

**DATA ACQUISITION MODELS
FOR
GROUNDWATER ASSESSMENT AND MANAGEMENT
IN THE URBAN AND RURAL AREAS OF ZAMBIA**

0872730

THESIS
PhD

MPA

2008

C1

By

NGOSA HOWARD MPAMBA

A Thesis

Submitted to the Directorate of Research and Graduate Studies of the
University of Zambia in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Hydrogeology – School of Mines



University of Zambia
Lusaka, Zambia



DECLARATION

This thesis was written and submitted in accordance with the rules and regulations governing the award of the Doctor of Philosophy Degree in Hydrogeology of the University of Zambia. I further declare that the thesis has neither in part nor in whole been presented as substance for award of any degree, either to this or any other University. Where other people's work has been drawn upon, acknowledgement has been made.

Signature of author:

A handwritten signature in black ink, appearing to read 'A. Hamby', is written above a horizontal dotted line.

CERTIFICATE OF APPROVAL

This thesis of **Ngosa Howard Mpamba** is approved as fulfilling the requirements for the award of the **DOCTOR OF PHILOSOPHY DEGREE in Hydrogeology** by the University of Zambia.


Chairman of the Board of Examiners:

Name: **DR. STEPHENS KAMBANI**

Signature: 


Internal Examiners:

Name: **DR. DANIEL C.W. NKHUWA**

Signature: 

Address: The University of Zambia, School of Mines, Department of Geology,
Great East Road, P.O. Box 32379, Lusaka, Zambia


Name: **DR. BENSON H. CHISHALA**

Signature: 

Address: The University of Zambia, School of Agricultural Sciences, Department
of Soil Science, Great East Road, P.O. Box 32379, Lusaka, Zambia

External Examiner:

Name: **PROF. TAMIRU ALEMAYEHU ABIYE**

Signature: 

Address: University of the Witwatersrand, School of Geosciences, Private Bag 3,
P.O. Box Wits 2050, Johannesburg, South Africa

School of Mines, Department of Geology

University of Zambia

Lusaka, Zambia

0278796

SUPERVISORS:

Dr. D.C.W. Nkhuwa (University of Zambia)

Dr. C. Mdala (University of Zambia)

Prof. I.A. Nyambe (University of Zambia)

Prof. Dr. Naoaki Shibasaki (Fukushima University – Japan)

Prof. Dr. Stefan Wornlich (Ruhr University Bochum – Germany)

NUMBER OF PAGES: xxxvi, 258

©Ngosa Howard Mpamba, Lusaka, Zambia, 2008

ABSTRACT

Availability of data and information on groundwater is important for sustainable utilisation of groundwater resources. Its assessment, development, utilisation and management largely depend on data acquisition; the aspect often overlooked or inconsistently carried out in most groundwater development projects in Zambia. The study attempts to develop a model for data acquisition procedure that recognises three sets of groundwater data and information that need to be collected in a participatory approach in the urban and rural areas of Zambia. The data sets are hydrogeological, groundwater quality and groundwater levels. Acquisition of these data sets is approached in two levels. Firstly, collection of the data sets as one entity with the involvement of stakeholders for potential use to support sustainable groundwater resources utilisation. Secondly, development of the mechanism as well as tools to facilitate data collection, transmission, storage, analysis and dissemination.

The methodology begins from an explicitly empirical conception of using the data set relations to investigate the quantity and quality of groundwater resources. Furthermore, it examines the nature of failure to collect groundwater data and information in Zambia, which has arisen due to mechanisms as well as tools for data acquisition that are weak, inappropriate or non-existent. The approach gives insight into some of the technical standards and regulations required to guide groundwater development and ensure submission of such data and information to relevant institutions. Groundwater occurrence, diversity, abstraction, replenishment and storage have been investigated in the study areas using data sets proposed for acquisition. Groundwater data and

information captured with inclusion of global positioning system (GPS), shows that the approach would render existing hydrogeological data useful for various analyses. The main aspects in the collection of the data sets at national scale must:

- recognize the borehole completion report form as official for collection of hydrogeological data;
- evaluate groundwater quality during construction of every borehole as a national interest,
- ensure regular water quality evaluation and groundwater level measurement for selected aquifers as well as the national groundwater observation network to provide data to the National Groundwater Data Base to facilitate efficient resource management,
- Incorporate a borehole numbering system based on the surface water basin blocks in the Zambezi and Congo River Basins, to facilitate sustainable groundwater resources development that recognises surface and groundwater interaction.

The thesis, through evaluation of past and current groundwater development approaches highlights the method used to collect data in the study areas, providing insight that data must be collected in the same manner from boreholes constructed in urban and rural areas of Zambia, as a way of promoting systematic data capture, as well as a better understanding of the economic value of groundwater resources. Furthermore, it reinforces the identified need to establish a Data Base through an integrated approach that allows most stakeholders to collaborate and participate in data acquisition and storage for effective water resources management.

ACKNOWLEDGEMENTS

The Ministry of Energy and Water Development through the Department of Water Affairs funded the PhD studies and supported the research through the on going groundwater development programmes in Lusaka urban and adjacent areas, and Gwembe District. Cooperating partners funded the Gwembe District borehole drilling programme for Trachoma control. I therefore wish to show my gratitude to the Director of the Department of Water Affairs, Mr. Adam Hussen, for all the logistical support, Colin B. Glassco the cooperating partner for MEWD on the Trachoma Control Project, Dr. Wiafe Kwasi Boateng for initiating the Trachoma Control Project in Gwembe District, and all my workmates who participated in any way during the research period. Thanks are also due to Mr. O. Silembo for taking interest in discussing the water quality parameters and participation in groundwater sampling.

Lusaka Water and Sewerage Company played an important role in providing groundwater data and information on all their abstraction boreholes. This was possible through Mr. H. Mtine and Mr. G. Chikama.

Analysis of data and information was completed during the short-term research visit to Ruhr University Bochum in Germany, financed by the Deutscher Akademischer Austausch Dienst (DAAD). I therefore wish to thank DAAD for the financial support, Ms Renate Charlotte with the Germany Embassy in Zambia, Ms Nora Pruefer and Ms Marina Palm of DAAD for efficiently handling all correspondence from DAAD. Thanks are due to Prof. Dr. S. Wohnlich for the short-term research visit, Dr. Frank Wisotzky, Dr.

Steffen Bender and the following staff I worked and had discussions with during the short term research visit: Till Rubbert, Tillman Mieseler, Molla Demlie, Stephan Lenk, Vera Eisenberg, Kathrin Bitomsky, Eva Krampe, Judith Orilski, Martin Kluge, Doreen Mickie, Mischa Wolfram and Martin Leson.

Technical discussions were held with Mr. A. Hussen, Mr. S.F. Shisala, Mr. P. Chola, Mr. C. Chileshe, Mr. C. Maseka, Mr. S. Kang'omba, Dr. R. Bäumle, Mr. Mwala and Mr. K. Nyundu, which added value to the work presented in the thesis.

This study and the resulting thesis report would not have been realised without dedicated guidance and constructive comments from the supervisors: Dr. D.C.W. Nkhuwa (Zambia), Dr. C. Mdala (Zambia), Prof. I.A. Nyambe (Zambia); Prof. Naoaki Shibasaki (Japan) and Prof. Dr. Stefan Wöhnlich (Germany).

Finally, thanks are due to my wife Julie Mwiinga Mpamba, our daughter Hannah Mwila Mpamba and our son Samuel Mwiinga Mpamba for supporting me and accepting the inconvenience caused during the study period and completion of the thesis.

DEDICATION

This thesis is dedicated to Pastor A.M.C Mpamba and the wife Anna Mwila (Grandparents) who played a big role in my upbringing and education, my late father Oliver Mpamba, mother Susannah Mukuwa for being supportive, Aunt Kapesa Mpamba for requesting and encouraging me to do my PhD studies; and to the Mpamba family as a whole.

TABLE OF CONTENTS

DECLARATION.....	ii
CERTIFICATE OF APPROVAL.....	iii
SUPERVISORS AND NOTICE OF COPYRIGHT.....	iv
ABSTRACT.....	v
ACKNOWLEDGEMENT.....	vii
DEDICATION.....	ix
CONTENTS.....	x
List of Figures.....	xxi
List of Tables.....	xxix
List of Acronyms.....	xxxvi
1.0 Introduction.....	1
1.1 Background.....	3
1.2 Statement of the Problem and Hypothesis.....	4
1.2.1 Hypothesis.....	5
1.2.1.1 Hydrogeological Data.....	5
1.2.1.2 Groundwater Level Data.....	6
1.2.1.3 Groundwater Quality Data.....	6
1.3 Scope of Work.....	7
1.4 Objectives of the study.....	8
1.5 Outline.....	8

2.0 Literature Review.....	11
2.1 Review of Previous Works on Groundwater Monitoring in Zambia.....	11
2.1.1 Hydrogeological Data.....	11
2.1.2 Groundwater Quality Data.....	14
2.1.3 Groundwater Level Data.....	15
2.2 Consultations to Identify Existing Gaps in Knowledge on Data Collection.....	17
2.3 Importance of Groundwater Monitoring in the Water Sector.....	18
2.4 General Climate and Geomorphology of Zambia.....	18
2.4.1 Physiographic and General Information on the Study Areas.....	19
2.4.1.1 Lusaka urban and adjacent areas.....	19
2.4.1.2 Gwembe District.....	21
2.5 Regional Geology and Hydrogeology of Zambia.....	25
2.5.1 Geology.....	25
2.5.1.1 Cenozoic Super Group.....	26
2.5.1.2 Mesozoic Super Group.....	26
2.5.1.3 Karoo Super Group.....	26
2.5.1.4 Lower Palaeozoic Super Group.....	26
2.5.1.5 Katanga Super Group.....	27
2.5.1.6 Basement Complex.....	27
2.5.1.7 Intrusive Rocks.....	27
2.5.2 Hydrogeology.....	27

2.5.2.1	Aquifers where Groundwater flow is mainly in Fissures, Channels and Discontinuities.....	28
2.5.2.2	Aquifers where Intergranular Groundwater flow is dominant.....	29
2.5.2.3	Low Yielding Aquifers with Limited Potential.....	29
2.6	Geology and Hydrogeology of the Study Areas.....	30
2.6.1	Lusaka urban and adjacent areas.....	31
2.6.1.1	Geology.....	31
2.6.1.2	Hydrogeological Setting.....	33
2.6.1.3	Historical and Current Groundwater Development Scenario.....	34
2.6.1.4	Previous Studies on Groundwater Recharge and Water Balance.....	36
2.6.2	Gwembe District.....	38
2.6.2.1	Geology.....	38
2.6.2.2	Hydrogeological Setting.....	40
2.6.2.3	Historical and Current Groundwater Development Scenario.....	40
2.6.2.4	Hydrogeological Studies and Current Groundwater Development...	40
2.6.2.5	Previous Studies on Recharge and Water Balance.....	41
2.7	Groundwater Exploration and Development in Zambia.....	42
2.7.1	Current Groundwater Development Scenario in Zambia.....	43
2.7.1.1	Geophysical Investigation and Drilling.....	43
2.7.1.2	Borehole Drilling Guidelines and Procedure.....	45
2.7.1.3	Drilling Techniques Appropriate for Zambia.....	48
2.8	The Concept of Basin-wide Water Resources Management in Zambia.....	50
2.8.1	Numbering of Mine De-watering Shafts in Zambia.....	52

3.0	Research Methodology.....	53
3.1	Proposed Data Acquisition Model.....	53
3.1.1	Adaptations to the Proposed Data Acquisition Model.....	55
3.1.2	Justification for Proposing the Data Acquisition Model.....	56
3.2	Selection of the Study Areas.....	59
3.3	Field Work and Collection of Data in the Study Areas.....	61
3.3.1	Collection of Hydrogeological Data.....	61
3.3.1.1	Accuracy of Hydrogeological Data Analysis.....	61
3.3.2	Collection of Groundwater Quality Data.....	62
3.3.2.1	Accuracy of Groundwater Quality Data Analysis.....	65
3.3.2.2	Classification of Groundwater Type and for other uses.....	66
3.3.3	Collection of Groundwater Level Data.....	68
3.3.3.1	Accuracy of Groundwater Level Data Analysis.....	72
3.4	Data collection, Transmission, Storage, Analysis and Dissemination.....	77
3.4.1	National Groundwater Database.....	78
4.0	Results and Discussion.....	79
4.1	Groundwater Level fluctuation in the main Aquifer Types in Zambia.....	79
4.2	Lusaka urban and adjacent areas.....	81
4.2.1	Hydrogeological Data Collection.....	81
4.2.1.1	Estimation of Groundwater Abstraction and Aquifer Storage.....	82
4.2.1.2	Aquifer Type and Groundwater Stress Areas.....	93
4.2.1.3	Conceptual Hydrogeological Model.....	99

4.2.2	Groundwater Level Data Collection.....	107
4.2.2.1	Designed Groundwater Monitoring Network for Aquifer Management.....	108
4.2.2.2	The Role of Lusaka South Forest Reserve on Water Resources on the Lusaka Plateau.....	115
4.2.2.3	Evaluation of the Factors affecting Effective Recharge on the Lusaka Plateau.....	125
4.2.2.4	Water Balance and Recharge Estimation.....	134
4.2.2.5	Hypothesis on Regional Groundwater flow in the Katanga Supergroup.....	139
4.2.3	Groundwater Quality Data Collection.....	143
4.2.3.1	Groundwater Type and Hydrochemical Characterisation.....	146
4.2.3.2	Groundwater Quality Evaluation for Groundwater and Irrigation uses.....	150
4.2.3.3	Groundwater Vulnerability Assessment and Mapping.....	153
4.2.3.4	Vulnerability Assessment of the Lusaka urban Aquifers.....	154
4.2.3.5	Effective use of DRASTIC Technique on the Lusaka Plateau.....	163
4.2.4	Water Planning for the Lusaka Plateau.....	164
4.2.4.1	Groundwater Management Strategy for the Lusaka Plateau.....	165
4.2.4.2	Exploitation and Abstraction of Groundwater in Lusaka urban Aquifers.....	167
4.2.4.3	Aquifer and Groundwater System on the Lusaka Plateau.....	169
4.3	Gwembe District.....	173

4.3.1	Hydrogeological Data Collection.....	173
4.3.1.1	Estimation of Groundwater Abstraction and Aquifer Storage.....	173
4.3.1.2	Conceptual Hydrogeological Model.....	178
4.3.2	Groundwater Level Data Collection.....	181
4.3.2.1	Designed Groundwater Monitoring Network for Aquifer Management.....	181
4.3.2.2	Expansion of Groundwater Level Measurements.....	183
4.3.2.3	Water Balance and Recharge Estimation.....	186
4.3.3	Groundwater Quality Data Collection.....	187
4.3.3.1	Groundwater Type and Hydrochemical Characterisation.....	188
4.3.3.2	Groundwater Quality Evaluation for Domestic and Irrigation use.....	193
4.3.3.3	Impact of Groundwater Quality on the Operation and Maintenance of Handpumps.....	197
4.3.3.4	Proposed Groundwater usage in Gwembe District.....	198
4.3.3.5	Exploitation and Abstraction of Groundwater for Munyumbwe Township.....	199
4.4	Borehole Numbering.....	202
4.5	Strategy for Enhancing Groundwater Exploration in Zambia.....	205
4.6.1	Hydrogeological and Water Quality Data.....	206
4.6.2	Groundwater Level Measurement and Routine Water Quality Evaluation.....	207
4.6.3	Database for Storage, Analysis and Dissemination.....	208
4.6	Scientific Contribution of the Study.....	209

4.6.1	Interpretation of Groundwater Abstraction in Lusaka urban.....	209
4.6.2	The Role of Lusaka South Reserve.....	210
4.6.3	Information on Recharge Mechanism and Aquifer System for the Lusaka Plateau.....	210
4.6.4	Design and Documentation of the Lusaka Plateau Groundwater Monitoring Network.....	211
4.6.5	Hypothesis on Regional Groundwater Flow.....	211
4.6.6	Documentation on the Aquifer Systems of Gwembe District.....	211
4.6.7	Documentation on the Aquifer around Munyumbwe Township in Gwembe District.....	211
4.6.8	Documentation of the Borehole Numbering System.....	212
4.6.9	Documentation on Groundwater Observation Boreholes.....	212
4.6.10	Document on the Data Acquisition Model for Groundwater Data and Information Collection.....	212
4.7	Further Research needs in Hydrogeology in Zambia.....	212
5.0	Conclusion.....	213
6.0	References.....	214
APPENDIX – A1.....		226
▶	Table 3.3 Water Quality Guidelines for Drinking Water.....	226

APPENDIX – A2.....	227
▶ Table 3.4 Criteria for Evaluation of Groundwater for Irrigation.....	227
APPENDIX – B1.....	229
▶ Groundwater Level Observation Data Form.....	229
APPENDIX – B2.....	230
▶ Borehole Completion Report for observation borehole MB1 (BH1).....	230
▶ Borehole Completion Report for observation borehole MB1 (BH2).....	231
▶ Borehole Completion Report for observation borehole MB2.....	232
APPENDIX – B3.....	233
▶ Mongu DWA Groundwater Level Measurements.....	233
APPENDIX – C1.....	234
▶ Sample of the excel electronic database for boreholes located in Lusaka urban and adjacent areas.....	234
APPENDIX – C2.....	235
▶ Table 4.8 Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2002 to March 2003.....	236
▶ Table 4.9 Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2003 to March 2004.....	237

▶ Table 4.10	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2004 to March 2005.....	238
▶ Table 4.11	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2005 to March 2006.....	239
▶ Table 4.12	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2006 to March 2007.....	240
▶ Table 4.13	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2007 to December 2007.....	241
APPENDIX – C3.....		242
▶ Table 4.16	Sheki Sheki DWA Met. Station rainfall records for 2003/2004 Rainy Season (after Siwale, 2006).....	242
▶ Table 4.17	Sheki Sheki DWA Met. Station rainfall records for 2004/2005 Rainy Season (after Siwale, 2006).....	243
▶ Table 4.18	Sheki Sheki DWA Met. Station rainfall records for 2005/2006 Rainy Season (after Siwale, 2006).....	244
APPENDIX – D1.....		245
▶ Table 4.30	Evaluation of Water Quality Results for the Lusaka Plateau with Stiffs Method.....	245

APPENDIX – E1.....	246
▶ Table 4.67 Projected groundwater level reading at observation boreholes for Lusaka Plateau using increased abstraction scenarios expected in the absence of groundwater control.....	246
APPENDIX – F1.....	247
▶ Sample of the excel electronic database for boreholes located in Gwembe District.....	247
APPENDIX – F2.....	248
▶ Table 4.51 Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	248
▶ Table 4.52 Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	249
▶ Table 4.53 Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	250
▶ Table 4.54 Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	251
APPENDIX – G1.....	252
▶ Table 4.59 Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	253

- ▶ Table 4.60 Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....254
- ▶ Table 4.61 Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....255
- ▶ Table 4.62 Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....256
- ▶ Table 4.63 Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....257

- APPENDIX – G2.....252
- ▶ Figure 4.64 Summarised flow chart of the proposed groundwater data and information capture model.....258

LIST OF FIGURES

Figure 2.1	Borehole Completion Report Form used by DWA to capture borehole drilling data and information.....	12
Figure 2.2	Map showing drainage in the three main sub-river basins in Lusaka urban and adjacent areas.....	20
Figure 2.3	Crossing a flush stream in Gwembe District when water flow depth has reduced.....	23
Figure 2.4	Photos showing dense grass and heavy foliage on trees in the wet season but absent in the dry season in Gwembe District.....	23
Figure 2.5	Map showing location of Munyumbwe the administrative centre of Gwembe District.....	24
Figure 2.6	Major continental and regional tectonic events: Mwembeshi shear zone associated thrusting and transport in the Lufilian Arc and the Zambezi thrust belt (after Daly, 1988; Peters, 1990; Nkhuwa, 1996).....	28
Figure 2.7	Map of Zambia showing the three main types of aquifers (Source: JICA Report, 1995).....	30
Figure 2.8	Simplified geological map of the Lusaka Plateau (after: Simpson et al., 1963).....	32
Figure 2.9	The uplift of the Lusaka Plateau due to tectonic events (Nkhuwa, 1996).....	33
Figure 2.10	Map of the geology of Southern Province (Source: Geological Department of Zambia).....	39

Figure 3.1	The data acquisition model used to capture groundwater data and information in the studied areas.....	54
Figure 3.2	Map of Zambia showing the study areas: Gwembe District, Lusaka urban and Mongu.....	60
Figure 3.3	Map of Zambia showing groundwater monitoring stations in the three main aquifer types in the studied areas: MB – 1 comprises two boreholes in Lusaka Urban, MB – 2 comprises one borehole in Gwembe District and MB – 3 comprises one borehole in Mongu.....	69
Figure 3.4	Section for Observation Borehole MB – 2 located in the sandstone-mudstone intercalation.....	71
Figure 3.5	Section for Observation Borehole BH1 located in the schist.....	72
Figure 3.6	Section and picture for Observation Borehole BH2 located in the carbonates in Lusaka urban.....	72
Figure 3.7	Distribution of Mean Annual Precipitation in Zambia in relation to the neighbouring countries (Ashton <i>et al.</i> , 2001).....	74
Figure 3.8	Location of Meteorological Stations and Voluntary Rainfall Stations in Zambia.....	75
Figure 4.1	Groundwater Monitoring Borehole MB – 3 in the aquifer type where intergranular groundwater flow dominates (March to July 2002).....	80
Figure 4.2	Groundwater Monitoring Borehole MB – 1 (BH1) in the aquifer type where groundwater flow is mainly through fissures, channels or discontinuities (March to July 2004).....	80

Figure 4.3 Groundwater Monitoring Borehole MB – 2 in the low yield aquifer type with limited potential (March to July 2004).....80

Figure 4.4 Map showing distribution of high and low yielding boreholes in the Cheta and Chunga Formations; and Lusaka Dolomite on Lusaka Plateau.....84

Figure 4.5 Map showing groundwater flow and the main recharge area: February to April 2005.....89

Figure 4.6 Photos showing bare soil cover in a portion of Forest 26 in a depression with Forest 55 at the horizon (top) and Chilenje area at the horizon (bottom). This forms the main recharge area for aquifers on Lusaka Plateau.....90

Figure 4.7 Groundwater flow pattern for the period August to October 2004 in the dry season on Lusaka Plateau.....91

Figure 4.8 Elevation difference between Lusaka Plateau and its edges (Prepared from USGS DEM)92

Figure 4.9 Distribution of soil cover over the aquifers in Lusaka urban and adjacent areas.....93

Figure 4.10 Distribution of permeable and low permeable soil layers over the aquifers in Lusaka urban and adjacent areas.....94

Figure 4.11 Map showing distribution of the main groundwater intersection depth in aquifers in Lusaka urban and adjacent areas.....95

Figure 4.12 Depiction of groundwater stress when Drawdown is located at point C below the main intersection depth at point B.....96

Figure 4.13	Map showing distribution of groundwater stressed areas in Lusaka urban and adjacent areas.....	98
Figure 4.14	Geological Model and drainage density for Lusaka urban and adjacent areas.....	100
Figure 4.15	Conceptual Hydrogeological Model for Lusaka Urban and adjacent areas.....	101
Figure 4.16	Section lines 1 to 4 on the Geological Model.....	103
Figure 4.17	Elevation difference between Lusaka Plateau and its edges in the East-West direction (Prepared from USGS DEM).....	104
Figure 4.18	Section line 2 – 2 on Geological Model show the slope to the north and south.....	106
Figure 4.19	Section line 3 – 3 on Geological Model show the slope to the north and south.....	106
Figure 4.20	Section line 4 – 4 on Geological Model show the slope to the east and west.....	106
Figure 4.21	Groundwater level fluctuation at observation borehole BH1 and BH2on Lusaka Plateau at DWA Sheki-Sheki offices.....	108
Figure 4.22	Comparison of groundwater level rise from October to December 2007 to the level rise for 2006/2007 rainy season at Observation Borehole BH1 and BH2 on Lusaka Plateau at DWA Sheki-Sheki offices.....	110
Figure 4.23	Groundwater level response to rainfall at Observation Borehole BH1 in the schist and BH2 in the carbonates from 2003/04 to 2005/06 rainy season.....	111

Figure 4.24	Presence of fractures and sinkholes on most carbonate areas covered by laterite in Lusaka urban and adjacent areas.....	112
Figure 4.25	Map of Lusaka Plateau showing the designed groundwater-monitoring network and meteorological stations.....	113
Figure 4.26	Map showing groundwater flow direction after 2006/2007 rainy season: 31 May 2007.....	116
Figure 4.27	Map showing groundwater flow direction at the start of 2007/2008 rainy season: 23 October 2007.....	116
Figure 4.28	Map showing groundwater flow direction: 31 December 2007.....	117
Figure 4.29	Map showing groundwater flow direction: 16 January 2008.....	117
Figure 4.30	Map showing groundwater flow direction: 20 February 2008.....	118
Figure 4.31	Groundwater level rise during 2007/2008 rainy season: October 2007 to January 2008.....	120
Figure 4.32	Map showing groundwater level rise and flow direction: 2007/2008 rainy season.....	122
Figure 4.33	Groundwater fluctuation at DWA Sheki-Sheki office: December 2003 to January 2008.....	128
Figure 4.34	Rainfall distribution on Lusaka Plateau: 2003/2004 rainy season.....	129
Figure 4.35	Rainfall distribution on Lusaka Plateau: 2004/2005 rainy season.....	130
Figure 4.36	Rainfall distribution on Lusaka Plateau: 2005/2006 rainy season.....	130
Figure 4.37	Rainfall distribution on Lusaka Plateau: 2006/2007 rainy season.....	131
Figure 4.38	Rainfall distribution on Lusaka Plateau: October to December 2007.....	131

Figure 4.39	Flooding in Kamwala area due to high groundwater table and subsequent accumulation of rainy water on Lusaka Plateau: October to December 2007.....	133
Figure 4.40	Draining of floods in Kamwala area on Lusaka Plateau by pumping and construction of emergency drains: December 2007 to February 2008.....	134
Figure 4.41	Proposed hypothesis on regional groundwater flow that sustain groundwater levels and periodical water table recovery on Lusaka Plateau.....	140
Figure 4.42	Proposed regional groundwater flow direction in the Katanga Supergroup (modified after JICA Report, 1995).....	142
Figure 4.43	Map showing distribution of boreholes sampled for groundwater quality analysis on Lusaka Plateau.....	143
Figure 4.44	Map showing groundwater types in Lusaka urban and adjacent areas.....	146
Figure 4.45	Chemical facies of groundwater in Lusaka urban and adjacent areas. ¹ calcium magnesium sulphate chloride; ² calcium magnesium bicarbonate; ³ sodium sulphate chloride; ⁴ sodium bicarbonate.....	148
Figure 4.46	Correlation of nitrate and chloride concentration in boreholes on Lusaka Plateau.....	149
Figure 4.47	Map showing distribution of Magnesium Hazard in Lusaka urban and adjacent areas.....	153
Figure 4.48	Map showing yield distribution in wards in Gwembe District.....	174

Figure 4.49	Fractures in compact mudstone around Munyumbwe in Gwembe District.....	177
Figure 4.50	Map showing the Conceptual Hydrogeological Model of part of Gwembe District in the studied areas with mudstone, sandstone and Basement Complex.....	178
Figure 4.51	Map of Gwembe District showing the main aquifer lithologies of mudstone (15), sandstone (10) and Basement Complex (5) in the studied areas.....	179
Figure 4.52	Graphing for groundwater level fluctuations at observation borehole MB-2 located at Makuyu World Vision premises from July 2004 to July 2005.....	183
Figure 4.53	Map showing the designed groundwater-monitoring network and wards comprising Gwembe District.....	185
Figure 4.54	Chemical facies of groundwater in the Basement Complex aquifer lithology of Gwembe District. ¹ calcium magnesium sulphate chloride; ² calcium magnesium bicarbonate; ³ sodium sulphate chloride; ⁴ sodium bicarbonate.....	189
Figure 4.55	Chemical facies of groundwater in the sandstone aquifer lithology of Gwembe District. ¹ calcium magnesium sulphate chloride; ² calcium magnesium bicarbonate; ³ sodium sulphate chloride; ⁴ sodium bicarbonate.....	190
Figure 4.56	Chemical facies of groundwater in the sandstone aquifer lithology of Gwembe District. ¹ calcium magnesium sulphate chloride; ² calcium	

	magnesium bicarbonate; ³ sodium sulphate chloride; ⁴ sodium bicarbonate.....	190
Figure 4.57	Na/Cl ratio for boreholes in Gwembe District ^A mudstone, ^B sandstone and ^C Basement Complex aquifer lithologies.....	192
Figure 4.58	Correlation of nitrate and chloride concentration for boreholes in Gwembe District.....	193
Figure 4.59	Correlation of nitrate concentration to borehole depth in Gwembe District.....	194
Figure 4.60	Map showing groundwater irrigation potential in wards of Gwembe District.....	197
Figure 4.61	Map showing proposed groundwater protection measures around Munyumbwe in Gwembe District.....	200
Figure 4.62	Delineation of the aquifer management area for groundwater protection in Gwembe District.....	201
Figure 4.63	Description of the proposed borehole numbering system based on the basin blocks (sub-catchments) in the two main river basins: Zambezi and Congo River Systems.....	204
Figure 4.64	Summarised flow chart of the proposed groundwater data and information capture model.....	258

LIST OF TABLES

Table 2.1	Borehole data with grid/map reference and borehole numbering (after Hadwen, 1972; Jones & Topfer, 1972; DWA, 1982 – 2001).....	13
Table 2.2	Stratigraphy of Zambia (after JICA Report, 1995).....	25
Table 2.3	Data on boreholes drilled in Lusaka Dolomite from 1959 to 1961 (after Simpson <i>et al.</i> , 1963).....	35
Table 2.4	Different recharge values determined for the Lusaka Plateau from 1963 to 1999 (after Burdon & Papakis, 1963; Von Hoyer <i>et al.</i> , 1978; JICA Report, 1995; Nkhuwa, 1996; Maseka and Nyambe, 1999).....	37
Table 2.5	Characteristics of the main aquifer lithology in Lusaka urban and adjacent areas (after JICA Report, 1995).....	38
Table 2.6	Characteristics of the main aquifer lithologies in Gwembe District (after JICA Report, 1995).....	42
Table 2.7	Borehole drilling guidelines and procedure followed by the Department of Water Affairs when constructing boreholes (after DWA, 1982).....	46
Table 2.8	Summary of Hydrogeological data and information collected by a Driller during borehole drilling using a borehole completion report form.....	47
Table 2.9	Groundwater Potential values recommended for groundwater development for Zambia (after JICA Report, 1995).....	51
Table 2.10	Catchments and Sub-catchment in Zambia (after JICA Report, 1995)....	52

Table 3.1	Groundwater monitoring concerns expected to be addressed following collection of information using the proposed data acquisition procedure	56
Table 3.2	How to collect information related to aquifer system and groundwater system (after Kovalevsky <i>et al.</i> , 2004).....	58
Table 3.3	Water Quality Guidelines for drinking water (after WHO, 1980; ZBS, 1990).....	226
Table 3.4	Criteria for evaluation of groundwater for irrigation (after US Department of Agriculture, 1954).....	227
Table 3.5	Proposed preliminary countrywide groundwater monitoring network for Zambia (modified from Mpamba, 2003).....	76
Table 4.0	Sample of the excel electronic data base for boreholes located in Lusaka urban and adjacent areas.....	234
Table 4.1	Data on LWSC boreholes located in the marble on Lusaka Plateau...	85
Table 4.2	Data on recently drilled abstraction boreholes located in the marble in Lusaka urban and adjacent areas (after Mpamba, 2005).....	86
Table 4.3	Data on boreholes drilled from February to April 2005 on Lusaka Plateau.....	88
Table 4.4	Procedure for identification of groundwater stressed areas using main water intersection depth and drawdown from hydrogeological data.....	97
Table 4.5	Arbitrary classification of lithologies to develop a geological model for Lusaka Plateau.....	101

