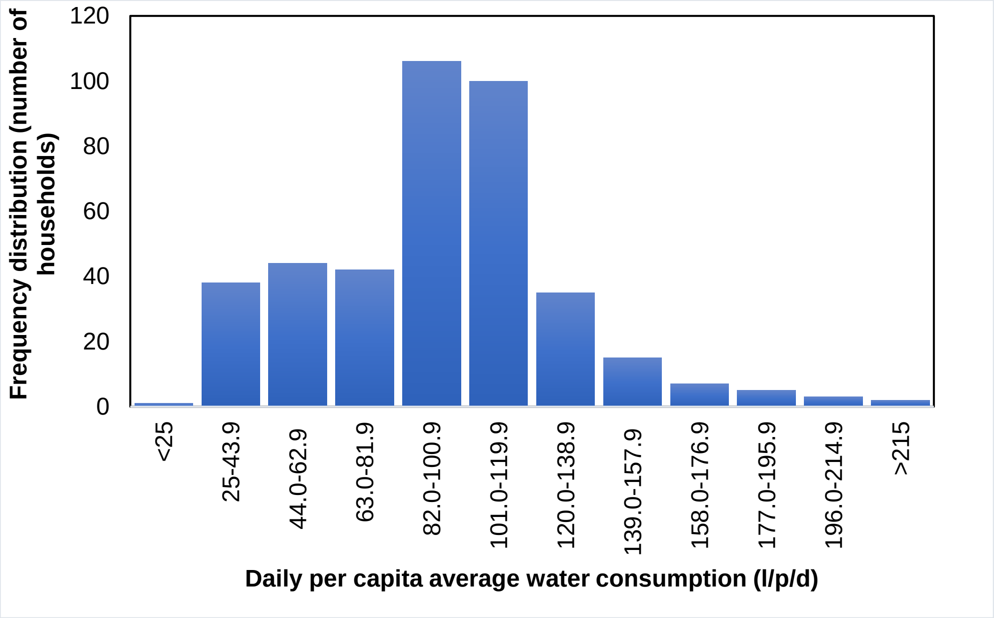


Figure 5. 4 Frequency distribution of average per capita water consumption (Source: authour's analysis)

5.2.3. The effect of per capita income on the average water consumption

The results of each analysed group either with or without pipe connection reveal that the average daily per capita water consumption increases with income levels (i.e. 73, 78, 94 and 112 l/p/d in informal settlements, low-, middle- and high-income groups, respectively, for non-piped households), with an average per capita water for the full sample of 93 l/p/d. Households with some piped connections have indicated the use of showers, wash hand basins and cistern toilets. The average daily per capita water consumption for households with pipe water also increases with income levels (i.e. 91, 97, 113 and 133 l/p/d in informal settlements, low-, middle- and high-income groups, respectively). The distribution of water end use reveals slight variations between income groups for both household with and without pipe connection (Figures 5.5a, b). Figure 5.5a shows that the highest distribution is showering (21%), then followed by toilet flushing (16%) and clothes washing (15%). In Figure 5.5b, the highest distribution fraction is bathing (22%), followed by laundry (18%) and toilet use (15%). These are in contrast to many developing countries where toilet use consistently represents the largest component of indoor water end use (WHO and UNICEF, 2017).

5.3 Average per capita water use for the different water end-uses (micro-components)

Here, a household's total water consumption is divided into a number of micro-components: Showering, bucket bath, toilet flushing, house washing, cooking, dish washing, clothes washing, wash hand basin, garden watering and vehicle washing. The distribution of average daily use of each of these components in all income groups is shown in Figures 5.5a, b. Only some of the households recorded shower, hand wash basin and cistern flush use. Of the 398 surveyed households, none were recorded to have a swimming pool. However, some households recorded owning a garden area (34%) and vehicle (61%). In agreement with (Domene and Saurí, 2006), daily per capita consumption decreases with the number of household occupants.

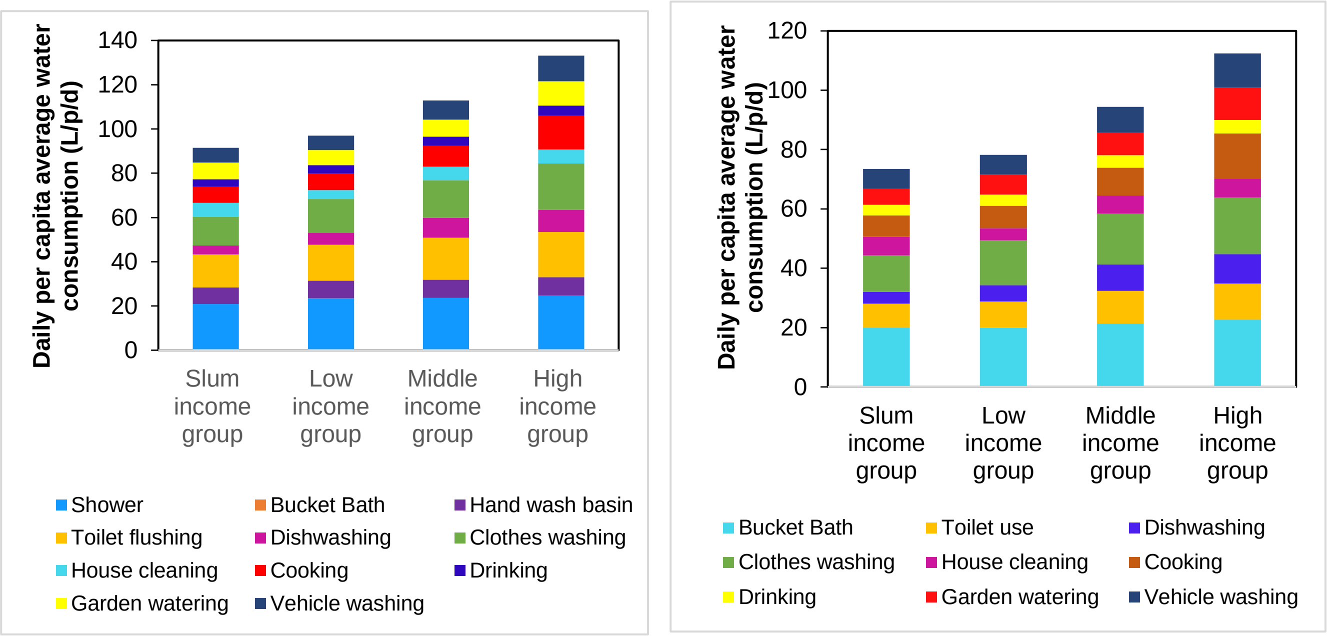


Figure 5.5a **Figure 5.5b**

Figure 5. 5 Impact of per capita monthly income on water end uses in Freetown with piped-connection (a) and without piped-connection (b)

A summary of average values for different micro-components per person (e.g. frequency, duration of use and flow rate) is illustrated in Table 5.4 It shows the comparison between these parameters in informal settlements, low-, middle- and high-income households. Statistical analysis (mean, median, standard deviation, variance, minimum, maximum, skewness, kurtosis and confidence interval) for parameters presented in Table 5.4 are shown in Tables C3.1 – C3.10 (Appendix C3). The water use characteristics for different micro-components of the households in different income groups are briefly discussed in the following sections (5.3.1 to 5.3.12):

5.3.1. Showering

Showering is only common to some households (47%) and has a positive relationship to household income. The daily per capita water use for showering is a function of the number of times taken, the duration and flow rate of shower. The number of times a shower is taken rises across income groups. The average number of showers in the full sample is moderate (0.52 shw/p/d), with an average flow rate of shower (6.93 L/min) (Table 5.4). Most of the households with pipe connections recorded a low tap pressure flow of their water supply, especially in peak hours of the day. The specific shower types in the households were not investigated. The average duration is 3.28 min/shower, and the times a shower is taken increases with per capita income. Showering accounts for the highest (18%) distribution of indoor daily water end-use, but showers are only taken by households when tap water is available, as pipe water is rationed throughout the study area.

5.3.2. Bathing (Bucket)

In all income groups, having a bucket bath is common to all households and accounts for 16% of total water use (Figure 5.5b). The results show a frequency of 0.92 to 0.96 per capita per day (Table 5.4). The average daily per capita use varies from 20 litres (L) in the lower-income groups to 23 litres (L) in the high-income group. The use of bathtubs is not a common practice in Freetown, because of the volume of water it will consume. Generally, in all income groups, as the size of the household increases, the amount of water used for bathing per person decreases. The smallest household size (2 persons) has the highest water consumption per capita and the larger-size (8–12 persons) households have the lowest per capita usage (Butler and Memon, 2006). The quantity of water required to maintain good hygiene may vary significantly depending on the water collection behaviour (Domene and Saurí, 2006; Grafton *et al.*, 2011a).

5.3.3. Toilet Use and Flushing

Based on the survey of the households involved in this study, the toilets were either pit latrines (52%), single flush with cistern (34%) or pour flush (14%) with average capacities of 1.8, 5.7 and 2.8 L respectively (Table 5.4). Toilet flushing refers to the use of these various toilet types. The calculated average toilet flush per capita per day was 2.8 times/day. The frequency of per capita toilet use was higher in the informal settlement slum (3.19 times/day) and low-income households (3.25 times/day) than in the other high-income households. The average number of occupants in the informal settlement group was 6.2 and are largely engaged in petty trading businesses close to their houses. In Aho et al. (2016) it was explained that the higher frequencies and volumes used by the lower-income level groups may be because of the squalid conditions in which these households live in. Therefore, they are at high risk of water-related diseases and would spend most of their time using the toilets. The low frequency in the high-income-level households may be because of small household size or that they spend most of their time during the day at the workplace, where some flushing at home is replaced by flushing at the workplace. From the data presented in Table 5.4, it appears that in the high-income households, water consumed for personal hygiene-related activities is still high because of their awareness to maintain healthy hygiene.

5.3.4. Hand Wash Basin Tap Use

The tap use considered in this study is water used in hand wash basin taps (teeth cleaning, hand washing, ablution, kitchen sink) where applicable. In all income groups, hand wash basin users are low, accounting for only 5% of total water use (Figure 5.5). Similarly to shower use, hand wash basin usage is influenced by the number of times the hand wash basin tap is used, and this is subject to when pipe water is available to the household.

Table 5. 4 Summary of mean values of water end-use parameters (398 households) Source: authour's analyses

End-use	Parameter/variable	Unit	Overall sample	Slum income	Low income	Middle income	High income	Comparison with Past Studies
Shower	Number of showering per capita per day	shw/p/d	0.52	0.34	0.35	0.51	0.92	(0.51shw/p/d) (Hussien et al., 2016)
	Duration of each shower	min/shw	3.28	3.02	3.43	3.32	3.35	(0.13–0.17min/shw) (Marinoski *et al.*, 2014)
	Flow rate	L/min	6.93	4.60	4.12	7.86	9.54	
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.94	0.92	0.92	0.94	0.96	(0–1bt/p/d) (Gleick, 1996)
	Volume of water used in each bath	L/bt	20.80	20.04	20.30	21.38	22.73	(20L) (Ogunbode and Ifabiyi, 2014)
Hand wash basins	Number of times using hand wash basins per capita per day	brt/p/d	3.07	3.20	3.02	3.00	2.72	(10brt/p/d) (Hussien et al., 2016)
	Duration of tap use	sec/brt use	59.55	58.17	57.41	59.29	62.00	(3–4brt use) (Gato-trinidad et al., 2011)
	Flow rate	L/min	2.65	2.41	2.73	2.80	3.02	(2–5L/min) (Purshouse *et al.*, 2015)
Toilet flushing	Number of flushing toilet use per capita per day	tf/p/d	3.05	3.19	3.25	3.16	2.61	(2–7tf/p/d) (Burton *et al.*, 2020)
	Volume of water use per person in each toilet flush	L/tf	5.71	4.37	4.33	5.81	7.02	(4–10L) (Bradley, 2004)
	Number of latrine use per capita per day	lat/p/d	2.96	3.11	3.04	3.04	2.80	(1–3lat/p/d) (Bradley, 2004)
	Volume use per person for each pit use	L/lat/fl	1.82	1.78	1.82	1.84	2.01	(2–3L) (Howard and Bartram, 2003)
	Number of pour flush latrine use per capita per day	pf/p/d	3.02	3.12	3.11	3.06	2.96	
	Volume use per person for each pour flush use	L/pf/d	2.8	2.77	2.83	2.95	2.90	(2–3L) (Mara, 1985)
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	2.00	2.00	2.00	
	Volume of water used in each dishwashing	vol/wsh	6.91	6.02	6.52	8.57	9.99	(15–23L) (Schuetze and Santiago-Fandiño, 2013)

House cleaning	Number of house cleaning per day	wsh/d	0.16	0.18	0.15	0.16	0.18	(3–78L) (Ziegelmayer *et al.*, 2010)
	Total volume used per household per day	L/p/d	8.42	9.84	7.58	7.20	6.37	(1–20L) (Howard and Bartram, 2003)
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.26	0.28	0.29	0.26	0.21	
	Volume of water used per wash per day	L/wsh/d	16.50	17.85	18.64	19.51	21.10	(5–20L) (White et al., 2002)
Vehicle washing	Number of vehicle washed per day	wsh/d	2.23	1.33	1.38	2.68	1.66	
	Volume used per day	L/wsh/d	10.38	9.60	9.51	10.77	10.78	
Cooking	Volume of water consumed in cooking	L/p/d	12.11	9.86	10.08	11.98	16.48	(10–50L) (Gleick, 1996)
Drinking	Volume of water consumed for drinking	L/p/d	4.17	3.56	3.88	4.18	4.51	(2.7–3.7L) (UN-Water, 2015)
Garden	Volume of water consumed for garden	L/p/d	9.24	7.50	7.80	8.07	10.54	(0.4t/d) (Roberts, 2005)
	Total water consumption	L/p/d	93	91	97	113	133	(28–244L) for 5–50% piped households with MWSU access (Thomson *et al.*, 2001)

Note: L/p/d = litre per person per day, L = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, t = time, No./d = number per day, unit for all volumes = litres.

As with showers, the flow rates from the hand wash basin increases with household income. The reason for this could be that households in the higher-income group have better fitted plumbing structures to increase the flow to their homes. The frequency of hand wash basin use also rises with income. The average duration of hand wash basin tap use for all income groups is 59 s per use. When multiplied with the number of times of hand wash basin tap use, the total daily per capita tap use duration becomes 3.10, 2.89, 2.96 and 2.81 min/p/d for informal settlement, low-, middle- and high-income households, respectively. These figures are similar to values found in the literature of Victoria, Australia (Gato-trinidad et al., 2011). The analysis also showed that households with taps, use more water per capita than those without (Ramulongo et al., 2017).

5.3.5. Dishwashing

The use of a dishwasher is not common in Freetown, mainly because of the lack of energy and irregular water supply to operate it. None of the respondents recorded owning a dishwasher in both the rainy and dry seasons' surveys. Dish washing is mainly done manually in a bowl of water and mostly done at the household level. Per capita dishwashing accounts for 5% of the average total water usage. The daily water consumption for dishwashing is a function of the number of dish-washing sessions a day and the volume of water used in each wash. The frequency of dish-washing is 0.51 per person per day for all income levels, i.e. after each meal (breakfast and dinner). There is a considerable mean difference in total per capita water use between households in the lower-income levels (6.02 and 6.52 L/p/d) for informal and low-income groups, respectively, and those in the higher-income groups as they use 8.57 and 9.99 L/p/d for middle- and high-income households, respectively (Table 5.4). Families in the lower-income groups are larger in number and they undertake certain activities (e.g. eating and sleeping) communally. Therefore, they may use less dishes and water than families in higher-income households.

5.3.6. Clothes Washing

Water-saving household appliances such as washing machines are not common in the survey area. The reason could be mainly because of the lack of energy to power the appliance and continuous water availability for its operation. Hence, clothes and dishes are done mostly by hand in a bowl of water as it is more efficient and inexpensive in this region (Howard and Bartram, 2003). Of the 398-sample survey, only two respondents in the middle-income level group recorded owning a washing machine but hardly use it because of a lack of constant energy and piped water supplies. Washing clothes by a washing machine can use from 40 to 200 L per wash depending on the technology (Schuetze and Santiago-Fandiño, 2013). It has been observed that washing clothes by hand in a bowl with water uses much less volume (20 L) and is more sustainable.

The main parameters to identify water consumption for clothes washing are the number of times clothes washing is done per day and the volume of water used per wash. Clothes’ washing is done from 0.21 times/day for the high-income group to 0.28, 0.29 and 0.26 times/day in informal settlement, low- and middle-income groups, respectively. Previous studies have observed that people with more clothes might not have to wash clothes more often as people with fewer clothes (Ziegelmayer *et al.*, 2010).

Other parameters that can influence the number of clothes washing per household per week can be seasonal (temperature) variability and the number of occupants in the household (Arouna and Dabbert, 2010). Clothes washing can become more frequent in hot and dusty weather (Viljoen, 2000). The average per capita water use is 18, 19, 20 and 21 L/p/d in informal settlement, low-, middle- and high-income families, respectively.

5.3.7. House Washing

Analysis of daily average water use for house cleaning is shown in Table 5.4 and Figure 5.5. It can be seen that a slight variation exists in daily volume used among the households. The volume for house washing constitutes about 5% of the total daily water consumption. The average quantity of 8 L/p/d could be because of the many multitenant apartment and compound houses (rooms) present in the area. These multitenant households usually share communal space, e.g. toilets, kitchen spaces, if present, and room sizes are usually small, and so do not require much water for cleaning activities. Cleaning activity is mostly done with water in a container. The frequency of cleaning is from 0.15 to 0.18 times/day (Table 5.4). Most of the high-income households have their floors carpeted or covered in linoleum mats, which uses less water to clean.

5.3.8. Cooking

The per capita water consumption per day in developing countries can be as low as 20L (Gleick, 2010). The UN also noted that a human being needs 50 L of water per day in order to prepare meals and to have enough for personal hygiene. The current study shows that the average volume of water required to prepare food increases with family income, accounting for 9.86, 10.1, 11.9 and 16.5 L/p/d in informal settlement, low-, middle- and high-income households, respectively (Table 5.4).

5.3.9. Drinking

In this survey, drinking accounts for 3% of the total household water consumption. The average per capita drinking consumption is 4 L per day, which is slightly above the 2.7–3.7 L designated by (Danquah *et al.*, 2015). The analysis revealed that 37% of the respondents are concerned with the quality of the water they collect and 48% of all the households explained that they perform some form of treatment such as adding sterilising tablets or leaving it to settle in a special container before use. Therefore, more than 75% of the total households explained that they prefer to consume packaged water, that is, water in plastic sachets or bottled which they believe has been properly prepared for consumption. This is in line with the (Bain *et al.*, 2012) observation who explained that more than 35% of households consume bottled and package water at home in consideration for quality.

5.3.10. Outdoor Water Usage

The outdoor use is composed of garden watering, swimming pool usage and vehicle washing. No information on the outdoor activity swimming was recorded in the whole sample. This could be due to several reasons such as a decrease in temperature condition, and economic and physical water scarcity.

5.3.11. Vehicle Washing

The analyses show that in the case of vehicle washing, the highest frequency of vehicles washed per day is the middle-income group (2.68 wsh/d). However, in terms of volume of water used per wash per day, the highest consumers are the high-income households. The consumption of average daily per capita water use of 10.38/wsh/d is because of seasonality and availability of water sources for use. It can be seen from the data in Table 5.4 and Figures 5.5a & 5.5b that the average per capita water use for vehicle washing accounts for 7% of the total daily water consumption. Water used for vehicle washing is collected from the MHWS (viz. tap, rain, wells, streams, tanks and springs). None of the households recorded using a water hose for washing vehicles. Some households also indicated that their vehicles are sometimes washed at car washing centres.

5.3.12. Garden Watering

In terms of garden watering, and like most of the other end-uses, none of the households recorded using a water hose. Most of the houses recorded only one watering session per day, either in the morning or in the evening. During the rainy season survey, none of the households recorded water consumption for gardens. This may be because they depend on the rain to water their gardens. In order to measure the seasonality impact, the survey was repeated during April (2018) to account for water consumption variations in the dry season. The total volume of water used for garden watering increases slightly with income levels: 7.50, 7.80, 8.07 and 10.54 L/p/d in the informal slum-, low-, middle- and high-income households, respectively.

5.4 Statistical modelling of daily per capita water usage with household socio-economic characteristics

The water consumption data from the full 398 households were divided into calibration and validation sets. Then, 70% of the data were used for calibration (i.e. training), while the remaining 30% were spared for validation (i.e. testing) purposes. The calibration data set was used to develop statistical models to predict per capita consumption as a function of household socio-economic characteristics. The household socio-economic characteristics were divided into three groups, that is:

1. Socio-demographic characteristics: e.g., number of children, adult females, adult males, elders 66–75 years and elders over 76 years.
2. Physical characteristics: e.g., the number of rooms, household size, the total area of floors and house type.
3. Water-use characteristics: e.g., shower volume, toilet flushing volume, time spent to fetch water and distance to water source.

5.4.1. Models based on multiple linear regression (Stepwise)

The Stepwise multiple regression approach has been previously used successfully to predict water demand (Hussien et al., 2016). The technique readily selects the combination of relevant independent variables to develop the best-fit model based on strong statistical foundations and saves on the intense computational effort required by some other methods (e.g. evolutionary polynomial regression). It is a potential approach for selecting the best predictor variable from a large number of variables.

The Stepwise multiple regression approach is applied using IBM SPSS Statistics (v. 25) software to determine the best subset model for daily per capita water use estimation. Using the calibration set of data, the relationship between the independent variables (household socio-economic and water use characteristics) and the dependent variable (per capita water consumption) was investigated, and the values of the correlation coefficient (R) are shown in Table 5.5. From the table, it can be seen that the strongest significant relationships of per capita consumption are with the number of occupants ($R = -0.728$) in the household and time spent to fetch water for use ($R = -0.711$).

The acceptance or deletion of an independent variable for the regression model is based on the strength of the relationship (i.e., the strength of the correlation) and also its contribution to the decrease in the residual sum of squares (Hussien et al., 2016). The regression coefficients and model are then statistically verified at every iteration to select or delete the independent variable.

Table 5. 5 Correlation Coefficients between Household Characteristics and Per Capita Water Consumption (Source: authour's analysis).

		Correlation Coefficient Value (R)												
		Demographic Characteristics					Physical Characteristics				Water Use Characteristics			
		No. of Children	No. of Adult Females	No. of Adult Males	No. of Elders 66–75 ($E_{66–75}$)	No. of Elders >76 ($E_{>76}$)	No. of Occupants	No. of Rooms	No. of Floors	Total Built-Up Area (m^2)	Shower Volume (L)	Toilet Flush Volume (L)	Distance to Source (m)	Time Spent (min)
Per capita water consumption (L/p/d)	All investigated households	−0.527	−0.593	−0.512	−0.534	−0.251	−0.728	−0.163	−0.056	0.021	0.631	0.562	−0.531	−0.711
	Informal slum households	−0.605	−0.721	−0.534	−0.527	−0.283	−0.760	−0.204	−0.501	0.319	0.582	0.673	−0.745	−0.763
	Low-income households	−0.590	−0.654	−0.403	−0.364	−0.273	−0.758	−0.261	−0.426	−0.427	0.675	0.635	0.782	−0.731
	Middle-income households	−0.648	−0.683	−0.493	−0.379	−0.261	−0.783	−0.593	−0.413	−0.526	0.719	0.630	−0.664	−0.726
	High-income households	−0.572	−0.650	−0.484	−0.243	−0.252	−0.819	−0.673	−0.529	0.537	0.720	0.743	−0.745	−0.718

Note: L/p/d = litres per capita per day.

Using the STEPWISE approach with the calibration set of data of the 398 investigated households, four models were developed based on demographic, physical, water use and whole characteristics (i.e. Model 1, 2, 3 and 4 in Table 5.6). The same process is repeated using the calibration set of informal slum-, low-, and middle- and high-income households' data. These models are also shown in Table 5.6 and they are statistically significant at ($p < 0.05$).

In total, 20 models were developed. The predictions from these models were plotted against the actual per capita water consumption values obtained from the study, as shown in Figure 5.6. The figure shows that the trend-lines of validation and calibration sets are almost indistinguishable in all cases. Additionally, the R^2 value improves further when the water consumption data are disaggregated into the various income groups, i.e. informal slum, low, middle and high.

The twenty models developed in Stepwise regression were compared using R^2 values as shown in Table 5.6. As seen from the table, R^2 values are relatively moderate (over 0.8) in most cases within each income group. The modelling approach suggests a stronger effect of demographic and water use characteristics on per capita water consumption when data were disaggregated into household income groups, as compared to the whole sample of households. Household physical characteristics have a minimal effect.

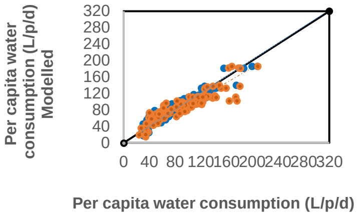
Table 5. 6 Models and coefficient of determination (R2) using multiple linear regression method (STEPWISE)

	Model	R^2	
		Calibration set	Validation set
All investigated households	Model based on demographic characteristics of the household $\mathrm{TW_w} = 169.90 - 10.97 \times \mathrm{Nc_w} - 20.25 \times \mathrm{N_{AFw}} - 12.34 \times \mathrm{N_{AMw}} + 18.58 \times \mathrm{E_{66-75w}} - 23.81 \times \mathrm{E_{>76w}} \ldots\ldots (1)$	0.64	0.68
	Model based on physical characteristics of the household $\mathrm{TW_w} = 169.52 - 1.60 \times \mathrm{N_{ROw}} - 14.28 \times \mathrm{N_{HSw}} + 2.14 \times \mathrm{A_w}\ \ 3.85 \times \mathrm{N_{FLw}} \ldots\ldots (2)$	0.69	0.75
	Model based on water use characteristics of the household $\mathrm{TW_w} = 107.25 + 0.88 \times \mathrm{S_{Hw}} + 1.04 \times \mathrm{F_{Vw}} + 0.02 \times \mathrm{T_{Sw}} + 0.89 \times \mathrm{D_{Sw}} \ldots\ldots (3)$	0.65	0.70
	Model based on all (demographic, physical and water use) characteristics of the household $\mathrm{TW_w} = 158.17 + 10.51 \times \mathrm{Nc_w} + 8.65 \times \mathrm{N_{AMw}} + 7.82 \times \mathrm{N_{AFw}} + 17.82 \times \mathrm{E_{66-75w}} + 13.92 \times \mathrm{E_{>76w_w}} - 2.53 \times \mathrm{N_{ROw}} - 9.36 \times \mathrm{N_{HSw}} - 0.74 \times \mathrm{A_w} - 1.83 \times \mathrm{N_{FLw}} + 0.52 \times \mathrm{S_{Hw}} + 1.65 \times \mathrm{F_{Vw}} - 4.56 \times \mathrm{T_{Sw}} - 8.44 \times \mathrm{D_{Sw}} \ldots\ldots (4)$	0.75	0.77
Informal settlement households	Model based on demographic characteristics of the household $\mathrm{TW_S} = 160.34 - 17.74 \times \mathrm{Ncs} - 19.51 \times \mathrm{N_{AMS}} - 24.32 \times \mathrm{N_{AFS}} - 22.18 \times \mathrm{E_{66-75S}} - 24.47$	0.84	0.82
	Model based on physical characteristics of the household $\mathrm{TW_S} = 173.06 - 17.76 \times \mathrm{N_{ROs}} - 19.81 \times \mathrm{N_{HSs}} - 0.74 \times \mathrm{A_s} - 15.50 \times \mathrm{N_{FLs}} \ldots\ldots (6)$	0.80	0.89
	Model based on water use characteristics of the household $\mathrm{TW_S} = 172.26 + 0.52 \times \mathrm{S_{HS}} + 4.47 \times \mathrm{F_{VS}} - 0.94 \times \mathrm{T_{SS}} + 0.62 \times \mathrm{D_{SS}} \ldots\ldots (7)$	0.86	0.83

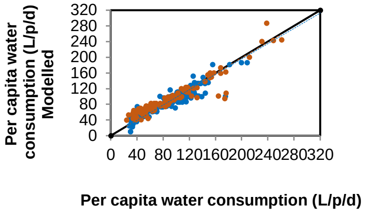
	Model based on all (demographic, physical and water use) characteristics of the household $\mathrm{TW_S} = 136.89 + 10.12 \times \mathrm{N_{Cs}} + 8.76 \times \mathrm{N_{AMs}} + 17.11 \times \mathrm{N_{AFs}} - 13.71 \times \mathrm{E_{66-75s}} + 20.148 \times \mathrm{E_{>76s_s}} + 17.87 \times \mathrm{N_{ROs}} + 13.09 \times \mathrm{N_{HSs}} - 0.32 \times \mathrm{A_s} + 3.24 \times \mathrm{N_{FLs}} - 0.87 \times \mathrm{S_{Hs}} + 6.80 \times \mathrm{F_{Vs}} + 0.52\ \mathrm{x}\ \mathrm{T_{Ss}} - 0.16 \times \mathrm{D_{Ss}} \quad \ldots\ldots\ldots\ldots\ldots (8)$	0.93	0.92
Low-income households	Model based on demographic characteristics of the household $\mathrm{TW_l} = 174.63 - 12.61 \times \mathrm{N_{Cl}} - 15.46 \times \mathrm{N_{AMl}} - 23.14 \times \mathrm{N_{AFl}} - 13.29 \times \mathrm{E_{66-75l}} - 24.91 \times \mathrm{E_{>76l}} \quad \ldots\ldots\ldots\ldots\ldots (9)$	0.74	0.78
	Model based on physical characteristics of the household $\mathrm{TW_l} = 154.96 - 0.58 \times \mathrm{N_{ROl}} - 14.49 \times \mathrm{N_{HSl}} + 0.52 \times \mathrm{A_l} - 3.17 \times \mathrm{N_{FLl}} \quad \ldots\ldots\ldots\ldots\ldots (10)$	0.82	0.88
	Model based on water use characteristics of the household $\mathrm{TW_l} = 110.90 + 1.70 \times \mathrm{S_{Hl}} + 3.69 \times \mathrm{FV_l} - 0.73 \times \mathrm{T_{SS}} - 1.96 \times \mathrm{D_{SS}} \ldots\ldots (3) \quad \ldots\ldots\ldots\ldots\ldots (11)$	0.78	0.83
	Model based on all (demographic, physical and water use) characteristics of the household $\mathrm{TW_l} = 143.17 + 28.07 \times \mathrm{N_{Cl}} + 19.57 \times \mathrm{N_{AMl}} + 6.28 \times N_{AFl} - 10.75 \times \mathrm{E_{66-75l}} + 21.72 \times \mathrm{E_{>76l_l}} + 11.78 \times \mathrm{N_{ROl_l}} + 23.03 \times \mathrm{N_{HSl}} - 0.63 \times \mathrm{A_l} + 13.50 \times \mathrm{N_{FLl}} + 1.34 \times \mathrm{S_{Hl}} + 2.00 \times \mathrm{F_{Vl}} + 0.26 \times \mathrm{T_{Sl}} - 2.75 \times \mathrm{D_{Sl}} \quad \ldots\ldots\ldots\ldots\ldots (12)$	0.86	0.92
Middle-income households	Model based on demographic characteristics of the household $\mathrm{TW_m} = 176.00 - 9.69 \times \mathrm{N_{Cm}} - 17.36 \times \mathrm{N_{AMm}} - 19.78 \times \mathrm{N_{AFm}} - 17.83 \times \mathrm{E_{66-75m}} - 20.72 \times \mathrm{E_{>76m}} \quad \ldots\ldots\ldots\ldots\ldots (13)$	0.74	0.76
	Model based on physical characteristics of the household $\mathrm{TW_m} = 186.65 + 0.67 \times \mathrm{N_{ROm}} - 15.00 \times \mathrm{N_{HSm}} - 0.54 \times \mathrm{A_m} - 3.57 \times \mathrm{N_{FLm}} \quad \ldots\ldots\ldots\ldots\ldots (14)$	0.81	0.84
	Model based on water use characteristics of the household $\mathrm{TW_m} = 98.87 + 0.52 \times \mathrm{S_{Hm}} + 1.66 \times \mathrm{F_{Vm}} - \times 1.77\ \mathrm{T_{Sm}} + 0.72 \times \mathrm{D_{Sm}} \ldots\ldots (3) \quad \ldots\ldots\ldots\ldots\ldots (15)$	0.80	0.82

	Model based on all (demographic, physical and water use) characteristics of the household $\mathrm{TW_m} = 141.57 - 3.43 \times \mathrm{N_{Cm}} - 4.59 \times \mathrm{N_{AMm}} - 10.05 \times \mathrm{N_{AFm}} - 5.32 \times \mathrm{E_{66-75m}} - 16.73\ \mathrm{E_{>76m_m}} + 2.80 \times \mathrm{N_{ROm}} - 3.71 \times \mathrm{N_{HSm}} - 0.69 \times \mathrm{A_m} - 3.36 \times \mathrm{N_{FLm}} + 1.56 \times \mathrm{S_{Hm}} + 1.92 \times \mathrm{F_{Vm}} - 0.21 \times \mathrm{T_{Sm}} - 2.61 \times \mathrm{D_{Sm}} \ldots\ldots\ldots\ldots (16)$	0.73	0.85
High-income households	Model based on demographic characteristics of the household $\mathrm{TW_h} = 163.4 - 8.09 \times \mathrm{N_{Ch}} - 16.42 \times \mathrm{N_{AMh}} - 19.60 \times \mathrm{N_{AFh}} - 19.61 \times \mathrm{E_{66-75h}} - 4.83 \times \mathrm{E_{>76h}} \ldots\ldots\ldots\ldots (17)$	0.84	0.81
	Model based on physical characteristics of the household $\mathrm{TW_h} = 251.50 - 3.67 \times \mathrm{N_{ROh}} - 26.68 \times \mathrm{N_{HSh}} + 0.78 \times \mathrm{A_h} - 5.64 \times \mathrm{N_{FLh}} \ldots\ldots\ldots\ldots (18)$	0.83	0.87
	Model based on water use characteristics of the household $\mathrm{TW_h} = 113.72 + 0.95 \times \mathrm{S_{Hh}} + 1.99 \times \mathrm{F_{Vh}} - 0.87 \times \mathrm{T_{Sh}} - 6.38 \times \mathrm{D_{Sh}} \ldots\ldots\ldots\ldots (19)$	0.82	0.77
	Model based on all (demographic, physical and water use) characteristics of the household $\mathrm{TW_h} = 270.81 - 28.97 \times \mathrm{N_{Ch}} - 24.71 \times \mathrm{N_{AMh}} - 33.14 \times \mathrm{N_{AFh}} - 56.93\ \mathrm{E_{66-75h}} - 13.63 \times \mathrm{E_{>76h}} - 3.9. \times \mathrm{N_{ROh}} + 26.31 \times \mathrm{N_{HSh}} - 0.14 \times \mathrm{A_h} - 15.46 \times \mathrm{N_{FLh}} - 0.31 \times \mathrm{S_{Hh}} + 2.75 \times \mathrm{F_{Vh}} + 0.41 \times \mathrm{T_{Sh}} + 4.71 \times \mathrm{D_{Sh}} \ldots\ldots\ldots\ldots (20)$	0.90	0.95

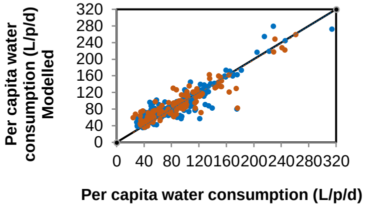
Notes: * TW = daily per capita water consumption (L/p/d), A = total household floor area (m^2), w = whole sample, N_C = number of children in the household, N_{FL} = number of floors in the household, s = slum-income , household, N_{AF} = number of adult females in the household, S_H = shower volume (L), l = low-income households, N_{AM} = number of adult males in the household, F_V = flushing volume (L), m = middle-income, $E_{66–75}$ = number of elders 66–75 years in the household, T_S = time spent to fetch water (L), h = high-income households, $E_{>76}$ = number of elders >76 years in the household, D_S = distance to water point (m), N_{RO} = number of rooms in the household, N_{HS} = number of occupants in the household, m = middle income household



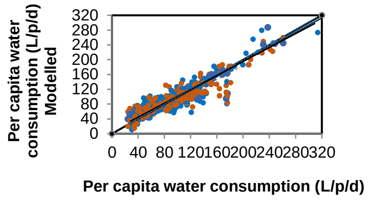
a. All investigated households based on demographic characteristics



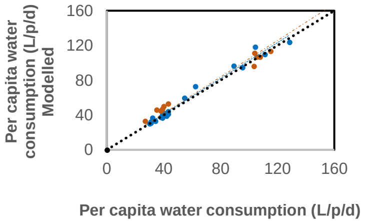
b. All investigated households based on physical characteristics



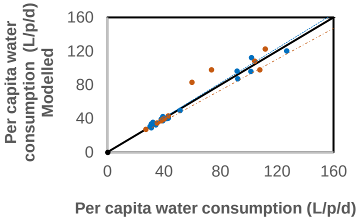
c. All investigated households based on water use characteristics



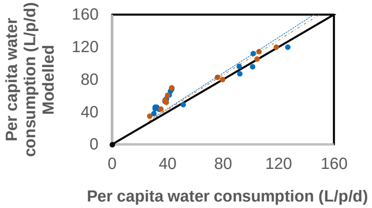
d. All investigated households based on demographic, physical and water use characteristics



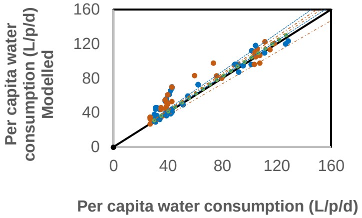
e. Informal slum households based on demographic characteristics



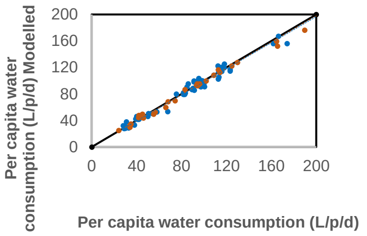
f. Informal slum households based on physical characteristics



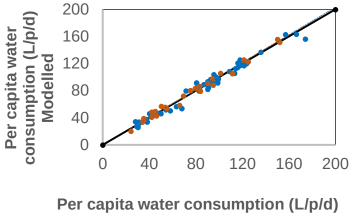
g. Informal slum households based on water use characteristics



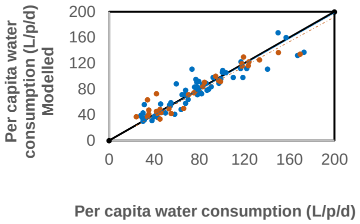
h. Informal slum households based on demographic, physical and water use characteristics



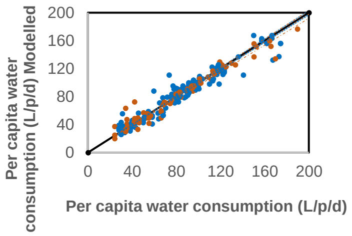
i. Low-income households based on demographic characteristics



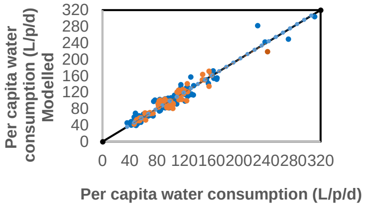
j. Low-income households based on physical characteristics



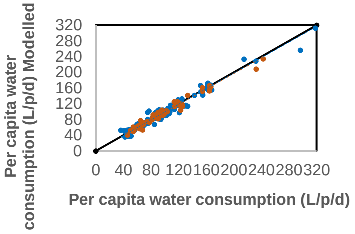
k. Low-income households based on water use characteristics



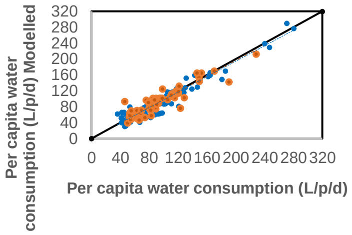
l. Low-income households based on demographics, physical and water use characteristics



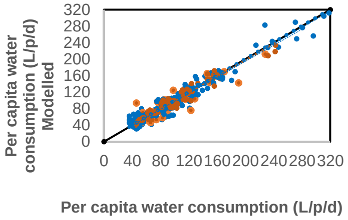
m. Middle-income households based on demographic characteristics



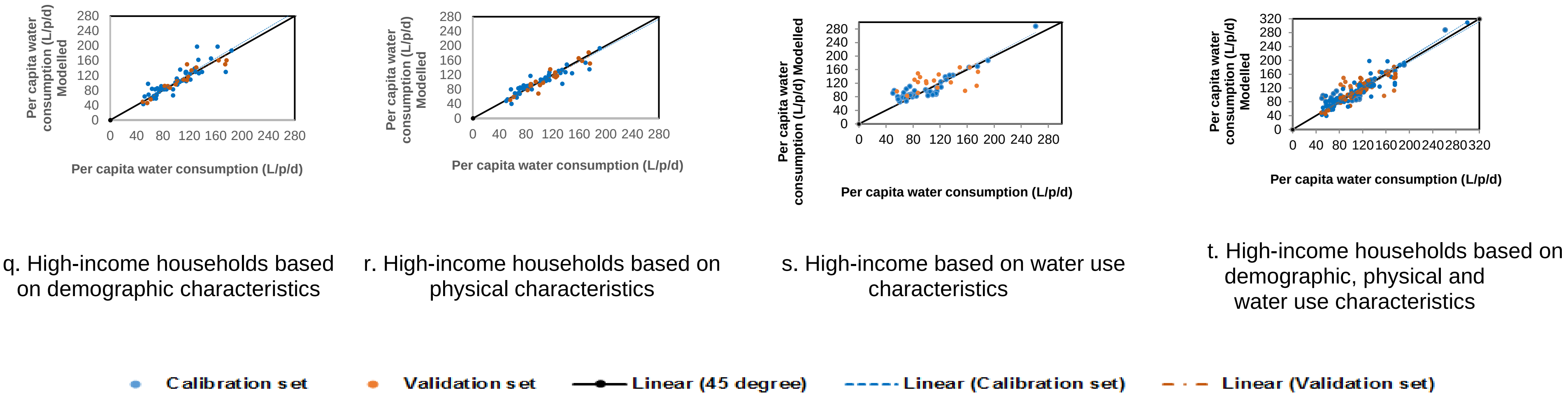
n. Middle-income households based on physical characteristics



o. Middle-income households based on water use characteristics



p. Middle-income households based on demographic, physical and water use characteristics



q. High-income households based on demographic characteristics

r. High-income households based on physical characteristics

s. High-income based on water use characteristics

t. High-income households based on demographic, physical and water use characteristics

Figure 5. 6 Relationship between Actual and Predicted Household Water Consumption using Linear Regression Stepwise Method

5.5 Seasonal variability of water consumption (dry season survey)

In order to capture the seasonal variability of water consumption, the full survey conducted in the rain season of August 2017 was repeated in dry season in April 2018 (Appendix A); after a review of the questions to suit the dry season available water sources (rainwater, streams). Daily average per capita water consumption was found to be about 7% higher than the daily average per capita consumption for the full sample in the rain season, whilst daily average per capita water consumption was almost 14% lower than the full survey in the dry season.

5.5.1 Average per capita water consumption in dry and rainy season

The frequency distribution and cumulative frequency of per capita average water consumption for all surveyed households during the rainy and dry season are shown in Figure 5.7. From this figure, it can be seen that the number of households which consume more than 93 L/p/d is decreased from 71% in the rainy to 6% of households in the dry season. Further analysis of the dry season survey shows that the daily per capita average water consumption is mainly between 26 and 75 L/p/d compared to that in the rainy season, which is between 75 and 120 L/p/d. (Table C4.1 and C4.2 in Appendix C4). Additional analysis revealed that the majority of the consumption is lower in the dry season because of the water scarcity and limited access to alternative water sources. The analysis revealed that productive time is lost to trekking and queuing for long hours to collect daily water for use. These values of both seasonal surveys are not in agreement with those of the (WHO/UNICEF JMP, 2018) report, which showed that per capita consumption ranges between 40 and 78 L/p/d during both seasons in the year.

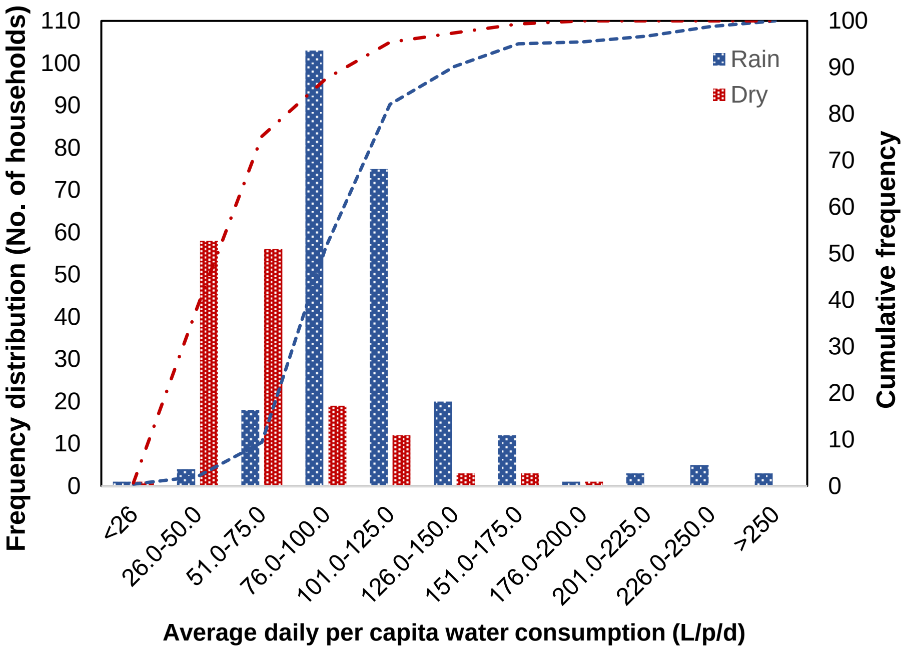


Figure 5. 7 Seasonal Variability of Per Capita Average Water Consumption

5.5.2 Average per Capita Water End-use in Dry Season

Figure 5.8 shows the average per capita water end-uses during the dry season in informal settlement slum, low, middle and high income households. For showering, hand wash basin and toilet uses, only 2%, 3%, 17% and 15% of households in the informal settlement slum, low, middle and high income households undertake these activities respectively. The households either have a shower or take a bucket bath. Apart from the various toilet use types and hand wash basin, all water end uses increase with the increase in per capita income. Only households with indoor piped water connections recorded volumes for shower, hand wash basin taps and cistern toilet flushing. Garden watering accounts for 7% of daily water use. Garden watering was not recorded in the rainy season survey, households stated that they rely on the rain to water their gardens. Likewise to the rainy season survey, the analysis of daily per capita water consumption in the dry season revealed that the highest water end-use is showering (Figure 5.8).

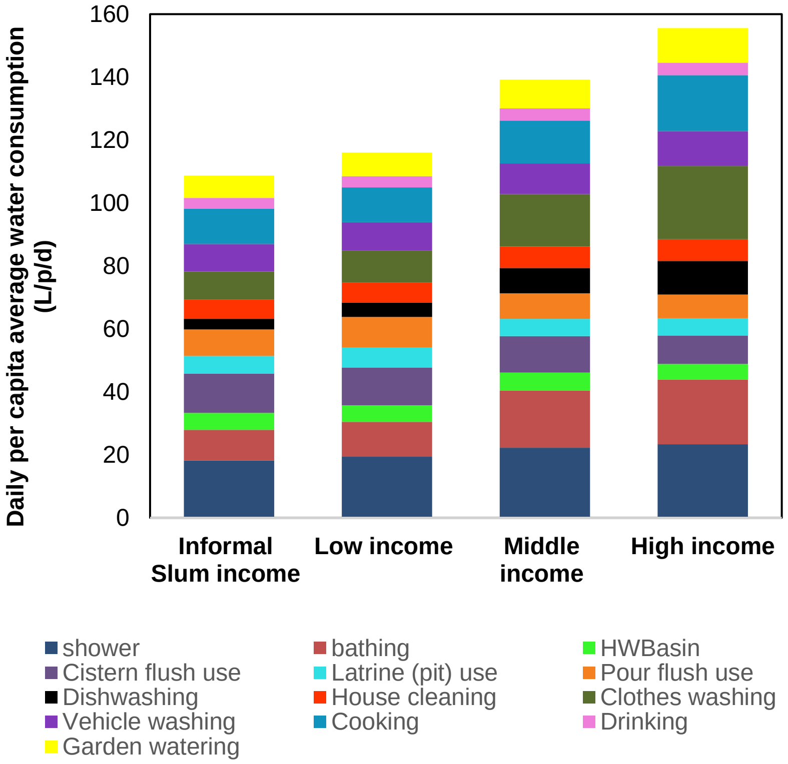


Figure 5. 8 Average Per Capita Water End-Uses in Dry Season

5.5.3 Seasonal Variability of Water End-use

To study the seasonal variability of water end-uses, a two-tailed t-test is used at a 95% confidence interval, as shown in Table 5.7. It can be observed from this table that the *p* value of bathing, cistern flushing, latrine use, hand wash basin taps, pour flush use and house cleaning is higher than 0.05. This explains that there is no statistically significant difference between the consumption in the rainy and dry season. These finding are in agreement with (Gleick, 1996; Tshikolomo *et al.*, 2012; Rathnayaka *et al.*, 2015), which showed that toilet use and bathing are less sensitive for seasonality. Conversely, the other water end-uses (i.e. shower, dishwashing, clothes washing, drinking, cooking, vehicle washing and garden watering) have a statistically significant difference ($p < 0.05$) between the two seasons (Table 5.7).

Table 5. 7 Statistical Comparison of Water End-uses between Rainy and Dry Season

Water End-Use	Average Water Consumption (L/p/d)		Mean Different (Rain-Dry Season)	Percentage Difference	t Value	Significant (2-Tailed) (*p*)
	Rainy	Dry				
Showering	30.00	21.83	8.17	53.2	2.243	0.026
Bathing	20.70	16.50	4.2	27.3	−1.062	0.290
Hand wash basin	8.04	5.19	2.85	18.5	−1.043	0.299
Cistern flushing	14.37	11.37	3.0	19.5	1.009	0.315
Latrine use	5.68	5.40	0.28	1.8	−1.705	0.090
Pour flush use	8.96	8.41	0.55	3.6	1.232	0.220
Dishwashing	8.40	7.64	0.76	4.9	8.514	0.000
Clothes washing	19.25	15.43	3.82	24.9	2.827	0.005
Drinking	4.38	3.78	0.6	3.9	−2.244	0.026
Cooking	10.83	14.15	−3.32	−21.6	4.121	0.000
House cleaning	8.96	6.60	2.36	15.4	−0.150	0.881
Vehicle washing	11.53	10.25	1.28	8.3	1.276	0.020
Garden watering	0.00	9.18	−9.18	−59.7	−2.695	0.013

Note: $p < 0.05$ = significant difference between rainy and dry. $p > 0.05$ = no significant difference between rainy and dry.

An efficient technique of studying and estimating per capita water consumption is to separate the various water end-uses into component parts (Marinoski *et al.*, 2014). During the dry season, indoor water use (105.4 L/p/d) decreases compared to rainy season consumption (115.8 L/p/d) for households with piped connections (Table 5.7), whereas outdoor use (vehicle washing and garden watering) shows a slight seasonal increase from 11.53 L/p/d in the rainy season to 19.43 L/p/d in the dry season. Similarly, in the dry season, for households without a piped connection and with either a latrine or pour flush toilet, indoor water use (72.4 and 75.6 L/p/d) decreases compared to rainy season consumption (89.7 and 93.0 L/p/d) for latrine and pour flush toilet types, respectively. The outdoor use (vehicle washing and garden watering) maintains the same seasonal increase. The seasonal variability of water end-uses in the surveyed households is shown in Figure C5.1 to Figure C5.13 (Appendix C5).

The summary of average values of water end-use parameters (number of use, duration of use, flow rate where applicable and volume) is illustrated in Table 5.8. The table shows the comparison of these parameters between rain and dry season. Statistical analysis (mean, median, standard deviation, variance, minimum, maximum, skewness, kurtosis and confidence interval) for parameters presented in Table 5.8 are shown in Tables C3.1 – C3.10 (Appendix C3). The key findings are explained in the following sections:

Showering

The reliability of pipe water supplies, in general, deteriorates in the dry season. Showering is only common to some households with piped water connection (44%) and increases with family income. Showers were the greatest end-uses among households, accounting for 16% and 20% on average for the dry and rain season respectively. Shower use ranged between 13% and 22% in the lower and upper-income levels respectively.

The comparison of rainy and dry questionnaire-based studies showed that 100% of the households in the dry season consume between 18 to 25 L/p/d for showering, whereas in the rainy season, only 28% of households consume 25 L/p/d or less, with the remaining 72% consuming above 25 L/p/d (Figure C5.1 in Appendix C5). There is a reduction in the number of households during the rainy (15%) and dry (13%) season. The decrease in shower water use and number of households taking a shower is attributed to water scarcity. However, the average duration of each shower decreases from 3.61 min/shower in the rainy to 2.36 min/shower in the dry season, with an increase in shower flow rate of 7.02 L/min in the rainy to 9.25 L/min in the dry season (Table 5.8). This finding is consistent with Inocencio et al. (1999) explanation, which stated that household activity water usage can vary greatly depending on associated technology and water availability.

Table 5. 8 Statistical Variability of mean values of Water End-uses Parameters

End-Use	Parameter/Variable	Unit	Overall Survey		Slum Income		Low Income		Middle Income		High Income	
			Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry
Shower	Number of showers taken per capita per day	shw/p/d	0.39	0.70	0.36	0.36	0.33	0.44	0.40	0.76	0.51	0.94
	Duration of each shower	min/shw	3.61	2.36	3.40	2.50	3.30	2.55	3.80	2.36	4.38	2.37
	Flow rate	L/min	7.02	9.25	5.95	7.20	5.30	7.61	7.36	9.42	9.49	9.87
Bathing (Bucket)	Number of baths taken per capita per day	bt/p/d	0.95	0.97	0.94	0.95	0.91	0.96	0.95	0.98	0.94	0.99
	Volume of water used in each bath	L/bt	20.70	16.50	19.80	9.50	18.20	11.03	20.80	18.25	25.00	20.46
Hand wash basins	Number of times hand wash basins are used per capita per day	brt/p/d	3.06	2.06	3.36	2.30	3.02	2.20	3.29	2.22	3.57	1.90
	Duration of tap use	sec/brt use	60.62	57.09	58.00	56.00	57.00	57.00	58.93	58.07	62.00	57.00
	Flow rate	L/min	2.63	2.65	2.51	2.51	2.47	2.53	2.64	2.64	2.68	2.69
Toilet flushing	Number of toilet flushes used per capita per day	tf/p/d	3.11	2.52	3.13	3.00	3.07	2.84	3.04	2.51	3.23	1.80
	Volume of water used per person in each toilet flush	L/tf	4.80	4.51	4.30	4.15	4.25	4.25	4.80	4.60	5.20	5.00
	Number of latrines used per capita per day	lat/p/d	2.6	3.00	3.4	3.15	3.3	3.22	3.1	3.01	2.9	2.72
	Volume used per person for each pit use	L/lat/fl	1.8	1.80	1.7	1.80	1.8	1.95	1.9	1.81	2.1	2.01
	Number of pour flush latrines used per capita per day	pf/p/d	3.20	3.00	3.35	3.12	3.29	3.27	3.17	2.80	2.98	2.52
	Volume used per person for each pour flush use	L/pf/d	2.8	2.85	2.5	2.72	2.5	2.98	3.0	2.92	3.0	3.00
Dishwashing (bowl)	Number of dish-washing per day	dws/d	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Volume of water used in each dishwashing	vol/wsh	8.40	7.64	7.83	3.38	6.52	4.60	8.70	8.01	8.70	10.71
House cleaning	Number of house cleaning per day	wsh/d	0.16	0.14	0.21	0.14	0.14	0.14	0.14	0.21	0.14	0.21

	Total volume used per household per day	L/p/d	8.96	6.60	16.80	6.09	7.84	6.40	7.84	6.85	3.92	6.89
Clothes washing (hand)	Number of clothes-washing sessions	wsh/d	0.25	0.28	0.29	0.28	0.29	0.28	0.29	0.21	0.14	0.21
	Volume of water used per wash per day	L/wsh/d	19.25	15.43	19.72	8.94	20.01	10.00	19.72	16.61	12.65	23.24
Vehicle washing	Number of vehicles washed per day	wsh/d	2.00	2.00	1.43	1.41	1.43	1.43	1.71	1.71	4.00	2.00
	Volume used per day	L/wsh/d	11.53	10.25	9.8	8.70	9.6	9.04	10.9	9.78	12.0	11.12
Cooking	Volume of water consumed in cooking	L/p/d	10.83	14.15	9.79	11.16	9.57	11.14	10.87	13.60	15.22	17.80
Drinking	Volume of water consumed for drinking	L/p/d	4.38	3.78	4.9	3.48	4.3	3.56	4.3	3.85	4.6	3.94
Garden	Volume of water consumed for garden	L/p/d	0.0	9.18	0.0	7.14	0.0	7.50	0.0	9.15	0.0	11.00
Total water consumption		L/p/d	120	89	109	64	106	70	125	92	132	111

Note: L/p/d = litre per person per day, L = litre, p = person, d = day, wsh = washes, min = minute, vol = volume, bt = bath, shw = shower, sec = second, brt = bathroom tap, tf = toilet flushing, lat = latrine, pf = pour flush, fl = flush, dws = dishwash, No./d = number per day

Bathing

The second largest water consumption was observed for bathing (bucket), i.e. 14%–16%, on average, for the rainy and 14%–19%, on average, for the dry months. The comparison of rainy and dry surveys showed that the number of households consuming higher than 23 L/p/d for bathing decreased from 52% in the rainy to 6% of households in the dry season (Figure C5.2 in Appendix C5). This can be due to the seasonality of water during the rainy months compared to the dry months. This is in accordance with the finding that developing countries generally use a much lower volume of water for bathing (5 to 15 L/p/d) (Gleick, 1996).

Hand Wash Basin Tap Use

In agreement with the rainy survey results for most of the other water end-uses, the analysis of dry season water consumption shows a decrease in the volume for hand wash basin taps in the surveyed households (Table 5.8). In terms of duration and flow rate of the use of hand wash basin taps, there is a slight decrease between the rainy and dry season (Table 5.8) across income groups. Then again, the number of uses decreases from 3.06 during the rainy months to 2.06 bathroom tap uses per day during the dry months, suggesting the impact of seasonality. Further analysis shows that the number of surveyed households which consumes more than 7.0 L/p/d is decreased from 92 in rainy to 5 households in dry season (Figure C5.3 in Appendix C5).

Dishwashing

Per capita dishwashing accounts for 5% of the average total water usage (Figure C5.7 in Appendix C 5). Table 5.8 shows no significant change in daily per capita water consumption for dishwashing between rainy and dry season. The number of times dishes are washed remains the same across all income groups; as dishwashing is done in a bowl of water and decreases slightly in the dry season (Table 5.8). The daily water consumption for dishwashing is a function of the number of dish-washing a day and the volume of water used in each wash. The frequency of dish-washing is 0.51 per person per day for all income levels, i.e., after each meal (breakfast and dinner). There is a considerable mean difference in total per capita water use between households in the lower-income levels (6.02 and 6.52 L/p/d) for informal and low-income groups, respectively, and those in the higher income groups as they use 8.57 and 9.99 L/p/d for middle- and high-income households, respectively (Table 5.4). Families in the lower-income groups are larger in number and they undertake certain activities (e.g. eating and sleeping) communally. Therefore, they may use less dishes and water than families in higher-income households.

Toilet Flushing

The average amount of water used in each toilet use type decreased slightly between both seasons. In line with the observation from the analysis previously, the analysis of water consumption in dry season shows that the number of times toilet use (all types) per person per day decreases slightly to 2.52 tf/p/d and 3.00 pf/p/d for cistern and pour flush users, but increases from 2.6 lat/p/d to 3.00 lat/p/d for latrine users between the rain and dry season (Table 5.8). The low frequency in the high-income-level households may be because of low household size or that they spend most of their time during the day at the workplace, where some flushing at home is replaced by flushing at the workplace. From the data presented in Table 5.4, it appears that in the high-income households, water consumed for personal hygiene-related activities is still high because of their awareness to maintain healthy hygiene. Accordingly, the daily per capita water use for toilet is not significantly different between rain and dry period for latrine and pour flush users (Table 5.7), though slightly different for cistern flush users. More households are using pit latrines in the dry season because of water scarcity (Figures C5.4 – C5.6 in Appendix C5).

Clothes Washing

The questionnaire-based study analysis shows that the volume of water use per clothes washing (19.25 l/wsh/d) is broadly similar in both seasons; but with slightly lower volumes in the dry season as shown in Table 5.8. However, the number of times of clothes washing is done per day increased from 0.25 during the rainy season to 0.28 washes per day during dry months. This also corresponds with the statistical analysis presented in Table 5.7. Further analysis shows that the number of surveyed households which consumes more than 37 L/p/d is increased from 0 in the rainy season to 5 households in dry season (Figure C5. 9 in Appendix C5). The explanation for this could be because clothes washing can become more frequent in hot and dusty weather in the dry season (Viljoen, 2016). Other parameters that can influence the number of clothes washing per household per week can be seasonal (temperature) variability and the number of occupants in the household (Arouna and Dabbert, 2010). Approximately, 46% of households tend to use more than 20 L/p/d for clothes washing in rainy season, while 3% increases their consumption to more than 40 L/p/d in dry months.

House Washing

In terms of water consumption for house washing, there was a decrease in the time house washing is carried out between the rainy and dry season (Table 5.8). However, the volume of each house washing session decreases from 8.96 L/p/d in rainy to 6.60 L/p/d during the dry season (Table 5.8). This may be due to physical and economic scarcity as a result of the change of rainfall patterns during the dry season (UNDP, 2018). Water availability during the seasons has an impact on the per capita water end uses (Figure C5. 8 in Appendix C5).

Cooking

The analysis of the survey revealed that the daily per capita average water consumption for cooking purposes increases from 10.83 in rainy months to 14.15 L/p/d during dry months (Table 5.8). This explains the significant statistical difference (Table 5.7). Further analysis shows that the surveyed households which use more than 16 L/p/d for cooking is increased from 11% in rainy to 29% of households in dry season (Figure C5. 12 in Appendix C5). The explanation for this could be that many ingredients need to be properly washed before preparing meals during the dry and dusty months.

Drinking

The amount of water an average person would need to drink for a day is about 3 L/p/d, and it depends on the surrounding environment and weather conditions (Gleick, 1996;United Nations Children's Fund, 2018). The estimate of the average per capita daily water consumption for the survey is given in Table 5.8. However, as the study area falls within the tropical climate, the analysis shows that the number of surveyed households which consume more than 3.5 L/p/d increases from 73% in the rainy season to 100% households in dry season (Figure C5. 11 in Appendix C5).

Vehicle Washing

Similarly to bathing, dishwashing, toilet use, clothes washing and drinking, the volume of water consumed in vehicle washing decreased slightly during the rainy and dry season (Table 5.8). However, the average per capita water consumption for vehicle washing is significantly greater during the rainy season equated to the dry season (Table 5.7). For example, the number of households which use more than 12 L/p/d for vehicle washing tends to decrease from 17% in rain to 12% of households in dry season (Figure C5.10 in Appendix C5). This is due to the impact of water scarcity due to rainfall patterns in the dry season (Table 5.8).

Garden Watering

In both surveys, only 20% of households recorded water allocation for garden watering in the dry season. Many households stated that they rely on rainfall to water their garden. The number of surveyed households which consumes more than 9 L/p/d is only 61% (Figure C5.13 in Appendix C5). Garden watering consumption increases with increase in per capita income; 7.14, 7.50, 9.15 and 11.0 L/p/d in informal settlement slum, low, middle and high income households, respectively (Table 5.8). This is because of the garden size and water affordability during periods of water shortage.

5.6 Summary

This chapter analysed the determinants of per capita water consumption at the end-use level in a low- and middle-income urban city, Freetown. The impact of household characteristics (demographic, socio-economic and physical) on per capita water consumption was investigated. The significant finding is that insufficient water supply is predominant in the city and very little or no research has been conducted to understand the factors affecting water scarcity and what coping mechanisms have been employed by residents. In the model generated by further stepwise regression analysis, 20 statistical models, based on stepwise regression analysis were developed to estimate daily per capita water consumption on the basis of household socio-economic characteristics. The developed models have been trained and validated.

The best fit models were plotted against the actual per capita water consumption from the questionnaire-based data.

The main messages from the analysis in this chapter are:

- The per capita water consumption in litres per day was positively correlated with family income and the number of containers used by households for water storage.
- Per capita water consumption is significantly negatively affected by distance to water points and the time spent to fetch water and return home.
- Seasonal variation has a considerable impact on per capita water consumption depending on the available multiple water sources to households.
- Piped water supply was extremely insufficient to meet the daily per capita water needs of the households.
- The available duration period of pipe water supply from the service provider, and distance to the water source covered by many households make them to lose valuable time in collecting water for their daily consumption.

CHAPTER 6: GIS BASED GROUNDWATER FLOW MODELS DEVELOPMENT, VALIDATION, SENSITIVITY ANALYSIS, RESULTS AND DISCUSSIONS

6.1 Introduction

It is no longer a problem to model any area of interest that has data scarcity with the development of Geographical Information Systems (Solomatine and Ostfeld, 2008; Wilson and Band, 2016).

Before undertaking this study, there were no hydrogeological maps or investigations on aquifer parameters, thematic maps, or risk assessments for water vulnerability in the study region. The purpose of this study is to understand the spatial and temporal evolution of groundwater levels under sustainable abstraction in order to support future domestic water needs. So, five numerical simulations are performed taking into account hydrogeological data as well as natural and artificial discharges from deep wells.

This chapter presents the development of three-dimensional numeric finite difference computer models for groundwater flow and quantity analysis. The models consider the flow and interaction between the unsaturated and saturated flow zones, described by the flow equations as discussed in Chapter 4.

6.2 Groundwater Quantity Modelling

Groundwater systems are frequently affected by natural processes and human activities, and therefore there is a need to monitor, manage and maintain the groundwater resources within the standard limits to ensure the social and economic benefits from this resource.

Groundwater flow modelling study has proved to be the potential tool to study the aquifer response and thereby evolves appropriate management schemes. The application of superposition modelling approach to evaluate changes in stress and responses to groundwater flow modelling to understand the groundwater system is not new. Effective groundwater management requires, firstly, a good understanding of the aquifer system, secondly, the practical measures to monitor abstraction, and thirdly, supplement groundwater resource through artificial recharge. It is therefore necessary to quantify the aquifer response under different input and output stresses to achieve this (Reilly and Harbaugh, 2004).

Based on the problem types identified in the study area in Table 4.6 of Chapter 4 (understanding of groundwater system, estimation of aquifer properties, understanding the present system and predicting the future), the study has developed 5 numerical models using GIS spatial datasets and pumping test data from boreholes to simulate groundwater interaction and flow. The developed models include:

i. A numerical model developed to compare the simulated and observed heads of the area that will give an estimation of the aquifer properties.
ii. A numerical model to simulate the pumping interference patterns of the wells/boreholes on a transient model in the watershed, to predict the future behaviour of the system and evaluate water balance.
iii. A regional unstructured grid model for understanding of the groundwater system and determination of sources of water to wells. Also, to produce the water balance of the entire watershed.
iv. A numerical model built using recharge values correlated with elevation of the area to identify area of high groundwater zone by infiltration in the watershed,
v. Build the numerical simulation of infiltration galleries for water supply predicting the future water potential, understand and plan management strategies to monitor abstraction.

Moreover, within the context of present study the novel elements include an integration of water consumption data as discussed in Chapter 5, into groundwater simulation to assess adequacy of the available resource and explore the potential groundwater resource has to augment the current supply regime.

Groundwater models can be classified as confined aquifer model, unconfined aquifer models and semi-confined aquifer models in the various numerical codes used in the simulation process (Widodo, 2013; Stefania *et al.*, 2018). The groundwater flow models can be characterised as saturated groundwater flow and unsaturated flow models (Gelhar and Gutjahr, 1985; Stefania *et al.*, 2018).

6.3 Soil Water Budget Model Development

The monthly and annual Potential Evapotranspiration (PET) for the Freetown watershed (drainage basin) using the Thornthwaite formula (Section 4.10.2) is determined. The Thornthwaite technique is a robust method for estimating precipitation and evapotranspiration (PET) climate conditions based on air temperature. Climate information for soil water budget (SWB) model codes (Westenbroek et al., 2018) was obtained from the Sierra Leone Meteorological Agency (Table 6.1). Hydrogeologist use water budgets to estimate the amount of water in the soil (recharge), because this helps them predict periods of flooding and droughts. The water budget graphs can then be used to describe the climate and seasonality of an area. The method is a simplistic way of modelling and defining the hydrologic processes. The result will serve as data to compare other methods used in the study. Information for the SWB is found in Appendix D1.1 to D1.4 in Appendix D1.

Table 6. 1 Climate information for Freetown 2016 (Source: Sierra Leone Meteorological Agency)

		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Freetown Valley bottom	P	11.2	6.1	19.1	104.0	201.8	360.0	498.0	505.4	484.5	308.0	99.0	8.7
	E_p	84.0	75.4	88.0	146.2	250.00	400.0	481.8	463.0	460.1	291.9	79.2	91.4
Freetown Mountain heights	P	5.8	6.8	5.3	35.3	116.7	299.9	584	593.9	487.2	420.0	198.0	10.0
	E_p	74.6	86.2	88.7	98.3	120.0	290.0	544.5	470.0	456.0	317.8	190.5	61.36

6.3.1 SWB Spreadsheet Model code development

Numerical values of water surplus and water deficiency were obtained in a simple bookkeeping technique with precipitation, P (income), evaporation and transpiration E_p (expenditure), soil moisture as a reserve that may be drawn upon as long as it lasts (Thornthwaite, 1948; Thornthwaite and Mather, 1955, 1957). The SWB concept is simple, but has been widely applied in a variety of countries to analyse retention and surplus of resources over time, especially in areas with distinct wet and dry seasons.
Parameter used in the SWB method:

- P = Precipitation is the amount of water added to the soil in a given period.
- E_p = Potential Evapotranspiration is the amount of water that could be used, if available for evaporation (from the sun) and transpiration (from plant).
- S_t = Storage is the amount of water in the soil. It cannot go above 100mm or below 0mm
- ΔS_t = change in Storage is the amount of change in the water held in the soil monthly
- E_A = Actual Evapotranspiration is the amount of water that is used. This is different from E_p when there is not enough water
- D = Deficit is when there is not enough storage to meet the needs of E_p,
- S = Surplus is when there is more water than the soil can hold, water runs off and is lost to the system. Storage cannot go above 100.

Solution for completing the soil water budget chart:
The information from Table 6.1 was copied directly into Table 6.2 and totalled up the months. In a month of the natural flow volume, the first step in calculating and tracking the new change in the soil moisture is to subtract the potential the precipitation ($P-E_p$). Negative values of $P-E_p$ represent a potential water deficiency while positive $P-E_p$ values represent a potential surplus. In the soil moisture and change in soil moisture values (S_t, ΔS_t), if the new soil moisture value is still below the maximum water holding capacity, the Thornthwaite method then calculates a new reduced accumulated potential water loss value. The calculations are shown in Table 6.2.
When $P-E_p$ is positive, actual evapotranspiration $E_A = E_p$. The E_A is equal only to the amount of water that can be extracted from the soil moisture (ΔS_t). In a month where $S_t = 0$, E_A will be P + storage from month before. S = surplus is when there is more

water than the soil can hold, water runs off and it is lost to the system. Storage cannot go above 100mm. If the soil moisture reaches the maximum soil moisture capacity, any excess precipitation is added to the daily soil moisture. Under most conditions, the soil moisture surplus value is equivalent to the daily groundwater recharge. One can only have a surplus when water storage = 100mm. Surplus is equal to precipitation minus evapotranspiration minus change in storage ($S = P - Ep - \Delta S_t$). D = deficit and is when there is not enough storage to meet the needs of Ep.

Table 6. 2 Comparative Moisture Data of Valley Bottom and Mountain Heights, Freetown Watershed (Source: authour's analysis)

Freetown Valley Height		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Totals**
	P	11.22	6.07	19.09	103.96	201.84	360.00	498.00	505.35	484.48	308.00	98.97	8.75	2605.72
	E_p	84.03	75.43	88.00	146.20	250.00	339.90	481.79	463.00	460.00	291.88	79.15	91.37	2850.75
	$P - E_p$	-72.81	-69.36	-68.91	-42.25	-48.16	20.10	16.21	42.35	24.48	16.12	19.82	-82.62	
	ΔS_t	0.00	0.00	0.00	0.00	0.00	20.10	79.90	0.00	0.00	0.00	-19.82	-80.18	
	S_t	0.00	0.00	0.00	0.00	0.00	20.10	100.00	100.00	100.00	100.00	80.18	0.00	
	E_A	11.23	17.29	36.38	140.34	342.18	339.90	481.79	463.00	460.00	291.88	79.15	88.93	2752.07
	D	72.81	69.36	68.91	42.25	48.16	0.00	0.00	0.00	0.00	0.00	0.00	82.62	384.11
	S	0.00	0.00	0.00	0.00	0.00	0.00	16.21	42.35	24.48	16.12	0.00	0.00	99.16
Freetown Mountain Height		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals
	P	5.8	6.8	5.3	35.3	116.7	299.9	584	593.9	487.2	420	198	10	2762.9
	E_p	74.6	86.2	88.7	98.3	120	290	544.5	470	456	317.8	190.5	61.36	2797.96
	$P - E_p$	-68.8	-79.4	-83.4	-63	-3.3	9.9	39.5	123.9	31.2	102.2	7.5	-51.36	
	ΔS_t	0	0	0	0	0	9.9	90.1	0	0	0	0	-51.36	
	S_t	0	0	0	0	0	9.9	100	100	100	100	100	48.64	
	E_A	5.8	6.8	5.3	35.3	116.7	290	544.5	470	456	317.8	190.5	61.36	2500.06
	D	68.8	79.4	83.4	63	3.3	0	0	0	0	0	0	0	297.9
	S	0	0	0	0	0	0	50.6	123.9	31.2	102.2	7.5	0	315.4

*Assuming that 50 percent of the water available for runoff in any month is held over until the following month. In watersheds of less than 100 square miles, the percentage is likely to be lower.

From Table 6.2, the comparison of potential evapotranspiration analysis through the year follows a uniform pattern in most part of the Freetown watershed. It rises to the maximum in July. The comparison of precipitation is variable from the valley bottom to the mountains. In the valley bottom the precipitation is less than the actual evapotranspiration. In times of excess rainfall water is stored in the soil. The precipitation exhibits marked seasonal variation with too much rain in the rainy season and far too little in the dry season.

Precipitation (P) increased with elevation and falls from late October to mid-April, and the dry season is consistently dry. To obtain the moisture index, the precipitation and potential evapotranspiration are to be compared. Where the precipitation is exactly the same as the potential evapotranspiration all the time, and water is available as needed, then there is neither water deficiency nor water surplus, and the climate is neither moist nor dry. In the valley bottom, water deficiency becomes larger (Table 6.2) with respect to potential evapotranspiration, the climate becomes dry; as water surplus becomes larger, in the mountain heights (Table 6.2), and the climate becomes more humid. As seen in the table, water deficiency in the valley bottom goes below minus 285mm. However, in the mountain, water surplus increases by 17mm. The comparison of precipitation, potential evapotranspiration and actual evapotranspiration (climate graphs) at the valley bottom and mountain heights in Freetown are shown in Figures 6.1 and 6.2 respectively.

In Freetown Valley bottom, the total average annual precipitation is 245mm less than the potential evapotranspiration. It shows months where the precipitation is less than the need.

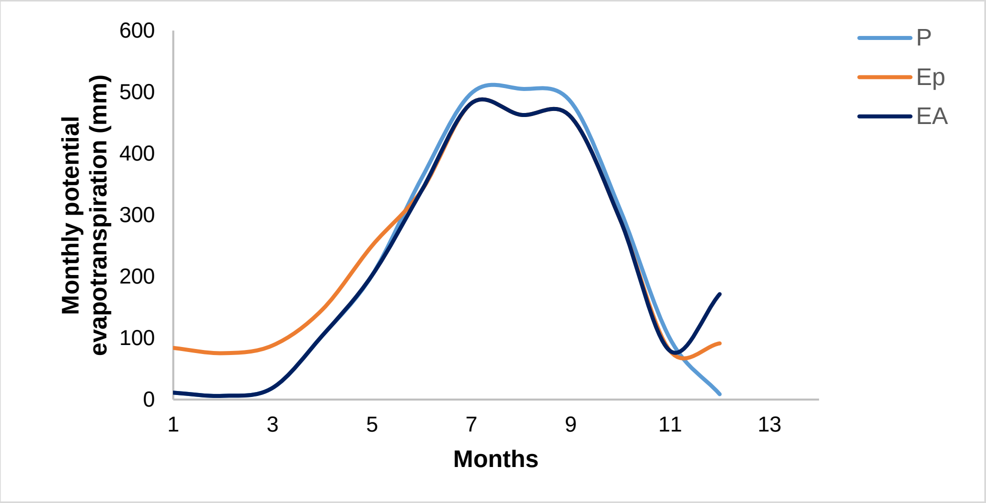


Figure 6. 1 Precipitation, potential evapotranspiration and actual evapotranspiration in Valley bottom, Freetown watershed (Source authour's construction)

In Mountain height, the total average annual precipitation is 2763mm, less than the potential evapotranspiration, 2798mm. Here the surplus that runs off amounts to 315mm.

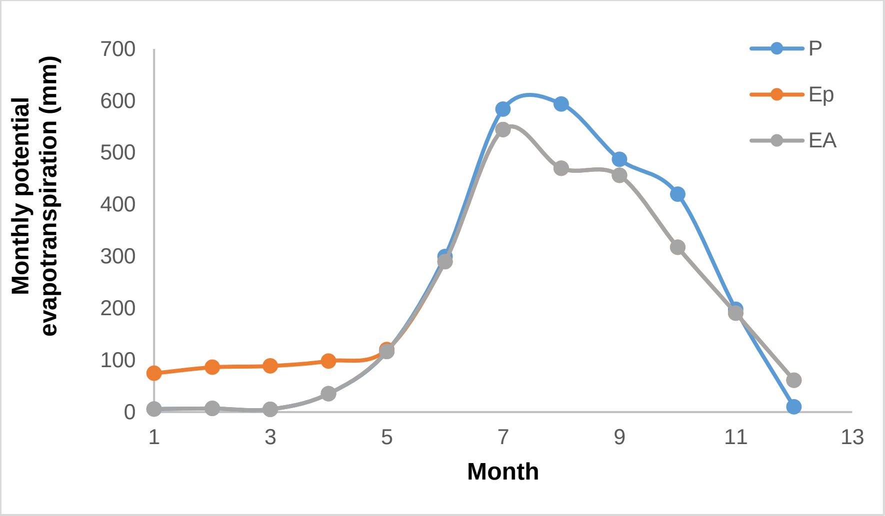


Figure 6. 2 Precipitation, potential evapotranspiration and actual evapotranspiration in Mountain heights Freetown watershed (Source: authour's construction)

6.4 GIS Based Groundwater 3D finite-difference numerical models development

MODFLOW three-dimensional (3D) finite-difference numeric method (FDM) have been modified with many new capabilities in MODFLOW-2005 and MODFLOW 6 (ModelMuse 4) to simulates external stresses, such as flow to wells, areal recharge, evapotranspiration in steady and non-steady flow in an irregularly shaped flow groundwater system. These can be unconfined, confined, or a combination of both (Harbaugh, 2005).

The basic idea is to solve a finite difference equation, starting with the initial distribution of heads and then compute the heads at later time instants. FDM models have been used by Bobba *et al.* (1997) and Qiu *et al.* (2015) to solve different types of groundwater problems including seawater intrusion.

The study has developed 5 numerical models using GIS spatial datasets and pumping test data from boreholes to model groundwater flow by McDonald and Harbaugh (1988).

6.4.1 Model development and set up

Model development includes the selection of the grid design, boundary and initial conditions, and initial values of the aquifer parameters. Grid design includes the method of discretization, the boundary conditions, numbers of model layers, and the grid cell size or node spacing. In the lack of site-specific data, a variety of geostatistical environments are available for generating model grids utilising the available field data and processing downloaded digital elevation models (DEMs) for each of the specific numerical model. There are several steps that should be done to get a complete and correct groundwater model that can predict the future seasonal responses of the aquifer system accurately. The utility roles of the software in the preparation of input and output model data, as well as the list of MODFLOW packages (MODFLOW 2005 and MODFLOW 6) by Harbaugh, (2005) used in the different groundwater flow (GWF) models setup to simulate steady and transient states for the aquifer system, are shown in Tables D2.4 and D2.5 in Appendix D.

6.5 The Numerical Models Calibration Process

In groundwater model calibration, the model that is “calibrated” is required to address many hydrologic problems (Thomas and Harbaugh, 2004). The model is built with the intended purpose to simulate the objectives of the watershed as detailed in Table 4.6 of Chapter 4. Numerical model calibration is the modification of model input data for the purpose of making the model more closely match to observed heads and flows. The adjustment of parameters is done automatically by using nonlinear regression statistical techniques integrated in MODFLOW package. The 5 developed models in this study are used to estimate the aquifer properties, understand the past, understand the present, and to forecast the future of the groundwater system of the watershed (Table 4.6). The model calibration processes in this study are based on the MODFLOW model.

The main parameters namely recharge rate and hydraulic conductivity need to be adjusted systematically and then allow the model to repeatedly run until the computed values corresponding to the field observed values attain an acceptable level of accuracy (Thomas and Harbaugh, 2004; Qassem et al., 2013).

For the sensitivity analysis, an independent set of field data was prepared using class feature fishnet (shapefiles) in the model calibration and design. An applied groundwater modelling case on a mesoscale that covers the most relevant physical process that influences the underground flow regime (regional flow, rivers, piezometers, and lakes). The numerical simulation (sensitivity analysis) was constructed in MODFLOW 6 on steady-state conditions with variable hydraulic conductivity and recharge rate at depth to represent interbedded low conductivity layers.

The model domain selected in this study covers an area of 25.5 km^2 of the entire study area, which is the densely populated area with limited access to the piped network and few wells serving the communities Figure 6.3.

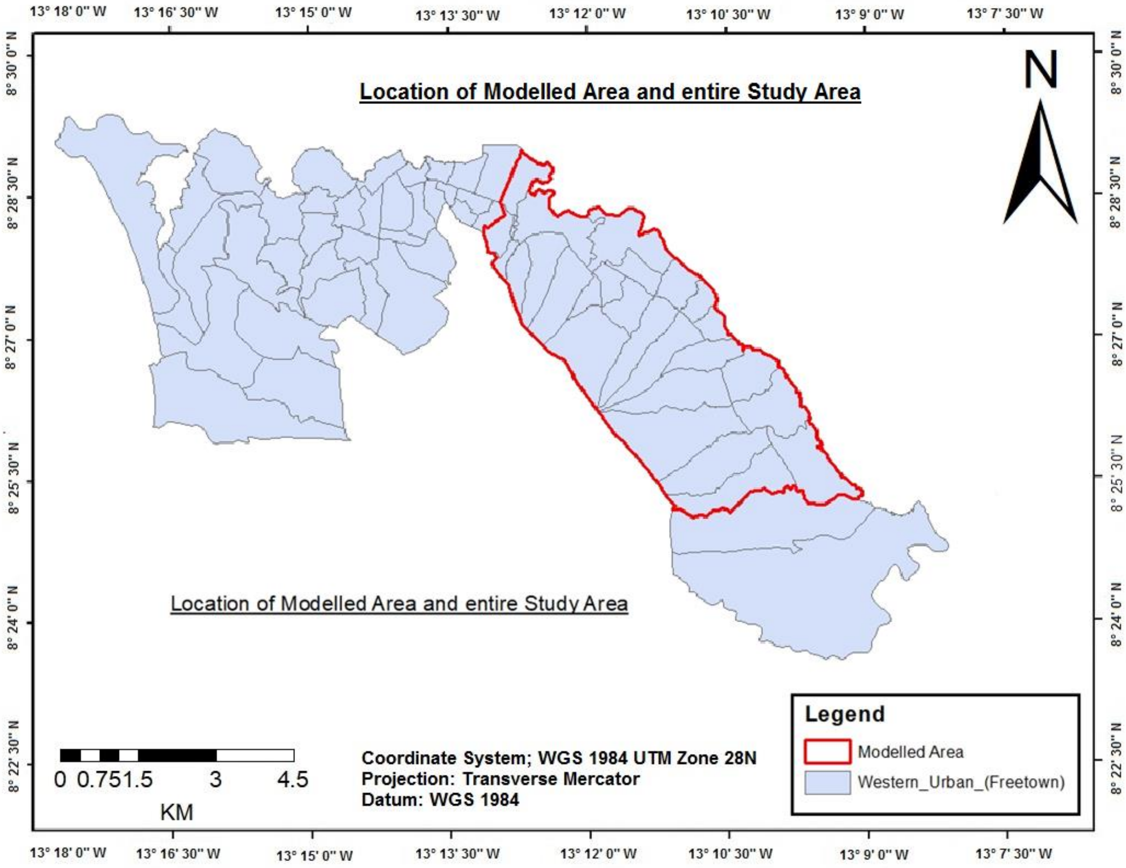


Figure 6. 3 Administrative Map of entire Study Area and Groundwater Flow Modelled area inset (Source: authour's construction)

Because of the dearth of hydrogeological information in the study area, the five numerical simulations were developed to estimate recharge rate, hydraulic conductivity, transmissivity, pumping capacity, drawdown capacity, regional water balance, zone budget and potential groundwater over a period of time in the area using rainfall and pumping well data obtained from the Meteorological Agency and Drilling companies. The results of the developed simulations are in good agreement with the observed data and that of Wada et al. (2014). The behaviour of the aquifer and water table depths from the simulated numerical models has proved the area of being able to supply groundwater for per capita consumption on a sustained basis.

6.5.1 Model Calibration for Recharge Capacity in the Study Area

The estimation of groundwater recharge is a critical component of any groundwater flow analysis. To study the relationship between rainfall (recharge) and the groundwater levels influenced by the varying topography in the watershed a numerical model was developed using the numerical code MODFLOW-NWT. Scanlon et al. (2002) describes various approaches to measuring groundwater recharge, including selecting the appropriate techniques. As with most typical unconfined aquifers, groundwater recharge from precipitation is the primary input to the study area. Many modelling studies obtain recharge rates through model calibrations e.g. Schilling et al. (2006). For this study, recharge estimates were obtained from the rainfall and elevation data of the Sierra Leone Meteorology Department[13] of the study area presented in MS Excel format (Table 6.3). Both values show a linear relationship, as elevation increases recharge rates increases (Goodale et al., 1998; Seneviratne *et al.*, 2012). The unit for recharge values was collected in millimetres per year (mm/yr), but ModelMuse MODFLOW-NWT unit for recharge is cubic metres per second (m^3/s). Column 5 in Table 6.3 shows the conversion values from mm/year to m^3/s (Pulido-Velazquez *et al.*, 2015). The formula is also considering the second part of the equation which is the correlation of elevation to recharge and change of unit segment. This model focuses on assessing the feasibility of managed aquifer recharge in the Freetown watershed and presenting a system for development and operation of aquifer recharge and recovery.

a). Conceptual model and b). Model Geometry

The conceptual setup of the model is based on limited data available. The aquifer has been conceptualised as a single hydrogeological layer. But, the single layer model was further divided into four homogenous computational layers for positioning of injection and recovery wells screens.

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[13] https://slmet.gov.sl

Table 6. 3 Elevation and recharge values with corresponding topography information (Source: Sierra Leone Meteorology Department, 2017)

X-coordinate	Y-coordinate	Elevation in metres (masl)	Recharge (mm/yr)	Recharge (m^3/s)
696895	937643	40	48.787	$1.547x10^{-9}$
701414	934797	50	64.754	$2.053\ x10^{-9}$
696893	937651	60	80.721	$2.560\ x10^{-9}$
698621	936939	70	96.688	$3.066\ x10^{-9}$
698663	937060	80	112.655	$3.572\ x10^{-9}$
698188	937091	90	128.622	$4.079\ x10^{-9}$
698188	937091	110	160.556	$5.091\ x10^{-9}$
700620	935723	120	176.523	$5.597\ x10^{-9}$
698188	937098	140	208.457	$6.610\ x10^{-9}$
701414	933636	160	240.391	$7.623\ x10^{-9}$
698939	936480	200	304.259	$9.648\ x10^{-9}$
699767	935920	240	368.127	$1.167\ x10^{-8}$
701023	935947	260	400.061	$1.268\ x10^{-8}$
701876	933117	280	431.995	$1.369\ x10^{-8}$
699070	935974	293	452.7521	$1.435\ x10^{-8}$

The inflow to the model domain consists of recharge from precipitation, and subsurface flow from the neighbouring aquifer. The outflow includes discharge to existing pumping wells, neighbouring aquifer and evapotranspiration. The model was setup using MODFLOW code (Techniques, 2005). The required model development and configuration information for the recharge capacity numerical simulation are shown in Table 6.4.

Table 6. 4 Model Development and Configuration Information for Recharge Simulation (Source: authour’s construction)

Model Development and Configuration		
Model Design	a). Conceptual Model	- covers an area of 25.5 km^2 - A single layer divided into 4 homogenous layers
	b). Model Geometry	- rectangular, convertible aquifer overlain by a thick unsaturated zone
	c). Model Grid and layering	- 4 layers: 1 Alluvial + 3 Fractured rock (No grid)
Boundary array (cell type)	d). Constant head boundary - *Head dependent flux*	- Drain Package (DRN) - Evapotranspiration Package (EVT)
	- Specified flux	- Recharge Package (RCH) - Well Package (WEL)
Model Calibration Parameters	Time Steady state calibration (-1 to 0)	- Stress (when boundary condition change) period is not relevant in steady state
	Spatial datasets (layer top and bottom)	- discretised with no grid, use of topographic information - Polygon shapefile of the basin domain - Shapefile of the waterways (drains)
	Hydrogeologic characteristics	- hydraulic conductivity - drain conductance
Boundary Condition	e). Initial Condition and Stress	- initial head condition is top of model - hydraulic conductivity, GHB conductance, EVT, and recharge are model calibration parameters

c). Model Grid and Layering

The finite-difference mesh consists of one alluvial layer and three fractured aquifers with no grid option. The elevation of the first layer was obtained from ASTER 30m x 30 m DEM (digital elevation model). The aquifer is divided into four homogenous layers with thickness varying linearly from 15 m in the alluvial bed to 220 m in the fractured aquifer. The bottom aquifer is confined and the others are convertible (unconfined or confined).

d). Constant Head Boundary

Recharge from precipitation was simulated as a specified flux boundary in the Recharge Package of MODFLOW and was applied to the top most active layer so that the location of the recharge can move up and down as the cells in the surface convert from wet and dry. Initial value of recharge from precipitation was estimated as 3.80 x $10^{-8}$$m^3$/s (of the annual precipitation).

The well package of MODFLOW simulates a specified-flux boundary in each model cell to which a well is assigned based on the withdrawal rate for each well. Actual daily pumping rates were obtained by multiplying the yield of each well (available from existing records) at steady state, a total of 6x10^{-2} m^3/sec was used as input to the model.

The discharge by evapotranspiration from the model was simulated using a head dependent function that decreased linearly with depth. In order to simulate evapotranspiration, maximum evapotranspiration rate, elevation of evapotranspiration surface, and extinction depth (water table depth below which EVT ceases to occur) need to be specified in the model. Groundwater extraction depends on the elevation of the groundwater table when the groundwater table lies between the surface of evapotranspiration and the extinction depth (Shah et al., 2007). The evapotranspiration rate of 4.75 x 10^{-9} m^3/s (Colombani *et al.*, 2021) is assumed to occur when the water table reaches the land surface (Model_Top). The extinction depth was assumed to be 0.5 m below land surface.

e). Initial conditions and hydraulic properties

The initial head condition was the top of the model (Model_Top), run on a steady state model using no flow boundary. The observed steady state groundwater level distribution for the model was based on groundwater level measurements in 2016 - 2017. These groundwater levels are assumed to represent equilibrium conditions. Due to lack of subsurface information, the aquifer conditions were defined as homogenous. Four zones of different hydraulic conductivity (K in m/s) were used for layers of the aquifer dominated by fractured crystalline material and alluvial material (gravel and sand formation). In this model, the K_x values used were 1 x10^{-5}, 1 x10^{-7}, 1 x10^{-8}, 1 x10^{-9} from the 1st to 4th layer. The K_y and K_z = K_x. The K values in this model were considered to be the effective properties of the bulk aquifer at the regional scale. A sensitivity analysis of this parameter (K) in presented in Section 6.14.

Hydraulic conductivity, general head boundary (GHB) conductance, EVT, and recharge were used as model calibration parameters. The most significant inflow to the model comes from recharge. Figure 6.4 shows the region in the study area with changing recharge rate. Recharge is increasing from the east to west direction. Understanding the recharge rate provides insight into large-scale hydrologic processes and has identified the watershed as a rich aquifer for future well construction to support increased water consumption. High recharge (red shaded areas) where the water table is elevated and discharge (greenish-blue) where water table is low.

The volumetric water budget for the recharge simulation in cubic metres per day (m^3/d) is shown in Table 6.5. Recharge is the most significant inflow from the table. Most of the outflow from the model is via the existing pumping wells (drains), followed by the components of evapotranspiration and outflow recharge to neighbouring aquifer. The detailed discretisation process and volumetric budget of the recharge numerical simulation is shown in Table D3.1 in Appendix D3.

Table 6. 5 Volumetric Water Budget of the Whole Model Domain after Recharge Simulation Run (Source: generated from Modflow Run)

Flow term	Flow In (m^3/d)	Flow Out (m^3/d)
STORAGE	0.0	0.0
CONSTANT HEAD	0.0	0.0
DRAINS	0.0	6.97×10^3
EVAPOTRANSPIRATION	0.0	4.34×10^3
RECHARGE	11.55×10^3	2.38×10^2
TOTAL OUT	11.55×10^3	11.55×10^3

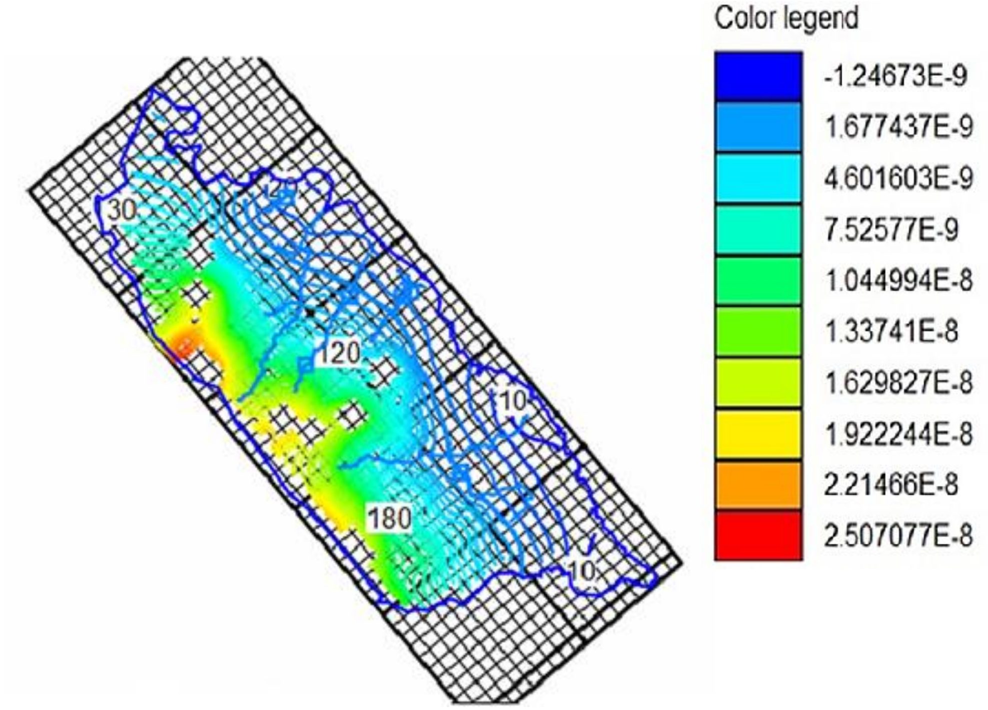


Figure 6. 4 Steady state distribution of recharge rate with elevation (Source: generated from ModelMuse MODFLOW simulation run)

6.5.2 Numerical Model Calibration of observed and simulated heads in the Study Area

The purpose of this model is to simulate the impacts of human activities on groundwater flow systems when formulating sustainable groundwater resources development scenarios. The model was developed using groundwater level data (Table D2.6 in Appendix D) and QGIS application. A regional model using MODFLOW 6 numerical code was used to plot the output observed and simulated. The calibrated model parameters and packages used for the observed and simulated model are listed in Table 6.6. The following subsections present the model geometry, model grid layering, model input, and model calibration of the observed heads simulation in the study area.

a). Conceptual model and b). Model Geometry

The groundwater flow system was modelled using the MODFLOW code (Winston, 2019). A shapefile was created from the CSV. delineated file with UTM coordinates information shown in Table D2.6 in Appendix D using QGIS. The shapefile is imported into MODFLOW 6 with the MODFLOW-NWT option. In MODFLOW 6, the position of the piezometers (wells) are inserted and the solver gives only the simulated heads. The piezometers are inserted as *head observation* (OBS).

c). Model Grid and Layering

Using the model domain area (25.5 km^2), the piezometers were inserted at different depths and the model was run to create the NAM.file. The finite-difference mesh consisting of 51 rows and 19 columns was constructed with a no grid angle of 40 degrees. In the vertical directions, the model consists of five aquifer layers with varying layer thicknesses. For temporal discretisation, the model was simulated under steady-state conditions.

The detailed 30m resolution Digital Elevation Map (DEM) obtained from USGS Earthdata website was re-sampled to allow groundwater/surface water exchange at reasonable computation time. Model top layer (Land surface elevations) were then extracted from the re-sampled 30m DEM. Due to lack of subsurface information, the aquifer conditions were defined as homogenous.

d). Constant Head Boundary conditions

Along the boundaries of the aquifer, different types of boundary conditions (RCH, DRN and ETS) were specified. A specified head boundary conditions, based on the observed ground water level data (19 wells) was used. The model is bounded by recharge and evapotranspiration fluxes at the top and by fractured layer at the bottom.

Table 6. 6 Model Development and Configuration Information for Observed and Simulated Heads (Source: authour's construction)

Model Development and Configuration		
Model Design	a). Conceptual Model	- covers an area of 25.5 km^2
	b). Model Geometry	- rectangular, confined aquifers with varied thickness
	c). Model Grid and layering	- 5 layers: 5 Fractured rock (No grid)
Flow Package	NPF: Node Property Flow	- Iterative Model Solution, Linear inner maximum iterations value of 100
Boundary array (cell type)	d). Constant head boundary - *Head dependent flux*	- Drain Package (DRN) - Evapotranspiration Segment Package (ETS)
	- Specified flux	- Recharge Package (RCH)
Model Calibration Parameters	Time Steady state calibration (-1 to 0)	- Stress (when boundary condition change) period is not relevant in steady state
	Spatial datasets (layer top and bottom)	- Discretised with no grid, use of topographic information - Polygon shapefile of the basin domain - Shapefile of the waterways (drains) - Piezometer shapefile created from data.csv file (Table D2.6 in Appendix D)
	e). Hydrogeologic characteristics	- hydraulic conductivity - drain conductance - recharge rate - evapotranspiration rate
Boundary Condition	e). Initial Condition and Stress	- initial head condition is top of model - hydraulic conductivity, DRN conductance, ETS, and recharge are model calibration parameters

e). Initial Conditions and Hydraulic Properties

The MODFLOW drain package was used to simulate the effect of the drainage swampy areas on the groundwater flow regime. In addition to a drain elevation, the drain conductance (0.003 m^2/s) needs to be specified in the drain package. Variable Horizontal Hydraulic Conductivity K_x (K) Case (layer, 1 x 10^{-4}, 5 x10^{-6}, 1 x10^{-6}, 9 x10^{-7}

and 5 x 10^{-7} from the 1st to 5th layer and assume an Isotropic aquifer. K_y (K22) = K_x. K_z (K33) = K_x /10. The aquifer types for all five layers are confined. Recharge from precipitation was simulated as a specified flux boundary in the Recharge Package of MODFLOW and was applied to the topmost active layer at a rate of 5.39×10^{-9} m^3/s. Discharge by evapotranspiration from the model was simulated with a head-dependent function that decreased linearly with depth. The evapotranspiration rate is assumed to occur when the water table is at the land surface at 3.61×10^{-8} m^3/s. The model was run on a steady state by assuming a general head boundary (GHB) over the modelled area.

Model Simulation and Output

During model calibration the model parameters were adjusted until the simulated head matched the observed values. The normalised root mean-squared error between the observed and simulated groundwater level values was 0.2 m.

Although the calibration results seem to be relatively acceptable, it needs to be emphasised that the developed model has several significant simplifying assumptions, most important of which are the introduction of homogeneous hydraulic conductivity zones, and recharge inflow from the neighbouring aquifer (represented by the GHB).

The total volumetric water budget (Table 6.7) of the calibrated model domain simulated with the numerical groundwater flow model consists of: recharge 8.0×10^4 m^3/d (inflow from the specified flux), outflow through evapotranspiration of 1.2×10^4 m^3/d and outflow through the drains 6.8×10^4 m^3/d. Figure 6.5 present the groundwater scatter plot for the comparison between the observed and simulated heads. Where the residual value is negative, it shows that the simulated head is too high compared to the observed value. Where the residual value is positive, it shows that the simulated head is too low compared to the observed head. Figure 6.6 shows the head distribution of the groundwater in the modelled area at steady state calibration. The obtained pattern of groundwater heads presented in Figures 6.5 and 6.6 show the influence of the assumptions. Nevertheless, the obtained gradient of groundwater head, as confirmed by the calibration results, gives some confidence that the developed model is an overall representative of the groundwater flow in this aquifer.

Further improvements of the model are certainly possible, but for this study that focuses on the methodology for determination of aquifer properties and changes to external and manmade influence (Table 4.6 of Chapter 4), the performance measures show that the model is reasonably well calibrated for the intended purpose. It should also be noted that obtaining a good match between the observed and simulated head is necessary for attaining a reliable estimate of flux and hydraulic conductivities of the aquifer (Techniques, 2005).

Table 6. 7 Volumetric Water Budget of the whole Model Domain for the observed and simulated model calibration at Steady State (Source: generated by Modflow simulation Run)

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
STORAGE	0.0	0.0
CONSTANT HEAD	0.0	0.0
DRAINS	0.0	$6.8x10^4$
EVAPOTRANSPIRATION	0.0	$1.2x10^4$
RECHARGE	$8.0x10^4$	0
TOTAL IN	$8.0x10^4$	0
TOTAL OUT	0	$8.0x10^4$

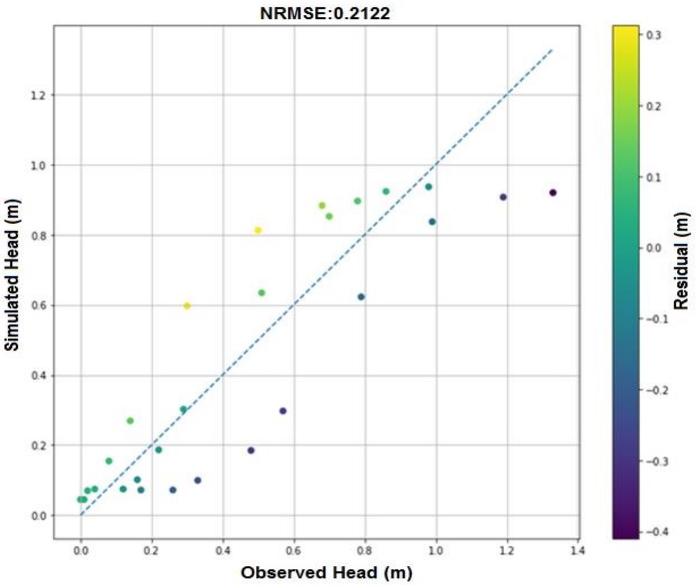


Figure 6. 5 Groundwater Scatter Observed Versus Simulated Water Levels and Residual Plot for Steady State Calibration generated from Modflow Simulation Run

The residual is the difference between the observed and simulated heads. It can be seen in Figure 6.5 that the residual varies between -0.35 to 0.3m. This indicates that the simulated results, for the selected calibrated parameter values are in a broader agreement with the observed values (Colombani *et al.*, 2021). The detailed model discretisation information of the calibrated observed versus simulated model is presented in Table D4.1 in Appendix D4.

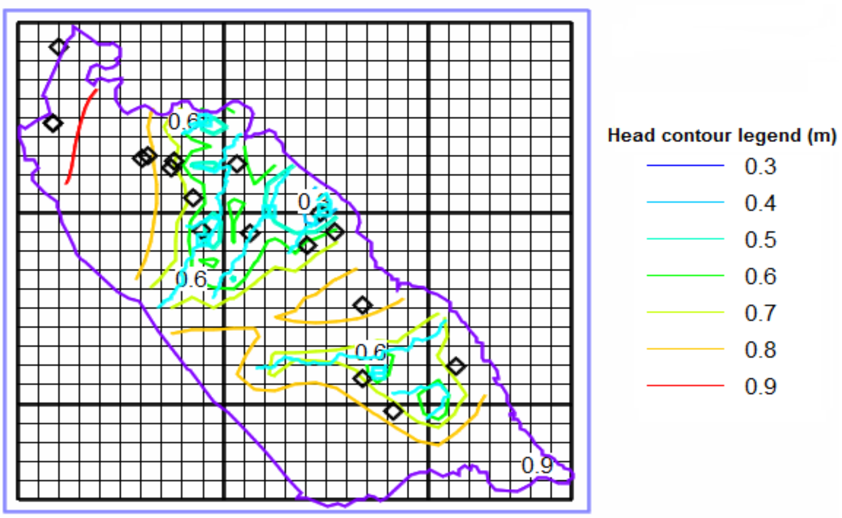


Figure 6. 6 Groundwater head distribution during steady state calibration (Source: generated from Modflow simulation Run)

6.5.3 Model Calibration for the Wells Interference pattern in the Study Area

The objective of the wells interference model calibration was to determine how much water can be extracted out from the hydrologic setup, under seasonal variability conditions and further monitor the interference of these wells with each other for a period of 15 years period. The model was calibrated and simulated under steady and transient stress periods to understand the groundwater system using MODFLOW-2005 numerical codes. The wells will be observed every year during the transient period. The boundary condition is a CHD time-variant specified head regional flow package, where stress periods can change within or between each other. The calibrated model parameters and flow packages used for the interference patterns between the wells are listed in Table 6.8.

Table 6. 8 Model Development and Configuration Information on Interference Wells Patterns (Source: authour’s construction)

Model Development and Configuration		
Model Design	a). Conceptual Model	- covers an area of 25.5 km^2 calibrated with
	b). Model Geometry	- rectangular, convertible aquifer with thickness of 80 metres
	c). Model Grid and layering	- 1 layer: Alluvial aquifer, no grid option and further divided into 3 layers
Flow Package	LPF: Layer Property Flow	- PCG: Preconditioned Conjugate Gradient package, maximum number of outer iterations of 20 with maximum number of inner iterations = 30
Boundary array (cell type)	d). Constant head boundary - *Head dependent flux*	- Evapotranspiration Package (EVT)
	- Specified flux	- Recharge Package (RCH) - Well package (WEL)
	- Specified head	- Time-variant (CHD)
Model Calibration Parameters	Time Steady state calibration (-1 to 0) Transient state calibration (0 – 15 years)	- Stress (when boundary condition change) period is not relevant in steady state - Transient state (15 years)
	e). Spatial datasets (layer top and bottom)	- Discretised with no grid, use of topographic information - A polygon shapefile of the basin domain - Shapefile created from all wells - Raster. (grd) file, set values of cells by interpolation using fitted surface
	Hydrogeologic characteristics	- hydraulic conductivity - recharge rate (9.51 x10^{-8} m^3/s) - evapotranspiration rate (6.02 x10^{-8} m^3/s)
Boundary Condition	f). Initial Condition and Stress	- initial head condition is top of model - hydraulic conductivity, evapotranspiration, recharge, specific storage and specific yield are model calibration parameters
Solver	PCG	- Preconditioned Conjugate Gradient package

a). Conceptual model and b). Model Geometry

To study the interference patterns between the wells resulting from abstraction at varying pumping rates in the rain and dry season, a numerical model was developed using the numerical code MODFLOW-2005. The regional groundwater steady state interference wells flow model was calibrated with the thirteen wells but no pumping rates were assigned. The calibration was performed using the preconditioned conjugate gradient package to solve the finite difference equations in each step of a MODFLOW stress period. The steady state calibration tests whether the boundary conditions are satisfactory and create steady state head solutions for initial conditions for transient calibration. The model is then run in the steady state.

c). Model Grid and Layering

The finite-difference mesh consists of one alluvial layer with a thickness of 80 metres. This layer is further subdivided into three homogenous aquifer layers with no grid option. The aquifer is represented as convertible (unconfined or confined).

d). Constant Head Boundary

Recharge was applied to the top most active layer to allow up and down movement of the recharge as the cells in the surface convert from wet and dry. Recharge rate from annual precipitation was calculated as 9.51 $x10^{-8}$ m^3/s. All the thirteen wells are assumed to be placed at depth of forty metres below the surface. Pumping rate interpretation is set at Direct, but wells are only activated in the transient state simulation. The evapotranspiration depth is set at 0.5m below the surface and evapotranspiration rate is estimated at 6.02 $x10^{-8}$ m^3/s.

e). Numerical Model Spatial Discretisation

Using the ESPG projection 32628, the polygon shapefile of the basin domain, shapefile of the wells and raster surfer.(grd) file interpolated with fitted surface are imported into MODFLOW-2005. The model domain covers an area of 25.5 km^2. The finite-difference mesh consisting of 64 rows and 62 columns was constructed with a no grid angle of 0 degrees. In the vertical directions, the model consists of a single layer divided into three alluvial aquifer layers with thickness of 80 m. For temporal discretisation, the model was simulated under steady-state and transient-state conditions.

f). Initial Condition and Hydraulic Properties

The assumption made here is that the water table is 8 metres below the surface. This takes into consideration the depth of the water table in the dry and rainy seasons. The hydraulic conductivity values were $K_x = 1 \times 10^{-5}$, K_y (K22) = K_x. K_z (K33) = K_x /10. Boundary conditions, specific storage ($1.2 \times 10^{-5} L^{-1}$), specific yield (0.12) and the water levels attained through the steady state model calibration is then used as the initial condition in the transient model calibration. The steady state calibration tests whether the boundary conditions are satisfactory and create initial conditions for transient calibration. The model is then run in the steady state. Table 6.9 presents the volumetric water budget at the end of the steady state simulation. The output control for the steady state shows that the constant head and evapotranspiration are taking water out of the system when there are no wells. Water into the system is through recharge. Storage is not a requirement in the system as shown in Table 6.9.

Table 6. 9 Summary Volumetric Water Budget at Steady state of Wells Interference generated from Modflow Run

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
STORAGE	0.0	0.0
CONSTANT HEAD	0.0	3.4×10^4
WELLS	0.0	0.0
EVAPOTRANSPIRATION	0.0	5.9×10^4
RECHARGE	9.3×10^4	0
TOTAL IN	9.3×10^4	0
TOTAL OUT	0	9.3×10^4

Transient Calibration

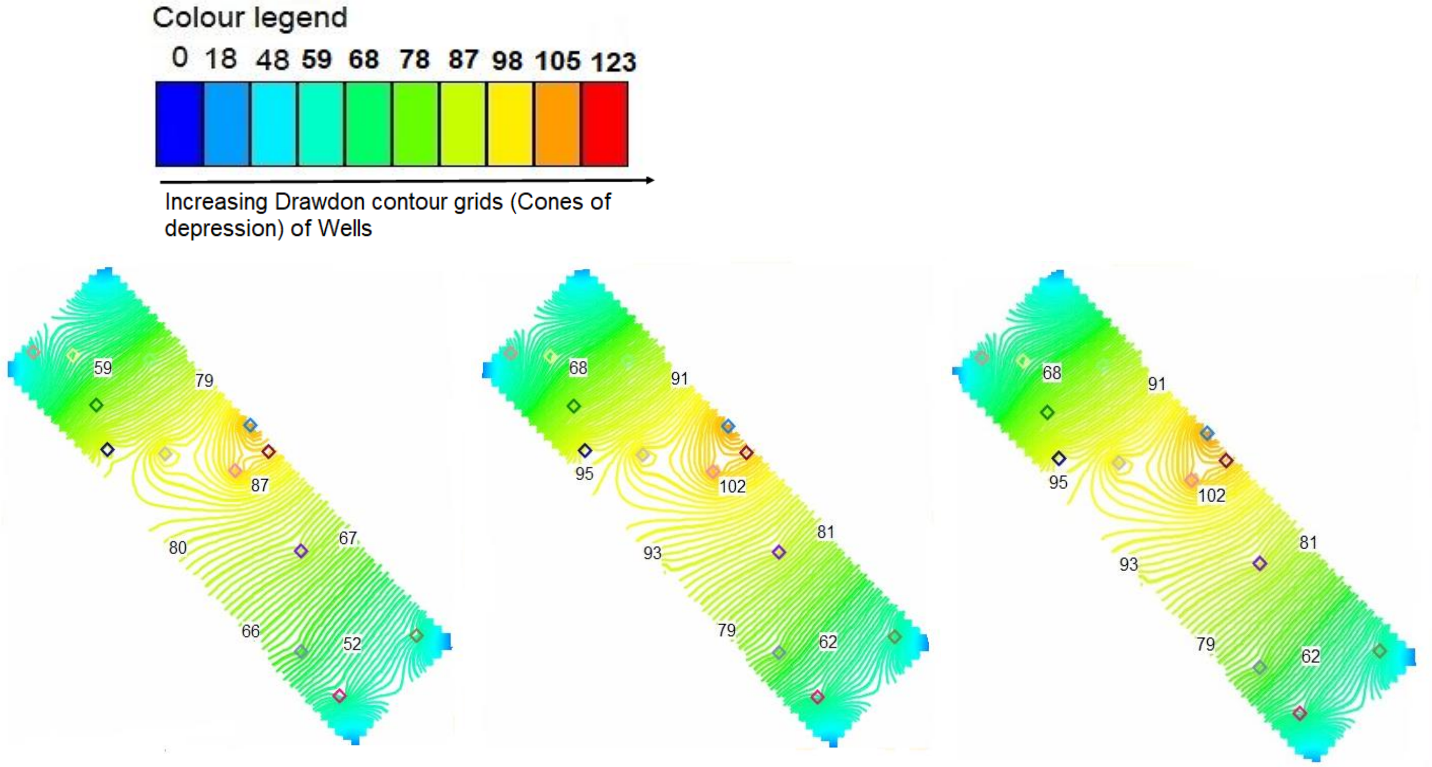
The transient calibration was modelled for a fifteen-year period (473364000 seconds) and monitored every year (31557600 seconds). The wells are activated in the transient calibration. The pumping rates used have considered the seasonal variability pumping capacity, water availability due to recharge and duration of pumping. The assumptions are that the wells will pump water at a rate of -5×10^{-3} m^3/s during the daytime in the dry season and pump at -1.5×10^{-2} m^3/s in the day time during the rainy season. It is also assumed that there is no pumping in the night-time. Among the thirteen wells, seven wells were pumping at $-5\text{x}10^{-3}$ m^3/s and six wells were pumping at $-1.5\text{x}10^{-2}$ m^3/s. This assumption stems from the fact that aquifers that supply a well do not always maintain the same water level. Groundwater levels are affected by the dry season, seasonal variations in rainfall, and pumping. Water levels in a well can be lowered if the pumping rate exceeds the rate of recharge of the aquifer surrounding it through precipitation or another underground flow.

At the end of the transient simulation run, the result, Table 6.10 shows that storage is taking 2.74 $\text{x}10^{-5}$ m^3/d out of the system, constant head is taking out 2.38 $\text{x}10^{4}$ m^3/d and evapotranspiration is taking out 5.87 $\text{x}10^{4}$ m^3/d. Recharge is the main input at 9.3 x 10^4 m^3/d into the system. The wells once activated are taking out 1.08 $\text{x}10^{4}$ m^3/d from the system, it means that water that comes from the pumping wells is not water from the regional flow, but mainly from the swamps and creeks. There is change in the evapotranspiration leaving or entering the aquifer system before and after the wells were activated. When the wells were not activated at steady state, the evapotranspiration was slightly high at 5.9 $\text{x}10^{4}$ m^3/d.

Table 6. 10 Summary of volumetric water budget after transient model run of wells interference

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
STORAGE	8.41×10^{-4}	$2.74 \text{x}10^{-5}$
CONSTANT HEAD	2.99×10^{2}	2.38×10^{4}
WELLS	0.0	1.08×10^{4}
EVAPOTRANSPIRATION	0.0	5.87×10^{4}
RECHARGE	9.30×10^{4}	0.0
TOTAL IN	9.30×10^{4}	0.0
TOTAL OUT		9.30×10^{4}

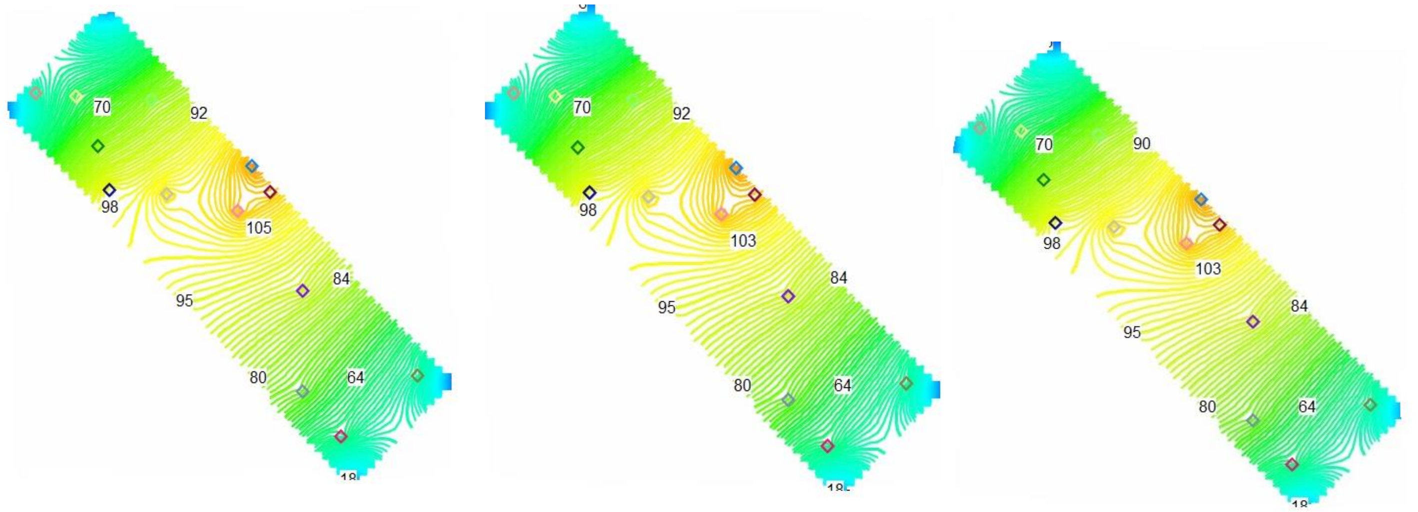
The message from this model calibration is shown in the drawdown heads for years 1, 2, 3, 4, 5 and 15 in Figures 6.7 a – f. The development of the interference patterns between the drawdown levels and cones of depressions of the transient simulation can be seen from year 1 through year 5, where the results at the end of year 5 (Drawdown_P2_S05) and year 15 (Drawdown_P2_S15) are the same in Figures 6.7 e and f. This explains that the model reached steady state in year 5, and therefore there is no change in the interference pattern from the end of the fifth year to the fifteenth year. It means that during the first five years of abstraction the wells developed interference relationship between each other until an equilibrium phase is reached. The initial water table was set at 8 metres below the surface. After the simulation, it can be seen that the water table varies from seven (7) to twenty-three (23) metres below the surface during the rain and dry seasons. The heads and cones of depressions and shown in Figures 6.7 a – f are presented as the initial to actual representations. The wells with the highest pumping rates (-1.5×10^{-2} m^3/s) have a more detailed drawdown from the simulation. The result of this model calibration is discussed in Section 6.12.3. The detailed discretisation information and volumetric budget for the wells interference simulation can be found in Table D5.1 in Appendix D5.



(a) Drawdown in contour grid for year 1 (Drawdown_P2_S01)

(b) Drawdown in contour grid for year 2 (Drawdown_P2_S02)

(c) Drawdown in contour grid for year 3 (Drawdown_P2_S03)



(d) Drawdown in contour grid for year 4 (Drawdown_P2_S04)

(e) Drawdown in contour grid for year 5 (Drawdown_P2_S05)

(f) Drawdown in contour grid for year 15 (Drawdown_P2_S15)

Figure 6. 7 Drawdown Cones of depression in Contour Grids for Interference Wells generated from Modflow Run

6.5.4 Model Calibration for Interaction of Alluvial Aquifer with Regional Flow, River and Wells in Unstructured Grid Discretisation

The objective of this model setup and simulation is to create the geospatial environment of an alluvial aquifer with the interaction of regional flow, river and wells. They will help to determine the sources of water to wells, determination of responsible bodies causing impacts on the groundwater system, changes due to external and manmade activities. The simulation is created as a quadtree refined unstructured grid (DISV) with the NPF and GNC flow packages. A quadtree refined grid, starts with a structured grid and then subdivides cells into four equal parts both horizontally and vertically to make it uniform. These cells are further subdivided into finer cells as seen in Figure 6.8. The switch DISV discretisation technique improves the numerical model and provides an acceptable representation of the groundwater flow physical system that is represented by the constructed mathematical model (United States Geological Survey, 2018).

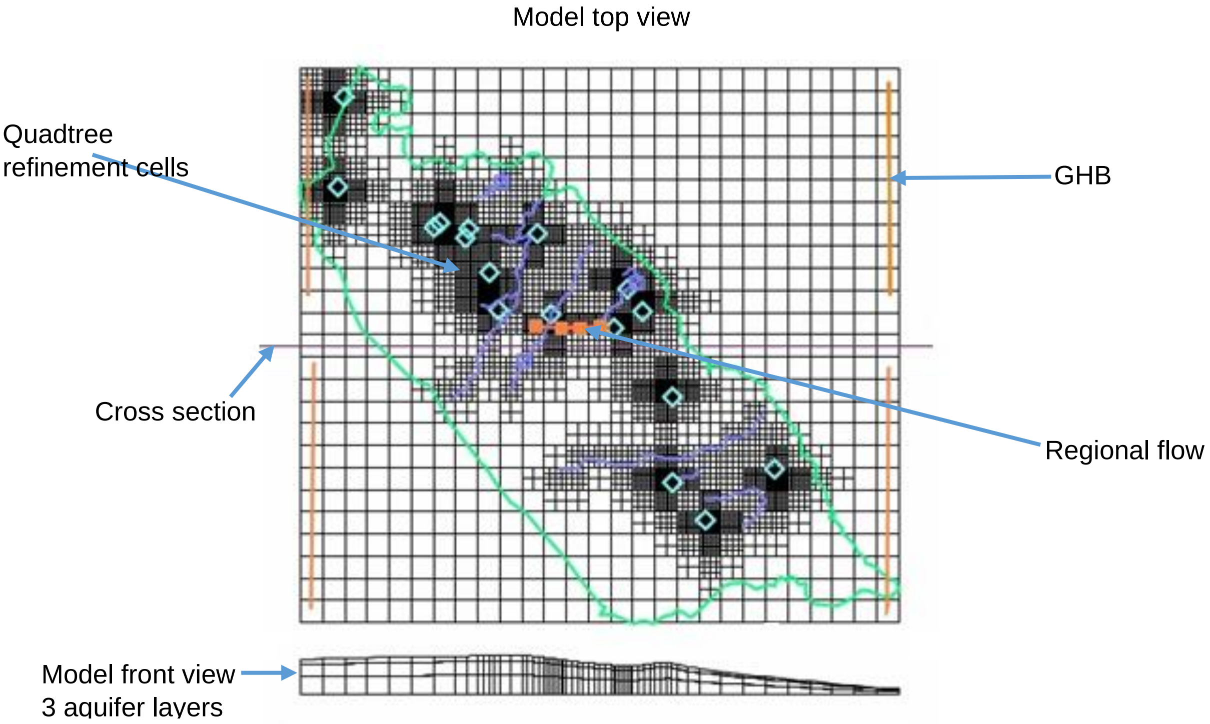


Figure 6. 8 Regional Unstructured Grid Groundwater Flow Model Discretisation (Source: authour's construction)

The main changes of the groundwater flow are related to its boundary conditions (Table 6.11). The refinement is done to see the impact of certain areas (interaction between surface and subsurface waterways) in the model. This type of discretisation enhances the impact of the groundwater simulation and flow. If the system had been modelled without refinement, the contour lines will not be seriously affected. No cell size is selected to do the refinement, a quadtree refinement of 4 was done. This means that because the initial cell size is 100, it divides into 50, then 25, then 12.5, and finally 6.25. The required model development packages and configuration information are shown in Table 6.11.

Table 6. 11 Model Development and Configuration Information for Interaction of Alluvial Aquifer with Regional Flow, River and Wells in Unstructured Grid Discretisation (Source: authour's construction)

Model Development and Configuration		
Model Design	a). Conceptual Model	- covers an area of 25.5 km^2
	b). Model Geometry	- rectangular, confined aquifer
	c). Model Grid and layering	- 3 aquifer layers (No grid) with bottom elevation at -120 m
Flow Package	NPF: Node Property Flow GNC: Ghost-Node Correction	- Iterative Model Solution, Linear inner maximum iterations value of 100
Boundary array (cell type)	d). Constant head boundary - *Head dependent flux*	- General Head Boundary (GHB) - River Package (RIV)
	- Specified flux	- Well Package (WEL)
Model Calibration Parameters	Time Steady state calibration	- Confined and run on steady state (-1 to 0 seconds)
	Spatial datasets (layer top and bottom)	- EPSG Projection 32628 - Discretised with no grid, use of topographic information - Polygon shapefile of the basin domain - Shapefile of the waterways (drains) - Piezometer shapefile created from well data
	Hydrogeologic characteristics	- Hydraulic conductivity - River conductance
Boundary Condition	Initial Condition and Stress	- Initial head condition is top of model - Hydraulic conductivity, RIV conductance are model calibration parameters

a). Conceptual model and b). Model Geometry

The regional groundwater flow system was modelled using the MODFLOW 6 numerical code (Anderson et al., 2015). The topography in the form of point shapefile and raster file of the domain using EPSG Projection 32628 was imported into MODFLOW 6 and then simulated with IMS solver. For temporal discretisation, all layers are confined and run on steady state.

c). Model Grid Layering and d). Constant Head Boundary

In this model, the general head boundary (GHB) is set at all layers of the confined aquifer and runs in a steady state. Conceptually, the GHB is a fixed head that is far from the model that can be affected by model stresses over time. GHB cells are connected to an external body of water (or another feature) by *boundary heads*. In this calibration, the boundary heads on the west of the model domain was set at 55m and 90m on the east with direct GHB conductance of $1x10^{-2}m^2/s$. The rate of flow of water into and out of the GHB cell is proportional to the difference between the *boundary head* and the head within the cell. Conductance is the factor relating the difference in head to the rate of flow.

The WEL package was activated as drains to see how much water can be extracted from the groundwater system. Each well is imported into ModelMuse from the .csv file as a separate object with point topography to the model top with set values of cells by fitted surface interpolation. Pumping rate interpretation is set at direct, and each well is pumping at a rate of $3 \times 10^{-2}m^3/s$.

To study the interaction between surface water (rivers) and the groundwater system, the RIV package was activated and river shapefile was imported as single multipart object with set values of enclosed cells. The river stage was set at the model top. River conductance is a parameter that reflects how much the boundary condition is connected to the aquifer with regards to the riverbed materials. River conductance is calculated as $1x10^{-2}m^2/s$. A two (2) quadtree refinement is done along the river. The river bottom is at a distance of the model top minus 1 metre, as given by the digital elevation model.

e). Initial Conditions and Hydraulic Properties

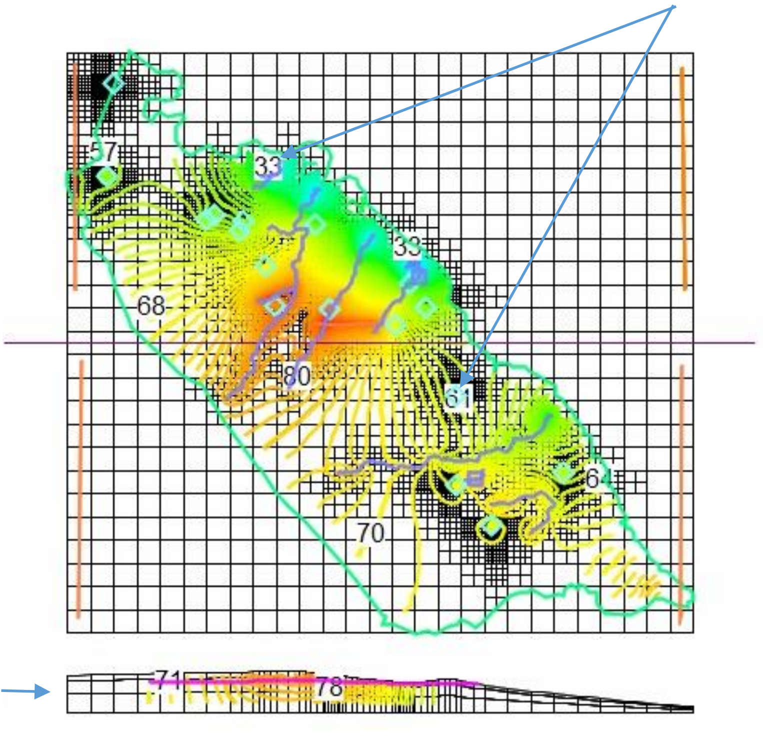
Initial Conditions and Hydraulic PropertiesThe aquifer layers in the vertical direction have a thickness of 120 m. The aquifer has been divided into upper, middle and lower aquifers. The thickness of the upper, middle and lower aquifers has been calculated as 15%, 35% and 50% of the entire thickness based on the progressive thickness of aquifer technique by Brookfield (2016) and Winston (2019). Horizontal hydraulic conductivity K_x $(1 \times 10^{-})^4$ from the 1st to 3rd layer are assumed to be Isotropic aquifer. $K_y = K_x$. $K_z = K_x /10$. Modflow Initial head is the model top. Steady-state simulation run time is 5.34 seconds, an indication that simulations can be done in less time and this optimises the number of cells during calculation, which is the main feature of the unstructured DISV grid. The refinement has also highlighted the contour lines and flow direction. The main changes in the groundwater flow are related to the boundary conditions.

Model Simulation and Output

The most significant inflow to the model comes from the river ($2.23 \times 10^5 m^3/d$). The general head boundary is also pumping water into the groundwater system ($5.45 \times 10^4 m^3/d$). Table 6.12 presents a summary of the regional volumetric water budget following the steady state simulation run. The river is taking more water out of the groundwater system which is an indication of it acting as a gaining and losing source at some stage during interaction with the aquifer environment. Inflow from the GHB is mainly from other water sources (e.g. swamps). The simulated drawdown heads/capture zones of the wells (metres) and the water table cross section at a steady state are shown in Figure 6.9. The result is discussed in Section 6.12.4. The detailed discretisation information and volumetric budget for the unstructured grid simulation are found in Table D6.1 in Appendix D6

Table 6. 12 Summary of Volumetric Water Budget at Steady-state Unstructured Grid Simulation generated from Modflow Run

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
WELL	0.0	4.14×10^4
RIVER	2.23×10^5	2.33×10^5
GENERAL HEAD BOUNDARY	5.45×10^4	3.62×10^3
TOTAL IN	2.78×10^5	0
TOTAL OUT		2.78×10^5



Drawdown heads (metres)

Cross section showing water table level (reddish pink)

Figure 6. 9 Regional simulated drawdown heads (metres) and the water table cross section generated from Modflow Run

6.5.5 Model Calibration for future Water Supply Management from Infiltration Galleries

The objectives for undertaking this water supply management calibration (Table 4.6 in Section 4.11) are (i) identify management strategies to monitor future abstraction, (ii) simulate the behaviour of the groundwater system and (iii) evaluate the water balance to maximize the total quantity of water that can be recovered from high head gradient areas for future sustainable and improved water supply to the residents. In this model calibration, the area of interest is within a river plain aquifer, about 1km long between the following (X,Y) Coordinates 696381, 704481, and 931738, 939238 represented in Figure 6.10, selected using QGIS environments. One criterion for the area of interest is that it must have a radius of influence and cone of depression. Once the area domain has been selected, the procedure included downloading the AsterDEM, define the alluvial aquifer, set hydraulic parameters and set up boundary conditions. The calibrated model parameters, Modflow packages and spatial information used for modelling water supply from infiltration galleries are listed in Table 6.13.

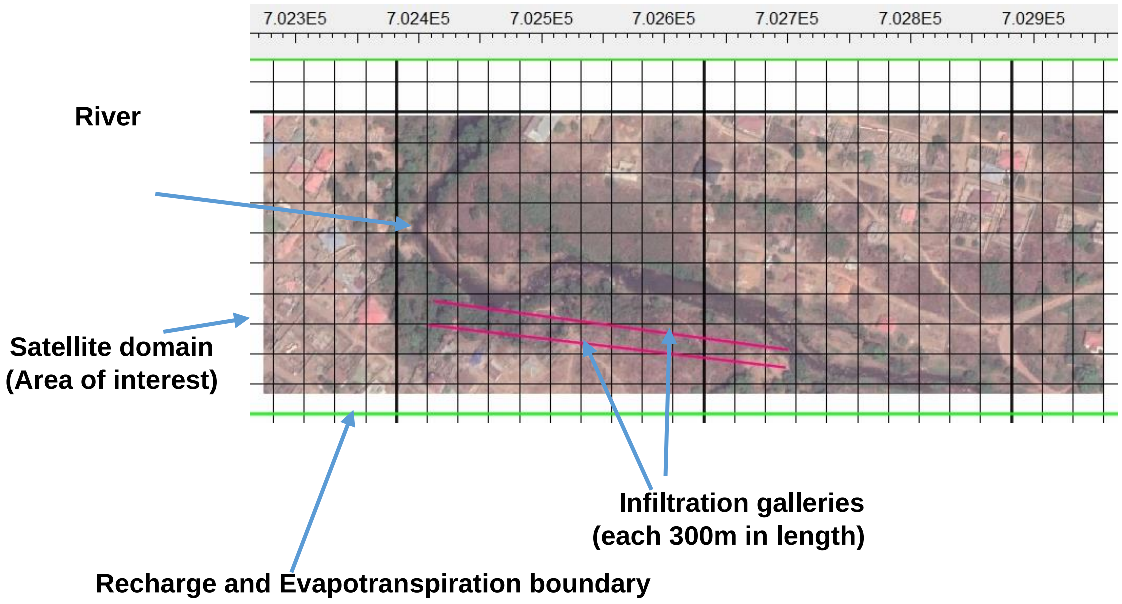


Figure 6. 10 Satellite domain and area of interest for Water Supply from Infiltration Galleries Model Calibration (Source: authour's construction)

Table 6. 13 Model Development and Configuration Information for Simulation of Future Water Supply Management from Infiltration Galleries (Source: authour's construction)

Model Development and Configuration Information		
Model Design	a). Conceptual Model	- Domain area of 25.5 km^2 simulated using MODFLOW-NWT
	b). Model Geometry	- Convertible rectangular alluvial aquifer layer
	c). Model Grid and layering	- Single alluvial aquifer layer (No grid) - Vertical discretisation into 5 layers at depth of 70 m
Flow Package	UPW: Upstream Weighting package	- Iterative Model Solution, Linear inner maximum iterations value of 100
Boundary array (cell type)	d). Constant head boundary - *Head dependent flux*	- Drain Package (DRN) - River Package (RIV) - Evapotranspiration Package (EVT)
	- Specified flux	- Recharge Package (RCH)
Model Calibration Parameters	Time Steady state calibration (-1 to 0 seconds)	- Convertible and output on steady state run at 3.64 seconds
	Spatial datasets	- EPSG Projection 32628 - Polygon of the raster extension area - Alluvial aquifer shapefile - Contour shapefile - Polygonise river shapefile - Background map, Google satellite of domain - Infiltration gallery (polyline construction)
	Hydrogeologic characteristics	- Hydraulic conductivity - River conductance - Drain conductance
Boundary Condition	e). Initial Condition and Stress	- Initial head condition is top of model - Hydraulic conductivity, RIV/DRN conductances, RCH, EVT are model calibration parameters
Solver	NWT – Newton Solver	- Maximum number iterations equal 100

a). Conceptual model and b). Model Geometry

MODFLOW-NWT was used to simulate the river related to a valley in the southwest region of the watershed, to see how much water supply can be abstracted if two infiltration galleries each of three hundred metres in length are inserted in the identified area. Infiltration galleries can vary in length from a few metres to several hundreds of metres (Bekele *et al.*, 2009). To achieve the same yield, infiltration galleries can be either significantly longer or greater in diameter for considerable advantage in a permeable geological environment. The selected area is primarily composed of alluvial sediments, weathered, and fractured gabbroic materials.

c). Model Grid Layering and d). Constant Head Boundary

The base map of the study area was imported into the model and was set according to the UTM coordinate system. The model is based on a rectangular block-cantered grid system covering the entire model domain. Fitted surface interpolation was chosen while importing the topographic map. A three-dimensional model is set up to represent a vertical section of the riverbed. The cross-section of the model setup used in the numerical simulation is shown in Figure 6.10. The finite difference 3-D simulation grid was constructed with 97 rows, 108 columns and with a no grid angle of 0 degrees.

A polygon of the aquifer domain is needed because the lower aquifers of the watershed are dry and water is concentrated only in the alluvial aquifer layer. Therefore, the alluvial aquifer needs to be defined in the form of a shapefile. The model extension domain is calibrated with a grid cell size of 25m and a single aquifer which is convertible and further discretised into five (5) layers (Alluvial aquifer). The alluvial aquifer shapefile is imported into MODFLOW as a single multipart object with two Z formulas from top of the model to the bottom of the alluvial aquifer. The calibration was performed using the upstream weighting package. The contour shapefile of the domain is imported as a single multipart elevation object into MODFLOW and set values by fitted surface interpolation. In temporal discretisation, the model was simulated under steady-state conditions.

e). Initial Conditions and Boundary Stress Conditions

Modflow initial head condition was the model top and run on a steady state simulation using no flow boundary. Recharge, evapotranspiration, hydraulic conductivity, river conductance and drain conductance were used as model calibration parameters. The aquifer conditions were defined as homogenous and isotropic throughout with

hydraulic conductivity (m/s) values of K_x as 5 x 10^{-4}, $K_y = K_x$ and $K_z = K_x/10$. Recharge and evapotranspiration flux surrounded the model boundaries.
Recharge location is set as the top active cell to allow an up and down movement as the cells in the surface convert from wet and dry. The top layer (alluvial aquifer) has a slightly higher hydraulic conductivity value of 5 x 10^{-4} m/s and recharge rate is 1.26 x10^{-8} m^3/s.

To simulate evapotranspiration, a maximum evapotranspiration rate of 4.43 x10^{-8} m^3/s was used. The top of the model was taken as the evapotranspiration surface and the evapotranspiration depth was 1 m below the surface.

The drain package was represented in the model as the infiltration galleries because they will take water out of the groundwater system. They are created with a polyline object of 300m each in length. Drain elevation was set at 5 metres below the model top with a conductance of 1x$10^{-3}$$m^2$/s.

In the Modflow river package, the polygonised shapefile of the river was imported as a single multipart object and set values of intersected cells. The river stage is the model top and the river bottom is assumed as the model top minus 2 metres. A direct conductance interpretation of 1x$10^{-3}$$m^2$/s was used because it will apply the conductance to all the cells.

Model Simulation and Output

Table 6.14 presents a summary of the volumetric water budget following the end of simulation steady state run. The simulated drawdown heads for steady state and the water table cross section are shown in Figure 6.11. The importance of Figure 6.11 is discussed in Results and Discussions Section (6.12.4)

The most significant inflow to the groundwater system comes from the river at 1.40x$10^5$$m^3$/d. Recharge is also pumping into the system at 1.02x$10^3$$m^3$/d. The river is taking out 1.19x$10^5$$m^3$/d, evapotranspiration is taking out 5.16 x$10^2$$m^3$/d and the drains (infiltration galleries) are taking 2.22x$10^4$$m^3$/d out of the aquifer system. There is evidence of diverging flow at some point along the river (contours are pointing downstream) into the groundwater system (Losing River) and converging flow where the river is taking water (Gaining River) from the groundwater system.

The detailed discretisation and volumetric budget for the infiltration galleries for water supply simulation are found in Table D7.1 in Appendix D7.

Table 6. 14 Summary of volumetric water budget after steady-state water supply from infiltration galleries simulation generated from Modflow Run

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
STORAGE	0.0	0.0
CONSTANT HEAD	0.0	0.0
DRAINS	0.0	2.22 x10^4
RIVER LEAKAGE	1.41 x10^5	1.19 x10^5
EVAPOTRANSPIRATION	0.00	5.16x10^2
RECHARGE	1.02 x10^3	0.0
TOTAL IN	1.42 x10^5	0.0
TOTAL OUT		1.42 x10^5

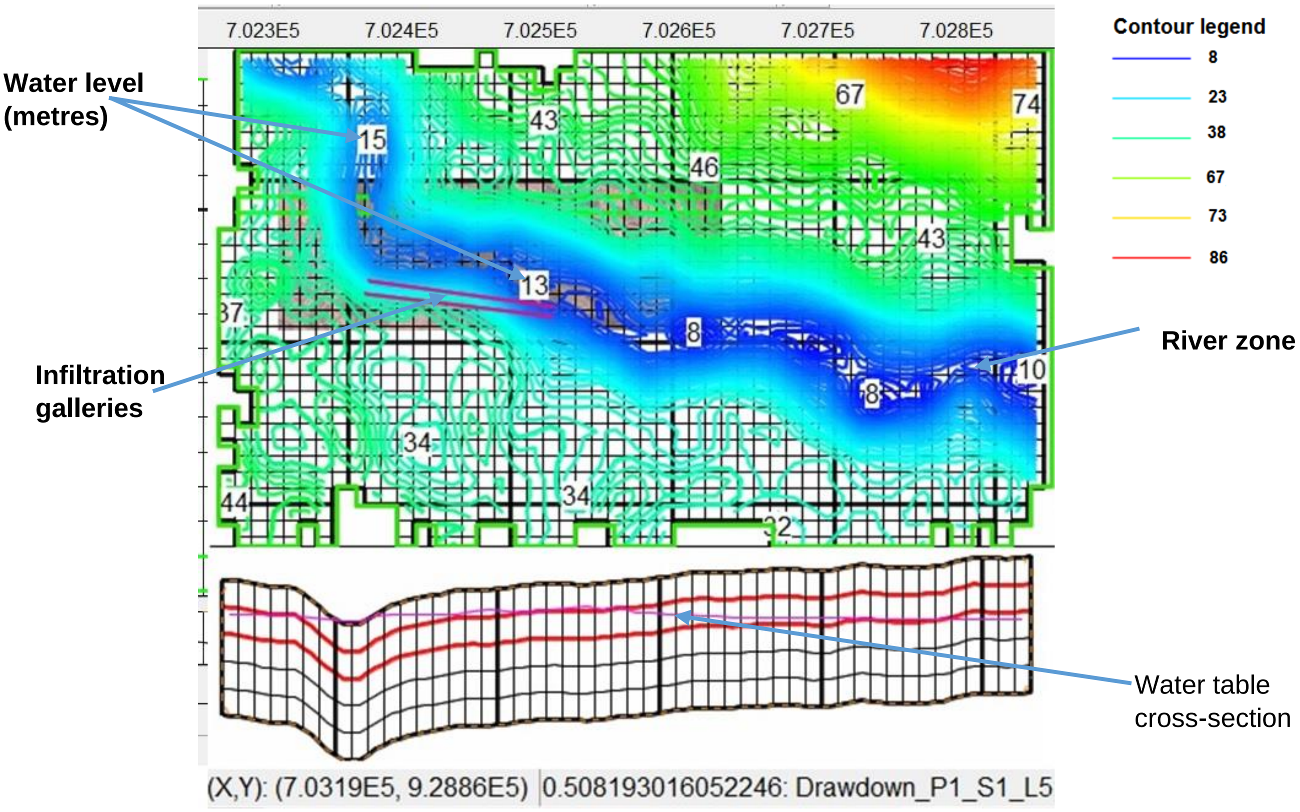


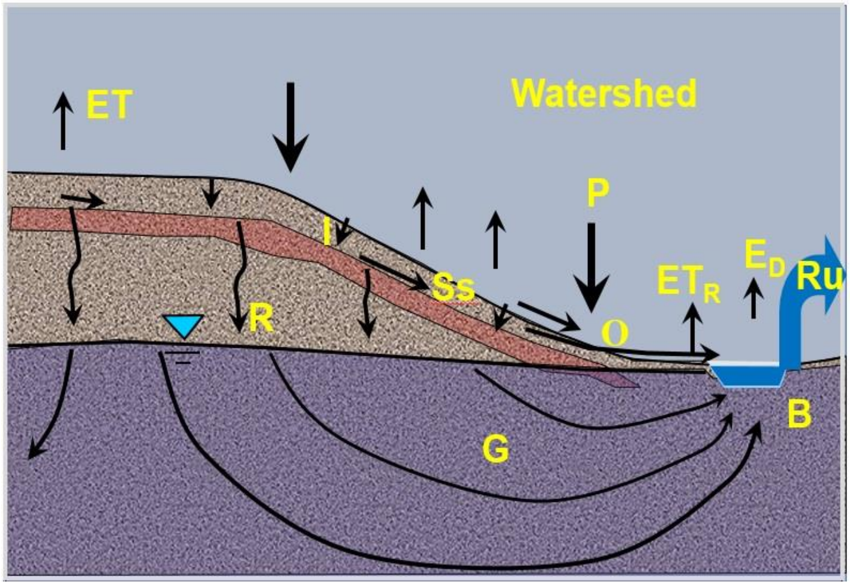
Figure 6. 11 Simulated drawdown heads in and cross section of the Infiltration galleries water level in metres generated from Modflow Run

6.6 Groundwater Models Validation

Regardless of how sophisticated the modelling approach is, it can only give a simplistic representation of complex field conditions when applied to a subsurface flow problem. Validation involves ensuring a model accurately represents the real world. A model should be viewed in this way as a dynamic representation of nature that can be refined and improved with time. Konikow (1986) suggests that models should be viewed in this light as dynamic representations of nature. In order to establish the validity of predicted results, new data can be collected and then evaluated, validated, or invalidated (Konikow and Bredehoeft, 1992). Hence, the validation process is required to evaluate a model's performance and generate confidence that a model is suitable for making decisions on water management and monitoring.

To validate the developed models and gain confidence in the simulation results, simple one-dimensional analytical watershed problems using same methods as the complicated three-dimensional numerical groundwater models have been designed and the volumetric budget is calculated analytically (Wegehenkel, 2005; Corbari and Mancini, 2014; Turkeltaub *et al.*, 2015). The outputs from this validation process will be compared to the results of the numerical simulation. This will then interpret the magnitude and broaden awareness and understanding of water budgets (Song *et al.*, 2015).

The approach is based on how all the processes namely groundwater flow, surface runoff, stream flow, precipitation, evapotranspiration infiltration etc. work together to create the hydrologic cycle (Arnold et al., 1993; Liang et al., 2003). A watershed includes the streams with tributaries in that surface area and the underground aquifers and soils that supply water to those streams. An example of a watershed is shown in Figure 6.12 (Arnold and Allen, 1996; Burbey *et al.*, 2012).



S_S = Stormflow
Re/R = Recharge
I = Infiltration
ET = Evapotranspiration
ET_R = Riparian Evapotranspiration
E_D = Direct Evaporation
Ru = Runoff
G = Groundwater
O = Overflow
B = Baseflow
P = Precipitation

Figure 6. 12 Diagram of a watershed courtesy of Clemson University Field Hydrogeology (2012)

The water balance method will look at a really simplistic way of modelling the hydrologic processes and is based on the law of conservation of mass. The process involves defining the system and control volume and then apply the law of conservation of mass to the water volume flowing into and out of the system. The basic conservation equation states that the amount of water entering a controlled volume of a system during a defined period of time minus the amount of water leaving the system within that defined period of time is equal to the change in the amount of the quantity stored in the volume during the time period (Δt) as shown in the control volume diagram in Figure 6.13.

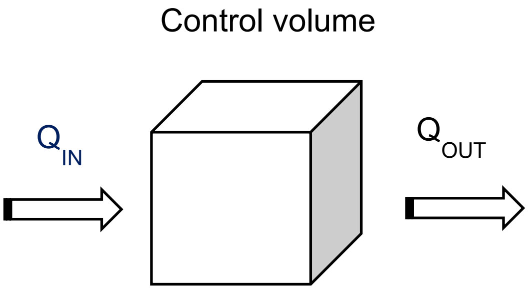


Figure 6. 13 Conservation of mass control volume

$$INFLOW - OUTFLOW = \Delta STORAGE\ (Change\ in\ storage) \qquad \text{(Eq 6.1)}$$

Where,

Q = volumetric flow rate or the discharge rate (m^3/s),

INFLOW = volume from water balance components into the watershed

OUTFLOW = volume from water balance components out of the watershed

ΔSTORAGE = Change in storage

Three situations exist from this equation, if IN flow is greater than OUT flow, then ΔS is positive (greater than zero), therefore volume in storage will increase.

$$INFLOW > OUTFLOW,\ \Delta STORAGE > 0 \qquad \text{(Eq. 6.2)}$$

If IN flow is less than OUT flow, then ΔS is less than zero and volume in storage will decrease.

$$INFLOW < OUTFLOW,\ \Delta STORAGE < 0 \qquad \text{(Eq. 6.3)}$$

If IN flow is equal to OUT flow, then ΔS is equal to zero and the volume is stabilise with no change.

$$INFLOW = OUTFLOW,\ \Delta STORAGE = 0 \qquad \text{(Eq. 6.4)}$$

The main water resources of Freetown consist of surface water resulting from precipitation (rainfall), perennial rivers, swamps, and groundwater. Currently, data on these resources quantities only exists online for up to the 2017 water year, so all calculations are based on that year.

Equation (6.1) is applied to the hydrologic system of the Freetown watershed. The first part in applying the water balance equation is to solve the problem symbolically before applying the figures. This means that all the water balance components (e.g. precipitation, evapotranspiration, baseflow etc) must be identified either as an inflow or outflow from the watershed to write the solving equation that applies to the watershed situation.

Each of these water balance components is composed of one or more terms. For example, the inflow component may consist of the sum of all the following: recharge from precipitation, baseflow across a boundary, water introduced through injection wells, and infiltration from losing rivers as depicted by the arrows in Figure 6.12.

The design water balance method involves quantifying all fluxes (water budget components) across the watershed boundaries using the weather data in Table 6.15 and Table 6.16 displaying the seasonal discharge data for estimating the water balance components. The total inflow, outflow, and/or volume change related to storage variation are the validation values. The fluxes are estimated using one-dimensional models for the long-term numerical simulations (Carrera-Hernández et al., 2012).

Table 6. 15 Water Balance Component: Precipitation (P) and Evapotranspiration (EVT) all in mm/yr.

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
P	2	1.7	17.3	35	176	352	940.3	1219.3	754.3	258.7	104.3	8	3868
EVT	0.96	0.7	7.7	15.4	74.4	158.8	436.3	588.9	394.5	111.8	47.6	3.3	1840.3

Source: Sierra Leone Meteorological Agency

Table 6. 16 Seasonal Discharge of some Catchments in Sierra Leone.

Region	**Area (km^2)**	**Estimated mean annual discharge (10^6 m^3/year)**	**Monthly average discharge rainy season (m^3/s)**			**Monthly average discharge dry season (m^3/s)**		
			Mean	Min	Max	Mean	Min	Max
Modelled area	25.5	35	23.7	0.44	46	6.89	0.34	21.7
Freetown	74	132	69	1.3	135	20	1	63
Western Area	557	1,020	668	10	1,296	84	8	500

Source: MAFFS-MFMR (2004)

6.6.1 Validation process of Numerical Models Simulations

A validation process has been defined to ensure that the simplistic water balance models provide a good representation of a real system (numerical models developed in Sections 6.5.1 to 6.5.5) to compare the magnitude of the components in the watershed.

a. Applying water balance equation over the entire watershed

From the information in Table 6.16, it is possible to calculate the average annual evapotranspiration (ET) from soil, plant and from all surface water on the land to the atmosphere using equation 6.1. Using Figure 6.14 to represents the conservation of mass control volume for the 25.5 km^2 drainage area (A), with a mean annual runoff, Q of 1.1m^3/s out of the watershed, and an average annual precipitation (P) of 3.8m/year (Table 6.15).

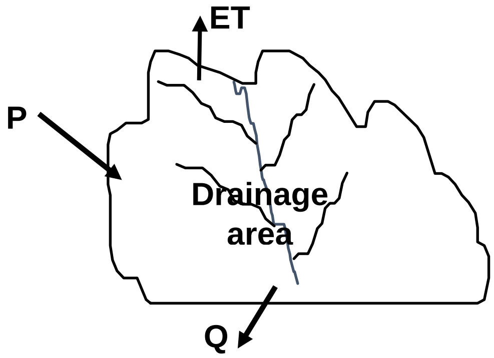


Figure 6. 14 Conservation of Mass Control Volume Watershed (Source: authour's construction)

Given information:

- Drainage area, A = 25.5 km^2
- Mean annual runoff, Q = 1.1m^3/s (outflow)
- Average annual precipitation, P = 3.8m/yr (inflow)
- Δt = change of time is for a period of 1 year

Find:

- Average annual evapotranspiration, ET

Assuming there are no losses of groundwater to nearby water bodies, and that since data and calculation period is for a year, then the change in storage is equal to zero If the year starts from September 1st to 31st of August, then the assumption is that the volume of water stored in the watershed on September 1st, is the same as on August 31st, it may change over the course of the year but the net change in water in the year is assumed to be zero. This is a fair assumption as the watershed has not experienced a major drought event.

Assumption:

- $\Delta S = 0$

Water Balance Equation:

$$IN - OUT = \Delta S$$

$$P - (ET + Q) = 0 \qquad \text{(Eq 6.5)}$$

$$Solving\ for\ ET = P - Q \qquad \text{(Eq 6.6)}$$

Conversion of units

To have the ET expressed in metre per year (m/yr), the Q (m^3/s) should be converted to metres per year (m/y), by dividing the watershed area A, and applying the unit conversion as in equation 6.7 below:

$$\mathrm{Q} = \frac{1.1\frac{\cancel{\mathrm{m^3}}}{\mathrm{s}}\mathrm{x}\frac{86400\mathrm{s}}{\cancel{\mathrm{days}}}\mathrm{x}\frac{365\ \cancel{\mathrm{days}}}{\mathrm{year}}}{25.5\cancel{\mathrm{km^2}}\mathrm{x}10^6\cancel{\mathrm{m^2}}/\cancel{\mathrm{km^2}}} = 1.36\,\frac{\mathrm{m}}{\mathrm{yr}} \qquad \text{(Eq. 6.7)}$$

Substituting for Q in equation 6.6

$$\mathrm{ET} = \mathrm{P} - \mathrm{Q} \quad \text{then, } \mathrm{ET} = 3.8 - 1.36 = 2.44\,\frac{\mathrm{m}}{\mathrm{yr}}$$

From the calculation, it is seen that in the watershed, it rains more than it evaporates annually. Comparing the magnitude in the control volume, precipitation is twice the evapotranspiration over the one-year period. It is also common that actual ET from high elevation areas is in fact less than from open water in valley or swamp evaporation.

b. **Applying water balance equation to calculate changes in the soil water storage.**

This control volume is the watershed with a moderate slope topography of area A, 25.5 km^2, which has experienced a period of rainfall (storm) with an average rainfall intensity (i) of 40 mm per hour for 40 minutes.