Table 4.6	Borehole data used to develop a geological model for Lusaka Plateau.....	102
Table 4.7	Borehole data used to generate vertical geological cross sections 2-2 to 4-4 for Lusaka Plateau.....	105
Table 4.8	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2002 to March 2003.....	236
Table 4.9	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2003 to March 2004.....	237
Table 4.10	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2004 to March 2005.....	238
Table 4.11	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2005 to March 2006.....	239
Table 4.12	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2006 to March 2007.....	240
Table 4.13	Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2007 to December 2007.....	241
Table 4.14	Summary of annual rainfall at Met. Stations on Lusaka Plateau (Source: Met. Department - Zambia).....	109
Table 4.15	Rainfall amounts received at Met. Stations on Lusaka Plateau from October – December 2007 (Source: Met. Department - Zambia).....	109
Table 4.16	Sheki Sheki DWA Met. Station rainfall records for 2003/2004 rainy season (after Siwale, 2006).....	242

Table 4.17	Sheki Sheki DWA Met. Station rainfall records for 2004/2005 rainy season (after Siwale, 2006).....	243
Table 4.18	Sheki Sheki DWA Met. Station rainfall records for 2005/2006 rainy season (after Siwale, 2006).....	244
Table 4.19	Data on groundwater level measurements at observation boreholes for Lusaka Plateau: February 2007 to February 2008.....	119
Table 4.20	Data on groundwater level drop and rise at observation boreholes for Lusaka Plateau: May 2007 to February 2008.....	121
Table 4.21	Correlation of rainfall amounts received at Sheki-Sheki DWA Met. Station with infiltration situation on the carbonates in Lusaka urban (after Siwale, 2006).....	126
Table 4.22	Average Rainfall-Rainy days relationship for Lusaka Plateau.....	129
Table 4.23	Rainfall-Rainy days relationship for Lusaka Plateau.....	132
Table 4.24	Data on the effect of abstraction and natural groundwater aquifer outflow; and recharge at BH1 and BH2 on Lusaka Plateau.....	136
Table 4.25	Estimation of inflows for Lusaka Plateau using groundwater level measurements: February 2007 to February 2008.....	137
Table 4.26	Estimation of outflows for Lusaka Plateau using groundwater level measurements: February 2007 to February 2008.....	137
Table 4.27	Groundwater quality data for boreholes drilled in Lusaka urban and adjacent areas by the Department of Water Affairs.....	144
Table 4.28	Groundwater quality data for boreholes drilled in Lusaka urban and adjacent areas by the Department of Water Affairs.....	145

Table 4.29	Boreholes used to show distribution of groundwater type based on classification by Stiffs method.....	147
Table 4.30	Evaluation of groundwater quality results for Lusaka Plateau by Stiffs method.....	245
Table 4.31	Combined SAR, MH, and Cl Toxicity results for boreholes located in aquifers in Lusaka Urban an adjacent areas.....	151
Table 4.32	Groundwater quality results showing boreholes with high Magnesium Hazard values >50% and those with ≤50% values.....	152
Table 4.33	The DRASTIC parameters and their relative weights (after Aller et al; 1987).....	156
Table 4.34	Ranges and ratings of aquifer media in DRASTIC (after Aller et al; 1987).....	156
Table 4.35	Assigned weights for DRASTIC features for the Lusaka urban aquifers.....	157
Table 4.36	Ranges and ratings for depth to water table.....	157
Table 4.37	Information required from Hydrogeological data in DRASTIC vulnerability technique.....	158
Table 4.38	Ranges and ratings for topography.....	159
Table 4.39	Ranges and ratings for aquifer media.....	159
Table 4.40	Ranges and ratings for permeability in soils media.....	159
Table 4.41	Factors for the slope.....	160
Table 4.42	Factors for the rainfall.....	160
Table 4.43	Factors for soil permeability for recharge.....	161

Table 4.44	Ranges and ratings for recharge.....	161
Table 4.45	Factors for soil permeability for impact of Vadose zone.....	162
Table 4.46	Factors for depth to the water table.....	162
Table 4.47	Ranges and ratings for Vadose zone impact.....	162
Table 4.48	Ranges and ratings for hydraulic conductivity of aquifer.....	163
Table 4.49	Suggested aquifer systems for Lusaka Plateau.....	171
Table 4.50	Sample of the excel electronic database for boreholes located in Gwembe District.....	247
Table 4.51	Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	248
Table 4.52	Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	249
Table 4.53	Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	250
Table 4.54	Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006.....	251
Table 4.55	Data on boreholes located around Munyumbwe Township.....	175
Table 4.56	Borehole data used to develop a geological model for Gwembe District.....	180
Table 4.57	Arbitrary classification used to develop a geological model for Gwembe District.....	181
Table 4.58	Groundwater level readings in meters for MB – 2 at Makuyu World Vision premises: June 2003 to June 2005.....	182

Table 4.59	Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	253
Table 4.60	Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	254
Table 4.61	Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	255
Table 4.62	Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	256
Table 4.63	Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006.....	257
Table 4.64	Combined SAR, MH and Cl Toxicity for boreholes in mudstone aquifer.....	195
Table 4.65	Combined SAR, MH and Cl Toxicity for boreholes in Basement Complex aquifer.....	196
Table 4.66	Combined SAR, MH and Cl Toxicity for boreholes in sandstone aquifer.....	196
Table 4.67	Projected groundwater level reading at observation boreholes for Lusaka Plateau using increased abstraction scenarios expected in the absence of groundwater control.....	246
Table 4.68	Assigned catchment codes and number of sub-catchments for Zambia (JICA Report, 1995).....	204

LIST OF ACRONYMS

MEWD	Ministry of Energy and Water Development
DWA	Department of Water Affairs
JICA	Japanese International Cooperation Agency
ECZ	Environmental Council of Zambia
NGOs	Non Governmental Organizations
MLGH	Ministry of Local Government and Housing
DISS	Department of Infrastructure and Support Services
NWASCO	National Water Supply and Sanitation Council
GPS	Geographical Positioning System
MH	Magnesium Hazard
MACO	Ministry of Agriculture and Cooperatives
LWSC	Lusaka Water and Sewerage Company
WRAP	Water Resources Action Programme
MDGs	Millennium Development Goals
WRTC	Water Resources Technical Committee
PAWD	Partnership for African's Water Development
WATSAN	Water and Sanitation
GWP	Global Water Partnership
NISIR	National Institute for Scientific and Industrial Research
UNZA	The University of Zambia
D-WASHE	District Water, Sanitation, Health and Education

1.0 INTRODUCTION

Zambia is endowed with relatively abundant water resources in the Southern Africa region (MEWD, 1994). However, there is an urgent need to re-define this abundance for both surface water and groundwater resources in terms of quantity and quality. Taking this step would greatly help the country to realise the economic value of the resource and foster sustainable management practices. Water resources management has not been effective from the legal point of view due to limitations in the Water Act of 1948 (WRAP, 2005). In addition, technical aspects necessary for sustainable water resources management have also in the long run been affected. The Water Act (Act of 1948) only regulates surface water resources development and utilisation, whereas groundwater resources are still regarded as privately owned (WRAP, 2003). Hence, groundwater exploitation is not controlled to the extent that groundwater data and information is not readily available. This situation makes the effort towards water resources management futile.

Since 1992, the Zambian government has been addressing water resources management activities (WRAP, 2005). According to Chola (2003) historical and current status of water resources management evolved from a scenario of combined water resources development, management and water supply approach to a separation of water supply functions from water resources development and management functions. This change has been due to the implementation of the water sector reforms by the Ministry of Energy and Water Development. The change also resulted in the development of the national Water Policy (MEWD, 1994); and the enactment of the National Water Supply and Sanitation

Bill (1997) that regulates the water supply and sanitation service delivery. Other documents that have a bearing on the direction of the water sector reforms and are relevant to this study includes the; Irrigation Policy and Strategy, and National Disaster Management Policy.

To study the social economic impact of groundwater, a research on groundwater monitoring in the urban and rural areas of Zambia was initiated by the Ministry of Energy and Water Development (MEWD) as a joint effort with the University of Zambia in collaboration with Ruhr University Bochum in Germany. The study was conducted during the period January 2001 to February 2008 in Gwembe District and; Lusaka urban and adjacent areas. Additionally, Mongu was also included to specifically allow comparison of groundwater level fluctuation in the three main aquifer types in Zambia.

The theoretical description of groundwater monitoring in this study refers to the assessment of groundwater resources in aquifers in terms of quantity and quality on a short and long-term basis. It is multidisplinary in nature involving activities undertaken by the Department of Water Affairs (DWA), through three Sections, namely Water Resources and Management, Groundwater Resources and Surface Water Resources. Through these Sections, the Department of Water Affairs has the mandate and responsibility to develop and manage water resources in Zambia. This includes the responsibility to:

- 1) Oversee and control water resources development activities for sustainable resource development,
- 2) Provide sufficient and reliable data on water resources availability for effective planning, utilisation and management of the resource to meet the country's water demand,
- 3) Carry out development and management activities aimed at water conservation.

1.1 Background

Surface and groundwater resources exploitation contributes significantly in meeting domestic, industrial and agricultural water requirements in Zambia (JICA Report, 1995). Hence, recognition of water resources as one of the major factors in the socio-economic development of Zambia entails improvement in resource management through efficient data and information acquisition.

Despite heavy reliance on groundwater for various uses, the status of groundwater data acquisition and generation of data into information to support management is still a major concern in Zambia. Therefore, the Ministry of Energy and Water Development is strengthening groundwater-monitoring activities through research to address groundwater data requirements.

1.2 Statement on the Problem and Hypothesis

Zambia like most other countries in Southern Africa region is faced with challenges in accessing data and information on groundwater resource (SADC, 2001). Since 1990s, about 500 boreholes are constructed annually by private contractors and DWA (JICA Report, 1995). This is often carried out in response to ad hock demands from individual residential plots, small farm holdings, commercial farms and the need to provide domestic water supply to the urban and rural communities.

MEWD, through DWA is the principal government institution charged with the responsibility of developing groundwater resources and to keep records on boreholes drilled in Zambia. However, DWA cannot execute this task effectively and efficiently due to inadequacies in the legal provisions (WRAP, 2005). DWA only collects and keep records of basic hydrogeological data gathered during construction of their own boreholes and those submitted on a voluntary basis to DWA by private drilling companies. Private borehole drilling contractors are currently not obliged by law to collect and submit borehole records (WRAP, 2005). This has created difficulties at policy, strategic and operation levels to access groundwater data and information. The setback with DWA records is that groundwater quality and groundwater levels are often not treated as part of groundwater resources and therefore rarely collected. Of particular interest is that groundwater is recognised as one of the main sources of fresh water in Zambia. Above all, it is the cheapest option and most reliable source of potable water for the rural communities. A good number of towns and cities abstract about 30 – 60% of

their domestic water supply from groundwater sources (JICA Report, 1995). Expansion in irrigated agriculture is also progressively exerting pressure on the same resource.

Large-scale groundwater abstraction and development dates back to the early 1900s. It is associated with dewatering of mines and supply to meet domestic, industrial and agricultural demands. Therefore, sufficient knowledge on groundwater resources availability is important for groundwater experts, Policy makers, decision makers at strategic level and stakeholders for sustainable use of the resource. To achieve this, there is need to improve on data collection and database management.

1.2.1 Hypothesis

Systematic collection of hydrogeological, groundwater level and groundwater quality data and their combined use is adequate to generate information to support sustainable groundwater resources utilisation and management.

The strength of these data sets lie in the intricate relationship to describe groundwater quantity and quality, even when the procedure employed to collect the respective data differs. The following theoretical understanding on each data set is important for testing the hypothesis:

1.2.1.1 Hydrogeological Data

It is collected by a driller during borehole construction. The details that are recorded include, borehole depth, static water level, depth to water intersection, thickness of

formations drilled through, casing pipes inserted into the borehole, yield, pump testing results, date of construction, location of the site and other descriptive information. This data is used to generate information on the status of groundwater quantity for each borehole. When information for a number of boreholes is aggregated and analysed, available quantities of groundwater in any given area could be estimated (Freeze and Cherry, 1979).

1.2.1.2 Groundwater Level Data

It is collected at different times during the lifespan of a borehole and recorded as static water level. A driller measures and records the static water level during construction of a borehole. Other people may also measure the water level at the same borehole at any other desired time during the lifespan of the borehole. Therefore, when groundwater levels are taken at regular intervals for a long time, the data provides information on the changes in groundwater quantity in an aquifer as affected by recharge, natural drainage and exploitation (Freeze and Cherry, 1979; Lerner et al., 1990; Lloyd, 1999).

1.2.1.2 Groundwater Quality Data

It is collected at different times during the lifespan of a borehole. At the time of borehole construction, it provides baseline values on the status of groundwater quality. Routine evaluation of groundwater quality during the lifespan of boreholes provides information on water quality trend in the aquifer as affected by natural interaction of water with soil and anthropogenic activities (Freeze and Cherry, 1979; Kovalevsky et al., 2004).

1.3 Scope of Work

Provision of water from groundwater sources is achieved in Zambia mainly through springs, construction of boreholes and open wells (hand dug wells); a common practice in both the rural and urban areas. However, the pace and magnitude of groundwater exploitation have been dictated by demand. In spite of the different levels of the country's development, boreholes are still a valuable means of acquiring hydrogeological, groundwater quality and groundwater level data in Zambia.

According to Boddy and Paton (1998), data refers to raw unanalysed facts, figures and events; whereas information refers to useful knowledge derived from data. The two terms are finally linked through the information system, which is a set of people, procedures and resources that collects, transforms data into information and then disseminates this information (Boddy and Paton, 1998).

In view of the above and to avoid discourse, the terms groundwater data and groundwater information are not used loosely or interchangeably in this thesis. Sound groundwater management practices are based on scientific and statistical data. It is therefore inevitable for Zambia to develop a groundwater monitoring strategy and system to facilitate management of the resource. Therefore, the study is specifically tailored to address challenges associated with non-availability of groundwater data and information as well as the mechanism to deal with Collection, Transmission, Storage, Analysis and Dissemination.

1.4 Objectives of the Study

The main objective is to identify the best and practical way of improving groundwater resources data and information collection with stakeholder participation in Zambia.

Therefore, the specific objectives are:

- To examine the extent to which groundwater monitoring is implemented.
- To define the type of data and information that must be collected to enhance groundwater resource management.
- To promote long-term cost effective hydrogeological, groundwater quality and groundwater level data acquisition.
- To identify and document the best drilling practices as well as methods carried out in different parts of Zambia.
- To establish the procedure for groundwater data and information collection system to support updating of the national groundwater database.
- To compare the outcome of collecting groundwater data and information in the urban and rural areas.
- To recommend a suitable national borehole numbering system for use on borehole completion report forms.

1.5 Outline

The thesis covers three areas, background and review of available literature, information and methods; and presentation of the current work.

Chapter 1 establishes the background to this work, giving a fairly comprehensive overview on the water resources and associated management challenges in Zambia. Focus is on groundwater and the role it plays for the socio-economic benefit of Zambia. The aim of the chapter is to set the scene for the reader unfamiliar with the various groundwater resources data and how it relates to each other in describing groundwater resources. Finally, hypothesis testing for sustainable groundwater resources utilisation is presented as the main topic of this research.

Chapter 2 reviews groundwater monitoring activities in detail, the general climate, geology and hydrogeology of Zambia with emphasis on the study areas. Particular attention is given to the scenario on groundwater development and the linkages to the concept of Basin-wide water resources management.

Methodology on hypothesis testing using the proposed data acquisition models and how the study was organised is the subject of chapter 3. Approaches for justifying data set relations are described based on the known facts in hydrogeology. The primary aim is to use data set relationship to establish and argue for a systematic methodology to investigate the field application in data acquisition.

Chapter 4 of the thesis covers data analysis and discussion of results from the view point of the application of hydrogeology. The authors' ideas are scientifically presented in a descriptive manner to provide information and giving sufficient detail to serve as a useful

reference. The main contributions of the study to the science of hydrogeology in Zambia and further research needs are given at the end of this chapter.

In chapter 5, the conclusion emerging from the study is summarised followed by the implied recommendation for Zambia to adopt the data acquisition model.

2. LITERATURE REVIEW

To be objective in addressing the topic of groundwater monitoring, each of the three data sets (hydrogeology, groundwater quality and groundwater level) was examined in detail on how its collection was achieved and subsequent use in resource utilisation from the early years of groundwater development in Zambia.

2.1 Review of Previous Works on Groundwater Monitoring in Zambia

Groundwater monitoring, has been done since 1950s, involving collection of hydrogeological, groundwater quality and groundwater level data (Jones and Topfer, 1972; Hadwen, 1972; Von Hoyer *et al*, 1978; JICA Report, 1995; Nkhuwa, 1996, Maseka and Nyambe, 1999). However, groundwater quality and groundwater level data is only in reports, whereas hydrogeological data is in completion reports as hard copies on box files. Furthermore, the three data sets have not been consistently collected and were not treated as one entity for resource evaluation as proposed in this study. Moreover, the approach of collecting these data sets as separate entities created difficulties in the effective use of the information to plan for resource development and management. Given the situation described above, additional evidence on each aspect is provided and good practices identified.

2.1.1 Hydrogeological Data

On hydrogeological data, literature review revealed that borehole data and information have been collected by the Department of Water Affairs during borehole drilling using a borehole completion report form (Figure 2.1).

Most of the records only give descriptive information on the borehole location and no borehole number, grid reference or Geographical Positioning System (GPS) coordinates are indicated even when the forms have a provision for recording such. However, Jones and Topfer (1972), as well as Hadwen (1972) show borehole records with grid/Map reference and borehole numbers in their publication on Kabwe and Ndola respectively (Table 2.1).

Table 2.1: Borehole data with grid/map reference and borehole numbering (after Hadwen, 1972; Jones & Topfer, 1972; DWA, 1982 – 2001).

Borehole No.	Grid/Map reference	Location and Owner of Borehole	Date constructed
19	PQ 532024	Kabwe Observation Well 45B23	14-10-66
20	PQ 519023	Kabwe Observation Well 45B20	19-10-66
21	PQ 499069	Kabwe Observation Well 45B21	21-10-66
22	PQ 472058	Kabwe Observation Well 45B22	26-10-66
41	PR768687	N. Rise Sub Police Station	26-5-54
42	PR771633	Skyways Rural Boma Ndola	Pre 54
76	PR777645	Ndola Golf Course	2-9-58
41	PP 513981	793 Maplehurst Heslop K.	5-5-55
51	PQ 582025	Kabwe High School	15-8-57
54	PQ 517060	Mukobeko Township	6-3-61
43	PQ 516073	PWD Road depot	16-12-55
2846/1	510960 of 1528A ₄	B.M. Ntamba	9-2-83

The type of numbering in table 2.1 has not continued and details on the basis of such a numbering system are not available. Since the reasons for the omission of such details on most existing borehole records are unknown, a lengthy and cumbersome procedure of determining the grid/Map reference at that time is the obvious assumption for now. This is because in the past, techniques and innovative instruments such as GPS units were not available for use. However, availability of GPS units does not seem to have improved the situation, since most of the recent records do not also have GPS coordinates for both successful and dry boreholes (JICA Report, 1995). Although lack of consistency in recording of hydrogeological data is evident, the following summarised issues are worth noting:

- Collection of hydrogeological data using a completion form (Figure 2.1) is a good practice. It allows capture of useful data and information such as name of property and owner, locality, borehole number, depth of borehole, static water level, grid/Map reference or GPS coordinates, casing details and many others.

2.1.2 Groundwater Quality Data

Water quality analysis has been done before in various groundwater development projects, although it is for selected parameters that do not necessarily include all cations and anions (Jones and Topfer, 1972; Hadwen, 1972; Chenov, 1978). Similarly, groundwater samples were analysed for selected water quality parameters from 1980s to 1990s (JICA Report, 1995). Records are mainly available in reports and project documents. The Department of Water Affairs has no formal way of keeping water quality

data as is the case for hydrogeological data, which is on completion report forms and in box files. The scenario therefore indicates that:

- A standard reporting format with defined water quality parameters for analysis in any groundwater development programme and projects is lacking.
- Groundwater quality analysis should be made part of the groundwater resources development requirement to avoid analysis when and as seen necessary.

2.1.3 Groundwater Level Data

Monthly measurement records of groundwater levels for mining towns and the city of Lusaka are available in reports for dates as early as 1950s (Hadwen, 1972; Jones and Topfer, 1972; Von Hoyer *et al.*, 1978; Chenov, 1978; JICA Report, 1995; Nkhuwa, 1996, Maseka and Nyambe, 1999). According to Jones and Topfer (1972) continuous monthly groundwater level measurements were done at observation boreholes for five years from 1965-71 in Kabwe urban. A groundwater contour map for Kakontwe limestone in Ndola was once produced based on the water level measurements at observation boreholes (Hadwen, 1972). All these boreholes can not be located and are therefore not available to allow for measurement of water levels. In the case of Lusaka urban, a good number of observation boreholes were constructed in the Lusaka Dolomite for water level measurement (Von Hoyer *et al.*, 1978). Similarly, these boreholes are now used for abstraction by private property owners and are no longer available for water level measurement. The most recent countrywide systematic groundwater level observations were done for one year using production boreholes and open wells during the preparation

of the Water Resources Master Plan for Zambia (JICA Report, 1995). The main aim was to investigate the seasonal groundwater level fluctuation and effects of groundwater abstraction in Mongu, Lusaka, Kabwe and Ndola. On the other hand, DWA occasionally take monthly groundwater levels in production boreholes and open wells as a routine activity and during drought assessment (DWA Annual Reports, 1980s). Moreover, recent evaluation of groundwater monitoring activities indicates that limitations are associated with non-permanency of observation boreholes, financial implications, equipment and inadequate institutional capacity to sustain groundwater level measurements (Mpamba, 2003). What was evident from the review of groundwater data is that:

- Groundwater levels have been carried out on a monthly basis, both regularly and in an ad hock manner using open wells, observation and production boreholes.
- Security and permanent access to constructed boreholes has not been well taken care of, resulting in failure to continue taking measurements to date.
- There is no standard format of reporting groundwater level data.

It would be a fair statement to say that at the moment, groundwater quality and groundwater level data are not given due attention as important data and information to contribute to resources assessment and management in Zambia. Furthermore, most of the existing data is useful mainly for statistical analysis and not for spatial analysis because of lacking coordinates.

2.2 Consultations to Identify Existing Gaps in Knowledge on Data Collection

This study recognised the role stakeholders play in groundwater data and information collection. Consultations were therefore made to highlight gaps in knowledge on data that is necessary and possible to collect by various stakeholders for submission to support resource development and management. The multi-stakeholder consultative forum and WATSAN co-ordination meeting for Drought Mitigation chaired by the Department of Infrastructure and Support Services (DISS) under the Ministry of Local Government and Housing (MLGH) was used to reach a number of stakeholders. These are stakeholders involved in groundwater development for rural water supply, who through this process indicated that failure to collect the required groundwater data and information is attributed to the following:

- Lack of knowledge on the data to be collected and purpose for which it must be collected.
- The mistaken belief that omitting certain activities viewed not to be important in the provision of water to rural communities reduces drilling costs.
- Lack of capacity, uniformity and know how among private drilling contractors on how best to collect groundwater data and information.
- Lack of proactivity by the institution charged with the responsibility to request and keep groundwater data and information to sensitize stakeholders on the importance of this exercise.

2.3 Importance of Groundwater Monitoring in the Water Sector

It is important to mention that the three proposed data sets have relevance to two ministries that perhaps can not do without it if they have to achieve meaningful planning, policing and management of water resources. The two ministries are:

- 1) The Ministry of Energy and Water Resources Development would use the data and information from both urban and rural areas to enhance groundwater resources development planning, water resources management, formulation of guidelines and policies.

- 2) The Ministry of Local Government and Housing would use the data and information from urban areas to put in place by – laws that are current and aimed at reinforcing proper town and country planning; whereas data and information from rural areas would greatly support the operation and maintenance of rural water supply facilities to ensure improved sustainability and water coverage.

2.4 General Climate and Geomorphology of Zambia

Zambia experiences a sub-tropical climate with three distinct seasons, namely; a dry season from mid April to August, a hot season form September to October and the rainy season from November to April. Lowest temperatures (17°C to 20°C) even much lower than this range are experienced in the month of June and the highest (28°C to 38°C) in the month of October. Average annual rainfall varies from 1500mm in the northern part of the country to 600mm in the southern part. The Intertropical Convergence Zone (ITCZ), a wettest low pressure zone on earth that vary as much as 40° to 45° of latitude

north or south of the equator is responsible for the precipitation of up to 200 days each year in the equatorial region (Rosenberg, 2008). The ITCZ is also responsible for the rainfall distribution pattern over Zambia, such that the northern parts of the country near the equator receives higher rainfall amounts than the southern parts (JICA Report, 1995).

Most parts of the country are located on the elevated plateau between 900m to 1500m above mean sea level, formed by a series of gently rolling landscape whose monotony is broken by isolated hills, ridges, escarpments and valleys. Another distinguishing characteristic of the terrain are the wetlands, which are wide spread due to lack of integrated drainage that occur in the two main watersheds – Zambezi and Congo River basins (Chenov, 1978).

2.4.1 Physiographic and General Information on the Study Areas

2.4.1.1 Lusaka urban and adjacent areas

The study area is located between latitude, 15° 18' S (UTM Northings 8308156) and 15° 34' S (UTM Northings 8278431), and longitude 28° 10' E (UTM Eastings 625256) and 28° 30' E (UTM Eastings 660845). It is part of the Mid Tertiary peneplain of Central Africa, which occurs at an elevation of 1260m above mean sea level (amsl). The average rainfall is 865mm (WRAP, 2005). Annual Potential Evaporation by THORTHWAITE method is 938mm (Nkhuwa 1996). Three main river basins, Chunga – Mwembeshi, Chongwe and Kafue (Figure 2.2) drain Lusaka urban and adjacent areas that are underlain by mainly carbonate –rocks. Because of the presence of sinkholes, epikarst and permeable laterite, it is generally rare to find surface streams on the Lusaka carbonate

rocks (Lambert, 1963). Lusaka Plateau comprises Lusaka urban and adjacent areas that are within 20km radius from Lusaka city centre. Lusaka urban has a population of about 1,247,939 people (CSO, 2004). Water demand towards domestic, industrial and agricultural activities in the study area is met by surface and groundwater sources. Competing users for the two water sources are private residences, small holdings, industrial sites, commercial farms; and Lusaka Water and Sewerage Company (LWSC).

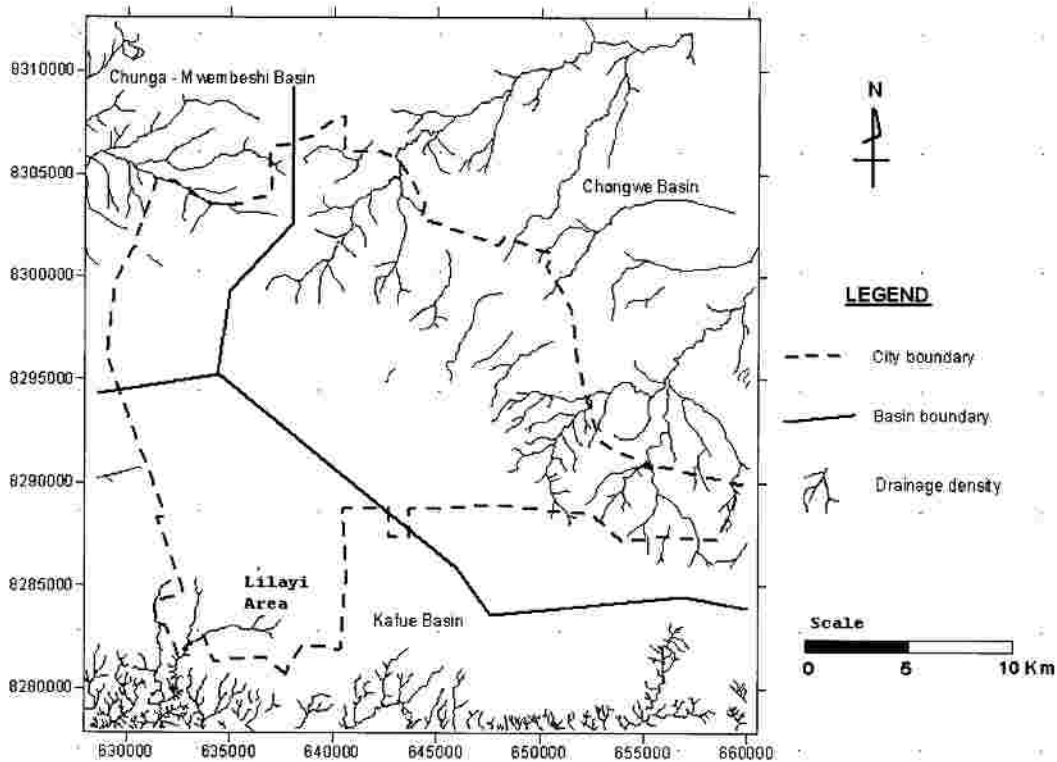


Figure 2.2 Map showing drainage in the main sub-river basins in Lusaka urban and adjacent areas

In the context of the current groundwater development and abstraction trends, the scenario has not changed much from the historical increase in water demand and abstraction described on Lusaka Plateau by Lambert (1963). Lusaka Water and Sewerage

Company (LWSC), the water utility responsible for water supply to the city abstracts about 50% of its daily water requirements from aquifers in the Lusaka urban and adjacent areas and the other 50% is imported as treated surface water from Kafue River 60km south of the city (Nyambe and Maseka, 1999). Private individuals and industries also abstract quite a substantial amount. Irrigated agriculture in the adjacent areas is another activity that has increased exploitation levels in the same aquifers. The actual volume of groundwater abstracted annually is unknown due to inadequate groundwater data and information. Rapid growth of the city without town and country planning control, has resulted into industrial and housing units developing on the entire aquifers, which otherwise should have been protected. A number of low-density and high-density areas within the city use on-site sanitation facilities such as septic tanks and pit-latrines. These together with the current intensive generation of solid waste, renders deterioration of groundwater quality in the aquifers (Zulu and Nyambe, 2004). Water shortages, non-provision of water services to some peri-urban and newly developed low-density areas is the main reason for the ever increasing demand for borehole drilling in the same aquifers.

2.4.1.2 Gwembe District

The district is located in between latitude 16°20" S (UTM Northings 8194151) and 17°00" S (UTM Northings 8119887) and longitude 27°24" E (UTM Eastings 542725) and 28°26" E (UTM Eastings 652582). The area is part of the Gondwana and African surfaces, which is an extensive erosional surface at elevations varying from 900 to 600m above mean sea level (King, 1948, 1967; Dixey, 1945; Nyambe, 1993). Annual rainfall varies from 900 to 800mm, whereas the mean minimum and maximum temperature are

17 to 32°C (Nyambe, 1993). The current extent of Gwembe District occupies an area of 3925 Km² with a projected population of 57,668 people (CSO, 2000). Absence of perennial rivers and streams makes groundwater the only obvious and sole reliable source of water for domestic water supply and livestock in Gwembe District. The urbanized part of the district, which is located on the escarpment before descending into the valley, relies on both the surface water and groundwater for its water supply. The rural population of Gwembe District largely depend on rain feed agriculture that is dominated by subsistence farming involving livestock and crop production system. Maize, cotton, sorghum and millet are some of the crops that are grown seasonally. Effects of droughts and occasional flooding reduce agriculture productivity, whereas lack of adequate water during the dry season contributes to poor animal health forcing households to sell off their animals at very low prices.

Accessibility during rain season is limited due to the highly plastic nature of the weathered mudstones once wet and also the non-perennial streams that are flush in nature that transverse the district. Theses only flow during the rainy season when transporting storm water that mainly originates from the plateau on its way to Lake Kariba and create difficult to cross until the water levels go down to a reasonable depth (Figure 2.3). The main streams are Lufua, Chibuwe, Nankoli and Chezya, which cut deep gorges through the lower escarpment and exhibit a dendritic drainage pattern (Newton, 1963).