The assumption is that in a storm period evaporation is negligible because it is cloudy, humid and evaporation rate is very low compared to the rate of precipitation expected. Therefore, evaporation is not a component considered in this case. The total surface water flow during the 40 minutes was twenty-five thousand litres[14] (2.5x10^4l). It is also assumed that percolation due to gravity into deeper groundwater is negligible because of time of rainfall. The change in the soil water storage that occur during this period is calculated from the control volume reconstruction in Figure 6.15.

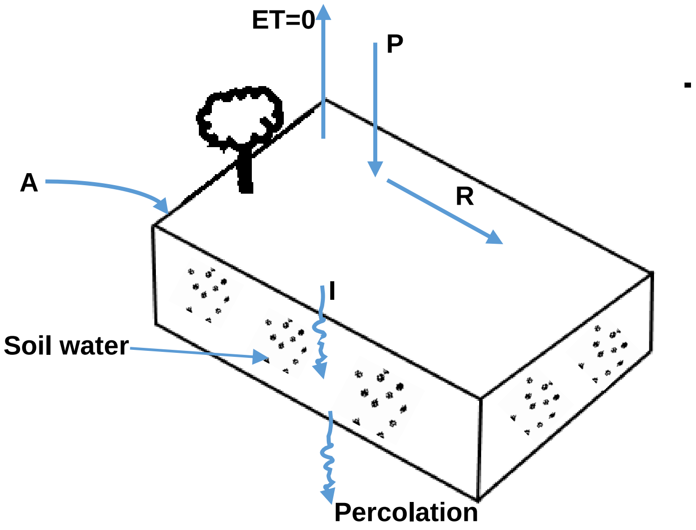


Figure 6. 15 Control Volume on a Moderate Slope during Storm fall (Source: authour's construction)

Precipitation (P) that falls to the surface is not actually an inflow to the control volume. Surface runoff (R) over the surface and infiltration (I) from the surface into the subsurface which is the inflow into the control volume. The control volume is the water stored in the soil under the 25.5 km^2 area and to do the water balance, the infiltration

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[14] https://slmet.gov.sl

volume has to be determined. Percolation is an outflow from the soil control volume, but equal to zero. Given the following data below:

Given information:

- Time period, Δt = 40 mins
- Rainfall intensity, (i) = 40mm/hr
- Surface runoff, (R) = 25x10^4 litres
- Area, A = 25.5km^2
- Storm precipitation, P

Assume:

- ET ~ 0
- Percolation ~ 0
-

Find:

- Change in storage of soil water, ΔS

Solution:

Water balance equation for soil water storage:

$$IN - OUT = \Delta S$$

$$\mathrm{I\ (infiltration)} - \mathrm{(outflow)} = \Delta S \qquad \text{(Eq 6.8)}$$

Determining how much water infiltrated into the soil will help inform on the increase in the soil water storage volume change. To figure out the infiltration, water on the surface has to be taken into consideration that is precipitation going in, runoff on the surface and infiltration soaking in and this will be the difference between precipitation and runoff. When water precipitates on the ground surface, the first thing that happens is that the water will soak into the soil until the precipitation rate overwhelms the infiltration capacity of the soil, then runoff happens because water does not infiltrate further into the soil.

$$Infiltration\ I = P - R \qquad \text{(Eq 6.9)}$$

$$Storm\ precipitation,\ P = i\ x\ \Delta t \qquad \text{(Eq 6.10)}$$

Hence,

$$\mathrm{P} = 40\frac{\cancel{\mathrm{mm}}}{\cancel{\mathrm{hr}}}\,\mathrm{x}\ 40\cancel{\mathrm{mins}}\ \mathrm{x}\frac{\cancel{\mathrm{hr}}}{60\ \cancel{\mathrm{mins}}}\,\mathrm{x}\frac{\mathrm{m}}{1000\cancel{\mathrm{mm}}} = 0.03\mathrm{m} = 30\mathrm{mm}$$

Converting R (surface runoff) into millimetres of runoff over the forty minutes period, to give the volume of water applied over the drainage area. The volume is then divided by the area (25.5km^2) to get the volume in unit of depth.

$$\mathrm{R} = \frac{2.5\mathrm{x}10^4\mathrm{lx}\frac{0.001\cancel{\mathrm{m}}^3}{\mathrm{l}}}{10^4\cancel{\mathrm{m}}^2} = 0.025\mathrm{m} = 25\mathrm{mm}$$

Substituting P and R into equation 6.9 below, infiltration can be calculated

$$I = 30mm - 25mm = 5mm$$

Infiltration is equal to the change in storage (Eq.6.8), therefore the change in storage over the 40 mins time period of storm fall is equal to 5mm.

$$\Delta S = 5mm$$

The water balance equation methods have been useful to estimate the water balance components (such as evapotranspiration, infiltration, baseflow etc) that cannot be measured easily especially in areas where the equipment and expertise are lacking, and to understand the dynamics of groundwater flow in the aquifer system. These are simple analytic ways of expressing volume of water in terms of depth applied over a watershed.

6.7 Groundater Numerical Models Results and Discussions

In this study, the groundwater numerical simulations developed earlier in this Chapter, have been implemented to explore the viability of groundwater as an additional top-up resource to meet the present and future water demand of Freetown. This chapter also focuses largely on the results of the various analyses carried out namely topographical characteristics using GIS environments, rainfall characteristics, temperature characteristics, assessment of groundwater flow, groundwater quantity analysis, and water supply from infiltration galleries.

6.7.1 Modelled Area for Groundwater Development

Information about Freetown's regional groundwater system on its location, pumping capacity, recharge potential and sustainable yield are practically unknown. Currently, a few numbers of industrial and personal boreholes/shallow hand-dug wells are found across the study area with only pumping test information and not in-depth hydrogeology data leading to a multitude of issues including unproductive wells, unsuccessful siting, poor construction and water quality issues. To deal with these problems, thematic digital maps of the modelled area that will provide the baseline information for guidance on sustainable groundwater abstraction were prepared. These maps will be used to support the discussion for water development, management and identify potential sites for new constructed vertical and horizontal wells. Figure 6.16 shows the land use and land cover map of the selected modelled area comprising an area of 25.5 km^2 within the study area.

Land use/land cover maps are prepared to deduce information on the details of its natural existence namely the vegetation cover, water body, land with shrub, and wasteland. Land use class includes the area occupied by man as defined in the built-up area for habitation and other purposes which include all major towns, settlements, habitations, neighbourhood villages. In the modelled area, the built-up land is identified by red colour and spread over an area of 22.0 km^2. The vegetation area constitutes 3.5 km^2 of the modelled area, while water is about 0.2 km^2.

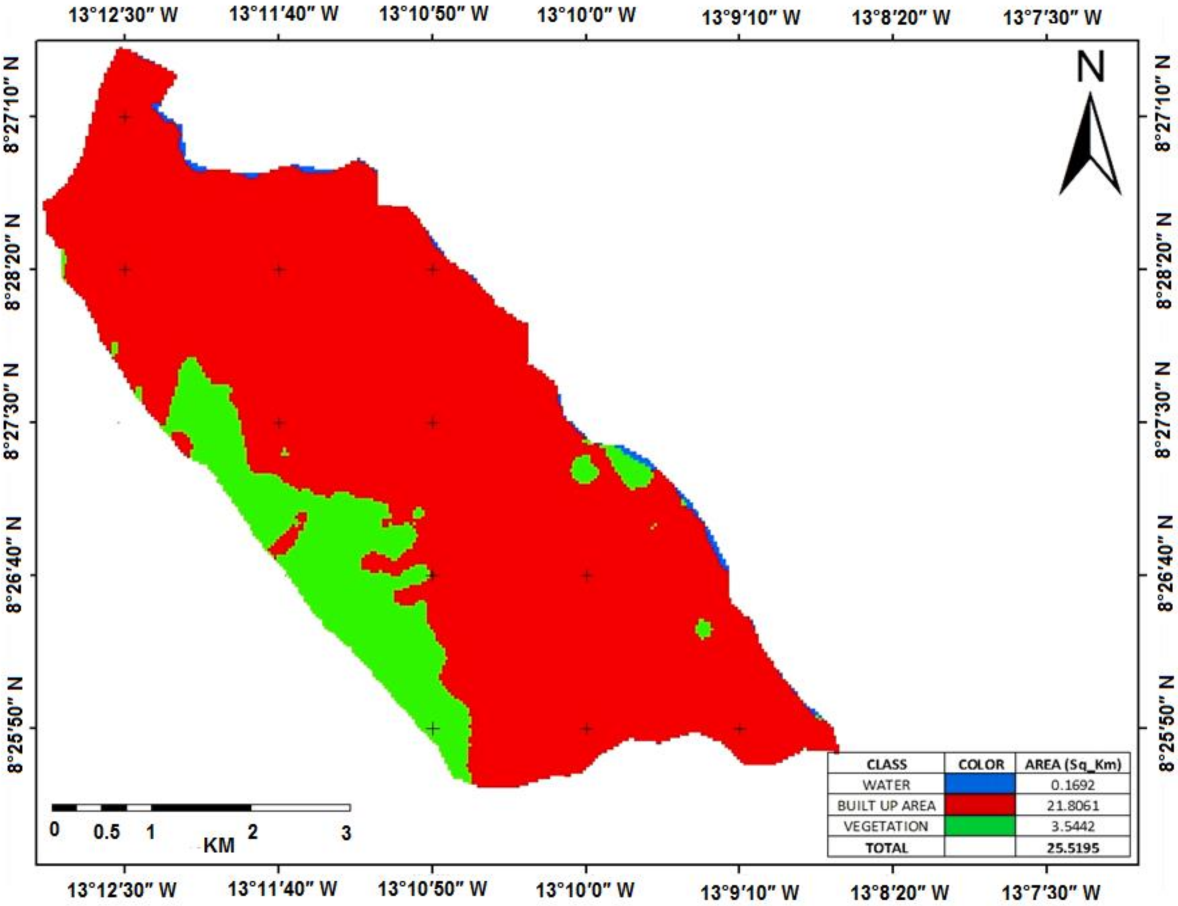

Figure 6. 16 Modelled Area Land Use and Land Cover distribution Map

(Source: authour’s construction)

6.8 Study of Topographical Characteristics

The topographical characteristics of the study area were analysed using ArcGIS techniques as explained in Section 4.6, Sub-Section 4.6.6 of Chapter 4. The maps prepared from OpenTopography Shuttle Radar Topography Mission (SRTM GL1) Global 30m resolution data downloaded and using GIS were land use/land cover map, geology map, aspect map, slope map, drainage density map, flow direction map, contour map, elevation map, curvature map, soil map, drainage water ways.

6.8.1 Hydrogeological Maps of Modelled Area

The different hydrogeology maps were prepared to provide supporting information on the study areas and also to serve as a valuable decision tool for water resources managers and planners in developing, managing, and protecting the water resources in the study area. The maps include slope map, drainage basin map, drainage density map, flow direction map, drainage waterways, contour map, elevation map, soil map, aspect map, and curvature map. The significance of creating these maps have been explained in Sub-sections 4.6.2 to 4.6.8 of Chapter 4. GIS plays an important role in understanding groundwater flow, drainage characteristics, and identifying groundwater potential zones. These maps will serve as the hydrogeologic information for the study area characterised by data scarcity. Figures 6.17 to 6.22 show the various hydrogeology maps of the modelled area.

The hydrological soil map shown in Figure 6.17 was classified as gravely ferralitic, shallow lateritic, weakly developed muds and hydromorphic clays. It was observed that the gravely ferralitic soil covers two-thirds of the total area, shallow lateritic, weakly developed muds, and hydromorphic clays occupy the rest of the area. Gravely ferralitic soil allows the water to percolate into the ground surface and is more prominent in the study area.

The drainage density map is shown in Figure 6.18. Drainage density depends on both climate and characteristics of the drainage basin. Soil permeability, infiltration difficulty, and the underlying rock type impact runoff in the watershed and will lead to an increase or decrease in surface water runoff. The analysis reveals that the drainage density in the modelled area ranges between 1.12 and 48.78 km^{-1}. These ranges are divided into classes of low (less than 20.37), medium (20.37 – 26.35), and high (more than 26.35). The low value of drainage density is observed in regions underlined by highly permeable material with vegetative cover and low relief.

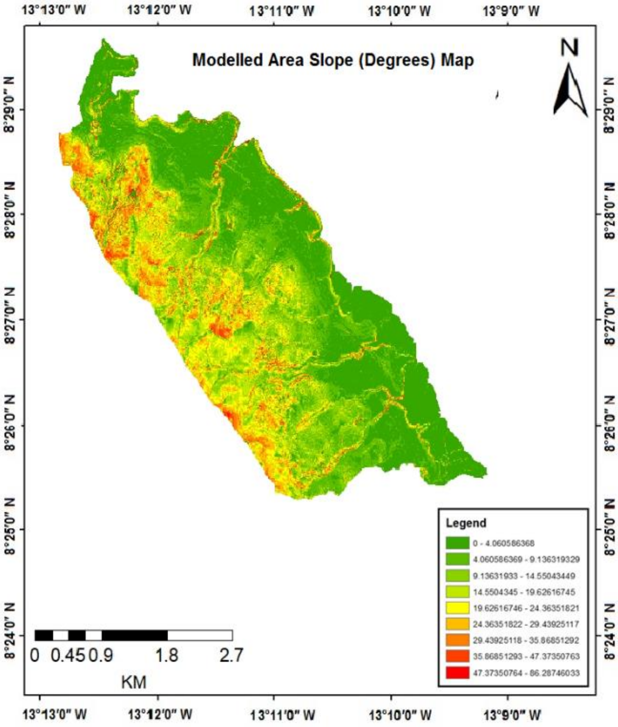

Figure 6. 20 Modelled Area Slope Map (Source: authour's construction)

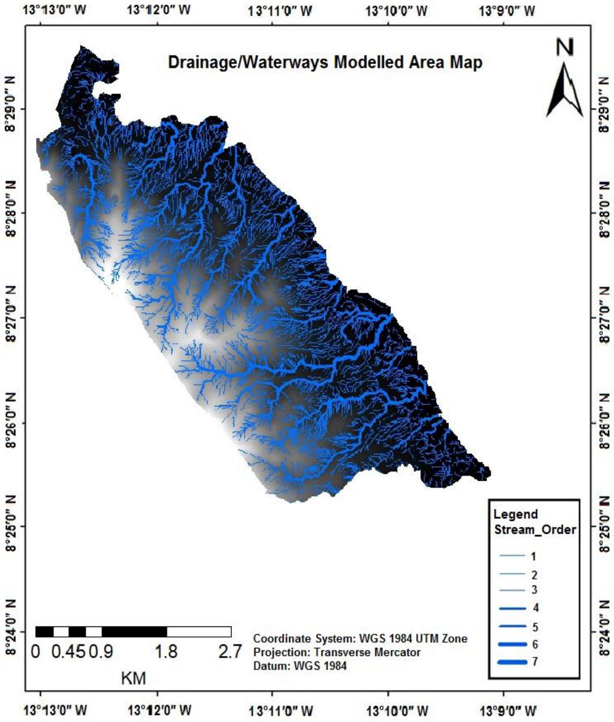

Figure 6. 19 Modelled Area Drainage Waterways Map (Source: authour's construction)

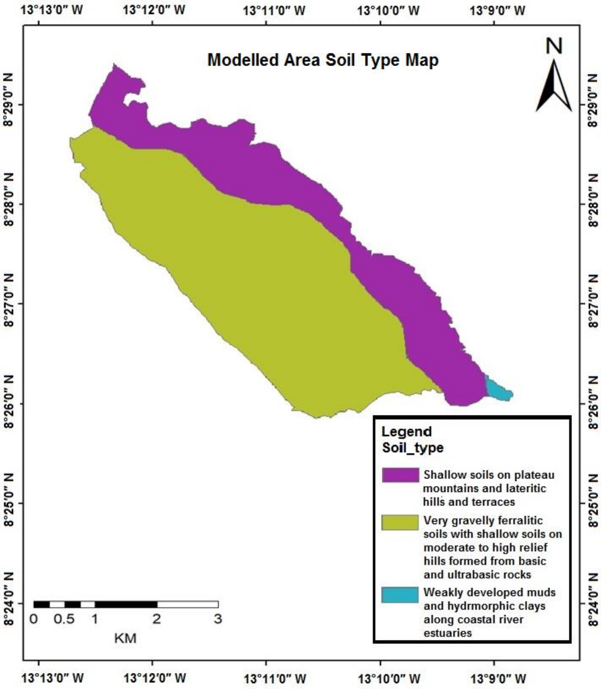

Figure 6. 17 Modelled Area Soil Map (Source: authour's construction)

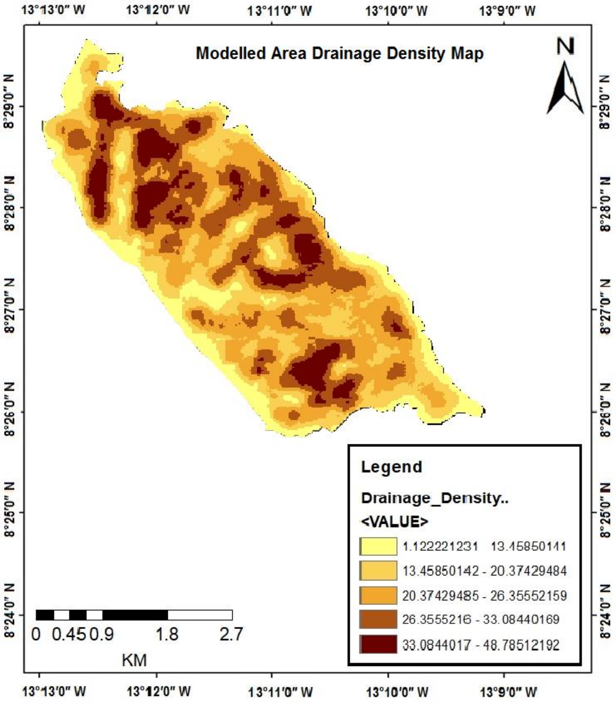

Figure 6. 18 Modelled Area Drainage Density Map (Source: authour's construction)

High-drainage density is observed in the regions of weak permeable material. Generally, the area has a low potential for overland flow with more infiltration and more groundwater storage capacity.

Figure 6.19 shows the drainage waterways of the modelled area. As a result of the fundamental relationship between drainage, texture, and density, an understanding of drainage patterns has long been a critical component of hydrogeological analyses (Ozdemir and Bird, 2009; Arkoprovo et al., 2012; Singh et al., 2014). Drainage waterway maps show us the direction in which surface water flows. Infiltration of surface water leads to groundwater formation in a particular region, so the flow direction of surface water is important. The drainage pattern can be used to identify the patterns. The next figure (Figure 6.20) shows the slope (degrees) map. A slope map is a good indicator of infiltration rate. Water will have a shorter period of contact with the surface when the slope is greater, thus reducing its rate of infiltration. A good groundwater potential will result in places where surface water infiltration is high and surface water contact is high. An area is then classified into several categories based on slopes (e.g. gentle slope, moderate slope, moderately steep to steep sloping, strongly sloping, and very mild slope).

In Freetown, the aquifers are unconfined aquifers and water is moving following the flow of gravity from the highest point to the lowest point. The direction is the same as the topography, and the groundwater table follows the same direction as the topography. At some points in time, the groundwater flow does not follow the topography, the direction of flow of water is generally determined by the hydraulic gradient and slope of the groundwater table. Hence, the same area map (Figure 6.21) can have different groundwater flow directions. Groundwater in a particular area is based on the infiltration of surface water, so the flow direction of the surface water is important. This could be identified by the pattern of drainage. The analysis from the eight direction pour point model discussed in Sub-Section 4.6.6 of Chapter 4, for flow direction shows that water is flowing from the east direction to more than one of the adjacent cells, but mostly flow is to the southwest in the study area.

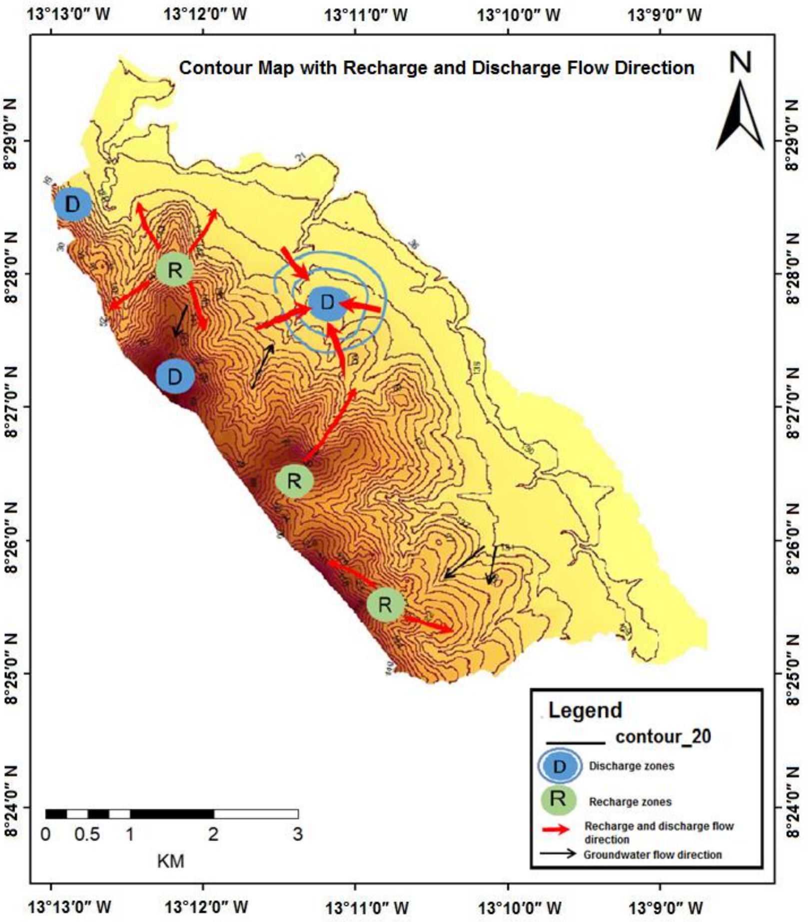

Figure 6. 21 Modelled Area Contour Map Showing Groundwater Recharge and Discharge Flow Direction (Source: authour's construction)

The contours shown in Figure 6.21 represent lines of equal heads in the groundwater and with values ranging from below 10 m along the coastal area to more than 250 m above sea level (asl) in the mountain ridges. Variation in the contour spacing represents a change in the hydraulic gradient. The flow direction of groundwater is perpendicular to the contour lines. Water table elevation is one major criterion to determine the position of the water table. The permeability may vary in the different zones of the aquifer, and therefore the elevation, contour, and flow direction maps are valuable in determining the horizontal groundwater flow direction Figure 6.22.

The output of the D8 flow direction analysis performed on the modelled area is shown in Figure 6.22. The resulting flow direction was the input for the flow accumulation analysis. Flow direction is mainly from the northeast to southwest in the watershed.

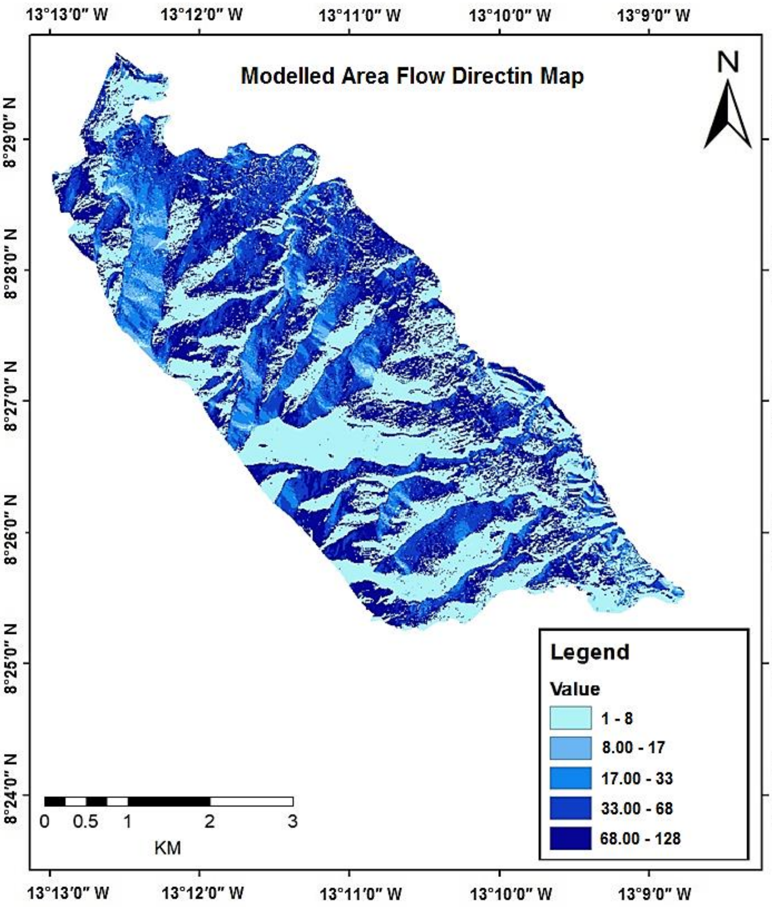

Figure 6. 22 Modelled Area Groundwater Flow Direction Map (Source: authour's construction)

6.9 Study of Rainfall and Temperature Characteristics

A systematic analysis of the rainfall and temperature trends will help to understand the patterns and behaviours of the rainfall occurrence and would solve many problems relating to water development, planning, and operation management. From the rainfall characteristics study, the rainfall is classified into annual and seasonal (monsoon) rainfall. The classification is based on fluctuation in temperature linked to climate change and the impact on precipitation. The classification of average annual rainfall (normal, scare and surplus) was determined by the Arithmetic Average Method discussed in Sub-Section 4.7.1 of Chapter 4.

The classification of annual and seasonal rainfall is shown in Table 6.17. With the increasing water demand, temperature characteristics study will help to understand the seasonal variability impact and environmental security on watershed hydrology and water resources.

6.9.1 Seasonal Rainfall and Temperature Analysis

From the Table 6.17, it was observed that the average values of annual and monsoon rainfall were 3351mm and 3087mm respectively. The standard deviation for annual and monsoon rainfall were 1095mm and 1057mm and the coefficient of variation of 33 percent and 34 percent respectively. The month of August received maximum rainfall of 1690.5mm in the year 1998, followed by rainfall of 1635.4mm in the month of July in the same year, 1998. The month of February was found to be the driest month with an average rainfall of 5.01mm followed by January with an average rainfall of 8.39mm. During the study period of 29 years, 76 percent was observed as normal rainfall, 3 percent as scarce and 21 percent as surplus rainfall (The observation of normal, scarce, and surplus rainfall was based on the average arithmetic method discussed earlier in Sub-Section 4.7.1 of Chapter 4). It was also observed that in the monsoon period similar values of 76 percent rainfall was normal, 3 percent scarce and 21 percent in surplus. The highest and lowest rainfall was 6231mm and 1473mm occurred in the year 1998 and 2016 respectively. The scarce period was observed in the year 2016. From the above discussion it is observed that the area receives extra rainfall during monsoon season, which can be conserved by various artificial recharge structures in order to efficiently use the water for domestic purposes throughout the year.

Table 6. 17 Classification of Annual and Seasonal (Monsoon) Rainfall

Year	Rainfall (mm)		Rainfall Classification	
	Annual	**Monsoon**	**Annual**	**Monsoon**
1990	3034.8	2947.7	Normal	Normal
1991	2349.6	2100.8	Normal	Normal
1992	3031.8	2502.2	Normal	Normal
1993	3181.8	2523.6	Normal	Normal
1994	5181	4842.9	Surplus	Surplus
1995	2991.9	2805.5	Normal	Normal
1996	5063.5	4702.2	Surplus	Surplus
1997	2460.2	2274.6	Normal	Normal
1998	6231.2	6065.6	Surplus	Surplus
1999	4946.8	4587.4	Surplus	Surplus
2000	2785.9	2470.1	Normal	Normal
2001	3170.4	2985.1	Normal	Normal
2002	3090.9	2771.8	Normal	Normal
2003	2618.4	2453.9	Normal	Normal
2004	2924.1	2620.5	Normal	Normal
2005	2350.93	2323.09	Normal	Normal
2006	2412.77	2298	Normal	Normal
2007	3206.5	2986.3	Normal	Normal
2008	3736.8	3547	Normal	Normal
2009	2752.4	2647	Normal	Normal
2010	2364.3	2137.4	Normal	Normal
2011	2694.4	2282.6	Normal	Normal
2012	2901.6	2500.7	Normal	Normal
2013	4313.6	3913.4	Normal	Normal
2014	4928.5	4473.1	Surplus	Surplus
2015	4519.2	4230.2	Surplus	Surplus
2016	1472.5	1371.9	Scarce	Scarce
2017	3868.9	3628.9	Normal	Normal
2018	2607.2	2518.5	Normal	Normal
Mean	3351.4	3086.6	22 Normal	22 Normal
Std. Dev	1094.8	1057.3	6 Surplus	6 Surplus
Coefficient of variation	32.6	34.2	1 Scarce	1 Scarce

***Source: Weather Atlas and Sierra Leone Meteorology Department*[15] [16]**

The mean, coefficient of variation, standard deviation and percentage contribution of the seasonal rainfall and temperature data are shown in Tables 6.18 and 6.19 respectively. From Table 6.18, it was observed that during the pre-monsoon season (March to May), the total mean rainfall received was 229.03mm with the standard

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[15] https://www.weather-atlas.com/en/sierra-leone/freetown-climate

[16] https://slmet.gov.sl/

deviation 173.72mm and coefficient of variation of 75.8 percent. During the monsoon season (June to November) the region receives a mean rainfall of 3089.6mm with a standard deviation of 1434.7mm and coefficient of variation of 46.48 percent respectively. During the post-monsoon season (December to February) the region receives a mean rainfall of 35.81mm with standard deviation of 56.82 mm and coefficient of variation 158.7 percent. The contribution of rainfall during Pre-monsoon, Monsoon and Post-monsoon was 7 percent, 92 percent and 1 percent respectively, which showed that the study area receives more rainfall during the monsoon season and hence groundwater can be efficiently preserved during this period by infrastructure system that can support and improve aquifer performance such as reservoirs for scarce period (Langridge and Daniels, 2017).

Table 6. 18 Normal, Above Normal and Scarce Seasonal (Monsoon) Rainfall generated from authour's analyses

Season	**Months**	**Mean(mm)**	**StD(mm)**	**CV%**	**NM**	**NP$_R$(%)**	**X$_1$(mm)**	**X$_2$(mm)**
Pre monsoon	March	15.95	21.74	136.33	4	13.79	7.98	31.9
	April	45.70	69.60	152.31	9	31.03	22.85	91.4
	May	167.37	82.38	49.22	3	10.34	83.69	334.74
Total Monsoon		**229.02**	173.72	75.86			114.51	458.04
	June	367.03	160.25	43.66	11	37.93	183.52	734.06
	July	726.50	397.66	54.74	6	20.68	363.25	1453
	August	880.70	307.75	34.94	6	20.68	440.35	1761.4
	September	672.02	319.69	47.57	10	34.48	336.01	1344.04
	October	328.71	181.99	55.36	7	24.14	164.36	657.42
	November	111.66	67.39	60.35	0		55.83	223.32
Total Post monsoon		**3086.62**	1434.73	46.48			1543.31	6173.24
	December	22.40	31.09	138.79	13	44.83	11.20	44.8
	January	8.40	18.20	216.78	15	51.72	4.20	16.8
	February	5.01	7.53	150.25	15	51.72	2.51	10.02
Total Annual		**35.81**	56.82	158.68			17.91	71.62
		3351.45	1094.8	32.6	99		1675.73	6702.9

NM = Normal rainfall, StD = Standard Deviation, NP$_R$ = Percentage of normal rainfall, X$_1$ = Mean/2, X$_2$ = 2*Mean

Table 6. 19 Normal and Above Normal Annual Temperature generated from authour’s analyses

Months	Mean(^{O}C)	StD(^{0}C)	CV%	NT	NP$_T$(%)	X$_1$(^{0}C)	X$_2$(^{0}C)
January	30.97	0.99	3.19	16	55.17	15.48	61.94
February	31.28	1.39	4.46	15	51.72	15.64	62.55
March	31.54	1.25	3.97	7	24.14	15.77	63.08
April	31.63	1.21	3.81	8	27.59	15.81	63.26
May	31.50	0.86	2.74	12	41.38	15.75	62.99
June	30.08	0.85	2.82	18	62.07	15.04	60.16
July	28.75	0.79	2.76	7	24.14	14.37	57.50
August	28.07	0.82	2.93	3	10.34	14.03	56.13
September	28.97	1.08	3.71	12	41.38	14.48	57.93
October	30.12	1.19	3.95	17	58.62	15.06	60.24
November	30.66	0.81	2.65	18	62.07	15.33	61.32
December	31.07	1.29	4.15	11	37.93	15.53	62.14
Annual	30.38	1.41	4.65	144			

NT = Normal temperature, NP$_T$ = Percentage of normal temperature, X$_1$ = Mean/2, X$_2$ = 2*Mean

The data of mean, coefficient of variation, standard deviation and percentage contribution of the temperature are shown in Table 6.19. From the table it was observed that lowest temperatures occur in the months of July, August and September, with August being the coldest month. April is the hottest month. The average mean temperature was 30.38^{0}C with the standard deviation 1.41 ^{0}C and coefficient of variation of 4.65 percent. During the study period of 29 years, 42 percent was observed as normal temperature, 33 percent as hot and 25 percent as cold temperature. This explains the moderate to high annual evapotranspiration rates greater than 900mm from the Sierra Leone Meteorology Department[17], in the study area, similar to those observe in Tirivarombo et al. (2018) and Condon et al. (2020).

Rainfall and temperature trend analysis

Rainfall and temperature trends indicate a long run growth or decline in the rainfall and temperature time series due to various factors such as urbanization or deforestation of the watershed. From the observed rainfall and temperature data, yearly trend, monthly trend and seasonal trend were analysed.

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[17] https://slmet.gov.sl/

Yearly trend Analysis

The yearly trend analysis is shown in Figure 6.23. Yearly trend analysis of the rainfall and temperature data were considered in three cyclic orders. The first cyclic order was considered from 1990-2000, the second cyclic order was considered from 2001-2009, and the third from 2010 - 2018. From the time series curve, it was observed that in the first cycle, the study area receives the maximum rainfall of 6231.2mm, followed by the second highest of 5063.5mm in the years 1998 and 1996 respectively. The average rainfall observed was around 3750.8mm in the first cycle with an average temperature of 30.3^{0}C. During the second cycle it was observed that the region received the lowest average yearly rainfall of 2918.1mm and an average temperature of 31.1^{0}C which was the highest of the three cycles. During the third cycle it was observed that the study area received a minimum rainfall of 1472.5mm in the year 2016. The third cycle experienced the lowest average temperature of 29.8^{0}C. The average rainfall in the third cycle was 3296.7mm. It was observed that depending on the change in temperature, the annual rainfall in this region increases or decreases at a rate of 25.25mm/yr to 32.45mm/year. It was also observed that the annual average rainfall was 3351.45 mm.

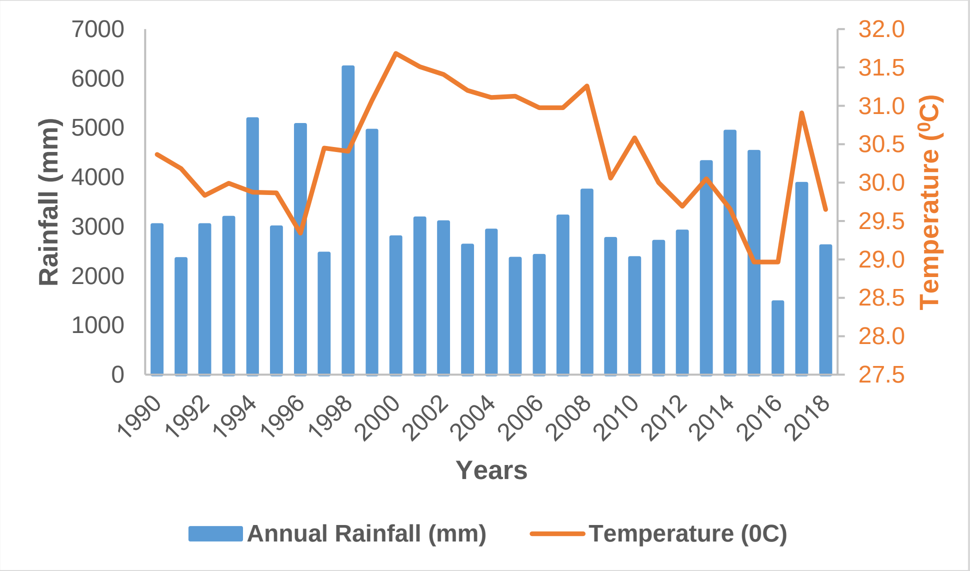

Figure 6. 23 Annual Rainfall and Temperature Trend for the Period 1990 to 2018 (Source: authour's construction)

Monthly trend analysis

The data was analysed from time series curve using linear regression least squares method explained in Sub-Section 4.7.1 of Chapter 4. Monthly trend analysis for January to December is found in Figure G1.1 to G1. 12 of Appendix G.

From the monthly trend graph, it was observed that during the month of January, February, March, April, November and December there was very little rain or no rain at all. In the month of April and May due to pre-monsoon showers, it was observed that the moving average shows an increasing trend and is more noticeable in the recent years. Rainfall during the month of May, June, July and August increase at a rate of 199.65mm, 359.4mm, and 154.19mm/month. During the month of September and October the trend analysis shows that there is decreasing trend of about 208.67mm/month and 343.3mm/month respectively. The rainfall in the month of November also showed a decrease at a rate of 217.1mm/month with further decrease into post monsoon period. The plots show the relatively maximum amount of rainfall in monsoonal months that is, June to November, while in the case of maximum temperature and minimum temperature, the variability is more or less the same for all months when compared to the rainfall. It became clear that the maximum and minimum temperature are low during monsoon seasons and are comparatively high during pre-monsoon months The rainfall received in an area is an important factor in determining the amount of water available to meet various demands such as per capita water consumption.

Seasonal trend analysis (pre monsoon, monsoon, post monsoon)

Seasonal trend analyses are shown in Figure G2.1 to Figure G2.3 in Appendix G. From the analysis it was observed that the average rainfall in the Pre-monsoon season (March to May) was 229.01mm and highest and the lowest rainfall was 635.8mm and 12.4mm respectively. It was observed that the rainfall during the pre-monsoon in the first cycle was high for the period of four years and for the remaining period the rainfall was falling below the moving average. During the Monsoon season the trend analysis showed that the average rainfall received was 3086.62mm and the highest and lowest rainfall received was 6065.6mm and 1371.9mm respectively. From the graph it was observed that the rainfall was below the average for a period of almost nineteen years. During the Post monsoon season the trend analysis shows that the average rainfall received was 35.80mm and its highest and lowest rainfall received was 114.5mm and 0mm respectively. From the trend it was observed that the rainfall was above the moving average for a period of five years (2010 – 2014) and below for the rest of the years (2015 – 2018). Various meteorological parameters need to be analysed for the purpose of making policy decisions as rainfall is a dominant factor in deciding how the available water is to be used in an area.

6.10 Estimation of aquifer and hydraulic parameters

Data sources, definition of all parameters and methods of analysis have been discussed in Section 4.9 of Chapter 4. Estimation of the aquifer parameters were carried out by conventional method using pumping test data and recovery test data (Table F1.1 in Appendix F). Based on the analysis, the estimated values of Transmissibility (T) and Storativity (S) are shown in the Table 6.20. From the table it was observed that the storativity was found to be in the range of 9.68 $x10^{-5}$ to 1.61 $x10^{-4}$. According to Rackley (2017), aquifer parameters assume different values because of the geological composition inhomogeneity in the well surrounding; and for unconfined aquifers, this gives them a fluid surface mobility of 1.0×10^{-5}. The transmissivity values are varying between 1.6 m^2/d and 82.4 m^2/d with an average of 25m^2/d because of the unconfined nature of the aquifer.

The hydraulic conductivity values vary from 1.0×10^0 m/d to 5.02×10^2 m/d with an average of 8.47×10^1m/d. The range of values reveals moderate hydraulic conductivity (Todd and Mays, 2004). According to Wright (1992) and Offodile (2002), a transmissivity range of 5 to 50m^2/d could be regarded as high potential aquifer in fractured crystalline basement rock formations. Besides the conventional analytical methods, the time drawdown data were analysed using simulation software (AQTESOLV v4.0) to determine the aquifer parameters. Aqtesolv is the most comprehensive software for analysing pumping test data of confined, unconfined and fractured aquifer solutions. Figure 6.24 and Figure 6.25 present the estimated transmissivity and storativity values.

Both the conventional results (Theis' and Jacob's solution) and software simulation were found to be almost the same. The calculated hydraulic parameter values from the pumping test data are shown in Table F1.1 in Appendix F. The values are satisfactory for water abstraction from the aquifer based on the estimated aquifer parameter values.

Most of the methods described and the results in this study only require pumping test data from the pumped aquifer. The results in Table 6.20 have been estimated from similar methods used by Kruseman and de Ridder (1971) and Carmichael and Gellein (2009).

Table 6. 20 Estimated values of Transmissivity and Storativity generated from authour's analysis

SI. No	Methods	Transmissivity [m^2/day]	Storativity	Remarks
1.	Theis	21	$9.69 x 10^{-5}$	Pumping test
2.	Cooper Jacob's	65	$6.71 x 10^{-5}$	Pumping test
3.	Chow	80	$2.60 x 10^{-5}$	Pumping test
4.	Theis Recovery	86	$1.61 x 10^{-4}$	Recovery test

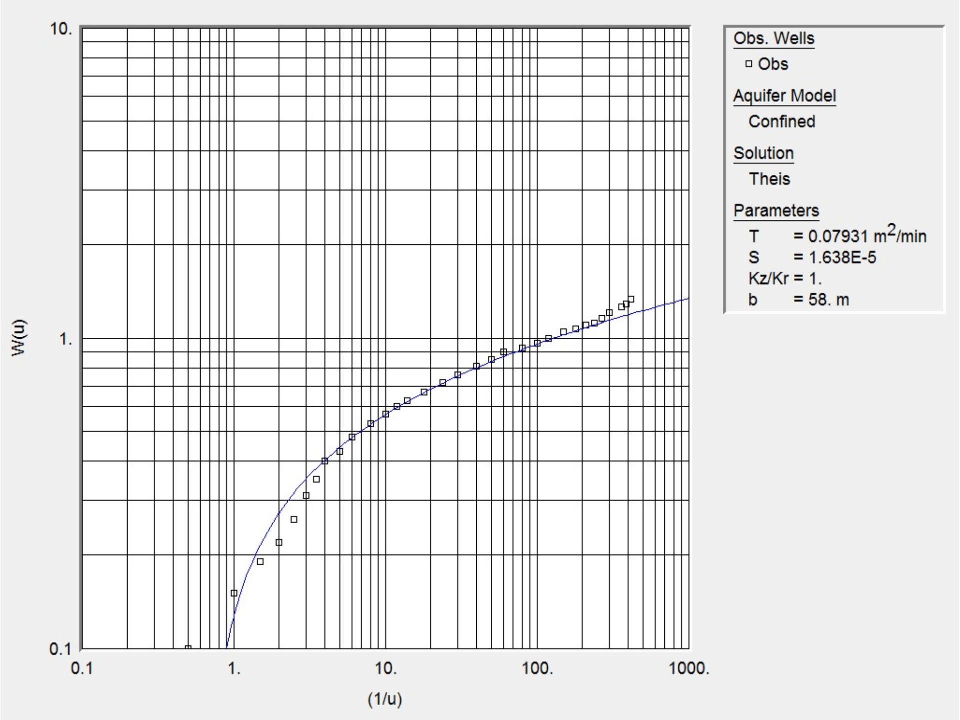

Figure 6. 24 Analysis of Pumping test data for Transmissivity and Storativity values using Theis method in Aqtesolve software

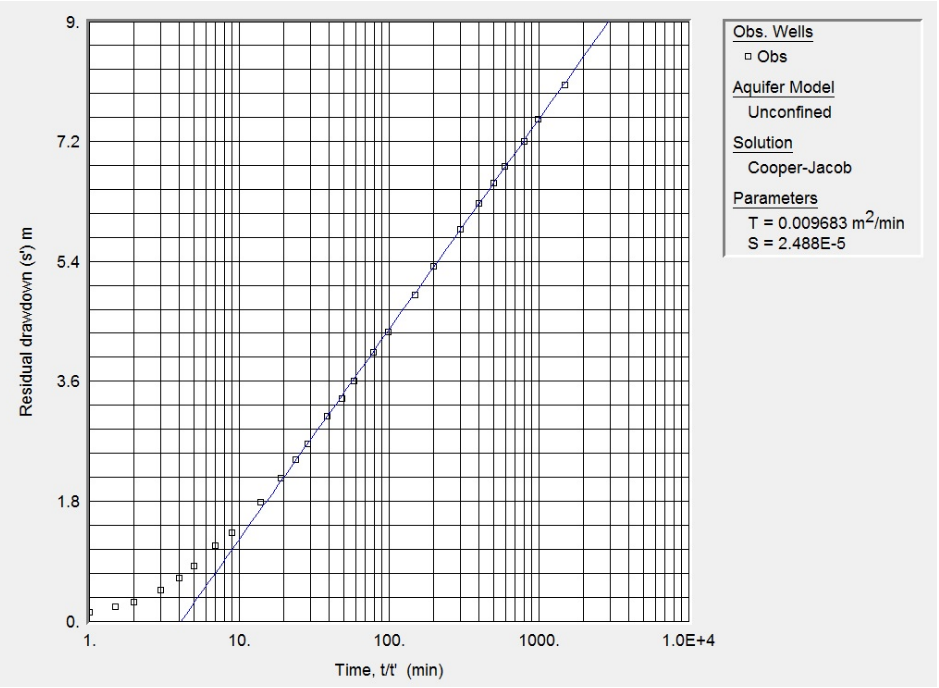

Figure 6. 25 Analysis of Pumping test data for Transmissivity and Storativity values using Theis method in Aqtesolve software

6.11 Water Balance Study

Notwithstanding the dearth of knowledge base on the hydrogeology of the study area, it was possible to produce a useable account of the aquifers[18]. In the eastern and south-eastern parts of the study area, the alluvial and lateritic crust are permeable and thick enough to form a groundwater aquifer that has been supporting the industrial sector and some private consumption at Kissy and Wellington (Danert, 2015). With the potential for new wells siting, infiltration galleries can be constructed along perennial rivers and valleys to provide an adequate water supply for the neighbourhoods in densely populated areas and supply areas with no piped water supply.

6.12 Groundwater Quantity Modelling and Analysis

Using data on rainfall, temperature, hydrologic thematic maps such as soil, land use, flow direction, contour, slope, and drainage waterways integrated in geographic information system (GIS) as the main input data, the groundwater quantity and recharge capacity for the research area is estimated over a period of time using ModelMuse MODFLOW numerical packages.

Five different scenarios presented in Sections 6.5.1 to 6.5.5 were developed to simulate the objectives of the study which include understanding of groundwater system, estimation of aquifer properties and predicting the future capability of the groundwater system. The results of the groundwater numerical simulations are discussed in Sections 6.12.1 to 6.12.5.

6.12.1 Result on the Model Calibration for Recharge Capacity Numerical Modelling

In this section, the simulation results obtained from the numerical groundwater flow model to study the recharge capacity in Section 6.5.1 is presented. The recharge map

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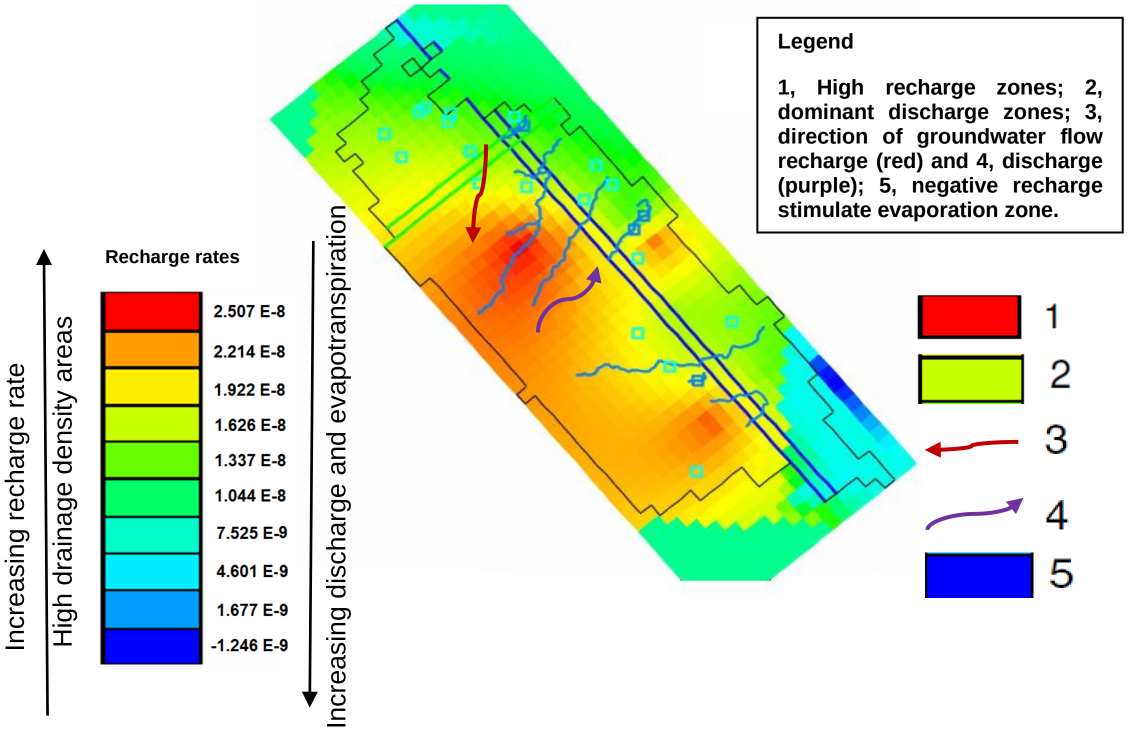
[18] http://www.rural-water-supply.net/en/resources/details/565

simulated in the flow model corresponding to stress period one is shown in Figure 6.26. The Figure's legend demonstrates that both elevation and recharge have a linear relationship, as evapotranspiration decreases with elevation. The purpose of this study is to assess the possibility of managed aquifer recharge and to present planning level model for development and operation of aquifer recharge in the area. The concerns include (1) how much is the infiltration capacity? (2) where to locate the abstraction wells and what should be their pumping rates in order to maximize output without causing air in the pump?

The legend (Figure 6.26) shows areas of high recharge (1) and dominant discharge zones (2). Recharge rate is increasing in the direction of the area coloured red (3), this area also corresponds to an area with high hydraulic gradient and drainage density. Groundwater discharge flow direction is from an area of high to low hydraulic gradient coloured purple on the map (4). The negative recharge rate areas coloured in blue on the map (5) stimulate the evaporation zone.



Legend

1, High recharge zones; 2, dominant discharge zones; 3, direction of groundwater flow recharge (red) and 4, discharge (purple); 5, negative recharge stimulate evaporation zone.

Figure 6. 26 Recharge Rate Output Map Showing Satisfactory Aquifer Potential Zones generated from Modflow Run

Sener et al. (2005) observed that a high drainage density is associated with a highly permeable lithology and potential for high groundwater recharge. Consequently, an area with high drainage density implies high percolation and recharge rates. Comparing the study area drainage density map in Figure 6.18 and the output simulated recharge map shown in Figure 6.26, the highest drainage density occurs in region of high recharge potential (red coloured areas). The results also indicate that areas in the central part with steep slopes and thin soil layers (greenish area) have low percolation potential, whereas low elevated areas and flat terrains have a high potential for groundwater recharge.

The locations of high recharge and high potential aquifers are displayed as the red areas in the figure. This comparison is based on the assumption that regions with aquifers should have high recharge rates and the fact that the aquifers are also unconfined (Council National Research, 1994; McMahon *et al.*, 2011; Fileccia et al., 2018). A comparison of the slope map (Figure 6.20) of the study area reveals a correlation between zones of high groundwater potential to the simulated recharge map (Figure 6.26) output result. In the study conducted by Fileccia et al. (2018) the groundwater recharge potential zones in Sierra Leone have been classified into six aquifer categories (A – F). Zones A and C are classified as high potential, B and D moderate potential, E and F low aquifer potential zones. Based on the estimation of aquifer properties in Section 6.10 and simulation results, most of the study area is classified into moderate (zone D) with pocket zones of high (C) recharge potential. Negative recharge rates simulate a constant evapotranspiration rate.

Modelling the recharge adds valuable understanding to the design effectiveness and appropriate water management strategies for sustainable abstraction. The recharge capacity simulation map displayed in Figure 6.26 can be used as a baseline guide to estimate and determine vulnerable regions for the pollution pathway of groundwater, as high recharge zones are classified as sources of pollutants to groundwater because recharge can help move excess accumulated salts faster to deeper parts of the aquifer (Shaban et al., 2006).

6.12.2 Result on the Model Calibration for Observed and Simulated Heads Numerical Modelling

In this section, the simulation results obtained from the numerical model calibration of observed and simulated heads (discussed in Sub-Section 6.5.2) is presented. In the study, the attempt was to simulate the impacts of human activities on groundwater flow systems when formulating sustainable groundwater resources and to assure consistency among aquifer properties.

For 19 piezometers in the modelled area, the groundwater model is calibrated under a steady-state flow condition. Results of the study indicate that with the application of the right groundwater control measure and management they can return the groundwater level to equilibrium, as well as maintain groundwater resources for domestic use.

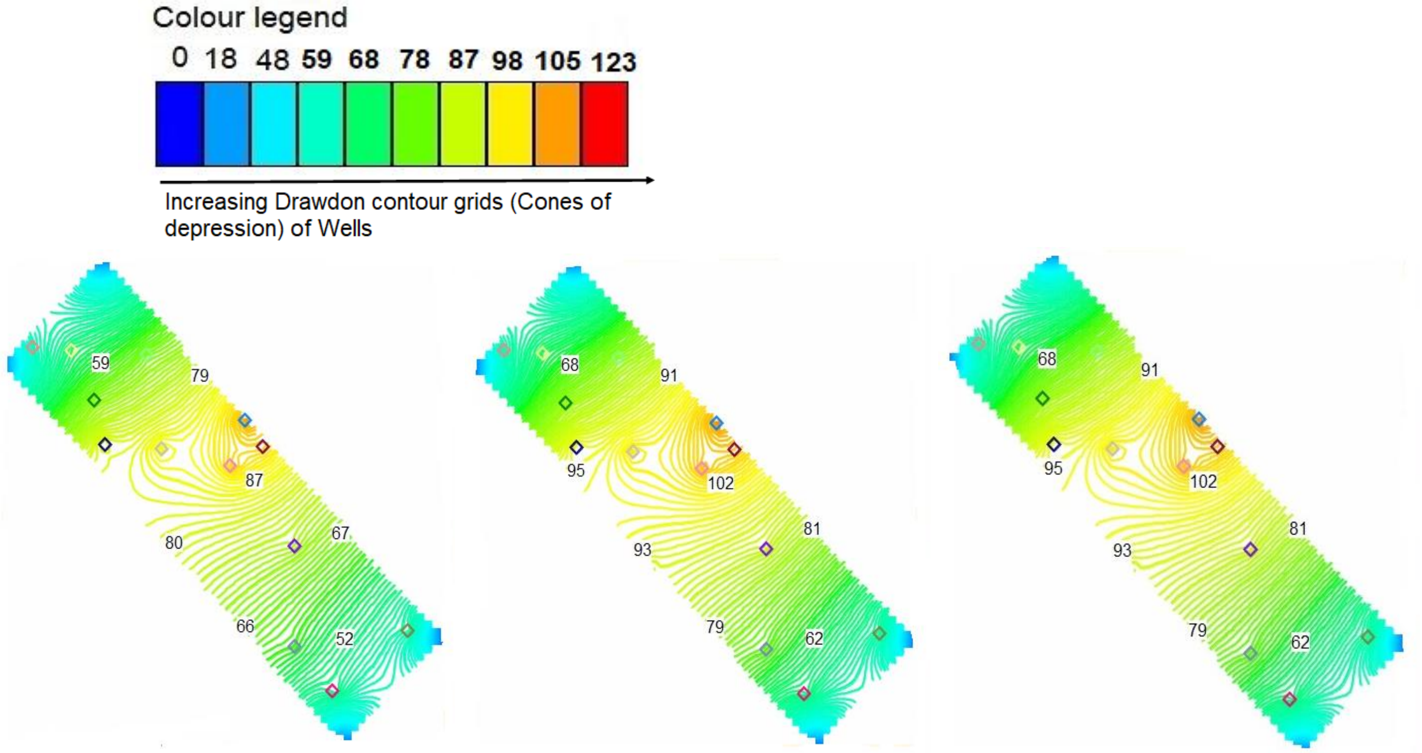
Figure 6.6 reveals the head distribution obtained at end of the steady state numerical simulation for nineteen piezometers. The head distribution values range from 0.3m to 0.9m below the surface. The NRMSE at the nineteen observation piezometers is 0.2 m, physically indicating that the value predicted by the model is in quite good agreement with the observed value.

6.12.3 Result on the Numerical Model Calibration for Wells Interference Patterns

The goal of the numerical simulation developed to study the interference of the wells is to quantitatively assess the interference effect of long-term groundwater abstraction from domestic consumption between neighbouring wells. The detailed procedure of the numerical simulation model set up is explained in Sub-Section 6.5.3.

The model was run in steady-state first and then transient calibration was simulated for fifteen years (473364000 seconds) and monitored annually (31557600 seconds). During transient calibration, the wells are activated. Considering seasonal variability in pumping capacities, the availability of water due to recharge, and the duration of pumping, the pumping rates were determined. Figure 6.27 a-f presents the model results which showed that in the transient simulation, varying interference patterns between the drawdown levels and cones of depression can be seen from year 1 to year 5. By the end of the 5th year, the model has reached a steady state, so whatever happens after that is irrelevant. In each well, the cone of depression varies from approximately one hundred and five metres (105 m) to below one metre (-1 m). A more detailed drawdown is available for the wells with the highest pumping rate. It can be seen that the cones of depression in year 5 (Drawdown_P2_S05) and year 15 (Drawdown_P2_S15) have attained equilibrium (same). As a result of the simulation, the water table varies between seven (7) and twenty-three (23) metres below the surface during the rainy and dry seasons.

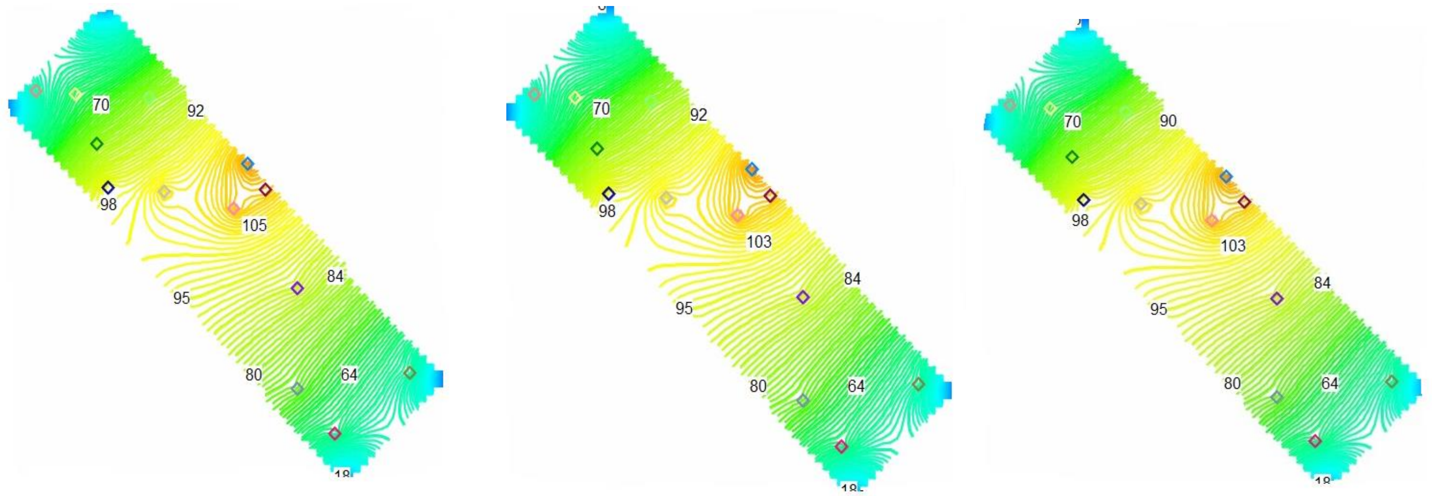
For the wells interference simulation, the values of the parameters applied to simulate the 13 wells are; hydraulic conductivity of $1x10^{-5}$m/s (0.864m/d), a specific yield value of 0.12, recharge of $9.51x10^{-8}m^3/s$, evapotranspiration of 6.02 $x10^{-8}m^3/s$, specific storage is 1.2 $x10^{-5}$ with aquifer thickness of 80m. These values yielded a favourable 9.3 $x10^4$ m^3/d for the volumetric water budget from the simulation (Table 6.10 and Table 6.21). From this simulation, it shows that aquifer characteristics needed for a successful simulation are met and that significant quantities of water can be abstracted from fractured crystalline unconfined aquifers with a saturated thickness of 10 to 80 m established from the wells drilling properties.



(a) Drawdown in contour grid for year 1 (Drawdown_P2_S01) generated from Modflow Run

(b) Drawdown in contour grid for year 2 (Drawdown_P2_S02) generated from Modflow Run

(c) Drawdown in contour grid for year 3 (Drawdown_P2_S03) generated from Modflow Run



(d) Drawdown in contour grid for year 4 (Drawdown_P2_S04) generated from Modflow Run

(e) Drawdown in contour grid for year 5 (Drawdown_P2_S05) generated from Modflow Run

(f) Drawdown in contour grid for year 15 (Drawdown_P2_S15) generated from Modflow Run

Figure 6. 27 Transient Simulation Drawdown Contour Grids (Cones of Depression) of Wells Interference Patterns in metres generated from Modflow Run

Groundwater balance by the simulation

From Table 6.10 the volumetric water budget after transient model run of wells interference numerical flow modelling is shown. This output simulation result and the input calibration data discussed in Sub-Section 6.5.3 was used to calculate the groundwater balance by the simulation shown in Table 6.21. The method used in this calculation is water balance method similar to the JICA (2003) report and Zhou and Li (2011b).

The purpose of calculating the groundwater balance is to determine whether the groundwater resource of the study area is considered a renewable water resource that receives recharge from rainfall and other water sources to the entire aquifer system.

Table 6. 21 Calculated Groundwater Balance by the Groundwater Simulation (Source: authour's analysis)

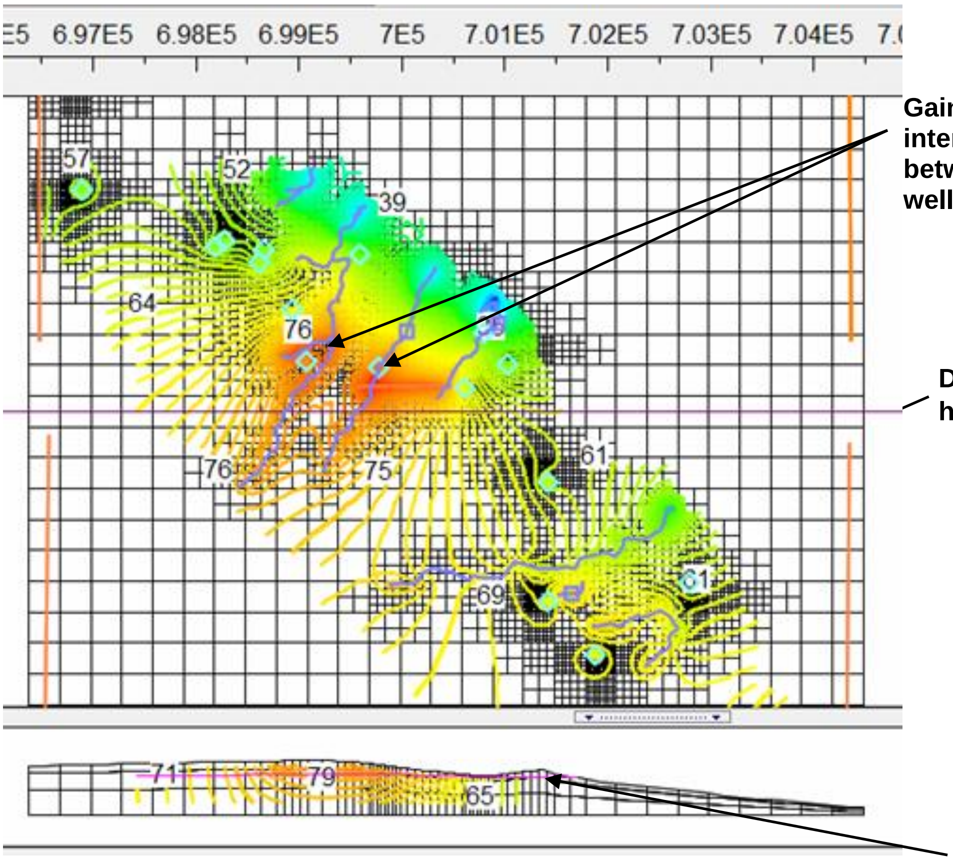
Groundwater budget	**Items**	**Groundwater Simulation Result**			
		Volumetric budget	Rainfall contribution	Pumping rate	Percentage contribution
Groundwater In the model	Recharge	9.30x10^{4}m^{3}/d	3000mm/yr	1.1x10^{0} m^{3}/s	100%
	Storage and Constant Head	2.99x10^{2} m^{3}/d	9.6 mm /yr	3.5x10^{-3} m^{3}/s	0.32%
Groundwater flowing out of the model	Pumping from wells	1.08x10^{4} m^{3}/d	348mm /yr	1x10^{-1} m^{3}/s	11%
	Storage, Constant Head and Evapotranspiration	8.25x10^{4}m^{3}/d	2662mm/ yr	9 x10^{-1} m^{3}/s	89%

From groundwater recharge given to the model which was estimated from an average rainfall of 3000mm/yr, 11% is pumped by the wells and 89% flows away from the study area. Groundwater level that was calculated by this simulation shows regional groundwater flow. Analysis from the prepared thematic maps discussed in Chapter 4 and the conducted simulations show that groundwater in the study area is moving from northeast to southwest direction. Groundwater resource of the study area is considered a renewable water resource that receives recharge and is involved in the whole aquifer system.

6.12.4 Results on the Model Calibration for Interaction of Alluvial Aquifer with Regional Flow, Rivers and Wells in Unstructured Grid Discretisation

In this section, the simulation result obtained from the DISV unstructured regional numerical groundwater flow model discussed in Section 6.5.4 is presented. The purpose of the study was to understand the sources of water to wells, determination of responsible bodies causing impacts on the groundwater system, changes due to external and manmade activities in the aquifer system to support domestic water consumption. The reason for the DISV model discretisation and Quadtree refinement in this simulation process are explained in Sub-Section 6.5.4.

The water table contours simulated with the numerical groundwater flow model corresponding to stress period one (steady state) is shown in Figure 6.28.



Gaining and losing interactive zones between rivers and wells

Drawdown heads (metres)

Cross section of phreatic water table

Figure 6. 28 Regional Gaining and Losing Interactive Rivers and Wells Zones in Unstructured Grid Simulation generated from Modflow Run

The graphic result from the DISV unstructured regional numerical groundwater flow modelling is imported as a contour grid data (Figure 6.28). From the simulation, the main changes in the groundwater flow are related to the boundary conditions. The refinement (DISV) is done to see the impact of certain areas in the model where interaction between the water sources (rivers, wells) is taking place. The DISV grid discretisation enhances the impact of the groundwater simulation and flow. If the system was modelled without refinement, the contour lines will not be seriously affected or pronounced as seen in Figure 6.28. The influence and capture zones of the wells are seen in detail. There is some interaction between the wells and the river, at some point, the river is giving water to the wells and at other points, the river is draining water from the wells. In the cross-section (Figure 6.28), the first layer of the water table is phreatic, and the other layers are confined.

Table 6.22 presents the volumetric water budget of the regional unstructured grid simulation result. Inflow into the model is from the river and general head boundary packages. Outflow was through the wells, general head boundary and river leakage.

Table 6. 22 Summary of Volumetric Water Budget at Steady-State Unstructured Grid Simulation generated from Modflow Run

Flow term	Inflow (m^3/d)	Outflow (m^3/d)
WELL	0.0	4.14×10^4
RIVER	2.23×10^5	2.33×10^5
GENERAL HEAD BOUNDARY	5.45×10^4	3.62×10^3
TOTAL IN	2.78×10^5	0
TOTAL OUT		2.78×10^5

The total volumetric water budget (2.78×10^5 m^3/d) consists of: inflow from the river of 2.23×10^5 m^3/d and general head boundary of 5.45×10^4 m^3/d. Outflow through river leakage of 2.33×10^5 m^3/d, outflow through the wells (drains) 4.14×10^4 m^3/d and general head boundary of 3.62×10^3 m^3/d.

One characteristic observation in the simulation is that when the water table of the river stage is higher than the aquifer, the river will provide water to the aquifer as ‘River Leakage’ in the IN because it is an inflow to the aquifer. When the water table in the aquifer is higher than the river, the river will take water out of the system. This is evidence of the river acting as a losing or gaining water source. In this study where the wells are taking water out of the system, the wells are acting as drains (DRN package).

For the rivers in this numerical model, initially, the river stage was set at the model top and the river bottom was one metre below the model top (Model_Top minus 1m). Following the simulation run the river stage is at 79.6m, making the new river bottom (79.6m – 1.0), 78.6m. This explains that the water in the aquifer is higher than the river stage, hence water is going out of the aquifer system. At some point from the cross-section (Figure 6.28), river stage is at 61.3m, and the river bottom is at 60.3m. The water table of the river stage is higher than the aquifer, the river will provide water to the aquifer as ‘River Leakage’ in the IN.

6.12.5 Results on the Model Calibration for Future Water Supply Management from Infiltration Galleries

In this section, the result for the numerical simulation of water supply from infiltration galleries discussed in Sub-Section 6.5.5 is presented. The objective of the numerical simulation study was to simulate water supply along a perennial river related to a valley to see how much water can be extracted to maximise household water consumption if infiltration galleries were inserted in the region.

The performance of the infiltration galleries management design was evaluated in terms of volumetric water budget to compensate domestic water consumption. The water budget result in (Table 6.14 in Sub-Section 6.5.5) reveals that the main inflow into the aquifer system is from the river (1.41 x10^5 m^3/d) and then recharge from rainfall. Outflow from the model is from the drains (wells), river and evapotranspiration.

Groundwater balance by the simulation

The calculation of the groundwater balance for the simulation of water supply from infiltration galleries is conducted by the same water balance method used in Sub-Section 6.12.3. The data used in the groundwater balance calculation is based on the same data used in the numerical model calibration explained in Sub-Section 6.5.5. Of groundwater recharge given to the model, which is 400 mm/year, 16 % is pumped up by the wells and 84% flows away from the study area. The calculated water balance is shown in Table 6.23.

Table 6. 23 Calculated Groundwater Balance by the Groundwater Simulation (Source: authour's analysis)

Groundwater budget	**Items**	**Result**			
		Volumetric budget	Rainfall contribution	Pumping rate	Percentage contribution
Groundwater in	Groundwater recharge	$1.42x10^5m^3/d$	400mm/yr	$1.64m^3/s$	100%
Groundwater out	Pumping from wells	$2.2x10^4m^3/d$	63mm /yr	$0.26m^3/s$	16%
	Groundwater flowing out from the Model	$1.19x10^5m^3$ /d	337mm/ yr	$1.38m^3/s$	84%

6.13 Water Demand Management for Domestic Water Consumption

In an actual groundwater management scheme, it is required to link the flow and storage managements in parts for sustainable abstractions (Henriksen et al., 2008). Data from the Knoema atlas website[19] accessed on the 27th of March 2021, states that the dam capacity per capita for Sierra Leone in 2017, was 29.38 m^3/yr which is eighty

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[19] **https://knoema.com/atlas/Sierra-Leone/topics/Water/Dam-Capacity/Dam-capacity-per-capita**

litres per day (80 l/d). However, for Freetown city, the current dam supply capacity allocated to domestic use is thirty-four Million litres per day (34Ml/d) (Atkins, 2008b). This leaves an equivalent per capita allocation of thirty-two litres per person per day (32 l/p/d) to twenty-eight litres per person per day to (28 l/p/d), based on the existing available population information from the Statistics Sierra Leone 2015 census at 1,055,964 and the online Metro area population data[20] for 2020 at 1,202,000.

In the regional numerical groundwater flow model (Sub-Section 6.12.4), conducted with the minimum pumping rate of -3×10^{-2} m^3/s the analysis revealed an abstractable groundwater volume of $101 \times 10^6 m^3/yr$ (2.78×10^5 m^3/d) presented in Table 6.22. The simulation results for water supply from infiltration galleries (Table 6.14 and in Sub-Section 6.12.5) have revealed an additional groundwater volume of 52 $\times 10^6 m^3$/year (1.42×10^5 m^3/d).

Based on data from the Metro area website for Freetown with a current population of 1,202, 000 persons in the year 2020, it implies from Atkins (2008) that the available dam capacity of water supply from the GUMA Valley is $12.4 \times 10^6 m^3$/year.

Combining the total regional abstractable groundwater volume from the existing wells in the area with the potential abstractable groundwater volume from infiltration galleries will give a grand total abstractable groundwater volume of $153 \times 10^6 m^3$/year for the watershed. According to the World Bank data website, the population growth rate for Sierra Leone is 2.14 percent per year (World Bank, 2020). The population and its future growth are strategical factors for groundwater allocation. The exact current per capita consumption in Freetown is not known. The analysis of the water consumption component in Chapter 5 of this research estimated per capita use variations between 150 and 8 litres per person per day. The average daily per capita water consumption obtained via the various household multiple sources (Table 5.2 of Chapter 5) varies from 73 to 112 (l/p/d) for households without piped water supply. In this water management study, the minimum requirements for emergencies recommended by Şen *et al.* (2013) of 50 litres/capita/day during the dry weather (hydrologic drought) or 70 litres/capita/day in the wettest weather (rainy season) are considered for water consumption allocation.

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[20] **https://www.macrotrends.net/cities/22445/freetown/population**

With these assumptions, the calculations from this research can help to answer a number of questions including as below:

1) Is the present groundwater resources enough for water supply?
2) What is the amount of yearly groundwater? For how many years it is sufficient without considering any other alternative water supply source?
3) What are the water supply amounts projected for 5, 10 and even 15 years? Is it sufficient at a 40% increase to the existing water supply? If not, what to do?
4) How many people can be supplied by groundwater resources during a dry (water scarcity) season?

Solution

The current available dam supply by the Guma Valley is $12.4 x 10^6 m^3$/year (Atkins, 2008a). It is assumed that in Freetown the water demand is only for domestic use. The regional abstractable groundwater volume from the wells (unstructured regional model) and potential infiltration galleries (Sub-Sections 6.5.4 and 6.5.5) is calculated as $153 x 10^6 m^3$/yr. In this calculation, the assumed current per capita water volume is taken as 32 litres per person per day (Atkins, 2008a). Using the above-mentioned numbers, the solutions to the above stated questions can be found as below.

1. In order to check whether the existing water supply is enough, the annual water consumption rate, Q_A, can be calculated as,

$$Q_A = Total\ population\ x\ litres\ per\ day\ x\ days\ in\ year \qquad \text{(Eq 6.11)}$$

Where,

Q_A is the annual water consumption rate

Population of Freetown in 2020 = 1,202, 000

Guma Valley distributable per capita volume = 32 litres per person

$$Q_A = 1{,}202{,}000 \text{ x } 32 \text{ x} 10^{-3} \text{ x } 365$$
$$= 14.0 \text{ x} 10^6 m^3/yr$$

Since the calculated amount is more than the existing Guma Valley dam water supply, ($14.0 \times 10^6 > 12.4 \times 10^6$), the annual dam water supply is insufficient to satisfy the domestic water supply. However, the calculated groundwater volume is more than the current water supply available (153×10^6 m^3/yr> 12.4×10^6 m^3/yr), the annual groundwater supply is sufficient to satisfy and increase the domestic water supply volume, i.e. increased per capita consumption from 32 to 70 litres per person per day.

2. The amount of remaining simulated annual groundwater water volume is:

$$153 \times 10^6 - 12.4 \times 10^6 = 141 \times 10^6 \text{ m}^3/\text{yr}$$

For future simple management prediction, with the same per capita water consumption rate (of 70l/p/d and 50l/p/d for the rain and dry season respectively), the question is for how many years of sustainability can this volume be continued? Since future available groundwater amount is 153×10^6 m^3/yr and the number of years to consume this amount is unknown, therefore let denote it by **y**. With the given population growth rate (2.14%), the yearly population based on 2.14% increase can be calculated using equation 6.12.

$$Yearly\ ppulation = Current\ population\ x\ (1 + 0.02) \qquad \text{(Eq 6.12)}$$

The number of future years can be calculated simply as follows:

a. Consider one year, then the population will increase to:

   1,202, 000 x (1 + 0.02) = 1,226,040 capita.

The annual water consumption in the rain and dry season for future years can be calculated using Equation 6.11.

Their annual water consumption is,

Rainy season

$$Q_A = 1{,}226{,}040 \text{ x } 70 \text{ x } 10^{-3} \text{x } 365 = 31.2 \text{ x } 10^6 \text{m}^3/\text{yr}$$

Dry season

$$Q_A = 1{,}226{,}040 \text{ x } 50 \text{ x } 10^{-3} \text{x } 365 = 22.4 \text{ x } 10^6 \text{m}^3/\text{yr}$$

This is still less than the available groundwater resource, and hence, one can make similar calculations for the second year with the new population, which is 1,226,040 x (1 + 0.02) = 1,250,560 capita and their water consumption is,

Rainy season

$$Q_A = 1{,}250{,}560 \text{ x } 70 \text{ x } 10^{-3} \text{x } 365 = 31.9 \text{ x } 10^6 \text{m}^3/\text{yr}$$

Dry season

$$Q_A = 1{,}250{,}560 \text{ x } 50 \text{ x } 10^{-3} \text{x } 365 = 22.8 \text{ x } 10^6 \text{m}^3/\text{yr}$$

There is still room for available groundwater cover. Hence, continuation of similar calculations yields the population of the fifteenth year as 1,586,013 x (1 + 0.02) = 1,617,733 and water demand is,

Rainy season

$$Q_A = 1{,}617{,}733 \text{ x } 70 \text{ x } 10^{-3} \text{x } 365 = 41.3 \text{ x } 10^6 \text{m}^3/\text{yr}$$

Dry season

$$Q_A = 1{,}617{,}733 \text{ x } 50 \text{ x } 10^{-3} \text{x } 365 = 29.5 \text{ x } 10^6 \text{m}^3/\text{yr}$$

Since the calculated groundwater volume is more than the current dam water supply available (12.4 x10^6 m^3/yr < 153 x10^6 m^3/yr), even with population increase after the twentieth year, it shows that the annual groundwater supply is sufficient to satisfy the domestic water supply needs for the next 20 years without causing any water stress or shortage if the volume provided by the Guma Valley (32l/p/d) is supplemented with groundwater source by an increase of 50%.

3. Even if the regional wells volumetric water balance discussed in Sub-Section 6.12.4 are the only source considered (101 x 10^6m^3/yr) after the end of the twentieth year, there is enough water before the water managers should consider the additional water supply from the infiltration galleries for a better and an efficient management strategy.

4. During the dry season (hydrologic drought) of the year, with the same original population and at 50 l/capita/day water consumption, the number of people (n), that can be supplied without water shortage is,

Number of people supplied = (n)

$$\frac{Available\ groundwater\ sources}{Litres\ per\ day\ x\ days\ in\ year} \qquad \text{(Eq 6.13)}$$

$$n = \frac{101 \text{ x } 10^{6}}{50\ x\ \ 10^{-3}\ x\ 365} = 5{,}561{,}395\ capita$$

According to Figure 6.28, the regional abstractable groundwater volume is calculated as 101 x10^6m^3/yr. Figure 6.29 present the aquifer test well locations in the modelled area.

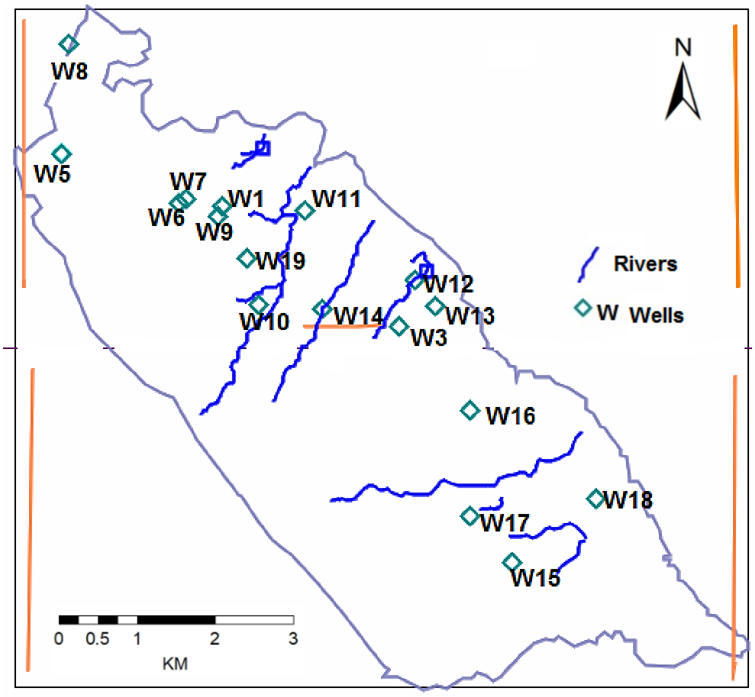

Figure 6. 29 Aquifer Test Well locations in Modelled Area (Source: authour's construction)

In the modelled, household water consumption activities during the rainy season (70l/p/d) need 31.2 x10^6m^3/yr (calculated from above). The Guma Valley water source according to Atkins (2008a) yields 12.4 x10^6m^3/yr for domestic consumption.

A logical management plan for water consumption activities with support from groundwater system and dam yield, (considering seasonality) can generate a few possible scenarios. One can then contemplate if the groundwater system and Guma Valley source are necessary for sustainable yield satisfaction of the water consumption activities in the modelled area.

Solution

It is helpful to consider a simple configuration of all the components in this problem, as shown in Figure 6.30.

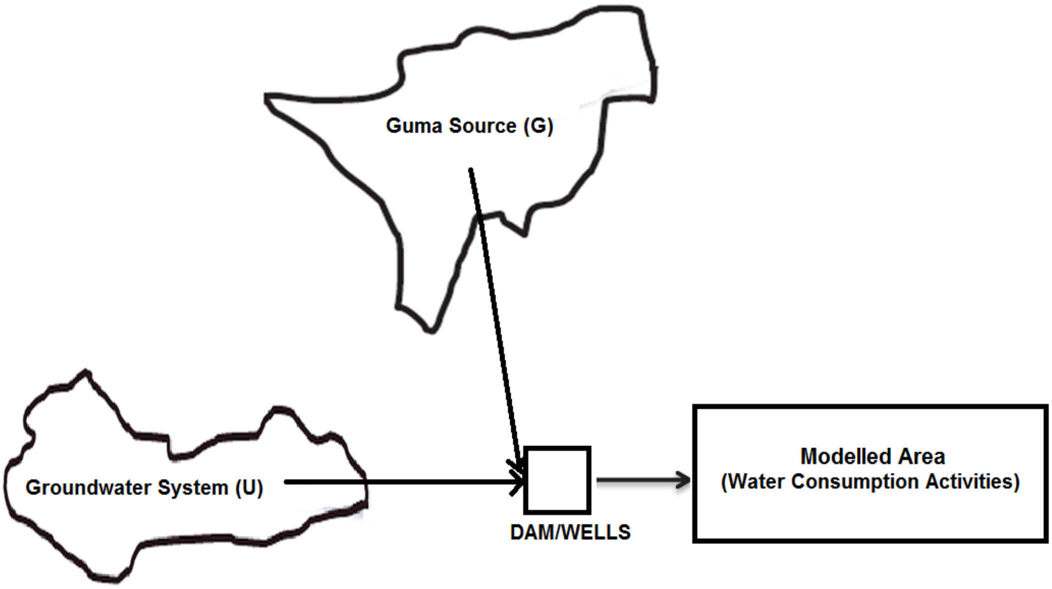

Figure 6. 30 Water Resources and Demand Centre Formation (Source: authour's construction)

1. In dry seasons, their combined use comes into practical application, and therefore, the logical management basis may have only one alternative as, G and U. This implies water from the Guma dam and groundwater withdrawal from the aquifer. In rainy season, there are various alternatives depending on the circumstances.

If only one water source is enough for domestic water consumption activities, then the logical arrangement should be through, G (Or) U. If only the two water sources should cover the domestic water consumption activities, then the following scenario (G and U) is possible.

2. Each water has its safe yield, but sustainable yield for the domestic water consumption activities is possible if the summation of these safe yields is more than the domestic water consumption activities water demand. The total safe yield, T_Y, of the system is,

$$T_Y = Guma\ dam\ water\ source\ (\mathrm{m^3/yr}) + \mathrm{Groundwater\ source}\ (\mathrm{m^3/yr}) \qquad \text{(Eq 6.14)}$$

$$= 12.4 \times 10^6 \mathrm{m^3/yr} + 31.2 \times 10^6 \mathrm{m^3/yr} = 43.6 \times 10^6 \mathrm{m^3/yr}$$

Since $43.6 \times 10^6 \mathrm{m^3/yr} > 31.2 \times 10^6 \mathrm{m^3/yr}$, the two sources can provide sustainable yield for the domestic water consumption activities.

By considering 70 and 50 litres per person per day as mentioned above, various scenarios can be conceived as shown in Table 6.24.

It is possible to draw Population versus Time (duration of water supply) curves by considering 50, 70, 100, and 150 litres/person/day consumption rates as shown in Figure 6.31.

Table 6. 24 Different Water Supply Scenarios (Source: authour's analysis)

Consumption 50 litres/capita/day			Consumption 70 litres /capita/day		
Population ($x10^6$)	Time (water supply use)		Population ($x10^6$)	Time (water supply use)	
	Day	Month		Day	Month
1.2	27720	924	1.2	21600	720
1.4	25200	840	1.4	19440	648
1.6	23040	768	1.6	19080	636
1.8	20520	684	1.8	18000	600
2.0	19080	636	2.0	16560	552
2.5	15120	504	2.5	13320	444
3.0	11550	385	3.0	9720	324
3.5	8640	288	3.5	7200	240
4.0	6120	204	4.0	5040	168
4.5	3960	132	4.5	3240	108
5.0	2520	84	5.0	1890	63
5.5	2160	72	5.5	1440	48

Figure 6.31 presents the per capita per day population demand versus time relationships curve. It can be interpreted as follows: If the water managers consider increasing the water distribution for domestic consumption at a rate of one hundred and fifty litres per person per day (150l/p/d) to the population of Freetown at the yearly growth rate of 2.14 percent calculated in this study, then the total abstractable volume simulated from the regional wells and infiltration galleries amounting to 153 $x10^6$ m^3/yr will serve Freetown for slightly over 200 months (16 years). Meanwhile, if they stick with the calculated 50 and 70 litres/person/day consumption rates as domestic water allocation to Freetown inhabitants, then the total abstractable yearly volume of 153 $x10^6$ m^3/yr will serve Freetown from over 800 to 900 months (66 – 75 years).

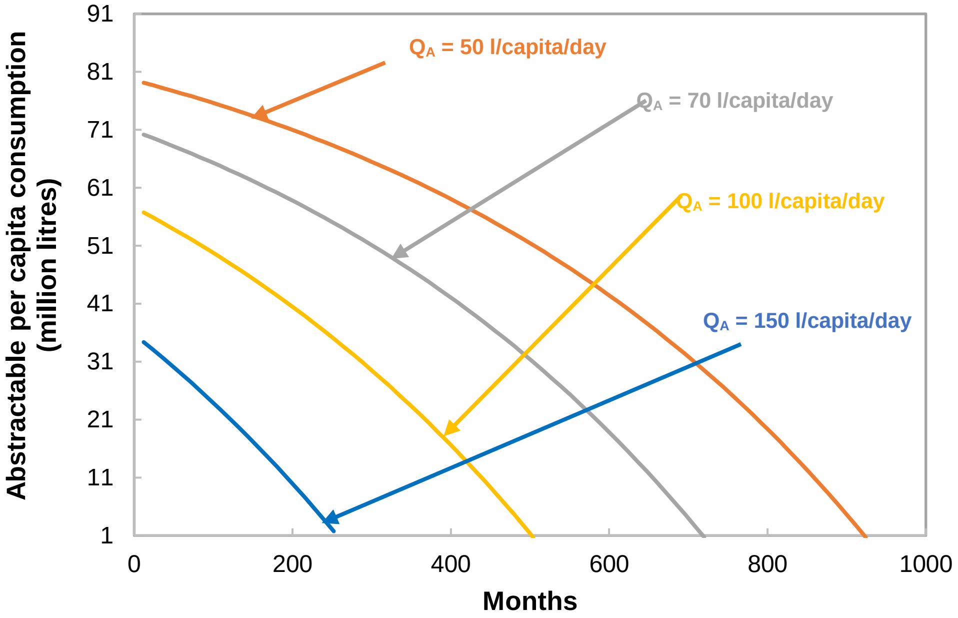

Figure 6. 31 Per Capita Per Day Demand Population Versus Time Relationships (Source: authour's construction)

6.14 Sensitivity Analysis

A tool to assess the quality of the groundwater flow predictions and volumetric water budgets from the numerical simulations is to have a subset of data to test if the predictions/water budgets are correct or how much the technology is missing the target. The analytical results can be used for making water supply decisions and strategies.

The numerical groundwater models in this study have been built at larger scales (with more coarse discretisation) in order to account for natural boundary conditions, and calibrated using 3D mathematical methods to correlate groundwater levels and flows. However, the sensitivity analysis was performed on a smaller scale with finer discretisation than the flow models to accurately define the target and minimise numerical distribution while still maintaining reasonable computation times. Using a well-defined interface between the models, a comprehensive sensitivity analysis was conducted. The sensitivity analysis model calibration cover all the steps of a model and boundary condition setup, working with spatial data, analysis of water balance and review of water levels on piezometers, a lake, river, elevation and regional flow (Gedeon and Mallants, 2012; Al-Muqdadi *et al.*, 2020). The model setup and configuration for the sensitivity simulation are shown in Table 6.25.

Table 6. 25 Model Setup and Configuration Information for Mesoscale Sensitivity Simulation generated from Modflow Run

Model Development and Configuration		
Model Design	Conceptual Model	- Mesoscale - 3 aquifer layers
	Model Geometry	- rectangular, confined aquifer overlain by a thick unsaturated zone
	a). Model Grid and layering	- 3 layers: 3 Fractured rock (No grid)
Flow Package	Node Property Flow Package	- Node property flow package (NPF)
Boundary array (cell type)	b). Boundary conditions - *Head dependent flux*	- General Head Boundary Package (GHB) - River Package (RIV)
	- Specified flux	- Recharge Package (RCH)
Model Calibration Parameters	Time Steady state calibration (-1 to 0 seconds)	- Stress (when boundary condition change) period is not relevant in steady state
	Spatial datasets (layer top and bottom)	- discretised with no grid, class feature fishnet (shapefiles)
	Hydrogeologic characteristics	- hydraulic conductivity - GHB conductance
Boundary Condition	c). Initial Condition and Stress	- initial head condition is top of model - hydraulic conductivity, GHB conductance, RIV, and recharge are model calibration parameters

a). Model Grid and Layering

The finite-difference mesh consists of three fractured aquifers with no grid option. All three aquifer layers are confined. Between the top of the model and lower aquifer bottom is a progressive thickness of the aquifer. This means that the first aquifer layer from the model top to the upper aquifer bottom will have 33% thickness of the total aquifer thickness, the middle and the lower part will have 66% and 1% of the thickness respectively.

b). and c). Initial conditions and hydraulic properties

The independent set (regional flow, lake, river, piezometer and elevation) for the calibration data was prepared as class feature fishnet shapefiles using ArcGIS tools. A rectangle object is used to create the recharge over the grid domain, with set values of enclosed cells. Recharge, GHB conductance and hydraulic conductivity are the dominant parameters of the sensitivity analysis. In this sensitivity calibration a low recharge rate (5.39×10^{-9} m^3/s) is used in the simulation. Recharge is set as top active cell to allow up and down movement of cells in the surface convert from wet and dry.

In the GHB package, the regional flow shapefile is imported as a single multipart object and set values of intersected cells. The boundary head is set at an elevation of 33m. Conductance is a key part of the sensitivity analysis and therefore a specific value of the conductance ($3 \times 10^{-3} m^2/s$) is set up to avoid the software interpreting the conductance by the length of the shapefile inside the cell. The lake fishnet feature is imported as a single multipart object and set values of enclosed cells at an elevation of 29.6m head boundary, with a direct conductance of 2×10^{-3} m^2/s.

In the RIV package, the river shapefile is imported as a single multipart object and set values of intersected cells. The river stage is set at 29.2 m with a direct river conductance of 4×10^{-3} m^2/s. River bottom is set at 28.3 m below surface.

Each of the three piezometers is imported into ModelMuse from the shapefile as a separate object with set values of intersected cells. In the OBS utility solver, the well screen elevation is at 22m, 24m and 24m respectively

The initial head condition was the model top, and run on a steady state simulation using no flow boundary. In this model, the K_x values were a bit higher 5×10^{-4} m/s, 6×10^{-5} m/s, 3×10^{-4} m/s, from the 1st to 3rd layer. The $K_y = K_x$ and $K_z = K_x/10$. The model setup for the sensitivity simulation is shown in Figure 6.32.

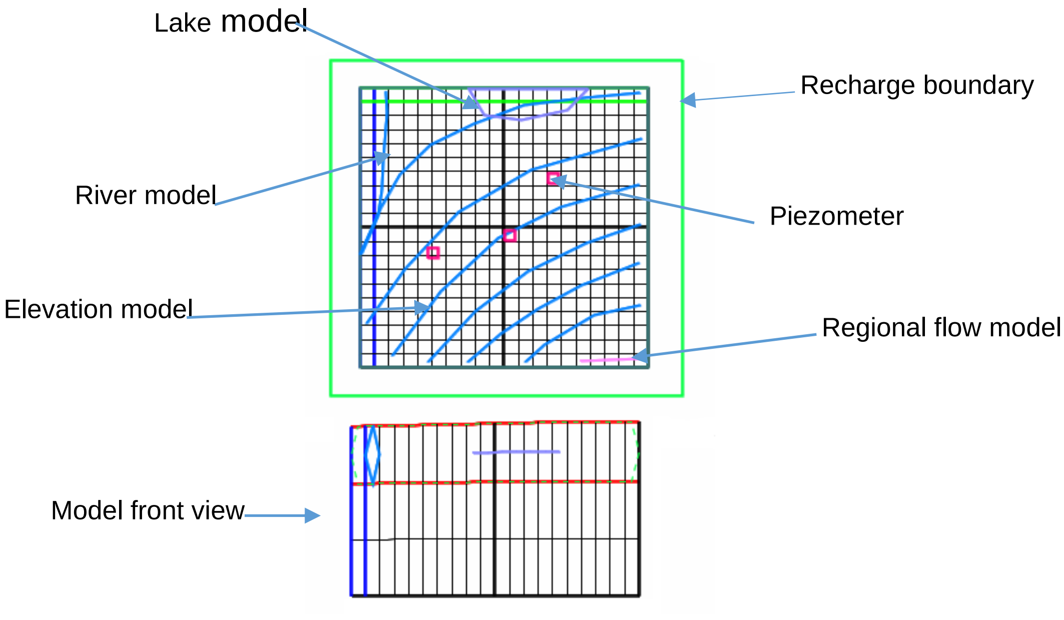

Figure 6. 32 Model Setup for Sensitivity Analysis Simulation (Source: authour's construction)

Sensitivity analysis has been performed on the model-independent parameters i.e., hydraulic conductivity (Kx, Ky and Kz) recharge (RCH) and conductance. The K values has been varied assuming that hydraulic conductivity decreases exponentially with depth. The sensitivity analysis results show that an increase in hydraulic conductivity helps to pump in more water into the aquifer. Recharge is recorded as a decrease of 100% to 10%. Recharge was applied at a steady state rate of $5.39\text{x}10^{-9}$ m^3/s. The resulting simulation characterised an aquifer system capable of supporting the 3 wells each yielding 19.3l/s without impacting the groundwater table in the aquifer from observed elevations. Recharge and hydraulic conductivity are two main parameters with equal influence on the magnitude of the model outcome. Steady-state simulation run time is 0.624 seconds, an indication that simulations can be done in less time and such simulation time optimises the number of cells.

Results indicate that regional flow simulated hydraulic heads are equally sensitive to hydraulic conductivity, groundwater recharge, and surface water bodies (lake and river) elevation. The surface water bodies (lake and river) are simulated to be either losing or gaining sources. Figure 6.33 shows how changing of K, by one order of magnitude can significantly vary distribution of the calculated hydraulic heads (metres).

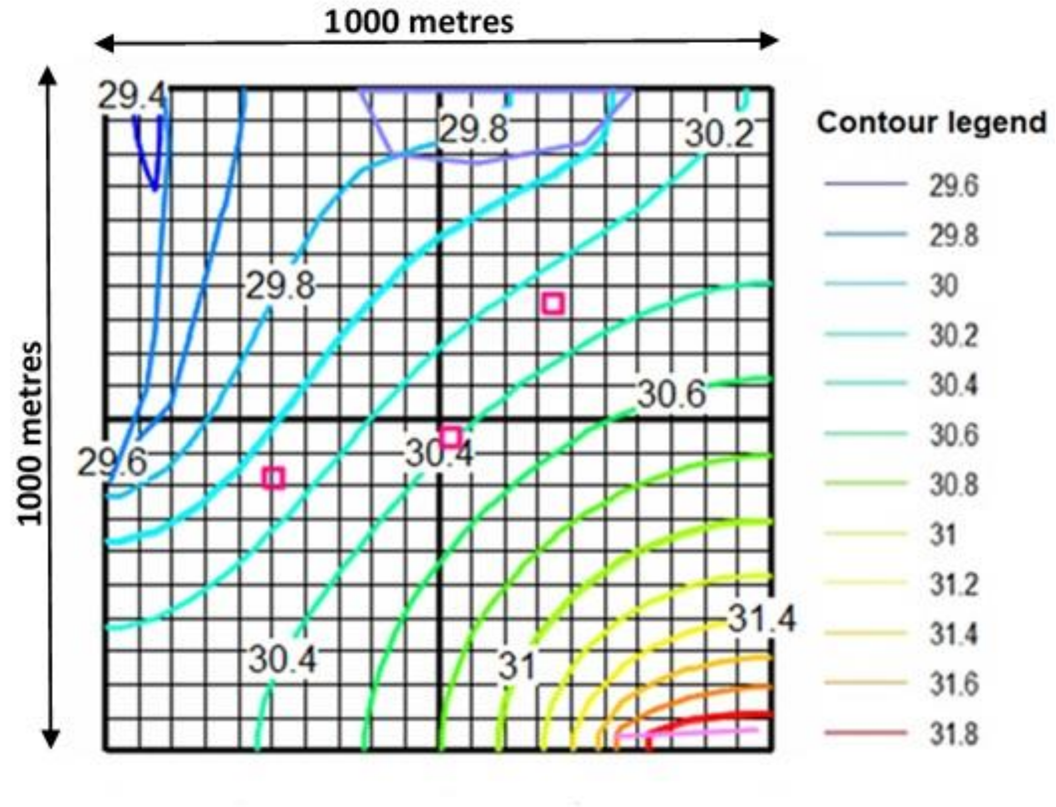

Figure 6. 33 Horizontal and Vertical Discretisation Grid using uniform layers for Sensitivity Model Simulation Heads (metres) at Steady state generated from Modflow Run

The results of sensitivity show that the aquifers are sensitive to the change of the longitudinal component of the hydraulic conductivity Kx with an average sensitivity value of -0.976 to -1.373, while a rather low sensitivity (-0.26E-05) to other hydraulic conductivity values (Table 6.26). This could be explained by the general groundwater flow direction with average velocities much higher than those in a transfer or vertical direction.

Volumetric water budget result (Table 6.27) showed the discrepancy for the final calibrated model was 0.00% with an inflow and outflow of 1.67×10^{3} m^{3}/day. The general head and recharge rates (Inflow) were 1.2×10^{3} m^{3}/day and 4.7×10^{2} m^{3}/day respectively. The automatic calibration technique in MODFLOW has showed significant enhancement in head residuals with mean maximum residuals of 1.64×10^{-4}m.

Table 6. 26 Model Sensitivity and improved Hydraulic Conductivity generated from Modflow Run.

Aquifer Layer	Initial Values (m/s)	Sensitivity/Iteration Number				Calibrated Values (m/s)
		1	2	3	4	
K_X	5 x 10^{-4}	-1.373	-0.976	-0.840	-0.517	5 x 10^{-4}
K_X	6 x 10^{-5}	0.001	0.000	0.000	0.000	5 x 10^{-4}
K_X	3 x 10^{-4}	0.001	0.000	0.000	0.000	5 x 10^{-5}
K_Z	5 x 10^{-4}	0.000	0.000	0.000	0.000	5 x 10^{-4}
K_Z	6 x 10^{-5}	0.000	0.000	0.000	0.000	4 x 10^{-4}
K_Z	3 x 10^{-4}	0.000	0.000	0.000	0.000	5 x 10^{-5}
K_Y	5 x 10^{-4}	0.000	0.000	0.000	0.000	3 x 10^{-4}
K_Y	6 x 10^{-5}	0.000	0.000	0.000	0.000	4 x 10^{-4}
K_Y	3 x 10^{-4}	0.000	0.000	0.000	0.000	5 x 10^{-5}

The volumetric budget is really close to that of the numerical simulations conducted for the study objectives. The detailed volumetric water budget and discretisation steps are found in Table E1.1 in Appendix E.

Table 6. 27 Summary of Volumetric Water Budget generated from Modflow Run

Flow term	Inflow: (m^3/d)	Outflow: (m^3/d)
RIVER	0.00	1.15 x10^3
GENERAL HEAD BOUNDARY	1.21 ×10^3	5.26 ×10^2
RECHARGE	4.66 ×10^2	0.00
TOTAL IN	1.67 ×10^3	0.00
TOTAL OUT		1.67 ×10^3

6.15 Comparison of Model Validation (analytical and numerical analysis for the observed data)

Baseflow caused by seasonal precipitation in the watershed was simulated using the water balance equation model. Baseflow estimated for this validation problem is defined as the average minimum annual daily discharge at the Freetown watershed which usually occurs between March and April when surface runoff and interflow are lowest and evapotranspiration is a dominant factor. The sources of inflow into the modelled area are precipitation (rainfall), surface water (rivers, streams) and groundwater flows into the watershed from outside the watershed. The common outflows include evapotranspiration, surface water (runoff, stormflows) and groundwater out of the watershed.

6.16 Summary

This chapter looked at the most important part of the groundwater modelling process which is the model calibration. In line with the objectives of simulating groundwater abstraction and recharge capacity for adequate and sustainable seasonal water consumption. Thematic maps (ASCII raster files and Shapefiles) were created to simulate the objectives in ArcGIS and QGIS environments so that the accurate real-world conditions bearing the coordinate system of the digital elevation model and location of groundwater resources can be visualised and interpolated into ModelMuse.

The simulations of groundwater quantity analysis and recharge assessment was performed using the necessary ModelMuse MODFLOW groundwater numerical flow packages. These simulations took into consideration the objectives to understand the regional groundwater system, predict artificial and natural changes in response to stress applied to the aquifer due from abstraction, evaluate the aquifer hydraulic properties, determine the performance of the wells/boreholes for future suitability and design artificial recharge zones such as infiltration galleries to provide realistic technical information for planning and adaptive strategies to water managers. Although groundwater flow models used in these hydrogeologic assessments and predictive simulations have numerous assumptions resulting from the hydraulic parameters and boundary conditions, they still provide the most inclusive volumetric analysis concerning the hydrogeologic processes and their impact on the aquifer system.

This chapter also focused on the results obtained from the various analyses carried out in Chapters 4 and the numerical models simulation discussed earlier. The aquifer hydrodynamic properties produced valuable information on the role of groundwater flow system to support domestic water consumption supply. The results from the topographical study highlight the percolation of water in the study area is adequate and natural recharge was high and increases with elevation. It was observed that the total abstractable groundwater level is quite substantial (153 x 10^6 cubic metres per year).

Additionally, in this chapter, the developed numerical models have been validated with simple analytical water balance methods to compare the different component contributions to the watershed. Two different situations of the watershed boundary have been defined where a simple groundwater flow and height model was designed with surface water interaction to provide a comprehensive tool for water resource managers in the development and planning of a 74km^2 watershed. The results of model validation indicated that the predicted values of the numerical simulations are significant with the results of observed ones. Hence, the developed models can be used for the study area.

ModelMuse MODFLOW model was subjected to a sensitivity analysis to decreased recharge and it was found that the model is highly sensitive to decreased recharge during the recharge of aquifers. Hydraulic conductivity and recharge play an important role in aquifer recharge, according to the sensitivity analysis.

CHAPTER 7: STRATEGY DEVELOPMENT FOR WATER SUPPLY AND MANAGEMENT

7.1 Introduction

In this chapter, geographic information systems were arranged to delineate the groundwater potential zones using rainfall data and seven thematic layers comprising geomorphology, lithology, drainage density, flow direction, land use/land cover, slope, and soil. An analytical hierarchy process (AHP) was used to normalise the weights, and an overlay analysis in ArcGIS 10.6.1 software was used to create a map of the groundwater potential zone. The eight factors were used to represent: rainfall as the major source of water; slope, which drives the water flow energy; flow direction which directs surface runoff for infiltration, drainage density, which controls the runoff distribution and infiltration rates; lithology, which controls hydraulic conductivity and infiltration, movement, and storage of water; geomorphology units, which determine surface runoff and infiltration; soil features, which govern the infiltration rates; and land use/land cover, which affects the recharge processes.

The groundwater potential zones (GWPZs) demarcation analysis has been conducted to identify new areas in the study area recommended for the construction of new boreholes/wells in densely populated areas. The safe yield has also been determined to know the amount of groundwater storage that can be extracted to meet domestic water supply needs during a given period without damaging the aquifer.

The main objective of the work was to delineate and map the groundwater potential zones using an integrated approach. The study will help in the planning and development of a sustainable water resources management.

7.2 Evaluation of Groundwater Potential Zones

For the evaluation of groundwater potential zones in the study area, the procedure includes acquisition of satellite data from STRM DEM and image processing using

Light Detection and Ranging (LiDAR)[21] tools, building of geodata base (discussed in Section 4.6 of Chapter 4), development of matrix for assigning weights to various features and ranking of the hydrogeological units are based on integration of all the thematic map layers in Geographic Information Systems environment.

A flow chart has been presented to indicate the procedure for the delineation of groundwater potential zones in Figure 7.1. The packages used to perform the data processing and analyses are LiDAR, Arc GIS 10.6.1 and MS Office.

Having created the thematic maps (discussed in Chapter 4), several other GIS functions followed, including weights assignment and normalisation (AHP), conversion of thematic maps to raster format, vectorization of thematic maps, and test/qualification of the map covering the aquifer recharge potential zones. Using the Saaty (1987) weighting formula in Table 7.1 as a guide, appropriate weights were assigned to the eight thematic layers based on their influence or contribution to groundwater recharge, since the overall goal of this study was to identify groundwater recharge zones.

The weights assigned to the thematic layers have been observed to introduce some bias due to their subjective nature, for instance, when weights are assigned by personal judgement.

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[21] https://earthexplorer.usgs.gov/

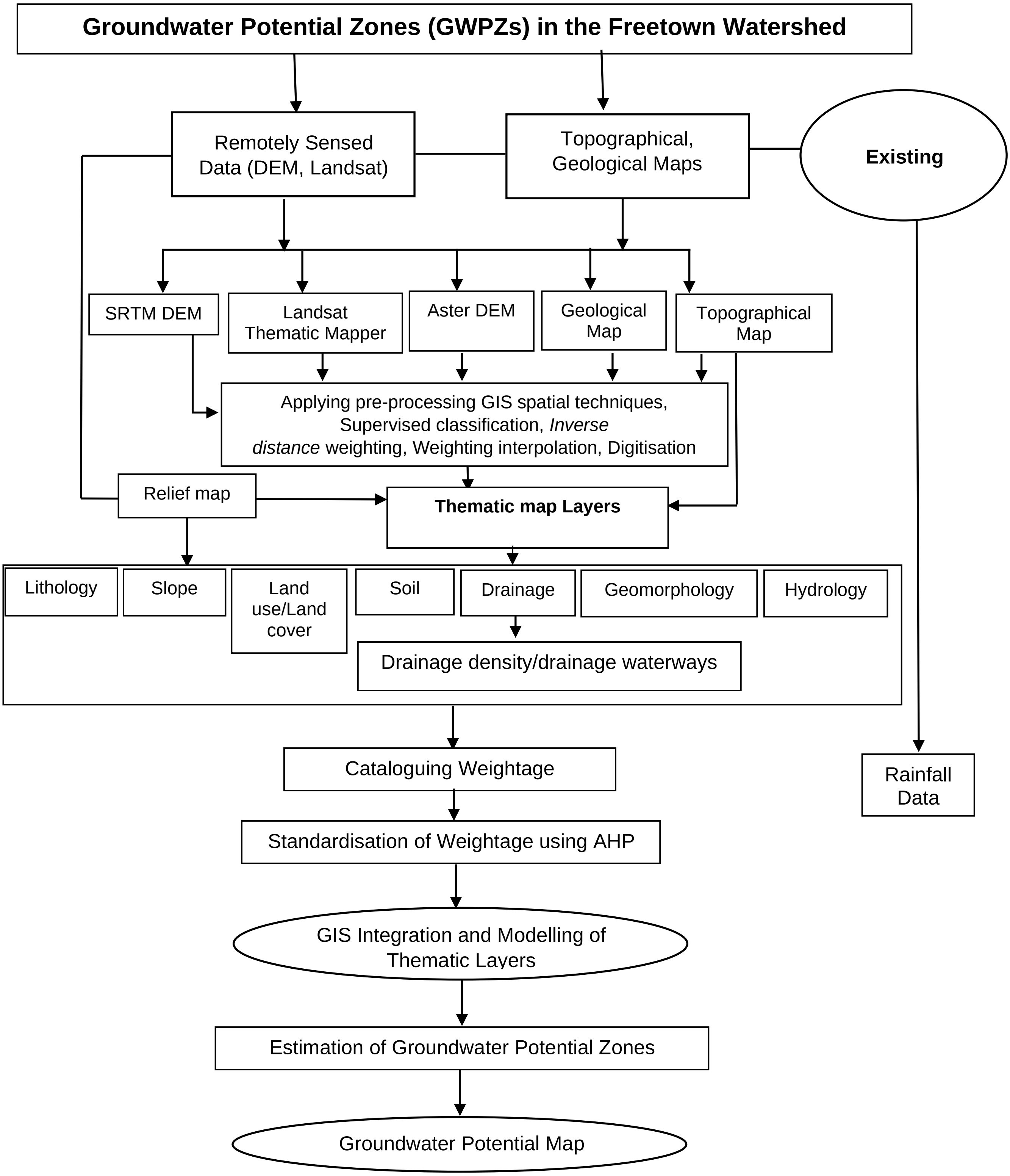

Figure 7. 1 Flow chart for Delineating Groundwater Potential Zones (Source: authour's construction)

7.3 Analysis of Groundwater Potential zones

Groundwater potential index (GWP) is a dimensionless value that measures the groundwater potential zones in a given area according to Malczewski and Rinner (2015) equation for the calculation of GWPZs. It is the sum of the product of weightage and rank of the schemes given below:

$$Groundwater\ potential\ index\ GWP = \sum(\mathrm{W} \times \mathrm{R}) \qquad \text{(Eq 7.1)}$$

where,

GWP - Groundwater Potential

W – Weightage of thematic layers

R – Rank (weights of the features in thematic layers)

The weightage and rankings of the eight themes are determined by the groundwater potential capacity. The ranks represent the importance of the subclasses of a particular theme. The values are given according to the suitability nature of the particular theme. By comparing the alternatives and evaluating the criteria, AHP technique generates a ranking of the solutions. A decision is made based on the alternative with the highest value as the first choice (Muralitharan and Palanivel, 2015). AHP technique is recommended when there are insufficient valid data for data analysis. The weightage and ranks are shown in Table 7.1.

The groundwater potential zones are derived by grouping the potential index using standard deviation procedure as outlined in Saaty (1987) and Murmu *et al.* (2019). Based on the grids resolution created for each feature, all grids are classified as Very high GWP (>8.0), High GWP (6 - 8), Good GWP (4 - 6), Moderate GWP (2 - 4) and Low GWP (<2.0) for attributes that favour groundwater potential (Awawdeh *et al.*, 2014; Murmu *et al.*, 2019; Owolabi *et al.*, 2020).

In this study, and based on these ranking and weightage (Table 7.1), the new effective intensity groundwater potential grid values were derived and categorised into four zones namely high, good, moderate, and low groundwater potential zones (Table 7.2) using the quartile classification method in Owolabi *et al.* (2020).

Table 7. 1 Assigning Parameter Ranking and Weightage (Source: authour's construction)

Thematic Layer	Map weight	Individual features	Groundwater potentiality	Ranks
Geomorphology unit	8	Coastal Plain	Very high	10
		Swamps	High	9
		Valley	Good	7
		Weathered insitu Laterite	Moderate	5
		Residual Hill	Low	2
		Denudation Hill	Low	2
Lithology unit	7	Beach sands	High	9
		Sand lignite	High	8
		Alluvium	Good	7
		Weathered gabbros, dunite	Moderate	4
		Fractured gabbros	Low	3
		Hard gabbro, dunite	Very low	1
Drainage Density (km/km^2)	3	0.08 -14.86	Very high	10
		14.86 - 21.98	High	9
		21.98 - 28.18	Good	7
		28.18 - 36.21	Good	6
		36.21 - 59.40	Moderate	5
Soil	6	Coastal river estuaries	High	7
		Gravely ferralitic	Good	6
		Shallow soils on plateau mountains	Moderate	5
		Lateritic hills and terraces	Moderate	4
		Weakly developed muds	Low	2
		Shallow soils from basic and ultrabasic rocks	Low	2
		Hydromorphic clays	Extremely low	1
Rainfall (mm/yr)	5	2584 - 3206	High	Good
		3206 - 3868	High	Good
		3868 - 4519	Very high	Very good
		4519 - 5063	Very high	High
Flow Direction (degree)	4	1 - 8 (East)	Low	Low
		8 - 32	Moderate	Good
		32 - 64	High	Very good
		64 - 128 (Northwest)	Very high	High
Slope (degree)	3	0 - 5.414	Very high	10
		5.414 - 12.859	High	8
		12.859 - 21.318	Good	7
		21.318 - 32.146	Moderate	6
		32.146 - 86.287	Low	5
Land Use/Land Cover	2	Water body	Very high	10
		Vegetation	Moderate	8
		Built-up area	Low	2

The formula for the groundwater potential zones (GWPZs) is as shown below:

$$GWPZs = \mathrm{Geoph} + \mathrm{Li} + \mathrm{Fd} + \mathrm{S} + \mathrm{Slp} + \mathrm{Dd} + \mathrm{LULC} + \mathrm{Rf} \qquad \text{(Eq 7.2)}$$

Where,

Geoph = geomorphology, Li = lithology, Fd = flow direction, S = soil, Slp = slope, Dd = drainage density, LULC= land use, and Rf= rainfall

In order to delineate the groundwater potential zones, different thematic layers including slope (Figure D9.1), geology (Figure 3.7), soil (Figure D9.2), geomorphology (Section 3.2.2), land use/ land cover (Figure 3.5), flow direction (Figure D9.8) and drainage density (Figure D9.6) maps shown in chapter 4 and appendix D9 were integrated. This provides a comprehensive indication about the groundwater potentiality of any area. Presently, groundwater potential zones have been demarcated by integration of thematic layers, using GIS technique. Each thematic layer consists of number of polygons, which correspond to different features. The polygons in each of the thematic layer have been categorised based on the influence of the feature on the groundwater sources. The ranks are assigned based on their weightage to delineate the groundwater potential zone. Higher number in the ranking order will show high potential zone and lower number in the ranking order will show low potential zone (Magesh et al., 2012).

7.4 Delineation of Groundwater Potential Zones

Table 7.2 present the intensity of thematic factors influencing groundwater potential zones. The groundwater potential zones are classified into four zones namely high, good, moderate and low groundwater potential zones.

7.4.1 High Groundwater Potential Zone

Based on the analysis of the thematic layers influencing groundwater potential, high potential zones are identified in near flat surfaces, along the coast and swamp valleys. These are areas where geomorphologic features consist of very gentle slopes indicating high groundwater potential.

Table 7. 2 Attributes of Groundwater Potential Zones (Source: authour's construction)

Parameters	**Groundwater Potential Zones**			
	High	**Good**	**Moderate**	**Low**
Geomorphology	Shallow undulating mountain plateau, coastal plains and swamp valleys	Weathered insitu Laterite on moderate undulating plains.	Residual hill and shallow plateau	Denudation and residual hills
Lithology	Mostly beach sands and alluvium with gravely soils	Moderately weathered /fractured gabbros	Moderately weathered and fractured gabbro	Hard gabbro
Slope	Very gentle	Gentle, moderate, slope	Gentle to moderate slope	Steep to very steep slope
Land use / Land cover	Dense vegetation, water bodies	Stony waste, open vegetation, land with shrub, water body	Stony waste, open forest, land with little shrub, few water body	Stony waste, land without shrub, no water body
Soils	Coastal river estuaries, shallow soils	Fine loamy	Weakly developed muds and shallow soils from ultrabasic rocks	Fine hydromorphic clayey
Drainage density	Very low to low	Low and moderate	Moderate to high	High
Rainfall	Very high percolation rate with flooded plains	Very good percolation rate, little runoff	Moderate to high runoff	Low rainfall with rapid runoff

7.4.2 Good groundwater potential zone

This zone is confined on gentle to very gentle slope with fractures in the weathered gabbro, shear zone and dykes. Geomorphologically, this zone stretch over shallow highly weathered lateritic materials, undulating alluvial plains, open vegetation with low drainage density which contributes to good potential zone (Murmu *et al.*, 2019; Owolabi *et al.*, 2020).

7.4.3 Moderate groundwater potential zone

This zone is defined with moderate undulated terrain with residual hills, soil and drainage density found to be low to moderate which support fair groundwater potential (Allafta et al., 2021). The soil type is shallow on plateau, clayey showing shallow alluvium and beach sand over stony waste, and land with and without shrub which fairly supports infiltration rate.

7.4.4 Low groundwater potential zone

This zone is confined on steep residual slope to very steep denudation slope which indicates poor groundwater potential. Drainage density is very low having shallow ultrabasic and clayey soils. Geomorphologically this zone stretches over mountainous bare land. There is a decrease in area of water bodies with scattered stony residual deposits and does not support groundwater potential (Muralitharan and Palanivel, 2015).

7.5 Classification of Groundwater Potential Zones

From the GIS operations in Figure 7.1 and the assignment of weights to the thematic layers in Table 7.1, the resulted groundwater potentiality map for the entire study area is shown in Figure 7.2.

Table 7.3 present information on constant discharge pump test and location of wells in the study area. A linear relationship was found between the well's discharge data and the total grid values obtained from the groundwater potential map for the respective wells. In this case, the groundwater potential in the Freetown watershed was well predicted by the AHP method. In order to ensure sustainable groundwater management, this technique can be used to select suitable well sites and to plan future groundwater abstraction in an efficient manner.

Table 7. 3 Constant Discharge Rates Aquifer Pump Test Information

Well Location	**Easting**	**Northing**	**Elevation (m)**	**Well Discharge m^3/hr**	**Well Bottom (m)**
Ascension Town	692750	937827	63	5.3	72
Adolphus Kissy	698663	937060	65	11.5	104
Allen Town	704104	928960	26	10	80
Portee	700620	935723	74	16	58
Cline Town	697256	938806	27	6.8	46
Blackhall Road	696893	937651	59	15.2	63
Brookfields	692662	937728	52	3.78	50
Hill Station	692887	935003	285	1.26	80
Cline Town	696970	938854	27	7.56	40
Dwarzak	694767	936168	146	1.2	79
Fourah Bay	696721	938647	32	10.8	36
Foulah Town	694758	938214	109	9	80
Mount Aureol	696118	937741	93	1.8	76
Murray Town	690870	939571	23	6	68
Aberdeen	688807	938954	47	5.6	60
Kingtom	692715	938604	14	9.3	64
Kroo Bay	693716	938462	18	15.2	68
Mansaray Lane	699070	936974	123	49	78
Lowcost Housing	699584	937012	51	38.5	126
Lumley	690212	935221	23	6.4	68
Rawdon Street	694501	938924	33	16.2	76
Rokupa	701023	935947	114	8.6	80
Susan's Bay	695231	935551	14	8	58
Tengbeh Town	692104	936945	105	2.8	78
Calaba Town	701876	933117	117	29.8	70
Wellington	701414	933636	79	24.5	60
Wilberforce	691735	936532	188	1.8	82
Congo Water	701414	934797	57	13.7	43
Old Wharf	702797	933818	46	17.6	60
Thunder Hill	699766	935919	104	15.1	74
Wilkinson Road	691617	938272	11	15	49
Congo Town	692147	938190	29	9.3	58
Bottle Field Calaba Town	702548	932309	65	16	64
Calaba Town	702684	932810	43	12.4	70
Cape Sierra Aberdeen	687588	939344	21	9.8	52
Carsel Farm Kissy	698187	937092	66	8.6	65
Fourah Bay	696006	938835	32	9	39
Gingerhall Mount Aureol	696119	937741	93	7.8	50
Allen Town	702275	931468	70	6.8	80
Blackhall Road Ashobie	696895	937643	55	8.2	68
Carsel Farm Kissy2	698188	937098	76	9.4	68
Carsel Farm Kissy3	698274	937147	52	10.3	48
Taylor Street Kissy	698621	937149	64	9	70
Hill Cut	692434	935041	52	1.6	78
Davies Street	698939	936480	87	4.6	70
Kamayama	690799	934430	38	3.8	42

Source: EDAL Drilling Company[22]

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[22] EDAL Drilling Company LTD

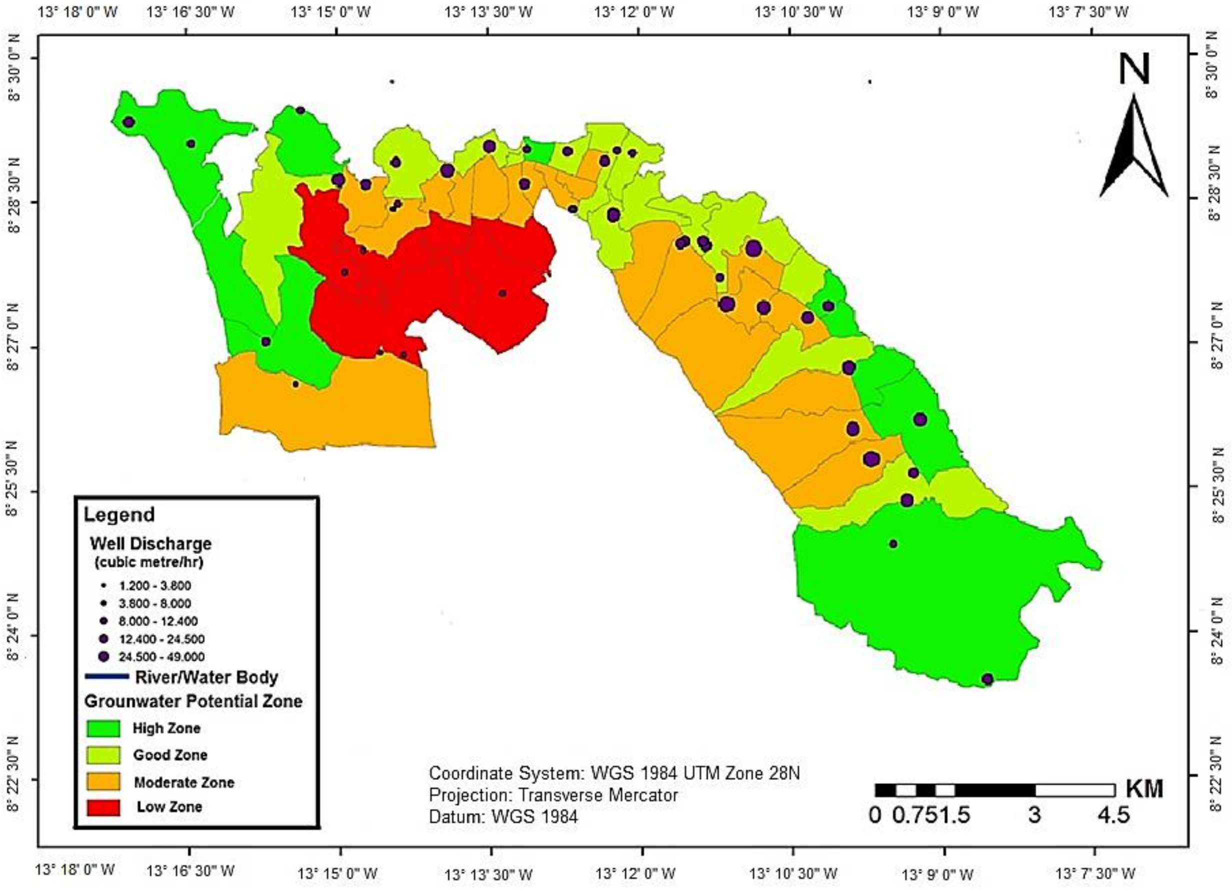


Figure 7. 2 Groundwater Potential Zones Guide Map and Well Discharge Points in the Study Area (Source: authour's construction)

Table 7. 4 Classification of Groundwater Potential Zones (Source: authour's construction)

Groundwater Potential Zone	Area (Km^2)	Percent of area covered (%)	Location
High	13.2	18	Wellington, Portee, Old Wharf, Aberdeen, Lumley.
Good	20.6	28	Susan's Bay, Kingtom, Cline Town, Wilkinson Road.
Moderate	29.4	40	Juba, Congo Town, Locust Housing, Calaba Town, Brookfields.
Low	10.4	14	Hill station, Dwarzak, Tengbeh Town, New England.
Total	73.6	100	-----

The final classification for groundwater potential zones is shown in Table 7.4. The analysis revealed that 18 percent (13.2 Km^2) of the area comes under high groundwater potential found in Wellington, Aberdeen, Portee, Old Wharf and Lumley (administrative city map of Figure 3.6). The undulating terrain and intensity in the shear zone is characterized by very gentle slope and geomorphological features like coastal plains and swamp valleys indicate a very high groundwater potential in these areas.

About 28 percent (20.6 Km^2) comes under good groundwater potential zone found in Susan’s Bay, Kingtom, Cline Town and Wilkinson Road. This zone is restricted to gentle, and moderate slope. The high intensity of lineament zone is in the weathered gabbros, shear zone and dykes. Geomorphologically this zone stretches over undulating alluvial plains, shallow clayey and gravely hills. The land use for this zone has stony waste, open vegetation, land with shrub, water body, which helps to maintain good groundwater potential.

The moderate and low groundwater potential occupy 40 percent (29.4 Km^2) and 14 percent (10.4 Km^2) respectively. Juba, Congo Town, Locust Housing, Calaba Town and Brookfields form part of the moderate groundwater potential areas. The low groundwater potential zone is restricted on steep to very steep slope. The slope indicates poor groundwater potential, where the geology is partly weathered gabbro. The lineament density is very low, soil type is fine loamy and clayey. Geomorphologically this zone stretches over denudation and residual hills. The land use for this zone stretches over stony waste and land without scrub. The drainage density is very high. Overall, the features are not supporting the groundwater potential. Hill station, Dwarzak, Tengbeh Town and New England form part of the low groundwater potential zone.

The groundwater potential map (Figure 7.2) established that the high groundwater potential zone is concentrated in the east to south-eastern and north-western region of the study area due to the distribution of beach sands along the coastal plains, alluvial cover and swamp valleys with high infiltration capacity. The result of the groundwater potential zone is similar to VES mapping analysis in the study by Fileccia et al. (2018). This indicates that, slope, lithology, flow direction, geomorphology, rainfall and soil types play an important role in groundwater development. Furthermore, the concentration of drainage density and waterways density also helps the infiltration capability of the groundwater system. Using the available well discharge rates for the wells from the drilling companies in the study area, the data has helped verified the groundwater potential.

7.6 Groundwater Management for Safe Yield and Sustainable Supply

Modest and operational management guidelines and rules must be put in place to support the mathematical groundwater modelling information in planning for sustainable groundwater abstraction for consumption. These guidelines and rules must be based on local knowledge and experiences to integrate strategies for adaptive management, planning and maintenance responsibilities.

The main focus of future strategy development and groundwater management must be scheduled in such a way that:

1. Groundwater abstractions must be designed to utilise the available sustainable supply and demand provisions without adverse impacts.
2. Identify potential zones that would support efficient and sustainable groundwater management.

To some extent, groundwater management should include several aims namely, recharge capacity, withdrawal rates and reasonable consumption to ensure sustainability. This study has looked at the per capita water consumption and have conducted regional groundwater simulations to determine the groundwater development potential of the study area.

Historically, the management of groundwater aquifer is based on the safe yield (Heath and Spruill, 2003; Kalf and Woolley, 2005; Hiscock et al., 2013). The theory of “safe yield” comes into perspective as the main objective, which is connected with the amount of supply that a water user can sustainably depend upon. According to Zhou (2009) and Molle (2011) the safe yield of an aquifer is defined as “the attainable rate of perennially withdrawing water from it for human usage.” In considering safe yield exploitation and natural replenishment of groundwater to maintain sustainable abstraction balance, a certain amount of water must be left within the aquifer for future and unpredicted emergency cases.

Overall, the safe yield must be adapted in such a way that neither groundwater quantity nor its quality should be allowed to reach unacceptable limits. In real situations, the safe yield should be less than the annual average recharge to recompense the minor groundwater losses Meinzer (1934).

Sen et al. (2013) have indicated that population and its future growth are the strategic aspects for groundwater distribution. Based on the analysis presented in Sections 6.13, the minimum requirements, for emergency situations and reasonable seasonal abstractable volume can be set at 50 litres/capita/day or 70 litres/capita/day in the dry and rainy season respectively.

Safe yield calculation

In considering the Freetown watershed for a safe yield situation, where the aquifer has 73 km^2 areal scope, its thickness is 50.6m, where aquifer hydraulic conductivity and the storativity are 5.8 x 10^{-2} m/min and 1.22 x 10^{-2} respectively (pumping test data Table F1.1). An observation well monitoring for several years has indicated that the piezometric level changes between 56m and 48m (from wells interference patterns discussed in Sub-Section 6.5.3). Lateral flow rate due to infiltration from far distances is 3.2 m^3/s (regional volumetric flow rate in Table 6.22).

Based on these circumstances, an attempt has been made to answer the following:

1. What will be the aquifer safe yield?
2. If each well pump is 5 litres per second in the rainy season, and 3 litres per second in the dry season, how many wells are needed for safe exploitation?

Solution

Assumption – In solving for the safe yield, since the piezometric level fluctuation already assumes the effects of the lateral flow, it does not enter the calculation. The safe yield assumes the pumping rate is equal to the total recharge rate.

1. In the meantime, long-term piezometric level fluctuation difference as in Bardsley and Campbell (1995) and Şen (2015) is 56 – 48 = 8m (data from Sub-Section 6.5.3) . Depending on water table (piezometer) drop, Δh, total amount of water that can be withdrawn from this aquifer can be calculated according to Equation (7.3), by the use of the specific yield, S_y, and the area, which yields annually safe yield water as follows:

$$V_w = S_y A\Delta h \qquad \text{(Eq 7.3)}$$

Where,

S_y = Specific yield
A = Area of the aquifer
Δh = Water table drop
$\mathbf{V_w}$ = Safe yield water volume (m^3/yr)
$\mathbf{Q_{wr}}$ = Well pump discharge in rainy season
$\mathbf{Q_{wd}}$ = Well pump discharge in dry season
$\mathbf{n_{wd}}$ = Number of wells in the dry season
$\mathbf{n_{wr}}$ = Number of wells in the rainy season

$$V_w = 1.22 \times 10^{-2} \times 73 \times 10^6 \times 8$$

$$= 7.1248 \times 10^6 \ m^3/yr$$

2. The pump discharge ($\mathbf{Q_{wr}}$) from a single well during the rainy season at 5 l/s (Sub-Section 6.5.3) is,

$$\mathbf{Q_{wr}} = 5 \text{ x } 10^{-3} \text{x } 365 \text{ x } 24 \text{ x } 60 \text{ x } 60$$

$$= 0.16 \text{ x } 10^6 m^3/\text{yr}$$

Hence, the number, $\mathbf{n_{wr}}$, of wells to support in the rainy season is

$$\mathbf{n_{wr}} = \frac{7.1248 \text{ x } 10^6}{0.16 \text{ x } 10^6} = 45 \ wells$$

The pump discharge ($\mathbf{Q_{wd}}$) from a single well during the dry season at 3 l/s is,

$$\mathbf{Q_{wd}} = 3 \text{ x } 10^{-3} \text{x } 365 \text{ x } 24 \text{ x } 60 \text{ x } 60$$

$$= 0.095 \text{ x } 10^{6} m^{3}/\text{yr}$$

Hence, the number, $\mathbf{n_{wd}}$, of wells to support in the dry season is

$$\mathbf{n_{wd}} = \frac{7.1248 \text{ x } 10^{6}}{0.095 \text{ x } 10^{6}} = 75 \; wells$$

Consequently, from the numerical model of interference wells simulated over a fifteen-year period (Sub-Section 6.5.3) and to maintain enough water supply during the year, a maximum of 78 wells are enough in case any of the 75 wells are failing in the dry season pumping at a rate of 3x10^{-3}m^{3}/s, then an additional back-up of 3 wells must be drilled. A sustainable management method therefore requires only 78 wells.

7.7 Management Strategies identification

The aquifer's safe yield and the number of wells to be constructed and maintained safe sustainable exploitation in the rainy and dry seasons have been estimated. The values are higher than the estimated annual pumping discharge and less than the annual average recharge. This is indicating that groundwater is annually underexploited to the yearly replenishment of the aquifer. It means that more abstraction water points can be constructed without any impact on the aquifer system. In the previous sections, the possibility of infiltration galleries to supply water has been considered in Sub-Section 6.5.5, as it was observed in the analysis of the questionnaire-based studies (Chapter 5) that several communities are without piped water networks. Some of these communities are located along an area with a perennial river and the advantages of installing infiltration galleries are highly favoured to the communities. The selection site and data for design are presented.

7.7.1 Selection of Site for Water Supply Simulation of Infiltration Galleries

Based on discussions in Sections 7.4 and 7.5 to identify groundwater potential zones, the potential site for water supply through infiltration galleries has been identified on the following site selection criteria:

1. The area of interest is within a river plain aquifer, about 0.25 km^2.
2. Infiltration gallery 1 is 300 metres in length (discussed in Sub-Section 5.5.5) and located at 8.400874, -13.161689 (702411, 929090) and 8.400500, -13.159076 (702699, 929050).
3. Infiltration gallery 2 is 300 metres in length and located at the following coordinates 8.400702, -13.161726 (702407, 929050) and 8.400373, -13.159095 (702697, 929036).
4. Geologically, the aquifer is primarily composed of alluvial sediments, weathered, and fractured gabbro materials.
5. The site slope range between 0° to 24°.
6. The soil is gravelly and alluvial in nature.
7. The site is on the 1st and 2nd stream order (as shown in Figure D9.7), perennial riverbed throughout the dry season.
8. The site has a high riverbank that allows manual or motorized suction pumps to operate.

7.7.2 Data for the Design of Infiltration Galleries

A trench about 5 to 7 metres below ground level (GL) should be excavated such that the infiltration galleries will have cones of depression and a radius of influence. The construction should be completed at the peak of the dry season and the infiltration galleries should be buried two metres below the water table to sustain water in the wells at all times. The construction and planning should consider many factors, including:

- water demand for the community it will supply;
- the sustainable yield of the groundwater system which has been conducted;
- the preferred site has been selected with safe isolation distances from all kinds of pollution sources and proximity to residents’ water points;

- depth to the water table is higher and will reduce the cost of excavation and have water at all times in the year;
- the permeability of the unsaturated zone materials is important because it will help to determine the area of influence and the length of the design for the infiltration galleries to be fitted, that will maintain a constant yearly pumping rate.

The cross-sectional details of the infiltration galleries are shown in Figure 7.3. Guidelines for the design of infiltration galleries are provided below:

Catchment Area = 0.25 sq.km (0.1mi^2)
Nature of Catchment = very high groundwater potential zone (Section 7.5)
Average annual rainfall = 3350 mm
84 percent dependable rainfall = 2814 mm (from the groundwater balance by the simulation calculation method in Table 6.23)
Length of each infiltration gallery pipe = 300 m (two infiltration galleries have been simulated for water supply)

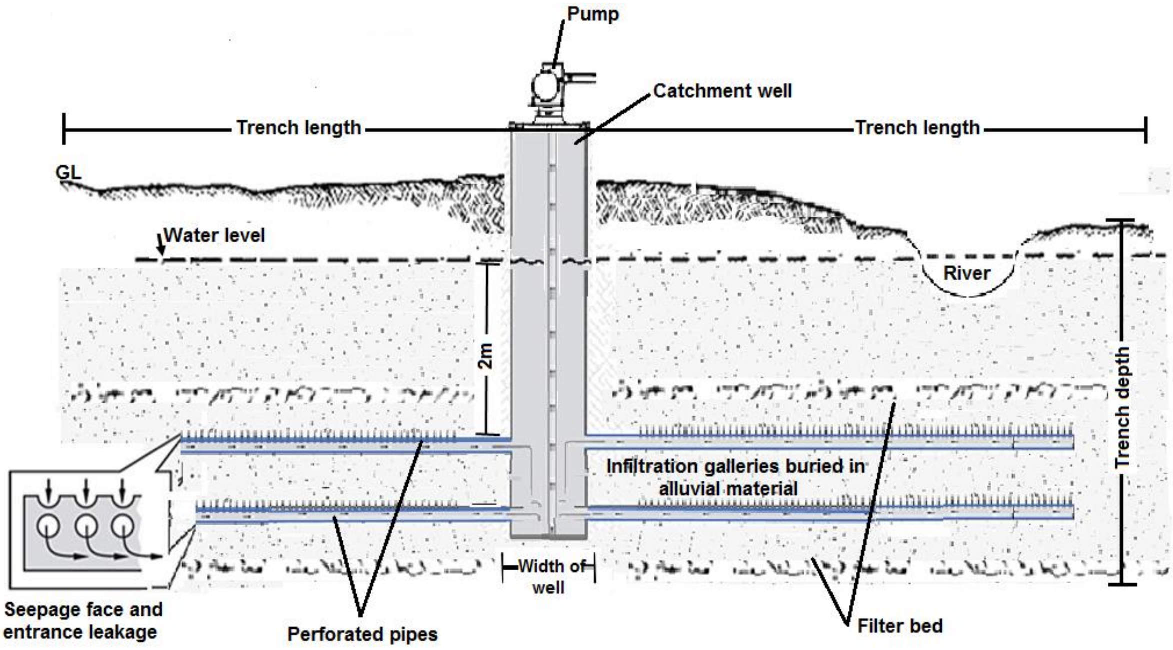


Figure 7. 3 Cross Sectional details of Infiltration Galleries (Source: authour's construction)

7.8 Summary

This chapter has focused on groundwater strategy development for sustainable water supply management, aquifer safe yield assessment and extension of water supply through infiltration galleries. From the study, it is apparent that GIS technique has proved to be the most practical tool for the delineation of groundwater potential zones. Through GIS analysis and MODFLOW simulation, a suitable site for the location and sustainable recharge of the infiltration galleries was selected and simulated as explained in Sub-Section 6.5.5. The suitable structure designed for water supply in the communities without piped water supply is the infiltration gallery (Feulner, 1964; AAFC, 2006).

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The growing demand for water uses worldwide can lead to difficulties in accessing the resource and over exploitation leading to conflicts with challenging stresses. The numerous exploitations of groundwater resources have resulted in a drop in water table levels. Hence, the need to study groundwater development for sustainable abstraction.

Freetown, the capital city of Sierra Leone comprises of over thirty-one neighbourhoods, having a population of 1,055,964 as per the 2015 Statistics Sierra Leone Housing Census. The main source of water to the Freetown municipality is through the Guma Valley dam distributing surface water. Due to the increase in population, dam capacity, urbanisation, and industrialisation, the demand for water supply to households for domestic use has increased and the available Guma Valley dam water is not sufficient to meet the city’s demand.

It is only these recent years that consideration has been given to the study of the groundwater development of the region in order to help alleviate water shortage problems. Hence, there was a direct need to explore the groundwater potential. The study which aimed aim to develop a strategy to manage groundwater resources sustainably to households in Freetown, Sierra Leone under the influence of seasonal variability, constitute the first comprehensive attempt to model groundwater quantity and recharge capacity within the Freetown watershed, to support per capita water consumption. ‘A Water Consumption Questionnaire-Based Study and Groundwater Modelling Investigation: Groundwater Management under Seasonal Variability in Freetown Sierra Leone’ was selected as a topic for the research. Based on the present study, the various analyses were carried out, the results of the analyses were discussed in previous chapters and the following conclusions were drawn.

8.2 Conclusions

The thesis draws on a combination of structured literature reviews and analyses of primary and secondary data to address the objectives from the two main components: what are the factors that influence seasonal per capita water end-use consumption patterns, what development and management strategies should be put in place to sustain aquifer reliability and recharge capacity for an increased abstraction of water supply. The specific questions that the thesis sought to address are presented in Section 1.2 of Chapter 1.

The thesis presents a diverse set of findings concerning improved understanding of per capita water end-use consumption, seasonal variability impact on water end-use consumption, modelling per capita water consumption with household characteristics, topographical characteristics and groundwater quantity development. The study is well-placed to explore the possibility of strategies on sustainable abstraction for seasonal per capita water consumption.

The main findings of the thesis have been summarised from the results of the questionnaire-based water consumption study (Chapter 5), the five groundwater numerical simulations modelling the problems identified in the Freetown watershed (Chapter 6) and the strategies developed for sustainable seasonal water consumption (Chapter 7). This chapter synthesises the main findings from these chapters to respond to the research questions (Section 1.2 of Chapter 1) of the two components of the study.

8.2.1 Summary of main Findings

The relationship between household characteristics, water use characteristics and seasonal variation have considerable impact on per capita water end-use characteristics. Naturally, household coping strategies are strongly influenced by socio-economic status, and of course, the extent of water access and unreliability. In both the review in Chapter 2 and the analysis in Chapter 5, the households have implemented particular coping strategies shaped by inequalities relating to income status, level of education and housing occupancy. The demographic and water use characteristics provide more accurate predictions of per capita water consumption than the predictions resulting from the use of physical characteristics of the investigated households. The finding of the questionnaire-based study in Chapter 5 are therefore important in shedding light on issues related to demographic and water use characteristics and other strategies to be developed to ensure adequate and sustainable per capita water supply.

Field studies have shown that the area receives more rainfall during the monsoon season, and the water can be effectively conserved during this period by conservative structures to reduce the impact of seasonal variability on groundwater resource. Analyses of the interaction between the water bodies in the study area (Section 6.5.4) have proven that they can serve as a gaining or losing source throughout the seasons. Difference in the flow direction has been partly attributed to the presence of hills and valleys in the watershed.

Aquifer tests have displayed hydraulic properties of the groundwater system. GIS tools were used to analyse and interpret groundwater recharge and potential zones for the constructions of new wells/boreholes and infiltration galleries. The ModelMuse MODFLOW code was applied to simulate the present and future groundwater quantity and flow in the Freetown watershed as presented in Table 4.6.

Hereunder, are presented the major findings and conclusions of the study. The implementation of the Theis, Cooper Jacob and Chow analytical methods were useful for the estimation of aquifer and hydraulic parameters from pumping tests data. Storativity or storage coefficient (S) was found to range from 9.68×10^{-5} to 1.61×10^{-4}. The calculated transmissivity (T) ranged between 1.6 m^2/d to 82.4m^2/d, with average of 25m^2/d, which is acceptable for water abstraction from the aquifer system (Wright, 1992). The hydraulic conductivity values ranged from 1.0×10^0m/d to 5.02×10^2m/d with an average of 8.47×10^1m/d. The range of values reveals moderate hydraulic conductivity (Edet et al., 2014). Accordingly, hydrologic thematic layers and soil analyses revealed that the aquifer is mainly composed of fractured crystalline to weathered and alluvial materials. These formations can adequately store and transmit significant quantity of water to wells/boreholes/infiltration galleries in the study area.

The soil water balance (SWB) analysis of the watershed has been helpful to show how seasonal variability impact groundwater resource in Freetown valley and mountain heights. SWB shows that the dry months begins in December and ends in April. July to September tend to be the wettest months in the year with total deficit value reaching 384 mm in the valley bottom and 297 mm in the mountain heights respectively. The results also show that the valley bottom of the watershed has a lower capability to preserve water (high evapotranspiration), and that annual rainfall is higher than the annual evapotranspiration. This affects the recharge capacity in different part to the watershed to support the groundwater system as a gaining or losing water body.

The numerical model developed to simulate recharge capacity has been useful to determine the magnitude and direction of groundwater flow under natural and artificial recharge processes. The simulation has helped to confirm that the surface topography and the hydraulic gradient controls groundwater flow conditions of the watershed in the Northeast/Southwest direction along the rivers.

The numerical model for the simulation of interference patterns of the wells in Section 6.5.3 has been useful to answer questions on the hydrogeologic effect of seasonality on groundwater resources. It has demonstrated that the wells/boreholes pumping rates and time for abstraction in the dry season should be considered. Pumping must only be done during the day time at a pumping rate of $3x10^{-3}m^3/s$. The model has been helpful to simulate seasonal variability and human impacts on the wells with static water level from 7 metres to 23 metres (based on elevation of undulating topography) as minimum water level to sustain usage and demand in the dry season within the study area.

The question on what is the aquifer’s safe yield for the dry and rainy seasons at a rate at which groundwater can be withdrawn from the aquifer without causing an undesirable adverse effect has been achieved. In Chapter 7, the strategy designed for the number of wells to be constructed for both dry (78 wells) and rainy (45 wells) seasons and the pumping rate at which residents can sustainably abstract water supply during the stipulated season without damaging the aquifer has been achieved. This strategy will also mitigate groundwater stresses caused by natural and artificial processes.

It is evident that all the objectives which consisted of the tasks in the two components of this thesis, namely to understand the per capita water consumption patterns, understand the groundwater system, estimate the aquifer properties and predict the future groundwater quantity flow system are fully realised. The availability of hydrogeologic maps, in combination with the intuitions generated by this study, is important to hydrogeologists, water resources managers and planners. This suggests that the findings in this thesis may have wider resonance with other countries in the sub-region with similar water related problems.

The results (Section 6.12.4) of the numerical model for the interaction of alluvial aquifer with regional flow, river and wells developed in Section 6.5.4, has helped to confirm that the groundwater budget of $2.78 \times 10^5 m^3/d$ is underexploited and that the key groundwater recharge sources to the watershed is dominantly by rainfall and surface water bodies. The results of the groundwater demand management scheme in Section 6.13 have indicated that the average water consumption patterns for the next twenty years and more can likely be 70l/p/d and 50l/p/d for the rain and dry season respectively. Integration of GIS technique has provided an excellent tool for the determination of the groundwater potential zones in the study area. Based on the analysis, moderate, good and high groundwater potential zones were identified in areas occupying $29.4km^2$, $20.6km^2$ and $13.2\ km^2$ respectively. Analysis of the contour map has revealed that the northwest-southwest region of the watershed constitutes significant groundwater recharge potential zones. Additionally, the numerical model developed to simulate infiltration galleries for water supply has helped to identify the suitable site along a perennial river with total volumetric water budget of $1.42 \times 10^5 m^3/d$.

It is concluded that the available groundwater potential was sufficient to overcome the per capita water demand for the next twenty years and more. Hence, to maintain the sustainability of the groundwater abstraction, effective groundwater management in its distribution is essential. Additionally, the practicable rate of perennially withdrawing water has been calculated to manage the groundwater potential without adverse effect on the aquifer.

Appendix D2.7 presents the limitations of the water consumption questionnaire-based study and the groundwater quantity flow modelling which offer further guidance to researchers and water resource managers engaged in groundwater development and quantity management for adequate water consumption.

8.3 Recommendations

Based on the nature of the area (data scarce), considerable efforts were made to cover a wide range of important aspects in developing thematic maps, modelling, analysing water consumption end-uses at a per capita scale and groundwater quantity development for sustainable abstraction. The following recommendations are proposed to maintain and manage the groundwater quantity sustainably,

- Groundwater mathematical modelling of the entire Freetown aquifer system can be recommended to get more reliable and accurate results using this study as baseline data.
- Other factors influencing the water levels e.g. aquifer properties (transmissivity), land use/land cover, topographic elevation, slope angle and proximity to surface water body can be considered along with the rainfall depth and replenishment.
- Construction of artificial recharge structure like infiltration galleries is recommended in the identified site to provide water supply to no piped water service areas after consideration of financial details.
- Based on current information, intensive monitoring and evaluation of future water development should be linked with water conservation measures.
- Monitoring of all wells should be undertaken as a procedure to help ensure that aquifer safe yield is maintained, and to provide early warning of unexpected problems in the long-term.
- Advance artificial recharge opportunities (increase surface runoff entering the aquifer) need to be evaluated within the entire watershed of available water supplies, to manage existing and projected water demands, and related costs and benefits to ensure that the opportunity is economically justified.
- The Ministry of Water Resources should assume leadership in supporting the development of the new wells (water points) and artificial recharge by providing technical and financial assistance to the municipality by developing regulations and guidelines.
- There is a need to develop a policy and install more serving wells at short distances to reduce the long distance covered and queuing time.
- A strategic plan of the groundwater abstraction system must be designed for per capita demand that should be accessed based on the available water during each season (i.e., rainy and dry).

8.3.1 Scope for Future Work

The above study is mainly focused on available water for sustainable domestic consumption and groundwater recharge development to support the current service provider to meet its demand. There are other factors involved such as climate change impact on recharge, water availability and the contamination of groundwater. Hence the research has revealed that there is scope for further study in this area to focus on

- Modelling of other factors such as aquifer properties (specific yield), land use/land cover, slope angle and proximity to surface water body which influence groundwater level fluctuations.
- Investigation on the improvement of groundwater potential and groundwater quality after the implementation of the artificial recharge structures (infiltration galleries) in the study area, as a pilot study.
- Investigate the other environmental impacts associated with abstraction and distribution of water for example, greenhouse gas emissions.
- Running the transient states to validate the models.
- Performing geophysical investigations; this will help determine the actual thickness and variation of the different layers throughout the catchment area.
- Gather reliable information on the amount of water recharged and discharged into the ground at different points for each season in the entire Freetown watershed
- Schedule aquifer/permeability tests so that hydrogeological parameters are more certain.

- The risk and resilience of the water system in meeting per capita demand can be assessed by taking into account the availability of water during different seasons (i.e., rainy and dry).

APPENDICES

APPENDIX A: WATER CONSUMPTION SURVEY FORM (RAINY SEASON SURVEY)

Good morning/afternoon/evening. Thank you for kindly participating in this questionnaire. The survey is being conducted to collect data on household consumption of water usage in the face of seasonal and climate variability. This questionnaire is part of a research aimed at investigating water use, practice and behaviour in residential settlements in Freetown. Be assured that your answers will be confidential and used for educational purposes only.

Data Protection and Confidentiality Statement

The following questionnaire will require approximately 25 – 30 minutes of your time to complete. There is no reward for responding nor is there any known risk. Your participation is highly valued but voluntary. All information would be treated with maximum confidentiality and only reported in aggregate, please do not include your name. Be assured that your answers will be used for education and research purpose only.

Instructions on how to complete the questionnaire:

If you would prefer, you can complete the questionnaire using a pen and by printing it out.

How to answer the questions:
You can tick the correct option or answer (Tick your answer like this: ☑)

If some questions do not apply to your household you should answer them accordingly with either "N/A" or leaving it blank.

If you cannot give any precise information, please enter approximate values.
Every response is valuable to us!

Again, we thank you for participating in this important research project survey.

Participant No:_________________ Date of interview___________________ Location_____________________

Socio-economic characteristics of the household:

Q1 a-	Occupants		
How many people live in your household?		Number	
How many children under 14 live in your household?		Number	
How many adult males (15- 65 years) live in your household?		Number	
How many adult females (15- 65 years) live in your household?		Number	
How many people aged 66 - 75 years live in your household?		Number	
How many people 76 years and over live in your household?		Number	

Q2 a- f	Building type – Please tick in the box the one that applies to you					
What is your **tenure** status?		Owner of the property……..	On rents……..	Family property……	Government property…	
How many rooms are there in your household?		1 ……..	2 ……..	3 ……..	4 ……..	Other ……..
How many floors in your household?		1 ……..	2 ……..	3 ……..	4 ……..	Other ……..
What type of house do you live in?		Separate house	Apartment	Compound house (rooms)		
What is the total area of all floors in m^2 of your household?		100-150 ……..	150-200 ……..	200-250 ……..	250-300 ……..	Other ……..
What is the garden area in m^2 of your household?		n/a ……..	1-20 ……..	21-40 ……..	41-60 ……..	Other ……..
How much is your family income in Leones per month?		………………..… Le/month				

Q3	Current education/working status (Please give the number of people)				
How many people in your household are **Males** and how many are **Females** (*Please give the number of male and female in the boxes*)		Number of male	……………..	Number of female	……………
Fully employed		Number of male	……………..	Number of female	……………
Partly (temporary) employed		Number of male	……………..	Number of female	……………
Self employed		Number of male	……………..	Number of female	……………

Unemployed seeking job	Number of male	……………..	Number of female	……………	
Unemployed but not seeking a job	Number of male	……………..	Number of female	……………	
House wife/house-husband	Number of male	……………..	Number of female	……………	
Pupil (primary institution)	Number of male	……………..	Number of female	……………	
Pupil (secondary institution)	Number of male	……………..	Number of female	……………	
Student (tertiary institution)	Number of male	……………..	Number of female	……………	
Retired	Number of male	……………..	Number of female	……………	
If you are fully employed, please tick your occupation in the next box	Artisan/craftsmen ☐	Civil servant ☐	Trading/business ☐	Technical engineer ☐	Other (please specify)

Q4a-d	House category						
In what category is your house put under by the Freetown City Council? (please tick in the box)		Informal settlement (slum) ☐	Low income ☐	Middle income ☐	High income ☐	Other (please specify)	
What kind of material is your household constructed with? *Please tick*		Concrete	Board	Corrugated Zinc	Mud	Thatch	Other
How long has your family lived at this property since 2002? *Please tick your answer.*		1 – 2 years	3 – 6 years	7 – 10 years	11 – 14 years	Other (please specify)	
Where did your family live before coming to Freetown? Please tick in the box		Same property	Western Urban	Western Rural	Province	Abroad	Other (please specify)
Q5	Belief						
		Islam ☐	Christianity ☐	Traditional ☐	None ☐	Other (please specify)	

In your household, how many practice the following religions? Please give the number						
Q6	Qualification					
What is the highest level of education achieved by anyone in this household? *Please tick **ALL** that apply*		GCE O Level/WASSCE ☐	GCE A Level ☐	HTC, HND ☐	City Guilds ☐	Other (please specify)
		Apprentice ☐	Vocational or work related ☐	Degree (BA, BSc) or higher degree (MS, MA, PhD) ☐		

Water supply and source

Water source			
Q7	Is your home connected to a main water supply?	☐ Yes	Go to Q 9
		☐ Yes, but water supply currently disconnected	Go to Q 8
		☐ No	Go to Q 8
Q8	What is/are the main source (s) of water used by your household for all purposes, such as cooking, scrubbing and washing? *Please tick **all** that apply in the box*		

Piped water from neighbour	☐	Purchase tanker truck water	☐
Water stored in tanks/drum or bucket	☐	Household piped water	☐
Rainwater harvesting/collection	☐	Protected dug well with hand pump	☐
Public (Street) tap	☐	Borehole	☐
Surface water (river, dam, stream, canal, lake, creek)	☐	Pumping station	☐

Open unprotected well	☐	Small-scale Vendor cart with 5 gallon drums	☐
Community Gravity/spring	☐	Other (please specify):	☐

Q8b	Who fetches water most often for the household? *(Please tick in the correct box)*	Male adult ☐	Female adult ☐	Male child (Under 15) ☐	Female child (Under 15) ☐	Other (please specify)	
Q9	How is your household charged for water consumption? Please tick **one** box	Water meter ☐	Flat fee ☐	Not charged ☐	Don’t know ☐	Other (please specify)	
Q10	Approximately how much do you spend or pay per day/month/annum for your water service? *Please give your answer in Leones where it apply*	………..Le/day	………Le/month	………Le/year	Obligatory	Not obligatory	Other (please specify)
Q11	Do you think that the bills you receive are accurate? *Please tick **one** box*	Yes ☐	No ☐	Not sure ☐	Not applicable ☐	Other (please specify)	

Q12a	So as far as you know, does anyone in your household use any other sources of water for drinking purposes apart from using the tap?	☐ Yes ☐ No Go to Q 13
Q12b	PROMPT: What are they? *Please tick in the box all that apply*	
	☐ Rainwater Go to Q 12 c &then Q 18	☐ Bottled water Q 12 c - Q12 f, and them move to Q13
	☐ Well water Go to Q 12 c &then Q 20	☐ Sachet water Q 12 c, g - Q12 i, and them move to Q13
	☐ Stream water Go to Q 12 c &then Q 19	☐ Tanker truck water Q 12c, j - Q12 l, and them move to Q13

☐ Spring water Go to Q 12 c &then Q 19Other source (please specify)…………………………………………………………………………………….