Figure 2.3 Crossing a flush stream in Gwembe District when water flow depth has reduced.

Once the rain season is over, the area becomes bare devoid of the dense green grass and heavy foliage on trees characteristic of the wet season (Figure 2.4).



Figure 2.4 Photos showing dense grass and heavy foliage on trees in the wet season (Left) but absent in the dry season (Right) in Gwembe District

Munyumbwe the administrative centre of Gwembe District is located at a point where boundaries of Jongola, Lukonde, Syampande and Fumbo wards meet (Figure 2.5). The district comprises of twelve wards, namely; Luumbo, Chisale, Bbondo, Fumbo, Syampande, Lukonde, Jongola, Chibuwe, Sinafala, Masanga and Jumbo/Khoma. It is currently among the least developed districts in Zambia. However, the potential for economic development is high except that it is hampered by poor communication (Road network and telecommunication). Tourism, mining of metallic and non-metallic ores, agriculture and fishing are the most promising economic ventures that could see the district improve within a few years. Natural mineral water bottling is also among those activities that are viable due to a number of natural springs.

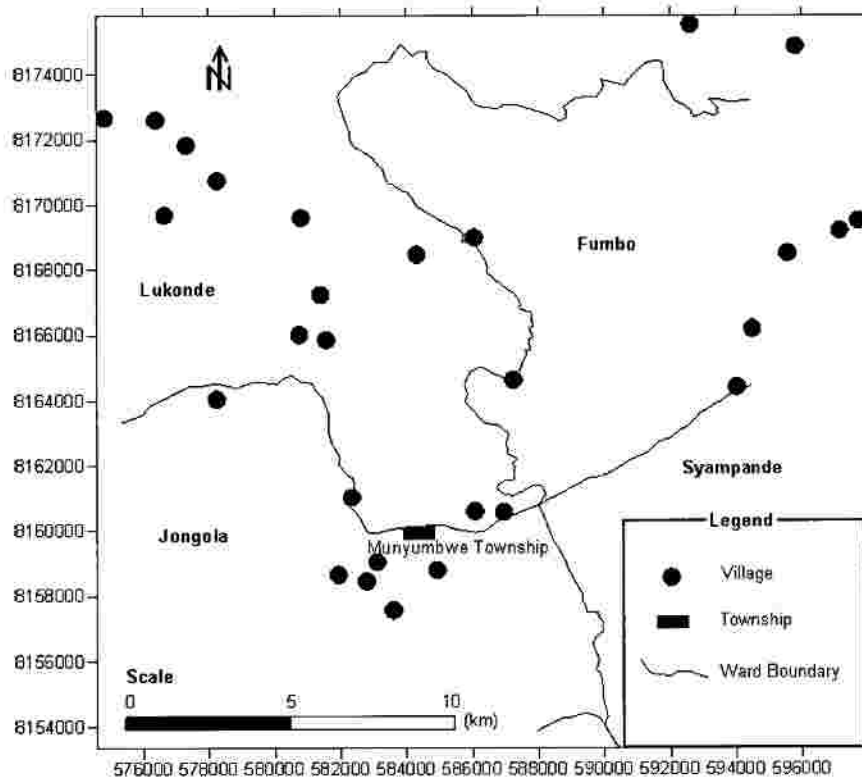


Figure 2.5 Map showing the location of Munyumbwe the administrative centre of Gwembe District

2.5 Regional Geology and Hydrogeology of Zambia

2.5.1 Geology

The geology of Zambia comprises various rock formations and layers consisting of igneous, sedimentary and metamorphic rocks from Precambrian to recent times (Table 2.2). These are summarised below:

Table 2.2: Stratigraphy of Zambia (after JICA Report, 1995)

Geological Age		Super Group	Groups or Formation	Rocks and Sediments
Cenozoic Era	Quaternary	Cenozoic Super Group	Alluvium	Alluvium sands, Gravel with clay
	Tertiary		Kalahari Group	Fine sand, Sandstone with clay
Mesozoic Era	Cretaceous	Mesozoic Super Group	Lower Cretaceous Formation	Mudstones, Siltstones
	Jurassic Carboniferous	Karoo Super Group	Upper Karoo Group	Basalt, Interbedded sandstones, Sandstones, Mudstones, Siltstones
			Lower Karoo Group	Mudstones with coal measure, Siltstones, Sandstones, Conglomerates
Palaeozoic Era	Silurian Ordovician	Lower Palaeozoic Super Group		Quartzites, Shales, Sandstones
	Early Palaeozoic Precambrian	Katanga Super Group	Kundelung Group	Carbonate rocks with shales, Shales, Siltstones
Upper Roan Group			Dolomites, Argillites	
Lower Roan Group			Quartzites, Argillites, Dolomites, Conglomerate, Mine series shales	
Basement and Muva Super Group			Muva Group	Shales, Mudstones, Sandstones
		Basement Complex	Basement gneisses, Migmatites, Schists	
Various age mainly older Precambrian		Intrusive and Metamorphic Rocks		Basic-igneous rocks, Meta-igneous rocks, Amphibolites, Metasediments, Metavolcanics

2.5.1.1 Cenozoic Super Group

The layers comprise tertiary sandstone, quaternary consolidated sand layers (duricrusts) and clay layers. In a larger part of the extreme west of Zambia (Barotse Basin), Cenozoic Super Group over lies the Mesozoic Super Group (JICA Report, 1995).

2.5.1.2 Mesozoic Super Group

It has an estimated thickness of 100m of mudstones judged to be cretaceous in age based on the discovery of certain fossils. The distribution is along the Zambezi River and to the west of Zambia, over lying the basalt of the Karoo Super Group (JICA Report, 1995).

2.5.1.3 Karoo Super Group

Tillites of fluvio-glacial origin, mudstones coal measure, marls, conglomerates and basalts corresponding to the Carboniferous to Jurassic period compose the Karoo Super Group. It is distributed along the Luangwa River, mid-Zambezi Valley and western part of Zambia (Nyambe, 1993; JICA Report, 1995).

2.5.1.4 Lower Palaeozoic Super Group

It comprises shales, quartzites and arkose sandstones. Lower Palaeozoic Super Group is extremely limited and its existence is only evident in the mid-Zambezi Valley and western parts of Zambia, where it over lies the Katanga Super Group (JICA Report, 1995).

2.5.1.5 Katanga Super Group

The Katanga Super Group comprises shale, sandstone, quartzites, limestones, conglomerates and dolomite layers that range from Precambrian to Cambrian in age. It is distributed in the northern and central parts of Zambia (JICA Report, 1995).

2.5.1.6 Basement Complex

It is the oldest system in Zambia that consists of highly deformed gneiss, schists, conglomerates, quartzites, crystalline limestone, migmatites and granites. The outcrops are mainly in the east and south-eastern parts of Zambia (JICA Report, 1995).

2.5.1.7 Intrusive Rocks

These are of varying age and type, which mainly intrude the Precambrian rocks and the majority are granites. The remainder are gabbros, dolerites, syenites, etc (JICA Report, 1995)

2.5.2 Hydrogeology

The ability of the rock types distributed in Zambia to allow for recharge and hold water depends on the state of weathering and tectonic structures such as folds, faults and shear zones. Thrusting and transport movements in the Lufilian Arc and the Zambezi mobile Belt (Figure 2.6) created these tectonic structures (Dixey, 1945; Hitchon, 1958; Moore, 1964; Matheson and Newman, 1966).

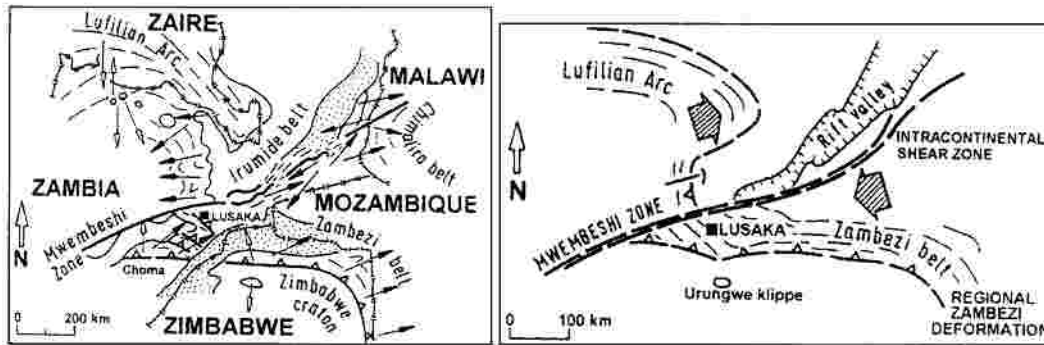


Figure 2.6 Major continental and regional tectonic events: Mwembeshi shear zone associated thrusting and transport in the Lufilian Arc and the Zambezi thrust belt [After Daly, 1988; Peters, 1990. Nkhuwa, 1996]

According to Lambert (1961), rocks of the Katanga age possess the highest groundwater potential as a single geological sequence that occupies the Northern and Central parts of Zambia; and that they cross in three northwesterly – trending synforms at Lusaka, Chisamba and Kabwe. The Lower Katanga Dolomite is by far the most important aquifer from which Towns such as Lusaka, Ndola, Kabwe and Mazabuka derive part of their water supply (Lambert, 1961). Aquifers in Zambia are classified into three main types (Figure 2.7), based on the discharge and mechanism that controls groundwater flow as follows:

2.5.2.1 Aquifers Where Groundwater Flow is Mainly in Fissures, Channels and Discontinuities

Groundwater occurs in secondary rock features and structures such as weathered zones, faults, joints, fractures and solution features that usually extend to around 30m to 40m in

depth within consolidated hard rocks. They may occasionally extend to more than 90m in depth. Such aquifers may be subdivided into two, namely:

- **Highly productive aquifers:** These include Upper Roan Dolomite and Kundelungu Limestone ($1-70 \text{ l s}^{-1}$), but have limited and very narrow area of distribution. Some large cities such as Ndola and so on are located on such aquifers.
- **Locally productive aquifers:** The Lower Roan Quartzite, Muva sediments, granites and undifferentiated Kundelungu Formations ($0.1-10 \text{ l s}^{-1}$).

2.5.2.2 Aquifers Where Intergranular Groundwater Flow is Dominant

These are found in the Alluvial Formation, Kalahari Group and Karoo Group. These aquifers are distributed mainly in the Western, Southern and Eastern parts of Zambia. They are also distributed around Chambeshi River and Lake Bangweulu ($0.1 - 15 \text{ l s}^{-1}$)

2.5.2.3 Low Yielding Aquifers with Limited Potential

These aquifers are mainly distributed in Eastern and Southern parts of Zambia ($0-2 \text{ l s}^{-1}$). They include the major part of Argillaceous Formation, Karoo basalts and older Basement Complex.

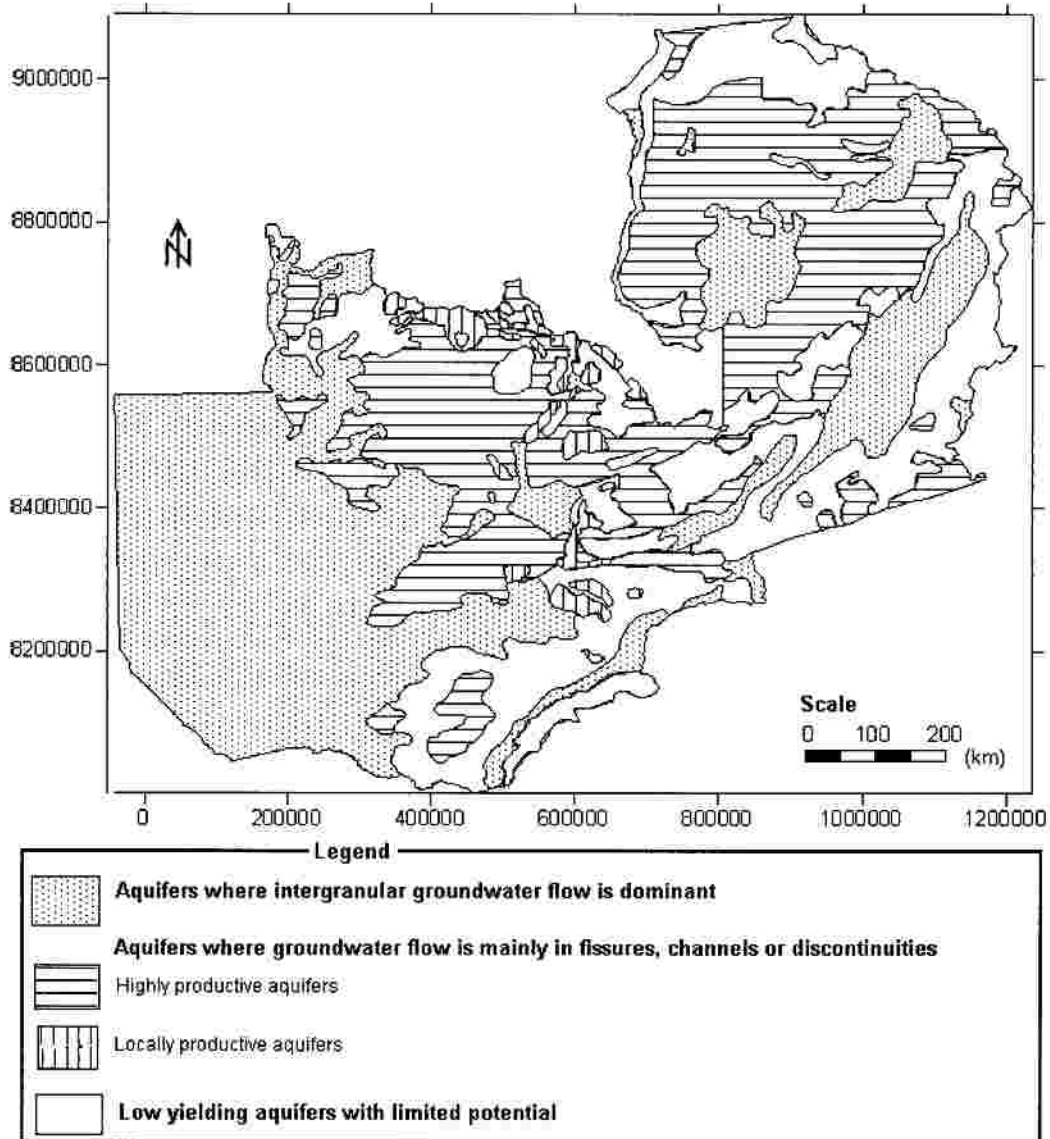


Figure 2.7 Map of Zambia showing the three main types of aquifers [Source: JICA Report – 1995]

2.6 Geology and Hydrogeology of the Study Areas

This section brings out important aspects on geology and hydrogeology of the studied areas, in order to compare existing information to that which has come out of this study.

2.6.1 Lusaka urban and adjacent areas

2.6.1.1 Geology

Extensive geological mapping and field surveys by Simpson et al (1963), Smith (1963), Matheson and Newman (1966), have shown that Lusaka Plateau comprises the Lusaka Dolomite, Cheta and Chunga Formations (Figure 2.8). The major rocks comprise gneisses and quartzites of the Chunga Formation, schists and quartzites of the Cheta Formation, which is dominated by thick and extensive sequences of limestones and dolomitic limestones. Since the limestones and dolomitic limestones are metamorphosed, it has been suggested that they be called marbles and dolomitic marbles in order to differentiate the various carbonate rocks (Nkhuwa, 1996). The Lusaka Dolomite and Cheta Formations belong to the Katanga Supergroup, while the Chunga Formation constitutes the Basement Complex. Carbonates occupy an area of about 470km² in the study area, whereas the combined area occupied by schist and quartzite is about 221km² (Mpamba, 2005).

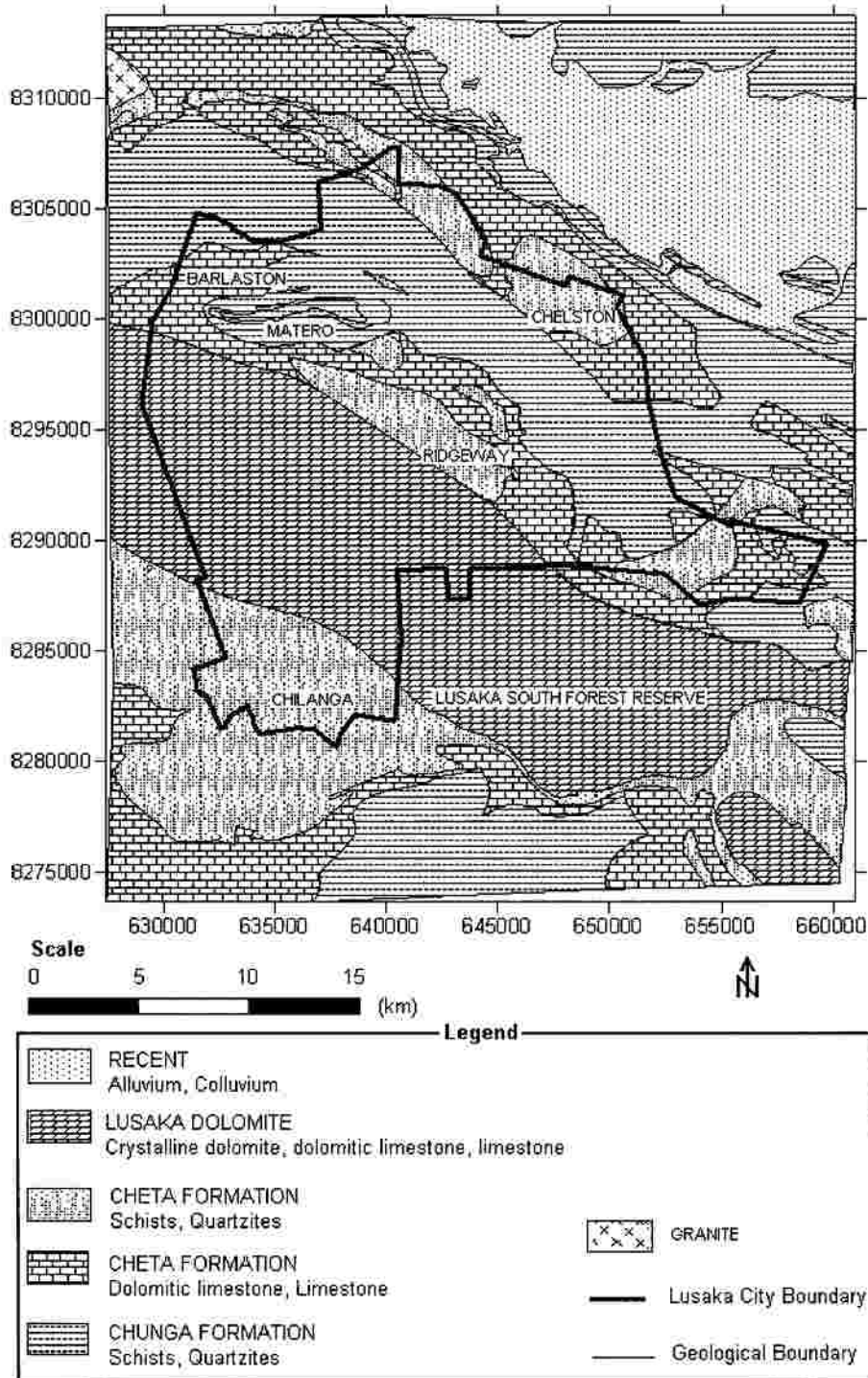


Figure 2.8 Simplified geological map of the Lusaka Plateau [after: Simpson et al., 1963].

Tectonic events are suggested to have caused the uplift resulting in the current Lusaka Plateau (Figure 2.9). These tectonic events are postulated to be associated with recumbent folding accompanied by faulting (Simpson *et al.*, 1963) and thrusting (Drysdall and Smith 1960).

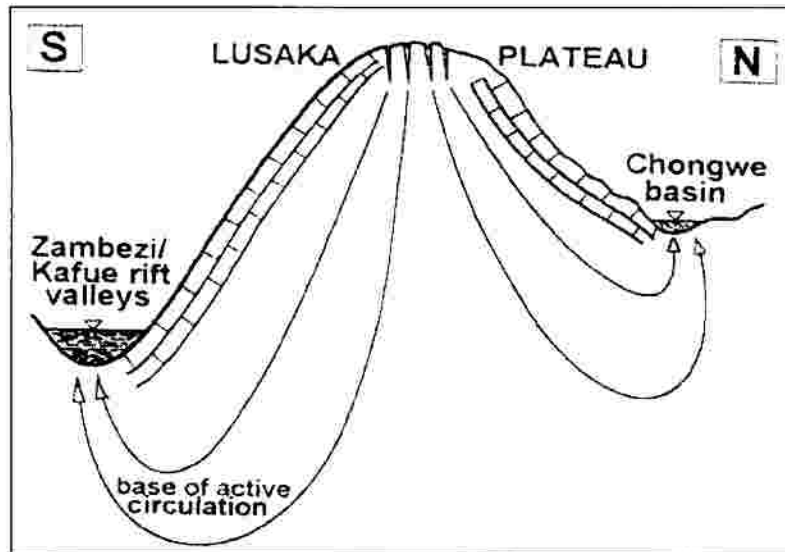


Figure 2.9 The uplift of Lusaka Plateau due to tectonic events (not to scale) [Source: Nkhuwa, 1996].

2.6.1.2 Hydrogeological Setting

Outcropping within the study areas, are the Cheta Formation (schists and quartzites), Chunga Formation (schists and quartzite) and Lusaka Dolomite (marbles and dolomites) belonging to the Katanga Supergroup a single geological sequence that occupies the northern and central parts of Zambia. These are all aquifers each with a different potential. However, Lusaka Dolomite has the highest groundwater potential due to a well-developed karstic system (Nkhuwa, 1996). From a regional point of view, rocks of the Katanga age which cross in three northwesterly – trending synforms at Lusaka,

Chisamba and Kabwe possess the highest groundwater potential. The Lower Katanga Dolomite is by far the most important aquifer from which cities like Ndola, Kabwe, Lusaka and Mazabuka town derive part of their underground water supply (Simpson *et al.*, 1963). The combined thickness of the Lusaka Dolomite and Cheta Limestone is not known, due to the absence of deep drilling on Lusaka Plateau (Nkhuwa, 1996).

2.6.1.3 Historical and Current Groundwater Resources Development Scenario

Exploration and exploitation of groundwater resources in the Lusaka urban aquifers dates back to 1950s the time when Lusaka was established as the capital city. The city water supply has historically depended on groundwater from Lusaka Dolomite south of the city. According to Lambert (1963), from 1950s to 1963 private residential plots, smallholdings and a few industrial sites were dependent on individual water supplies from groundwater sources. Hence, Lusaka was once described as the only city in the past or present British territories in Africa that derived its water supply entirely from boreholes (Lambert, 1963). A substantial groundwater abstraction level of $43,000 \text{ m}^3 \text{ day}^{-1}$ was achieved from boreholes constructed in the Lusaka Dolomite from 1959 to 1961 (Simpson *et al.*, 1963). Examination of the historical borehole details (Table 2.3) shows that boreholes are characterised by high yields, low drawdown, main intersection depth to the water ranging from 15m to 39m and an average borehole depth of 53m. This gives baseline data of the aquifer in its natural state and is worth comparing to the current scenario when the aquifer is extensively exploited.

Table 2.3: Data on boreholes drilled in the Lusaka Dolomite from 1959 to 1961
(after Lambert, 1963).

No.	Location	Borehole depth (m bgl)	First Water Intersection depth (m bgl)	Main Water Intersection depth (m bgl)	Static Water Level (m bgl)	Pump Intake (m bgl)	Drawdown (m bgl)	Borehole Yield (l/sec)
1	New Waterworks	49.08	30.3	31.2	11.7	42	24	131.4
2	New Waterworks	49.08	29.1	30.9	15	39	30	43.8
5	New Waterworks	42	39	39	12	23.4	21	87.6
1-17-59	Old Mumbwa Rd	39	4.5	26.4	0.78	6	1.8	26.3
2-17-59	Old Mumbwa Rd	44.7	3	24	0.63	6	3.9	18.9
3-17-59	Old Mumbwa Rd	45	1.8	15	1.2	6	2.4	15.8
4-17-59	Old Mumbwa Rd	60	3.3	36	1.8	6	5.1	34.7
5-17-59	Old Mumbwa Rd	74.1	2.1	12.6	2.1	40.5	40.5	3.7
14-17-59	Beacon C 360	59.1	6.6	36	6.6	32.4	6.3	28.4
2-2-61	Beacon C 361	68.4	8.1	36.3	8.1	39.3	11.7	36.6
Average		53.05	12.78	28.74	5.9913	24.06	14.67	42.718

bgl = Below ground level.

Between September and November 1961, two major factors affected water levels in unused boreholes at the old water works for the first time (Simpson *et al.*, 1963):

- 1) Groundwater abstraction
- 2) Construction of a deep drainage network, which was fully operational during the 1960/61 season, to drain the commercial and industrial areas of Lusaka on the dolomite.

The effects of groundwater abstraction and groundwater drainage through the deep drainage network, led to a reduction of dewatering of a nearby quarry from 7570 m³ day⁻¹ to 2838 m³ day⁻¹ because of a declining groundwater table. This scenario provides an understanding of how quickly the dolomite aquifer responds to the effects of abstraction

and induced drainage. Over-pumping and the danger of aquifer depletion attributed to oversiting and intense development of farms and residential areas, each with their own borehole, have been a source of great concern from the late 1950s to early 1960s (Lambert, 1963).

2.6.1.4 Previous Studies on Groundwater Recharge and Water Balance

Estimates of groundwater recharge by rainfall for the Lusaka Plateau vary widely from 8% to 35% of the annual rainfall (Burdon and Papakis, 1963; Von Hoyer *et al.*, 1978; JICA Report, 1995; Nkhuwa, 1996, Maseka and Nyambe, 1999). The difference in the estimates could be attributed to the methods used to determine the annual recharge (Table 2.4). However, the amount of groundwater recommended to be withdrawn from the aquifer should not exceed the estimated groundwater recharge of 8% of the annual rainfall (JICA Report, 1995). This is the renewable groundwater due to rainfall. In the case of the Lusaka Plateau, this is calculated as $45.44 \times 10^6 \text{m}^3 \text{ year}^{-1}$ based on the effective estimated surface area available for recharge and the long-term average annual rainfall of 822mm calculated from meteorological records from 1938 to 1994 (Nkhuwa, 1996). Other studies include determination of infiltration capacity that has been estimated as 76mm hr^{-1} for soils on the Lusaka Dolomite (Taque, 1969), while effective porosity is in the range of 2.5% - 7.5% (Jones and Topfer, 1972). Borehole logs in the marbles show fracturing and karstic development extending to an average depth of 80m (Von Hoyer *et al.*, 1978 and Nkhuwa, 1996). Each of the hydrogeological studies carried out in the study area has had its own strengths and weaknesses, but they have been able to compliment

each other in improving our understanding of the Lusaka urban aquifers. It includes characteristics and the safe yield of aquifer on the Lusaka Plateau (Table 2.5).

Table 2.4: Different recharge values determined for the Lusaka Plateau from 1963 to 1999 (after Burdon and Papakis, 1963; Von Hoyer *et al.*, 1978; JICA Report, 1995; Nkhuwa, 1996, Maseka and Nyambe, 1999).

Method	Author	Value (%)
Hydrological and meteorological analysis involving comparison of areas in Mediterranean countries with karstic features	Burdon & Papakis (1963)	35
Hydrological and meteorological analysis with the use of the relative plant-available moisture (RAM) values	Von Hoyer <i>et al.</i> , (1978)	22
Hydrological and meteorological analysis using PENMAN and THORTHWAITE and the RAM values from Von Hoyer <i>et al.</i> , (1978)	Nkhuwa (1996)	23
Hydrogeological surveys, groundwater levels, numerical simulation, surface water and meteorological analysis	JICA Report (1995)	8
Annual variation of groundwater levels	Maseka & Nyambe (1999)	27

Even with all the available results from various detailed studies, uncertainties still exist about the groundwater resources in these aquifers in terms of storage, replenishment and side effects arising from their over-exploitation (Nkhuwa 1996).

Table 2.5: Characteristics of the main aquifer lithology on Lusaka Plateau (after JICA Report, 1995)

Aquifer Lithology	Permeability coefficient (m/s)	Specific Yield
Limestone, Dolomite	1.51×10^{-5}	0.05
Schist	1.20×10^{-6}	0.02

2.6.2 Gwembe District

2.6.2.1 Geology

Three features mainly represent the general geology of the study area: the Basement Complex (schist, gneiss and metamorphic rocks) Karoo Supergroup (sandstone, mudstone and conglomerate) and Katanga Supergroup (shale, sandstone and conglomerate) on the extreme northern part of Gwembe District (Figure 2.10). The sediments of the Karoo Supergroup that occupy a great deal of Gwembe District are a thick succession of continental sediments of Permo-Triassic age and include a coal measure near the base (Pagella and Drysdall, 1966; Money et al., 1968). According to Gair (1959) and Smith (1960), Karoo rocks which are located in the mid-Zambezi area are described to be down warped, partly fault-bounded and rift like depression. Further geological work by Nyambe (1993) indicates that the Gwembe Coal Formation is a fluvial deposition of sandstones, siltstones and mudstones in channels and on the floodplains.

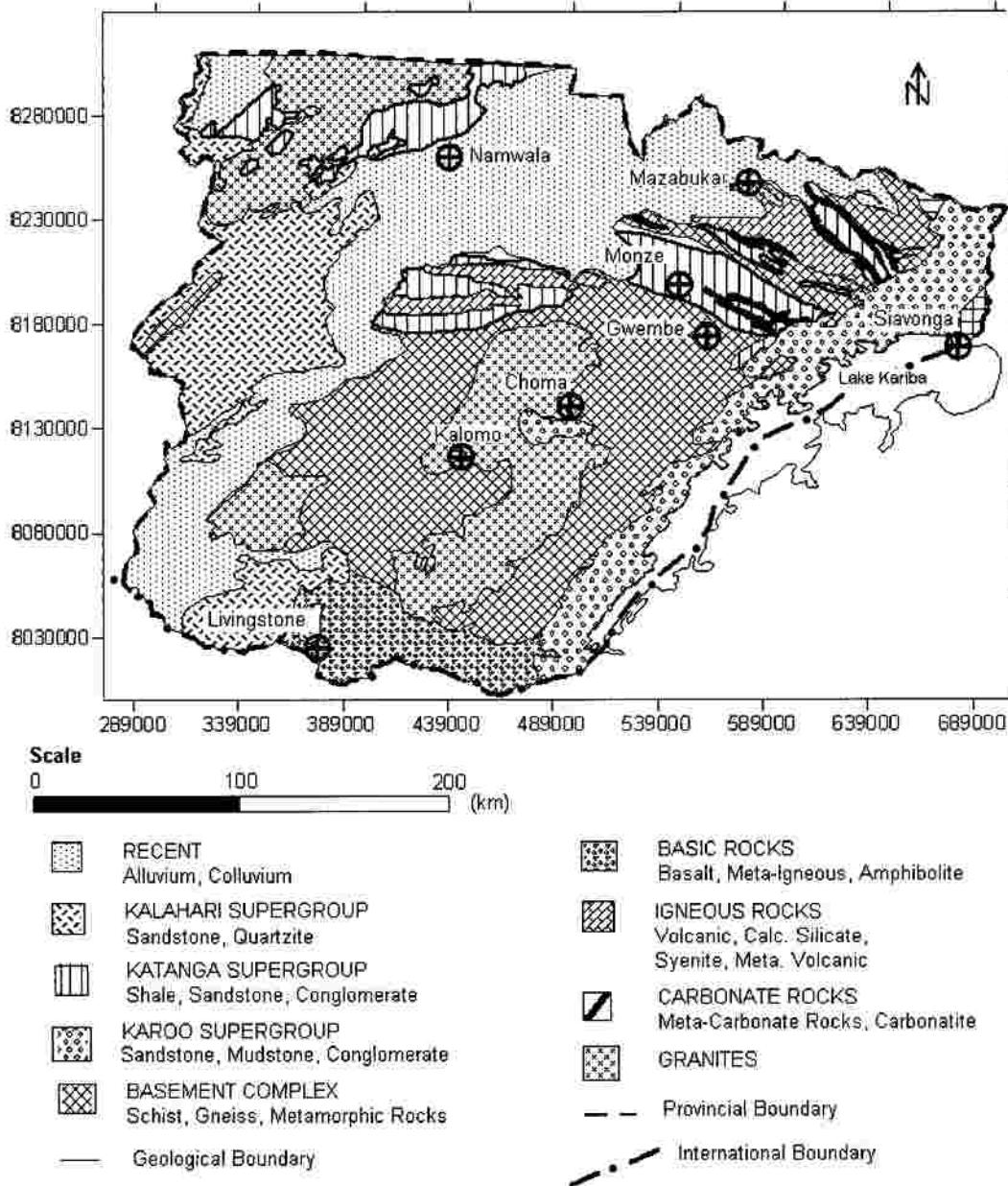


Figure 2.10 Map of the geology of Southern Province [Source: Geological Survey Department of Zambia]

2.6.2.2 Hydrogeological Setting of Gwembe District

The rock type and its physical conditions are the most important factors with regard to groundwater resources in Gwembe District. Lambert (1961) indicated that the Basement rocks are poor in groundwater because they mainly consist of granite-gneisses with very shallow depths of decomposition, whereas the dense texture and high retentiveness makes mudstones and shales very poor aquifers with yields rarely more than 0.5 l s^{-1} . Mudstones are thick and devoid of parting horizons. Hence, groundwater is only available within the weathered zone and fracture system or sandstone horizons. The sandstones are good aquifers due to jointing and fracture system.

2.6.2.3 Historical Groundwater Development Scenario

According to Lambert (1961) large-scale rural groundwater development activities in Gwembe District started during the resettlement of the Tonga people from the Valley that was flooded during the construction of Kariba Dam. Most of the boreholes constructed in Siavonga-Lusitu, Gwembe-Chipepo areas and Sinazongwe were characterized by low yields, whereas analysis of water from boreholes drilled at that time proved to contain a fairly high concentration of fluoride (Lambert, 1961).

2.6.2.4 Hydrogeological Studies and Current Groundwater Development

There are no other detailed hydrogeological studies that have taken place in Gwembe District since the JICA study (1995) that resulted in the preparation of the National Water Resources Master Plan for Zambia. The Ministry of Energy and Water Development carried out a study that gives statistical information on operational rate of water point

sources in terms of groundwater abstraction by the rural communities and coverage (CMMU, 1997), as a basis for water point planning and assessment of water coverage for rural water supply facilities.

Groundwater resources development in Gwembe District is also demand driven like in most parts of Zambia, and centred on rural water supply to meet the domestic and livestock water requirements. The whole district of Gwembe currently has only four boreholes that are equipped with motorized pumps. Abstraction from about 300 boreholes is achieved by means of hand pumps that have a maximum abstraction rate of about 0.2 l s^{-1} . Standard borehole yield under pumping conditions of 10 hours operation in a rural set up is estimated to be $7.5 \text{ m}^3 \text{ day}^{-1}$ (JICA Report, 1995). Based on this yield, the number of boreholes required for the rural population in Gwembe District is calculated by dividing the district water demand with the daily water demand of $7.5 \text{ m}^3 \text{ day}^{-1}$ (JICA Report, 1995).

2.6.2.5 Previous Studies on Recharge and Water Balance

The annual Groundwater potential, which is also referred to as the annual recharge for Gwembe District is estimated at 9 % of the annual rainfall ($285 \times 10^6 \text{ m}^3 \text{ year}^{-1}$) based on the groundwater level measurements carried out from May 1994 to April 1995 at two water points (Hand dug wells) using a monthly measurement frequency (JICA, 1995). Aquifer characteristics and safe yield were also determined during the same study (Table 2.6).

Table 2.6: Characteristics of the main aquifer lithology in Gwembe District (after JICA Report, 1995)

Aquifer Lithology	Permeability coefficient (m/s)	Specific Yield
Mudstone, Gneiss	5.0×10^{-7}	0.04
Sandstone	3.1×10^{-6}	0.02
Granite, Schist	1.7×10^{-6}	0.03

2.7 Groundwater Exploration and Development in Zambia

The need for groundwater development in Zambia is ever increasing on a yearly basis, both in the urban and rural areas and it constitutes a big challenge regarding groundwater resources management. Increase in demand is attributable to the growing water requirements to meet domestic, industrial and agricultural water demand. Although Zambia is endowed with abundant surface and ground water resources (WRAP, 2003), issues of quantity and quality, in time and space, are not yet well understood to allow for sustainable development and effective utilisation of the resource.

Some rural communities of Zambia entirely depend on groundwater sources for their water requirements, whereas a number of towns and cities in urban areas derive part of their water supplies from groundwater sources. Besides domestic and industrial water requirements, promotion of irrigation as a national target to attain stable crop production (MACO, 2003) is also exerting pressure on groundwater resources. The prevailing situation offers the opportunity to explore and exploit as much groundwater resource as possible for economic growth. But at the same time, this may encourage over exploitation

of some aquifers and eventual water depletion as well as water quality deterioration. The current rate of groundwater development and abstraction in certain areas, if not controlled, could even lead to effects such as aquifer depletion, stream flow reduction in dry season, land subsidence *etc.*

2.7.1 Current Groundwater Development Scenario in Zambia

Most of the groundwater development activities taking place in Zambia are as a result of demand and not according to plans. Sustainable groundwater development always includes the exploration phase as a prerequisite. However, high costs involved in exploratory drilling limits this type of approach to projects such as groundwater resources development for urban water supply schemes.

Groundwater development for rural water supply and private individuals, including those for companies, do not include any exploration costs. This is because it is regarded as an extra expense that is not necessary. As such, in most cases the drilling is wholly dependent on results from geophysical investigation carried out based on geological structures, geological maps *etc.*

2.7.1.1 Geophysical Investigations and Drilling

Electrical resistivity prospecting using Wenner configuration is the most widely used geophysical investigation technique in the Department of Water Affairs to locate sites for borehole drilling. The reasons for this are two fold:

- It is easy for most technicians to learn the technique and use it to select drilling sites with a good success rate.
- The Department of Water Affairs has for a long time not been able to acquire other modern equipment for carrying out groundwater prospecting.

There are times when dry boreholes, low yielding boreholes and high yielding boreholes have been encountered by the Department of Water Affairs with this method. However, knowledge of the type of aquifers and geology distributed in respective parts of Zambia help to quickly determine the right procedure to adopt to investigate groundwater potential for drilling sites. A combination of horizontal profiling followed by vertical sounding has in most cases, proved effective in selecting suitable drilling points in low yielding aquifers with limited potential and in aquifers where groundwater flow is mainly in fissures, discontinuities or solution channels such as on the Lusaka Dolomite and other carbonate covered areas.

Boreholes drilled in the study area were all located using electrical resistivity prospecting method with Wenner configuration. Interpretation of results is usually based on geophysical anomalies associated with lithological contacts, weathering profiles, fractures and cavities that are assumed to be water bearing. According to Kang'omba (2004 – personal communication), in extremely difficult areas with very low groundwater potential, geomorphology and indigenous knowledge on anthills and special trees that grow near water have been used to select areas where to effectively use geophysical method to collect data for a drilling site. This approach has so far proved effective in

areas previously associated with low rate of successful boreholes. The Department of Water Affairs has successfully utilized resistivity depth sounding data to determine suitable drilling depths and recommend the possible drilling methods with an average of about 95% success drilling rates. In groundwater development projects for rural water supply, resistivity depth sounding data has also been used to recommend drilling methods, plan for drilling in terms of selection of suitable tools, equipment, accessories and consumables required to successfully implement the project. This approach has been useful in controlling project implementation cost by employing appropriate drilling techniques and methods, as well as providing the correct tools and equipment to drilling crews.

2.7.1.2 Borehole Drilling Guidelines and Procedure

Drilling guidelines and procedures are closely linked to reliable collection of hydrogeological data during borehole construction. These include, borehole construction details, materials used for construction, details related to aquifer lithology, yield assessment and preparation of borehole completion report. There are no guidelines and procedures that have been developed to direct borehole drilling in Zambia. However, over years standard ways of borehole construction have been developed and adopted as a good practice by the Department of Water affairs (Table 2.7). These have helped to ensure good workmanship, to uphold high standards when constructing boreholes equipped with motorized pumps and boreholes meant for the various rural water supply projects. Most drilling contracts entered on between DWA and the private drilling

contractors to construct boreholes on behalf of the Ministry of Energy and Water Development (DWA, 1980 – 2001) were based on the same good practices.

Table 2.7: Borehole drilling guidelines and procedures followed by the Department of Water Affairs when constructing boreholes (after DWA, 1982).

Activity	Large Diameter Boreholes	Small Diameter Boreholes
Borehole verticality	Must be vertical	Must be vertical
Drilling diameter	At least 213mm to allow for casing with at least 150mm casing, gravel packing and pump installation.	At least 156.25mm to allow for casing, gravel packing and inserting with at least 100mm casing to allow for Handpump installation.
Lithology sampling	Every 3m and at the change of formation	Every 3m and at the change of formation
Casing	Cased to the bottom using suitable non – polluting material, screens at aquifer position and plain casings at non – aquifer position. Bottom plugged in loose formations.	Cased to the bottom using suitable non – polluting material, screens at aquifer position and plain casings at non – aquifer position. Bottom plugged in loose formations.
Gravel packing	Annular space must be gravel packed at the screen and aquifer position with durable and suitable size of material in respect to size of the aquifer materials.	Annular space must be gravel packed at the screen and aquifer position with durable and suitable size of material in respect to size of the aquifer materials.
Well Development	Must be done with Airlift method for at least 30 minutes or until the water is clear of drilling cuttings.	Must be done with Airlift method for at least 30 minutes or until the water is clear of drilling cuttings.
Yield	Must be done by Airlift method or motorized pump for .at least 6 hrs.	Must be done by Airlift method or motorized pump for .at least 6 hrs.
Grouting	By placing concrete mixture up to 6m depth from ground surface.	By placing concrete mixture up to 6m depth from ground surface.
Dry Borehole Report	To be filled with drilling material. Must be prepared for both dry and successful boreholes.	To be filled with drilling material. Must be prepared for both dry and successful boreholes.

Boreholes drilled during the study period conform to the standard construction guidelines and procedures adopted over years by the Department of Water Affairs. Table 2.8 outlines the type of information to be collected, the best time to collect it, some of the

difficulties associated with non-collection and recording of hydrogeological data on a completion report form during borehole construction.

Table 2.8: Summary of Hydrogeological data and information that must be collected by a Driller during borehole construction using a completion report form.

Information Type	Best Time to collect	Difficulties if not collected at time of Drilling
Borehole depth, Name of Property, Name of Owner, Province, District, Location and Chief,	During drilling	Could be collected any other time at an increased cost.
Water intersection depth, Lithology / Formation, Casing Details, Contractor, Dated Drilled	During drilling	Impossible to get at any other time.
Yield	During well development, and Pump Testing.	Could be collected any other time at an increased cost.
Grid Reference/ GPS coordinates.	During drilling, Pump Testing, Pump installation.	<ul style="list-style-type: none"> • Difficult to get at a later date and at an increased cost, especially when there is more than one borehole in the same premises. • Difficult to get when location is not known or borehole changes hands.

In addition, Japanese funded groundwater development projects have been instrumental in undertaking projects with laid down details on construction of boreholes and thereby ensuring capacity building for government drillers (MWED, 1992).

2.7.1.3 Drilling Techniques Appropriate for Zambia

Failure and short life span of most boreholes drilled in Zambia are attributed to the use of inappropriate drilling techniques and methods that may arise as a result of lack of know how to drill in areas with complex geology and with lithologies that vary within short distances, vertically and horizontally or failure to properly drill boreholes in areas with certain geologic formations. Experience gained from the study area, is that in uniform lithology, the degree of weathering or presence of cavities and laterite may also lead to poor borehole construction. Whereas in highly weathered schists, especially on Lusaka plateau, boreholes normally require drilling, casing and gravel packing to be done within a period of at most 8 hours. When this is not achieved in the stated period, the schists dissolve along the portion filled with water and form the slurry that makes it difficult to place gravel pack in the borehole between the casing pipes and the annular space of the hole. This situation results in continuous abstraction of turbid water and eventual reduction of borehole depth. It may also lead to pump damage.

Good borehole construction in limestone and dolomite areas of Lusaka with cavities and laterite is only possible and manageable with the use of temporal casing pipes that allow for drilling to the required depth, followed by casing and gravel packing. Failure to do this usually results in a borehole with a compromised life span.

The Department of Water Affairs has successfully utilized various drilling techniques, methods and approaches in different parts of Zambia during groundwater development projects. The purpose of this section is not to describe the drilling techniques and method,

but to indicate where each of them is often applied in Zambia. These are summarized as follows:

- (I). **Air percussion:** It is widely used in most parts of Central, Northern and Southern provinces of Zambia in consolidated sediments and hard rock areas.
- (II). **Air rotary:** In North-Western province, air rotary using a tricone or a wing bit precede mud drilling in the highly weathered schist after installation of conductor pipes to the hard rock. This method is also used in some parts of Southern, Eastern, Northern and Luapula provinces
- (III). **Air percussion with water injection:** in the sandstone and mudstone areas of Southern Province such as Gwembe and Sinazongwe districts, this method is used to clear off cuttings from the borehole when little water has been encountered. However, in most areas of Kalomo and Siavonga Districts that have very hard formations such as granites, the method provides cooling effects to the drill string and prolong the life span of the bit. This method is also used in Northern and Lusaka provinces.
- (IV). **Air percussion with foam injection:** This method is used in most consolidated geological formations found in the Northern Province. In Southern Province, It is mostly used in the mudstone and sandstone areas of Gwembe and Sinazongwe districts.
- (V). **Mud drilling:** Boreholes in the alluvial deposits around Chama District of Eastern Province, sand areas of Namwala and Mazabuka districts along the Kafue flats get constructed using mud drilling. Western Province is the only

special case where mud drilling is widely used due to a thick layer of Kalahari sands over lying basalts.

(VI). Mud drilling and air percussion: The thick layer of Kalahari sands overlying the basalts in most parts of Western Province (Mongu, Senanga, Sesheke areas etc) and the South – western parts of Southern Province (Kazungula area) require a combination of mud drilling and air percussion when drilling boreholes. Mud drilling method is used up to the hard formation then followed by air percussion drilling after inserting conductor pipes to the hard formation.

2.8 The Concept of Basin-wide Water Resources Management in Zambia

In this study, emphasis is on assessing groundwater resources in terms of quantity and quality by ensuring availability of groundwater data and information. The source of groundwater recharge in Zambia is precipitation that falls annually from October to April. Therefore, recommendations for groundwater resources development are that it should not exceed the groundwater resources potential values (Table 2.9). Whereas, recommendations for surface water resources utilisation are that it should be guided by the established surface water resources potential in the 34 basin blocks in the Zambezi and Congo River basins (JICA Report, 1995).

In brief, this is a clear indication that groundwater abstraction should be limited to the amount of recharge from precipitation and must recognize the issues to do with surface water – groundwater interaction (Xu and Beekman, 2003). Hence, the borehole

numbering system should conform to the surface water basins to facilitate allocation of groundwater without causing negative effects on stream flows.

Table 2.9: Groundwater potential values recommended for groundwater development for Zambia (after JICA Report, 1995).

Province	Annual Groundwater Potential	
	Annual Recharge (%)	Total volume (10^9 m ³ /year)
Lusaka	8.0	1.5
Copperbelt	6.8	2.6
Central	8.6	7.7
Northwestern	7.8	11.4
Western	6.8	7.0
Southern	9.4	5.7
Luapula	6.8	3.9
Northern	7.0	11.5
Eastern	9.2	6.1

(Note: Modified from the National Water Resources Master Plan for Zambia)

According to the proposed water resources management strategy, the basin blocks represent sub-catchments that are part of the six catchments; namely, Zambezi, Kafue, Luangwa, Chambeshi, Luapula and Tanganyika (WRAP, 2005). Block divisions for the Zambezi and Congo River basins are comparable to the proposed catchments and sub-catchments (Table 2.10) as follows:

Table 2.10: *Catchments and Sub-catchments in Zambia (after JICA Report, 1995).*

Catchment	Sub-catchments
Zambezi Main River	9 basin blocks from BZ-1 to BZ-9
Kafue River	11 basin blocks from BK-1 to BK-11
Luangwa River	5 basin blocks from BL-1 to BL-5
Chambeshi River	2 basin blocks from BC-1 to BC-2
Luapula River	5 basin blocks from BP-1 to BP-5
Lake Tanganyika	2 basin blocks from BT-1 to BT-2

2.8.1 Numbering of Mine De-watering Shafts in Zambia.

High volumes of groundwater extraction and de-watering to support mining activities have affected headwaters of certain river basins in Zambia (Warren, 1972). Most underground mining activities in Zambia require de-watering to keep the working areas dry for effective mining and safety of the miners. This continues even when mines are closed. Examples of areas with deep groundwater de-water shafts is the Copperbelt and Central provinces of Zambia, which are located on the Kafue Catchment. The Davis shaft for the mine in Kabwe is about 488m deep and de-watering in excess of 118,300 m³/day was recorded when the mine was active (Jones, 1972). Mining shafts on the Copperbelt and in Central provinces cut through a geological strata that hosts both local and regional aquifers in the Katanga Supergroup (Jones, 1972; Hadwen, 1972). Since de-watering activities may in the long run have effects on local and regional groundwater flow, they also require numbering to facilitate water resources management. Therefore, de-watering shafts may be considered as large diameter borehole and numbered accordingly. This should also include documentation of geological strata, aquifer characteristics and water quality to facilitate assessment of the economic value of groundwater from the shafts.

3.0 RESEARCH METHODOLOGY

In this study, a methodology was adopted that emphasized not only on collecting data, but also aimed at identifying:

- What to do (**a strategy**) and,
- How to do it (**a system**).

The *strategy* is defined as the need to regularly and consistently collect hydrogeological (Borehole drilling information), groundwater quality and groundwater level data. Whereas the *system* is defined as the role of the Ministry of Energy and Water Development to guide and involve stakeholders in collection, transmission, storage, analysis and dissemination of the three data sets in order to enhance sustainable groundwater resource development and management.

3.1 Proposed Data Acquisition Model

A trilogue approach that links the data sets was adopted as a way of improving on the understanding of the aquifers regarding the quantity and quality of groundwater on a short term and long term basis. Therefore, the proposed model (Figure 3.1) defined the type of data to collect and guided the acquisition of relevant groundwater data and information in the study areas selected to represent the urban and rural areas.



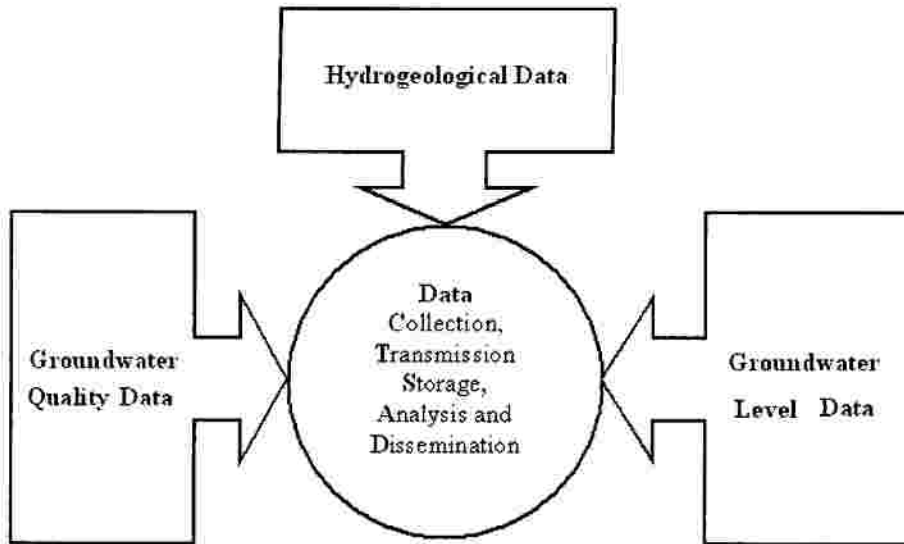


Figure 3.1 The data acquisition model used to capture groundwater data and information in the study areas.

Moreover, the need to replicate the approach is another aspect that was given much attention, when outlining steps to take during collection of data in the study areas. Therefore, it was important that the proposed approach of using the model be analysed fully for the following reasons:

- To determine the practical viability and the financial implication of generating the intended hydrogeological, groundwater quality and groundwater level observation data sets.
- To identify the principle data collectors and the equipment required to efficiently collect the data sets.
- To identify the various levels involved in collecting the proposed data sets.
- To evaluate the possibility of replicating the approach to all groundwater development projects.

All the three data sets were therefore collected in respect of the various recommendations and guidelines established regarding hydrogeological, groundwater sampling and groundwater level observation (Kovalevsky *et al.*, 2004).

3.1.1 Adaptations to the Proposed Data Acquisition Model

Several necessary adaptations to the proposed data acquisition model were made in order to introduce the practical linkage between groundwater quantity and quality. These were based on the following:

1. Hydrogeological data describes groundwater quantity at the time of borehole drilling and therefore relates to the other data sets on a short-term, but is inevitable for the aquifer dimension;
2. Groundwater quality data describes the quality of groundwater at the time of borehole drilling and at any other time; and therefore relates to the other data sets on both the short-term and long term;
3. Groundwater level data describes groundwater quantity at the time of borehole drilling and at any other time; and therefore relates to the other data sets on both the short-term and long term.

In brief, it was clear that acquisition and analysis of the proposed data sets would be useful in providing information directly or indirectly on groundwater quantity and quality status for resource assessment and management (Table 3.1).

Table 3.1 Groundwater monitoring concerns expected to be addressed following collection of information using the proposed data acquisition procedure

Data sets	Possible groundwater resources assessment				Desired data collection frequency
	Quantity		Quality		
	Short term	Long term	Short term	Long term	
Hydrogeological data	Yes				Regularly
Groundwater level data	Yes	Yes			Daily
Groundwater quality data			Yes	Yes	Regularly

3.1.2 Justification for Proposing the Data Acquisition Model

According to Kovalevsky *et al.*, (2004), it is important to have knowledge about the nature of the aquifer system and groundwater system when undertaking any groundwater assessment study. The aquifer system comprises of the following, some of which could be obtained from hydrogeological data:

- **the geometry:** the extent and thickness of the aquifer or aquifer system and possible interlayered aquitards,
- **the boundary conditions:** head controlled, flow controlled and no – flow boundaries,
- **the aquifer type(s):** confined, semi – confined, unconfined or perched unconfined,
- **hydraulic parameters:** porosity, intrinsic permeability etc.

On the other hand, groundwater system is defined by the following components:

- the quantity of groundwater stored in the aquifer system and its quality,
- the water table levels and their fluctuations over time indicating changes in the amount of water stored in the aquifer,

- groundwater head (piezometric) fluctuations of confined or semi – confined aquifers indicating the changes over time of the hydraulic pressure in the aquifer,
- recharge and discharge sources, the time – dependent rates of discharge, and recharge from each source (hydraulic stress),
- groundwater budget being a comparison between the sum of all recharge and other inflow components and the sum of all discharge components plus the change in storage over a specific period of time (e.g. six months, one year etc),
- chemical composition.

Groundwater quality analysis is an important aspect of groundwater development that should not be neglected because it gives an understanding of how suitable groundwater is for any desired use. The quality of groundwater is said to be a function of the sources and sinks of chemical elements along the groundwater flow path (William, 1997). Residence time therefore influences the water – rock interaction and varying groundwater chemistry (Titus, 2003). According to William (1997), relative concentrations of dissolved constituents are determined by the available supply from the solid phases and solubility of secondary minerals formed from weathering processes. This influence increases with long flow path. Once groundwater is taken out of its environment, the chemical elements are able to undergo physical chemical changes. Special attention should be given to the sampling programme, to try by all means to conform to the recommended groundwater sampling procedure. It is important to obtain a water sample that represents groundwater within an aquifer (Kovalevsky *et al.*, 2004).

Table 3.2 gives details on how collection of hydrogeological, groundwater quality and groundwater level data relates to the aquifer system and groundwater system; and could be the source of information to help identify aquifer and groundwater systems in various parts of Zambia.

Table 3.2: How to collect information related to aquifer system and groundwater system (after Kovalevsky et al., 2004).

Type of information	Source
Aquifer geometry	Borehole drilling data, geology, geophysical well logs, geo – electrical surveys, seismic surveys.
Water table and Piezometric levels	Observation boreholes and Piezometers
Hydraulic parameters	Continuous pumping test
Boundary conditions	Borehole drilling data, observation wells, geology
Groundwater storage	Borehole drilling data, pump tests
Groundwater budget	Precipitation, stream flow, abstraction volumes etc
Groundwater quality	Borehole water quality analysis

3.2 Selection of the Study Areas

Two main study areas, Lusaka Plateau (Lusaka urban and adjacent areas) and Gwembe District (Figure 1.3) were selected to represent the urban and rural areas of Zambia, respectively. Additionally, Mongu was identified as a minor study area. The two main study areas needed to fulfil the following criteria:

(a) **Urban area:** needed to be an area with the following characteristics: (i) a lot of on going groundwater development activities, (ii) a substantial number of boreholes with completion reports as evidence of large scale groundwater utilization, (iii) presence of settlements with on site sanitation and other anthropogenic activities capable of influencing groundwater quality, (iv) hosts one of the three main aquifer types. On this basis, Lusaka urban and adjacent areas were selected.

(b) **Rural areas:** needed to be an area with the following characteristics: (i) having a lot of on going groundwater development activities, (ii) under developed groundwater resources with minimal utilization, (iii) groundwater as a preferred water source option due to scarcity, low running costs and presence of anthropogenic activities capable of influencing groundwater quality, (iv) hosts one of the three main aquifer types. Gwembe District was selected on this basis.

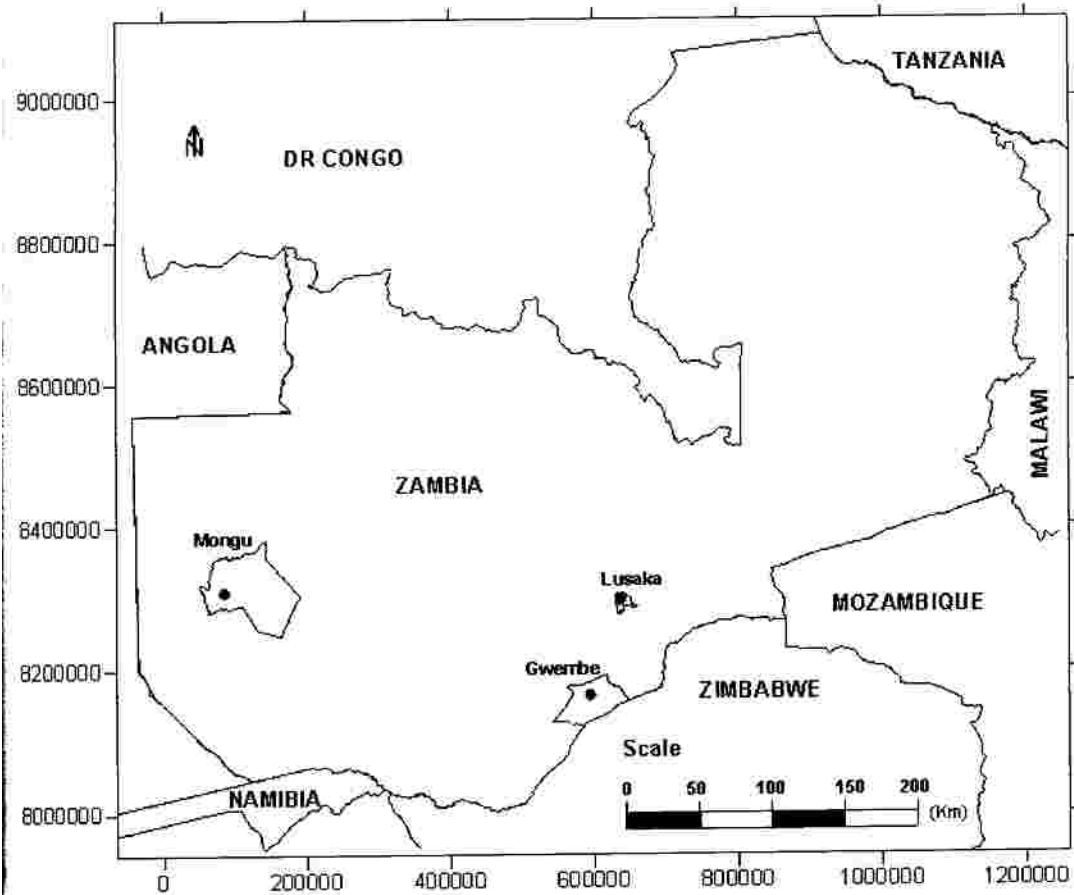


Figure 3.2 Map of Zambia showing the study areas: Gwembe District, Lusaka urban and Mongu

Lusaka urban is located on one of the three main aquifer types where groundwater flow is mainly in fissures, channels or discontinuities, whereas Gwembe District is located on the aquifer type classified as low yielding and with limited potential. Since there are three main aquifer types in Zambia, a location was required on the third aquifer type to take groundwater level measurements in order to have the opportunity to compare groundwater level response to recharge; and fluctuation pattern due to abstraction and natural aquifer drainage. In this regard, *Mongu* in the western part of Zambia hosts the aquifers where intergranular groundwater flow is dominant and was therefore selected.

3.3 Field Work and Collection of Data in the Study Areas

3.3.1 Collection of Hydrogeological Data

The exercise involved collection of existing data and new data generated during the study. Therefore, collection of existing data required examination of borehole completion reports on box files to identify boreholes located in the study area based on the descriptive information on the reports and then to take GPS coordinates. However, collection of new data required recording of all relevant information on a borehole completion report form by a driller during borehole construction for both dry and successful boreholes. To achieve this, the driller need skills and knowledge on how to give correct description of geological formations drilled through as well as to be able to use a GPS unit to take coordinates at the borehole sites.

GPS coordinates were taken using the Garmin Map 60 GPS unit in Universal Transverse Mercator (UTM) and World Geodetic System 1984 (WGS 84) as the datum. In Lusaka urban and adjacent areas, GPS coordinates were taken during borehole construction and pump testing, whereas in Gwembe District it was during borehole construction, equipping of boreholes with handpumps and inspection of constructed water points. The cost towards this exercise was the purchase of a GPS unit.

3.3.1.1 Accuracy of Hydrogeological Data Analysis

It is impossible for a driller to fully describe the lithology drilled through with out basic knowledge in geology. This implies that the accuracy decreases with increasing numbers of drillers with little knowledge in geology and a few years field experience or non at all.

The information recorded by a driller would help Hydrogeologists and researchers to identify boreholes drilled in a water table and confined aquifer. Much more, pump testing data becomes useful in generating aquifer parameters and to carry out other Geographical Information System (GIS) based spatial analysis (Freeze and Cherry, 1979; Kovalevsky *et al.*, 2004).

3.3.2 Collection of Groundwater Quality Data

This exercise attracted costs for sampling bottles, water sampling and transportation of samples to the laboratory as well as the actual sample analysis. To ensure objectivity and control the cost, most of the groundwater samples were collected during well development at the time of borehole construction. Transportation of samples to the laboratory was done during drilling inspection trips and by the drillers when collecting drilling materials. A few samples were collected in Lusaka urban and adjacent areas during pump testing, whereas for Gwembe District it was during handpump installation.