Q12 c	Then kindly state the main source and other sources for each use of water from the list using their numbers. Please write “0” for none.	

	Main source	Other source
Drinking	…………………	…………………
Cooking	…………………	…………………
Washing clothes	…………………	…………………
House cleaning	…………………	…………………
Bathing/washing your bodies	………………	…………………
Domestic agriculture	………………….	…………………
Flushing toilets	………………….	…………………

1 Piped water from neighbour
2 Water stored in tanks/drum or bucket
3 Public (street) tap
4 Borehole
5 Protected dug well with hand pump
6 Unprotected dug well
7 Protected spring
8 Unprotected spring
9 Rainwater collection in closed containers
10 Rainwater collection in open containers
11 Bottled water
12 Small-scale Vendor cart
13 Purchase Tanker-truck water
14 Surface water (river dam, lake, pond, stream)
15 Sachet water
16 Other (please specify)……………

Q12 d	What is the volume of water contained in each bottle? *Please give your answers in litres*	…………………………….litres	……………………don't know	Other (please specify)
Q12 e	How many bottles are purchased every **day** and every **week?** *Please give your answers in number of bottles bought*	……………………….Every day	………………………… Every week	Other (please specify)
Q12 f	How much is the cost per bottle? Please give your answer in Leones.	……………………………………..Leones	Other (please specify)	
Q12 g	What is the volume of water contained in each sachet? *Please give your answers in litres*	…………………………….litres	……………………don't know	Other (please specify)
Q12 h	How many sachets are purchased every **day** and every **week?** *Please give your answers in number of sachets bought*	………………………Every day	………………………… Every week	Other (please specify)
Q12 i	How much is the cost per sachet? Please give your answer in Leones.	……………………………………..Leones	Other (please specify)	
Q12 j	What is the volume of water you received from the tanker truck? *Please give your answers in litres*	…………………………………...….litres	Other (please specify)	
Q12 k	How often do you receive water from your tankers trucks? *Please give your answers in number of tankers truck water bought per week/per month*	………………………Per week	…………………………. Per month	Other (please specify)

Q12 l	How much is the cost per tanker truck? Please give your answer in Leones.	………………………………………..Leones		Other (please specify)		
Q13	So as far as you know, how does your household treat your water supply in any of the following ways before drinking it? *Please tick those which apply*	PROMPT: What are they? *Please tick in the box* ☐ Filter the water ☐ Use sterilizing tablets ☐ Boil the water, (allowing it to cool before using it) ☐ Leave it under the sun for several hours ☐ Put it into a special fridge or clay pot ☐ Any other treatment? …………………………………………………………………………… ☐ None of the above				
Q14 a	How long does your main water source provides water a day? *Please tick **one** box only*	1 – 12 hrs…….. ☐	12 – 24 hrs…….. ☐	12-18 hrs…….. ☐	18 – 24 hrs…….. ☐	Other (please specify)………..
Q14b	How many days in the week are you ***without*** water from your main source? *Please tick in the box*	1 – 2 days……... ☐	3 – 4 days……... ☐	5 – 6 days……... ☐	More than 6 days……...	Other (please specify)………..

Q14c	Have there been periods in the past year with **no tap** water service for several days at a time? *Please give your answer in **days***	1 – 2 days……..	3 – 4 days ……..	5 – 6 days ……..	7 – 10 days	Other (please specify)

Q15 a - d	Considering that your main source of water supply is **household (HH) water supply piped system**, please answer the following questions below. *(only answer the questions that apply to you)*			
Q15 a	What is the frequency of your household water supply system? *Please tick in the box*	☐ Most days or every day ☐ Once in a week ☐ Once in 2 days ☐ More than once a week ☐ I do not have a HH water supply system. My household do rain water harvesting. Go to Q 18a – Q 18h ☐ I do not have a HH water supply system. My household get water from borehole/hand pump Go to Q 16a – Q16h ☐ I do not have a HH water supply system. I get water from the public tap Go to Q 17a – Q17j ☐ I do not have a HH water supply system. I get my water from surface waters (stream, rivers etc) Go to Q 19 ☐ I do not have a HH water supply system. I get my water from an open unprotected well Go to Q 20		
Q15b	Is this frequency sufficient for your needs? *Please tick in the box*	Yes ☐	No ☐	Other (please specify)
			☐	Other (please specify)

Q15c	How often would you like to get your piped water? *Please give your answer in days*	…………………….days	prefer not to say		
Q15d	On the days that you get water, how many ***hours***do you usually get water for?	…………………….hours	☐ Don't know	Other (please specify)	
Q15e	What is (are) the size (s) of your container (s) that you use to collect your water in daily? *Please tick*	☐ 2.5 gallons canister ☐ 5 gallons canister	☐ 44 gallons drum ☐ Miss Piggy barrel	Other (please specify)	
Q15 f	How many of these ***containers*** are filled every **day** &every **week**? *Please give your answers in the boxes*	…………………………. Every day	…………………………. Every week	Other (please specify)	
Q 16 a – f	If you get your water supply from **a borehole or hand pump,** please answer these questions.				
Q 16a	If you fetch water from a borehole or hand pump, how far is it from you? *Please give your answer in metres*	Yes, I fetch water from a borehole/hand pump ..…………………… metres No, I do not get my water from borehole/hand pump ☐ Go to Q 17			
Q 16b	How long does it take to fetch water and return home? *Please give your answer in minutes*	………………………minutes	Don't know ☐	Other (please specify)	
Q 16c	How do you operate your borehole or hand pump? *(Please tick in the correct box*	Public electricity ☐	Own generator ☐	Solar powered ☐	Other (please specify)

Q 16d	If your hand pump breaks down, how promptly is it fixed? *Please give your answer in days*	………………………days	Don’t know ☐	Other (please specify)		
Q 16e	When there is no electricity or power to operate your borehole/ hand pump or it is not fixed quickly, what is your second water supply source? *(Please tick in the correct box)*	☐ Purchase tanker truck water Go to Q 12 j - Q12 l ☐ Purchase vendor cart water Go to Q 16f& Q 16h ☐ Use open surface water source (river, stream, spring etc) Go to Q19				
Q 16f	What is (are) the size (s) of ***container (s)*** you purchase from vendors pushing cart? *Please tick in the box*	5 gallons ☐	2.5 gallons ☐	Missy Piggy barrel ☐	44 gallon drum ☐	Other (please specify)
Q 16g	How many of these containers do you buy from your water vendor every ***day*** and every ***week***? *Please give the **numbers** bought*	………………………. Every day	……………………… Every week	Other (please specify)		
Q 16h	How much is the cost for each of your filled container? *Please give your answer in Leones*	……………………………….Le	Other (please specify)			
Q 17a - j	If you get your water from the **community public (street) tap**, please answer these questions. *If you only collect water from open source e.g. streams, rivers, springs skip these questions and go to Q 19.*					
Q 17a	What is the frequency of the public tap you get your water supply from? *Please tick in the box*	☐ Every day (24 hours) ☐ Every day (less than 24 hours) ☐ Once in 2 days	☐ Once in a week ☐ More than once a week	Other (please specify)		
Q17b	How far is the public tap from you? *Please give your answer in metres*	…………………………… metres	Other (please specify)			

Q17c	How long does it take to fetch water and return home? *Please give your answer in minutes*	…………………………… minutes	Other (please specify)			
Q17d	What is the size of your ***containers*** that you use to fetch water in? *Please tick in the box*	☐ 2.5 gallons canister ☐ 5 gallons canister	☐ 44 gallons drum ☐ Miss Piggy barrel	Other (please specify)		
Q17e	How many of these containers are filled every day and every week? *Please give the **numbers** filled*	……………………………. Every day	……………………Every week	Other (please specify)		
Q17f	How frequently has the public tap broken down in the past one year? *Please tick in the box*.	☐ Once every week ☐ Once every fortnight ☐ Once every month	☐ Once every 3 months ☐ Once in six months ☐ Never	Other (please specify)		
Q17g	How promptly is the tap fixed when it breaks down? *Please give your answer in weeks*	1 – 4 weeks ☐	5 – 10 weeks ☐	More than 10 weeks ☐	Other (please specify)	
Q17h	Are you able to fill all your containers every day? *Please tick the box*	Yes……… ☐	No…….. ☐	Other (please specify)		
Q17i	How often would you like to get your tap water? *Please tick the box*	Every day (24 hours) ☐	Once a day (less 24hrs) ☐	1 – 4 times a week ☐	Other (please specify)	
Q17j	On the days that you get water, how many hours do you usually get water for? *Please tick the box*	1 – 12 hrs ☐	13 – 18 hrs ☐	19 - 24 hrs ☐	25 – 48 hrs ☐	Other (please specify)

Q18a – h	If you do **rainwater harvesting/collection**, please answer these questions						
Q18a	How often do you harvest rain water? Please tick in the spaces	Few days …………	When it rains …………	Occasionally ……………	Sometimes ……………	Never ……………	Other (please specify)
Q18b	What is the total square footage of your roof/catchment area? *Please give your answer in square metre (*sq.mt)	………………………*(*sq.m)	Don't know ☐	Other (please specify)			
Q18c	What type of material is your roof made of? *Please tick in box*	Asphalt Shingle ☐	Tile shingle ☐	Wood shingle ☐	Corrugated metal ☐	Galvanized material ☐	Other (please specify)
Q18d	Does the place where you live currently have any form of rainwater harvesting structure such as a water tank or a storage tank that specifically collects rainwater?	Yes ☐ Go to Q18e	No Go to Q18h	Other (please specify)			
Q18e	If **yes**, what do you have? *(please tick one box)*	One or a few storage container or small tank (max total capacity 500 litres) ☐	Several water containers or tanks (capacity between 500 and 1000 litres) ☐	Large tank or tanks (capacity in excess of 1500 - 3500 litres) ☐	Don't know ☐	Other (please specify)	
Q18f	Why do you have a rainwater harvesting system? (Please tick all that apply)	No other water supply ☐	To save money on water ☐	Good for the environment ☐	Safe and clean ☐	Other (please specify)	
Q18g	What do you use the collected water for? *(Please tick all that apply)*	Drinking ☐ Washing clothes ☐ ☐	Watering the garden ☐ Flushing toilets ☐ ☐	Other (please specify)			

		Scrubbing floors Washing cars	
Q18h	If **No** - why not? (please tick all that apply)	I don't know how to install one ☐ No suitable downpipes on my property ☐ ☐ Too expensive to install ☐ Don't believe that I will save any money ☐ The water quality isn't good enough ☐ I don't believe that there are any benefits to the environment ☐ I live in a property belonging to someone else who won't install one ☐ I live in a house or flat with no outside space to install a water tank	Other (please specify)
Q19 a – f	If your main or second source is from a **Surface water source (e.g creek, stream, river, natural pond, dam, open well),** please answer these questions		
Q19 a	Are there other source (s) of surface water on or close to your property (e.g. creek, stream, river, natural pond, dam etc.)? Please tick in the box	☐ No	☐ Yes, please specify………………………………………….
Q19 b	Why do you prefer to use this water source?	It is the closest water source ☐ The water there is better (clearer) ☐ It is the easiest trip good path/ not steep) ☐ There is lots of water (container fills up quickly) ☐ It is easier to fill container (no pump /good pump) ☐ Because of the people you meet at the water source ☐ Family has always used this water source ☐ Because of the people you meet on the way to the source ☐	Other (please specify)
Q19 c - d	How many ***trips*** are made each day to collect water? *Please give your answer in the box* ☐ trips	How many ***people*** go on each trip to collect water? *Please give your answer in the box* ☐	

Q19 e - f	How many ***containers*** are filled on EACH trip to collect water? *Please give the number in the box* 5 gallon containers (23 litres) ☐ Other (please specify)…………… 2.5 gallon containers (11 litres) ☐ …………………………	How do you carry the water? On head ☐ Wheelbarrow ☐ Push cart ☐ Other (please specify)………………………

Q19 g - h

Are there some days of the week when more or less water is collected? *Please tick the* ***days*** *in the box when you need more and less water.*

More	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Less	Sun	Mon	Tue	Wed	Thu	Fri	Sat

Are there some months of the year when more or less water is collected? *Please tick the months in the box when you collect more and less water.*

More	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Less	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Q19 i	How is the water stored? *Please tick the box.*	In the container used to collect it ☐	In a separate large container ☐	In a tank ☐	Other (please specify)
Q20a-h	If your major source of domestic water supply is from an **Unprotected well/spring**, please answer these questions				
Q20 a	Is your well/spring for domestic use only?	☐ Yes Go to Q20 c		☐ No, Go to Q20 b	
Q20 b	If NO, what are your non-domestic uses?	Selling water ☐	Food business ☐	Other (please specify)…………………………………….	
Q20 c	How much is each of the different canister charged for per fill? *Please give your answer in* ***Leones*** *for each gallons in the box.*	1 gallon canister ………………….Le	2.5 gallons canister …………………. Le	5 gallons canister ……………….Le	Other (specify)………
Q20 d	What quantity of water is withdrawn each day from the well? Please give your answer in the number of gallons in the box	1 gallon canister ☐	2.5 gallons canister ☐	5 gallons canister ☐	Other (specify)………

Q20 e	Do you have water shortage problems with the well; when and why?	Yes ☐ No ☐	**If yes, When?**		**Why?**	
Q20 f	Are there some months where your household cannot use this for domestic purposes?	Yes ☐ No ☐	**If yes, When?**			
Q20 g	How frequently is the well cleaned and maintained?	Once in a quarter ☐	Once in 6 months ☐	Once a year ☐	Not cleaned in the last year ☐	Other (please specify)
Q20 h	How do you collect water from the well?	Rope tied to plastic container ☐	Rope tied to enamel container ☐	Insert own container into the well ☐	Have a pumping mechanism ☐	Other (please specify)

Household water consumption habits and patterns

Shower

How many showers do you take per week?	1 ……..	2 ……..	3 ……..	4 ……..	5 ……..	Other…..
How many minutes do you run the water for each shower?	<2 ……..	2-4 ……..	4-6 ……..	6-8 ……..	8-10 ……..	Other…..
How much is the shower flow rate in litres/minute?	…….. litres/minute					

Bath

How many baths do you take per week?	N/A ……..	0 ……..	1 ……..	2 ……..	3 ……..	Other …..
How much is the volume of water use for each bathing in litre?	1-40 ……..	40-80 …..	80-120 …..	120-160…..	160-200…..	Other …...

Bathroom sink (Tooth brushing, hand and face washing, ablution, etc.)

How many times do you use a bathroom sink (tap) for washing per day?	<= 3 ……..	4 ……..	5 ……..	6 ……..	7 ……..	8 ……..	Other …..
How many seconds does water run in each use (e.g. hand and face washing)?	1-10 ……..	10-20 …..	20-30 …..	30-40 …..	40-50 …..	50-60 …..	Other …..

How much is the average flow rate of each tap use in litres/minute?	…….. litres/minute

Toilet flushing

How many times a day do you use a toilet?	1 ……..	2 ……..	3 ……..	4 ……..	5 ……..	Other ….
How much is the volume of water use in each flush in litres?	………... litres					

Dishwashing

Manually	How many times does your family wash dishes per day?	0 ……..	1 ……..	2 ……..	3 ……..	4 ……..	Other …..
	How many minutes does water run in each wash?	1-3 ……..	3-6 ……..	6-9 …..	9-12 …..	12-15 …..	Other …..
	How much is the flow rate of washing tap in litres/minute?	…….. litres/minute					
Machines	How often do you use a dishwasher per week?	N/A …..	0 ……..	1 ……..	2 ……..	3 ……..	Other …..
	What is the brand of dishwashing machine?						
	What is the model of dishwashing machine?						

Laundry

Manually	How many times a week do you hand wash clothes?	0 ……..	1 ……..	2 ……..	3 ……..	4 ……..	Other …..
	How many minutes does water run in each wash?	1-4 ……..	4-8 ……..	8-12 …..	12-16 …..	16-20 …..	Other …..
	How much is the flow rate of washing tap in litres/minute?	…….. litres/minute					
Machines	How many loads of laundry do you use per week?	N/A …..	0 ……..	1 ……..	2 ……..	3 ……..	Other …..
	What is the brand of clothes washing machine?						
	What is the model of clothes washing machine?						
	What is the capacity of each wash in kilogram?	…….. kilogram					

Garden watering

How many times a week do you water the garden?	N/A ……	0..........	1 ……...	2 ….......	3 ….......	Other....
How many minutes does the water run in each watering?	1-15 …..	15-30 …..	30-45 …..	45-60 …..	60-75 …..	Other....
How much is the flow rate in litres/minute for irrigating the garden?	…….. litres/minute					

Other water consumptions

House washing	How often do you hose your paths, garage, bathrooms, driveways/house per week?	0 …..…..	1 …..…...	2..........	3 …….....	4 ….......	Other …...
	How many minutes does the water run each time?	1-4 …..	4-8 …..	8-12 …..	12-16 …..	16-20 …..	Other …...
	How much is the flow rate in litres/minute for hosing paths, driveways or house?	…….. litres/minute					
Vehicle washing	How many cars are washed at your household per week?	0..........	1 ………	2..........	3 …….....	4 ….......	Other …...
	How many minutes does water run for washing each car?	1-2 ……..	2-4 …..	4-6 …..	6-8 …..	8-10 …..	Other …...
	How much is the flow rate in litres/minute for washing car?	…….. litres/minute					
Swimming pool	How many times a year does your household replace water in a swimming pool?	N/A …....	0 …....	1 …....	2 …....	3 …....	Other …...
	How many m^3 of water are provided to fill the swimming pool?	……………….. m^3					

Thinking about your water supply and the environment

Awareness	***Please tick your answer***			
What do you intend to do with water in view of the increased prices?	Increase usage as I need it…………..	Decrease usage as necessary………..	Other………..	
Do you believe that encouraging all residents to conserve water is	Not Important	Important	Very Important	No Opinion
Is the quantity of water that you receive from your main (primary) source of water adequate?	Yes…………..	No…………	Not sure……..	Other ……….
Generally, what does the water look like?	Clear ………..	Cloudy………	Dirty……….	Other ………
What do you think about the quality of your water?	Very good………..	Good…………..	Poor………..	Other ……….
Overall, are you satisfied with your water service?	Yes…………..	No…………	Not sure……..	Other ……….
What is the extent of your satisfaction?	Very satisfied	Satisfied	Dissatisfied	Very dissatisfied

How often do you do the following in your daily life? (*please tick one answer per row)*	**Never**	**Occasionally**	**often**	**always**	**Not applicable**
Water your garden in the coolest part of the day to reduce evapotranspiration and save water?					
Collect and save rainwater in tanks or recycle waste water?					

Plug the sink when washing the dishes?					
How concerned are you about the following environmental issues? (*please tick one answer per row)*	**Not concerned**	**Fairly concerned**	**Concerned**	**Very concerned**	**No opinion**
Waste generation					
Air pollution					
Water pollution					
Natural resource depletion (forest, water, energy)					
Climate change (global warming)					
Endangered species and biodiversity					
Noise pollution					
Genetically modified organisms (GMO)					
Are you currently a member of or contributor/donator to any environmental organizations?	Yes…………..	No…………….	If yes, write in the name of the Organization		

In your opinion, what is the likelihood that your future water supply will be affected by the following: *Please tick **ONE** box on each line*					
	Extremely Likely	Very Likely	Moderately Likely	Unlikely	Never
Climate change					
Increasing population					
Infrastructural development					
Are you concerned about the **quality** of your water? *Please tick all that apply*					

☐ No ☐ Yes, we drink only bottled water ☐ Yes , we have had our well water tested during the past year	☐ Yes, we look at the water quality report sent by WHO and UNICEF ☐ Yes, we have our own treatment system ☐ Yes , we have had our well water tested during the past year ☐ Other (please specify)

Does your household use any means of transport for fetching the water? *Please tick in the box*	Yes ☐ No ☐		
	If yes, write in the means of transport…………………………………………………………		
Observation: What are the points of discharge of household's used water? *Please tick **all** that apply*	Piped sewer ☐ Soak-away/cesspit/septic system ☐ Sanitation facility ☐ Water body (lake, river, etc.) ☐	Open channel ☐ Street surface ☐ Space outside premises ☐ Premises' yard or garden ☐	Other (please specify)

When thinking about your local water supply, how important are the following issues to you? *Please tick* ***ONE** number on each line*					
	Extremely Important	Very Important	Moderately Important	Slightly Important	Not at all Important
Colour of the water	1	2	3	4	5
Taste of the water	1	2	3	4	5

Smell of the water	1	2	3	4	5
Clear drinking water	1	2	3	4	5
Reliable supply of water	1	2	3	4	5
Continuous supply of water	1	2	3	4	5
Sufficient water pressure	1	2	3	4	5
Safe drinking water	1	2	3	4	5
Effect on the environment	1	2	3	4	5
Cost of the water supply	1	2	3	4	5

APPENDIX B: HOUSEHOLD CHARACTERISTICS ANALYSIS

Appendix B1: Frequency Distribution of Household Characteristics

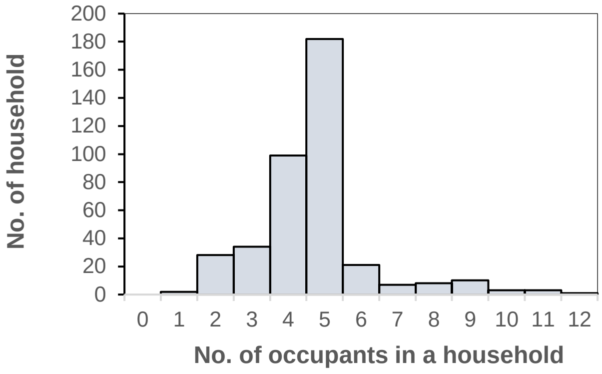


Figure B1.1 Frequency distribution of number of occupants in a household

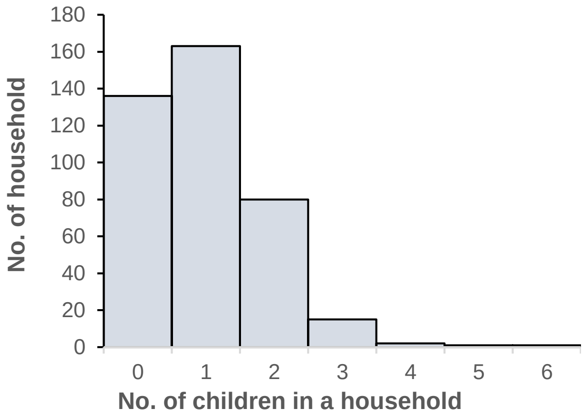


Figure B1.2 Frequency distribution of number of children in a household

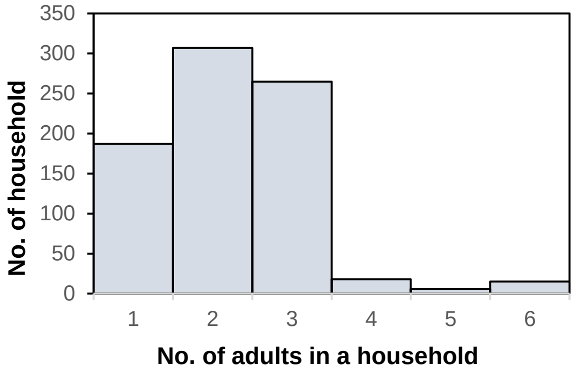


Figure B1.3 Frequency distribution of number of adults in a household

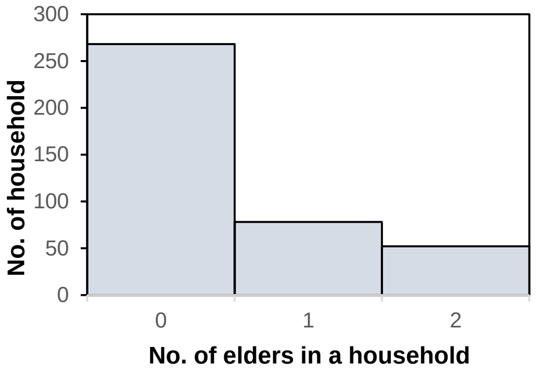


Figure B1.4 Frequency distribution of number of elders in a household

Figure B1.5 Frequency distribution of number of rooms in a household

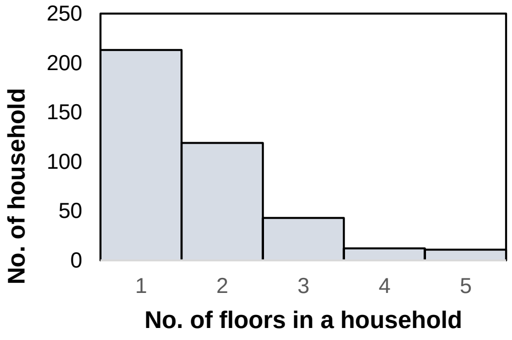


Figure B1.6 Frequency distribution of number of floors in a household

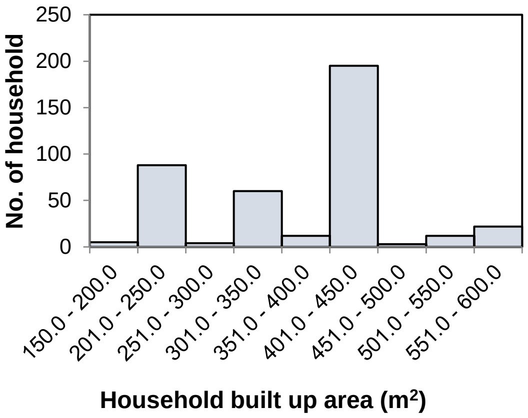


Figure B1.7 Frequency distribution of a household built up area

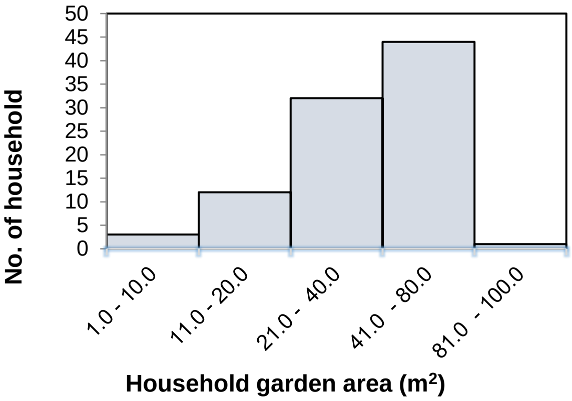


Figure B1.8 Frequency distribution of a household garden area

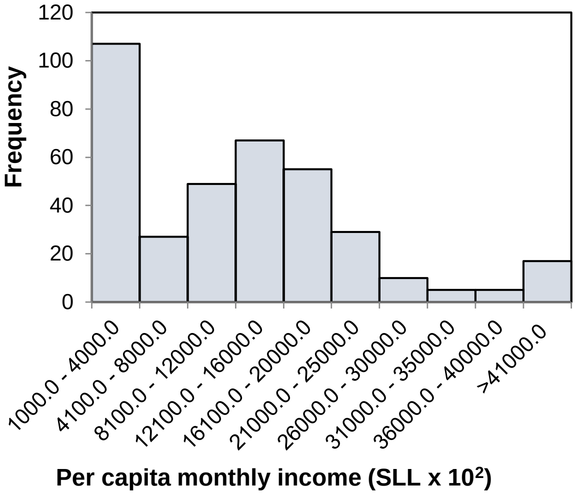


Figure B1.9 Frequency distribution of per capita monthly income

APPENDIX B2: STATISTICAL PARAMETERS OF HOUSEHOLD CHARACTERISTICS IN INFORMAL SETTLEMENT, LOW, MIDDLE AND HIGH INCOME GROUPS

TableB2.1 Summary of average values for household characteristics in different income groups

Household characteristics	Unit	All surveyed households			Informal slum group		Low income			Middle income			High income	
Gender		Male (67.3%)	Female (32.7%)		Male (74.2%)	Female (25.8%)	Male (66.0%)	Female (34.0%)		Male (67.0%)	Female (33.0%)		Male (67.2%)	Female (32.8%)
Household size (occupancy)	No./hh	4.69			6.03		5.08			4.50			4.13	
Number of children (<14 years)		0.97			1.68		1.08			0.90			0.69	
Number of adult males members (15-65 years)		1.35			1.81		1.32			1.31			1.36	
Number of adult females members (15-65 years)		2.06			1.97		2.30			1.99			1.98	
Number of elders (66-75 years)		0.21			0.32		0.25			0.19			0.16	
Number of elders (> 76 years)		0.13			0.26		0.13			0.14			0.04	
Number of rooms in the household		3.31			2.23		2.84			3.54			3.75	
Number of floors in the household		1.17			1.42		1.57			1.77			1.88	
Total built-up area of floors	m^2/hh	311.36			295.83		298.94			315.78			322.36	
Garden area per household		32.03			28.75		32.20			31.73			34.79	
Household type	%	H (60.6)	A (29.9)	C (9.5)	H (74.2)	C (25.8)	H (46.4)	A (33.0)	C (20.6)	H (62.1)	A (33.0)	C (4.9)	H (70.1)	A (29.9)
Monthly family income per household	SLL/mon (x10^6)	5.21			1.39		1.57			6.02			9.68	

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093), H* = Houses, A= Apartment, C =Compound houses (rooms)

Table B2.2 Summary of statistical parameters of household characteristics for the whole survey (398 households)

Household characteristics	**Unit**	**Mean**	**Median**	**Std deviation**	**Variance**	**Minimum**	**Maximum**	**Skewness**	**Kurtosis**	**Confidence interval (95%)**
Gender	Male (67.3%)					Female (32.7%)				
Household size (occupancy)	No./hh	4.69	5	1.58	2.51	1	12	1.24	3.78	0.15
Number of children (<14 years)	No./hh	0.97	1	0.92	0.84	0	6	1.09	2.54	0.09
Number of adult males members (15-65 years)	No./hh	1.35	1	0.91	0.83	0	6	1.21	3.39	0.09
Number of adult females members (15-65 years)	No./hh	2.06	2	1.06	1.14	0	5	0.52	0.43	0.10
Number of elders (66-75 years)	No./hh	0.21	0	0.42	0.18	0	2	1.71	1.73	0.04
Number of elders (> 76 years)	No./hh	0.13	0	0.33	0.11	0	1	2.20	2.85	0.03
Number of rooms in the household	No./hh	3.31	3	1.20	1.44	1	6	-0.15	-0.56	0.12
Number of floors in the household	No./hh	1.17	1	0.96	0.93	1	5	1.53	2.19	0.09
Total built-up area of floors	m^2/hh	311.36	290.00	70.35	4377.1	150	600	1.50	3.41	9.91
Garden area per household		32.03	30.00	12.66	160.38	0	100	1.05	3.10	2.55
Household type		Houses (60.6%) Apartment (29.9%) Compound houses – rooms (9.5%)								
No. of houses, apartments and compound house		Houses (241) Apartment (119) Compound houses – rooms (38)								
Monthly per capita income	SLL/mon ($x10^6$)	1.35	1.20	1.19	1.43E+6	0.10	8.50	2.16	7.19	0.17
Monthly family income		5.21	5.50	3.18	9.98E+6	0.95	17.00	0.45	0.15	0.18

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093)*

Table B2.3 Summary of statistical parameters of household characteristics in the informal slum income group

Household characteristics	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	Kurtosis	Confidence interval (95%)
Gender	Male (74.2%)						Female (25.8%)			
Household size (occupancy)	No./hh	6.03	5	2.25	5.09	2	12	0.84	0.42	0.82
Number of children (<14 years)	No./hh	1.68	2	1.19	1.43	0	6	1.43	4.59	0.43
Number of adult males members (15-65 years)	No./hh	1.81	1	1.13	0.42	1	5	1.71	2.55	0.41
Number of adult females members (15-65 years)	No./hh	1.97	2	1.04	1.09	0	4	0.06	1.40	0.38
Number of elders (66-75 years)	No./hh	0.32	0	0.47	0.22	0	1	0.79	-1.46	0.17
Number of elders (> 76 years)	No./hh	0.26	0	0.44	0.19	0	1	1.16	-0.69	0.16
Number of rooms in the household	No./hh	2.23	2	1.20	1.44	1	5	0.76	-0.09	0.44
Number of floors in the household	No./hh	1.42	1	0.80	0.65	1	5	3.12	12.60	0.29
Total built-up area of floors	m^2/hh	295.83	272.50	74.57	5561.74	150	440	0.23	-0.67	37.22
Garden area per household		28.75	30.00	6.26	40.23	25.00	50.00	0.33	-1.74	7.05
Household type		Houses (74.2%) Compound houses – rooms (25.8%)								
No. of houses, apartments and compound house		Houses (8) Compound houses – rooms (23)								
Monthly per capita income	SLL/month (x10^6)	0.25	0.25	0.09	1.5	0.10	0.47	0.39	-0.24	0.03
Monthly family income		1.39	0.39	0.93	1.53E+5	0.95	2.50	0.93	0.62	0.14

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093)*

Table B2. 4 Summary of statistical parameters of household characteristics in the low income group

Household characteristics	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	Kurtosis	Confidence interval (95%)
Gender	Male (66.0%)					Female (34.0%)				
Household size (occupancy)	No./hh	5.08	5	1.78	3.18	2	11	1.20	2.05	0.36
Number of children (<14 years)	No./hh	1.08	1	0.85	0.73	0	3	0.35	-0.59	0.17
Number of adult males members (15-65 years)	No./hh	1.32	1	1.06	1.13	0	6	1.49	4.19	0.21
Number of adult females members (15-65 years)	No./hh	2.30	2	1.04	1.08	0	5	0.67	0.61	0.21
Number of elders (66-75 years)	No./hh	0.25	0	0.46	0.21	0	2	1.48	1.05	0.09
Number of elders (> 76 years)	No./hh	0.13	0	0.34	0.11	0	1	2.14	2.66	0.07
Number of rooms in the household	No./hh	2.84	3	1.22	1.49	1	6	0.09	-0.60	0.25
Number of floors in the household	No./hh	1.57	1	0.92	0.86	1	5	1.99	4.28	0.19
Total built-up area of floors	m^2/hh	298.94	290.0	77.19	5958.89	150	600	2.17	5.76	21.15
Garden area per household		32.2	30.0	14.48	209.87	20	80	1.81	3.46	3.89
Household type		Houses (46.4%) Apartment (33.0%) Compound houses – rooms (20.6%)								
No. of houses, apartments and compound house		Houses (45) Apartment (32) Compound houses – rooms (20)								
Monthly per capita income	SLL/month ($x10^6$)	0.33	0.30	0.13	1.83E+4	0.10	0.90	1.58	3.08	0.02
Monthly family income		1.57	1.50	0.50	2.51E+5	0.95	3.0	1.16	0.73	0.10

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093)*

Table B2. 5 Summary of statistical parameters of household characteristics in the middle income group

Household characteristics	**Unit**	**Mean**	**Median**	**Std deviation**	**Variance**	**Minimum**	**Maximum**	**Skewness**	**Kurtosis**	**Confidence interval (95%)**
Gender	Male (67.0%)						Female (33.0%)			
Household size (occupancy)	No./hh	4.50	5	1.26	1.60	1	11	0.95	5.83	0.17
Number of children (<14 years)	No./hh	0.90	1	0.86	0.74	0	5	1.06	2.15	0.12
Number of adult males members (15-65 years)	No./hh	1.31	1	0.84	0.70	0	5	0.92	2.10	0.11
Number of adult females members (15-65 years)	No./hh	1.99	2	1.03	1.07	0	5	0.71	0.89	0.14
Number of elders (66-75 years)	No./hh	0.19	0	0.41	0.17	0	2	1.98	3.04	0.05
Number of elders (> 76 years)	No./hh	0.14	0	0.34	0.12	0	1	2.12	2.53	0.04
Number of rooms in the household	No./hh	3.54	3	1.08	1.17	1	6	-0.12	-0.55	0.15
Number of floors in the household	No./hh	1.77	1	0.99	0.98	1	5	1.36	1.45	0.13
Total built-up area of floors	m^2/hh	315.78	290	66.16	4377.1	230	600	1.29	1.71	13.51
Garden area per household		31.73	0	12.03	144.80	20	100	3.23	1.54	2.93
Household type		Houses (62.1%) Apartment (33.0%) Compound houses – rooms (4.9%)								
No. of houses, apartments and compound house		Houses (126) Apartment (67) Compound houses – rooms (10)								
Monthly per capita income	SLL/mon ($x10^6$)	1.49	1.30	0.87	7.65E+5	0.46	8.5	4.84	3.43	0.12
Monthly family income		6.02	6.00	1.33	1.79E+6	2.30	9.0	-0.77	3.18	0.12

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093)*

Table B2. 6 Summary of statistical parameters of household characteristics in the high income group

Household characteristics	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	Kurtosis	Confidence interval (95%)
Gender	Male (67.2%)						Female (32.8%)			
Household size (occupancy)	No./hh	4.13	4.00	1.34	1.78	2	9	0.21	1.37	0.32
Number of children (<14 years)	No./hh	0.69	0.85	1.34	0.72	0	4	1.39	2.45	0.20
Number of adult males members (15-65 years)	No./hh	1.36	1	0.73	0.53	0	3	-0.05	-0.25	0.17
Number of adult females members (15-65 years)	No./hh	1.98	2	1.16	1.35	0	5	0.20	-0.09	0.28
Number of elders (66-75 years)	No./hh	0.16	0	0.37	0.13	0	1	1.87	1.57	0.08
Number of elders (> 76 years)	No./hh	0.04	0	0.20	0.13	0	1	4.54	19.18	0.05
Number of rooms in the household	No./hh	3.75	4	1.01	1.03	1	6	-0.09	-0.09	0.24
Number of floors in the household	No./hh	1.88	2	0.97	0.94	1	5	1.25	1.68	0.23
Total built-up area of floors	m^2/hh	322.36	300	66.72	4389.40	230	600	-0.14	0.57	20.23
Garden area per household		34.79	30	14.25	41.96	25	100	1.45	1.96	5.48
Household type		Houses (70.1%) Apartment (29.9%)								
No. of houses, apartments and compound house		Houses (47) Apartment (20)								
Monthly per capita income	SLL/mon (x10^6)	2.67	2.25	1.22	1.49E+6	0.38	6.0	0.95	0.01	0.29
Monthly family income		9.68	9.00	2.25	5.1E+6	3.5	17.0	1.28	3.15	0.54

** hh household, SLL Sierra Leone Leones (1000 SLL ≈ £ 0.093)*

APPENDIX C: WATER CONSUMPTION ANALYSIS

Appendix C1: Relationship between Total Household Water Consumption and Household Characteristics

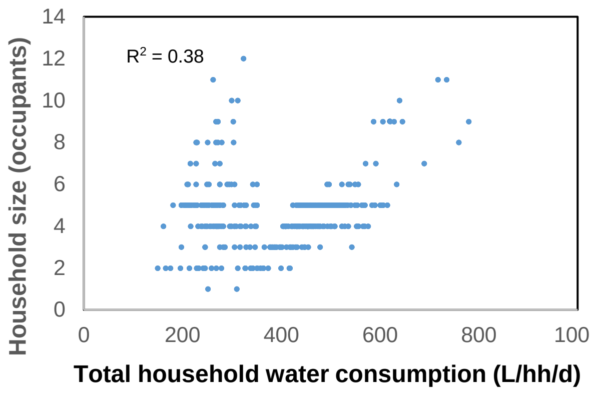


Figure C1.1 Relationship between household total average water consumption and household occupancy

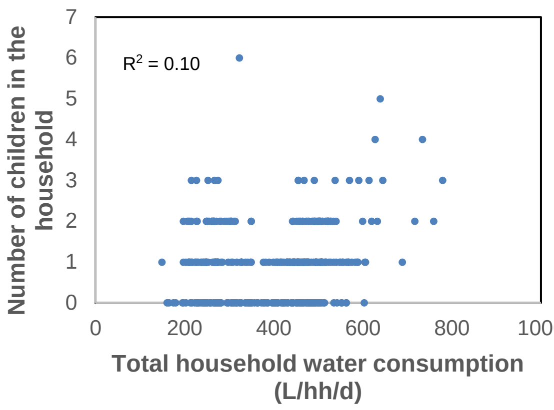


Figure C1.2 Relationship between household total average water consumption and number of children in the household

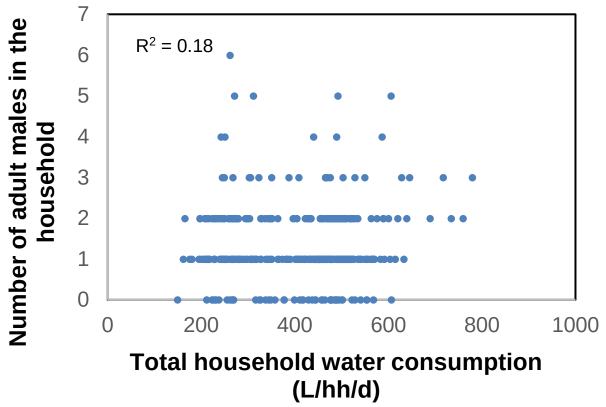


Figure C1.3 Relationship between household total average water consumption and number of adult males in the household

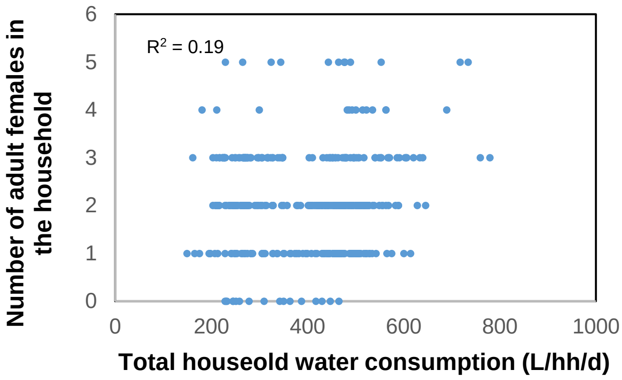


Figure C1.4 Relationship between household total average water consumption and number of adult females in the household

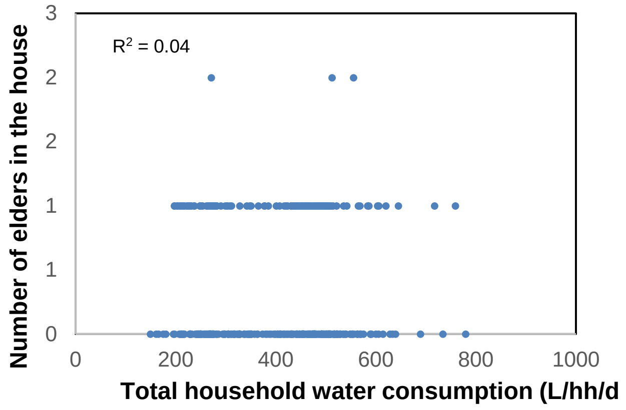


Figure C1.5 Relationship between household total average water consumption and number of elders in the household

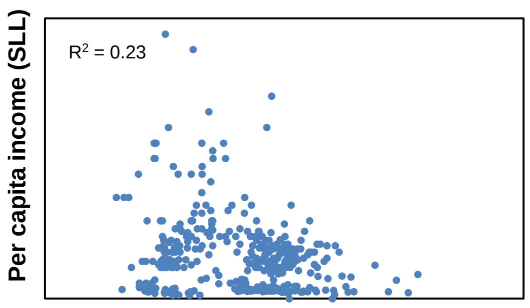


Figure C1.6 Relationship between household total average water consumption and per capita monthly income

Appendix C2: Relationship between Daily per Capita Average Water Consumption and Household Characteristics

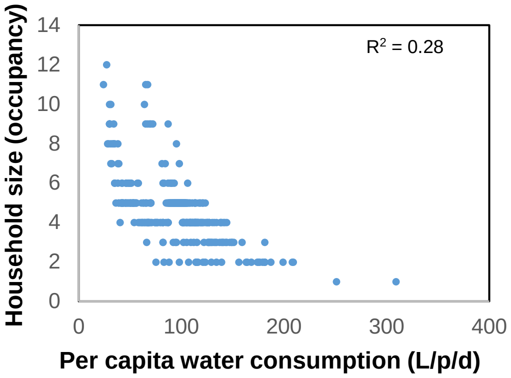


Figure C2.1 Relationship between daily per capita average water consumption and household occupancy

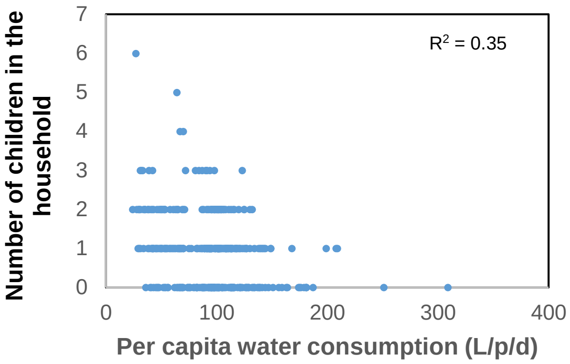


Figure C2.2 Relationship between daily per capita average water consumption and number of children in the household

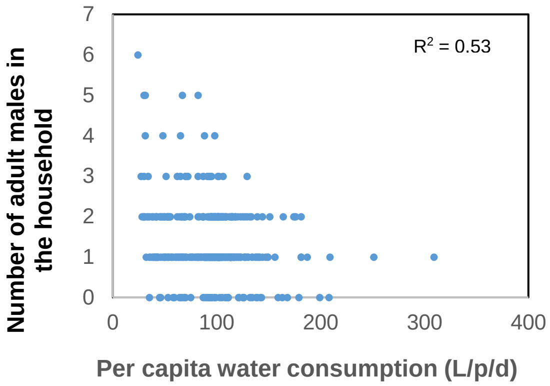


Figure C2.3 Relationship between daily per capita average water consumption and number of adult males in the household

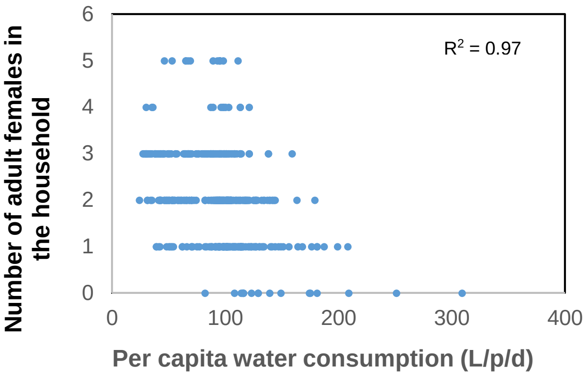


Figure C2.4 Relationship between daily per capita average water consumption and number of adult females in the household

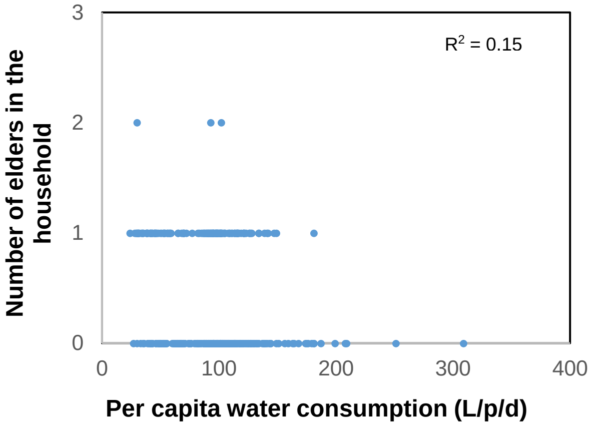


Figure C2.5 Relationship between daily per capita average water consumption and number of elders in the household

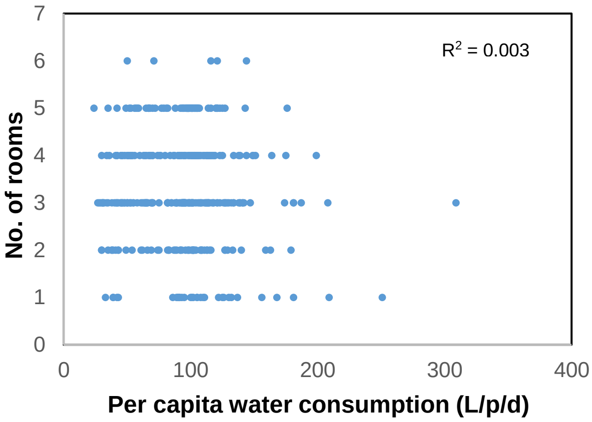


Figure C2.6 Relationship between daily per capita average water consumption and number of rooms in the household

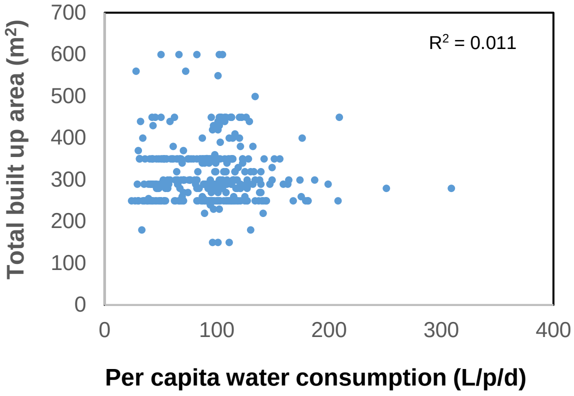


Figure C2.7 Relationship between daily per capita average water consumption and total built up area

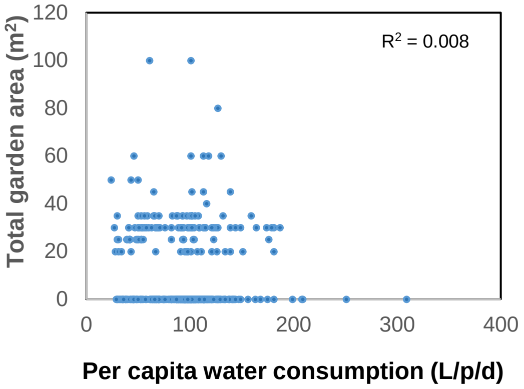


Figure C2.8 Relationship between daily per capita average water consumption and total garden area

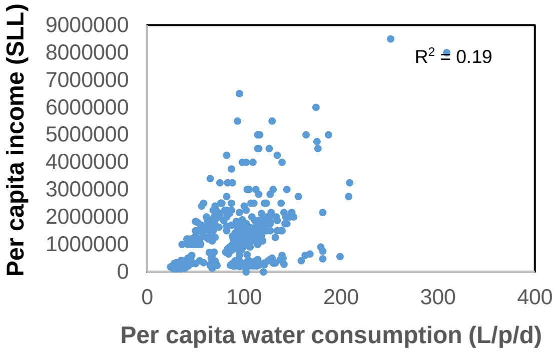


Figure C2.9 Relationship between daily per capita average water consumption and per capita income

Appendix C3: Statistical Parameters of Water End-Uses in Informal Slum, Low, Middle and High Income Household Groups

Table C3.1 Summary of water end-uses parameters for <u>all surveyed households</u> (245 households) in <u>rainy season</u>

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.40	0.32	0.20	0.04	0.00	0.61	0.20	-1.58	0.03
	Duration of each shower	min/shw	3.19	3.00	1.89	3.86	0.00	6.20	0.09	-1.65	0.24
	Flow rate	l/min	5.96	5.40	3.54	12.37	0.00	10.50	0.13	-1.64	0.45
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.94	0.95	0.07	0.00	0.46	1.07	-3.05	22.68	0.01
	Volume of water used in each bath	l/bt	20.32	20.00	2.87	8.28	10.00	30.00	0.14	1.61	0.36
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.24	2.83	1.66	2.64	0.00	4.40	-0.07	-1.89	0.21
	Duration of tap use	sec/brt	58.8	56.00	30.05	14.73	40.0	64.00	-0.13	-1.98	3.76
	Flow rate	l/min	2.51	2.00	1.37	1.79	0.00	4.00	0.07	-1.74	0.17
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.11	3.00	0.46	0.21	0.00	4.20	0.22	-1.82	0.20
	Volume of water use per person in each	l/tf	4.80	4.50	0.22	0.05	0.00	14.80	1.02	-0.95	0.76
	Number of latrine use per capita per day	lat/p/d	1.85	3.05	1.45	2.00	0.00	3.21	-0.24	-1.94	0.19
	Volume use per person for each pit use	l/lat/fl	3.04	1.77	0.86	0.70	0.00	2.13	-0.24	-1.93	0.11
	Number of pour flush latrine use per capita	pf/p/d	1.81	0.00	1.14	1.60	0.00	3.29	2.44	4.02	0.13
	Volume use per person for each pour flush	l/pf/d	3.15	0.00	3.33	11.60	0.00	12.04	2.40	4.22	0.31
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	1.94	4.83	0.00
	Volume of water used in each dishwashing	vol/wsh	8.07	8.00	2.95	8.74	2.00	19.00	1.92	4.79	0.37
House cleaning	Number of house cleaning per day	wsh/d	0.15	0.14	0.05	0.00	0.00	0.23	-1.19	3.67	0.01
	Total volume used per household per day	l/p/d	7.97	7.00	2.83	7.72	0.00	22.00	1.40	4.80	0.37
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.27	0.28	0.05	0.00	0.13	0.30	-2.34	4.17	0.01
	Volume of water used per wash per day	l/wsh/d	19.14	19.30	4.40	19.33	8.50	40.00	1.04	5.46	0.55
Vehicle washing	Number of vehicle washed per day	wsh/d	2.64	1.00	1.55	2.54	0.00	5.00	0.66	-0.98	0.20
	Volume used per day	l/wsh/d	10.55	9.30	5.44	30.96	0.00	20.00	0.10	-1.55	0.70
Cooking	Volume of water consumed in cooking	l/p/d	10.83	10.00	2.70	7.26	8.00	30.00	2.98	13.30	0.34
Drinking	Volume of water consumed for drinking	l/p/d	4.38	4.30	0.63	0.39	3.00	6.00	-0.35	-0.70	0.08

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.2 Summary of water end-uses parameters of informal settlement (slum) households in rainy season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.36	0.37	0.08	0.01	0.00	0.54	-0.20	-1.71	0.12
	Duration of each shower	min/shw	3.40	3.20	1.11	1.24	0.00	3.80	-0.12	-2.25	1.04
	Flow rate	l/min	5.95	5.80	1.05	1.10	0.00	6.40	-0.35	-2.10	1.78
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.94	0.95	0.04	0.00	0.85	0.98	-0.72	-0.41	0.03
	Volume of water used in each bath	l/bt	19.80	20.00	2.76	7.64	16.00	26.00	0.24	0.08	1.67
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.36	3.30	0.07	0.01	0.00	3.45	0.54	-2.05	1.03
	Duration of tap use	sec/brt	58.00	58.00	1.58	2.50	0.00	60.00	0.54	-2.05	17.76
	Flow rate	l/min	2.513	2.80	0.38	0.15	0.00	3.00	0.62	-1.82	0.82
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.13	3.10	0.08	0.01	0.00	3.20	0.54	-2.05	0.94
	Volume of water use per person in each	l/tf	4.30	4.20	0.22	0.05	0.00	5.60	0.55	-2.02	1.31
	Number of latrine use per capita per day	lat/p/d	3.4	3.08	0.09	0.01	0.00	3.21	-1.44	0.08	0.82
	Volume use per person for each pit use	l/lat/fl	1.7	1.83	0.10	0.01	0.00	1.99	-1.40	0.03	0.48
	Number of pour flush latrine use per capita	pf/p/d	3.35	3.11	0.12	0.02	0.00	3.20	2.18	3.26	0.71
	Volume use per person for each pour flush	l/pf/d	2.5	7.70	0.00	0.00	0.00	7.70	2.18	3.22	1.75
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	0.947	-0.721	0.00
	Volume of water used in each dishwashing	vol/wsh	7.83	9.00	2.71	6.73	6.00	14.00	0.57	-0.55	1.57
House cleaning	Number of house cleaning per day	wsh/d	0.21	0.21	0.02	0.00	0.16	0.23	-0.63	-0.86	0.01
	Total volume used per household per day	l/p/d	16.80	17.00	2.59	7.04	10.00	22.00	-0.81	4.42	1.60
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.29	0.28	0.01	0.00	0.27	0.30	-0.14	-0.82	0.01
	Volume of water used per wash per day	l/wsh/d	19.72	20.00	1.86	3.20	16.00	22.00	-0.42	0.01	1.08
Vehicle washing	Number of vehicle washed per day	wsh/d	1.43	1.00	0.52	0.27	0.00	2.00	0.31	-1.28	0.48
	Volume used per day	l/wsh/d	9.8	9.90	0.69	0.48	0.00	11.00	-0.50	-2.04	3.02
Cooking	Volume of water consumed in cooking	l/p/d	9.79	9.70	0.98	0.96	8.45	11.40	0.37	-0.88	0.59
Drinking	Volume of water consumed for drinking	l/p/d	4.9	5.00	0.36	0.13	3.80	5.20	-2.58	7.93	0.22

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.3 Summary of water end-uses parameters for low income households in rainy season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.33	0.30	0.16	0.02	0.00	0.50	0.22	-1.81	0.04
	Duration of each shower	min/shw	3.30	3.05	1.61	2.88	0.00	4.30	-0.23	-1.84	0.41
	Flow rate	l/min	5.30	5.30	2.53	6.97	0.00	6.20	-0.28	-1.89	0.64
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.91	0.92	0.03	0.00	0.85	1.07	1.01	5.71	0.01
	Volume of water used in each bath	l/bt	18.20	18.00	2.21	4.91	11.00	23.00	-0.98	1.81	0.53
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.02	2.40	1.49	2.26	0.00	4.00	-0.18	-1.84	0.37
	Duration of tap use	sec/brt	57.00	52.00	28.16	12.69	0.00	62.00	-0.28	-1.96	6.84
	Flow rate	l/min	2.47	2.00	1.26	1.55	0.00	3.00	-0.15	-1.84	0.30
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.25	1.25	1.57	2.63	0.00	3.80	0.60	-1.62	0.38
	Volume of water use per person in each	l/tf	4.42	4.22	2.18	4.68	0.00	4.74	0.55	-1.74	0.51
	Number of latrine use per capita per day	lat/p/d	3.01	2.85	1.51	2.29	0.00	3.21	0.24	-1.99	0.36
	Volume use per person for each pit use	l/lat/fl	1.75	1.70	0.87	0.76	0.00	1.83	0.24	-2.00	0.21
	Number of pour flush latrine use per capita	pf/p/d	3.29	1.57	1.50	1.51	0.00	3.29	1.93	1.79	0.28
	Volume use per person for each pour flush	l/pf/d	3.27	3.07	4.33	4.36	0.00	12.04	1.82	1.83	0.73
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	2.00	7.41	0.00
	Volume of water used in each dishwashing	vol/wsh	6.52	6.00	2.17	4.76	2.00	16.00	1.81	6.71	0.53
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.14	0.04	0.00	0.00	0.23	-1.49	6.60	0.01
	Total volume used per household per day	l/p/d	7.84	7.60	1.55	2.42	0.00	11.00	-1.27	4.43	0.49
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.29	0.28	0.01	0.00	0.21	0.30	-3.74	23.03	0.00
	Volume of water used per wash per day	l/wsh/d	20.01	20.00	1.77	3.13	16.00	23.00	-0.45	-0.44	0.42
Vehicle washing	Number of vehicle washed per day	wsh/d	1.43	1.00	0.88	0.50	0.00	3.00	0.84	0.04	0.19
	Volume used per day	l/wsh/d	9.6	9.00	4.69	23.25	0.00	10.80	-0.22	-1.99	1.15
Cooking	Volume of water consumed in cooking	l/p/d	9.57	9.70	0.84	0.71	8.00	11.50	0.58	-0.05	0.20
Drinking	Volume of water consumed for drinking	l/p/d	4.3	4.30	0.61	0.38	3.00	5.20	-0.43	-0.50	0.15

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.4 Summary of water end-uses parameters for middle income households in rainy season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.40	0.40	0.07	0.00	0.00	0.61	0.09	-1.73	0.04
	Duration of each shower	min/shw	3.80	4.00	1.44	2.08	0.00	5.60	0.16	-1.74	0.33
	Flow rate	l/min	7.36	7.30	2.58	6.73	0.00	9.40	0.05	-1.89	0.63
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.95	0.95	0.08	0.01	0.46	1.07	-3.32	19.43	0.01
	Volume of water used in each bath	l/bt	20.80	20.82	2.41	5.87	10.00	30.00	0.06	2.91	0.41
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.29	1.40	1.68	2.66	0.00	4.20	-0.01	-1.96	0.28
	Duration of tap use	sec/brt	58.93	57.00	30.64	15.30	0.00	64.00	-0.02	-2.02	5.09
	Flow rate	l/min	2.643	0.00	1.41	1.80	0.00	4.00	0.21	-1.70	0.23
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.04	0.00	2.44	2.49	0.00	4.00	0.14	-1.83	0.26
	Volume of water use per person in each	l/tf	4.80	0.00	3.87	3.25	0.00	4.90	1.27	-0.37	0.32
	Number of latrine use per capita per day	lat/p/d	3.1	3.06	1.95	1.83	0.00	3.21	-0.27	-1.93	0.25
	Volume use per person for each pit use	l/lat/fl	1.9	1.80	0.68	0.63	0.00	1.93	-0.29	-1.94	0.15
	Number of pour flush latrine use per capita	pf/p/d	3.17	0.00	0.00	1.16	0.00	3.27	2.57	4.68	0.16
	Volume use per person for each pour flush	l/pf/d	3.0	0.00	0.00	4.98	0.00	10.30	2.55	4.87	0.38
Dishwashing	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	1.78	2.21	0.00
(bowl)	Volume of water used in each dishwashing	vol/wsh	8.70	8.00	3.01	9.07	5.00	19.00	2.23	4.98	0.50
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.14	0.05	0.00	0.00	0.21	-1.31	3.50	0.01
	Total volume used per household per day	l/p/d	7.84	7.20	1.46	2.13	5.00	11.00	0.03	-0.67	0.24
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.29	0.29	0.02	0.00	0.20	0.30	-2.60	6.58	0.00
	Volume of water used per wash per day	l/wsh/d	19.72	19.30	4.75	21.90	10.00	40.00	1.63	6.02	0.79
Vehicle washing	Number of vehicle washed per day	wsh/d	1.71	2.00	1.69	2.86	0.00	5.00	0.25	-1.53	0.29
	Volume used per day	l/wsh/d	10.9	10.00	5.87	34.23	0.00	17.00	0.11	-1.72	0.97
Cooking	Volume of water consumed in cooking	l/p/d	10.87	10.00	2.21	4.87	8.00	20.00	1.67	3.02	0.37
Drinking	Volume of water consumed for drinking	l/p/d	4.3	4.00	0.63	0.39	3.00	5.20	-0.27	-0.91	0.10

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.5 Summary of water end-uses parameters for high income households in rainy season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.51	0.40	0.26	0.01	0.00	0.60	0.03	-1.92	0.11
	Duration of each shower	min/shw	4.38	1.75	2.03	0.81	0.00	6.20	0.09	-1.71	1.03
	Flow rate	l/min	9.49	3.65	4.67	8.12	0.00	10.50	0.04	-2.16	2.17
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.94	0.95	0.02	0.00	0.92	1.01	0.25	-0.17	0.01
	Volume of water used in each bath	l/bt	25.00	23.00	2.99	8.79	20.00	30.00	0.45	-0.63	1.35
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.57	3.54	1.71	4.56	0.00	4.40	-0.72	-1.43	0.77
	Duration of tap use	sec/brt	62.00	62.00	29.04	4.56	0.00	64.00	-0.83	-1.44	13.17
	Flow rate	l/min	2.687	2.55	1.35	0.25	0.00	4.00	-0.48	-1.34	0.60
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.23	3.00	1.51	0.30	0.00	4.20	-0.57	-1.48	0.71
	Volume of water use per person in each	l/tf	8.00	7.50	2.14	0.06	0.00	8.50	-0.81	-1.43	0.99
	Number of latrine use per capita per day	lat/p/d	2.9	3.09	0.06	0.00	0.00	3.21	-1.39	-0.06	0.59
	Volume use per person for each pit use	l/lat/fl	2.1	1.83	0.13	0.02	0.00	2.13	-1.32	-0.15	0.37
	Number of pour flush latrine use per capita	pf/p/d	2.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Volume use per person for each pour flush	l/pf/d	3.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	0.30	-1.64	0.00
	Volume of water used in each dishwashing	vol/wsh	8.70	8.00	2.20	9.49	5.00	19.00	1.83	4.69	1.40
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.14	0.04	0.00	0.00	0.21	-1.44	7.06	0.02
	Total volume used per household per day	l/p/d	3.92	3.60	0.82	1.40	3.00	8.00	1.97	5.07	0.54
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.14	0.13	0.03	0.00	0.13	0.28	4.33	19.53	0.01
	Volume of water used per wash per day	l/wsh/d	12.65	12.00	1.36	12.91	8.50	28.00	3.67	15.94	1.63
Vehicle washing	Number of vehicle washed per day	wsh/d	4.00	4.00	0.60	0.36	0.00	5.00	0.14	-1.99	0.93
	Volume used per day	l/wsh/d	12.0	10.00	2.42	5.87	0.00	20.00	0.35	-1.11	2.95
Cooking	Volume of water consumed in cooking	l/p/d	15.22	13.00	3.45	10.89	11.00	30.00	1.86	3.44	2.09
Drinking	Volume of water consumed for drinking	l/p/d	4.6	5.00	0.60	0.35	3.50	6.00	0.01	-0.45	0.28

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.6 Summary of water end-uses parameters for all surveyed households (153 households) in dry season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.70	0.80	0.18	0.03	0.36	1.14	-0.52	-0.01	1.82
	Duration of each shower	min/shw	2.36	2.00	0.66	0.43	0.00	4.00	-0.37	2.63	0.18
	Flow rate	l/min	9.25	10.00	1.02	1.02	7.11	10.87	-0.91	0.59	0.14
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.97	0.98	0.04	0.00	0.80	0.99	-3.35	11.28	0.23
	Volume of water used in each bath	l/bt	16.50	17.00	5.24	27.50	8.50	30.00	0.51	0.16	0.77
Hand wash basins	Number of times using hand wash basins	brt/p/d	2.06	2.00	0.41	0.17	1.50	3.24	1.44	2.32	3.75
	Duration of tap use	sec/brt	57.09	57.00	2.90	8.43	48.00	63.00	-0.83	2.33	3.16
	Flow rate	l/min	2.65	2.70	0.31	0.09	2.00	3.00	-0.97	0.39	0.29
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	2.52	2.52	0.40	0.16	1.70	3.11	-0.15	-1.18	0.50
	Volume of water use per person in each	l/tf	4.51	4.66	0.43	0.18	4.00	6.00	0.83	2.21	0.86
	Number of latrine use per capita per day	lat/p/d	3.00	3.00	0.16	0.03	2.60	3.21	-0.67	-0.21	0.36
	Volume use per person for each pit use	l/lat/fl	1.80	1.80	0.26	0.07	0.00	2.20	-5.48	39.48	0.45
	Number of pour flush latrine use per capita	pf/p/d	3.00	2.93	0.30	0.09	2.00	3.21	-0.69	-0.04	0.00
	Volume use per person for each pour flush	l/pf/d	2.85	3.00	0.09	0.01	2.75	3.09	-0.95	0.70	0.45
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	0.88	-1.25	0.07
	Volume of water used in each dishwashing	vol/wsh	7.64	7.02	3.95	15.58	2.02	19.00	1.07	1.10	0.65
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.21	0.04	0.00	0.14	0.42	1.37	9.18	0.06
	Total volume used per household per day	l/p/d	6.60	6.90	0.86	0.75	5.00	11.00	1.65	4.48	0.18
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.28	0.21	0.03	0.00	0.20	0.28	0.81	-1.26	0.45
	Volume of water used per wash per day	l/wsh/d	15.43	15.00	7.81	60.95	7.00	45.00	1.53	2.49	1.25
Vehicle washing	Number of vehicle washed per day	wsh/d	2.00	1.90	0.55	0.31	0.83	3.33	0.40	0.28	0.22
	Volume used per day	l/wsh/d	10.25	10.00	1.52	2.31	0.00	13.20	-2.29	19.04	0.77
Cooking	Volume of water consumed in cooking	l/p/d	14.15	13.60	2.56	6.57	11.09	17.88	0.43	-1.30	0.41
Drinking	Volume of water consumed for drinking	l/p/d	3.78	3.94	0.23	0.05	3.00	4.00	-1.64	2.57	0.03
Garden	Volume of water consumed for garden	l/p/d	9.18	9.00	1.76	2.99	6.00	12.00	-0.07	-0.65	0.60

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.7 Summary of water end-uses parameters of informal settlement (slum) households in dry season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.36	0.37	0.02	0.00	0.36	0.39	1.63	0.81	0.04
	Duration of each shower	min/shw	2.50	2.42	0.59	0.17	2.00	2.83	1.78	1.77	0.39
	Flow rate	l/min	7.20	7.23	0.04	0.00	7.20	7.26	1.62	0.74	1.16
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.95	0.97	0.07	0.00	0.80	0.99	-1.38	0.39	0.03
	Volume of water used in each bath	l/bt	9.50	10.00	0.75	0.56	9.00	12.00	1.52	3.92	0.43
Hand wash basins	Number of times using hand wash basins	brt/p/d	2.30	2.39	0.08	0.01	2.31	2.46	1.63	0.77	0.37
	Duration of tap use	sec/brt	56.00	56.00	0.00	0.00	0.00	56.00	1.92	2.04	7.72
	Flow rate	l/min	2.51	2.52	0.01	0.00	2.51	2.52	2.61	5.44	0.40
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.00	3.11	0.00	0.00	3.11	3.11	2.61	0.73	0.50
	Volume of water use per person in each	l/tf	4.15	4.15	0.00	0.00	4.15	4.15	2.61	-1.88	0.67
	Number of latrine use per capita per day	lat/p/d	3.15	3.09	0.08	0.01	3.00	3.21	0.36	-1.48	0.71
	Volume use per person for each pit use	l/lat/fl	1.80	1.86	0.09	0.01	1.72	1.98	0.33	-1.34	0.42
	Number of pour flush latrine use per capita	pf/p/d	3.12	3.08	0.06	0.00	3.08	3.21	-0.60	-3.32	0.60
	Volume use per person for each pour flush	l/pf/d	2.72	3.08	0.16	0.02	2.75	3.08	-1.73	1.75	0.57
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	-1.37	0.32	0.00
	Volume of water used in each dishwashing	vol/wsh	3.38	3.02	0.85	0.72	2.02	5.02	0.51	-0.13	0.49
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.14	0.00	0.00	0.14	0.14	1.12	-2.36	0.03
	Total volume used per household per day	l/p/d	6.09	6.00	1.47	2.15	6.00	11.00	0.47	-0.21	1.44
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.28	0.28	0.00	0.00	0.28	0.28	-1.10	-2.29	0.00
	Volume of water used per wash per day	l/wsh/d	8.94	9.00	1.55	2.41	7.00	12.00	0.63	-0.14	0.77
Vehicle washing	Number of vehicle washed per day	wsh/d	1.41	2.00	0.25	0.06	1.41	2.00	-0.77	-1.99	0.40
	Volume used per day	l/wsh/d	8.70	8.75	0.49	0.25	8.00	9.30	-0.93	-1.88	1.85
Cooking	Volume of water consumed in cooking	l/p/d	11.16	11.09	0.16	0.03	11.09	11.65	2.27	4.35	0.08
Drinking	Volume of water consumed for drinking	l/p/d	3.48	3.46	0.22	0.05	3.00	4.00	1.04	3.62	0.01
Garden	Volume of water consumed for garden	l/p/d	7.14	7.50	0.97	0.76	6.00	8.00	-0.45	-3.02	1.65

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.8 Summary of water end-uses parameters for low income households in dry season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.44	0.44	0.16	0.00	0.43	0.44	2.16	2.86	2.66
	Duration of each shower	min/shw	2.55	2.60	0.53	0.21	2.00	3.00	2.32	3.92	0.17
	Flow rate	l/min	7.61	7.64	0.52	7.48	7.11	8.06	2.18	2.99	2.63
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.96	0.98	0.05	0.00	0.80	0.99	-2.29	4.84	0.63
	Volume of water used in each bath	l/bt	11.93	11.00	3.76	14.12	9.00	22.00	1.91	2.90	0.36
Hand wash basins	Number of times using hand wash basins	brt/p/d	2.20	2.42	0.26	0.86	2.42	3.01	2.21	3.25	6.81
	Duration of tap use	sec/brt	57.00	57.00	0.43	0.19	57.00	58.00	2.16	2.86	0.37
	Flow rate	l/min	2.53	2.68	0.05	0.91	2.62	2.72	2.16	2.87	0.38
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	2.84	2.80	1.22	1.49	0.00	2.87	2.69	5.62	0.90
	Volume of water use per person in each	l/tf	4.25	4.30	1.86	3.47	0.00	4.30	2.69	5.61	1.47
	Number of latrine use per capita per day	lat/p/d	3.22	3.08	0.03	2.43	3.04	14.00	-0.30	-2.06	0.93
	Volume use per person for each pit use	l/lat/fl	1.95	1.89	0.12	0.97	1.79	14.00	-0.28	-2.04	1.34
	Number of pour flush latrine use per capita	pf/p/d	3.27	3.08	0.16	2.07	2.63	3.21	0.82	-1.41	0.05
	Volume use per person for each pour flush	l/pf/d	2.98	2.95	0.08	2.02	2.85	3.09	0.81	-1.44	0.68
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	0.37	0.51	2.66
	Volume of water used in each dishwashing	vol/wsh	5.60	5.00	2.38	3.06	2.02	10.02	1.16	0.73	1.05
House cleaning	Number of house cleaning per day	wsh/d	0.14	0.14	0.01	0.00	0.14	0.21	-2.80	9.06	0.00
	Total volume used per household per day	l/p/d	6.40	6.50	0.27	0.08	6.00	6.70	-0.43	-1.31	0.00
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.28	0.28	0.00	0.00	0.28	0.28	-1.06	-2.16	1.15
	Volume of water used per wash per day	l/wsh/d	10.00	9.00	2.66	7.07	7.00	17.00	1.18	0.54	0.10
Vehicle washing	Number of vehicle washed per day	wsh/d	1.43	1.43	0.23	0.53	1.43	2.00	1.12	-0.61	0.11
	Volume used per day	l/wsh/d	9.04	9.00	0.37	0.13	8.50	9.50	1.01	-1.05	0.56
Cooking	Volume of water consumed in cooking	l/p/d	11.64	11.37	0.00	0.00	5.00	11.37	-1.06	-2.16	1.61
Drinking	Volume of water consumed for drinking	l/p/d	3.56	4.00	0.22	0.05	0.50	4.00	-0.15	-2.14	1.05
Garden	Volume of water consumed for garden	l/p/d	7.50	7.50	1.12	8.74	6.00	9.00	1.86	1.74	0.05