Recommendations are such that parameters for groundwater quality analysis should be selected and determined by the objective of the investigation (Kovalevsky *et al.*, 2004). Hence, besides bacteriological investigations, parameters analysed in groundwater are the major ions consisting of the cations and anions as well as selected minor and trace elements. The cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) whereas the anions are chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}) and bicarbonate (HCO_3^-). This may also include selected minor and trace elements such as iron (Fe), manganese (Mn) and fluoride (F) etc. Therefore, selection of the water quality

parameters analysed in this study, considered the need to classify groundwater from the hydro-geochemistry point of view in terms of its suitability for domestic, industrial and agricultural uses.

Groundwater sampling and water analysis was a one time off activity for most boreholes. However, routine groundwater quality assessment requires the use of permanent boreholes from which to collect water samples for analysis on a regular basis. Therefore, groundwater quality analysis campaign comprised two categories:

1. **Category one:** This was aimed at generating baseline values for each borehole at the time of construction in order to facilitate checking of groundwater quality trends in future. The baseline values were then used in the second water quality category campaign to target some selected boreholes in Gwembe District, but not Lusaka urban and adjacent areas due to costs involved. Groundwater samples were collected to analyze for eleven water quality parameters (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Fe, Mn, NO_3^- , F, Cl^- , SO_4^{2-} , HCO_3^-) and the interpretation.
2. **Category two:** It was carried out for the rural area with the aim of investigating and establishing parameters that change seasonally and to determine the suitable measurement frequency for routine groundwater quality monitoring of boreholes in rural areas for parameters that changed within the four years of this study. Groundwater was sampled from randomly selected boreholes drilled from 2001 to 2005 in Gwembe District, but whose water quality was initially analyzed during category one campaign. Samples were collected in June 2004, December 2004

and May 2005. Two other parameters pH and EC were measured in the field at selected boreholes during category two campaigns in addition to the eleven parameters (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Fe, Mn, NO_3^- , F, Cl, SO_4^{2-} , HCO_3^-).

Since a number of parameters such as Fe, Mn etc change with time, groundwater sampling was done in such a way as to avoid certain parameters to change due to physical chemical changes induced by temperature, chemical reactions etc. To control this effect, sampling procedure involved collection of two groundwater samples from the same borehole, one sample for trace metals in a 500 ml polyethylene – sterilized sampling bottle containing a few drops of Nitric Acid as a preservative to keep elements that would otherwise change during storage and transportation before analysis of the water sample. The second groundwater sample was collected in a 1000 ml polyethylene – sterilized sampling bottle without any preservative.

The above two mentioned water quality sampling and analysis campaigns formed the Hydro-geochemical analysis for this study. It is also important to mention that groundwater quality conditions are representative of the influence of both the rainy and dry seasons in the two sampling campaigns. Water samples were analysed at the University of Zambia by Environmental Engineering and Geochemical Laboratories in conformity with “Standard methods for the examination of water and waste water APHA 1998”.

3.3.2.1 Accuracy of Groundwater Quality Data Analysis

A criterion for an accurate analysis is the difference between the sum of cations and sum of anions that has to be less than 5% of the sum of these two [Equation 3.1]. This is based on the fact that common major solutes in groundwater are positively and negatively charged species and therefore groundwater solution must be electrically balanced (William, 1997).

$$[(\Sigma\text{Cations} - \Sigma\text{Anions}) / \frac{1}{2}(\Sigma\text{Cations} + \Sigma\text{Anions})] \times 100 \quad \text{Equation 3 - 1}$$

To achieve this, measured concentrations in mg l^{-1} or ppm should be converted to an equivalent unit for each major ionic species and then laboratory data analysis accuracy is checked by computation of the cation / anion balance. According to William (1997), a positive number of the cation / anion balance means that either there are excess cations or insufficient anions in the analysis, whereas a negative balance would imply excess anions or insufficient cations. If the error does not arise from the two stated reasons, William (1997) has suggested the following:

- The design of the sampling programme neglected a major dissolved species;
- Laboratory error;
- Using unfiltered water samples that contain particulate matter that dissolves in the sample when acid is added for preservation purposes;
- The precipitation of a mineral in the sample container that removes the constituents of the mineral from water;

- In certain cases the dissolved species of the element or compound may not correspond to the typical species used in making the ion balance calculation.

3.3.2.1 Classification of Groundwater Types for different uses

Groundwater quality analysis based on major ion composition of groundwater is used to classify groundwater into various types based on the dominant cations and anions (Freeze and Cherry, 1979). Evaluation of groundwater for irrigation, industrial and domestic purposes are also achievable from the same water quality analysis results. Composition of the dominant cations and anions can be displayed graphically by several methods such as Piper, Stiff etc. However, for summarized presentations piper method is one of the most useful. When sodium and bicarbonate are the dominant cation and anion, then groundwater would be classified as NaHCO_3 type (Freeze and Cherry, 1979).

Groundwater that is used for irrigation must be compatible with both the crops and soils to which it would be applied (Scherer *et al.*, 1996). It is therefore, inevitable to evaluate its effect on plant growth and the soils using the Total Dissolved Solids (TDS) measured as Electrical Conductivity (EC) and the Sodium Adsorption Ratio (SAR), which are the two most important factors to look for in irrigation water quality analysis (Scherer *et al.*, 1996). The US Department of Agriculture (1954) recommends the use of sodium – adsorption ratio (SAR) to classify irrigation water as a direct reflection of the degree of adsorption of sodium by soil. When sodium is present in water it tends to reduce soil permeability and causes hardening of the soil. Sodium ions displace calcium ions or other ions and the process increases with high sodium content in water. The other evaluation of

water for irrigation is based on chloride toxicity, magnesium toxicity or hazard, boron toxicity etc. However, according to Hergert and Knudsen (1997), the following are the four basic criteria for evaluating irrigation water quality:

1. Total soluble salt content (salinity hazard) estimated by determination of Electrical Conductivity (EC) of water;
2. Relative proportion of sodium cations (Na^+) to other cations (sodium hazard – soil permeability) estimated by the sodium absorption ratio (SAR);
3. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) anion concentration as related to calcium (Ca^{2+}) plus magnesium (Mg^{2+}) concentration (alkalinity) as a high CO_3^{2-} and HCO_3^- tend to increase the SAR of the soil whereas the concentration of calcium and magnesium are reduced relative to sodium through precipitation of calcium carbonate (CaCO_3) and magnesium carbonate (MgCO_3). This occurs when the solution in the soil concentrates during soil drying;
4. Concentration of elements that may be toxic (toxicity) such as boron, chloride etc.

In this study, evaluation of groundwater for domestic and industrial purposes were based on World Health Organisation (WHO) guidelines and Zambia Bureau of Standards (ZBS) in Appendix A1, whereas for irrigation purposes it was based on chloride toxicity, magnesium hazard and sodium adsorption as recommended by US Department of Agriculture (1954) as shown in Appendix A2.

- Chloride toxicity is calculated as chloride ionic concentration in milliequivalent per litre (Cl).

- Magnesium Hazard (MH) is defined in percentage, where all ionic concentrations are expressed in milliequivalent per litre [Equation 3 – 2].

$$\text{Mg}^{2+}/(\text{Ca}^{2+} + \text{Mg}^{2+}) \quad \text{Equation 3 – 2}$$

Where Mg^{2+} = Magnesium ions

Ca^{2+} = Calcium ions

- According to Richards (1954), SAR is a measure of sodicity/alkali hazard of irrigation water (Equation 3 – 3), where all ionic concentrations are expressed in milliequivalent per litre.

$$\text{Na}^+ / [(1/2)(\text{Ca}^{2+} + \text{Mg}^{2+})^{1/2}] \quad \text{Equation 3 – 3}$$

Where Na^+ = Magnesium ions

Ca^{2+} = Calcium ions

Mg^{2+} = Magnesium ions

3.3.3 Collection of Groundwater Level Data

To facilitate groundwater level measurements, costs were attracted towards drilling of observation boreholes, water level measuring instruments, observer for taking measurements and data transfer to the central place for some stations. Two groundwater level measurement campaigns were carried out during the study using a special form

Appendix B1). The first campaign targeted the three main aquifer types in Zambia at monitoring stations MB-1, MB-2 and MB-3 (Figure 3.3), whereas the second campaign targeted the highly exploited aquifers on Lusaka Plateau.

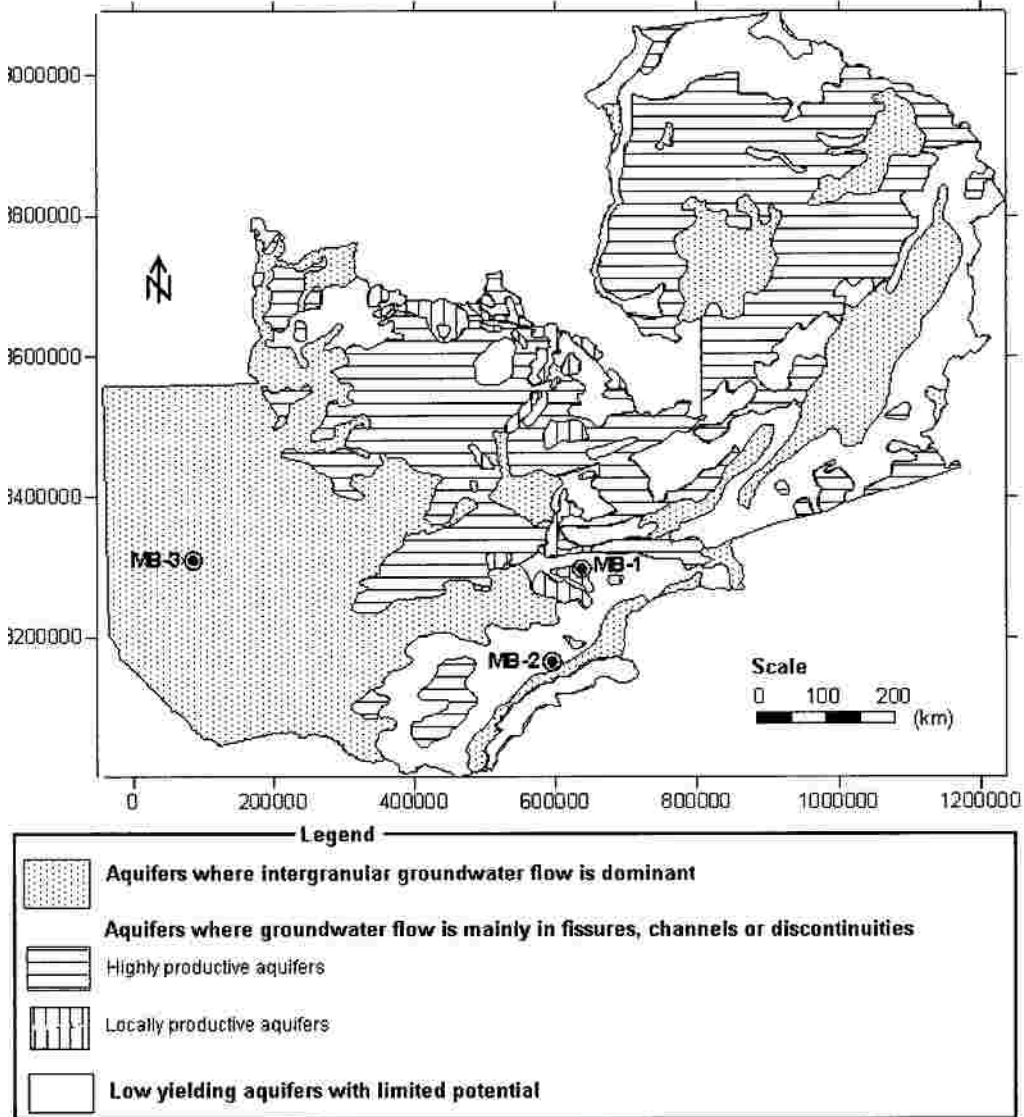


Figure 3.3 Map of Zambia showing groundwater monitoring stations in the three main aquifer types in the studied areas: MB-1 comprises two boreholes in Lusaka urban, MB-2 comprises one borehole in Gwembe District and MB-3 comprises one borehole in Mongu

The first and second campaigns were as follows:

1. **Campaign one:** This was aimed at generating data for DWA to use as a guide to establish groundwater level monitoring stations countrywide and to improve on the monthly groundwater level measurement frequency. In Gwembe District, a 50mm diameter observation borehole was constructed (MB-2) to a depth of 42m and cased with PVC pipes in the intercalated sandstone-mudstone aquifer (Figure 3.4) at World Vision premises in Makuyu village. In Mongu, a 150mm diameter observation borehole was constructed (MB-3) at DWA offices in the Kalahari sand aquifer to a depth of 50m and cased with steel pipes. In Lusaka urban, two observation boreholes were constructed (MB-1) and cased with PVC pipes to a depth of 30m in the schist and 36m in the carbonate aquifers of the Cheta Formation (Figure 3.5) at DWA premises along Sheki-Sheki road. Station observers took daily readings of depth to water table using graduated contact meter tapes that make sound on contact with water. Three measurement frequencies (monthly, weekly and daily) were adopted for this study. A weekly and daily frequency was for the first time used during this study, whereas the monthly frequency has been used occasionally over years in the Department of Water Affairs when taking water level readings at production wells. The length of the protection pipe above the ground level is subtracted from all readings when recording details on the reporting form. Completion reports are in Appendix B2.
2. **Campaign two:** It was carried out to investigate the extent of using observation boreholes for aquifer management. The two observation boreholes constructed in Lusaka urban under campaign one, facilitated daily water fluctuation data that

culminated in the subsequent design and construction of additional observation boreholes for the Lusaka Plateau groundwater monitoring network. The design of the monitoring network took into consideration information needs targeting groundwater quantity and quality, geology and aquifer lithology, drainage pattern and morphology, distribution of meteorological stations, security and permanent accesses to the installation, as well as the planned groundwater modelling. Station observers took daily readings of depth to water table using graduated contact meter tapes that make sound on contact with water for monitoring station MB-1 and other observation boreholes constructed on Lusaka Plateau during the study. A combination of measurement frequencies was ranging from daily to every 10 days for MB-1 and from every 10 days to 30 days for the other observation boreholes constructed during the study on Lusaka Plateau.

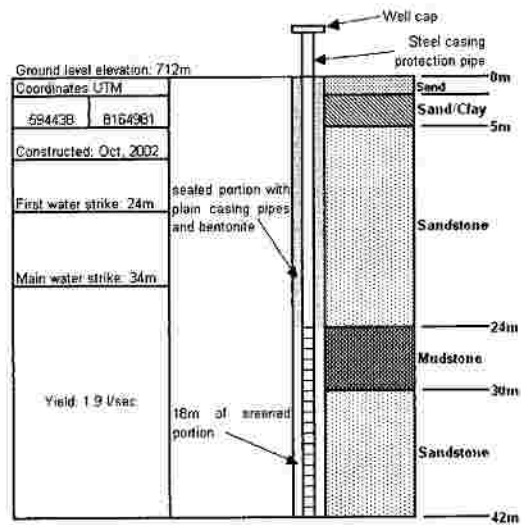


Figure 3.4 Section for Observation Borehole MB – 2, located in sandstone-mudstone intercalation.

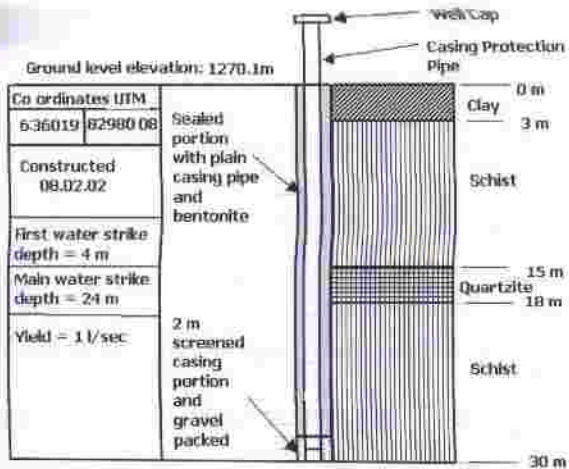


Figure 3.5 Section for Observation Borehole BH1 located in the schist in Lusaka urban

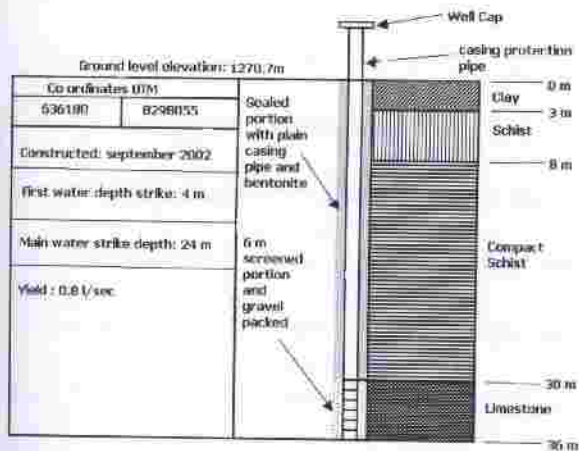


Figure 3.6 Section and picture for Observation Borehole BH2 located in the carbonate in Lusaka urban

3.3.3.1 Accuracy of Groundwater Level Data Analysis

According to Lerner *et al.*, (1990), recharge is defined as the downward flow of water reaching the water table thereby forming an addition to the groundwater reservoir. There are a number of recharge estimation methods that are used in different parts of the world,

but of special interest to this study are those that could accommodate groundwater level observation data in the estimation of recharge such as the Cumulative Rainfall Departure (CRD) method and the Equal Volume (EV) method. These two methods have been successfully used in the estimation of recharge in Southern Africa (Xu and Beekman, 2003). A number of studies have recommended control of groundwater abstraction in Zambia in aquifers with large scale groundwater exploitation (Von Hoyer *et al.*, 1978; JICA Report, 1995; Nkhuwa, 1996, Maseka and Nyambe, 1999). Therefore, regular measurement of depth to the water table at groundwater level observation boreholes is important; especial in collecting information pertaining to aquifer response to drainage, recharge and abstraction. Towns and locations with meteorological stations are recommended to ensure availability of rainfall data for calculation of a water balance and recharge estimation (Mpamba, 2003). Recent studies indicate that the Mean Annual Precipitation variation for Zambia ranges from 2000 mm/a in the north to 600 mm/a in the south (Figure 3.7). In addition, rainfall data and other information is available for meteorological stations distributed through out Zambia (Figure 3.8) where the required data from the Department of Meteorology is possible to access. Once a good and representative number of groundwater level observation boreholes are constructed in locations with meteorological stations, a fair understanding of the percentage (%) of rainfall, which goes towards groundwater recharge is possible. This would ensure sound development, utilization and management of groundwater resource.

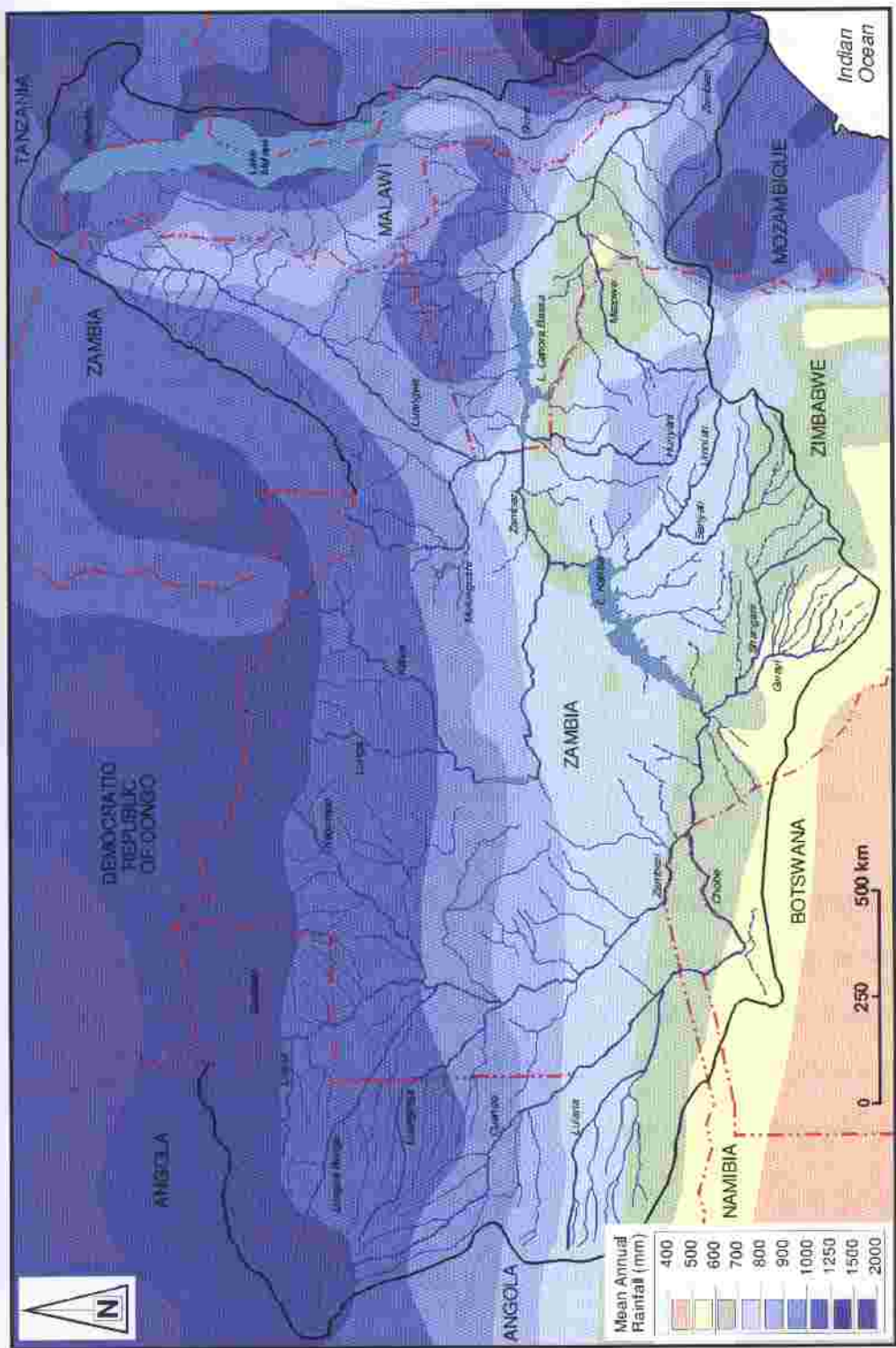


Figure 3.7 Distribution of Mean Annual Precipitation in Zambia in relation to the neighbouring countries (Ashton *et al.*, 2001)

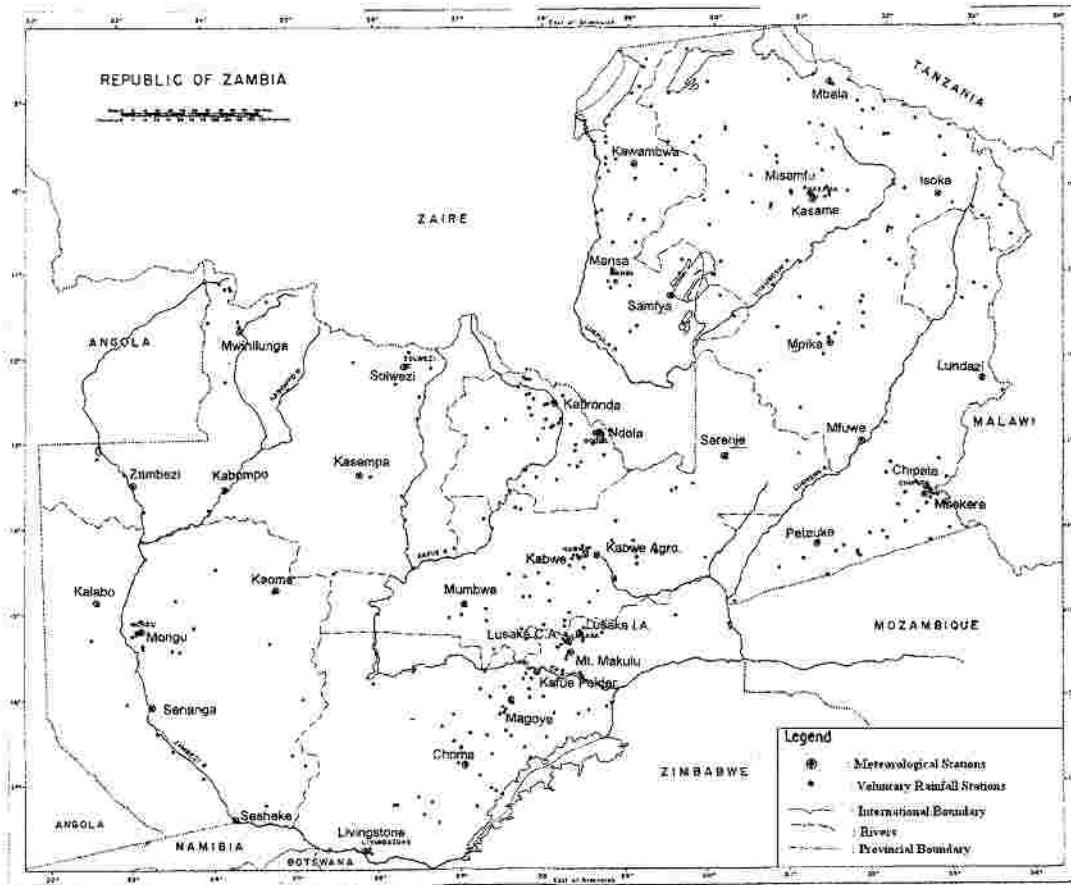


Figure 3.8 Locations of Meteorological Stations and Voluntary Rainfall Stations in Zambia

Based on the distribution of meteorological stations in relationship to the three main aquifer types of Zambia, a preliminary countrywide groundwater monitoring network consisting of observation boreholes at regional level (Table 3.5) was proposed (Mpamba, 2003). The aim was to facilitate implementation of the water resources management strategy by the Ministry of Energy and Water Development (WRAP, 2005).

Table 3.5: Proposed preliminary countrywide groundwater monitoring network for Zambia (modified from Mpamba, 2003)

Aquifer Type to be Monitored	Meteorological Station Name	Latitude (Deg.Min)		Longitude (Deg.Min)		Catchments
intergranular groundwater flow is dominant	Mwinilunga	11	45	24	26	Zambezi
	Zambezi	13	32	23	7	Zambezi
	Kabompo	13	36	24	12	Zambezi
	Samfya	11	21	29	32	Luapula
	Kalabo	14	57	22	42	Zambezi
	Mongu	15	15	23	9	Zambezi
	Kaoma	14	48	24	48	Zambezi
	Senanga	16	7	23	16	Zambezi
	Sesheke	17	28	24	18	Zambezi
	Mfuwe					Luangwa
Low yielding aquifers with limited potential	Livingstone	17	49	25	49	Zambezi
	Choma	16	51	27	4	Zambezi
	Magoye	16	8	27	38	Kafue
	Lundazi	12	17	33	12	Luangwa
	Chipata	13	33	32	35	Luangwa
	Petauke	14	15	31	17	Luangwa
	Mbala	8	51	31	20	Chambeshi
	Serenje	13	14	30	13	Luangwa
Highly productive aquifers	Lusaka C.A	15	25	28	19	Kafue
	Kabwe	14	27	28	28	Luangwa
	Ndola	13	0	28	39	Kafue
	Mt. Makulu	15	33	28	15	Kafue
	Kafironda	12	36	28	7	Kafue
	Solwezi	12	11	26	23	Kafue
Locally productive aquifers	Mumbwa	14	59	27	4	Kafue
	Mpika	11	54	31	26	Luangwa
	Isoka	10	10	32	40	Chambeshi
	Kasama	10	13	31	8	Chambeshi
	Kawambwa	9	48	29	5	Luapula
	Mansa	11	6	28	51	Luapula

According to Mpamba (2003) observation boreholes could be located at DWA premises, meteorological station, village or any other institution where security of the facility is assured. In areas with poor representation of meteorological stations, active voluntary rainfall stations could be ideal also to be part of the countrywide network as long as the following are fulfilled:

- stakeholders are willing to participate in collection of groundwater level data regularly,
- the location is representative of any of the three main aquifer types,
- safety of the facility and accessibility to data is assured.

3.4 Data Collection, Transmission, Storage, Analysis and Dissemination

Effecting groundwater management depends on availability of accurate and adequate data and information. This study therefore considered a system that is cost effective, provides for collection of appropriate, adequate and accurate, data and information necessary to assess the quality and quantity of groundwater resources. The other aspect of emphasis was that data and information collected should be useful in a short term and long term to satisfy the needs of planners, policy makers and other stakeholders on availability and level of groundwater usage.

The three data sets require data collectors and the use of standard procedure to collect data and information in a co-coordinated or centralized manner. Issues of storing data and information are usually meaningful with a well-established Data Base that has to eventually support analysis and dissemination of data and information for public consumption (Kovalevsky *et al.*, 2004). In view of the above, there was need to establish a National Groundwater Monitoring and Information Data Base that links the three data sets and other water resources related issues to support management decision process in accordance with the Ministry of Energy and Water Resources Development (WRAP, 2005). This includes accommodating issues to do with resources analysis that is integrated with the behaviour of the catchment (Lerner, 2001). To achieve this, inventory of existing data and information in the study areas

- stakeholders are willing to participate in collection of groundwater level data regularly,
- the location is representative of any of the three main aquifer types,
- safety of the facility and accessibility to data is assured.

3.4 Data Collection, Transmission, Storage, Analysis and Dissemination

Effecting groundwater management depends on availability of accurate and adequate data and information. This study therefore considered a system that is cost effective, provides for collection of appropriate, adequate and accurate, data and information necessary to assess the quality and quantity of groundwater resources. The other aspect of emphasis was that data and information collected should be useful in a short term and long term to satisfy the needs of planners, policy makers and other stakeholders on availability and level of groundwater usage.

The three data sets require data collectors and the use of standard procedure to collect data and information in a co-coordinated or centralized manner. Issues of storing data and information are usually meaningful with a well-established Data Base that has to eventually support analysis and dissemination of data and information for public consumption (Kovalevsky *et al.*, 2004). In view of the above, there was need to establish a National Groundwater Monitoring and Information Data Base that links the three data sets and other water resources related issues to support management decision process in accordance with the Ministry of Energy and Water Resources Development (WRAP, 2005). This includes accommodating issues to do with resources analysis that is integrated with the behaviour of the catchment (Lerner, 2001). To achieve this, inventory of existing data and information in the study areas

became pertinent in highlighting inadequacies and gaps that need addressing. To facilitate collection of data the following were proposed:

- groundwater level observation data forms;
- Water quality forms;
- establishment of the excel format electronic database based on the data and information on a borehole completion report form for rural water supply boreholes and boreholes with motorized pumps in urban areas.

3.4.1 National Groundwater Database.

The Ministry of Energy and Water Development through DWA maintains and updates the hard copy database on box files for boreholes constructed by the Ministry countrywide. Data and information on boreholes is on completion reports, geophysical survey reports are also on special forms at Drilling Section along Sheki-Sheki road in Lusaka. Such data is kept also at DWA provincial offices.

Groundwater quality and groundwater level data is the information that is only available in reports since there is no organized data storage system such as box files. The current database requires improvement through inclusion of GPS coordinates on borehole completion reports to allow for its use in GIS based analysis. This should also include establishment of an electronic database in the format that would accommodate groundwater quality and groundwater level data. The overall database should accommodate relevant data and information to allow for aquifer management, evaluation of the impact of groundwater abstraction on stream flows and to support borehole numbering and water resources management (WRAP, 2005).

4.0 RESULTS AND DISCUSSION

Geographical Information System (GIS) based spatial analysis of the collected data was achieved with the use of Surfer, Global Mapper, and Arc View. This facilitated display of various maps and scenarios for discussion on borehole yield distribution, depth to water intersection, distribution of aquifer lithologies, and usefulness of GPS coordinates in the evaluation of groundwater storage, occurrence, flow, water quality, groundwater diversity, replenishment and so on.

4.1 Groundwater Level fluctuation in the main aquifer types in Zambia

Figure 4.1 indicates that groundwater level response (Appendix B3) to recharge, aquifer drainage and abstraction is smooth in the aquifer type where intergranular groundwater flow dominates, than in the other two aquifer types that show a number of peaks and troughs (Figure 4.1 and 4.2). The observed peaks and troughs at monitoring stations MB-1 and MB-2, is a strong indication of the presence of preferential groundwater flow paths such as fractures, faults, channels etc, and that over abstraction could easily affect the aquifers in terms of depletion and migration of pollutants. Additionally, graphical representation of groundwater levels (Figure 4.1 to 4.3) indicates that daily reading frequency provided detailed information pertaining to aquifer response to drainage, recharge and abstraction than the weekly and monthly reading frequency. This is because weekly and monthly groundwater level readings do not represent a precise picture since a reading could lie at any point along the line representing daily groundwater level fluctuation. Therefore, groundwater level readings taken once a month by DWA are appropriate only for MB-3 and not for MB-1 and MB-2 where daily groundwater level readings would result in reliable data to facilitate understanding of the aquifer behaviour to abstraction, recharge and drainage.

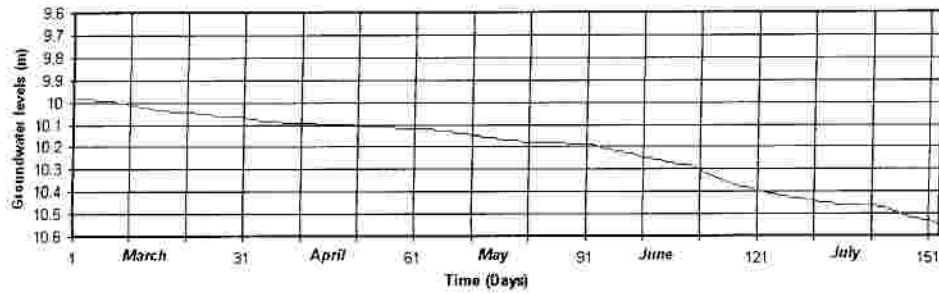


Figure 4.1 Observation Borehole at monitoring station MB – 3 in the aquifer where intergranular groundwater flow dominates: March to July 2002.

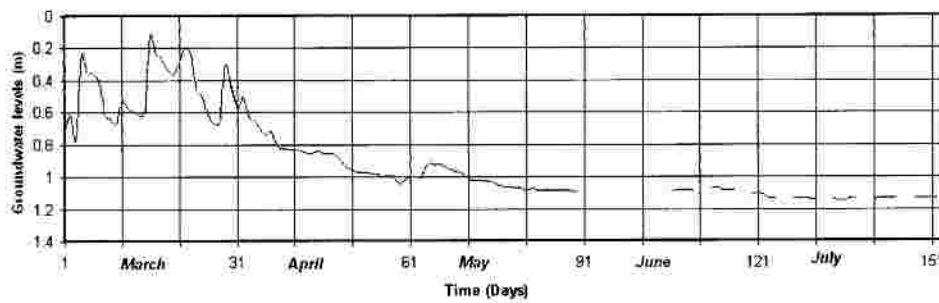


Figure 4.2 Observation Borehole BH1 at monitoring station MB – 1 in the aquifer type where groundwater flow is mainly through fissures, channels or discontinuities: March to July 2004.

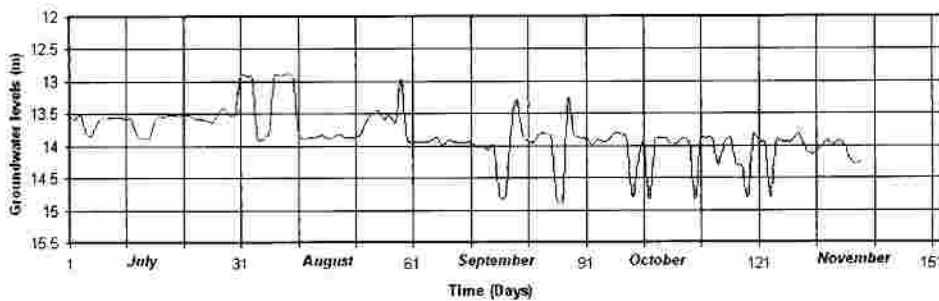


Figure 4.3 Observation Borehole at monitoring station MB – 2 in the Low yielding aquifer type with limited potential: July to November 2004.

The recommendation to construction observation boreholes in towns and district centres with meteorological stations (Mpamba, 2003), would ensure availability of groundwater level data (depth to the water table) that would be used with rainfall data to determine the water balance and recharge for various aquifer units (Xu and Beekman, 2003).

4.2 Lusaka urban and adjacent Areas

4.2.1 Hydrogeological Data Collection

There are a total of 1879 documented borehole records on Lusaka Plateau. These are used for domestic, industrial and irrigated agriculture, by three competing users namely; Lusaka Water and Sewerage Company (LWSC); private individuals and industries. Relevant data and information for the 1800 boreholes were entered into the Microsoft excel electronic database (Appendix C1) during the study period and used to estimate the available groundwater quantity and abstraction. It included also the spatial analysis of the distribution of the aquifer lithologies and soil cover.

Department of Water Affairs – Drilling Section: It has 1800 completion reports for boreholes located in Lusaka urban and adjacent areas, which are available as hard copies on box files. A total of 120 boreholes were constructed during the study period and 1680 boreholes were constructed before the study was initiated. Only 117 boreholes have GPS coordinates, most of which were constructed during the study period. Taking of GPS coordinates especially for boreholes constructed before the study period was not successful due to the following reasons:

- difficulties were experienced in physically locating premises and much more, even to identify boreholes for respective completion reports at premises that have more than one borehole drilled to the same depth.
- the GPS unit was being shared between the two study areas, resulting into missing out on some boreholes constructed during the study period.

Lusaka Water and Sewerage Company: The water utility has a total of 79 production boreholes distributed within Lusaka urban and the adjacent areas. Most of the boreholes (63 boreholes) have GPS co ordinates, but incomplete data and information on borehole completion reports is the main inadequacy. Only 8 borehole completion reports out of the 79 have most of the data and information expected on a borehole completion report form.

Private Individuals and Companies: Submission of borehole completion reports to the Department of Water Affairs is currently at the discretion of the private drilling contractors. Hence, most of the boreholes constructed by the private drillers for individuals and companies are not part of the 1800 borehole records at Drilling Section.

4.2.1.1 Estimation of Groundwater Abstraction and Aquifer Storage

The estimated groundwater abstraction for the 1879 borehole of $50.265 \times 10^6 \text{m}^3 \text{year}^{-1}$ to $65.385 \times 10^6 \text{m}^3 \text{year}^{-1}$ is more than the estimated annual recharge of $45.44 \times 10^6 \text{m}^3 \text{year}^{-1}$ at 8% of the annual rainfall. However, the current estimated abstraction does not include groundwater abstraction from most boreholes drilled by private drillers that do not submit records to DWA. This scenario indicates that groundwater

abstraction may be higher than the estimated figure and is sustained by groundwater from storage, especially from the carbonates of the Lusaka Dolomite stretching from Forest 26 and part of Forest 55 to Mwembeshi area.

The 1800 borehole records with DWA have a total yield of 5760 l s^{-1} ($20736 \text{ m}^3 \text{ hr}^{-1}$) representing an average of 3.2 l s^{-1} per borehole and a groundwater abstraction of $181.647 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ at 24 hours Pumpage. However, assumed pumpage at 1 hour and 3 hours gives an estimated groundwater abstraction of $7.569 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ and $22.706 \times 10^6 \text{ m}^3 \text{ year}^{-1}$, respectively. According to borehole completion report details, boreholes are used for domestic water requirements, irrigation purposes and industrial needs, implying that actual abstraction is likely to be more than the estimated figures especially for boreholes used for irrigation. On the other hand, Lusaka Water and Sewerage Company (LWSC) has 79 production boreholes with a total yield of 2259.86 l s^{-1} ($8135.49 \text{ m}^3 \text{ hr}^{-1}$) and represents a groundwater abstraction potential of $71.27 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ at 24 hours Pumpage. However, actual pumpage is estimated to be $42.705 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ from 72 boreholes.

Some of the 1879 boreholes were used to characterise the spatial distribution of high and low yielding boreholes drilled to various depths in the aquifers on Lusaka Plateau (Figure 4.4). It is evident from figure 4.4 that high yielding boreholes are not restricted only to the Lusaka Dolomite. The Cheta Formation is equally exploitable to more than 100m depth with high yields ($> 5 \text{ l/s}$). Additionally, spatial distribution of both high and low yielding boreholes, suggest uniform fracturing in all the aquifers as well as Karstification of the carbonates on Lusaka Plateau. Therefore, locating of good points for drilling would require effective borehole siting.

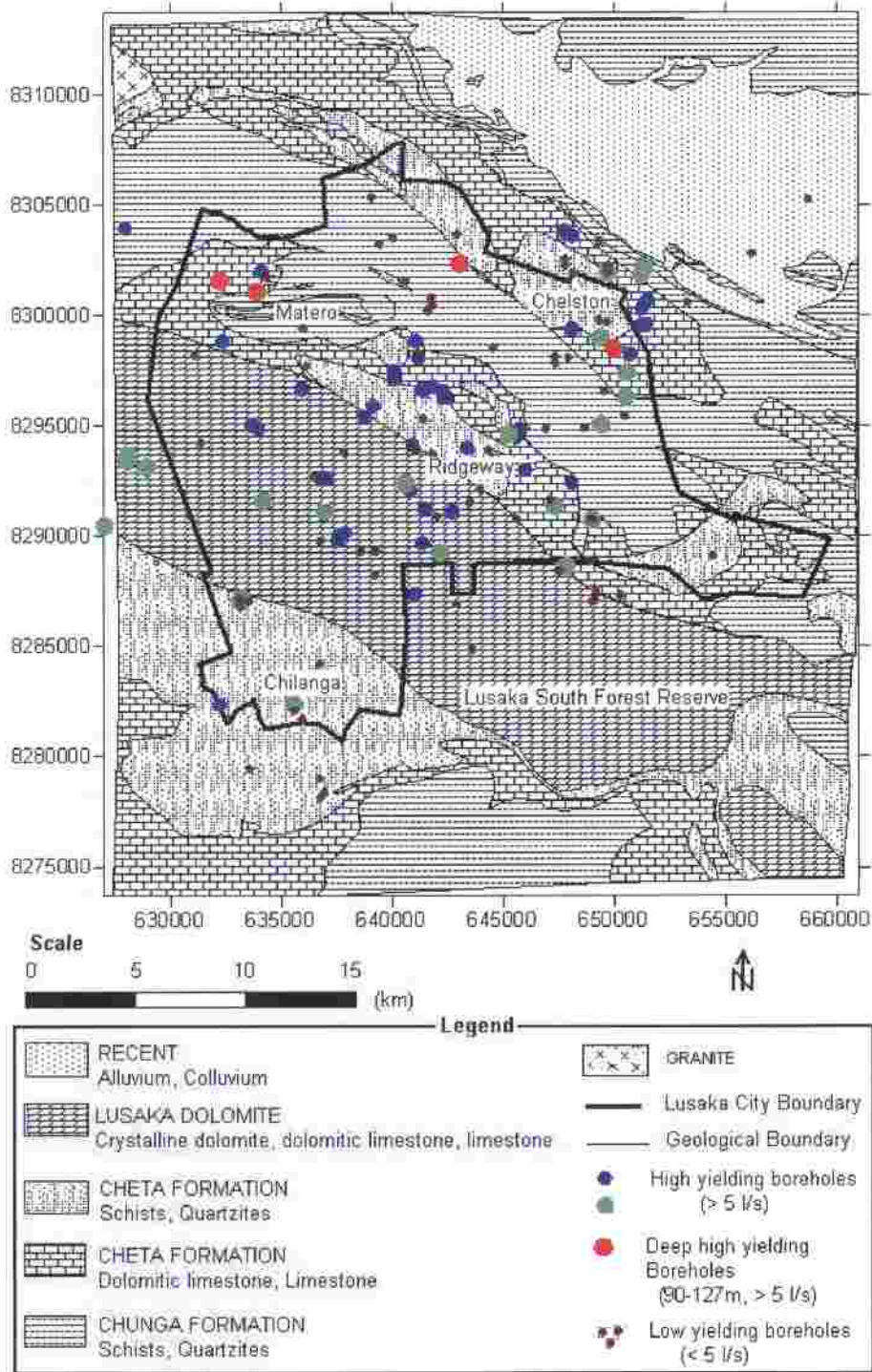


Figure 4.4 Map showing distribution of high and low yielding boreholes in the Cheta and Chunga Formations, and Lusaka Dolomite on Lusaka Plateau.

Drilling records of some boreholes constructed during the study, indicate that Lusaka Dolomite comprises the upper aquifer (0-50m) and the lower aquifer (79-150m). The upper aquifer is the most extensively exploited.

Comparison of historical data in Table 2.3 (Section 2.6.1.3) with LWSC boreholes (Table 4.1) and recently drilled DWA boreholes (Table 4.2) indicate a slight increase in the depth to the static water level, the first and main water intersection depth.

Table 4.1: *Data on LWSC boreholes located in the carbonates on Lusaka Plateau*

No.	X	Y	Borehole Depth (m bgl)	Borehole yield (l/sec)	First Water	Main Water	Pump Discharge (l/sec)	Pumping Depth (m bgl)	Drawdown (m bgl)
					Intersection depth (m bgl)	Intersection depth (m bgl)			
1	651238	8299585	50.0	27.8	7.5	23.0	26.4	34	5.34
2	651433	8299602	70.0	5.8			16.7	32	15.4
3	650740	8298255	60.0	7.2		28.3	7.2	30	7.93
4	648103	8299406	61.0	6.3	7.2	20.0	12.5	49	
5	641378	8289696	43.0	28.0		30.0	27.8	33	0.89
6	651252	8300339	60.0	13.9			13.9	30	7.36
7	642328	8296266	65.0	50.0	11	11.0	20.0	33	
8	642285	8296608	39.2	13.9			12.5	33	
9	641718	8300369	73.0	1.8		20.0	2.8	27	4.5
10	640120	8297508	56.4	50.0		30.0	20.8	27	
11	627941	8303967	45.0	13.0		30.0	8.3	35	
12	648130	8303606	66.0	22.1	4.4	17.8	22.2	38	20.7
13	647746	8303845	50.0	34.8	6.4	25.5	8.1	38	
14	647850	830381	55.0	5.6	6.7	38.5	8.3	35	
15	640827	8292071	65.0	20.0	10.3	30.0	20.8	40	5.98
16	643412	8294004		5.6	7	43.0	2.2	39	
17	636804	8292631	47.0	38.0	22	30.2	45.0	35	0.62
18	633684	8295028	50.0	40.0			27.8	45	
19	633697	8295028	50.0	41.7			41.9	42	
20	633747	8295030	38.0	27.8			27.8	48	
21	633966	8294882	81.0	13.9	5.4	12.2	20.8	30	
22	633691	8295079	65.0	50.0			50.0	36	
23	641020	8287387	66.0	300.0			166.7	45	
24	641022	8287386	66.0	300.0			166.7	44	
25	641497	8291252	65.0	166.7			70.8	35	
26	641498	8291245	70.0	40.0			27.8	46	
Average			58.3	50.9	8.8	26.0	33.7	36.9	7.6

bgl = Below ground level.

Table 4.2: Data on recently drilled abstraction boreholes located in the carbonates in Lusaka urban and adjacent areas (after Mpamba, 2005)

No.	X	Y	Borehole		Static Water	First Water	Main Water	Pumping	Drawdown (m bgl)
			Depth (m bgl)	Borehole yield (l/sec)	Level (m bgl)	Intersection (m bgl)	Intersection (m bgl)	Depth (m bgl)	
1	649398	8299005	40	5	29	30	36	36	0.06
2	640626	8301568	57.5	1.5	10.62	25	42	45	21.8
3	653290	8300603	55.5	3.6	16.24	30	36	42	10.5
4	647805	8302255	28.75	3	10.22	17.6	24	25	14.4
5	650562	8297406	40	7.5	13.37	28	36	34	7.3
6	649552	8296580	49	4	25.63	3.2	25	42	2.22
7	636148	8297720	52	1	27.6	42	50	45	4.24
8	643967	8292134	48	2	27	36	39	42	2.1
9	649183	8287537	37.77	0.7	17.62		27	34	10.4
10	642184	8289247	37	7	12		36	32	16.4
11	650528	8296324	50	5	20	38	40	36	0.72
12	648671	8294923	85.5	0.75	11.4	61	78	37	13.7
13	643522	8291522	60	1.8	14.5	18	36	45	33.5
14	649025	8287046	31.5	2.5	16.3	9	24	24	5.9
15	647126	8291656	49.5	4	13.1	19	27	42	10.5
16	647529	8288381	37.2	4	13.33	27	32	34	10.9
17	636787	8289793	31.5	0.75	7.57	5	19	21	17.9
18	635603	8282098	49.5	2	17	22	37	42	10.3
19	633145	8286790	34	3	10.4	18	28	26	11.3
20	635471	8283473	60	1.5	9.33	18	30	42	15.5
21	633561	8287083	50	2.5	10.3	12	24	42	3
22	628943	8293148	32	5.5	4.76	5	18	24	0.73
23	622452	8295079	42	3.5	8.33	12	36	36	5.17
24	633145	8287116	39.5	5	10	18	24	34	14.4
25	631091	8298213	47	2.1	1.8	3	34	42	22
26	639251	8288242	38.1	0.25	13.3	12	12	36	6
27	631379	8294244	49.5	0.5	2.7	18	44	45	37.4
28	649013	8290750	41.25	3	7.2	12	30	34	23
29	641625	8300213	67.5	1.5	15	48	54	48	23.7
30	641781	8300820	49	1.5	8.35	23	39	45	4.68
31	642897	8286916	57.88	0.5	16.25	40	52	52	32.4
32	634198	8291588	38	6	3	6.16	30	34	13.8
33	627398	8299011	39.8	3	1.8	3	6	25	17.3
34	636979	8291116	40	6	4.96	4	21	35	25.4
35	637857	8293819	48	0.9	24	12	32	30	24.6
36	633270	8287207	37.5	5.5	12.14	12	24	30	3.04
37	636709	8284191	36.5	3	15.94	18	30	27	2.06
38	633582	8279437	50	4	2.9	28	30	48	0.5
39	647850	8288649	42	6	15.2	30	30	27	12.9
Average			45.6	3.1	12.8	19.6	32.6	36.4	12.6

bgl = Below ground level.

An attempt was made to estimate groundwater in storage [Equation 4 – 1] in the main aquifers based on the hydrogeological data collected during the study:

$$V=Ahn \quad \text{Equation 4 – 1}$$

Where V = volume of groundwater as aquifer storage

A = area of aquifer

h = saturation depth of the aquifer

n = the effective porosity of the aquifer

Taking the effective porosity of 2.5% (Jones, 1972) for the 470Km² carbonates in the study area, minimum aquifer storage at an average effective aquifer depth of 50m, using equation 4 – 1 is therefore calculated as follows:

1) Min. aquifer storage = Carbonate covered area × Saturation depth × Effective porosity.

$$= 470\,000\,000\text{m}^2 \times 50\text{m} \times 0.025$$

$$= \underline{587.5 \times 10^6 \text{ m}^3}$$

The $587.5 \times 10^6\text{m}^3$ of groundwater in aquifer storage is in the most exploited upper part of the carbonate aquifer. However, not all this water is available for abstraction (Kovalevsky *et al.*, 2004), except for the part of groundwater recharge component that occurs every year. The estimated volume gives an idea that the groundwater storage in Lusaka urban aquifers is likely to be substantial, because current groundwater abstraction levels have not yet caused adverse effect such as reduction of aquifer yields on a large scale. Individual and localized reduction may however be present

due to high concentration of boreholes in certain areas as seen from a few cases of boreholes drying up which previously had yields of 2 l/s in isolated localities of Lusaka urban and adjacent areas. In brief, it implies that boreholes in low yielding areas of less than 1 l/s⁻¹ may require drilling to depths of 65-100m to take advantage of groundwater in storage if they are to provide sustainable yields during the driest period and in drought years.

The estimated minimum borehole density in Lusaka urban is about 1 borehole/km². Induced groundwater flow during pumpage is therefore able to introduce pollution to a larger part of the aquifer, considering that septic tanks and pit latrines are in most built up areas and are responsible for artificial recharge of aquifers with waste water. An informative approach though not the best, was therefore carried out with SURFER to define groundwater flow during the rainy season. Kriging of static water levels for boreholes drilled by DWA (Table 4.3) generated groundwater flow direction that strongly show that the main groundwater flow originates from Lusaka South Forest Reserve (Forest 26 & 55) southeast of the city boundary (Figures 4.5).

Table 4.3: Data on boreholes drilled by DWA on Lusaka Plateau: February to April 2005

UTM – WGS 84				Static water level Elev. (m amsl)	First Water Strike (m bgl)	Main Water Strike (m bgl)	Yield (l/sec)	Soil Cover		Date Drilled
X	Y	Elev. from DEM (m amsl)	Elev. by GPS Unit (m amsl)					Soil Type	Cover Depth (m bgl)	
647529	8288381	1298.8	1304	1285.5	27	32	4	Laterite	3	26.03.05
633907	8301098	1219.3	1225	1212.3	15	55	6	Gravel	5.5	17.02.05
639452	8303235	1221.8	1224	1210.8	34	40	2.5	Clay	4.5	28.03.05
640318	8294037	1289.4	1299	1274.4			3.5			14.04.05
647850	8288649	1300.7		1285.5	30	30	6	Laterite	3	21.02.05
643079	8302349	1214.9	1226	1195.9	36	78	5	Gravel	12	25.03.05

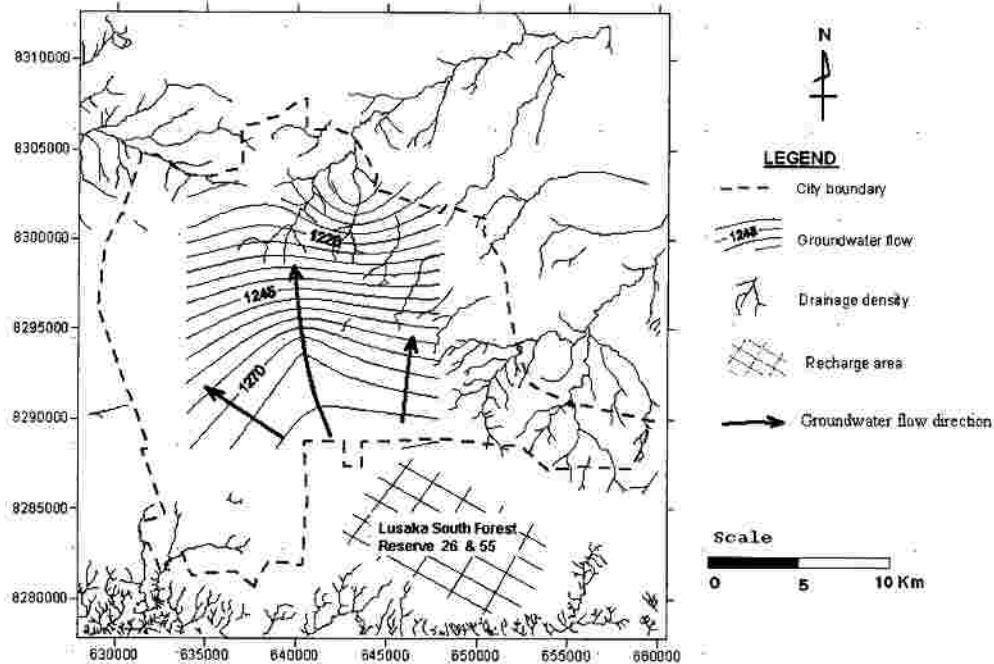


Figure 4.5 Map showing groundwater flow and the main recharge area: February to April 2005.

The flow is directed towards the streams emanating from Lusaka Plateau mainly along the schist-marble contact. Figures 4.5, supports earlier findings that Lusaka South Forest Reserve is indeed the main recharge area for the aquifers on Lusaka Plateau (Von Hoyer *et al.*, 1978; Maseka, 1994; JICA Report, 1995; Nkhuwa, 1996; Maseka and Nyambe, 1999 Nyambe and Maseka, 2000).

Much of Forest 26 is a depression that slopes in the East-West direction, whereas a portion of Forest 55 slopes towards Forest 26 (Figure 4.6) and towards the North-South direction. Although Lusaka South Forest Reserve shows bare soil cover with no trees, the porous and fractured carbonates as well as sinkholes present in the area allows much of the rainy water to infiltrate in this basin providing groundwater of better quality instead of generating runoff.



Figure 4.6 Photos showing bare soil cover in a portion of Forest 26 in a depression with Forest 55 at the horizon (top) and Chilenje area at the horizon (bottom). This forms the main recharge area for aquifers on Lusaka Plateau.

In contrast to Figure 4.5, kriging of static water levels for boreholes drilled from August to October 2004 generated a radial groundwater flow in Lusaka urban aquifers as a mound (Figure 4.7) but with the main groundwater flow direction being in the east west direction. This type of display may also be due to inadequate data points.

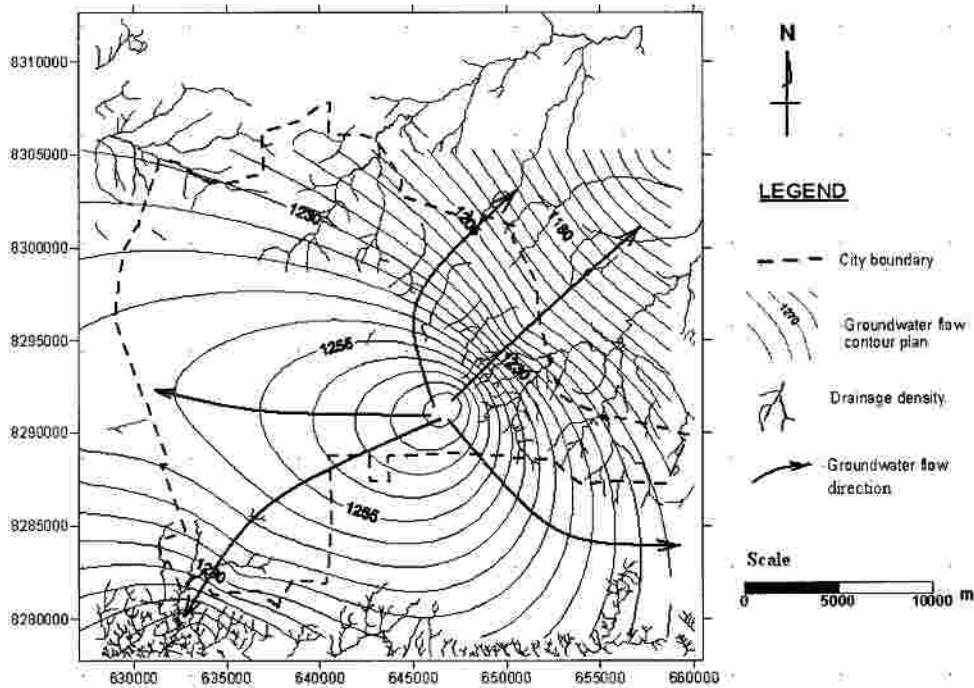


Figure 4.7 Groundwater flow pattern for the period from August to October 2004 in the dry season.

However, the scenario suggests a possibility of groundwater flow from some deep aquifer during the dry season, a phenomenon that requires further investigation through regular measurement of water levels in observation boreholes in the dry and rainy season. This would help establish if such a groundwater flow scenario exists and operates in the manner depicted. Moreover, the average elevation difference between the highest point on Lusaka Plateau and the lowest point at the edges of the Plateau in

all directions is about 60m (Figure 4.8). Therefore, radial groundwater flow from Lusaka Plateau is more likely than a possibility of recharged water to come to Lusaka Plateau from surrounding areas within 50km to 150km. This is on account that the area slopes in all directions from the highest part of Lusaka Plateau as the area is up lifted. On the other hand, the aquifer lithology that out crops on the Lusaka Plateau is part of the regional Katanga Supergroup stretching from beyond the Copperbelt area in the north to parts of Southern Province of Zambia. Hence; on a regional scale groundwater flow may possibly give rise to such a phenomenon.

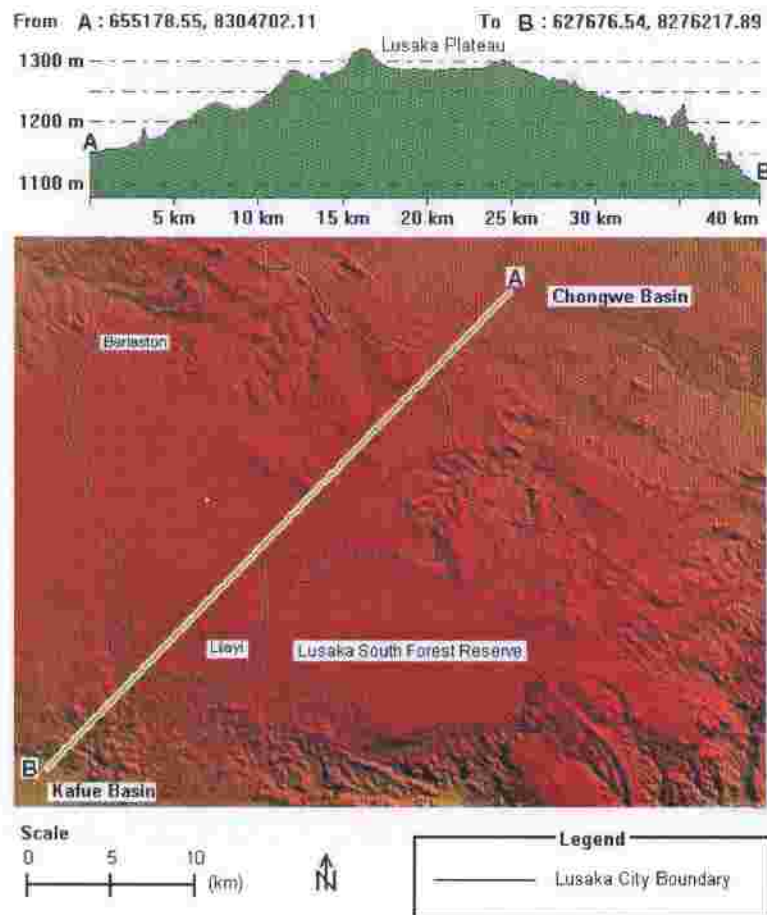


Figure 4.8 Elevation difference between Lusaka Plateau and its edges (Prepared from USGS DEM)

4.2.1.2 Aquifer Type and Groundwater Stress Areas

The aquifers on Lusaka Plateau could be inferred as semi – confined (Figure 4.9) based on the distribution of areas covered by soil layers.