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.9 Summary of water end-uses parameters for middle income households in dry season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.76	0.73	0.08	0.01	0.66	1.03	0.39	-1.82	0.10
	Duration of each shower	min/shw	2.36	2.00	0.48	0.22	2.00	3.00	0.55	-1.43	0.30
	Flow rate	l/min	9.42	9.17	0.39	0.15	8.80	10.00	0.28	-1.98	1.20
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.98	0.98	0.03	0.00	0.80	0.99	-1.40	0.56	0.02
	Volume of water used in each bath	l/bt	18.25	18.00	3.80	14.44	8.50	30.00	-1.36	3.43	0.73
Hand wash basins	Number of times using hand wash basins	brt/p/d	2.22	2.00	0.19	0.04	2.00	3.00	0.27	-1.98	0.37
	Duration of tap use	sec/brt	58.07	59.00	3.01	9.03	48.00	63.00	0.28	-1.97	7.39
	Flow rate	l/min	2.64	3.00	0.42	0.18	2.00	3.00	0.28	-1.98	0.32
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	2.51	2.53	0.10	0.01	2.00	2.57	0.20	-2.03	0.32
	Volume of water use per person in each	l/tf	4.60	4.64	0.22	0.05	4.00	4.90	0.20	-2.02	0.60
	Number of latrine use per capita per day	lat/p/d	3.01	3.00	0.09	0.01	2.85	3.20	0.26	-1.99	0.36
	Volume use per person for each pit use	l/lat/fl	1.81	1.84	0.38	0.15	0.00	2.15	0.33	-1.87	0.23
	Number of pour flush latrine use per capita	pf/p/d	2.80	2.75	0.16	0.03	2.60	3.00	2.29	3.37	0.25
	Volume use per person for each pour flush	l/pf/d	2.92	2.95	0.09	0.01	2.75	3.00	2.27	3.26	0.26
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	0.00	0.00	2.03	0.70	0.00
	Volume of water used in each dishwashing	vol/wsh	8.01	7.00	2.55	6.53	5.00	16.00	1.83	2.83	0.76
House cleaning	Number of house cleaning per day	wsh/d	0.21	0.21	0.03	0.00	0.20	0.42	0.39	4.16	0.02
	Total volume used per household per day	l/p/d	6.85	7.00	0.37	0.14	6.00	7.20	-1.52	2.21	0.07
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.21	0.21	0.01	0.00	0.20	0.22	-0.48	-1.83	0.00
	Volume of water used per wash per day	l/wsh/d	16.61	15.00	4.32	18.66	11.00	34.00	2.04	4.88	1.11
Vehicle washing	Number of vehicle washed per day	wsh/d	1.71	1.67	0.46	0.21	0.87	3.04	-0.51	-0.67	0.26
	Volume used per day	l/wsh/d	9.78	10.00	1.46	2.12	0.00	11.00	-1.38	0.01	1.30
Cooking	Volume of water consumed in cooking	l/p/d	13.60	13.55	0.12	0.02	13.45	14.00	0.81	-0.64	0.03
Drinking	Volume of water consumed for drinking	l/p/d	3.85	3.85	0.15	0.02	3.00	4.00	1.02	-2.07	0.00
Garden	Volume of water consumed for garden	l/p/d	9.15	9.00	0.54	0.26	8.50	10.00	1.90	1.71	0.86

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C3.10 Summary of water end-uses parameters for high income households in dry season

End-use	Parameter/variable	Unit	Mean	Median	Std deviation	Variance	Minimum	Maximum	Skewness	kurtosis	Confidence interval (95%)
Shower	Number of showering per capita per day	shw/p/d	0.94	0.96	0.09	0.01	0.73	1.14	-0.57	2.07	0.14
	Duration of each shower	min/shw	2.37	2.00	0.78	0.59	0.00	4.00	-0.58	3.51	0.37
	Flow rate	l/min	9.87	9.80	0.80	0.60	9.00	10.87	0.15	-1.76	1.48
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.99	0.99	0.01	0.00	0.90	0.99	-5.54	33.36	0.00
	Volume of water used in each bath	l/bt	20.46	20.00	4.17	17.39	12.00	30.00	0.93	1.14	1.25
Hand wash basins	Number of times using hand wash basins	brt/p/d	1.99	1.65	0.58	0.34	1.50	3.24	1.73	1.75	0.31
	Duration of tap use	sec/brt	57.00	57.00	1.82	3.30	54.00	63.00	1.63	5.05	8.49
	Flow rate	l/min	2.69	2.70	0.08	0.01	2.36	2.80	-3.72	16.28	0.40
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	1.80	1.80	0.10	0.01	1.70	2.00	0.25	-1.26	0.27
	Volume of water use per person in each	l/tf	5.00	5.00	0.38	0.15	4.50	6.00	1.64	2.65	0.75
	Number of latrine use per capita per day	lat/p/d	2.72	2.70	0.08	0.01	2.60	2.94	1.39	2.49	0.41
	Volume use per person for each pit use	l/lat/fl	2.01	2.00	0.04	0.00	2.00	2.20	4.47	20.00	0.30
	Number of pour flush latrine use per capita	pf/p/d	2.52	2.50	0.30	0.09	2.00	3.20	0.98	3.94	0.29
	Volume use per person for each pour flush	l/pf/d	3.00	3.00	0.02	0.00	2.95	3.02	-2.16	5.97	0.34
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	0.00	0.00	2.00	2.00	0.64	-0.72	0.00
	Volume of water used in each dishwashing	vol/wsh	10.71	8.50	4.17	17.35	5.50	19.00	0.97	-0.52	1.25
House cleaning	Number of house cleaning per day	wsh/d	0.21	0.21	0.00	0.00	0.21	0.21	6.40	41.00	0.02
	Total volume used per household per day	l/p/d	6.89	6.50	0.98	0.96	5.00	9.00	0.67	-0.41	0.65
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.21	0.21	0.00	0.00	0.20	0.22	0.92	2.64	0.00
	Volume of water used per wash per day	l/wsh/d	23.24	18.00	8.95	80.14	11.00	45.00	0.99	-0.19	2.69
Vehicle washing	Number of vehicle washed per day	wsh/d	2.00	2.00	0.61	0.37	0.83	3.33	0.10	0.02	0.20
	Volume used per day	l/wsh/d	11.12	10.50	1.26	1.60	10.00	13.20	0.73	-1.23	0.61
Cooking	Volume of water consumed in cooking	l/p/d	17.80	17.86	0.21	0.05	17.00	17.88	-3.62	11.69	0.06
Drinking	Volume of water consumed for drinking	l/p/d	3.94	4.00	0.20	0.04	3.00	4.00	-4.52	19.65	0.06
Garden	Volume of water consumed for garden	l/p/d	11.00	11.00	1.00	0.91	9.00	12.00	-0.73	-0.13	1.42

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Appendix C4: Comparison of Seasonal of Water End-Uses in Informal Slum, Low, Middle and High Income Household Groups

Table C4.1 Summary of seasonal water end-uses parameters for all surveyed households (398 households)

End-use	Parameter/variable	Unit	Overall survey		Slum income		Low income		Middle income		High income	
			Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry
Shower	Number of showering per capita per day	shw/p/d	0.39	0.70	0.36	0.36	0.33	0.44	0.40	0.76	0.51	0.94
	Duration of each shower	min/shw	3.61	2.36	3.40	2.50	3.30	2.55	3.80	2.36	4.38	2.37
	Flow rate	l/min	7.02	9.25	5.95	7.20	6.30	7.61	8.36	9.42	9.49	9.87
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.95	0.97	0.94	0.95	0.91	0.96	0.95	0.98	0.94	0.99
	Volume of water used in each bath	l/bt	20.70	16.50	19.80	9.50	18.20	11.93	20.80	18.25	25.00	20.46
Hand wash basins	Number of times using hand wash basins	brt/p/d	3.06	2.06	3.36	2.30	3.02	2.20	3.29	2.22	3.57	1.99
	Duration of tap use	sec/brt	60.62	57.09	58.00	56.00	57.00	57.00	58.93	58.07	62.00	57.00
	Flow rate	l/min	2.63	2.65	2.51	2.51	2.47	2.53	2.64	2.64	2.68	2.69
Toilet flushing	Number of flushing toilet use per capita	tf/p/d	3.11	2.52	3.13	3.00	3.07	2.84	3.04	2.51	3.23	1.80
	Volume of water use per person in each	l/tf	4.80	4.51	4.30	4.15	4.25	4.25	4.80	4.60	5.20	5.00
	Number of latrine use per capita per day	lat/p/d	2.6	3.00	3.4	3.15	3.3	3.22	3.1	3.01	2.9	2.72
	Volume use per person for each pit use	l/lat/fl	1.8	1.80	1.7	1.80	1.8	1.95	1.9	1.81	2.1	2.01
	Number of pour flush latrine use per capita	pf/p/d	3.20	3.00	3.35	3.12	3.29	3.27	3.17	2.80	2.98	2.52
	Volume use per person for each pour flush	l/pf/d	2.8	2.85	2.5	2.72	2.5	2.98	3.0	2.92	3.0	3.00
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Volume of water used in each dishwashing	vol/wsh	8.40	7.64	7.83	3.38	7.52	5.60	8.70	8.01	8.70	10.71
House cleaning	Number of house cleaning per day	wsh/d	0.16	0.14	0.21	0.14	0.14	0.14	0.14	0.21	0.14	0.21
	Total volume used per household per day	l/p/d	8.96	6.60	10.80	6.09	7.84	6.40	7.84	6.85	3.92	6.89
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.25	0.28	0.29	0.28	0.29	0.28	0.29	0.21	0.14	0.21
	Volume of water used per wash per day	l/wsh/d	19.25	15.43	19.72	8.94	20.01	10.00	19.72	16.61	12.65	23.24
Vehicle washing	Number of vehicle washed per day	wsh/d	2.00	2.00	1.43	1.41	1.43	1.43	1.71	1.71	4.00	2.00
	Volume used per day	l/wsh/d	11.53	10.25	9.3	8.70	9.8	9.04	10.9	9.78	12.0	11.12
Cooking	Volume of water consumed in cooking	l/p/d	10.83	14.15	9.79	11.16	9.87	11.64	10.87	13.60	15.22	17.80
Drinking	Volume of water consumed for drinking	l/p/d	4.38	3.78	4.9	3.48	4.3	3.56	4.3	3.85	4.6	3.94
Garden	Volume of water consumed for garden	l/p/d	0.0	9.18	0.0	7.14	0.0	7.50	0.0	9.15	0.0	11.00
Total water consumption		l/p/d	120	89	109	64	106	70	125	92	132	111

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Table C4.2 Summary of water end-uses parameters for all surveyed households (245 households) in rainy & (153 households) in dry season

End-use	Parameter/variable	Unit	Overall survey		Slum income		Low income		Middle income		High income	
			Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry
Shower	Number of showering per capita per day	shw/p/d	0.39	0.70	0.36	0.36	0.33	0.44	0.40	0.76	0.51	0.94
	Duration of each shower	min/shw	3.61	2.36	3.40	2.50	3.30	2.55	3.80	2.36	4.38	2.37
	Flow rate	l/min	7.02	9.25	5.95	7.20	6.30	7.61	7.36	9.42	9.49	9.87
Bathing (Bucket)	Number of taking bath per capita per day	bt/p/d	0.95	0.97	0.94	0.95	0.91	0.96	0.95	0.98	0.94	0.99
	Volume of water used in each bath	l/bt	20.70	16.50	19.80	9.50	18.20	11.93	20.80	18.25	25.00	20.46
Hand wash basins	Number of times using hand wash basins per	brt/p/d	3.06	2.06	3.36	2.30	3.02	2.40	3.29	2.22	3.57	1.90
	Duration of tap use	sec/brt	60.62	57.09	58.00	56.00	57.00	57.00	58.93	58.07	62.00	57.00
	Flow rate	l/min	2.63	2.65	2.51	2.51	2.47	2.53	2.64	2.64	2.68	2.69
Toilet flushing	Number of flushing toilet use per capita per	tf/p/d	3.11	2.52	3.13	3.00	3.07	2.84	3.04	2.51	3.23	1.80
	Volume of water use per person in each	l/tf	4.80	4.51	4.30	4.15	4.25	4.25	4.80	4.60	5.20	5.00
	Number of latrine use per capita per day	lat/p/d	3.04	3.00	3.4	3.15	3.3	3.22	3.1	3.01	2.9	2.72
	Volume use per person for each pit use	l/lat/fl	1.8	1.80	1.7	1.80	1.8	1.95	1.9	1.81	2.1	2.01
	Number of pour flush latrine use per capita	pf/p/d	3.20	3.00	3.35	3.12	3.29	3.27	3.17	2.80	2.98	2.52
	Volume use per person for each pour flush	l/pf/d	2.8	2.85	2.5	2.72	2.5	2.98	3.0	2.92	3.0	3.00
Dishwashing (bowl)	Number of washing dishes per day	dws/d	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Volume of water used in each dishwashing	vol/wsh	8.40	7.64	7.83	3.38	7.52	5.60	8.70	8.01	8.70	10.71
House cleaning	Number of house cleaning per day	wsh/d	0.16	0.14	0.21	0.14	0.14	0.14	0.14	0.21	0.14	0.21
	Total volume used per household per day	l/p/d	8.96	6.60	10.80	6.09	7.84	6.40	7.84	6.85	3.92	6.89
Clothes washing (hand)	Number of clothes washing sessions	wsh/d	0.25	0.28	0.29	0.28	0.29	0.28	0.29	0.21	0.14	0.21
	Volume of water used per wash per day	l/wsh/d	19.25	15.43	19.72	8.94	20.01	10.00	19.72	16.61	12.65	23.24
Vehicle washing	Number of vehicle washed per day	wsh/d	2.00	2.00	1.43	1.41	1.43	1.43	1.71	1.71	4.00	2.00
	Volume used per day	l/wsh/d	11.53	10.25	9.3	8.70	9.8	9.04	10.9	9.78	12.0	11.12
Cooking	Volume of water consumed in cooking	l/p/d	10.83	14.15	9.79	11.16	9.87	11.64	10.87	13.60	15.22	17.80
Drinking	Volume of water consumed for drinking	l/p/d	4.38	3.78	4.9	3.48	4.3	3.56	4.3	3.85	4.6	3.94
Garden	Volume of water consumed for garden	l/p/d	0.00	9.18	0.0	7.14	0.00	7.50	0.00	9.15	0.00	11.00

*l/p/d = litre per person per day.Note: l = litre, p =person, d=day, wsh= washes, min=minute, vol= volume, bt=bath, shw=shower, sec=second, brt=bathroom, tf=toilet flushing, lat=latrine, pf=pour flush, fl=flush, dws=dishwash, No./d = number per day

Appendix C5 Comparison between Water End-Uses in Rainy and Dry Season

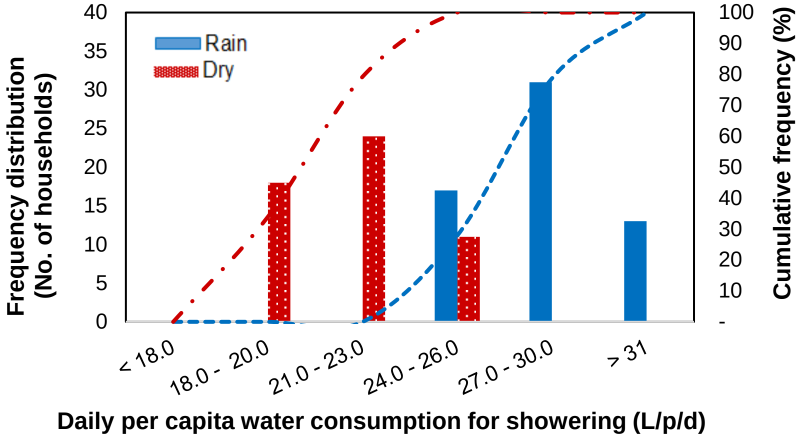


Figure C5. 1 Comparison between per capita water consumption for showering in rain and dry season

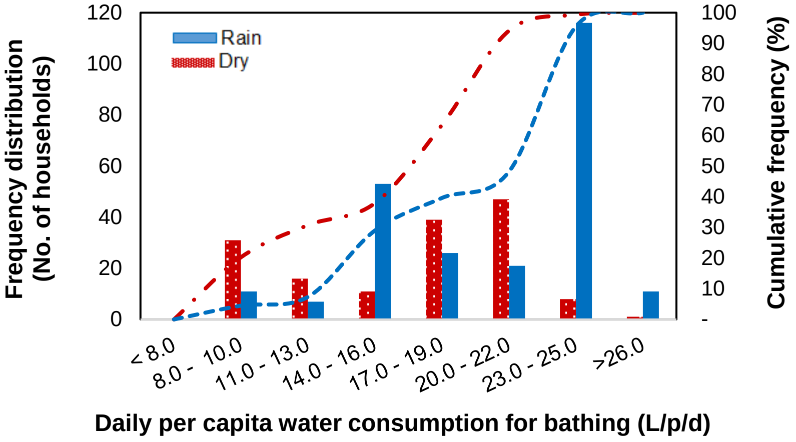


Figure C5. 2 Comparison between per capita water consumption for bathing in rain and dry season

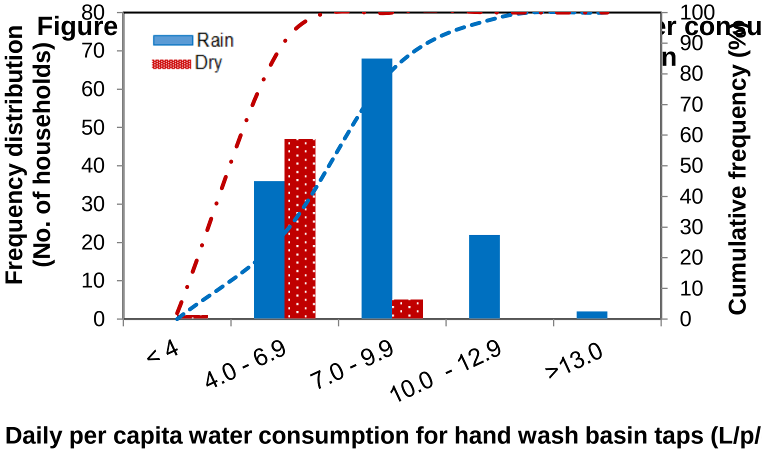


Figure C5. 3 Comparison between per capita water consumption for wash hand basin taps in rain and dry season

Figure C5. 2 Comparison between per capita water consumption
thing in rain and dry season

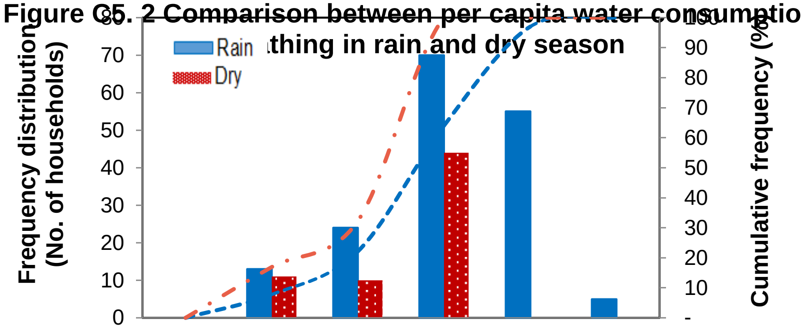


Figure C5. 4 Comparison between per capita water consumption for cistern toilet flushing in rain and dry season

Figure C5. 4 Comparison between per capita water consumption for cistern toilet flushing in rain and dry season

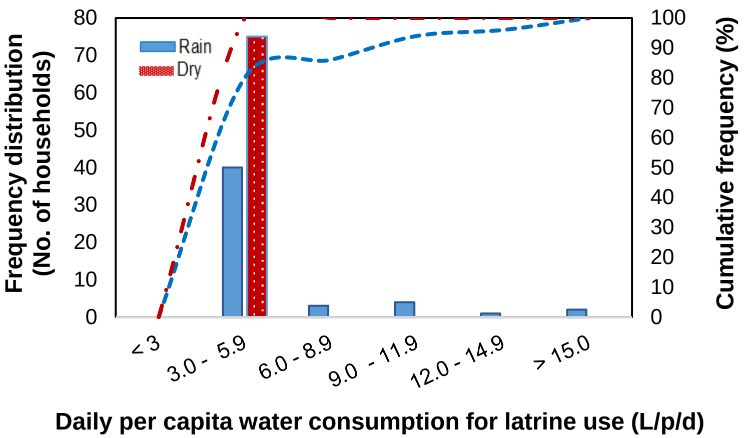


Figure C5. 5 Comparison between per capita water consumption for latrine in rain and dry season

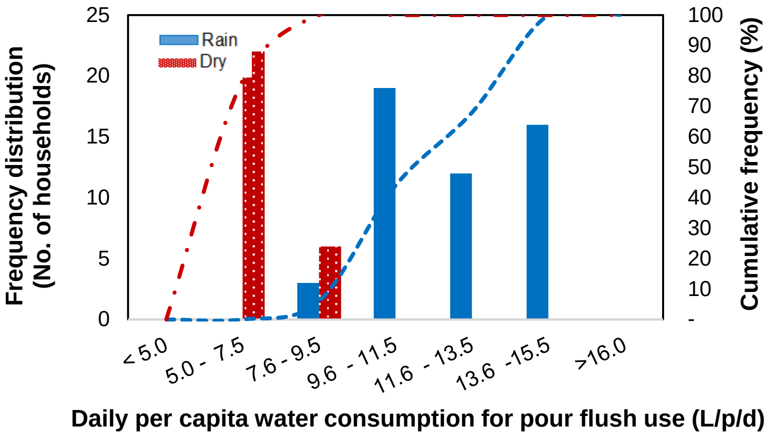


Figure C5. 6 Comparison between per capita water consumption for pour flush toilet in rain and dry season

Figure C5. 5 Comparison between per capita water consumption for latrine in rain and dry season

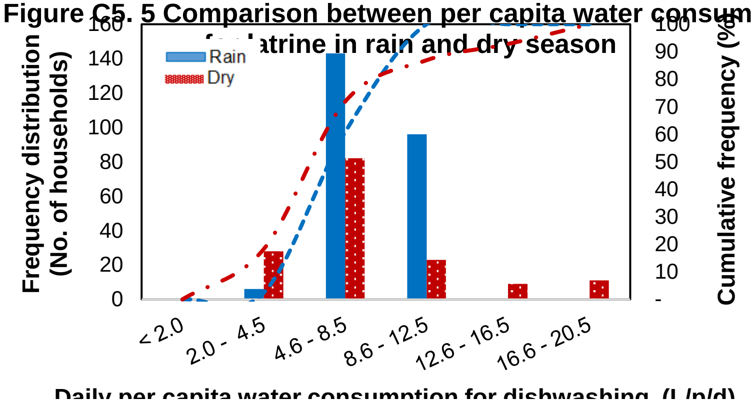


Figure C5. 7 Comparison between per capita water consumption for dishwashing in rain and dry season

Figure C5. 7 Comparison between per capita water consumption for dishwashing in rain and dry season

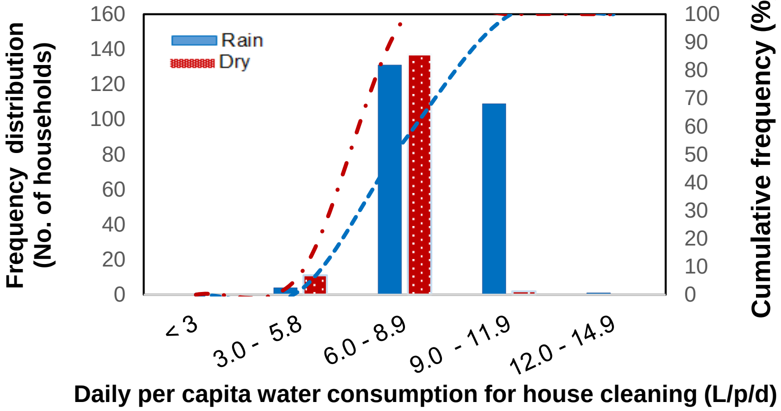


Figure C5. 8 Comparison between per capita water consumption for house cleaning in rain and dry season

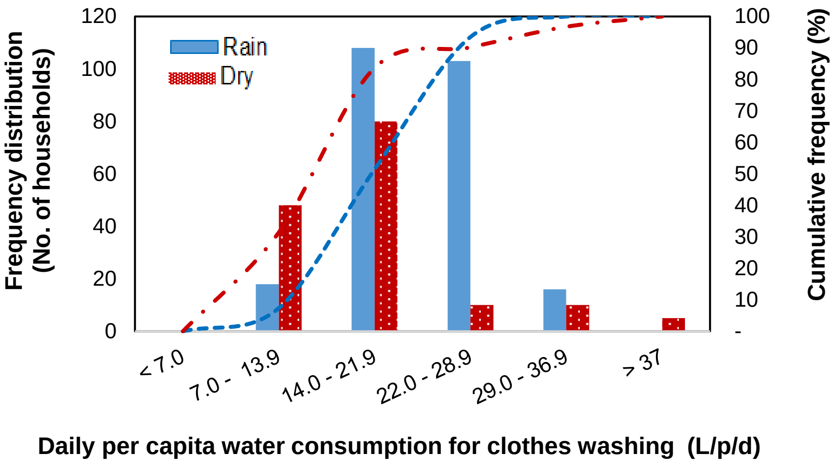


Figure C5. 9 Comparison between per capita water consumption for clothes washing in rain and dry season

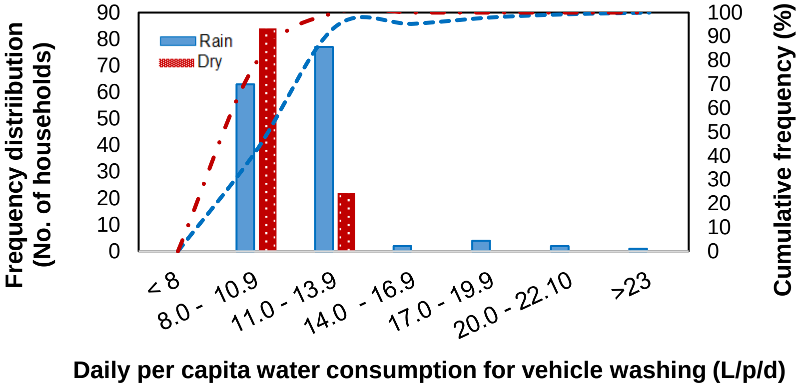


Figure C5. 10 Comparison between per capita water consumption for vehicle washing in rain and dry season

Figure C5. 9 Comparison between per capita water consumption for clothes washing in rain and dry season

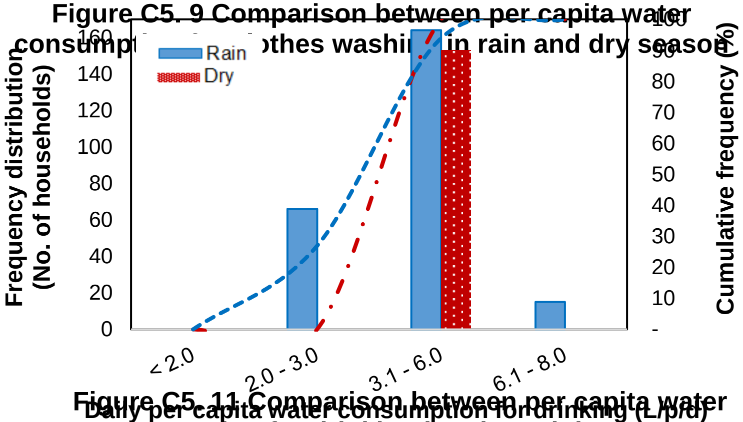


Figure C5. 11 Comparison between per capita water consumption for drinking in rain and dry season

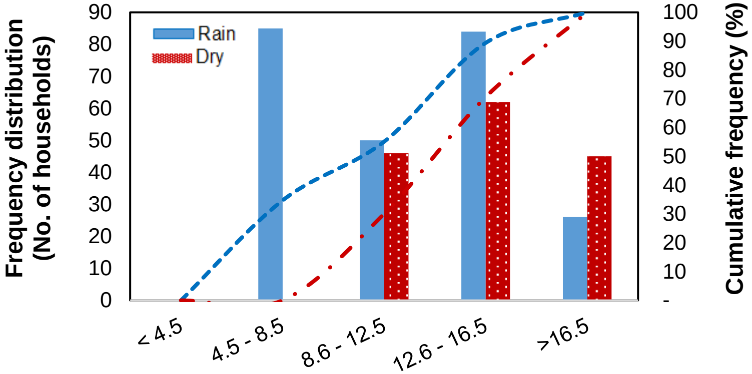


Figure C5. 12 Comparison between per capita water consumption for cooking in rain and dry season

Figure C5. 11 Comparison between per capita water consumption for drinking in rain and dry season

Figure C5. 12 Comparison between per capita water consumption for cooking in rain and dry season

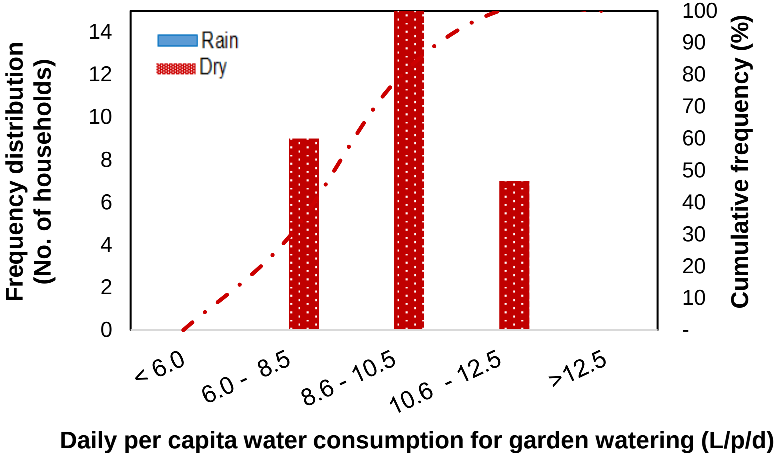


Figure C5. 13 Comparison between per capita water consumption for garden watering in dry season

Figure C5. 13 Comparison between per capita water consumption for garden watering in dry season

APPENDIX D: METHODOLOGY, SOIL WATER BUDGET, MODEL DEVELOPMENT AND RESULT ANALYSIS

Appendix D1: Climate data year 2016 for Valley bottom and Mountain top height

Table D1.1 Climate data year 2016 for Valley bottom

Valley bottom			
Year 2016	Precipitation (mm)	Evapotranspiration (mm)	Reference surplus (mm)
January	11.2245	84.03	0
February	6.06895	75.43	0
March	19.0922	88	0
April	103.955	146.2	0
May	201.842	250	0
June	360	339.9	20.1
July	498	481.786	16.214
August	505.345	463	42.345
September	484.481	460	24.481
October	308	291.877	16.123
November	98.97	79.1541	19.8159
December	8.74569	91.37	0
Annual	2605.72434	2850.7471	139.0789

Table D1.2 Precipitation, potential evapotranspiration and actual evapotranspiration data of Valley bottom, Freetown

Valley bottom	Months	P	E_p	E_A
	Jan	11.22	84.03	11.23
	Feb	6.07	75.43	6.07
	Mar	19.09	88.00	19.09
	Apr	103.96	146.20	103.96
	May	201.84	250.00	201.84
	Jun	360.00	339.90	339.90
	Jul	498.00	481.79	481.79
	Aug	505.35	463.00	463.00
	Sep	484.48	460.00	460.00
	Oct	308.00	291.88	291.88
	Nov	98.97	79.15	79.15
	Dec	8.75	91.37	171.48

Table D1.3 Climate data year 2016 for Mountain top heights

Mountain top heights			
Year 2016	Precipitation (mm)	Evapotranspiration (mm)	Reference surplus (mm)
January	5.8	74.6	0
February	6.8	86.2	0
March	5.3	88.7	0
April	35.3	98.3	0
May	116.7	120	0
June	299.9	290	9.9
July	584	544.5	39.5
August	593.9	470	123.9
September	487.2	456	31.2
October	420	317.8	102.2
November	198	190.5	7.5
December	10	61.36	0
Annual	2762.9	2797.96	111.1

Table D1.4 Precipitation, potential evapotranspiration and actual evapotranspiration data of Mountain top height, Freetown (2016)

Mountain top height	Months	P	E_p	E_A
	Jan	5.8	74.6	5.8
	Feb	6.8	86.2	6.8
	Mar	5.3	88.7	5.3
	Apr	35.3	98.3	35.3
	May	116.7	120	116.7
	Jun	299.9	290	290
	Jul	584	544.5	544.5
	Aug	593.9	470	470
	Sep	487.2	456	456
	Oct	420	317.8	317.8
	Nov	198	190.5	190.5
	Dec	10	61.36	61.36

APPENDIX D2.1 ASSUMPTIONS AND DATA REQUIREMENT FOR THE THEIS, COOPER-JACOB AND CHOW AQUIFER PARAMETERS CURVE-MATCHING ANALYSES

The Theis Recovery Solution Confined Aquifer assumes the following:

- The aquifer is confined and has an “apparent” infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is fully penetrating and pumped at a constant rate
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible.

The data requirements for the Theis Confined Aquifer Recovery Solution are:

- Recovery vs. time data at a pumping or observation well
- Distance from the pumping well to the observation well
- Pumping rate and duration

Assumptions for Theis Solution for Unconfined Aquifers

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- control well is fully or partially penetrating
- flow to control well is horizontal when control well is fully penetrating
- aquifer is unconfined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of a pumping well is very small so that storage in the well can be neglected
- no delayed gravity response in aquifer
- low velocity is proportional to tangent of the hydraulic gradient instead of the sine (which is actually the case)
- flow is horizontal and uniform in a vertical section through the axis of the well

- drawdown is small relative to saturated thickness of aquifer

The data requirements for the Theis Unconfined Aquifers Solution are:

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- saturated thickness
- partial penetration depths (optional)
- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

The Cooper-Jacob Confined Solution assumes the following:

- The aquifer is confined and has an “apparent” infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is pumped at a constant rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible
- The values of u are small (rule of thumb $u < 0.01$)
- diameter of a pumping well is very small so that storage in the well can be neglected
- values of uu are small (i.e., rr is small and tt is large)

The data requirements for the Cooper-Jacob Confined Aquifer Time-Drawdown Solution method are:

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Assumptions for Cooper-Jacob Solution for Unconfined Aquifers

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- control well is fully or partially penetrating
- flow to control well is horizontal when control well is fully penetrating
- aquifer is unconfined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of a pumping well is very small so that storage in the well can be neglected
- no delayed gravity response in aquifer
- low velocity is proportional to tangent of the hydraulic gradient instead of the sine (which is actually the case)
- flow is horizontal and uniform in a vertical section through the axis of the well
- drawdown is small relative to saturated thickness of aquifer

The data requirements for the Cooper-Jacob Unconfined Aquifer Time-Drawdown Solution method are:

- Drawdown vs. time data at an observation well
- Finite distance from the pumping well to the observation well
- Pumping rate (constant)

D2.2 CALCULATED VALUES OF THE HYDRAULIC PARAMETERS FROM PUMPING TEST DATA

Well_ID	**Easting**	**Northing**	**Hydraulic Conductivity (m/s)**	**Transmissivity (m^2/s)**	**Specific Capacity (m^3/s/m)**	**Storativity**
BH001	698663	937060	4.56 x 10^{-5}	4.51 x 10^{-5}	1.54 x 10^{-4}	9.08 x10^{-5}
BH002	702275	931468	4.84 x10^{-5}	4.23 x 10^{-4}	8.95 x 10^{-5}	6.27 x10^{-5}
BH003	700620	935723	8.0 x 10^{-5}	2.34 x 10^{-5}	5.48 x 10^{-5}	4.27 x10^{-5}
BH005	696893	937651	1.15 x10^{-4}	6.11 x 10^{-5}	6.33 x 10^{-5}	5.10 x10^{-5}
BH006	696895	937643	1.15 x 10^{-4}	2.71 x 10^{-5}	9.79 x 10^{-5}	5.80 x10^{-4}
BH007	698188	937091	1.38 x10^{-4}	1.79 x 10^{-4}	3.15 x 10^{-4}	4.95 x10^{-5}
BH009	698274	937147	1.76 x 10^{-4}	1.61 x 10^{-4}	8.85 x 10^{-5}	3.49 x10^{-5}
BH004	696970	938854	1.83 x10^{-4}	2.67 x 10^{-4}	5.49 x 10^{-4}	1.68 x10^{-5}
BH014	698621	936939	2.10 x 10^{-4}	1.91 x 10^{-5}	8.77 x 10^{-5}	5.61 x10^{-5}
BH015	699070	935974	5.82 x10^{-3}	6.29 x 10^{-4}	2.64 x 10^{-4}	5.95 x10^{-5}
BH016	699584	937012	2.41 x 10^{-4}	1.86 x 10^{-5}	9.38 x 10^{-5}	1.19 x10^{-4}
BH018	700801	936248	4.29 x10^{-3}	3.92 x 10^{-4}	5.79 x 10^{-4}	1.99 x10^{-5}
BH019	701023	935947	2.51 x 10^{-4}	2.28 x 10^{-5}	5.16 x 10^{-5}	6.85 x10^{-5}
BH020	699767	935920	2.74 x10^{-4}	1.61 x 10^{-4}	2.17 x 10^{-5}	5.70 x10^{-5}
BH021	701876	933117	5.31 x 10^{-3}	8.25 x 10^{-4}	2.06 x 10^{-5}	4.68x10^{-5}
BH022	701414	934797	2.82 x10^{-4}	6.44 x 10^{-4}	3.82 x 10^{-5}	3.28 x10^{-4}
BH023	701414	933636	1.31 x 10^{-5}	5.58 x 10^{-5}	2.48 x 10^{-5}	5.23 x10^{-5}
BH024	702797	933818	5.10 x10^{-4}	9.542 x 10^{-4}	6.91 x 10^{-4}	3.06 x10^{-4}
BH025	698939	936480	5.29 x 10^{-4}	5.06 x 10^{-4}	2.68 x 10^{-5}	5.38 x10^{-5}

TABLE D2.3 AQUIFER PROPERTIES AFTER SIMULATION

Model aquifer properties	Model_Top to Upper Aquifer Bottom	Middle aquifer Weathered formation	Lower aquifer bottom Fractured aquifer	Average
Transmissivity m^2/s, [m^2/d]	1x10^{-3} [86.04]	1.14 × 10^{-4}[9.83]	2.0 × 10^{-5}[1.73]	3.02× 10^{-4}[26.17]
	6.47 × 10^{-4}[55.94]	1.75 × 10^{-4}[15.18]	3.08× 10^{-5}[2.67]	
	4.19 × 10^{-4}[36.22]	2.71 × 10^{-4}[23.45]	4.77× 10^{-5}[4.12]	
Hydraulic conductivity m/s, [m/d]		3.59 × 10^{-6}[0.311]	1 x 10^{-7}[0.008]	3.9 x 10^{-6}[0.34]
	1.0 × 10^{-5}[0.864]	5.99 × 10^{-6} [0.518]	2.78 x 10^{-6} [0.240]	
	1.29 × 10^{-6}[0.112]	4.64 × 10^{-6}[0.401]	7.42 × 10^{-6} [0.642]	
	1.66 × 10^{-6}[0.144]		2.15 x 10^{-6}[0.186]	

APPENDIX D GROUNDWATER MODELS DEVELOPMENT/INPUT AND OUTPUT MODEL DATA

TABLE D2.4 UTILITY ROLES IN THE PREPARATION OF INPUT AND OUTPUT MODEL DATA

Processing utility	Input/output data functionality
MS Excel	1. Spreadsheet program used to prepare input files and create grids. 2. Prepares database to create shapefile within GIS/QGIS 3. Prepares data to be saved in another format readable by the model e.g. csv format. 4. Supports the processing of model output data files
Surfer Grid	1. Prepares spatial geo-referenced data for input into ModelMuse MODFLOW 2. Produces contouring 3D mapping surface
MS WordPad	Basic word processor and preparation of model input data
ArcGIS 10.6	1. Supports minimal and accessible data to produce basic modelling procedures 2. Prepares spatial and geo-referenced data for import into MODFLOW 3. Extracts maps and water flow information from DEM into raster and ASCII files 4. Supports digitised maps
QGIS Desktop 3.10.1	1. Processes geospatial files for ModelMuse MODFLOW 2. Provides watershed delineation of given area
Python	Scripts MODFLOW model development with programming language
Jupyter Notebook and Anaconda	Processes and executes digital commands, draws charts and takes notes

TABLE D2.5 LIST OF MODFLOW PACKAGES USED IN THE FLOW MODEL APPENDIX D

MODFLOW Package	MODFLOW File type	Description
Named file	NAM	Activates all the capabilities of the
Global output file	GLO	Presents the information on the application of the model process
Listing output file	LST	Contains information from the Groundwater Flow Process with time steps and volumetric budget from simulation run.
Basic	BA6	Defines the overall program procedures
Layer Property flow package	LPF	It contains information from the
Discretisation	DIS	Provides spatial discretization of the watershed
Horizontal Flow Barrier	HFB6	Provides the ability to simulate layers of thin, vertical, and low-permeability geologic features within the model domain
Boundary Condition	BC	System and boundary conceptualization for groundwater flow simulation (specified head boundaries)
Time variant specified head	CHD	Simulates regional flow specified head that can change within or between stress periods
Evapotranspiration	EVT	Important data in surface water interaction and impact on recharge
Head Observation Package Hob Out	HOB	Input files used to specify observation in the runs
Well	WELL	Points representing flows to wells in the finite difference equations, enable hydrologic estimation, water level for sustainable abstraction.
River	RIV	Supports the hydrologic cycle for surface and groundwater interaction.
Recharge	RCH	Represent finite difference equations, and enables hydrological capability for the recharge process
Hydraulic conductivity	K	Property of function to transmit water and rate of flow under hydraulic gradient
Preconditioned Conjugate Gradient	PGC	Solves the system It iteratively solves the system of finite difference equations using the Pre-Conditioned Gradient solver
Output Control	IBOUND	Displays commands on head and overall budget presented in the list file.
Data	DATA	Use of observed data for current or predictive run

APPENDIX D GROUNDWATER MODELS DEVELOPMENT/INPUT AND OUTPUT MODEL DATA

Table D2.6 Observed Piezometric data (Source: EDAL and BABA Drilling Companies)

Piezometer	Easting	Northing	Surface Elevation (m)	Screen Elevation (m)	Piezometric Level (m)
OBS_1	698663	937060	104	65	78
OBS_2	702275	931468	87	70	80
OBS_3	700620	935723	89	58	74
OBS_4	696893	937651	71	59	63
OBS_5	696895	937643	65	55	68
OBS_6	698188	937091	82	65	66
OBS_7	698274	937147	65	48	52
OBS_8	696970	938854	50	27	40
OBS_9	698621	936939	78	64	70
OBS_10	699070	935974	142	78	123
OBS_11	699584	937012	126	51	58
OBS_12	700801	936248	41	36	57
OBS_13	701023	935947	126	80	114
OBS_14	699767	935920	121	74	104
OBS_15	701876	933117	140	70	117
OBS_16	701414	934797	67	43	57
OBS_17	701414	933636	87	60	79
OBS_18	702797	933818	69	46	60
OBS_19	698939	936480	103	70	87

APPENDIX D2.7 LIMITATIONS OF THE STUDY

Water Consumption Questionnaire-Based Study

- The sample has a higher percentage of middle-income households compared to the slum- and low-income households that does not reflect the general population of the study area.
- Citing and referencing previous research studies relevant to the study area are limited.
- The research was unable to assess each of the separate individual volumes (namely: Piped water and all multiple household water sources) of water used in the study area.
- These limitations would influence the overall average per capita water consumption and, therefore, be unable to determine the actual average daily per capita water provided by the Guma Valley service provider.
- Future studies should be designed to take into consideration the volume of water accessible by households from each service facility type.
- This would be necessary to increase water security and seasonal reliability.

GIS and Groundwater Quantity Numerical Modelling

Presently, the amount of groundwater available for abstraction appears to be minimal, suggesting there is a lot of potential for further development of groundwater resources.

- The most significant data limitations are in the following subjects: borehole logs and yield, streamflow, hydrogeological parameters, aquifer monitoring and groundwater quality.
- Credible historical quantitative and qualitative data would have resulted in more detailed concepts, such as the classification and comparison of lithology types, analysis of basic parameters in specific aquifer layers and groundwater quality mapping.
- Lack of sufficient understanding of the subsurface could potentially introduce uncertainty in the computed water budget.

- Although, the length of available pumping tests records (up to 72 hours) is insufficient for the assessment of the groundwater magnitude, it is thought that longer record length will provide a more representation of the historical occurrence/development and therefore improves the prediction of the method.
- The rivers within the study area were modelled on the ModelMuse MODFLOW 2005 using the river package. The river package specifies the stage of the river at the beginning of the simulation and holds it constant throughout the simulation. Using the stream flow package will allow for greater flexibility in the representation of rivers because the stream stages can be calculated in accordance with the flow rates during simulation.
- Regulations for the construction of infiltration galleries for water diversion and supply may be affected by municipal regulations. Also, the prospective developers must review private or other agencies' properties to see if the proposed development will interfere with their infrastructure (utilities, etc). Furthermore, a hydrological analysis of the water source, adjacent lands, and water bodies, possibly identifying adverse effects to the aquatic environment must be conducted to reflect in the design and construction budget. These have not been done and therefore no cost has been attached for the infiltration galleries.
- This study considers only hydraulic issues to assess the feasibility of managed aquifer recharge, but future studies should also consider water quality aspects.

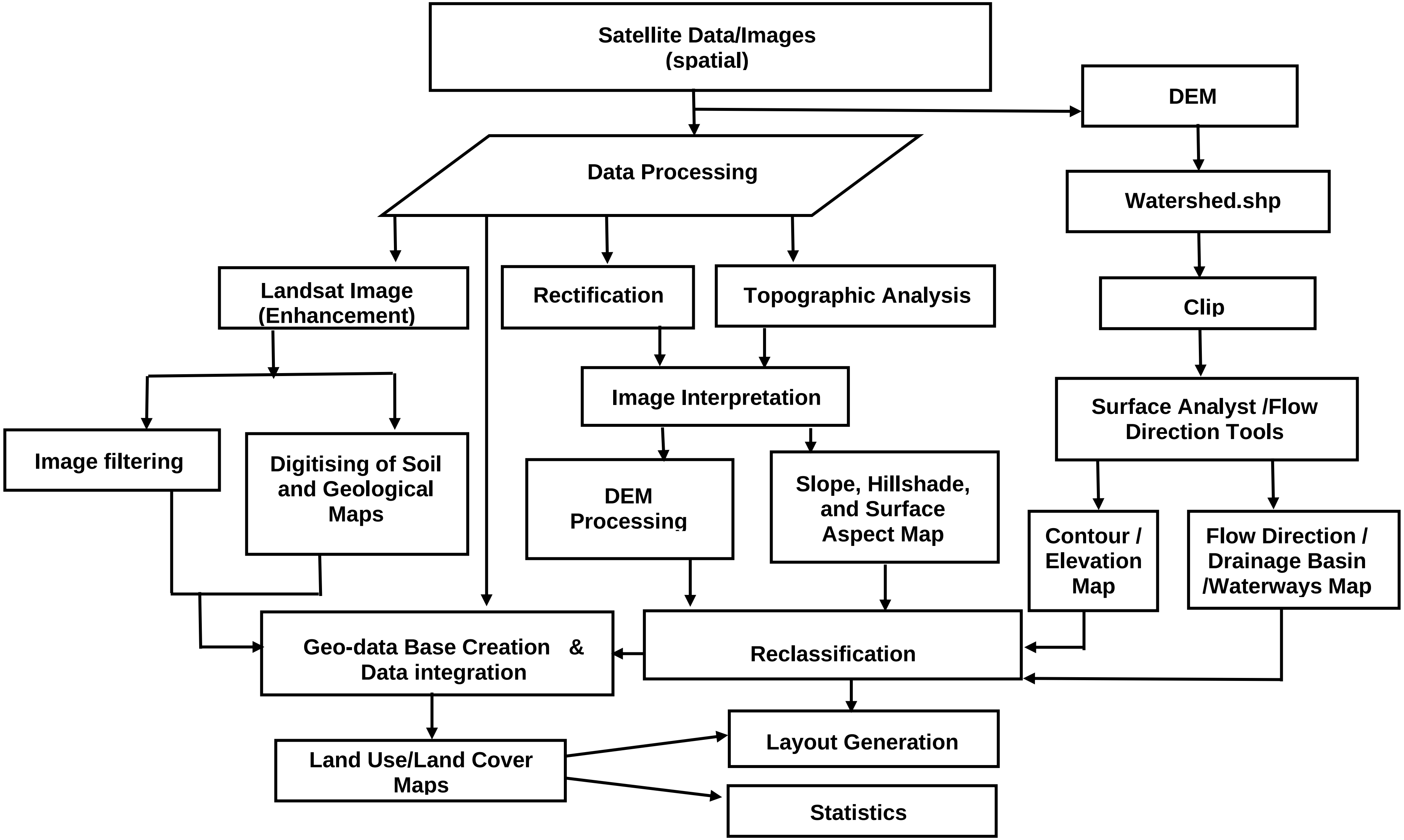
APPENDIX F GROUNDWATER MODELS APPLICATION RESULTS AND DISCUSSIONS

Table F1.1 Estimation of aquifer parameters from pumping test data

Well Location	Easting	Northing	Hydraulic Conductivity (m/d)	Transmissivity (m^2/d)	Specific Capacity (m^3/d/m)	Storativity
Adolphus St	698663	937060	3.94 x 10^{0}	3.90 x 10^{0}	1.31 x 10^{1}	9.08 x10^{-5}
Orugu	702275	931468	4.18 x10^{0}	3.65 x 10^{1}	7.73 x 10^{0}	6.27 x10^{-5}
Approved sch	700620	935723	6.89 x 10^{0}	2.02 x 10^{0}	4.73x 10^{0}	4.27 x10^{-5}
Blackhall Rd	696893	937651	9.94x10^{0}	5.28 x 10^{0}	5.47 x 10^{0}	5.10 x10^{-5}
Ashobie	696895	937643	9.94 x 10^{0}	2.37 x 10^{0}	8.46 x 10^{0}	5.80 x10^{-4}
Carsel farm 1	698188	937091	1.19 x10^{1}	1.55 x 10^{1}	2.72 x 10^{1}	4.95 x10^{-5}
Carsel farm2	698274	937147	1.52 x 10^{1}	1.39 x 10^{1}	7.65 x 10^{0}	3.49 x10^{-5}
Cline Town	696970	938854	1.58 x10^{1}	2.31 x 10^{1}	4.74 x 10^{1}	1.68 x10^{-5}
East End Mun	698621	936939	1.81 x 10^{1}	1.65 x 10^{0}	7.58 x 10^{0}	5.61 x10^{-5}
Mansaray Ln	699070	935974	5.03 x10^{2}	5.43 x 10^{1}	2.28 x 10^{1}	5.95 x10^{-5}
Lowcosy Housing	699584	937012	2.08 x 10^{1}	1.61 x 10^{0}	8.10 x 10^{0}	1.19 x10^{-4}
Portee	700801	936248	3.71 x10^{2}	3.39 x 10^{1}	5.00 x 10^{1}	1.99 x10^{-5}
Rokupa	701023	935947	2.17 x 10^{1}	1.97 x 10^{0}	4.46 x 10^{0}	6.85 x10^{-5}
Thunder Hill	699767	935920	2.37 x10^{1}	1.39 x 10^{1}	1.87 x 10^{0}	5.70 x10^{-5}
Calaba Town	701876	933117	4.59 x 10^{2}	7.13 x 10^{1}	1.78 x 10^{0}	4.68x10^{-5}
Congo water	701414	934797	2.44 x10^{1}	5.56 x 10^{1}	3.30 x 10^{1}	3.28 x10^{-4}
Industrial	701414	933636	1.09 x 10^{0}	4.82 x 10^{0}	2.14 x 10^{1}	5.23 x10^{-5}
Oldwharf	702797	933818	4.41 x10^{1}	8.24 x 10^{1}	5.97 x 10^{1}	3.06 x10^{-4}
Davies St	698939	936480	4.57 x 10^{1}	4.37 x 10^{1}	2.31 x 10^{0}	5.38 x10^{-5}

APPENDIX F GEOGRAPHIC INFORMATION SYSTEMS

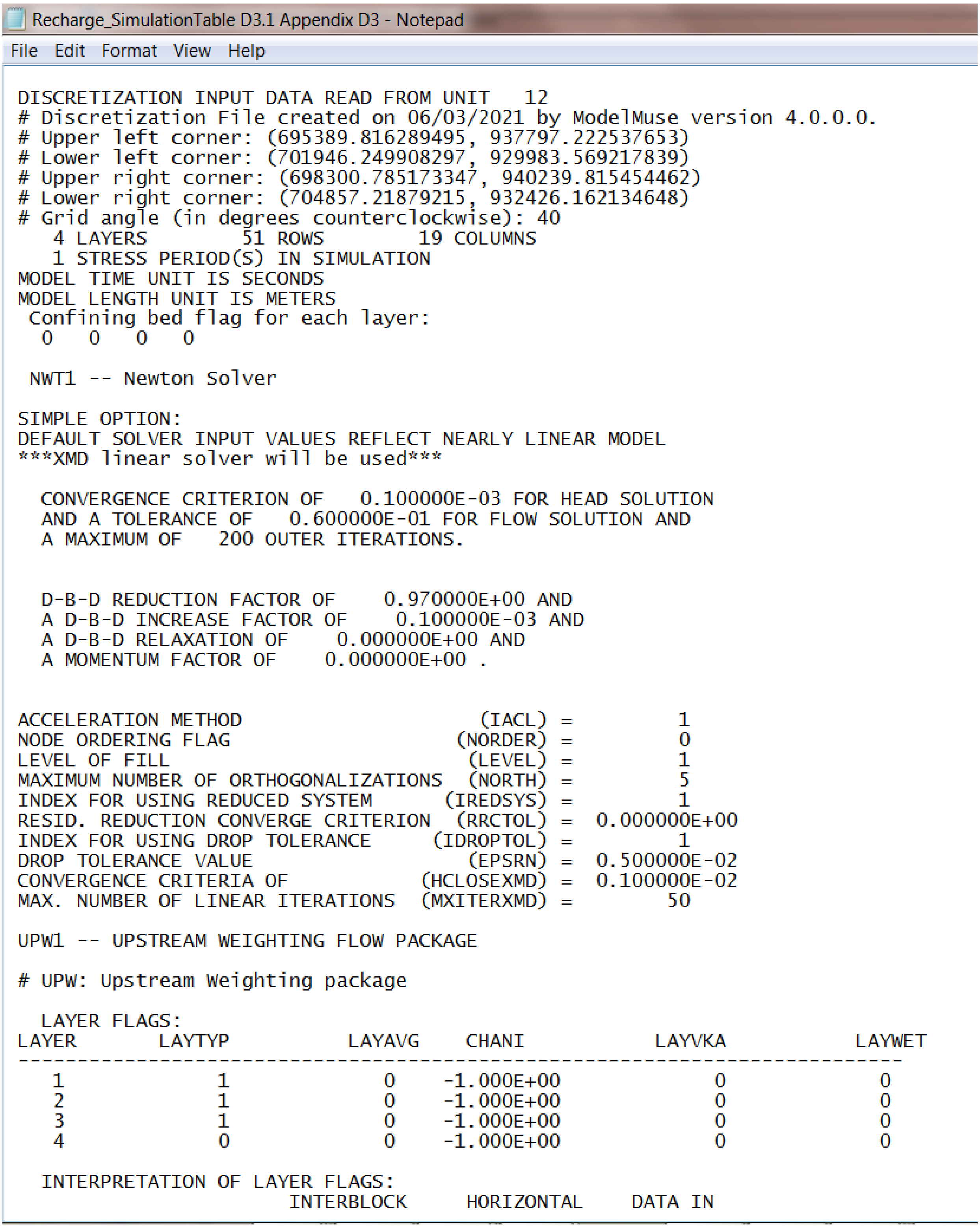
Figure F2.1 Flow Chart for Delineation of Landuse and Topographic patterns



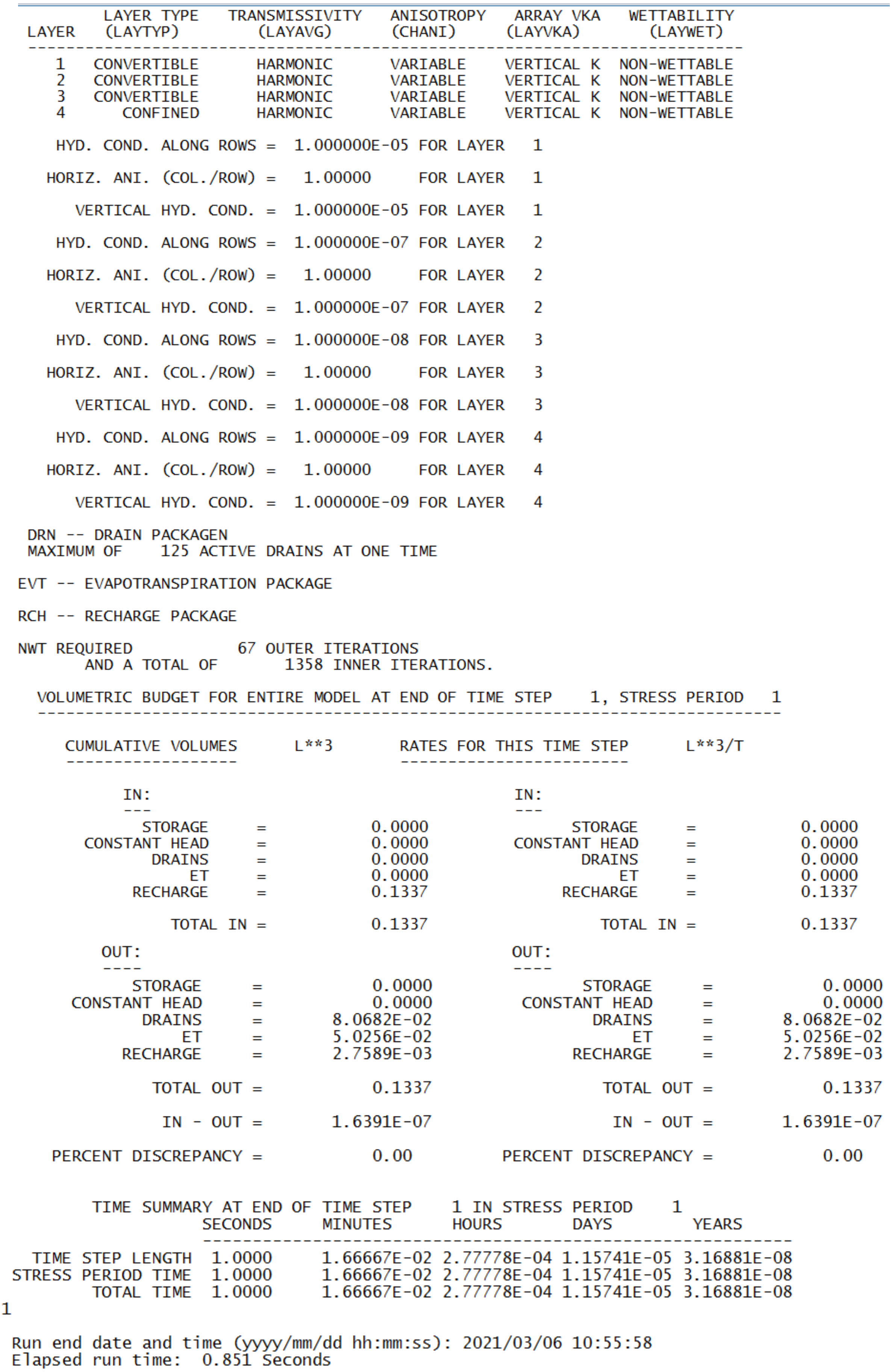
APPENDIX D3

Model Calibration for Recharge Capacity Appendix D3

Table D3.1 Appendix D3



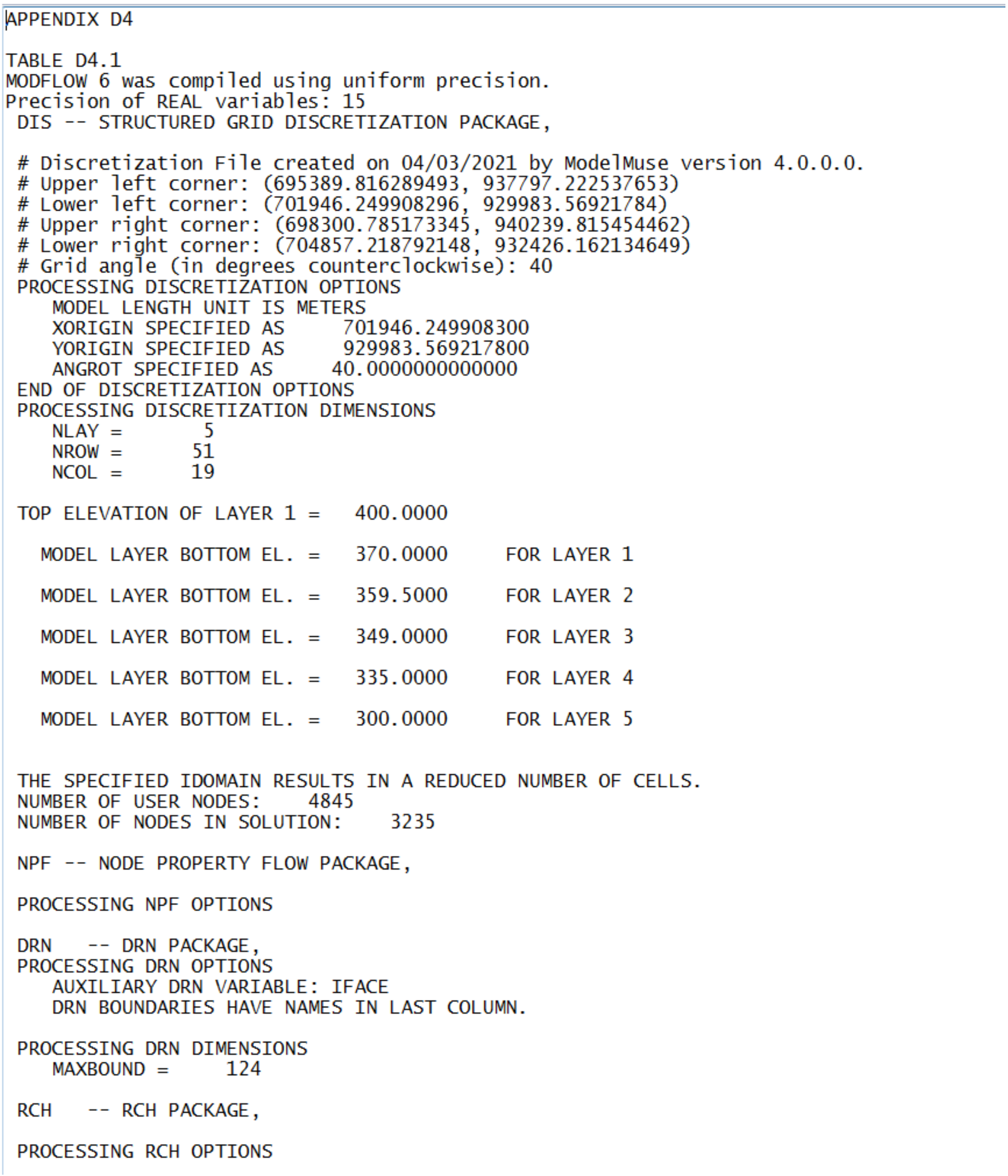
```
DISCRETIZATION INPUT DATA READ FROM UNIT   12
# Discretization File created on 06/03/2021 by ModelMuse version 4.0.0.0.
# Upper left corner: (695389.816289495, 937797.222537653)
# Lower left corner: (701946.249908297, 929983.569217839)
# Upper right corner: (698300.785173347, 940239.815454462)
# Lower right corner: (704857.21879215, 932426.162134648)
# Grid angle (in degrees counterclockwise): 40
   4 LAYERS         51 ROWS          19 COLUMNS
   1 STRESS PERIOD(S) IN SIMULATION
MODEL TIME UNIT IS SECONDS
MODEL LENGTH UNIT IS METERS
 Confining bed flag for each layer:
  0   0   0   0

 NWT1 -- Newton Solver

SIMPLE OPTION:
DEFAULT SOLVER INPUT VALUES REFLECT NEARLY LINEAR MODEL
***XMD linear solver will be used***

  CONVERGENCE CRITERION OF   0.100000E-03 FOR HEAD SOLUTION
  AND A TOLERANCE OF   0.600000E-01 FOR FLOW SOLUTION AND
  A MAXIMUM OF   200 OUTER ITERATIONS.


  D-B-D REDUCTION FACTOR OF    0.970000E+00 AND
  A D-B-D INCREASE FACTOR OF    0.100000E-03 AND
  A D-B-D RELAXATION OF    0.000000E+00 AND
  A MOMENTUM FACTOR OF    0.000000E+00 .


ACCELERATION METHOD                    (IACL) =          1
NODE ORDERING FLAG                   (NORDER) =          0
LEVEL OF FILL                         (LEVEL) =          1
MAXIMUM NUMBER OF ORTHOGONALIZATIONS  (NORTH) =          5
INDEX FOR USING REDUCED SYSTEM      (IREDSYS) =          1
RESID. REDUCTION CONVERGE CRITERION  (RRCTOL) =  0.000000E+00
INDEX FOR USING DROP TOLERANCE     (IDROPTOL) =          1
DROP TOLERANCE VALUE                  (EPSRN) =  0.500000E-02
CONVERGENCE CRITERIA OF           (HCLOSEXMD) =  0.100000E-02
MAX. NUMBER OF LINEAR ITERATIONS  (MXITERXMD) =         50

UPW1 -- UPSTREAM WEIGHTING FLOW PACKAGE

# UPW: Upstream Weighting package

  LAYER FLAGS:
LAYER       LAYTYP          LAYAVG    CHANI           LAYVKA           LAYWET
---------------------------------------------------------------------------
   1             1             0    -1.000E+00             0             0
   2             1             0    -1.000E+00             0             0
   3             1             0    -1.000E+00             0             0
   4             0             0    -1.000E+00             0             0

  INTERPRETATION OF LAYER FLAGS:
                       INTERBLOCK     HORIZONTAL    DATA IN
```



```
LAYER    LAYER TYPE    TRANSMISSIVITY    ANISOTROPY    ARRAY VKA    WETTABILITY
          (LAYTYP)        (LAYAVG)         (CHANI)      (LAYVKA)      (LAYWET)
---------------------------------------------------------------------------
   1    CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K  NON-WETTABLE
   2    CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K  NON-WETTABLE
   3    CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K  NON-WETTABLE
   4       CONFINED      HARMONIC      VARIABLE     VERTICAL K  NON-WETTABLE

    HYD. COND. ALONG ROWS =  1.000000E-05 FOR LAYER   1

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   1

      VERTICAL HYD. COND. =  1.000000E-05 FOR LAYER   1

    HYD. COND. ALONG ROWS =  1.000000E-07 FOR LAYER   2

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   2

      VERTICAL HYD. COND. =  1.000000E-07 FOR LAYER   2

    HYD. COND. ALONG ROWS =  1.000000E-08 FOR LAYER   3

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   3

      VERTICAL HYD. COND. =  1.000000E-08 FOR LAYER   3

    HYD. COND. ALONG ROWS =  1.000000E-09 FOR LAYER   4

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   4

      VERTICAL HYD. COND. =  1.000000E-09 FOR LAYER   4

 DRN -- DRAIN PACKAGEN
 MAXIMUM OF    125 ACTIVE DRAINS AT ONE TIME

EVT -- EVAPOTRANSPIRATION PACKAGE

RCH -- RECHARGE PACKAGE

NWT REQUIRED             67 OUTER ITERATIONS
       AND A TOTAL OF        1358 INNER ITERATIONS.

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
              DRAINS =           0.0000                DRAINS =           0.0000
                  ET =           0.0000                    ET =           0.0000
            RECHARGE =           0.1337              RECHARGE =           0.1337

            TOTAL IN =           0.1337              TOTAL IN =           0.1337

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
              DRAINS =       8.0682E-02                DRAINS =       8.0682E-02
                  ET =       5.0256E-02                    ET =       5.0256E-02
            RECHARGE =       2.7589E-03              RECHARGE =       2.7589E-03

           TOTAL OUT =           0.1337             TOTAL OUT =           0.1337

            IN - OUT =       1.6391E-07              IN - OUT =       1.6391E-07

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00

         TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
 STRESS PERIOD TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
         TOTAL TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
1

 Run end date and time (yyyy/mm/dd hh:mm:ss): 2021/03/06 10:55:58
 Elapsed run time:  0.851 Seconds
```

Model Calibration for Observed and Simulated Heads Appendix D4

Table D4.1 Appendix D4



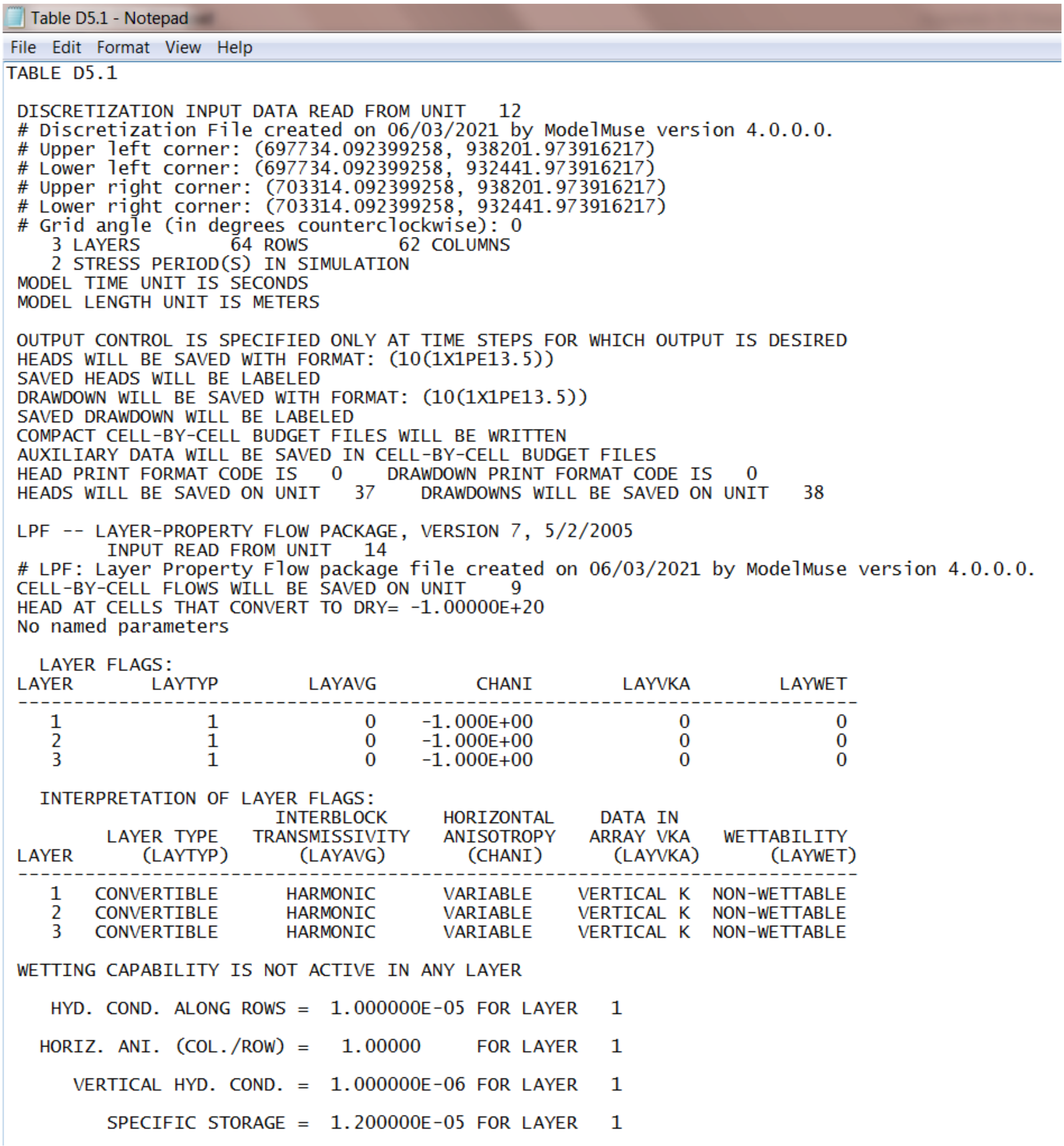
```
APPENDIX D4

TABLE D4.1
MODFLOW 6 was compiled using uniform precision.
Precision of REAL variables: 15
 DIS -- STRUCTURED GRID DISCRETIZATION PACKAGE,

 # Discretization File created on 04/03/2021 by ModelMuse version 4.0.0.0.
 # Upper left corner: (695389.816289493, 937797.222537653)
 # Lower left corner: (701946.249908296, 929983.56921784)
 # Upper right corner: (698300.785173345, 940239.815454462)
 # Lower right corner: (704857.218792148, 932426.162134649)
 # Grid angle (in degrees counterclockwise): 40
 PROCESSING DISCRETIZATION OPTIONS
    MODEL LENGTH UNIT IS METERS
    XORIGIN SPECIFIED AS     701946.249908300
    YORIGIN SPECIFIED AS     929983.569217800
    ANGROT SPECIFIED AS     40.0000000000000
 END OF DISCRETIZATION OPTIONS
 PROCESSING DISCRETIZATION DIMENSIONS
    NLAY =       5
    NROW =      51
    NCOL =      19

 TOP ELEVATION OF LAYER 1 =   400.0000

   MODEL LAYER BOTTOM EL. =   370.0000     FOR LAYER 1

   MODEL LAYER BOTTOM EL. =   359.5000     FOR LAYER 2

   MODEL LAYER BOTTOM EL. =   349.0000     FOR LAYER 3

   MODEL LAYER BOTTOM EL. =   335.0000     FOR LAYER 4

   MODEL LAYER BOTTOM EL. =   300.0000     FOR LAYER 5


 THE SPECIFIED IDOMAIN RESULTS IN A REDUCED NUMBER OF CELLS.
 NUMBER OF USER NODES:    4845
 NUMBER OF NODES IN SOLUTION:    3235

 NPF -- NODE PROPERTY FLOW PACKAGE,

 PROCESSING NPF OPTIONS

 DRN   -- DRN PACKAGE,
 PROCESSING DRN OPTIONS
    AUXILIARY DRN VARIABLE: IFACE
    DRN BOUNDARIES HAVE NAMES IN LAST COLUMN.

 PROCESSING DRN DIMENSIONS
    MAXBOUND =     124

 RCH   -- RCH PACKAGE,

 PROCESSING RCH OPTIONS
```

```
PROCESSING RCH DIMENSIONS
   MAXBOUND =      647
END OF RCH DIMENSIONS

EVT   -- EVT PACKAGE,

PROCESSING EVT OPTIONS

PROCESSING EVT DIMENSIONS
   MAXBOUND =      647
   NSEG = 1
END OF EVT DIMENSIONS

IC -- INITIAL CONDITIONS PACKAGE,

PROCESSING IC OPTIONS
END OF IC OPTIONS
PROCESSING GRIDDATA

    INITIAL HEAD =   400.0000     FOR LAYER 1

    INITIAL HEAD =   400.0000     FOR LAYER 2

    INITIAL HEAD =   400.0000     FOR LAYER 3

    INITIAL HEAD =   400.0000     FOR LAYER 4

    INITIAL HEAD =   400.0000     FOR LAYER 5
END PROCESSING GRIDDATA
PROCESSING GRIDDATA

               ICELLTYPE = 1 FOR LAYER 1

               ICELLTYPE = 1 FOR LAYER 2

               ICELLTYPE = 1 FOR LAYER 3

               ICELLTYPE = 1 FOR LAYER 4

               ICELLTYPE = 1 FOR LAYER 5

                       K =  0.4000000E-03 FOR LAYER 1

                       K =  0.5000000E-05 FOR LAYER 2

                       K =  0.1000000E-05 FOR LAYER 3

                       K =  0.9000000E-06 FOR LAYER 4

                       K =  0.5000000E-06 FOR LAYER 5

                     K33 =  0.4000000E-04 FOR LAYER 1

                     K33 =  0.5000000E-06 FOR LAYER 2

                     K33 =  0.1000000E-06 FOR LAYER 3
```

```
                     K33 =  0.9000000E-07 FOR LAYER 4

                     K33 =  0.5000000E-07 FOR LAYER 5

                     K22 =  0.4000000E-03 FOR LAYER 1

                     K22 =  0.5000000E-05 FOR LAYER 2

                     K22 =  0.1000000E-05 FOR LAYER 3

                     K22 =  0.9000000E-06 FOR LAYER 4

                     K22 =  0.5000000E-06 FOR LAYER 5


 VOLUME BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD    1
 --------------------------------------------------------------------------------------------------

    CUMULATIVE VOLUME      L**3       RATES FOR THIS TIME STEP      L**3/T          PACKAGE NAME
    ------------------                 ------------------------                     ----------------

          IN:                                      IN:
          ---                                      ---
                DRN =           0.0000                   DRN =           0.0000     DRN-1
                RCH =           0.9272                   RCH =           0.9272     RCH-1
                EVT =           0.0000                   EVT =           0.0000     EVT-1

           TOTAL IN =           0.9272              TOTAL IN =           0.9272

         OUT:                                     OUT:
         ----                                     ----
                DRN =           0.0000                   DRN =           0.7889     DRN-1
                RCH =           0.0000                   RCH =           0.0000     RCH-1
                EVT =           0.1395                   EVT =           0.1383     EVT-1

          TOTAL OUT =           0.9272             TOTAL OUT =           0.9272

           IN - OUT =       2.4733E-05              IN - OUT =       2.4733E-05

PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00


        TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                   SECONDS     MINUTES      HOURS       DAYS        YEARS
                   ----------------------------------------------------------
  TIME STEP LENGTH  1.0000      1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
STRESS PERIOD TIME  1.0000      1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
        TOTAL TIME  1.0000      1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
```