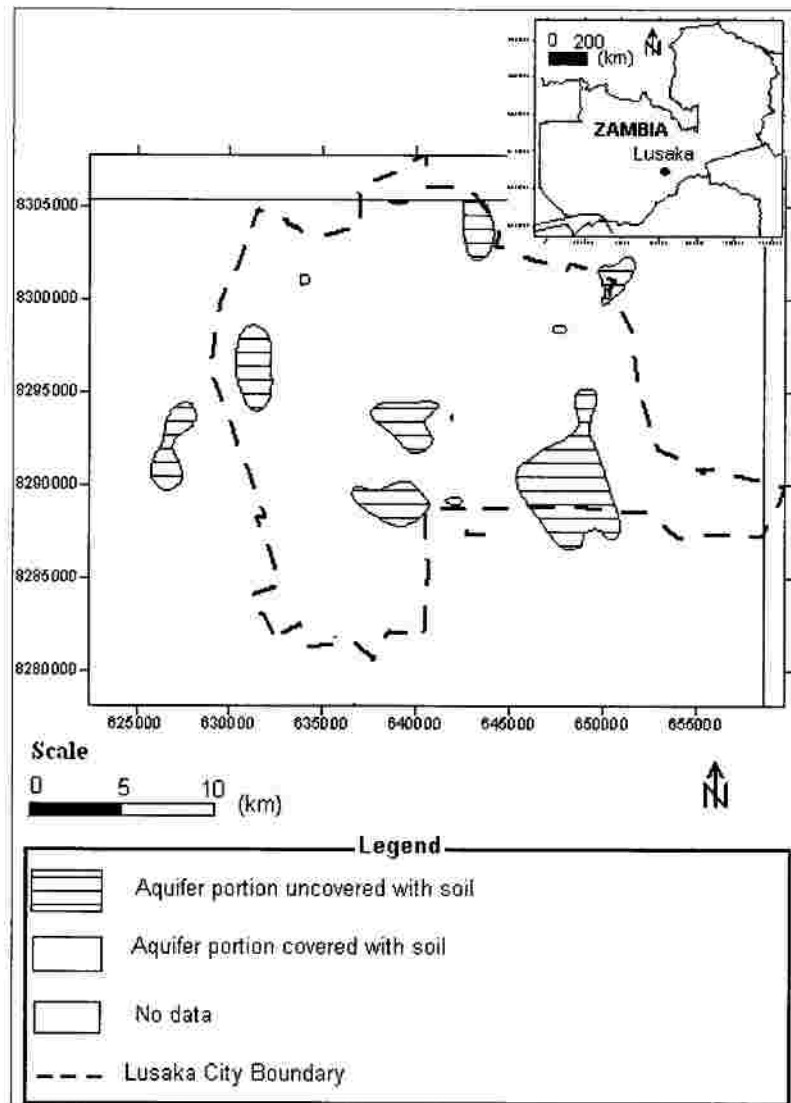


Figure 4.9 Distribution of soil cover over the aquifers in Lusaka urban and adjacent areas

However, further classification of the soil cover into low permeable (clay and schist) and permeable (laterite and gravel) soils (Figure 4.10) as well as consideration of the

presence of fractures and Karst features precludes the semi – confined nature and qualifies the aquifer as unconfined. It is important to mention also that the depth of clay and schist cover on carbonates is not thick enough in most of the places to offer a substantial aquifer protection against pollution as well as allow for natural attenuation.

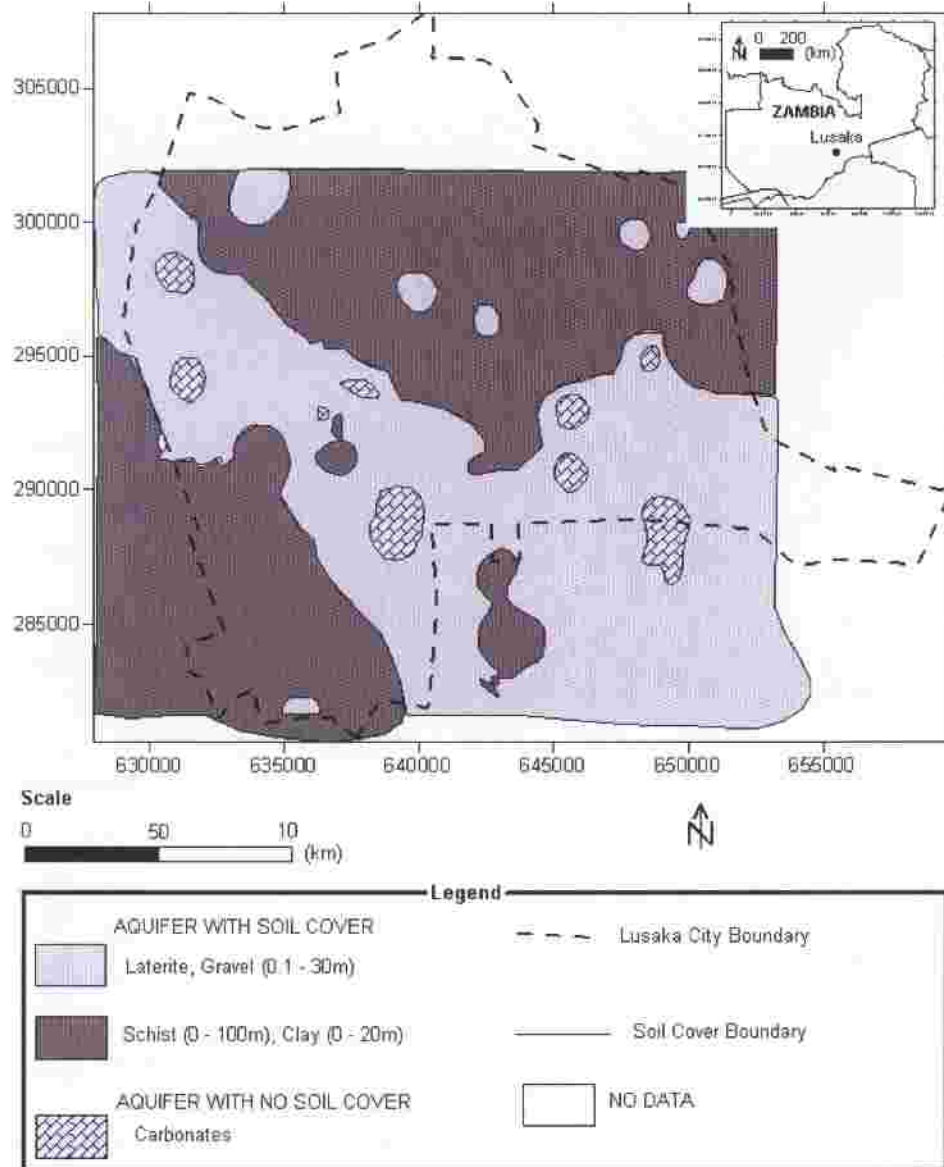


Figure 4.10 Distribution of low permeable and permeable soil layers over the aquifers in Lusaka urban and adjacent areas.

Spatial analysis of the main groundwater intersection depth that ranges from 5m to 65m in the upper aquifer in Lusaka urban (Figure 4.11) is important for groundwater quantity assessment.

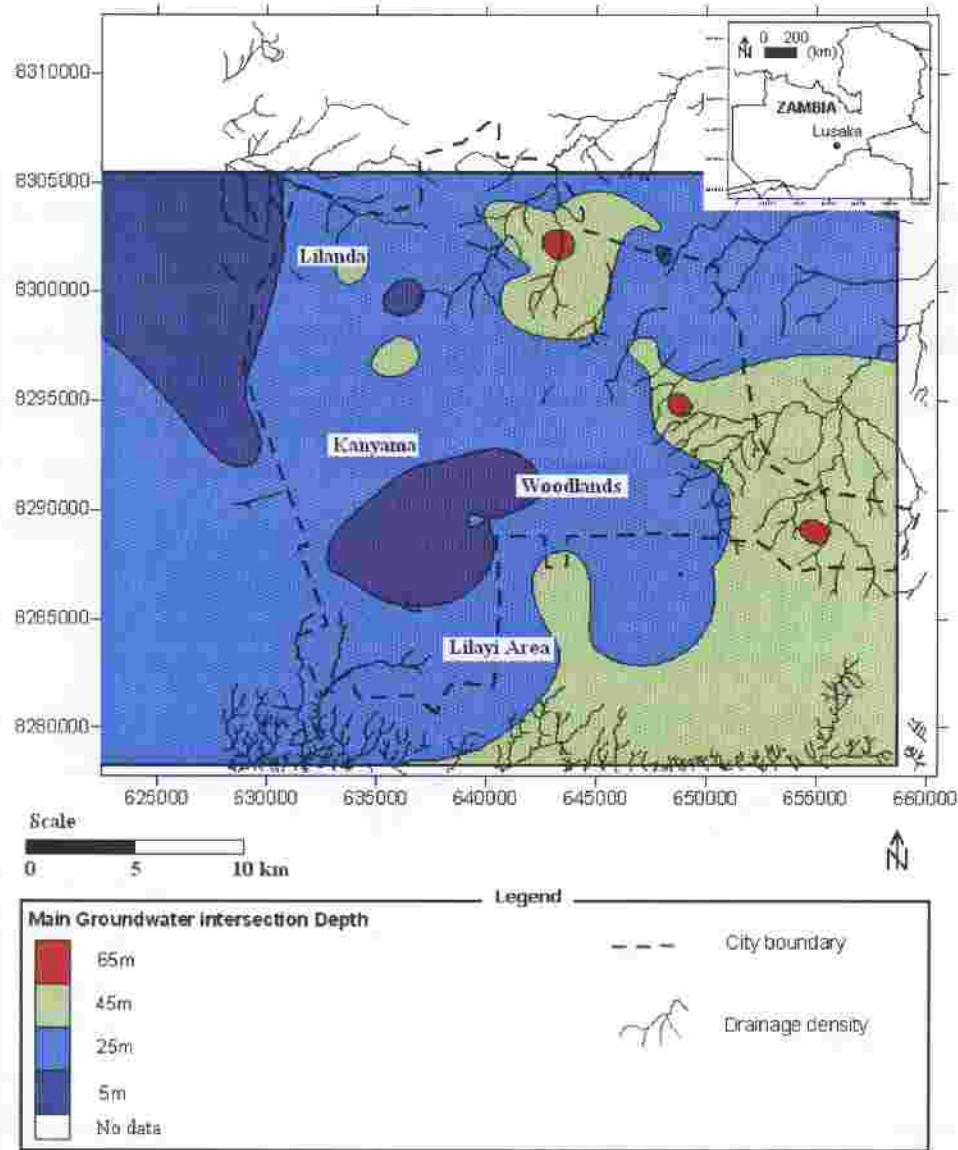


Figure 4.11 Map showing distribution of the main groundwater intersection depth in the aquifers in Lusaka urban and adjacent areas.

Figure 4.11 may serve as a guide for drilling of boreholes in Lusaka urban. However, data also shows that there are areas that experience a situation where, during pumpage the dynamic water level falls below the main groundwater intersection depth resulting into what may be considered a groundwater stress.

These are areas where the drawdown in boreholes goes down below the main water intersection depth during pump testing and abstraction, leading to scenario of dewatering or withdraw of groundwater from storage. Under normal situations, the drawdown (Figure 4.12) is above the main water intersection depth for areas with high groundwater potential or high transmissivity. However, when abstraction is quite high or groundwater potential is low, the drawdown may fall below the main water intersection depth observed at a time a borehole was drilled, leading to a groundwater stress situation.

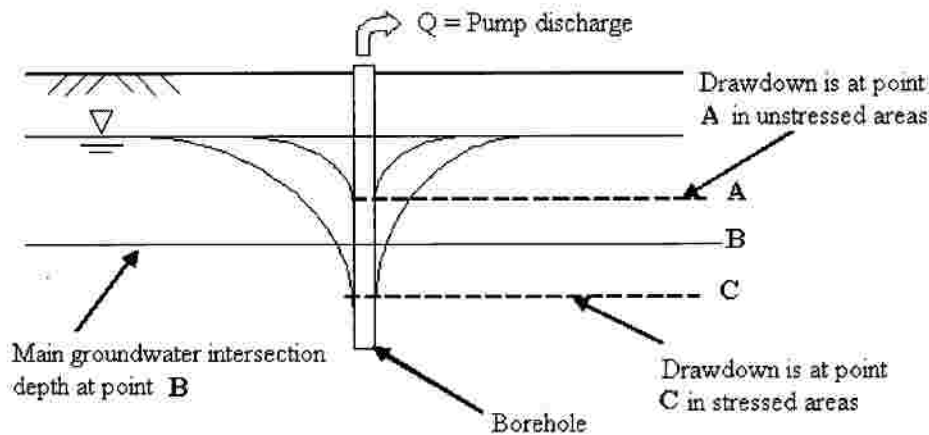


Figure 4.12 Depiction of groundwater stress during pumpage when Drawdown is located at point C below the main water intersection depth at point B.

To identify groundwater stressed areas, analysis of elevation difference between the drawdown and main water intersection depth for boreholes with coordinates was carried out with SURFER using the procedure in Table 4.4.

Table 4.4: Procedure for identification of groundwater stressed areas using the main water intersection depth and drawdown from hydrogeological data.

Range of difference between drawdown elevation and main water intersection elevation (m bgl)	Ranking of range	Remarks	Stress Class
-1.5 to 0	10	Initial stress	C
< -1.5	5	Serious stress	D
0 to 2.5	15	No stress – Good (2)	B
> 2.5	20	No stress – Excellent (1)	A

The range with a negative value in Table 4.4 indicates areas where dynamic water levels are observed to fall below the main water intersection during abstraction and are therefore considered prone to groundwater stress due to low groundwater potential, high abstraction and so on. On the other hand, positive values indicate areas where the dynamic water level remains above the main water intersection depth during abstraction, and are therefore considered not prone to groundwater stress because of high groundwater potential.

The resulting groundwater stress map (Figure 4.13) fit quite well in the groundwater flow pattern from the main recharge area during the rain season depicted in section 4.2.1.1 (Figure 4.5). There are two suggestions for this scenario. The first is that most of the groundwater is abstracted from storage during the dry season, which later has to be filled in the rain season by groundwater from the surrounding areas and main

recharge; the second scenario is that this area is likely to have high transmissivity such that it easily gets drained due to a high number of abstraction boreholes coupled with the effect of the underground drainage network constructed in the 1960s.

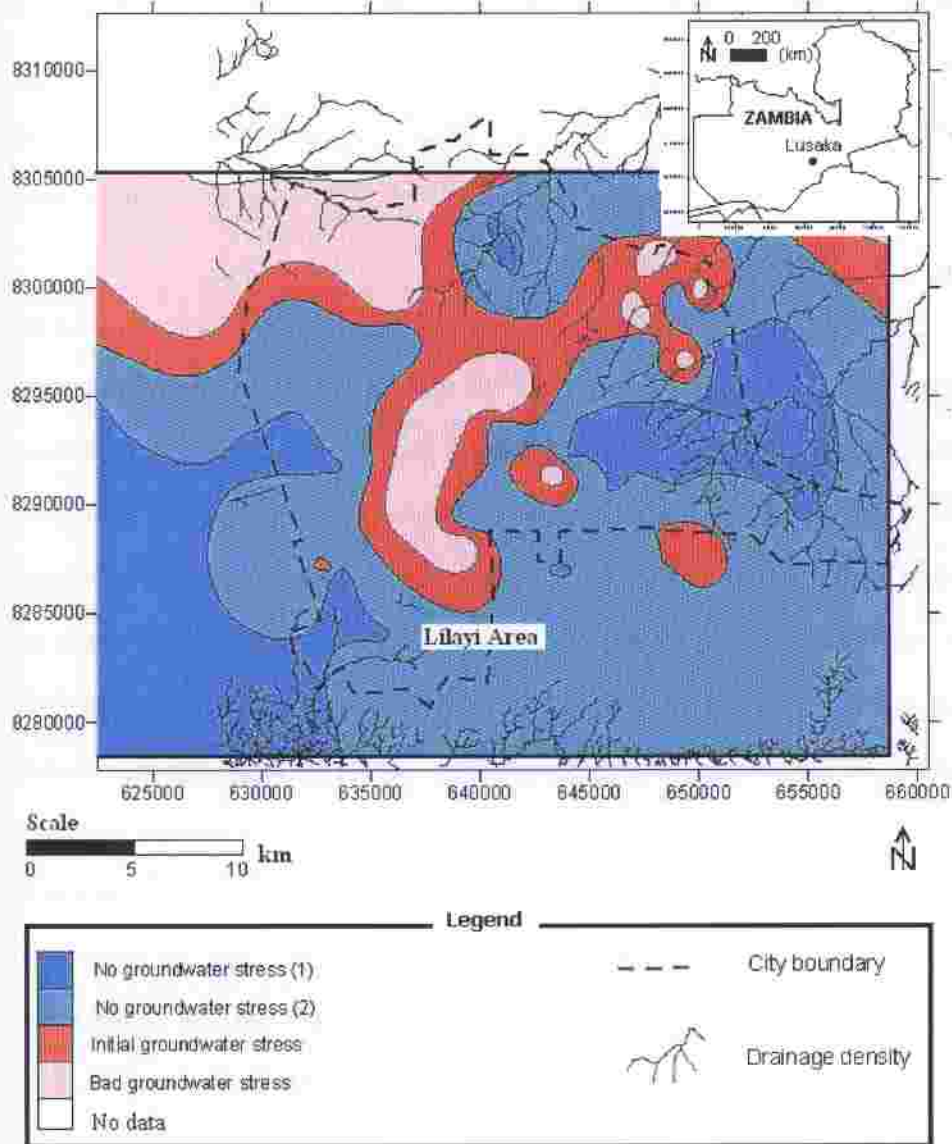


Figure 4.13 Map showing distribution of groundwater stressed areas in Lusaka urban and adjacent areas.

Areas that show initial and high groundwater stress need close monitoring now and in future, whereas those with no sign of groundwater stress are likely to support further groundwater development. Regulation of groundwater abstraction through use of low yield pumps is necessary for areas identifiable with groundwater stress. Otherwise, formation of karstic features and eventual land subsidence especially in the carbonates is likely to be accelerated. Therefore, pump testing of every borehole constructed on Lusaka Plateau is inevitable to identify groundwater stress areas during borehole construction.

4.2.1.3 Conceptual Hydrogeological Model

Evaluation of groundwater resources in the study area is of paramount importance. According to Wohnlich (1999), conceptual hydrogeological models are inevitable when carrying out groundwater resources evaluation as they provide insights in the distribution of aquifer parameters in the different aquifer lithologies, which are useful for numerical modelling and other aspects. A hydrogeological model can be developed using primary data as well as secondary data. On Lusaka Plateau, the geological model (Figure 4.14) and conceptual hydrogeological model for Lusaka urban and adjacent areas (Figure 4.15) were generated using hydrogeological data (Borehole drilling data) collected from the study area. To achieve this, boreholes with GPS coordinates were classified according to the aquifer lithologies (Table 4.5 and Table 4.6) to generate a geological model with Surfer (Grid – Data and Map – Contour) with Kriging and then indicated values of permeability coefficient for the main aquifer lithologies.

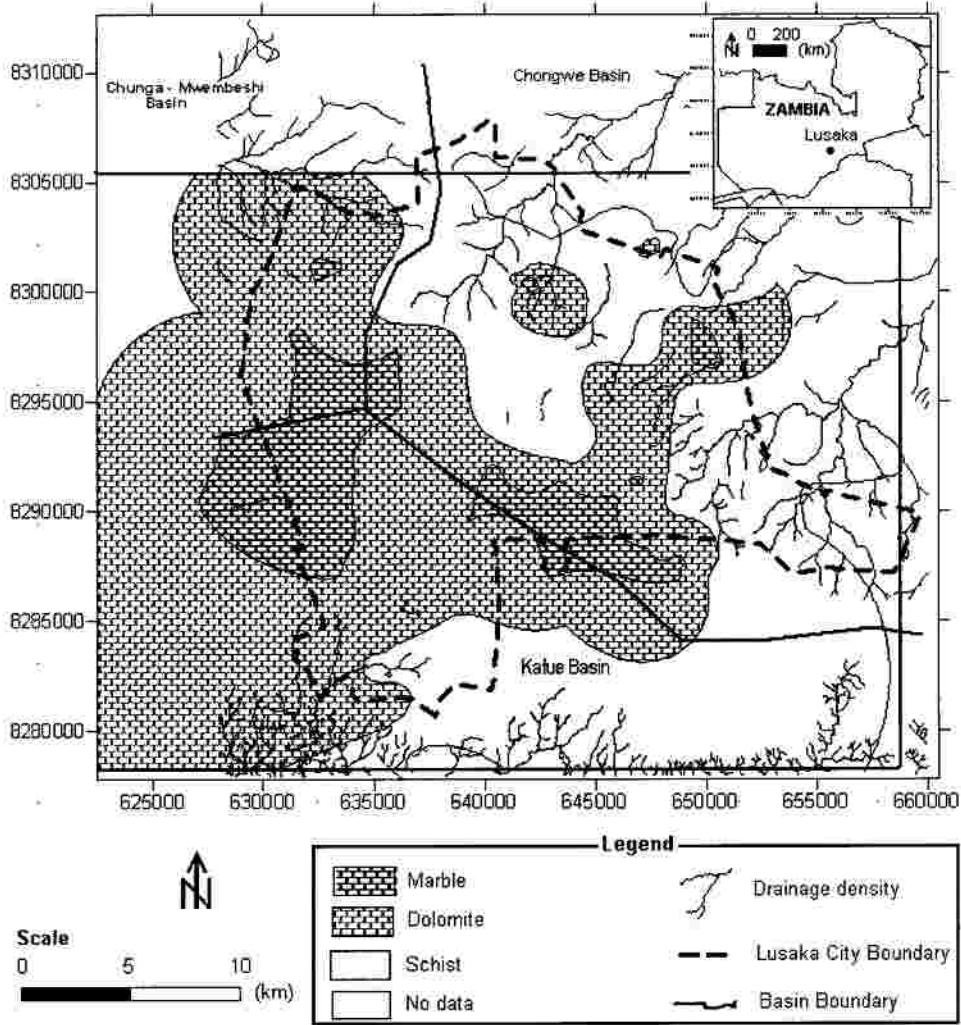


Figure 4.14 Geological Model and drainage density for Lusaka urban and adjacent areas

Based on the geological description of the predominant aquifer lithology for Lusaka urban (Matheson and Newman, 1966; Cairney, 1967), borehole data collected during the study seemed quite good and reliable for purposes of generating the main aquifer lithology.

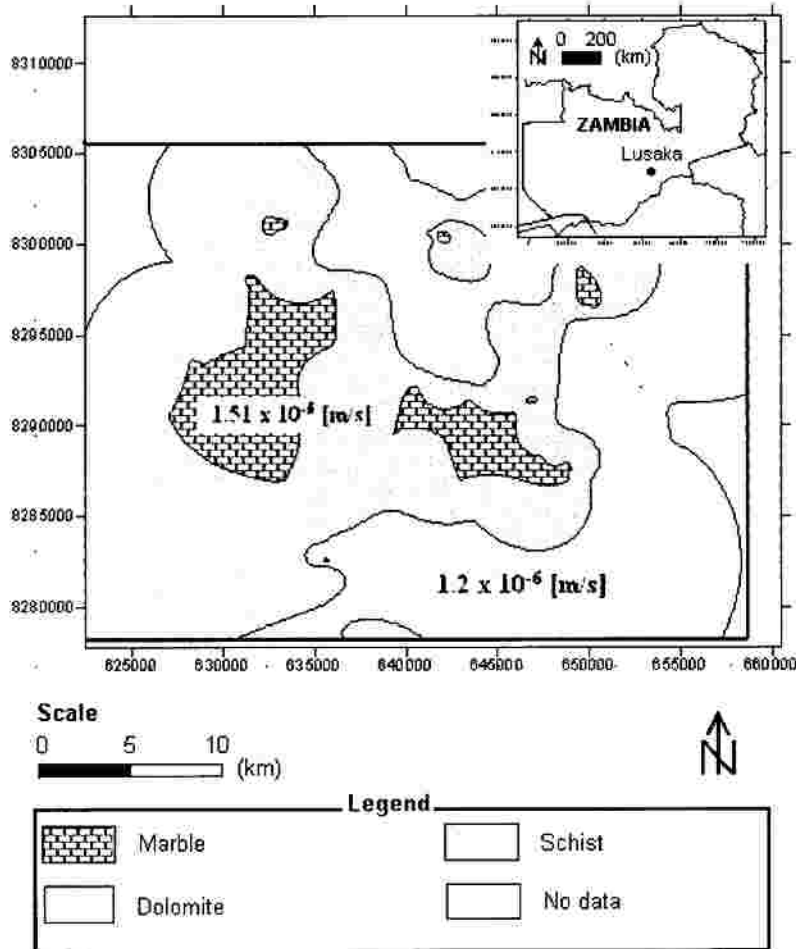


Figure 4.15 Conceptual Hydrogeological Model for Lusaka urban and adjacent areas.

Table 4.5: Arbitrary classification of lithologies to develop a geological model for Lusaka Plateau

GPS Coordinates for Individual Boreholes		Aquifer Lithology	Assigned Class
X	Y	Limestone	15
		Dolomite	10
		Schist	5

Table 4.6: Borehole data used to generate a geological model for Lusaka Plateau

No.	X	Y	F	Aquifer code value	No.	X	Y	F	Aquifer code value
1	649398	8299005	M	15	46	635602	8282387	S	5
2	647357	8297851	S	5	47	627009	8290494	M	15
3	649328	8299753	S	5	48	628943	8293148	M	15
4	640626	8301568	D	10	49	622452	8295079	D	10
5	653290	8300603	D	10	50	647955	8298111	D	10
6	658729	8305256	S	5	51	642021	8290886	M	15
7	647805	8302255	M	15	52	641860	8293724	S	5
8	648205	8301905	S	5	53	645618	8290765	M	15
9	651332	8302143	S	5	54	633145	8287116	M	15
10	651220	8301864	S	5	55	639311	8289326	M	15
11	649742	8301994	S	5	56	631091	8298213	M	15
12	649742	8301984	S	5	57	632237	8301587	M	15
13	649363	8303382	S	5	58	639251	8288242	D	10
14	649438	8295074	S	5	59	636000	8299404	S	5
15	650005	8298491	M	15	60	631379	8294244	M	15
16	649685	8299707	S	5	61	649013	8290750	M	15
17	650562	8297406	M	15	62	647356	8298139	S	5
18	649552	8296580	M	15	63	640937	8293966	S	5
19	648900	8288894	M	15	64	641074	8293944	S	5
20	636148	8297720	M	15	65	644561	8298551	D	10
21	650454	8295446	S	5	66	641625	8300213	D	10
22	643967	8292134	D	10	67	641781	8300820	D	10
23	641087	8294017	S	5	68	642897	8286916	M	15
24	649183	8287537	M	15	69	634198	8291588	M	15
25	642184	8289247	M	15	70	656201	8302830	S	5
26	650528	8296324	M	15	71	627398	8299011	D	10
27	641435	8295328	S	5	72	633907	8301098	M	15
28	648671	8294923	D	10	73	640065	8303514	S	5
29	650273	8287321	D	10	74	639452	8303235	D	10
30	643522	8291522	M	15	75	642944	8303656	S	5
31	645249	8294609	M	15	76	636979	8291116	D	10
32	640618	8292391	M	15	77	637857	8293819	M	15
33	649025	8287046	M	15	78	646953	8294887	M	15
34	647330	8291369	M	15	79	633270	8287207	M	15
35	647126	8291656	M	15	80	654416	8289119	S	5
36	647529	8288381	M	15	81	636709	8284191	D	10
37	649013	8290750	S	5	82	649154	8287101	D	10
38	636787	8289793	M	15	83	643605	8284865	D	10
39	636942	8278390	S	5	84	628076	8293678	M	15
40	636723	8279012	S	5	85	628038	8293405	M	15
41	635603	8282098	M	15	86	639071	8305354	S	5
42	633145	8286790	M	15	87	633582	8279437	D	10
43	636765	8278149	S	5	88	644359	8293890	S	5
44	635471	8283473	D	10	89	647804	8302562	S	5
45	633561	8287083	M	15	90	649741	8302273	S	5

F = Aquifer Formation, M = Marble, D = Dolomite, S = Schist

In addition, superimposing drainage density on the geological model (Figure 4.14) showed that streams emanating from Lusaka urban drain the aquifers as observed by

Lambert (1963). Therefore, over abstraction of groundwater if not controlled is likely to influence stream discharge in Chunga-Mwembeshi, Chongwe and Kafue basins. The aquifer is therefore strategic in sustaining stream flow in the dry season as well as supporting various water users that depend on the upper aquifer to meet domestic, industrial and agricultural water demand. Furthermore, sections were constructed on the hydrogeological model (Figure 4.16) based on borehole data along, and near to the section line to give more insight on the vertical distribution of the aquifer lithology.

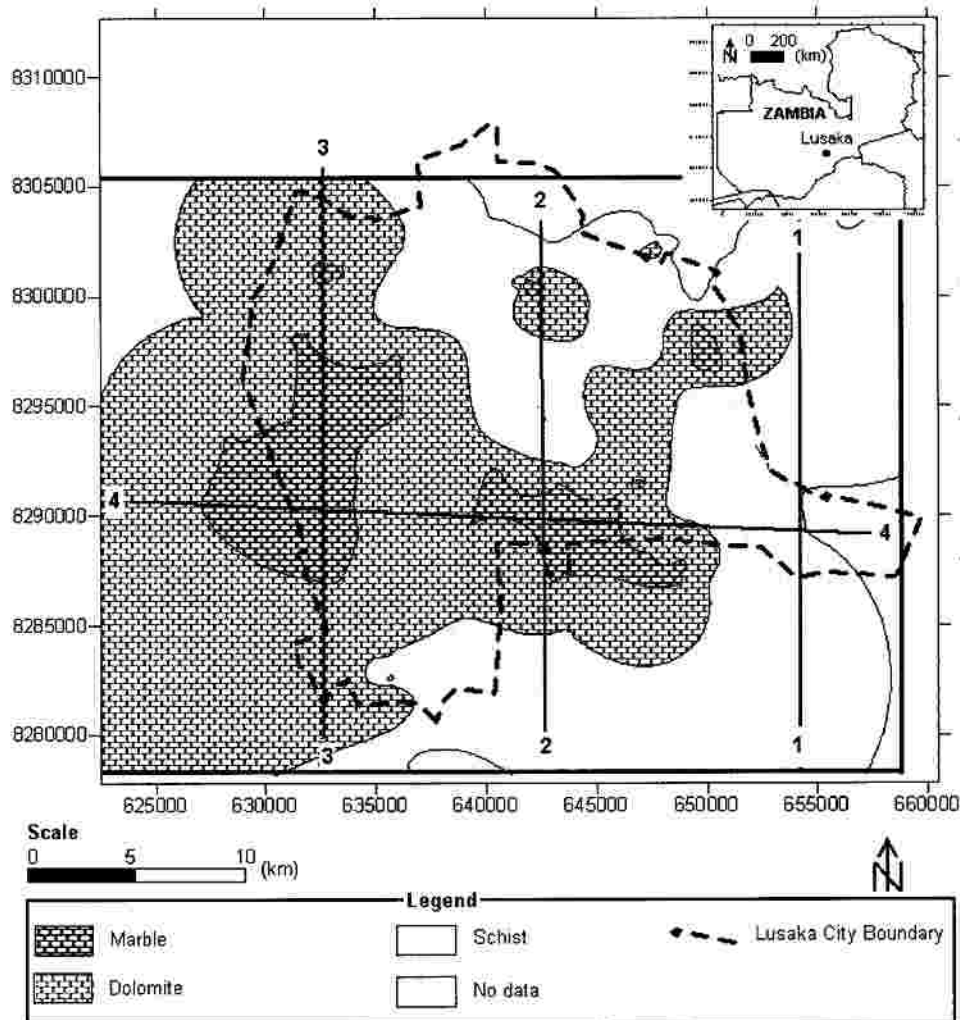


Figure 4.16 Section lines 1 to 4 on the Geological Model

Analysis of the Digital Elevation Model (DEM) for Lusaka Plateau in the east-west direction (Figure 4.17), coupled with data for some boreholes (Table 4.7) in the carbonate and schist aquifers, the constructed cross sections (Figure 4.18 to 4.20) provided details on the geometry, boundary conditions as well as the idea on how aquifer parameters are likely to be distributed in the vertical and horizontal direction.