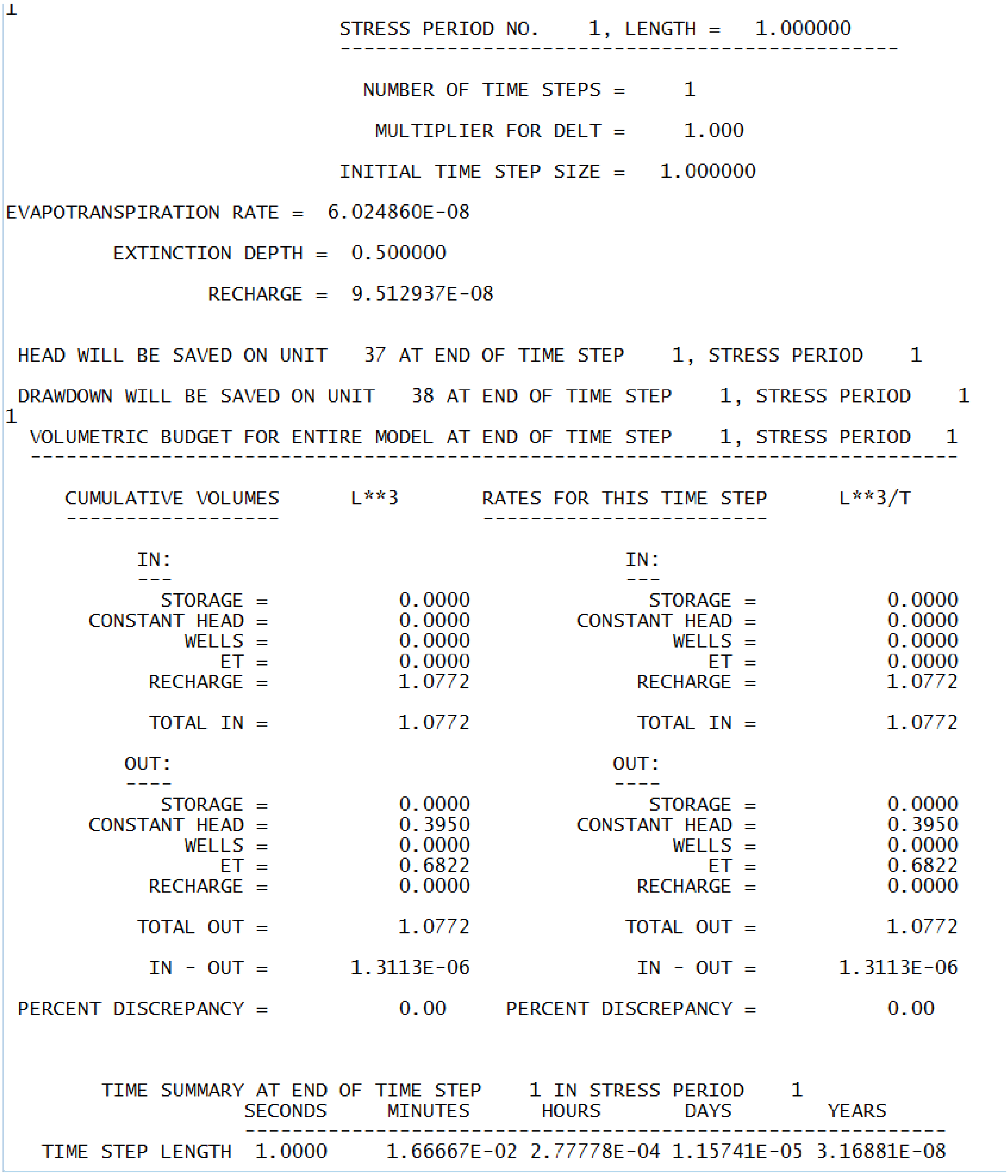
Model Calibration for Wells Interference Patterns Appendix D5

Table D5.1 Appendix D5

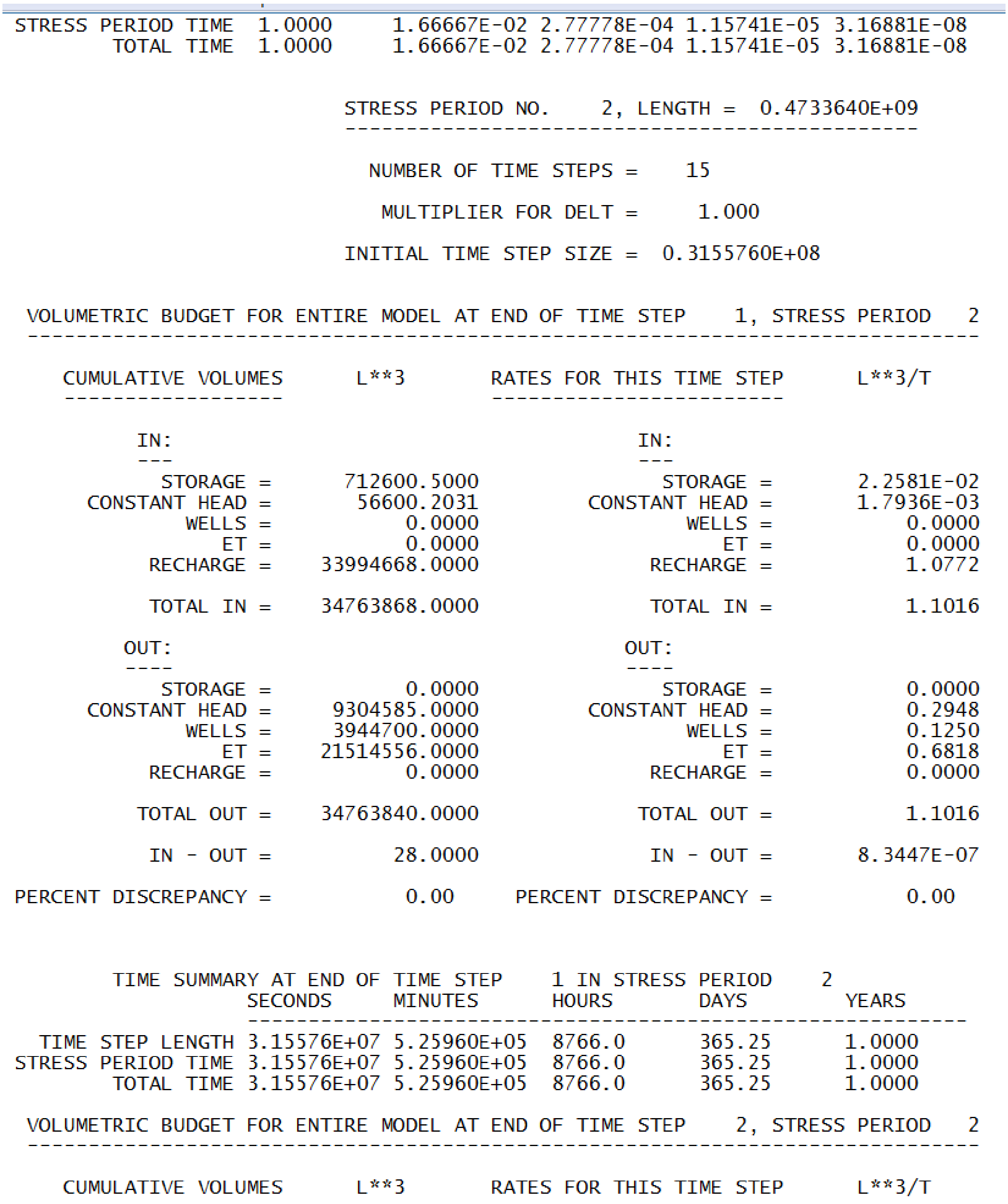


```
TABLE D5.1

 DISCRETIZATION INPUT DATA READ FROM UNIT   12
 # Discretization File created on 06/03/2021 by ModelMuse version 4.0.0.0.
 # Upper left corner: (697734.092399258, 938201.973916217)
 # Lower left corner: (697734.092399258, 932441.973916217)
 # Upper right corner: (703314.092399258, 938201.973916217)
 # Lower right corner: (703314.092399258, 932441.973916217)
 # Grid angle (in degrees counterclockwise): 0
    3 LAYERS        64 ROWS        62 COLUMNS
    2 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS SECONDS
 MODEL LENGTH UNIT IS METERS

 OUTPUT CONTROL IS SPECIFIED ONLY AT TIME STEPS FOR WHICH OUTPUT IS DESIRED
 HEADS WILL BE SAVED WITH FORMAT: (10(1X1PE13.5))
 SAVED HEADS WILL BE LABELED
 DRAWDOWN WILL BE SAVED WITH FORMAT: (10(1X1PE13.5))
 SAVED DRAWDOWN WILL BE LABELED
 COMPACT CELL-BY-CELL BUDGET FILES WILL BE WRITTEN
 AUXILIARY DATA WILL BE SAVED IN CELL-BY-CELL BUDGET FILES
 HEAD PRINT FORMAT CODE IS   0    DRAWDOWN PRINT FORMAT CODE IS   0
 HEADS WILL BE SAVED ON UNIT   37    DRAWDOWNS WILL BE SAVED ON UNIT   38

 LPF -- LAYER-PROPERTY FLOW PACKAGE, VERSION 7, 5/2/2005
         INPUT READ FROM UNIT   14
 # LPF: Layer Property Flow package file created on 06/03/2021 by ModelMuse version 4.0.0.0.
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT    9
 HEAD AT CELLS THAT CONVERT TO DRY= -1.00000E+20
 No named parameters

   LAYER FLAGS:
 LAYER       LAYTYP        LAYAVG         CHANI        LAYVKA        LAYWET
 ----------------------------------------------------------------------------
    1             1             0    -1.000E+00             0             0
    2             1             0    -1.000E+00             0             0
    3             1             0    -1.000E+00             0             0

   INTERPRETATION OF LAYER FLAGS:
                        INTERBLOCK     HORIZONTAL    DATA IN
         LAYER TYPE   TRANSMISSIVITY   ANISOTROPY   ARRAY VKA   WETTABILITY
 LAYER      (LAYTYP)      (LAYAVG)       (CHANI)      (LAYVKA)      (LAYWET)
 ----------------------------------------------------------------------------
    1   CONVERTIBLE      HARMONIC      VARIABLE    VERTICAL K  NON-WETTABLE
    2   CONVERTIBLE      HARMONIC      VARIABLE    VERTICAL K  NON-WETTABLE
    3   CONVERTIBLE      HARMONIC      VARIABLE    VERTICAL K  NON-WETTABLE

 WETTING CAPABILITY IS NOT ACTIVE IN ANY LAYER

    HYD. COND. ALONG ROWS =  1.000000E-05 FOR LAYER   1

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   1

      VERTICAL HYD. COND. =  1.000000E-06 FOR LAYER   1

         SPECIFIC STORAGE =  1.200000E-05 FOR LAYER   1
```

```
           SPECIFIC YIELD =   0.120000     FOR LAYER   3

 WEL -- WELL PACKAGE
 # WEL: Well package
  MAXIMUM OF      13 ACTIVE WELLS AT ONE TIME
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT    9
 AUXILIARY WELL VARIABLE: IFACE

     0 Well parameters

 EVT -- EVAPOTRANSPIRATION PACKAGE
 # EVT: Evapotranspiration package
 OPTION 1 -- EVAPOTRANSPIRATION FROM TOP LAYER
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT    9


     0 Evapotranspiration parameters

 RCH -- RECHARGE PACKAGE
 # RCH: Recharge package
 OPTION 3 -- RECHARGE TO HIGHEST ACTIVE NODE IN EACH VERTICAL COLUMN
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT    9


     0 Recharge parameters

 CHD -- TIME-VARIANT SPECIFIED-HEAD OPTION
 # CHD: Time-Variant Specified-Head package
 MAXIMUM OF    744 TIME-VARIANT SPECIFIED-HEAD CELLS AT ONE TIME
 AUXILIARY CHD VARIABLE: IFACE


     0 TIME-VARIANT SPECIFIED-HEAD PARAMETERS

 PCG -- CONJUGATE-GRADIENT SOLUTION PACKAGE
 # PCG: Preconditioned Conjugate Gradient package
 MAXIMUM OF     20 CALLS OF SOLUTION ROUTINE
 MAXIMUM OF     30 INTERNAL ITERATIONS PER CALL TO SOLUTION ROUTINE
 MATRIX PRECONDITIONING TYPE :    1



                                    SOLUTION BY THE CONJUGATE-GRADIENT METHOD
                                   ------------------------------------------
                       MAXIMUM NUMBER OF CALLS TO PCG ROUTINE =       20
                           MAXIMUM ITERATIONS PER CALL TO PCG =       30
                                  MATRIX PRECONDITIONING TYPE =        1
         RELAXATION FACTOR (ONLY USED WITH PRECOND. TYPE 1) =    0.10000E+01
 PARAMETER OF POLYNOMIAL PRECOND. = 2 (2) OR IS CALCULATED :        1
                             HEAD CHANGE CRITERION FOR CLOSURE =    0.10000E-02
                         RESIDUAL CHANGE CRITERION FOR CLOSURE =    0.10000E-02
               PCG HEAD AND RESIDUAL CHANGE PRINTOUT INTERVAL =        1
     PRINTING FROM SOLVER IS LIMITED(1) OR SUPPRESSED (>1) =        0
                                STEADY-STATE DAMPING PARAMETER =    0.10000E+01
                                   TRANSIENT DAMPING PARAMETER =    0.10000E+01
1
```



```
1
                              STRESS PERIOD NO.    1, LENGTH =   1.000000
                              -----------------------------------------------

                                NUMBER OF TIME STEPS =     1

                                 MULTIPLIER FOR DELT =     1.000

                              INITIAL TIME STEP SIZE =   1.000000

EVAPOTRANSPIRATION RATE =  6.024860E-08

         EXTINCTION DEPTH =  0.500000

                 RECHARGE =  9.512937E-08

 HEAD WILL BE SAVED ON UNIT   37 AT END OF TIME STEP    1, STRESS PERIOD    1

 DRAWDOWN WILL BE SAVED ON UNIT   38 AT END OF TIME STEP    1, STRESS PERIOD    1
1
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
               WELLS =           0.0000                 WELLS =           0.0000
                  ET =           0.0000                    ET =           0.0000
            RECHARGE =           1.0772              RECHARGE =           1.0772

            TOTAL IN =           1.0772              TOTAL IN =           1.0772

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.3950         CONSTANT HEAD =           0.3950
               WELLS =           0.0000                 WELLS =           0.0000
                  ET =           0.6822                    ET =           0.6822
            RECHARGE =           0.0000              RECHARGE =           0.0000

           TOTAL OUT =           1.0772             TOTAL OUT =           1.0772

            IN - OUT =       1.3113E-06              IN - OUT =       1.3113E-06

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00


        TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
```



```
 STRESS PERIOD TIME  1.0000      1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
         TOTAL TIME  1.0000      1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08

                           STRESS PERIOD NO.    2, LENGTH =  0.4733640E+09
                           -----------------------------------------------

                             NUMBER OF TIME STEPS =    15

                              MULTIPLIER FOR DELT =     1.000

                           INITIAL TIME STEP SIZE =  0.3155760E+08

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD    2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      712600.5000               STORAGE =      2.2581E-02
       CONSTANT HEAD =       56600.2031         CONSTANT HEAD =      1.7936E-03
               WELLS =          0.0000                  WELLS =          0.0000
                  ET =          0.0000                     ET =          0.0000
            RECHARGE =    33994668.0000              RECHARGE =          1.0772

            TOTAL IN =    34763868.0000              TOTAL IN =          1.1016

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =          0.0000                STORAGE =          0.0000
       CONSTANT HEAD =     9304585.0000         CONSTANT HEAD =          0.2948
               WELLS =     3944700.0000                 WELLS =          0.1250
                  ET =    21514556.0000                    ET =          0.6818
            RECHARGE =          0.0000               RECHARGE =          0.0000

           TOTAL OUT =    34763840.0000             TOTAL OUT =          1.1016

            IN - OUT =          28.0000              IN - OUT =      8.3447E-07

 PERCENT DISCREPANCY =          0.00     PERCENT DISCREPANCY =          0.00


         TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
         TOTAL TIME 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    2, STRESS PERIOD    2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
```

```
             IN:                                          IN:
             ---                                          ---
               STORAGE =      853579.2500                   STORAGE =      4.4673E-03
         CONSTANT HEAD =      154592.8906             CONSTANT HEAD =      3.1052E-03
                 WELLS =           0.0000                     WELLS =          0.0000
                    ET =           0.0000                        ET =          0.0000
              RECHARGE =    67989336.0000                  RECHARGE =          1.0772

              TOTAL IN =    68997512.0000                  TOTAL IN =          1.0848

            OUT:                                         OUT:
            ----                                         ----
               STORAGE =           0.0000                   STORAGE =          0.0000
         CONSTANT HEAD =    18140588.0000             CONSTANT HEAD =          0.2800
                 WELLS =     7889400.0000                     WELLS =          0.1250
                    ET =    42967508.0000                        ET =          0.6798
              RECHARGE =           0.0000                  RECHARGE =          0.0000

             TOTAL OUT =    68997496.0000                 TOTAL OUT =          1.0848

              IN - OUT =          16.0000                  IN - OUT =     -4.7684E-07

   PERCENT DISCREPANCY =             0.00       PERCENT DISCREPANCY =           -0.00




          TIME SUMMARY AT END OF TIME STEP    2 IN STRESS PERIOD    2
                     SECONDS     MINUTES      HOURS       DAYS        YEARS
                     -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 6.31152E+07 1.05192E+06  17532.      730.50      2.0000
         TOTAL TIME 6.31152E+07 1.05192E+06  17532.      730.50      2.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    3, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

             IN:                                          IN:
             ---                                          ---
               STORAGE =      889292.6250                   STORAGE =      1.1317E-03
         CONSTANT HEAD =      261515.3750             CONSTANT HEAD =      3.3882E-03
                 WELLS =           0.0000                     WELLS =          0.0000
                    ET =           0.0000                        ET =          0.0000
              RECHARGE =   101984000.0000                  RECHARGE =          1.0772

              TOTAL IN =   103134808.0000                  TOTAL IN =          1.0817

            OUT:                                         OUT:
            ----                                         ----
               STORAGE =           0.0000                   STORAGE =          0.0000
         CONSTANT HEAD =    26880248.0000             CONSTANT HEAD =          0.2769
                 WELLS =    11834100.0000                     WELLS =          0.1250
                    ET =    64420460.0000                        ET =          0.6798
              RECHARGE =           0.0000                  RECHARGE =          0.0000

             TOTAL OUT =   103134808.0000                 TOTAL OUT =          1.0817

              IN - OUT =           0.0000                  IN - OUT =     -2.3842E-07

   PERCENT DISCREPANCY =             0.00       PERCENT DISCREPANCY =           -0.00




          TIME SUMMARY AT END OF TIME STEP    3 IN STRESS PERIOD    2
                     SECONDS     MINUTES      HOURS       DAYS        YEARS
                     -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 9.46728E+07 1.57788E+06  26298.      1095.8      3.0000
         TOTAL TIME 9.46728E+07 1.57788E+06  26298.      1095.8      3.0000
STEP    4, STRESS PERIOD    2
```

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    4, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP       L**3/T
     ------------------                 ------------------------

           IN:                                       IN:
           ---                                       ---
             STORAGE =       897700.3750               STORAGE =        2.6643E-04
       CONSTANT HEAD =       370416.1250         CONSTANT HEAD =        3.4509E-03
               WELLS =            0.0000                 WELLS =            0.0000
                  ET =            0.0000                    ET =            0.0000
            RECHARGE =    135978672.0000              RECHARGE =            1.0772

            TOTAL IN =    137246784.0000              TOTAL IN =            1.0809

          OUT:                                      OUT:
          ----                                      ----
             STORAGE =            0.0000               STORAGE =            0.0000
       CONSTANT HEAD =     35598828.0000         CONSTANT HEAD =            0.2763
               WELLS =     15778800.0000                 WELLS =            0.1250
                  ET =     85869136.0000                    ET =            0.6797
            RECHARGE =            0.0000              RECHARGE =            0.0000

           TOTAL OUT =    137246768.0000             TOTAL OUT =            1.0809

            IN - OUT =           16.0000              IN - OUT =        4.7684E-07

 PERCENT DISCREPANCY =              0.00     PERCENT DISCREPANCY =              0.00




         TIME SUMMARY AT END OF TIME STEP    4 IN STRESS PERIOD     2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 1.26230E+08 2.10384E+06  35064.      1461.0      4.0000
         TOTAL TIME 1.26230E+08 2.10384E+06  35064.      1461.0      4.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    5, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP       L**3/T
     ------------------                 ------------------------

           IN:                                       IN:
           ---                                       ---
             STORAGE =       899393.1875               STORAGE =        5.3642E-05
       CONSTANT HEAD =       479729.3125         CONSTANT HEAD =        3.4639E-03
               WELLS =            0.0000                 WELLS =            0.0000
                  ET =            0.0000                    ET =            0.0000
            RECHARGE =    169973344.0000              RECHARGE =            1.0772

            TOTAL IN =    171352464.0000              TOTAL IN =            1.0807


          OUT:                                      OUT:
          ----                                      ----
             STORAGE =            0.0000               STORAGE =            0.0000
       CONSTANT HEAD =     44313224.0000         CONSTANT HEAD =            0.2761
               WELLS =     19723500.0000                 WELLS =            0.1250
                  ET =    107315760.0000                    ET =            0.6796
            RECHARGE =            0.0000              RECHARGE =            0.0000

           TOTAL OUT =    171352480.0000             TOTAL OUT =            1.0807

            IN - OUT =          -16.0000              IN - OUT =       -1.4305E-06

 PERCENT DISCREPANCY =             -0.00     PERCENT DISCREPANCY =             -0.00
```

```
           TIME SUMMARY AT END OF TIME STEP    5 IN STRESS PERIOD    2
                       SECONDS     MINUTES      HOURS       DAYS        YEARS
                       -----------------------------------------------------------
     TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
   STRESS PERIOD TIME 1.57788E+08 2.62980E+06  43830.      1826.2      5.0000
           TOTAL TIME 1.57788E+08 2.62980E+06  43830.      1826.2      5.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    6, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899719.1875               STORAGE =      1.0330E-05
       CONSTANT HEAD =      589115.1875         CONSTANT HEAD =      3.4662E-03
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
            RECHARGE =   203968016.0000              RECHARGE =          1.0772

            TOTAL IN =   205456848.0000              TOTAL IN =          1.0807

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.0000               STORAGE =          0.0000
       CONSTANT HEAD =    53026724.0000         CONSTANT HEAD =          0.2761
               WELLS =    23668200.0000                 WELLS =          0.1250
                  ET =   128761928.0000                    ET =          0.6796
            RECHARGE =           0.0000              RECHARGE =          0.0000

           TOTAL OUT =   205456864.0000             TOTAL OUT =          1.0807

            IN - OUT =         -16.0000              IN - OUT =      2.3842E-07

 PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          0.00



           TIME SUMMARY AT END OF TIME STEP    6 IN STRESS PERIOD    2
                       SECONDS     MINUTES      HOURS       DAYS        YEARS
                       -----------------------------------------------------------
     TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
   STRESS PERIOD TIME 1.89346E+08 3.15576E+06  52596.      2191.5      6.0000
           TOTAL TIME 1.89346E+08 3.15576E+06  52596.      2191.5      6.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    7, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899760.1875               STORAGE =      1.2983E-06
       CONSTANT HEAD =      698509.3125         CONSTANT HEAD =      3.4665E-03
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
            RECHARGE =   237962688.0000              RECHARGE =          1.0772

            TOTAL IN =   239560960.0000              TOTAL IN =          1.0807
```

```
      OUT:                                     OUT:
      ----                                     ----
         STORAGE =       3.2576E-03               STORAGE =      1.0323E-10
   CONSTANT HEAD =   61740192.0000          CONSTANT HEAD =          0.2761
           WELLS =   27612900.0000                  WELLS =          0.1250
              ET =  150208048.0000                     ET =          0.6796
        RECHARGE =          0.0000               RECHARGE =          0.0000

       TOTAL OUT =  239561136.0000              TOTAL OUT =          1.0807

        IN - OUT =       -176.0000               IN - OUT =     -5.7220E-06

PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          -0.00


          TIME SUMMARY AT END OF TIME STEP   7 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 2.20903E+08 3.68172E+06  61362.      2556.8      7.0000
         TOTAL TIME 2.20903E+08 3.68172E+06  61362.      2556.8      7.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    8, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

       IN:                                      IN:
       ---                                      ---
         STORAGE =     899760.8750                STORAGE =      2.0969E-08
   CONSTANT HEAD =     807903.7500          CONSTANT HEAD =      3.4665E-03
           WELLS =          0.0000                  WELLS =          0.0000
              ET =          0.0000                     ET =          0.0000
        RECHARGE =  271957344.0000               RECHARGE =          1.0772

        TOTAL IN =  273665024.0000               TOTAL IN =          1.0807

      OUT:                                     OUT:
      ----                                     ----
         STORAGE =       4.8204E-02               STORAGE =      1.4243E-09
   CONSTANT HEAD =   70453656.0000          CONSTANT HEAD =          0.2761
           WELLS =   31557600.0000                  WELLS =          0.1250
              ET =  171654160.0000                     ET =          0.6796
        RECHARGE =          0.0000               RECHARGE =          0.0000

       TOTAL OUT =  273665408.0000              TOTAL OUT =          1.0807

        IN - OUT =       -384.0000               IN - OUT =     -6.9141E-06

PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          -0.00


          TIME SUMMARY AT END OF TIME STEP   8 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 2.52461E+08 4.20768E+06  70128.      2922.0      8.0000
         TOTAL TIME 2.52461E+08 4.20768E+06  70128.      2922.0      8.0000
```

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    9, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899761.2500             STORAGE =       1.0930E-08
       CONSTANT HEAD =      917298.3750       CONSTANT HEAD =       3.4665E-03
               WELLS =           0.0000               WELLS =           0.0000
                  ET =           0.0000                  ET =           0.0000
            RECHARGE =   305952000.0000            RECHARGE =           1.0772

            TOTAL IN =   307769056.0000            TOTAL IN =           1.0807

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =       7.3591E-02             STORAGE =       8.0445E-10
       CONSTANT HEAD =    79167120.0000       CONSTANT HEAD =           0.2761
               WELLS =    35502300.0000               WELLS =           0.1250
                  ET =   193100272.0000                  ET =           0.6796
            RECHARGE =           0.0000            RECHARGE =           0.0000

           TOTAL OUT =   307769696.0000           TOTAL OUT =           1.0807

            IN - OUT =        -640.0000            IN - OUT =      -6.7949E-06

 PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          -0.00


         TIME SUMMARY AT END OF TIME STEP    9 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 2.84018E+08 4.73364E+06  78894.      3287.2      9.0000
         TOTAL TIME 2.84018E+08 4.73364E+06  78894.      3287.2      9.0000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   10, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899761.7500             STORAGE =       1.6001E-08
       CONSTANT HEAD =     1026693.3125       CONSTANT HEAD =       3.4665E-03
               WELLS =           0.0000               WELLS =           0.0000
                  ET =           0.0000                  ET =           0.0000
            RECHARGE =   339946656.0000            RECHARGE =           1.0772

            TOTAL IN =   341873120.0000            TOTAL IN =           1.0807

          OUT:                                     OUT:

             STORAGE =       9.1342E-02             STORAGE =       5.6252E-10
       CONSTANT HEAD =    87880584.0000       CONSTANT HEAD =           0.2761
               WELLS =    39447000.0000               WELLS =           0.1250
                  ET =   214546384.0000                  ET =           0.6796
            RECHARGE =           0.0000            RECHARGE =           0.0000

           TOTAL OUT =   341873984.0000           TOTAL OUT =           1.0807

            IN - OUT =        -864.0000            IN - OUT =      -6.6757E-06

 PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          -0.00


         TIME SUMMARY AT END OF TIME STEP   10 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
 STRESS PERIOD TIME 3.15576E+08 5.25960E+06  87660.      3652.5      10.000
         TOTAL TIME 3.15576E+08 5.25960E+06  87660.      3652.5      10.000
```

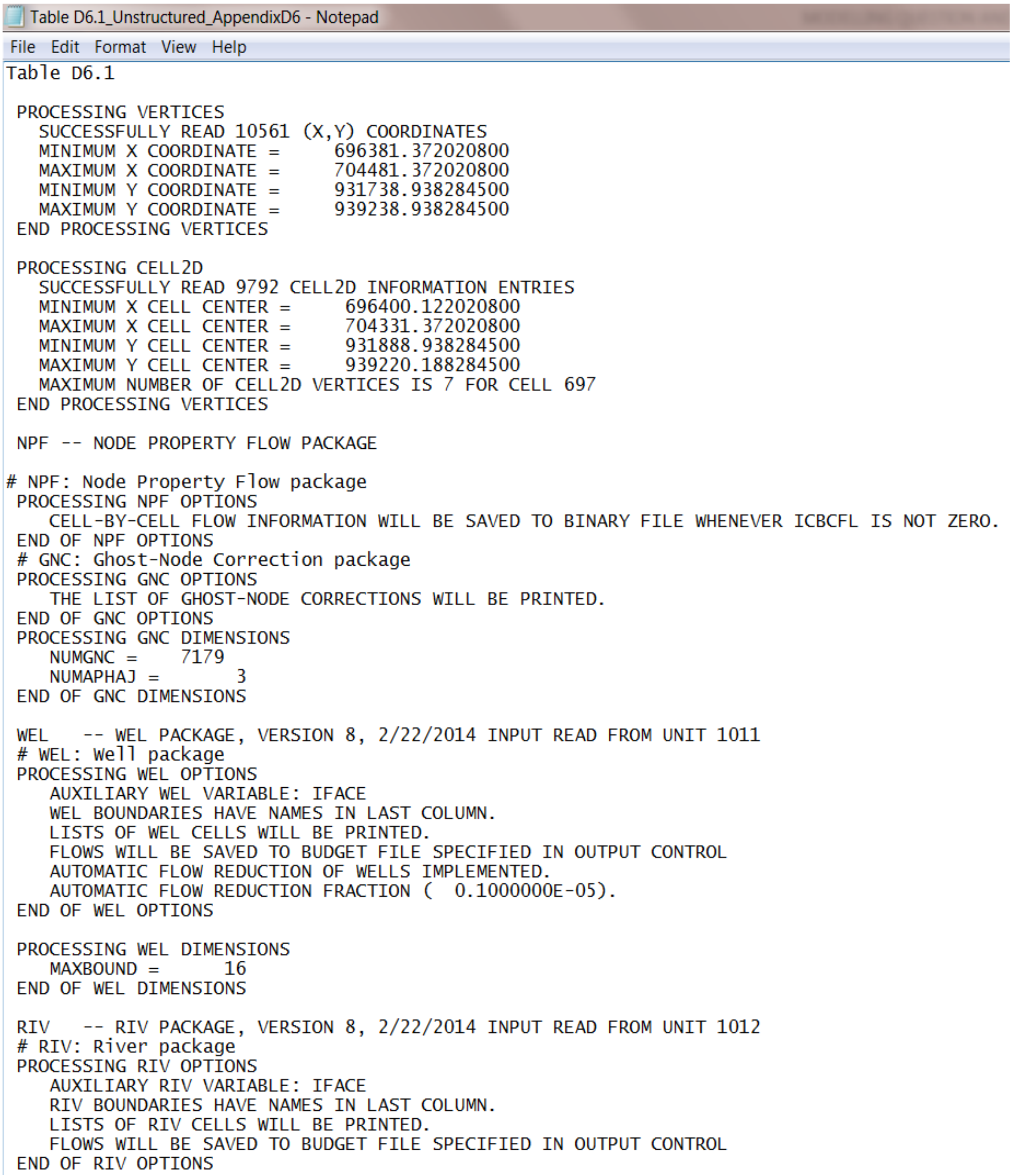
```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   11, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899762.0625               STORAGE =      1.0782E-08
       CONSTANT HEAD =     1136088.5000         CONSTANT HEAD =      3.4665E-03
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
            RECHARGE =   373941312.0000              RECHARGE =          1.0772

            TOTAL IN =   375977152.0000              TOTAL IN =          1.0807

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.1049               STORAGE =      4.2837E-10
       CONSTANT HEAD =    96594040.0000         CONSTANT HEAD =          0.2761
               WELLS =    43391700.0000                 WELLS =          0.1250
                  ET =   235992496.0000                    ET =          0.6796
            RECHARGE =           0.0000              RECHARGE =          0.0000

           TOTAL OUT =   375978240.0000             TOTAL OUT =          1.0807

            IN - OUT =       -1088.0000              IN - OUT =     -6.6757E-06

 PERCENT DISCREPANCY =            -0.00     PERCENT DISCREPANCY =           -0.00


        TIME SUMMARY AT END OF TIME STEP   11 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
  TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
STRESS PERIOD TIME 3.47134E+08 5.78556E+06  96426.      4017.8      11.000
        TOTAL TIME 3.47134E+08 5.78556E+06  96426.      4017.8      11.000

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   12, STRESS PERIOD   2
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =      899762.5000               STORAGE =      1.3420E-08
       CONSTANT HEAD =     1245483.8750         CONSTANT HEAD =      3.4665E-03
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
            RECHARGE =   407935968.0000              RECHARGE =          1.0772

            TOTAL IN =   410081216.0000              TOTAL IN =          1.0807

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.1160               STORAGE =      3.5334E-10
       CONSTANT HEAD =   105307496.0000         CONSTANT HEAD =          0.2761
               WELLS =    47336400.0000                 WELLS =          0.1250
                  ET =   257438608.0000                    ET =          0.6796
            RECHARGE =           0.0000              RECHARGE =          0.0000

           TOTAL OUT =   410082496.0000             TOTAL OUT =          1.0807

            IN - OUT =       -1280.0000              IN - OUT =     -6.4373E-06

 PERCENT DISCREPANCY =            -0.00     PERCENT DISCREPANCY =           -0.00


        TIME SUMMARY AT END OF TIME STEP   12 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
  TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
STRESS PERIOD TIME 3.78691E+08 6.31152E+06 1.05192E+05  4383.0      12.000
        TOTAL TIME 3.78691E+08 6.31152E+06 1.05192E+05  4383.0      12.000
```

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   13, STRESS PERIOD   2
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
            STORAGE =      899762.8750               STORAGE =      1.0969E-08
      CONSTANT HEAD =     1354879.5000         CONSTANT HEAD =      3.4665E-03
              WELLS =           0.0000                 WELLS =          0.0000
                 ET =           0.0000                    ET =          0.0000
           RECHARGE =   441930624.0000              RECHARGE =          1.0772

           TOTAL IN =   444185280.0000              TOTAL IN =          1.0807

         OUT:                                     OUT:
         ----                                     ----
            STORAGE =           0.1272               STORAGE =      3.5470E-10
      CONSTANT HEAD =   114020952.0000         CONSTANT HEAD =          0.2761
              WELLS =    51281100.0000                 WELLS =          0.1250
                 ET =   278884704.0000                    ET =          0.6796
           RECHARGE =           0.0000              RECHARGE =          0.0000

          TOTAL OUT =   444186752.0000             TOTAL OUT =          1.0807

           IN - OUT =       -1472.0000              IN - OUT =     -6.3181E-06

PERCENT DISCREPANCY =            -0.00     PERCENT DISCREPANCY =           -0.00


        TIME SUMMARY AT END OF TIME STEP   13 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
  TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
STRESS PERIOD TIME 4.10249E+08 6.83748E+06 1.13958E+05  4748.2      13.000
        TOTAL TIME 4.10249E+08 6.83748E+06 1.13958E+05  4748.2      13.000

 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   14, STRESS PERIOD   2
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
            STORAGE =      899763.3125               STORAGE =      1.3982E-08
      CONSTANT HEAD =     1464275.3750         CONSTANT HEAD =      3.4665E-03
              WELLS =           0.0000                 WELLS =          0.0000
                 ET =           0.0000                    ET =          0.0000
           RECHARGE =   475925280.0000              RECHARGE =          1.0772

           TOTAL IN =   478289312.0000              TOTAL IN =          1.0807

         OUT:                                     OUT:
         ----                                     ----
            STORAGE =           0.1371               STORAGE =      3.1378E-10
      CONSTANT HEAD =   122734400.0000         CONSTANT HEAD =          0.2761
              WELLS =    55225800.0000                 WELLS =          0.1250
                 ET =   300330816.0000                    ET =          0.6796
           RECHARGE =           0.0000              RECHARGE =          0.0000

          TOTAL OUT =   478291008.0000             TOTAL OUT =          1.0807

           IN - OUT =       -1696.0000              IN - OUT =     -6.1989E-06

PERCENT DISCREPANCY =            -0.00     PERCENT DISCREPANCY =           -0.00


        TIME SUMMARY AT END OF TIME STEP   14 IN STRESS PERIOD    2
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
  TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
STRESS PERIOD TIME 4.41806E+08 7.36344E+06 1.22724E+05  5113.5      14.000
        TOTAL TIME 4.41806E+08 7.36344E+06 1.22724E+05  5113.5      14.000
```

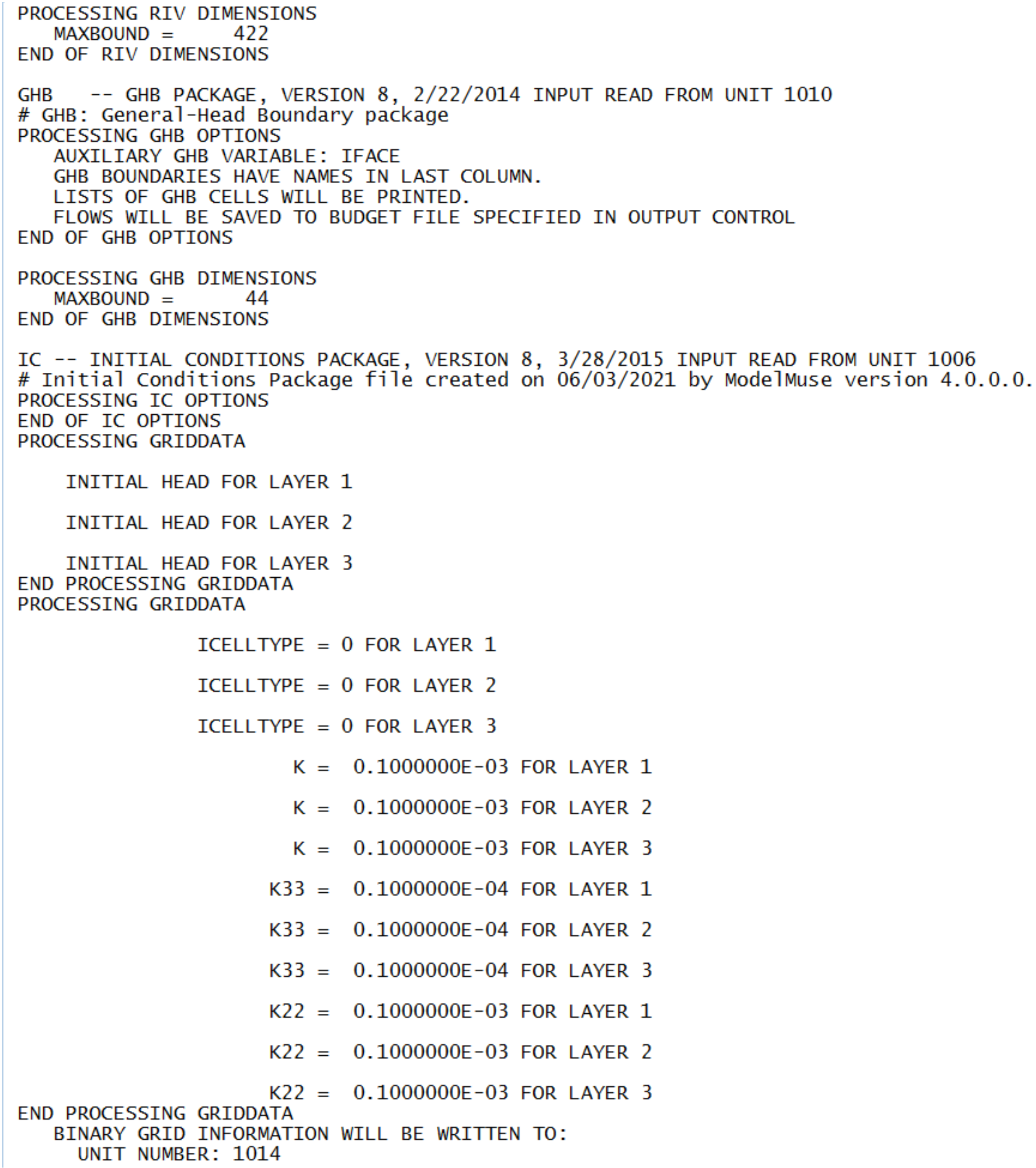
```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   15, STRESS PERIOD   2
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
            STORAGE =      899763.6250               STORAGE =      9.7363E-09
      CONSTANT HEAD =     1573671.3750         CONSTANT HEAD =      3.4666E-03
              WELLS =           0.0000                 WELLS =          0.0000
                 ET =           0.0000                    ET =          0.0000
           RECHARGE =   509919936.0000              RECHARGE =          1.0772

           TOTAL IN =   512393376.0000              TOTAL IN =          1.0807

         OUT:                                     OUT:
         ----                                     ----
            STORAGE =           0.1471               STORAGE =      3.1696E-10
      CONSTANT HEAD =   131447848.0000         CONSTANT HEAD =          0.2761
              WELLS =    59170500.0000                 WELLS =          0.1250
                 ET =   321776928.0000                    ET =          0.6796
           RECHARGE =           0.0000              RECHARGE =          0.0000

          TOTAL OUT =   512395264.0000             TOTAL OUT =          1.0807

           IN - OUT =       -1888.0000              IN - OUT =     -6.0797E-06

PERCENT DISCREPANCY =          -0.00     PERCENT DISCREPANCY =          -0.00



        TIME SUMMARY AT END OF TIME STEP   15 IN STRESS PERIOD    2
                   SECONDS     MINUTES      HOURS       DAYS        YEARS
                   -----------------------------------------------------------
  TIME STEP LENGTH 3.15576E+07 5.25960E+05  8766.0      365.25      1.0000
STRESS PERIOD TIME 4.73364E+08 7.88940E+06 1.31490E+05  5478.8      15.000
        TOTAL TIME 4.73364E+08 7.88940E+06 1.31490E+05  5478.8      15.000

Run end date and time (yyyy/mm/dd hh:mm:ss): 2021/03/06  7:24:35
Elapsed run time:  4.023 Seconds
```

Model Calibration for Interaction of Alluvial Aquifer with Regional Flow, River and Wells in Unstructured Grid Discretisation Appendix D6

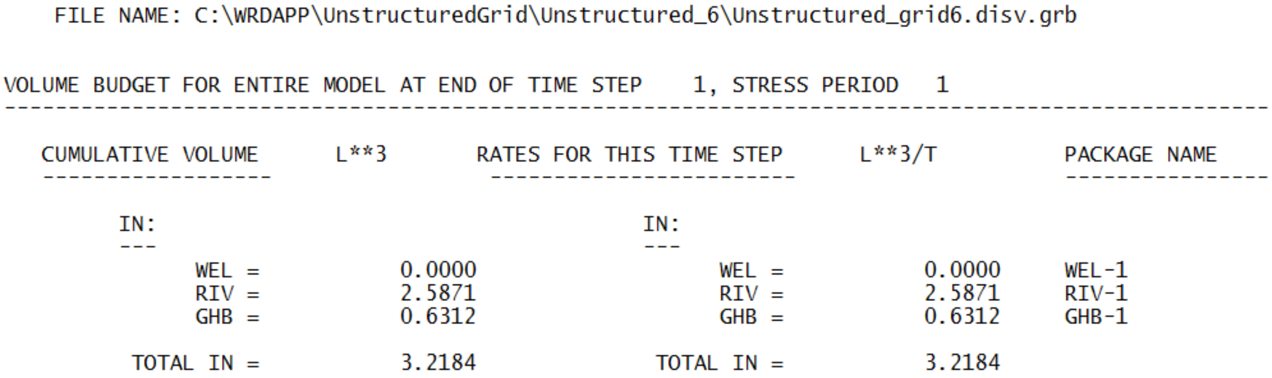
Table D6.1 Appendix D6



```
Table D6.1

 PROCESSING VERTICES
   SUCCESSFULLY READ 10561 (X,Y) COORDINATES
   MINIMUM X COORDINATE =     696381.372020800
   MAXIMUM X COORDINATE =     704481.372020800
   MINIMUM Y COORDINATE =     931738.938284500
   MAXIMUM Y COORDINATE =     939238.938284500
 END PROCESSING VERTICES

 PROCESSING CELL2D
   SUCCESSFULLY READ 9792 CELL2D INFORMATION ENTRIES
   MINIMUM X CELL CENTER =     696400.122020800
   MAXIMUM X CELL CENTER =     704331.372020800
   MINIMUM Y CELL CENTER =     931888.938284500
   MAXIMUM Y CELL CENTER =     939220.188284500
   MAXIMUM NUMBER OF CELL2D VERTICES IS 7 FOR CELL 697
 END PROCESSING VERTICES

 NPF -- NODE PROPERTY FLOW PACKAGE

# NPF: Node Property Flow package
 PROCESSING NPF OPTIONS
    CELL-BY-CELL FLOW INFORMATION WILL BE SAVED TO BINARY FILE WHENEVER ICBCFL IS NOT ZERO.
 END OF NPF OPTIONS
 # GNC: Ghost-Node Correction package
 PROCESSING GNC OPTIONS
    THE LIST OF GHOST-NODE CORRECTIONS WILL BE PRINTED.
 END OF GNC OPTIONS
 PROCESSING GNC DIMENSIONS
    NUMGNC =     7179
    NUMAPHAJ =        3
 END OF GNC DIMENSIONS

 WEL   -- WEL PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1011
 # WEL: Well package
 PROCESSING WEL OPTIONS
    AUXILIARY WEL VARIABLE: IFACE
    WEL BOUNDARIES HAVE NAMES IN LAST COLUMN.
    LISTS OF WEL CELLS WILL BE PRINTED.
    FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
    AUTOMATIC FLOW REDUCTION OF WELLS IMPLEMENTED.
    AUTOMATIC FLOW REDUCTION FRACTION (  0.1000000E-05).
 END OF WEL OPTIONS

 PROCESSING WEL DIMENSIONS
    MAXBOUND =      16
 END OF WEL DIMENSIONS

 RIV   -- RIV PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1012
 # RIV: River package
 PROCESSING RIV OPTIONS
    AUXILIARY RIV VARIABLE: IFACE
    RIV BOUNDARIES HAVE NAMES IN LAST COLUMN.
    LISTS OF RIV CELLS WILL BE PRINTED.
    FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
 END OF RIV OPTIONS
```



```
PROCESSING RIV DIMENSIONS
   MAXBOUND =      422
END OF RIV DIMENSIONS

GHB   -- GHB PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1010
# GHB: General-Head Boundary package
PROCESSING GHB OPTIONS
   AUXILIARY GHB VARIABLE: IFACE
   GHB BOUNDARIES HAVE NAMES IN LAST COLUMN.
   LISTS OF GHB CELLS WILL BE PRINTED.
   FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
END OF GHB OPTIONS

PROCESSING GHB DIMENSIONS
   MAXBOUND =       44
END OF GHB DIMENSIONS

IC -- INITIAL CONDITIONS PACKAGE, VERSION 8, 3/28/2015 INPUT READ FROM UNIT 1006
# Initial Conditions Package file created on 06/03/2021 by ModelMuse version 4.0.0.0.
PROCESSING IC OPTIONS
END OF IC OPTIONS
PROCESSING GRIDDATA

    INITIAL HEAD FOR LAYER 1

    INITIAL HEAD FOR LAYER 2

    INITIAL HEAD FOR LAYER 3
END PROCESSING GRIDDATA
PROCESSING GRIDDATA

               ICELLTYPE = 0 FOR LAYER 1

               ICELLTYPE = 0 FOR LAYER 2

               ICELLTYPE = 0 FOR LAYER 3

                       K =  0.1000000E-03 FOR LAYER 1

                       K =  0.1000000E-03 FOR LAYER 2

                       K =  0.1000000E-03 FOR LAYER 3

                     K33 =  0.1000000E-04 FOR LAYER 1

                     K33 =  0.1000000E-04 FOR LAYER 2

                     K33 =  0.1000000E-04 FOR LAYER 3

                     K22 =  0.1000000E-03 FOR LAYER 1

                     K22 =  0.1000000E-03 FOR LAYER 2

                     K22 =  0.1000000E-03 FOR LAYER 3
END PROCESSING GRIDDATA
   BINARY GRID INFORMATION WILL BE WRITTEN TO:
     UNIT NUMBER: 1014
```



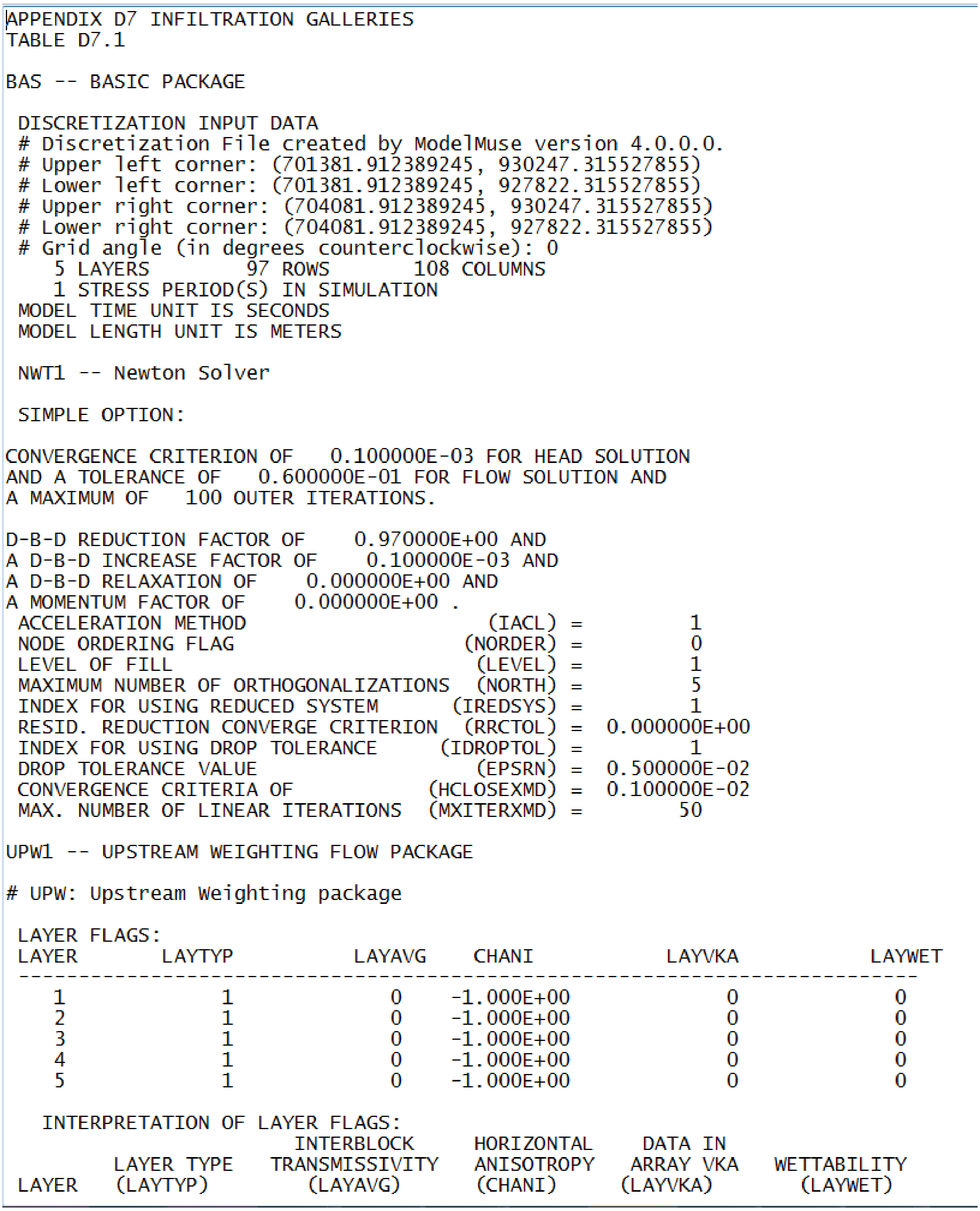
```
  FILE NAME: C:\WRDAPP\UnstructuredGrid\Unstructured_6\Unstructured_grid6.disv.grb

VOLUME BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
---------------------------------------------------------------------------------------------------

  CUMULATIVE VOLUME      L**3       RATES FOR THIS TIME STEP      L**3/T          PACKAGE NAME
  ------------------                 ------------------------                    ----------------

        IN:                                   IN:
        ---                                   ---
              WEL =           0.0000                WEL =           0.0000     WEL-1
              RIV =           2.5871                RIV =           2.5871     RIV-1
              GHB =           0.6312                GHB =           0.6312     GHB-1

         TOTAL IN =           3.2184           TOTAL IN =           3.2184
```

```
          OUT:                                          OUT:
          ----                                          ----
                 WEL =              0.4800                     WEL =              0.4800     WEL-1
                 RIV =              2.6964                     RIV =              2.6964     RIV-1
                 GHB =          4.1921E-02                     GHB =          4.1921E-02     GHB-1

           TOTAL OUT =              3.2184               TOTAL OUT =              3.2184

            IN - OUT =         -1.6740E-07                IN - OUT =         -1.6740E-07

PERCENT DISCREPANCY =               -0.00     PERCENT DISCREPANCY =               -0.00


         TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
 STRESS PERIOD TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
         TOTAL TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
```

APPENDIX D7 MODEL CALIBRATION FOR FUTURE WATER SUPPLY MANAGEMENT FROM INFILTRATION GALLERIES

APPENDIX D7

Table D7.1 Appendix D7



```
APPENDIX D7 INFILTRATION GALLERIES
TABLE D7.1

BAS -- BASIC PACKAGE

 DISCRETIZATION INPUT DATA
 # Discretization File created by ModelMuse version 4.0.0.0.
 # Upper left corner: (701381.912389245, 930247.315527855)
 # Lower left corner: (701381.912389245, 927822.315527855)
 # Upper right corner: (704081.912389245, 930247.315527855)
 # Lower right corner: (704081.912389245, 927822.315527855)
 # Grid angle (in degrees counterclockwise): 0
    5 LAYERS         97 ROWS        108 COLUMNS
    1 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS SECONDS
 MODEL LENGTH UNIT IS METERS

 NWT1 -- Newton Solver

 SIMPLE OPTION:

CONVERGENCE CRITERION OF    0.100000E-03 FOR HEAD SOLUTION
AND A TOLERANCE OF    0.600000E-01 FOR FLOW SOLUTION AND
A MAXIMUM OF    100 OUTER ITERATIONS.

D-B-D REDUCTION FACTOR OF     0.970000E+00 AND
A D-B-D INCREASE FACTOR OF     0.100000E-03 AND
A D-B-D RELAXATION OF     0.000000E+00 AND
A MOMENTUM FACTOR OF     0.000000E+00 .
 ACCELERATION METHOD                    (IACL) =          1
 NODE ORDERING FLAG                   (NORDER) =          0
 LEVEL OF FILL                         (LEVEL) =          1
 MAXIMUM NUMBER OF ORTHOGONALIZATIONS  (NORTH) =          5
 INDEX FOR USING REDUCED SYSTEM      (IREDSYS) =          1
 RESID. REDUCTION CONVERGE CRITERION  (RRCTOL) =  0.000000E+00
 INDEX FOR USING DROP TOLERANCE     (IDROPTOL) =          1
 DROP TOLERANCE VALUE                  (EPSRN) =  0.500000E-02
 CONVERGENCE CRITERIA OF           (HCLOSEXMD) =  0.100000E-02
 MAX. NUMBER OF LINEAR ITERATIONS  (MXITERXMD) =         50

UPW1 -- UPSTREAM WEIGHTING FLOW PACKAGE

# UPW: Upstream Weighting package

 LAYER FLAGS:
 LAYER       LAYTYP          LAYAVG    CHANI           LAYVKA           LAYWET
 ---------------------------------------------------------------------------
    1             1              0    -1.000E+00            0              0
    2             1              0    -1.000E+00            0              0
    3             1              0    -1.000E+00            0              0
    4             1              0    -1.000E+00            0              0
    5             1              0    -1.000E+00            0              0

   INTERPRETATION OF LAYER FLAGS:
                       INTERBLOCK     HORIZONTAL    DATA IN
        LAYER TYPE   TRANSMISSIVITY   ANISOTROPY   ARRAY VKA   WETTABILITY
 LAYER   (LAYTYP)       (LAYAVG)        (CHANI)     (LAYVKA)     (LAYWET)
```

```
 ----------------------------------------------------------------------------
    1   CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K   NON-WETTABLE
    2   CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K   NON-WETTABLE
    3   CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K   NON-WETTABLE
    4   CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K   NON-WETTABLE
    5   CONVERTIBLE      HARMONIC      VARIABLE     VERTICAL K   NON-WETTABLE

    HYD. COND. ALONG ROWS =  5.000000E-04 FOR LAYER   1

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   1

      VERTICAL HYD. COND. =  5.000000E-05 FOR LAYER   1

    HYD. COND. ALONG ROWS =  5.000000E-04 FOR LAYER   2

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   2

      VERTICAL HYD. COND. =  5.000000E-05 FOR LAYER   2

    HYD. COND. ALONG ROWS =  5.000000E-04 FOR LAYER   3

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   3

      VERTICAL HYD. COND. =  5.000000E-05 FOR LAYER   3

    HYD. COND. ALONG ROWS =  5.000000E-04 FOR LAYER   4

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   4

      VERTICAL HYD. COND. =  5.000000E-05 FOR LAYER   4

    HYD. COND. ALONG ROWS =  5.000000E-04 FOR LAYER   5

   HORIZ. ANI. (COL./ROW) =   1.00000     FOR LAYER   5

      VERTICAL HYD. COND. =  5.000000E-05 FOR LAYER   5

 DRN -- DRAIN PACKAGE,
 MAXIMUM OF     130 ACTIVE DRAINS AT ONE TIME

 RIV -- RIVER PACKAGE,

 MAXIMUM OF    2058 ACTIVE RIVER REACHES AT ONE TIME

 EVT -- EVAPOTRANSPIRATION PACKAGE,

 OPTION 1 -- EVAPOTRANSPIRATION FROM TOP LAYER

 RCH -- RECHARGE PACKAGE,

 OPTION 3 -- RECHARGE TO HIGHEST ACTIVE NODE IN EACH VERTICAL COLUMN


  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
```

```
          IN:                                      IN:
          ---                                      ---
            STORAGE     =           0.0000               STORAGE     =           0.0000
      CONSTANT HEAD     =           0.0000         CONSTANT HEAD     =           0.0000
             DRAINS     =           0.0000                DRAINS     =           0.0000
      RIVER LEAKAGE     =           1.6300         RIVER LEAKAGE     =           1.6300
                 ET     =           0.0000                    ET     =           0.0000
           RECHARGE     =       1.1867E-02              RECHARGE     =       1.1867E-02

               TOTAL IN =           1.6419                  TOTAL IN =           1.6419

         OUT:                                     OUT:
         ----                                     ----
            STORAGE     =           0.0000               STORAGE     =           0.0000
      CONSTANT HEAD     =           0.0000         CONSTANT HEAD     =           0.0000
             DRAINS     =           0.2572                DRAINS     =           0.2572
      RIVER LEAKAGE     =           1.3788         RIVER LEAKAGE     =           1.3788
                 ET     =       5.9760E-03                    ET     =       5.9760E-03
           RECHARGE     =           0.0000              RECHARGE     =           0.0000

              TOTAL OUT =           1.6420                 TOTAL OUT =           1.6420

               IN - OUT =      -5.1141E-05                  IN - OUT =      -5.1141E-05

    PERCENT DISCREPANCY =           -0.00        PERCENT DISCREPANCY =           -0.00




        TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                   SECONDS     MINUTES      HOURS       DAYS        YEARS
                   -----------------------------------------------------------
  TIME STEP LENGTH  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
STRESS PERIOD TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
        TOTAL TIME  1.0000     1.66667E-02 2.77778E-04 1.15741E-05 3.16881E-08
-

Run end date and time (yyyy/mm/dd hh:mm:ss): 2021/03/08 18:21:09
Elapsed run time:  3.305 Seconds
```

APPENDIX D: GROUDWATER METHODOLOGY, MODEL DEVELOPMENT AND IMPLEMENTATION

Appendix D9: Hydrogeological and Thematic Maps

Figure D9.1 Slope Map of Study Area

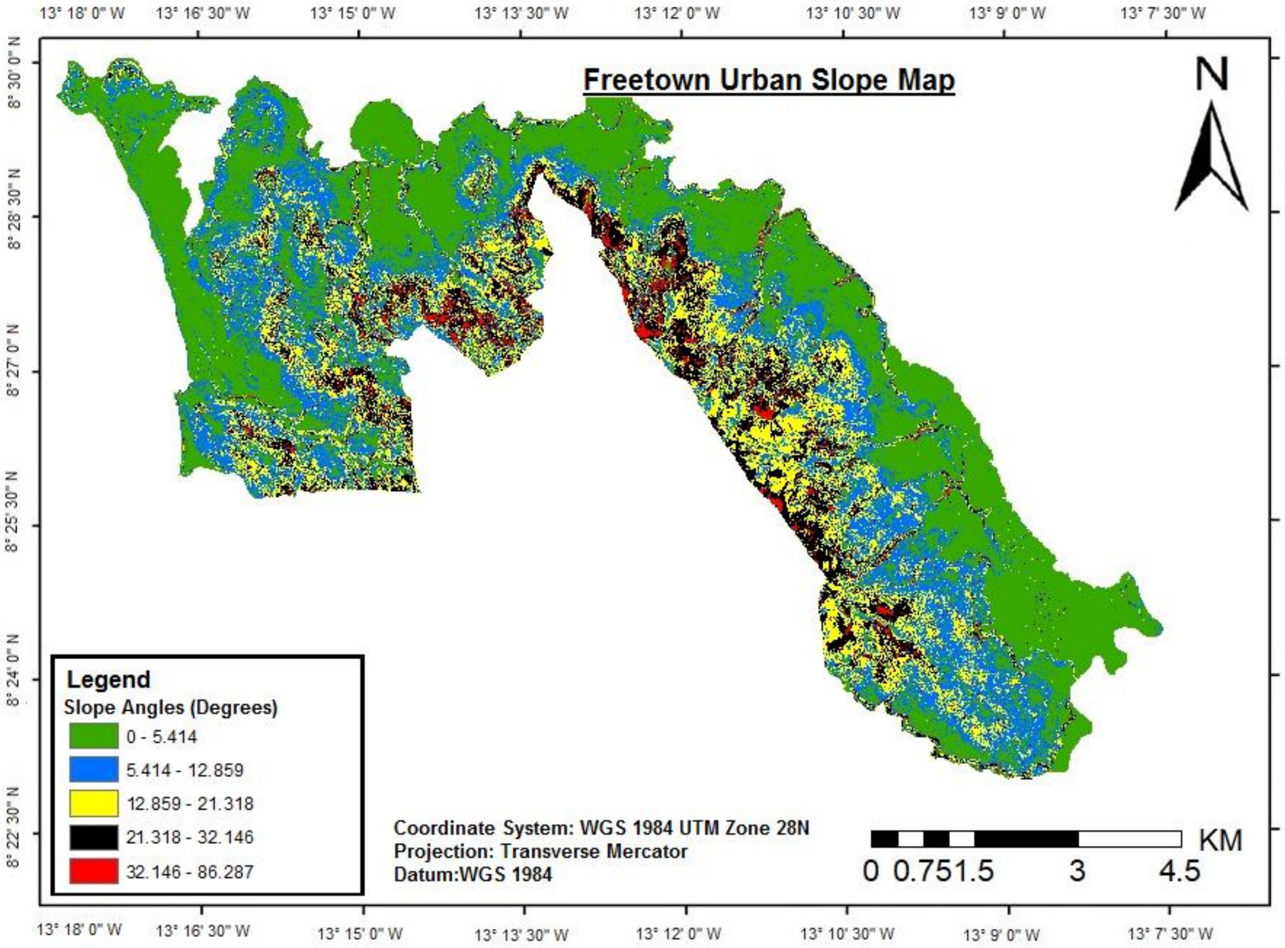


Figure D9.2 Soil Map of Study Area

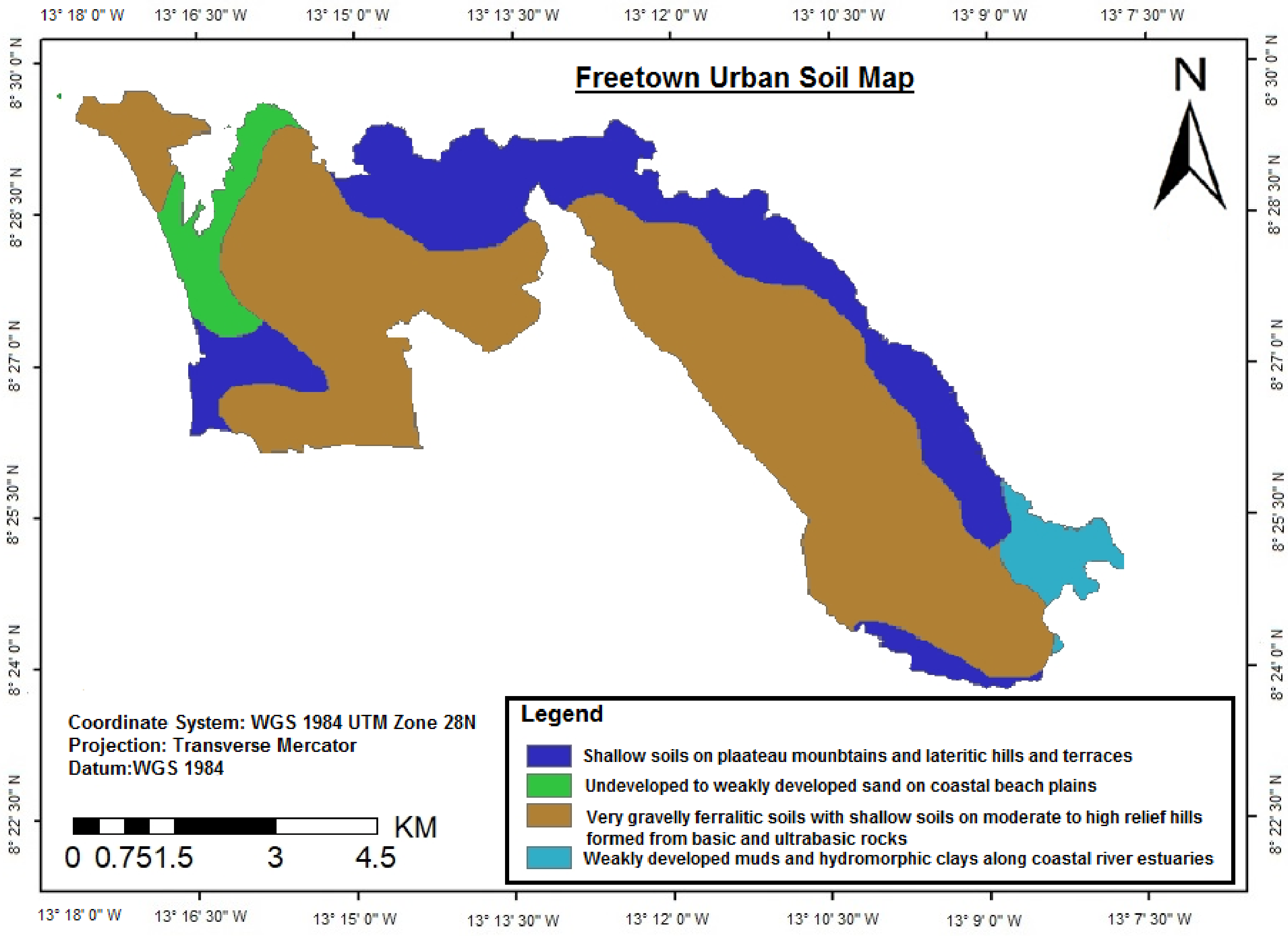


Figure D9.3 Aspect Map of Study Area

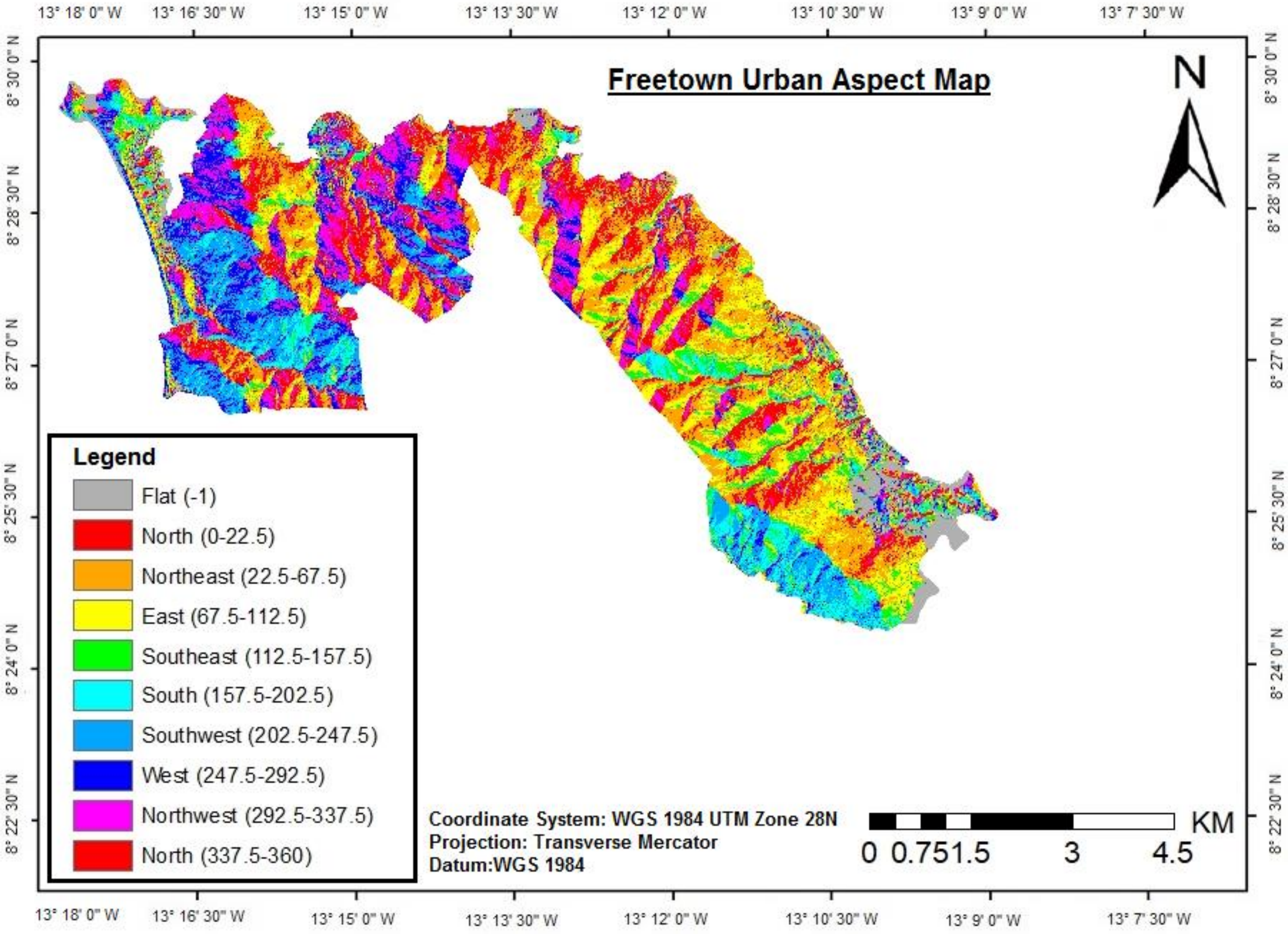


Figure D9.4 Contour Map of Study Area

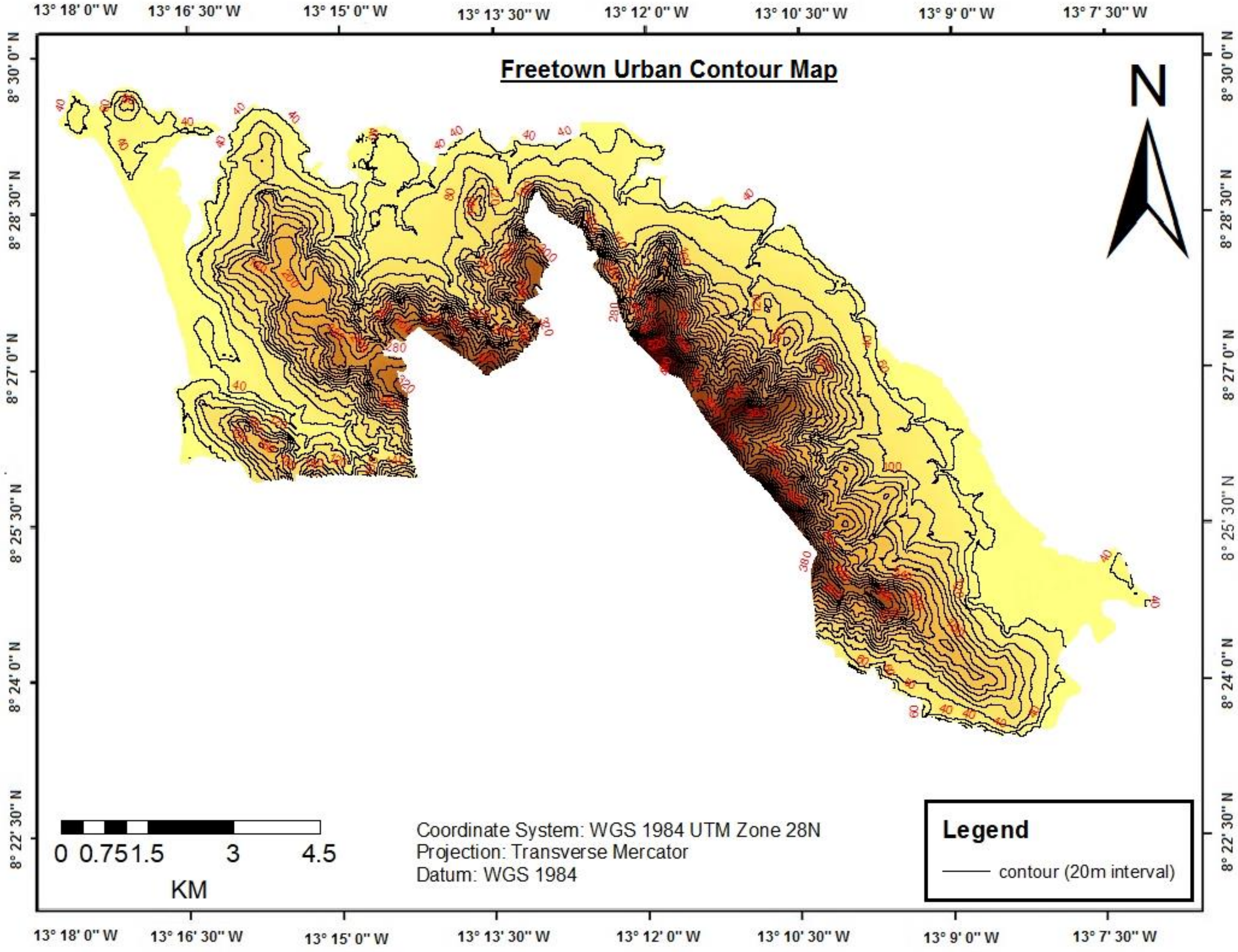


Figure D9.5 Drainage Basin Map of Study Area

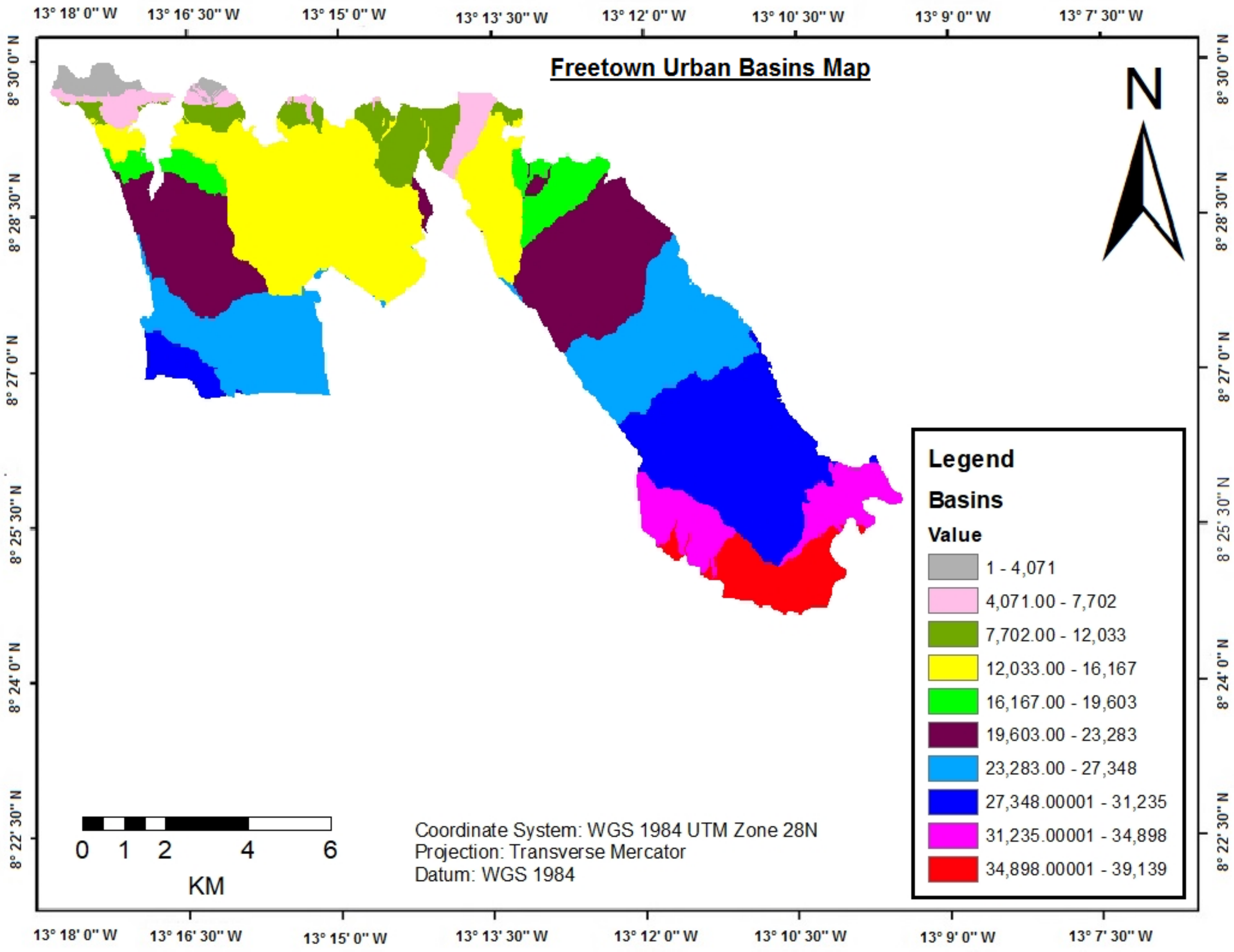


Figure D9.6 Drainage Density Map of Study Area

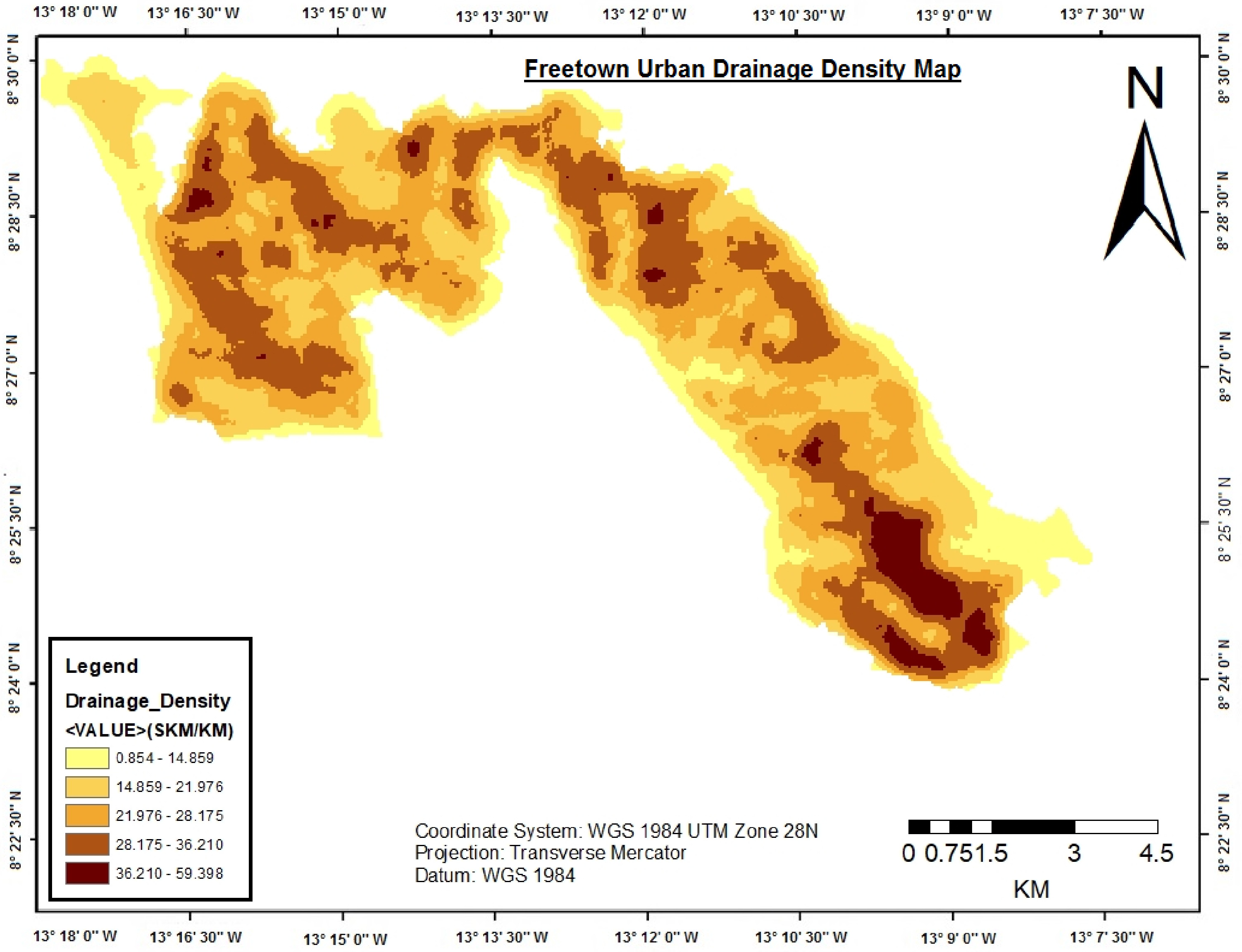


Figure D9.7 Waterways/Drainage Map of Study Area

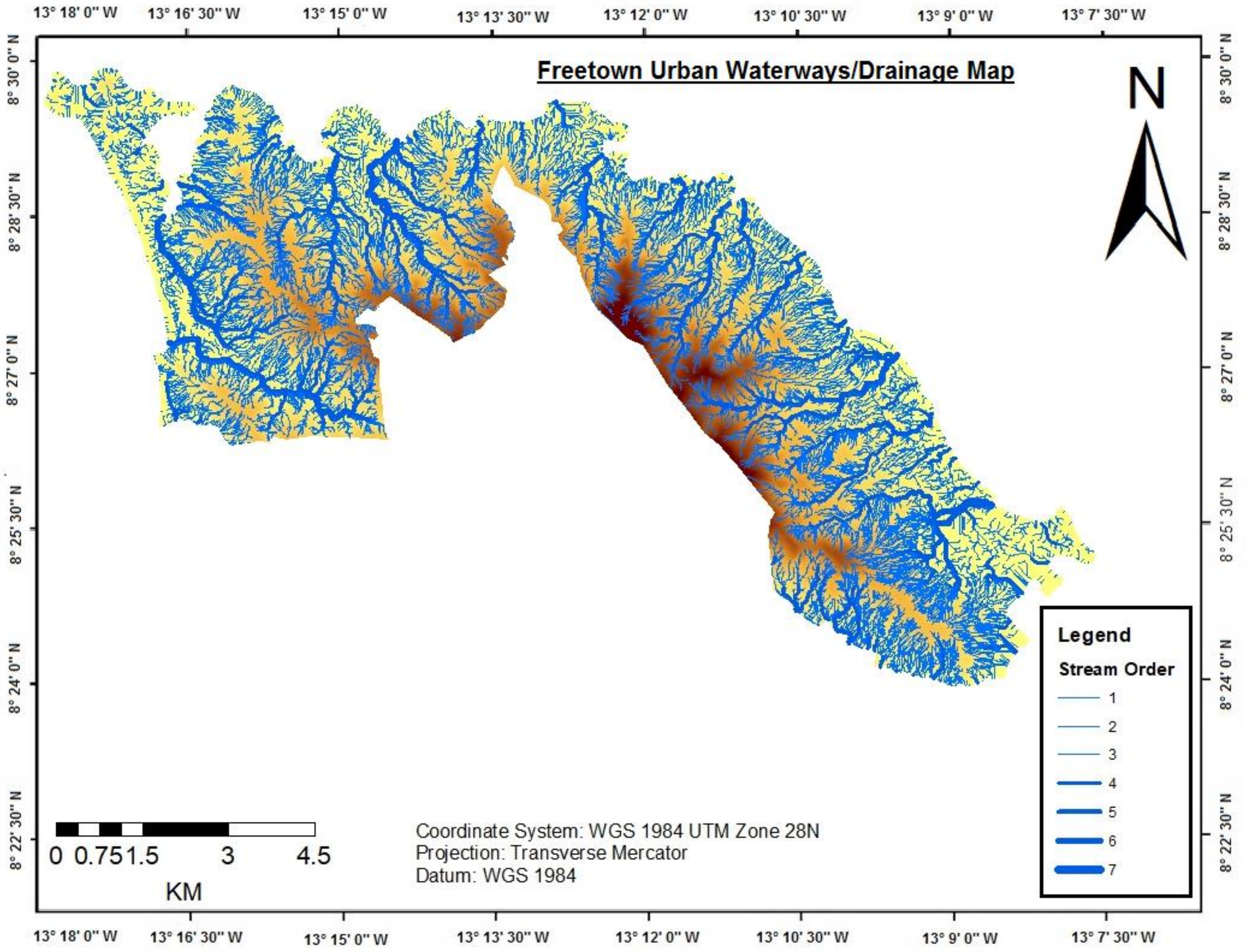


Figure D9.8 Flow Direction Map of Study Area

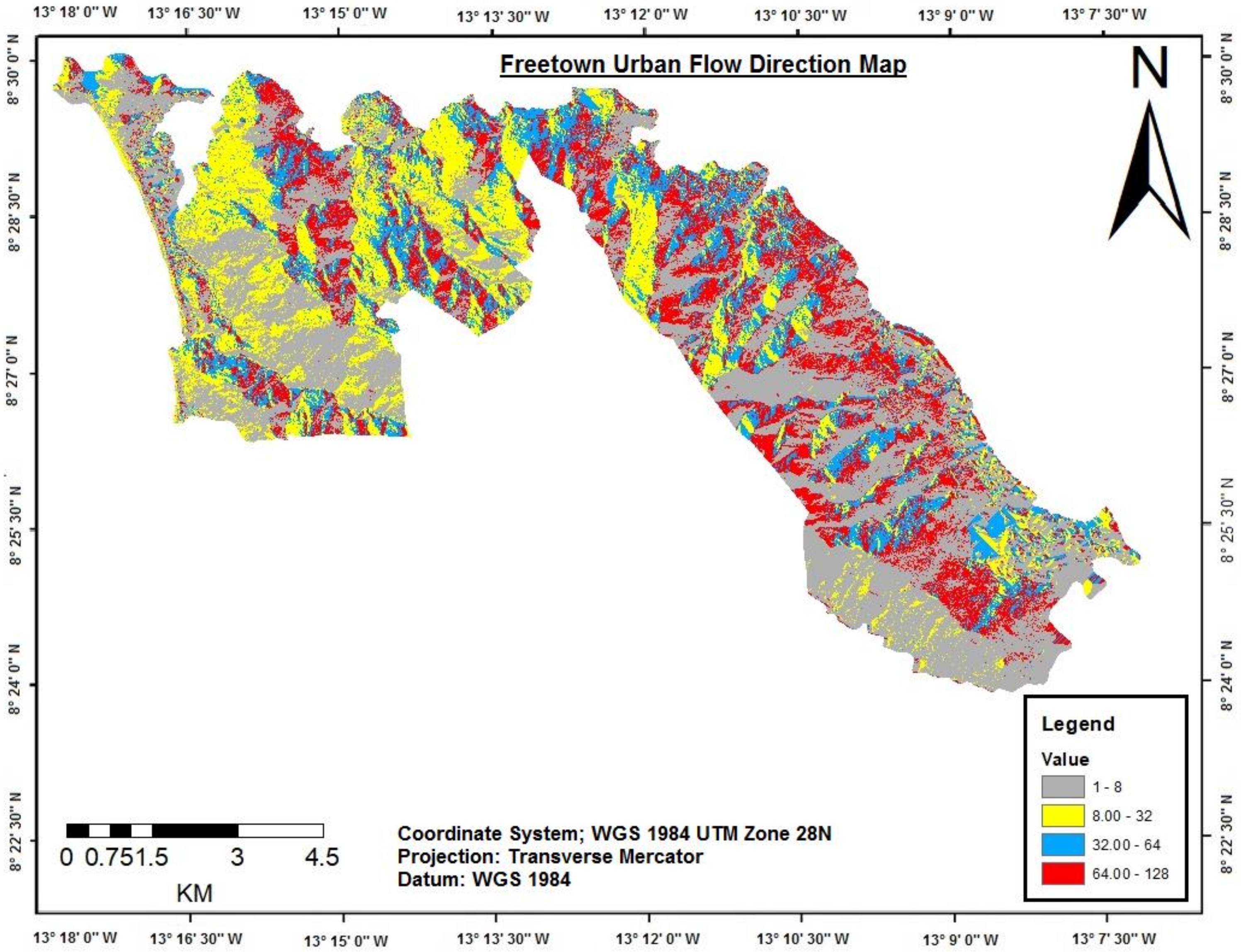


Figure D9.9 Curvature Map of Study Area

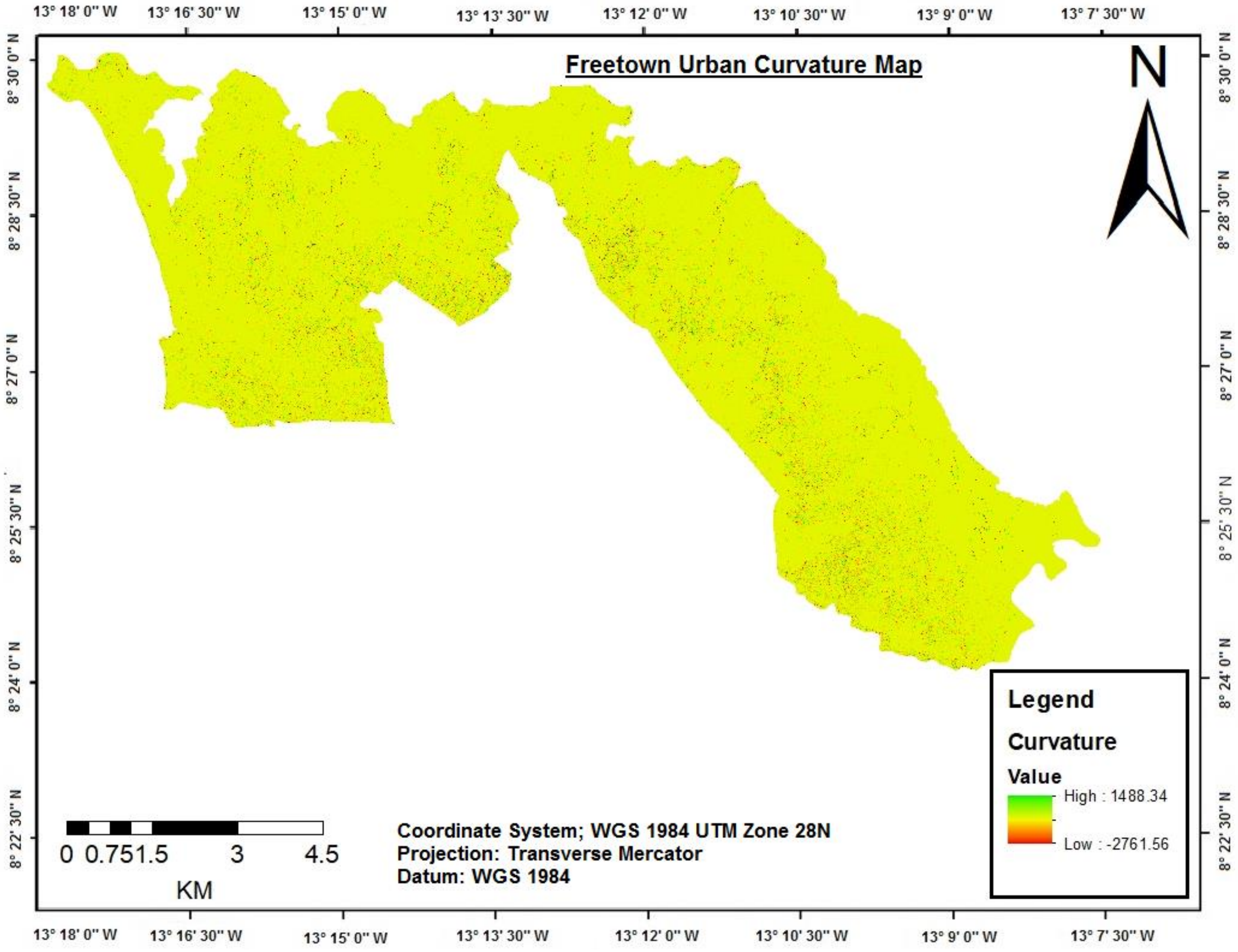


Figure D9.10 Elevation Map of Study Area

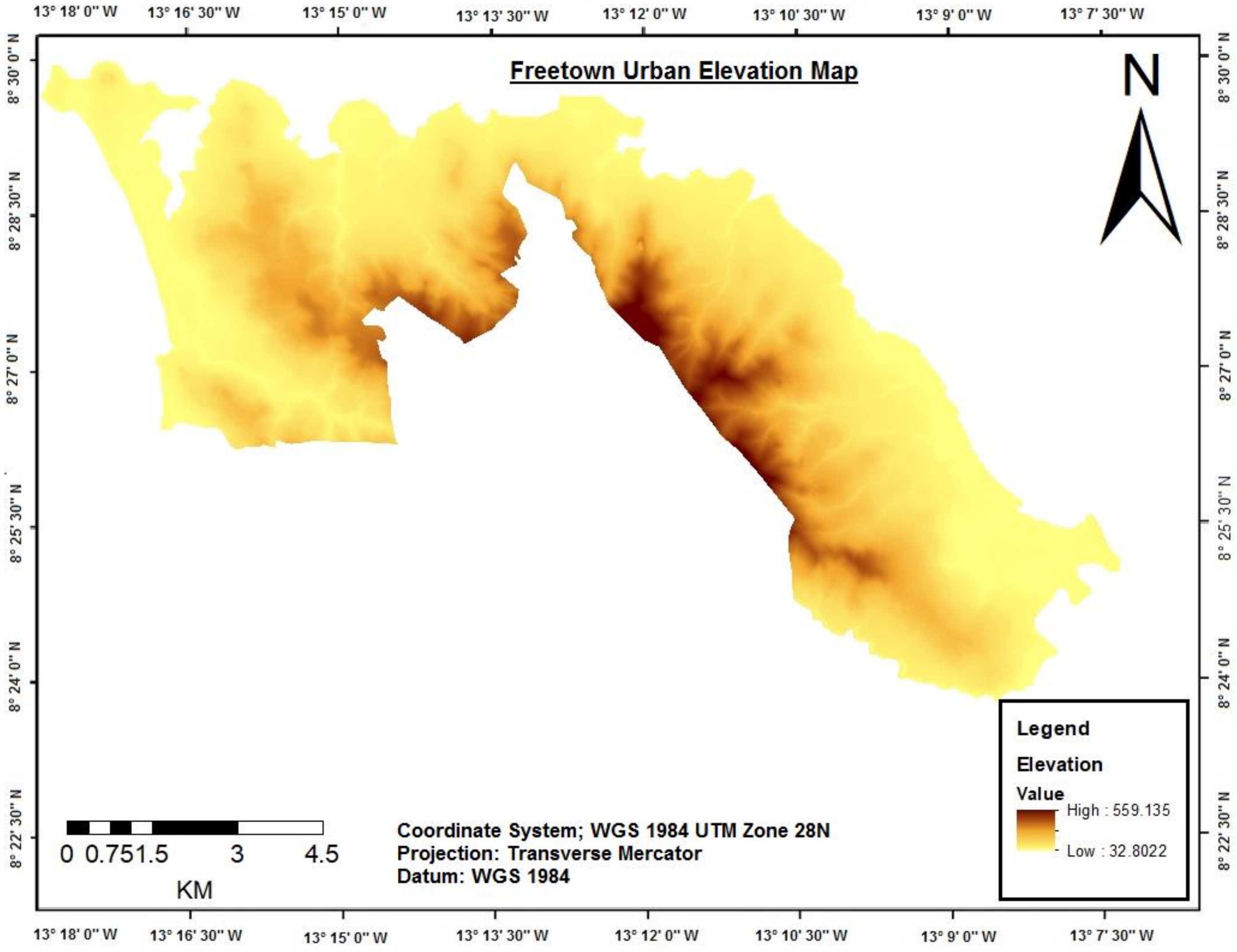
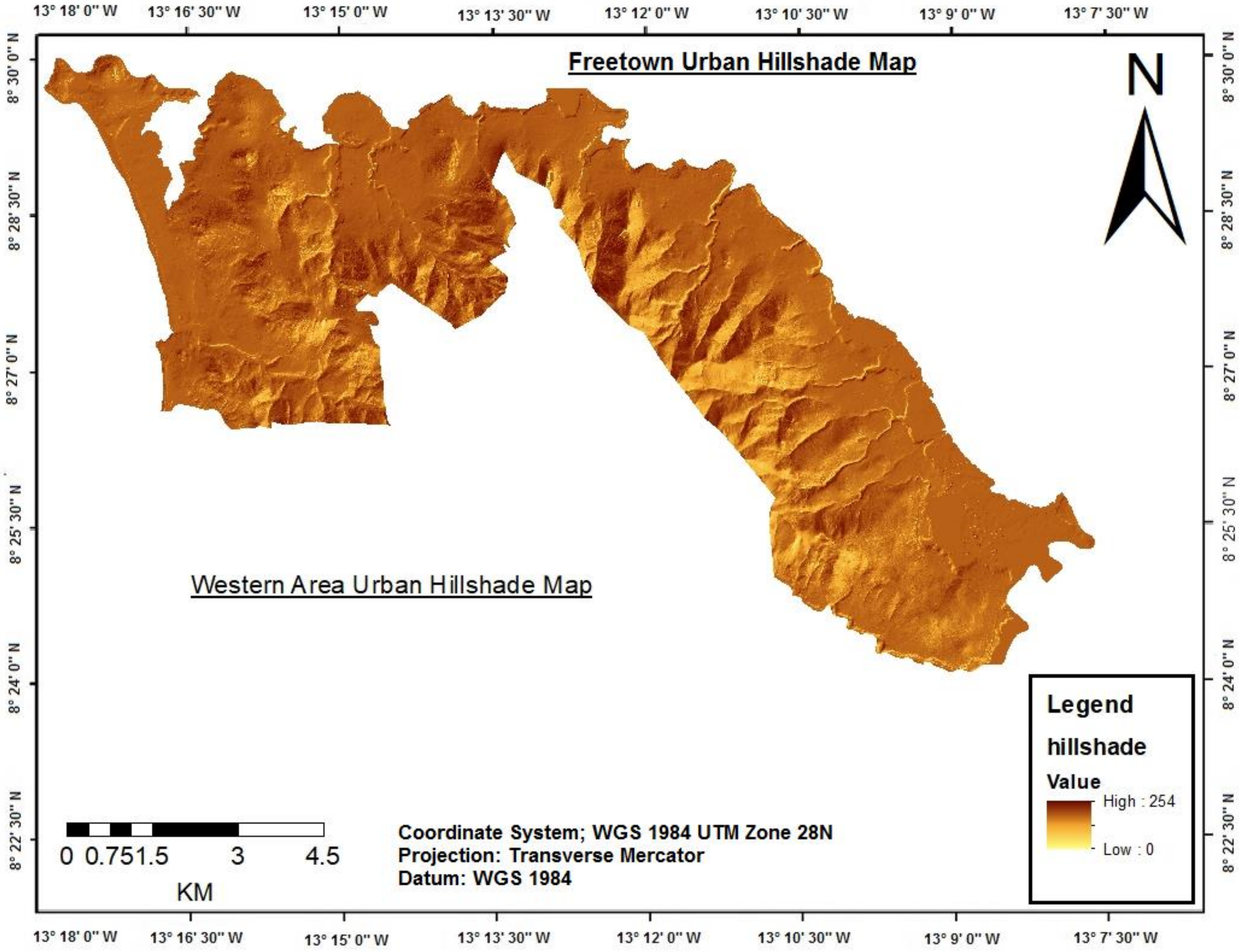
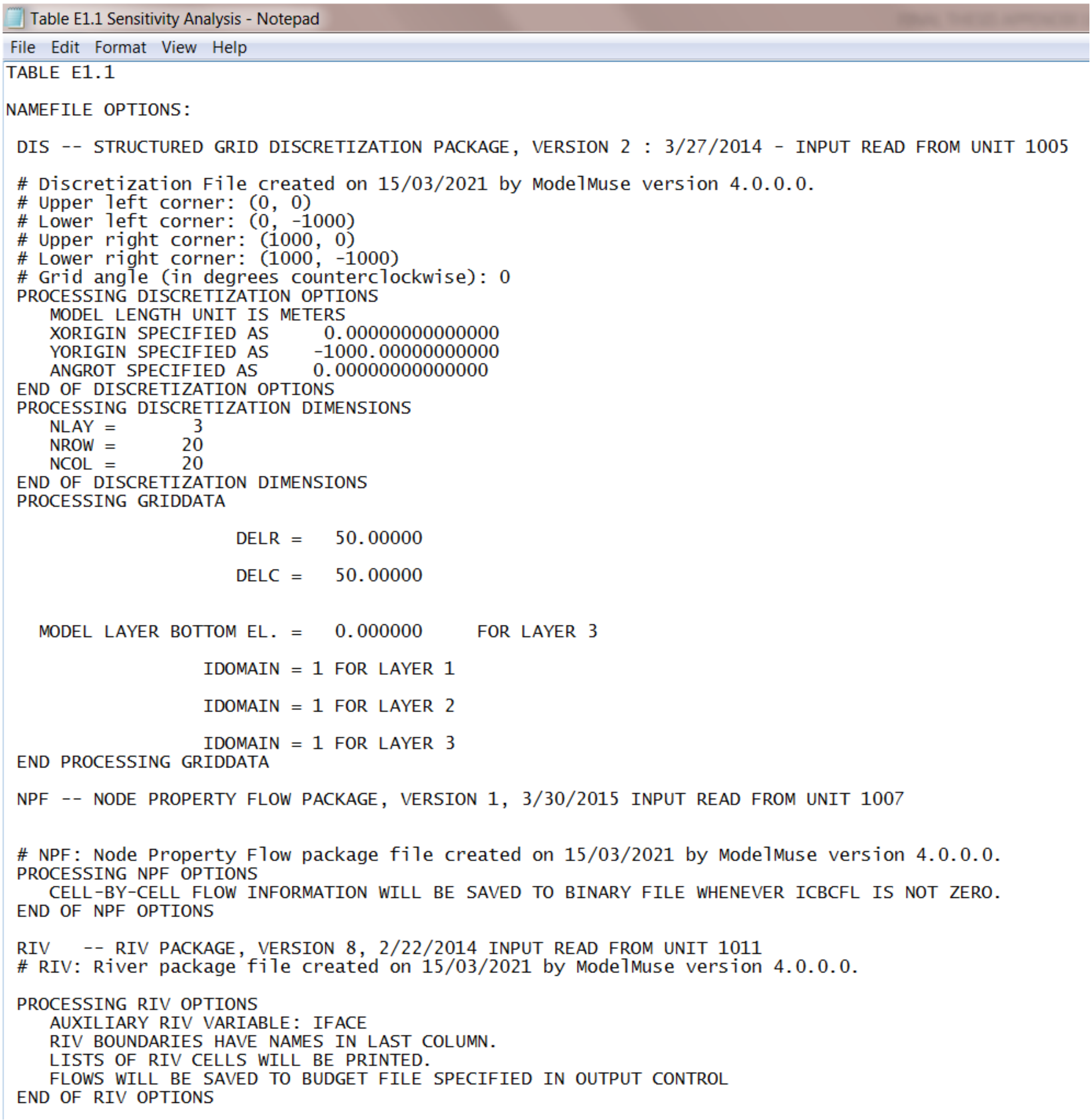


Figure D9.11 Hillshade Map of Study Area



APPENDIX E1 VALIDATION OF GROUNDWATER NUMERICAL MODELS AND PARAMETER SENSITIVITY ANALYSIS

Table E1.1 Appendix E1



```
TABLE E1.1

NAMEFILE OPTIONS:

 DIS -- STRUCTURED GRID DISCRETIZATION PACKAGE, VERSION 2 : 3/27/2014 - INPUT READ FROM UNIT 1005

 # Discretization File created on 15/03/2021 by ModelMuse version 4.0.0.0.
 # Upper left corner: (0, 0)
 # Lower left corner: (0, -1000)
 # Upper right corner: (1000, 0)
 # Lower right corner: (1000, -1000)
 # Grid angle (in degrees counterclockwise): 0
 PROCESSING DISCRETIZATION OPTIONS
    MODEL LENGTH UNIT IS METERS
    XORIGIN SPECIFIED AS      0.00000000000000
    YORIGIN SPECIFIED AS     -1000.00000000000
    ANGROT SPECIFIED AS      0.00000000000000
 END OF DISCRETIZATION OPTIONS
 PROCESSING DISCRETIZATION DIMENSIONS
    NLAY =        3
    NROW =       20
    NCOL =       20
 END OF DISCRETIZATION DIMENSIONS
 PROCESSING GRIDDATA

                     DELR =   50.00000

                     DELC =   50.00000


   MODEL LAYER BOTTOM EL. =   0.000000     FOR LAYER 3

                  IDOMAIN = 1 FOR LAYER 1

                  IDOMAIN = 1 FOR LAYER 2

                  IDOMAIN = 1 FOR LAYER 3
 END PROCESSING GRIDDATA

 NPF -- NODE PROPERTY FLOW PACKAGE, VERSION 1, 3/30/2015 INPUT READ FROM UNIT 1007


 # NPF: Node Property Flow package file created on 15/03/2021 by ModelMuse version 4.0.0.0.
 PROCESSING NPF OPTIONS
    CELL-BY-CELL FLOW INFORMATION WILL BE SAVED TO BINARY FILE WHENEVER ICBCFL IS NOT ZERO.
 END OF NPF OPTIONS

 RIV   -- RIV PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1011
 # RIV: River package file created on 15/03/2021 by ModelMuse version 4.0.0.0.

 PROCESSING RIV OPTIONS
    AUXILIARY RIV VARIABLE: IFACE
    RIV BOUNDARIES HAVE NAMES IN LAST COLUMN.
    LISTS OF RIV CELLS WILL BE PRINTED.
    FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
 END OF RIV OPTIONS
```

```
PROCESSING RIV DIMENSIONS
   MAXBOUND =       13
END OF RIV DIMENSIONS

GHB   -- GHB PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1010
# GHB: General-Head Boundary package file created on 15/03/2021 by ModelMuse version 4.0.0.0.

PROCESSING GHB OPTIONS
   AUXILIARY GHB VARIABLE: IFACE
   GHB BOUNDARIES HAVE NAMES IN LAST COLUMN.
   LISTS OF GHB CELLS WILL BE PRINTED.
   FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
END OF GHB OPTIONS

PROCESSING GHB DIMENSIONS
   MAXBOUND =       19
END OF GHB DIMENSIONS

RCH   -- RCH PACKAGE, VERSION 8, 2/22/2014 INPUT READ FROM UNIT 1012
# RCH: Recharge package file created on 15/03/2021 by ModelMuse version 4.0.0.0.

PROCESSING RCH OPTIONS
   LISTS OF RCH CELLS WILL BE PRINTED.
   FLOWS WILL BE SAVED TO BUDGET FILE SPECIFIED IN OUTPUT CONTROL
   RCH BOUNDARIES HAVE NAMES IN LAST COLUMN.
END OF RCH OPTIONS

PROCESSING RCH DIMENSIONS
   MAXBOUND =      400
END OF RCH DIMENSIONS

IC -- INITIAL CONDITIONS PACKAGE, VERSION 8, 3/28/2015 INPUT READ FROM UNIT 1006
# Initial Conditions Package file created on 15/03/2021 by ModelMuse version 4.0.0.0.
PROCESSING IC OPTIONS
END OF IC OPTIONS
PROCESSING GRIDDATA

                ICELLTYPE = 0 FOR LAYER 1

               ICELLTYPE = 0 FOR LAYER 2

               ICELLTYPE = 0 FOR LAYER 3

                       K =   0.5000000E-03 FOR LAYER 1

                       K =   0.6000000E-04 FOR LAYER 2

                       K =   0.3000000E-03 FOR LAYER 3

                     K33 =   0.5000000E-04 FOR LAYER 1

                     K33 =   0.6000000E-05 FOR LAYER 2

                     K33 =   0.3000000E-04 FOR LAYER 3

                     K22 =   0.5000000E-03 FOR LAYER 1

                     K22 =   0.6000000E-04 FOR LAYER 2

                     K22 =   0.3000000E-03 FOR LAYER 3
```

```
INNER ITERATION SUMMARY
--------------------------------------------------------------------------------------------------------------------------------
    TOTAL      OUTER     INNER                   MAXIMUM CHANGE         MAXIMUM                  MAXIMUM RESIDUAL        MAXIMUM
ITERATION  ITERATION ITERATION                   MODEL-(CELLID)          CHANGE                    MODEL-(CELLID)       RESIDUAL
--------------------------------------------------------------------------------------------------------------------------------
         1         1         1                  1_GWF-(3,20,20)  -1.373791                       1_GWF-(1,20,19)  0.1647869E-02
         2         1         2                  1_GWF-(3,20,20) -0.9764976                       1_GWF-(1,18,19)  0.7020846E-03
         3         1         3                  1_GWF-(3,20,20) -0.8408691                       1_GWF-(1,15,18)  0.3882257E-03
         4         1         4                  1_GWF-(3,20,20) -0.5171118                       1_GWF-(1,14,16)  0.2326444E-03
         5         1         5                  1_GWF-(3,20,20) -0.3967298                        1_GWF-(1,19,2)  0.1984032E-03
         6         1         6                  1_GWF-(3,20,20) -0.2765882                        1_GWF-(1,19,2)  0.1765814E-03
         7         1         7                  1_GWF-(3,20,20) -0.3254925                        1_GWF-(1,20,2)  0.2137637E-03
         8         1         8                  1_GWF-(3,20,20) -0.2967665                        1_GWF-(1,2,19)  0.1489812E-03
         9         1         9                  1_GWF-(3,20,20) -0.2203258                        1_GWF-(1,20,2)  0.1849635E-03
        10         1        10                  1_GWF-(3,20,20) -0.1560289                        1_GWF-(1,20,2)  0.8087187E-04
        11         1        11                  1_GWF-(3,20,20) -0.8883071E-01                    1_GWF-(1,20,2)  0.5913096E-04
        12         1        12                  1_GWF-(3,20,20) -0.4644841E-01                    1_GWF-(1,20,2)  0.2031086E-04
        13         1        13                  1_GWF-(3,20,20) -0.6514703E-02                    1_GWF-(1,20,2)  0.2725236E-04
        14         1        14                  1_GWF-(3,20,20) -0.1264586E-02                     1_GWF-(1,2,6)  0.6428363E-05
        15         1        15                  1_GWF-(3,20,20)  0.1067897E-02                    1_GWF-(1,20,2)  0.5915778E-05
        16         1        16                  1_GWF-(3,20,20)  0.6266560E-03                    1_GWF-(1,19,3) -0.1856984E-05
        17         1        17                  1_GWF-(3,20,20)  0.5509739E-03                    1_GWF-(1,19,3) -0.1099673E-05
        18         1        18                  1_GWF-(3,20,20)  0.3243110E-03                    1_GWF-(1,19,3) -0.6363980E-06
        19         1        19                  1_GWF-(3,20,20)  0.9857659E-04                    1_GWF-(1,19,3) -0.3690588E-06
        20         1        20                  1_GWF-(3,20,20)  0.2233513E-04                    1_GWF-(1,2,20)  0.4055083E-06
        21         1        21                  1_GWF-(3,20,20) -0.8314449E-05                    1_GWF-(1,2,20)  0.3273214E-06
        22         1        22                  1_GWF-(3,20,20) -0.2538162E-04                    1_GWF-(1,2,20)  0.4450782E-06
        23         1        23                  1_GWF-(3,20,20)  0.2006944E-05                    1_GWF-(1,19,2) -0.9445934E-07
        24         2         1                  1_GWF-(3,20,20) -0.3971717E-04                    1_GWF-(1,3,19)  0.8980312E-08
        25         2         2                  1_GWF-(3,20,20) -0.2676982E-05                     1_GWF-(1,2,6) -0.2067375E-08
```

```
 VOLUME BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ---------------------------------------------------------------------------------------------------

    CUMULATIVE VOLUME      L**3       RATES FOR THIS TIME STEP      L**3/T          PACKAGE NAME
    ------------------                 ------------------------                   ----------------

          IN:                                      IN:
          ---                                      ---
                RIV =           0.0000                     RIV =           0.0000     RIV-1
                GHB =       1.3964E-02                     GHB =       1.3964E-02     GHB-1
                RCH =       5.3907E-03                     RCH =       5.3907E-03     RCH-1

           TOTAL IN =       1.9355E-02                TOTAL IN =       1.9355E-02

         OUT:                                     OUT:
         ----                                     ----
                RIV =       1.3269E-02                     RIV =       1.3269E-02     RIV-1
                GHB =       6.0858E-03                     GHB =       6.0858E-03     GHB-1
                RCH =           0.0000                     RCH =           0.0000     RCH-1

          TOTAL OUT =       1.9354E-02               TOTAL OUT =       1.9354E-02

           IN - OUT =       3.4969E-07                IN - OUT =       3.4969E-07

 PERCENT DISCREPANCY =               0.00     PERCENT DISCREPANCY =               0.00


          TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH  1.0000     1.66667E-02  2.77778E-04  1.15741E-05  3.16881E-08
 STRESS PERIOD TIME  1.0000     1.66667E-02  2.77778E-04  1.15741E-05  3.16881E-08
         TOTAL TIME  1.0000     1.66667E-02  2.77778E-04  1.15741E-05  3.16881E-08
```

APPENDIX G: RAINFALL AND TEMPERATURE ANALYSIS

Appendix G1: Rainfall and Temperature Monthly Trend Maps

Figure G1.1 January Monthly Rainfall and Temperature Trend Map

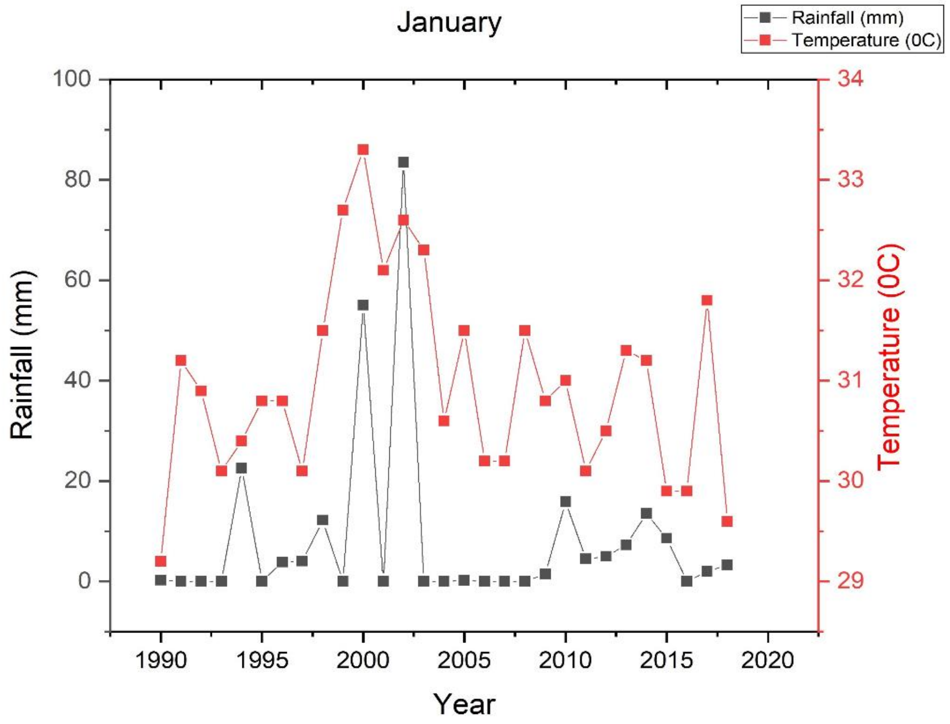


Figure G1.1 January rainfall and temperature trend (Source: authour's construction)

Figure G1.1 January rainfall and temperature trend (Source: authour's construction)

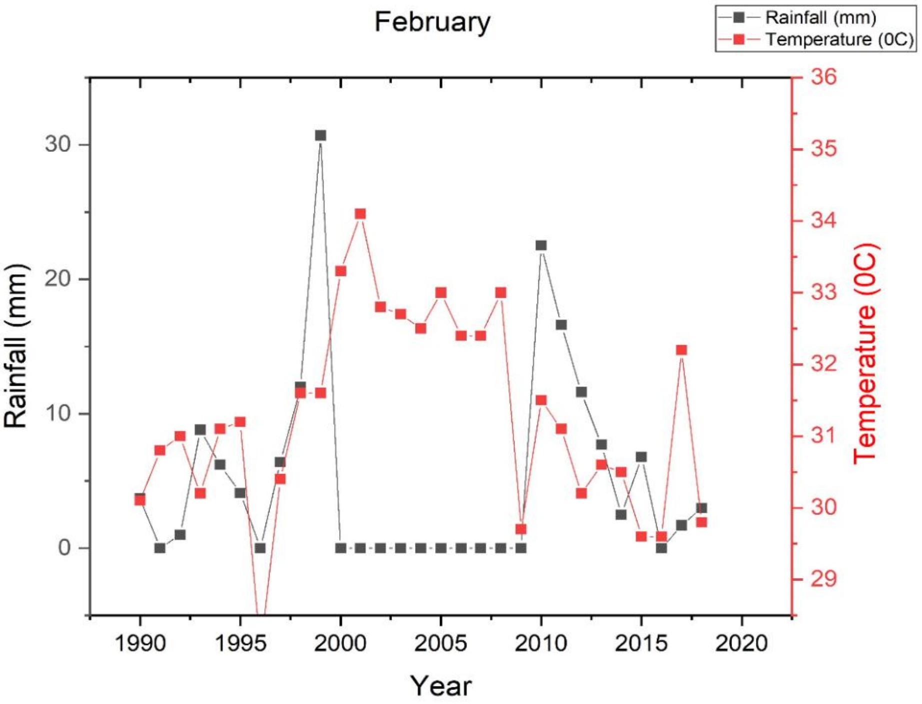


Figure G1.2 February rainfall and temperature trend (Source: authour's construction)

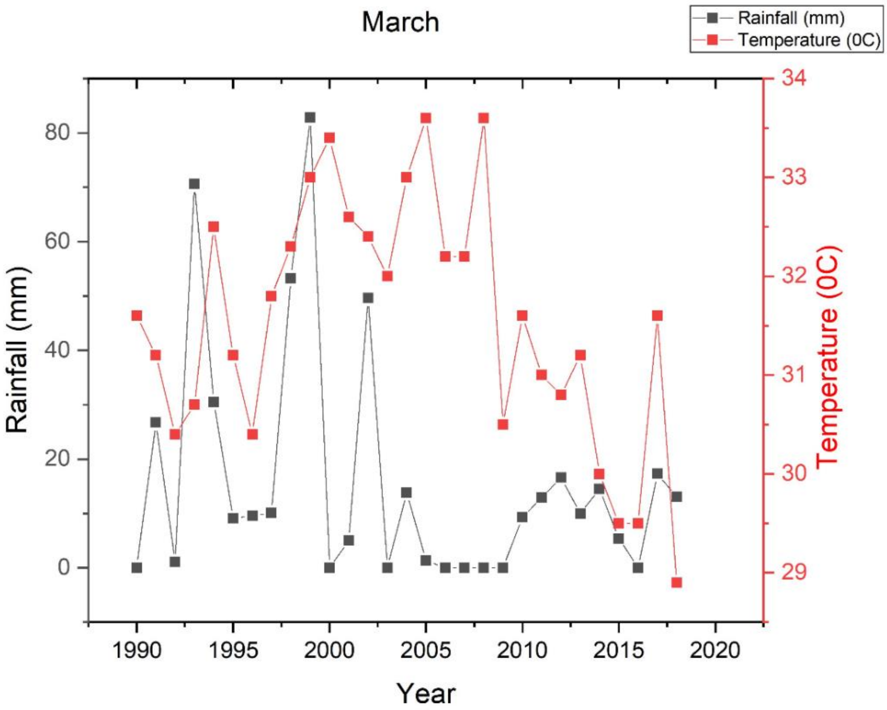


Figure G1.3 March rainfall and temperature trend (Source: authour's construction)

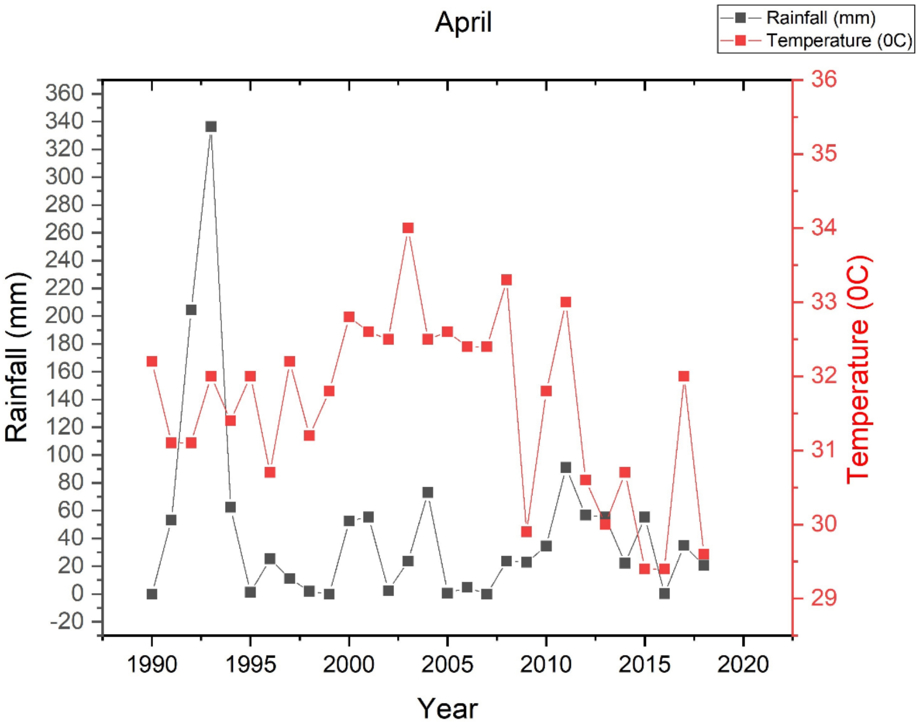


Figure G1.4 April rainfall and temperature trend (Source: authour's construction)

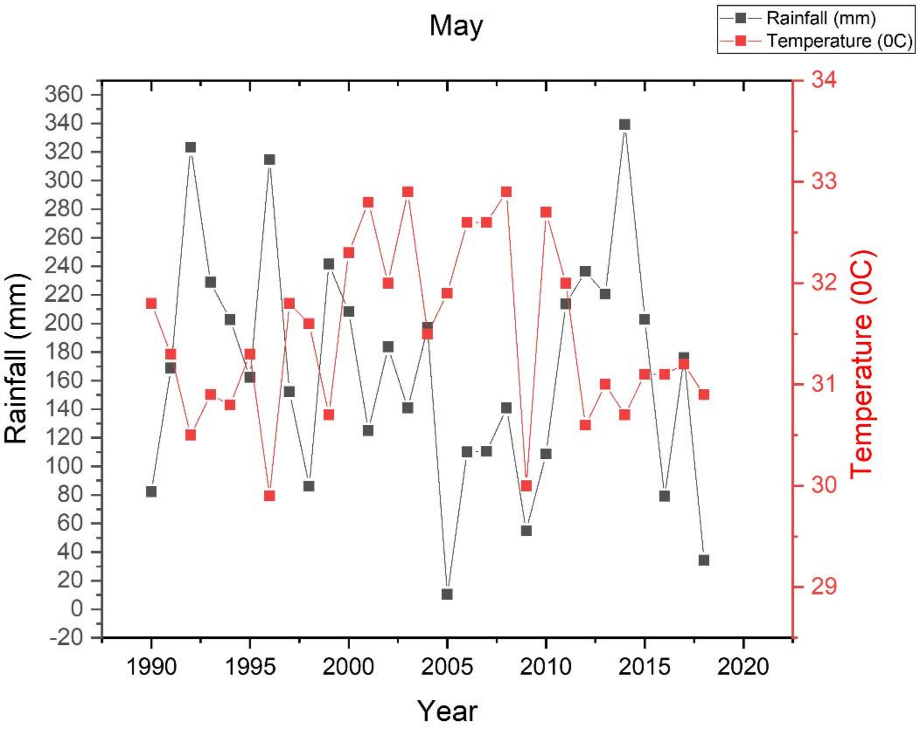


Figure G1.5 May rainfall and temperature trend (Source: authour's construction)

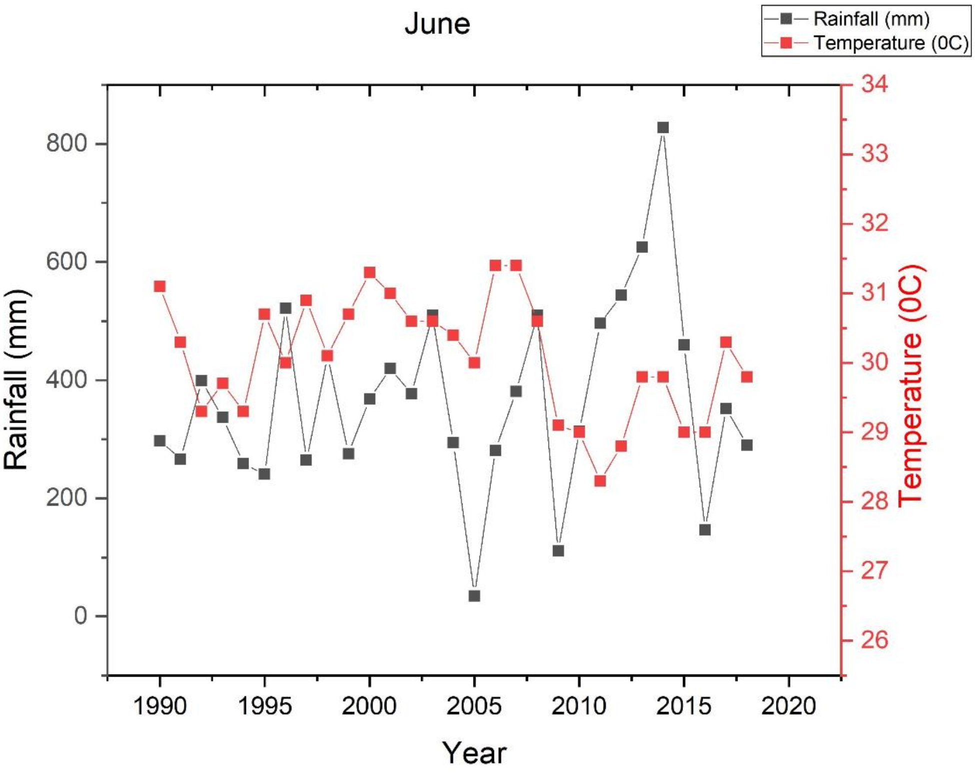


Figure G1.6 June rainfall and temperature trend (Source: authour's construction)

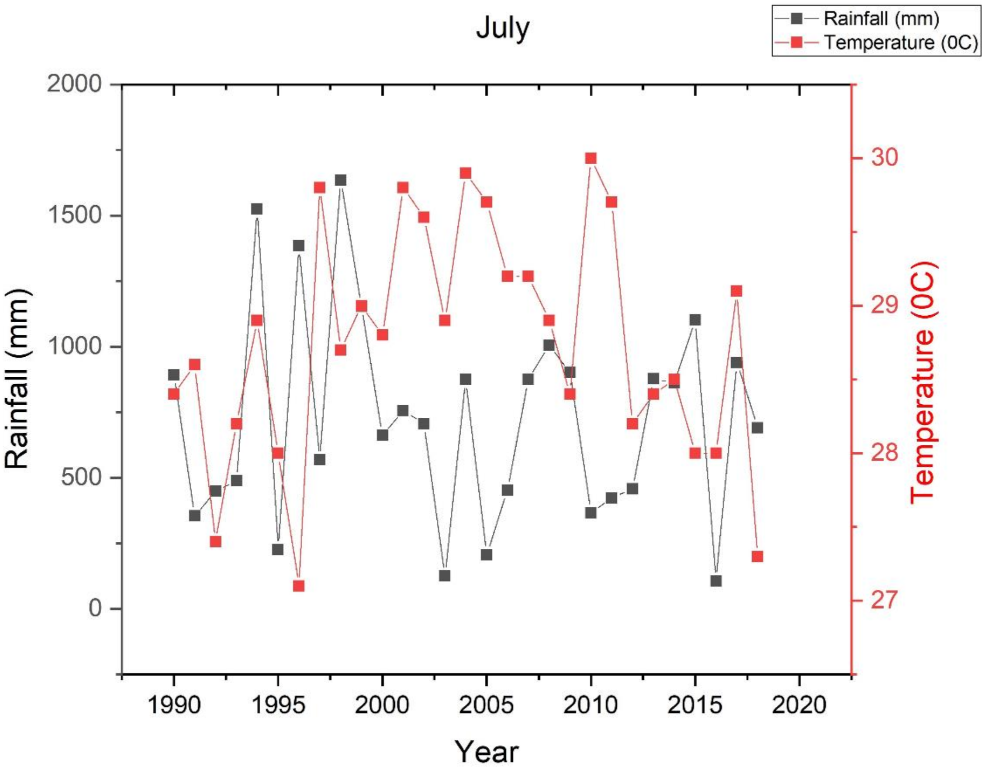


Figure G1.7 July rainfall and temperature trend (Source: authour's construction)

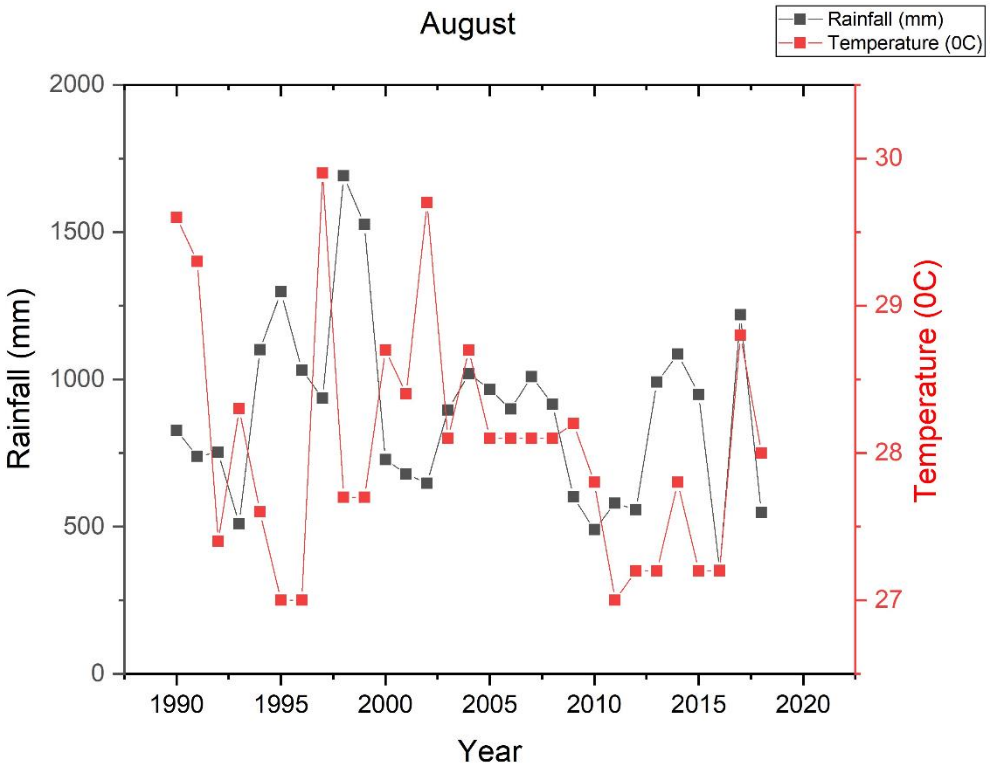


Figure G1.8 August rainfall and temperature trend (Source: authour's construction)

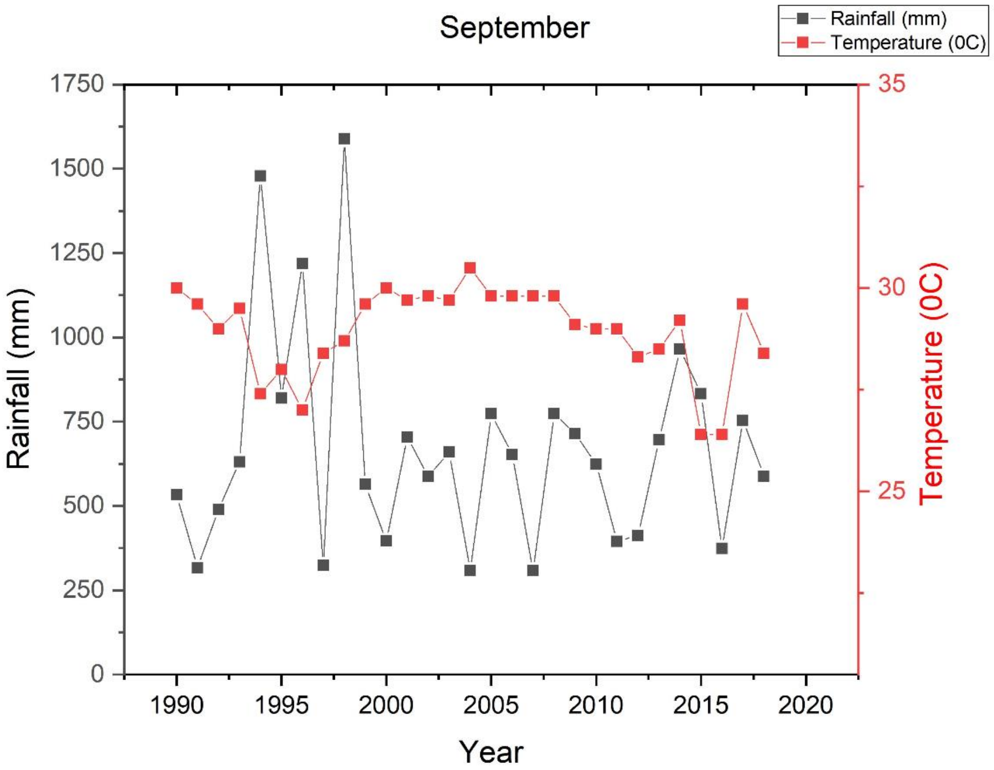


Figure G1.9 September rainfall and temperature trend (Source: authour's construction)

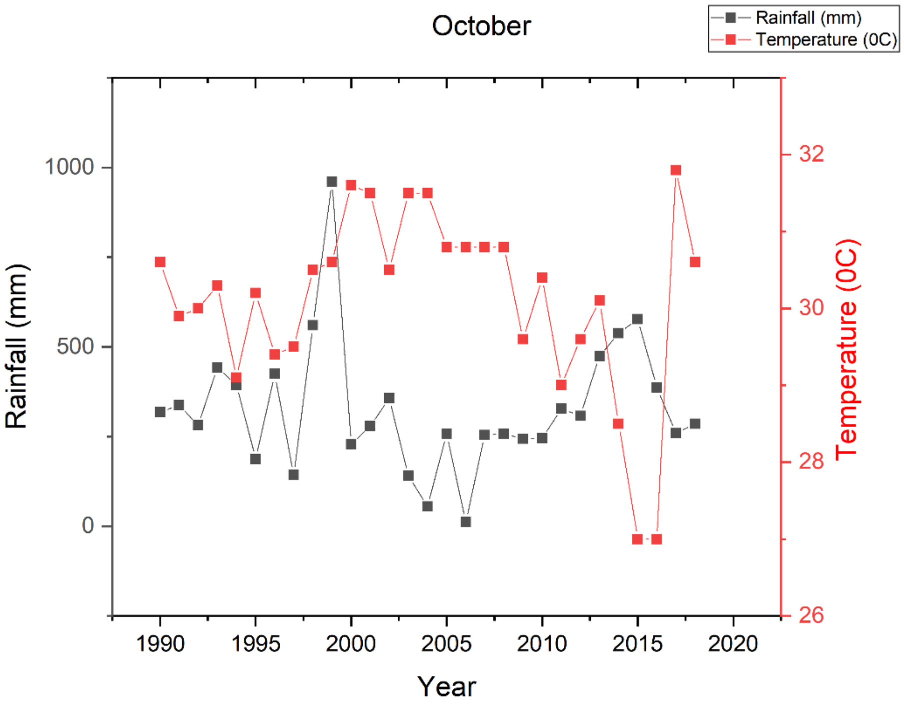


Figure G1.10 October rainfall and temperature trend (Source: authour’s construction)

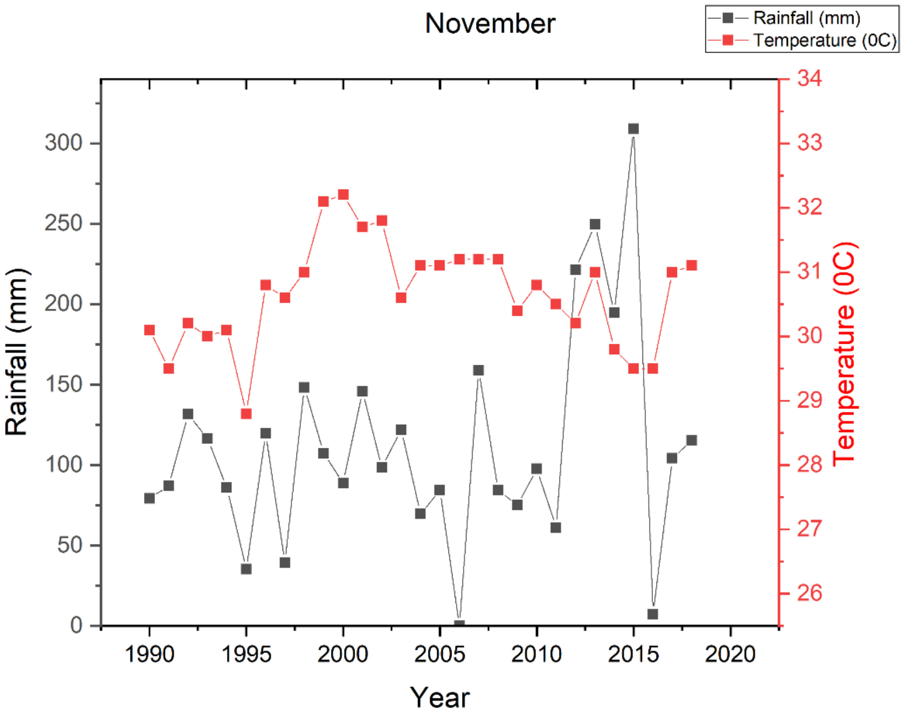


Figure G1.11 November rainfall and temperature trend (Source: authour’s construction)

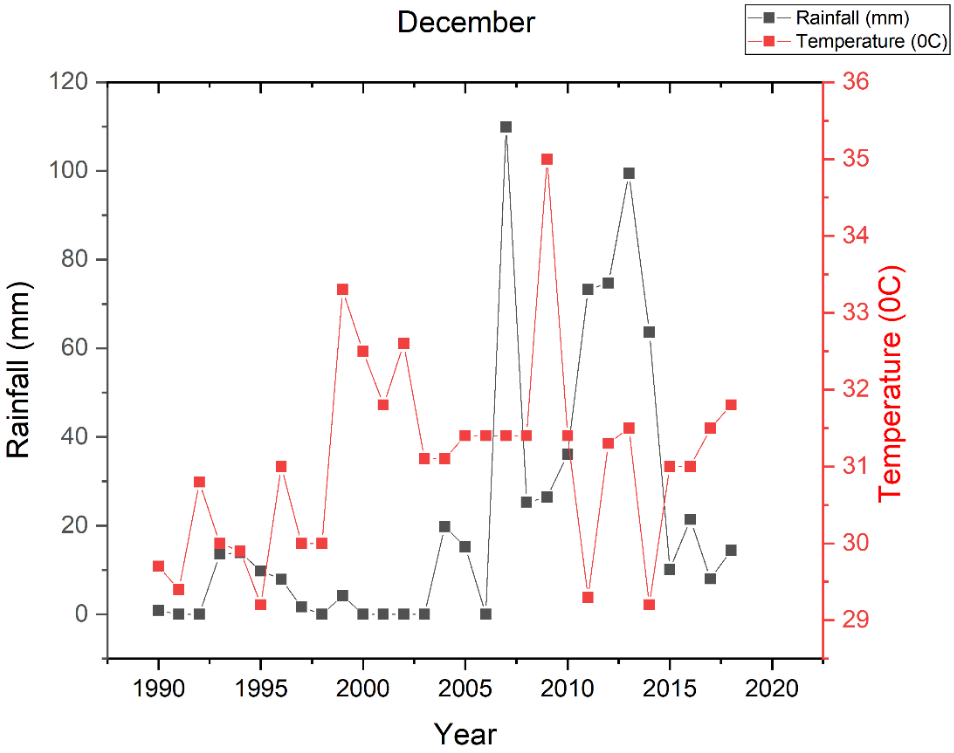


Figure G1.12 December rainfall and temperature trend (Source: authour’s construction)

APPENDIX G: RAINFALL AND TEMPERATURE ANALYSIS

Appendix G2: Rainfall and Temperature Seasonal Trend Maps (Pre-Monsoon, Monsoon and Post-Monsoon)

Figure G2.1 Pre-Monsoon Rainfall and Temperature Seasonal Trend Map

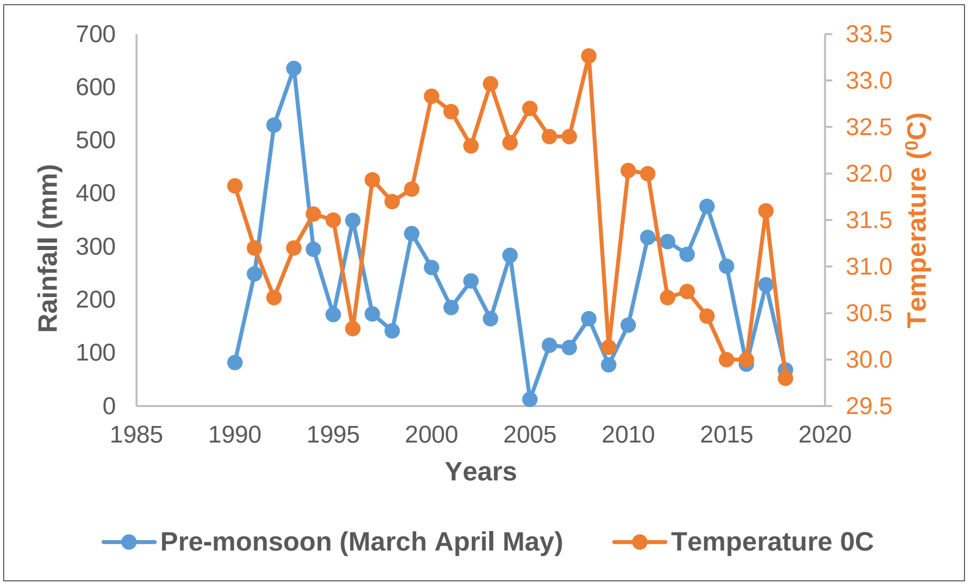


Figure G2.5 Pre-Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

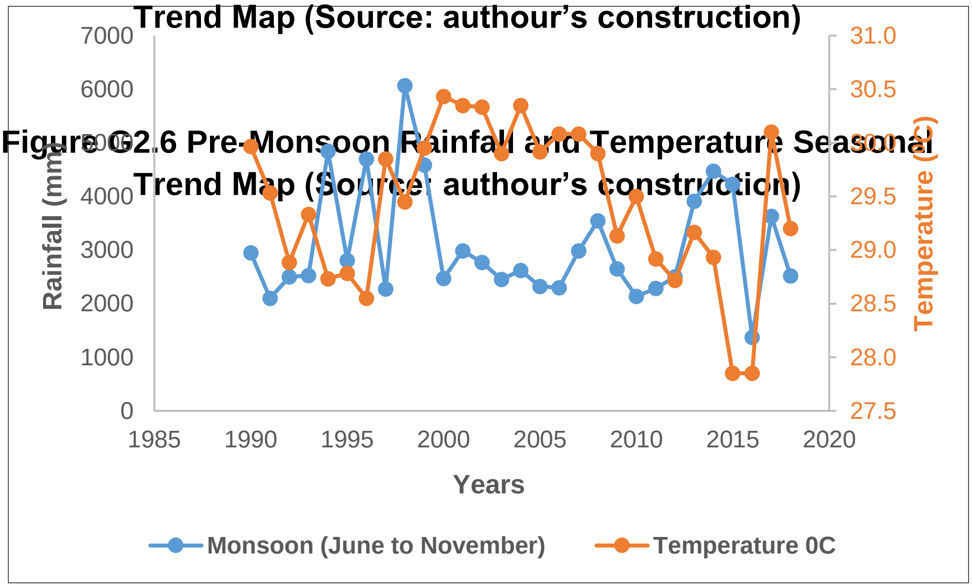


Figure G2.6 Pre-Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

Figure G2.2 Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

Figure G2.4 Pre-Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)Figure G2.2 Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

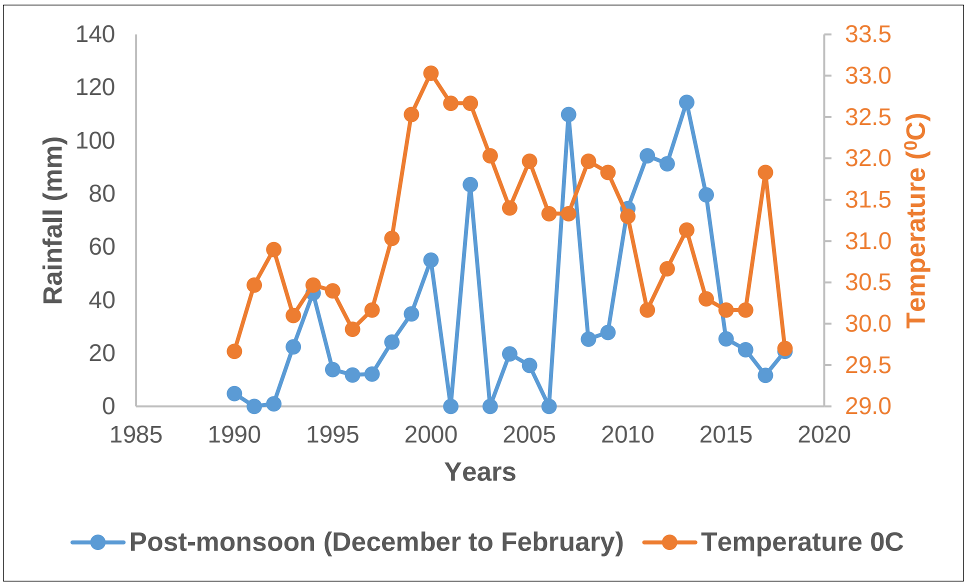


Figure G2.3 Post-Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

Figure G2.3 Post-Monsoon Rainfall and Temperature Seasonal Trend Map (Source: authour's construction)

CONVERSION FACTORS

Multiply	By	To obtain
cubic metre per second (m^3/s)	1000	litre per second (l/s)
cubic metre per second (m^3/s)	3600	cubic metre per hour (m^3/hr)
cubic metre per second (m^3/s)	60	cubic metre per minutes (m^3/min)
cubic metre per second (m^3/s)	86400	cubic metre per day (m^3/d)
cubic metre per second (m^3/s)	3.154e+7	cubic metre per year m^3/yr
cubic metre per minute (m^3/min)	1000	litre per minute (l/min)
cubic metre per minute (m^3/min)	60	cubic metre per hour (m^3/hr)
cubic metre per minute (m^3/min)	1440	cubic metre per day (m^3/d)
cubic metre per minute (m^3/min)	5.25e+5	cubic metre per year (m^3/yr)
cubic metre per hour (m^3/hr)	1000	litre per hour (l/hr)
cubic metre per hour (m^3/hr)	24	cubic metre per day (m^3/d)
cubic metre per hour (m^3/hr)	8760	cubic metre per year (m^3/yr)
cubic metre per day (m^3/d)	1000	litre per day (l/day)
cubic metre per day (m^3/d)	365	cubic metre per year (m^3/yr)
metre (m)	1000	litre (l)
metre per second (m/s)	86400	metre per day (m/d)
metre square per second (m^2/s)	1000	litre per second (l/s)
metre square per second (m^2/s)	1000	metre square per day (m^2/d)
square kilometre (km^2)	1e+6	square metre (m^2)

GLOSSARY

Alluvial aquifer - generally shallow sand and gravel deposits laid down over time in a river channel or floodplain. The name "alluvial" refers to the loose, unlayered nature of the material – often silt, clay, sand, and gravel, deposited by running water in and around rivers

Anisotropy - The condition of having different properties in different directions.

Anthropogenic materials are materials introduced into the environment primarily or exclusively by human activities. Such (inorganic and organic) chemicals, which originate in agricultural, industrial and domestic activities, may be introduced into the aqueous phase as it moves (=percolates) through the unsaturated zone.

Aquifer system - A body of permeable and poorly permeable material that functions regionally as a water-yielding unit; it comprises two or more permeable beds separated at least locally by confining beds that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system; includes both saturated and unsaturated parts of permeable material.

Aquifer test - A test to determine hydrologic properties of the aquifer involving the withdrawal of measured quantities of water from or addition of water to a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or additions.

Aquifer - A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Base flow - That part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge.

Capillary fringe - The lower subdivision of the unsaturated zone immediately above the water table in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by capillary forces.

Cone of depression - A depression of the potentiometric surface in the shape of an inverted cone that develops around a well which is being pumped.

Cone of impression - A rise of the potentiometric surface in the shape of a cone that develops around an injection well.

Confined aquifer - An aquifer bounded above and below by confining units of distinctly lower permeability than that of the aquifer itself.

Discharge area - An area in which groundwater is discharged to the land surface, surface water, or atmosphere.

Drawdown - The vertical distance the water elevation is lowered or the reduction of the pressure head due to the removal of water from a hydrogeologic unit.

Flow path - The subsurface course a water molecule or solute would follow in a given groundwater velocity field.

Gaining stream - A stream or reach of a stream whose flow is being increased by inflow of groundwater.

Groundwater divide - A ridge in the water table or other potentiometric surface from which groundwater moves away in both directions normal to the ridge line.

Groundwater flow - The movement of water in the zone of saturation.

Groundwater mound - A raised area in a water table or other potentiometric surface created by groundwater recharge.

Groundwater recharge [mm/yr, mm/d] - Inflow of water to a groundwater body from the surface. Infiltration of precipitation and its movement to the water table is one form of natural recharge. Many methods have been devised to increase natural recharge to utilise aquifer storage, termed artificial or managed aquifer recharge.

Groundwater system - A groundwater reservoir and its contained water. Also, the collective hydrodynamic and geochemical processes at work in the reservoir.

Head, static - The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

Heterogeneity - A characteristic of a medium in which material properties vary from point to point.

Homogeneity - A characteristic of a medium in which material properties are identical everywhere.

Hydraulic conductivity (K) [m/d, m/s] - The rate of flow of water through a porous medium /volume of water that will move through a medium in a unit of time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow.

Hydraulic gradient - Slope of the water table or potentiometric surface. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head [m] - The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

Hydrogeologic unit - Any soil or rock unit or zone which by virtue of its hydraulic properties has a distinct influence on the storage or movement of groundwater.

Hydrologic properties - Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.

Infiltration rate - The rate at which a soil or rock under specified conditions absorbs falling rain, melting snow, or surface water expressed in depth of water per unit time.

Infiltration - The downward entry of water into the soil or rock.

Losing stream - A stream or reach of a stream in which water flows from the stream bed into the ground. Synonymous with influent stream.

Moisture content - The ratio, expressed as a percentage, of either (a) the weight of water to the weight of solid particles expressed as moisture weight percentage or (b) the volume of water to the volume of solid particles expressed as moisture volume percentage in a given volume of porous medium.

Permeability (k) - The property of a porous medium to transmit fluids under hydraulic gradient.

Phreatic surface, or water table - is an imaginary surface that bounds the saturated zone from above. It is defined as the surface at every point of which the water pressure is atmospheric.

Piezometer - A devise used to measure groundwater pressure head at a point in the subsurface.

Pumping test - A field testing procedure to quantify aquifer properties at a site involving pumping water out of (or less commonly injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata. There are several different procedures employed depending on the physical properties to be quantified.

Recharge [mm] - The process of addition of water to the saturated zone; also the water added. The quantity of water that is added to a groundwater reservoir from areal distributed sources such as the direct infiltration of rainfall or leakage from an adjacent formation or from a watercourse crossing the aquifer.

Recharge area - An area in which water reaches the zone of saturation by surface infiltration.

Recharge capacity - The ability of the soils and underlying materials to allow precipitation and runoff to infiltrate and reach the zone of saturation.

Saturated zone - Those parts of the earth's crust in which all voids are filled with water under pressure greater than atmospheric.

Soil moisture - Subsurface liquid water in the unsaturated zone expressed as a fraction of the total porous medium volume occupied by water. It is less than or equal to the porosity, n.

Soil-water pressure - The pressure (positive or negative), in relation to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water.

Specific Capacity (S_C) [l/s/m, m^2/d, m^3/d/m] - The rate of discharge of water from the well divided by the resulting drawdown on the water level within the well.

Specific discharge - The rate of discharge of groundwater per unit area of a porous medium measured at right angle to the direction of flow. Synonymous with flow velocity or specific flux.

Specific storage Ss [m^{-1}] - Specific storage of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head.

Specific Yield Sy [dimensionless] - The amount of water in storage released from a column of aquifer of unit cross sectional area under unit decline of head. Expressed as a dimensionless proportion of the saturated mass of that aquifer unit. Effectively synonymous with the Storativity in an unconfined aquifer. Equivalent to Effective Porosity.

Specific yield - The ratio of the volume of water which the porous medium after being saturated, will yield by gravity to the volume of the porous medium.

Storage coefficient - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (virtually equal to the specific yield in an unconfined aquifer).

Storativity (Coefficient of Storage) S [dimensionless] - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Subsurface water - All water that occurs below the land surface.

Surface supply - water supply obtained from streams, lakes, and reservoirs.

Sustainable yield- the maximum quantity of water, calculated over a base period representative of longterm conditions in the basin and including any temporary surplus, that can be withdrawn annually from a groundwater supply without causing an undesirable result.

Transient - A pulse dampened oscillation or other temporary phenomena occurring in a system prior to reaching a steady-state condition.

Transmissivity T [m^2/d, m^2/s] - The integral of the hydraulic conductivity of an aquifer over its saturated thickness. It relates to the ability of an aquifer to transmit water through its entire thickness.

Unconfined Aquifer - A partially saturated aquifer which contains a water table which is free to fluctuate vertically under atmospheric pressure in response to discharge or recharge.

Unconsolidated - A deposit consisting of loose grains that are not held together by cement. River terrace deposits are a typical example of an unconsolidated aquifer.

Unsaturated flow - The movement of water in a porous medium in which the pore spaces are not filled to capacity with water.

Unsaturated Zone or Vadose Zone - The zone between the land surface and the water table. It includes the capillary fringe and may contain water under pressure less than that of the atmosphere.

Unsaturated zone - The zone between the land surface and the water table.

Water budget - an accounting of the total groundwater and surface water entering and leaving a basin including the changes in the amount of water store

Water content - The amount of water lost from the soil after drying it to constant weight at 1050C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil. Water-holding capacity - See specific retention.

Water Table - The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. The static water level in a well in an unconfined aquifer.

Water table - The upper surface of a zone of saturation except where that surface is formed by a confining unit.

Well - A bored, drilled or driven shaft, or a dug hole, whose depth is greater than the largest surface dimension.

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