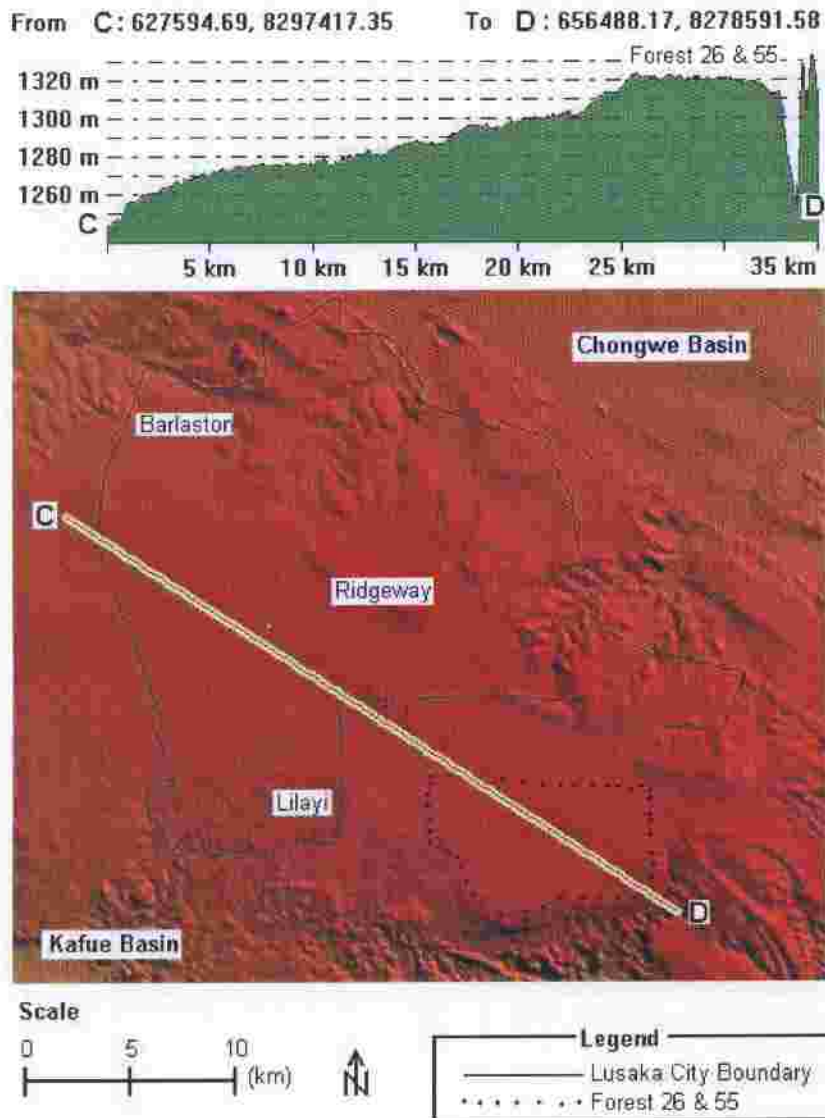


Figure 4.17 Elevation difference between Lusaka Plateau and its edges in the East-West direction
(Prepared from USGS DEM)

Table 4.7: Borehole data used to generate vertical geological cross sections 2-2 to 4-4 for Lusaka Plateau

Section	X	Y	Borehole Depth (m)	Aquifer lithology		Aquifer Cover		Main water intersection (m)	Yield (l/s)
				Type	Thickness (m)	Type	Thickness (m)		
2-2	642184	8289247	37	M	25	Laterite	12	36	7
	643522	8291522	60	M	57	Clay	3	36	1.8
	642021	8290886	27	M	23	Clay	4	18	0.8
	641860	8293724	50	S	50	Schist	50	32	1
	644561	8298551	60	D	42	Schist	18	48	1.5
	641625	8300213	67.5	D	13.5	Schist	54	54	1.5
	641781	8300820	49	D	13	Schist	36	39	1.5
	642897	8286916	57.88	M	51.88	Clay	6	52	0.5
	643079	8302349	121	S	109	Gravel	12	78	5
	640065	8303514	60	S	56	Clay	4	48	0.9
	639432	8303235	80	D	75.5	Clay	4.5	40	2.5
	642327	8296265	65	M	54	Laterite	11	11	50
	643411	8294004		M		Clay	5	43	5.6
	636723	8279012	43.5	S	25.5	Clay	18	27	0.8
	636765	8278149	60	S	60	Schist	60	57	0.4
	641435	8295328	54	S	42	Clay	12	30	4
3-3	633145	8286790	34	M	30	Clay	4	28	3
	633561	8287083	50	S	40	Schist	10	24	2.5
	633145	8287116	39.5	M	21.5	Schist	18	24	5
	631091	8298213	47	M	47	Marble	47	34	2.1
	632237	8301587	97.5	M	45.5	Clay	1.5	31	9
	631379	8294244	49.5	M	49.5	Marble	49.5	44	0.5
	634198	8291588	38	M	37	Clay	1	30	6
	633907	8301098	105	M	104.5	Gravel	5.5	55	6
	633270	8287207	37.5	M	34.5	Clay	3	24	5.5
	633582	8279437	50	D	38	Schist	12	30	4
	632221	8282367	51	S	48	Clay	3	21.3	5.1
	627398	8299011	39.8	D	37.8	Clay	2	6	3
	641781	8300820	49	D	13	Schist	36	39	1.5
633966	8294882	81	M	75.6	Gravel	5.4	12.2	13.9	
4-4	648900	828894	29.2	M	29.2	Marble	29.2		2
	649013	8290750	30	S	27	Gravel	3	28	7.5
	636787	8289793	31.5	M	29.6	Laterite	1.9	19	0.75
	627009	8290494	42	M	42	Marble	42	36	2
	639311	8289326	40	M	40	Marble	40	27	2.5
	634198	8291588	38	M	37	Clay	1	30	6
	636979	8291116	40	D	39	Clay	1	26	6
	639251	8288242	38.1	D	38.1	Dolomite	38.1	12	0.25
	654416	8289119	79.5	S	73.5	Clay	6	66	0.35
	636709	8284191	36.5	D	18.5	Clay	18	30	3
	635471	8283473	60	D	54	Clay	6	30	1.5
	631378	8289696	43	M	25	Sand	18	30	28

, M = Marble, D = Dolomite, S = Schist



Figure 4.18 Section 2 - 2 of Geological Model showing the slope to the north and south

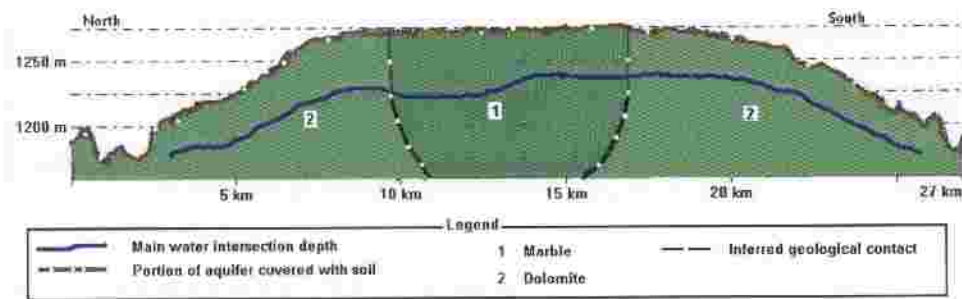


Figure 4.19 Section 3 - 3 on Geological Model showing the slope to the north and south

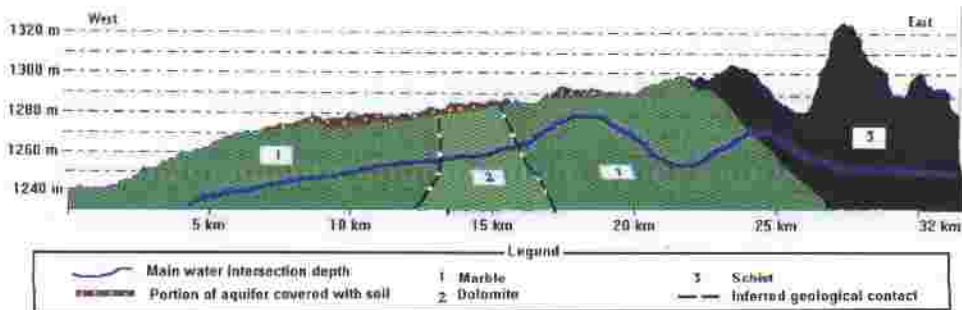


Figure 4.20 Section 4 - 4 on Geological Model showing the slope to the east and west

Figures 4.18 to 4.20 indicates that Lusaka urban is indeed a mould like plateau that slopes in all directions and thereby confirming that the recharge area for Lusaka urban aquifers is quite restricted in aerial extent at a local scale. Groundwater recharged in the immediate surrounding areas is not available for the central higher parts of Lusaka

urban aquifers. Moreover, the main groundwater intersection depths in all the cross sections indicate that groundwater flows from Lusaka Plateau to the surrounding areas. Hence, surrounding areas are likely to have also a high groundwater potential. Furthermore, analysis of the collected groundwater data and information together with the above three cross sections, indicated that Lusaka Plateau was an aquifer system as well as a groundwater system. As an aquifer system, it could be defined by the aquifer geometry, boundary conditions, aquifer type and hydraulic parameters, whereas by considering the quantity of groundwater in storage, recharge and discharge sources as well as the chemical composition of groundwater, it qualifies as a groundwater system.

4.2.2 Groundwater Level Data Collection

Measurement of groundwater levels in the carbonates and schist aquifer lithologies that occur in Lusaka urban and adjacent areas were carried out at observation boreholes from the month of April 2002 to February 2008. Groundwater level records are presented in Appendix C2 (Tables 4.8 to 4.13). The two aquifer lithologies form the main aquifers into which all the boreholes in the study area tap their water and from where the streams emanate. Location of the first pilot observation boreholes (BH1 and BH2) for this study was based on the two main aquifer lithologies and the cost associated with collection of data. Department of Water Affairs office premises along Sheki-Sheki road was ideal to host the two pilot observation boreholes because it lies at a location where the schist overlies the carbonate near a geological contact. BH1 was constructed in the schist and BH2 in the carbonates according to the recommended construction standards (Freeze and Cherry). Data was analyzed to evaluate aquifer response to recharge, drainage, abstraction and the usefulness of

having groundwater observation boreholes on Lusaka Plateau for the management of aquifers.

4.2.2.1 Designed Groundwater Monitoring Network for Aquifer Management

Figure 4.21 shows a continuous drop in the water levels due to abstraction effects in both the schist and the marble. Similar trends were observed in the past (Nkhuwa, 1996; Maseka and Nyambe, 1999). Carbonates are the most affected among the aquifer lithologies. A marked recovery of groundwater levels within a few days from the on-set of the rainy season also occurs, but with variations according to different rainfall amounts received annually (Table 4.14). High aquifer drainage is also evident during and at the end of the rainy season, before levels assume a steadier drop. Distinct periods of groundwater level rise (December – March) and fall (March – December), with the small episodic level rise and fall in the water table between March and December are important for estimating recharge and abstraction.

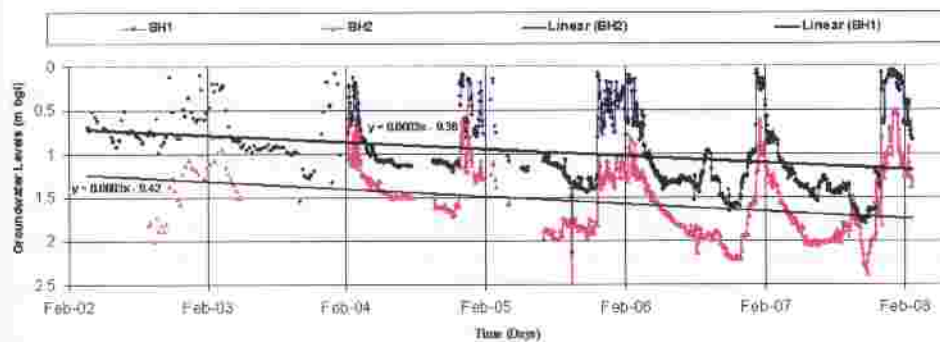


Figure 4.21 Groundwater level fluctuation at observation borehole BH1 and BH2 on Lusaka Plateau at DWA Sheki – Sheki offices.

Table 4.14: Summary of annual rainfall at Met. Stations on Lusaka Plateau

(Source: Met. Department – Zambia)

Hydrological Year	Sheki Sheki DWA		City Airport		Mt. Makulu		Int. Airport	
	Rainfall amount (mm)		Rainfall amount (mm)		Rainfall amount (mm)		Rainfall amount (mm)	
2002/2003	845.7	(74 days)	925.5	(68 days)	986.3	(83 days)	627.8	(80 days)
2003/2004	749.0	(59 days)	938.2	(57 days)	974.7	(70 days)	733.0	(69 days)
2004/2005	891.0	(51 days)	707.4	(44 days)	640.8	(55 days)	686.5	(60 days)
2005/2006	977.2	(61 days)	889.8	(67 days)	910.9	(80 days)	945.1	(71 days)
2006/2007	518.0	(52 days)	542.8	(48 days)	457.2	(38 days)	562.3	(42 days)
Average	796.2	(59.4 days)	800.7	(56.8 days)	794	(65.2 days)	710.94	(64.4 days)

Additionally, groundwater level fluctuations indicate that recharge is affected by a number of factors as opposed to considering rainfall as the only factor where recharge is high for rainfall amounts from 830mm and above; and considerably low for lower rainfall amounts (Von Hoyer et al., 1978; Maseka, 1994; JICA Report, 1995; Nkhuwa, 1996). Table 4.15 shows amounts of rainfall that caused rapid groundwater level recovery in aquifers from October to December 2007 (Figure 4.22) and caused widespread flooding in Lusaka urban because of factors other than rainfall amounts.

Table 4.15: Rainfall amounts received at Met. Stations on Lusaka Plateau from

October to December 2007 (Source: Met. Department – Zambia)

Hydrological Year	Sheki Sheki DWA		City Airport		Mt. Makulu		Int. Airport	
	Rainfall amount (mm)		Rainfall amount (mm)		Rainfall amount (mm)		Rainfall amount (mm)	
2007/2008	491.2	(33 days)	461	(36 days)	553	(33 days)	454	(40 days)

It is evident that the current groundwater abstraction, although more than the annual recharge of 8% of the annual rainfall is beneficial in keeping most places dry such as Kanyama *etc* that should be flooded by groundwater within Lusaka urban. This is

because the groundwater table gets lowered due to over abstraction especially during the dry season, such that it is not able to reach the ground surface during the rainy season to an extent of allowing excess rainwater to accumulate on the ground surface for longer periods.

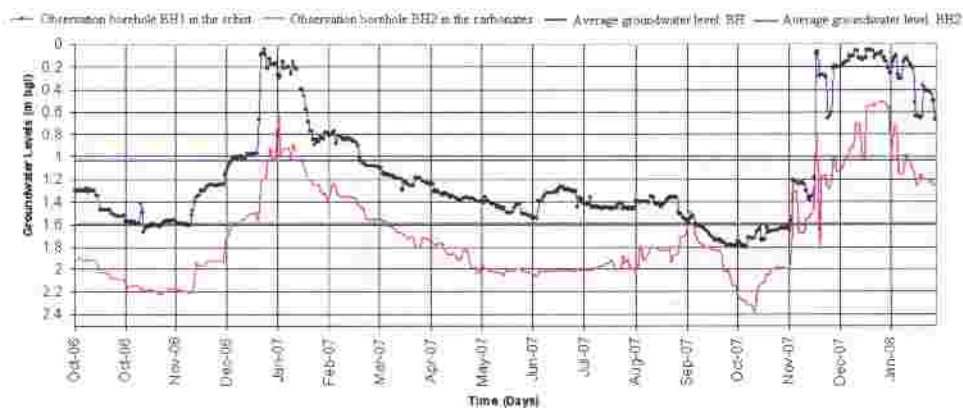


Figure 4.22 Comparison of groundwater level rise from October to December 2007 to the level rise for 2006/2007 rainy season at observation borehole BH1 and BH2 on Lusaka Plateau at DWA Sheki – Sheki offices.

A plot of groundwater levels (Appendix C2) and rainfall data in tables 4.16 to 4.18 (Appendix C3) shows evidence that direct recharge takes place in both the schist and carbonates (Figure 4.23). The two aquifer lithologies are likely to be hydraulically connected. According to Lloyds (1999), direct recharge occurs when water infiltrates the ground and percolates to the groundwater store. Rapid groundwater level response to rainfall is attributable also to recharge that occurs via preferential paths such as extensional fault zones and sinkholes (Xu and Beekman, 2003).

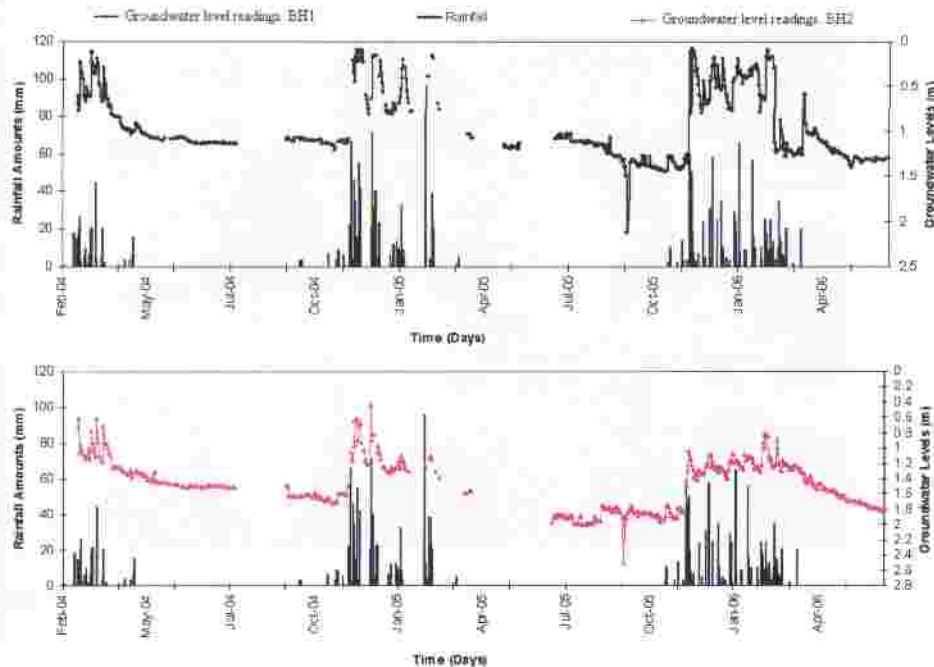


Figure 4.23 Groundwater level response to rainfall at observation borehole BH1 in the schist and BH2 in the carbonates from 2003/04 to 2005/06 rainy seasons.

In the case of Lusaka Plateau, direct recharge is likely to occur in the carbonates due to presence of fractures and sinkholes (Figure 4.24) some of which are exposed and others covered by a layer of laterite. This situation support findings by Taque (1969), that soils on the Lusaka Dolomite have 76mm hr^{-1} infiltration capacity and that recharge is high in the carbonates (Von Hoyer et al., 1978; Maseka, 1994; Nkhuwa, 1996). Rapid entry of water into the subsurface is also a clear indication that the aquifer has little protection from contamination.



Figure 4.24 Presence of fractures and sinkholes on most carbonate areas covered by laterite in Lusaka urban and adjacent areas.

The designed Lusaka Plateau groundwater monitoring network (Figure 4.25) is critical in providing additional data and information on the combined effect of rainfall amounts, rainy days and rainfall distribution on effective recharge in the upper aquifer (0-50m). This includes information on groundwater flow direction, the role of Lusaka South Forest Reserve (Forest 26 & 55) as the main recharge area, further groundwater resources evaluation and yearly groundwater recharge, planning for groundwater usage after every rainy season; observe abstraction effects, groundwater quality status and possible future abstraction control. Groundwater levels for April and May as observed at BH1 and BH2 seem to be useful in forecasting the lowest groundwater levels likely to obtain in October, the period when groundwater abstraction is at its highest. Furthermore, the Lusaka Plateau groundwater monitoring network would facilitate continuous assessment of groundwater quantitative status and function as a management tool to ensure sustainable utilisation of groundwater resources.

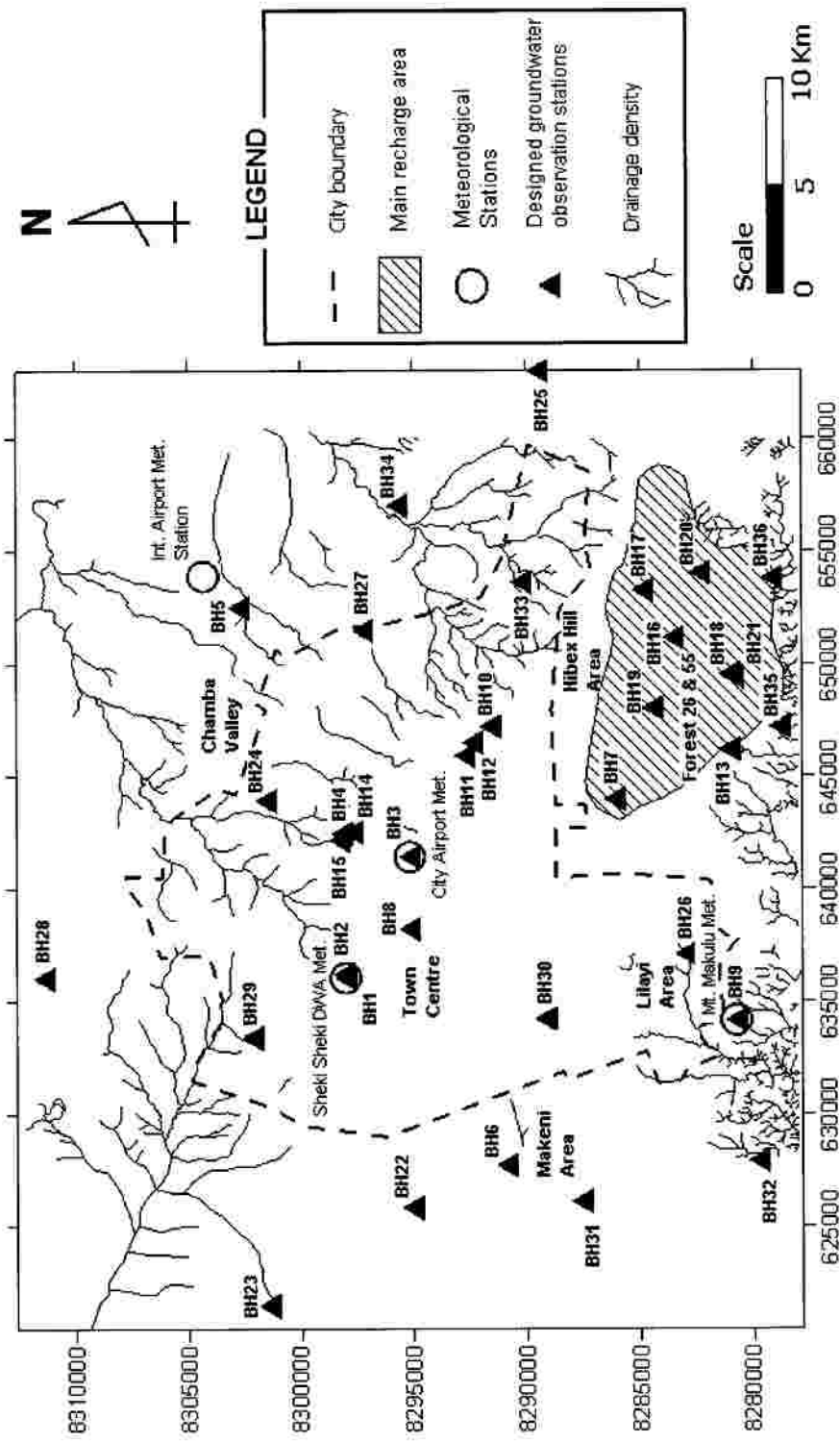


Figure 4.25 Map of Lusaka Plateau showing meteorological stations and the designed groundwater-monitoring network

The design of the Lusaka Plateau groundwater monitoring network took into consideration the following:

- **Information needs targeting quantity and quality:** water quality dynamics may affect groundwater use especially for domestic purposes considering the large number of settlements using on-site sanitation and reduction of areas for recharge of groundwater of better quality.
- **Geology and aquifer lithology:** schist and carbonates are the principal aquifer lithological units on Lusaka Plateau. The carbonate is the largest, most productive and exploited aquifer than the schist.
- **Drainage pattern and morphology:** all the streams emanating from Lusaka Plateau are dependant on groundwater, which is affected by recharge and abstraction.
- **Distribution of meteorological stations:** availability of groundwater in the upper aquifer on Lusaka Plateau is highly dependant on the effective recharge resulting from the combined effect of annual rainfall, rain days and rainfall distribution.
- **Security and permanent access to the installation:** previous observation boreholes constructed in the Lusaka Dolomite are now in private hands and are not accessible for measurements. Premises for government institutions are now preferred to host the installation to allow permanent access.
- **Planned groundwater modeling:** water levels and water quality data are important inputs in a groundwater model as well as for model calibration.

4.2.2.2 The Role of Lusaka South Forest Reserve on Water Resources on the Lusaka Plateau

The prominent groundwater flow direction from Forest 26 (Figures 4.26 to 4.30) generated from static water levels (Table 4.19) indicate that the flow crosses the main water divide for the three sub-river basins located within Lusaka urban. The scenario, depicted would appear to give further evidence of the extensive sub-surface drainage in a karst system. Additionally, the water divide in the carbonates is such that there is a flow boundary condition across the divide instead of none at all because of the karst. This situation has implications when considering groundwater modeling for Lusaka Plateau. Apparently Figures 4.26 to 4.28 are similar to that generated from static water levels of DWA boreholes constructed from February 2005 to April 2005 shown under section 4.2.1.1 (Figure 4.5). Furthermore, Figures 4.29 and 4.30 indicate that groundwater recharged in Forest 26 continues to extend its influence on the groundwater flow dynamics in all directions on Lusaka Plateau, but with a south-east to north-west direction as the main flow path. The main groundwater flow path coincides also with the area concentrated with a number of high yielding production boreholes (Section 4.2.1.1). In brief, the role of Lusaka South Forest Reserve is:

- to provide natural attenuation of pollution in the Lusaka urban aquifers through dilution and flushing out of pollutants every rainy season.
- to facilitate aquifer recovery and sustain groundwater levels in the Lusaka Plateau aquifers.
- to maintain groundwater flow and surface water flow on the Lusaka Plateau.

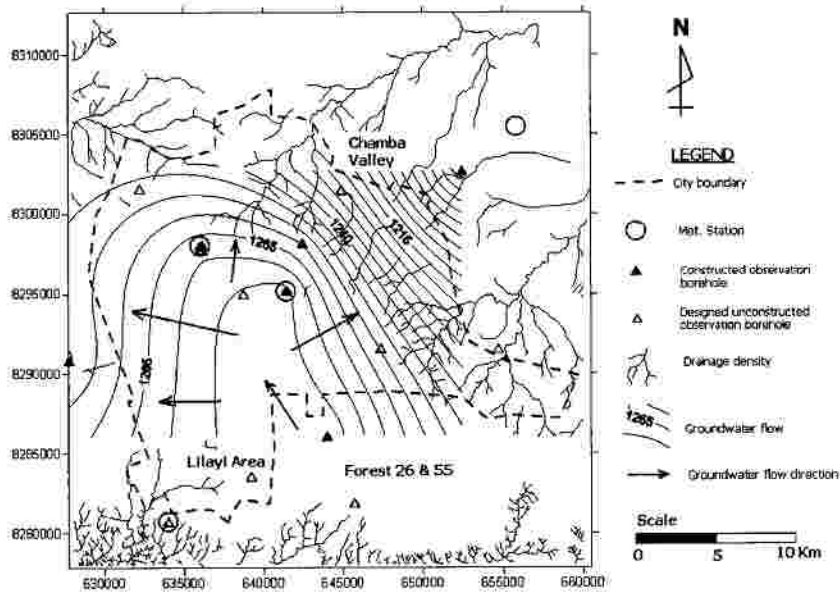


Figure 4.26 Map showing groundwater flow direction after 2006/2007 rainy season: 31 May 2007

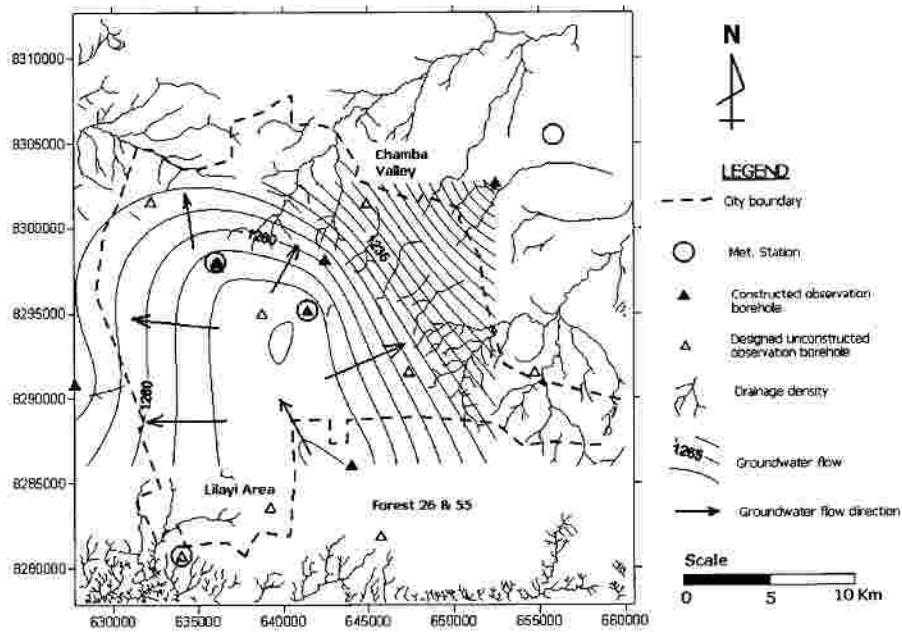


Figure 4.27 Map showing groundwater flow direction at the start of 2007/2008 rainy season: 23 October 2007

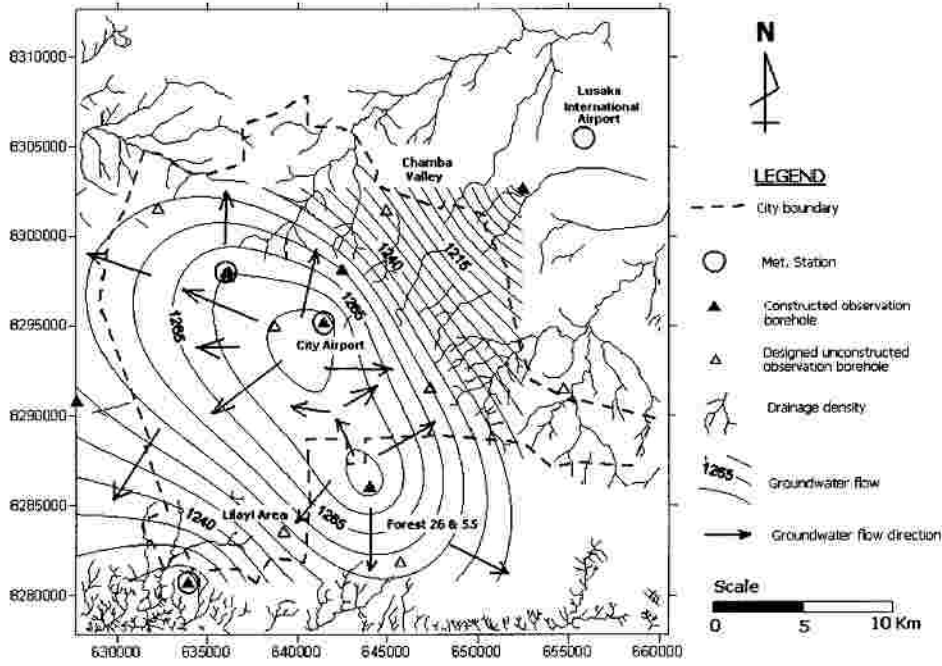


Figure 4.28 Map showing groundwater flow direction: 31 December 2007

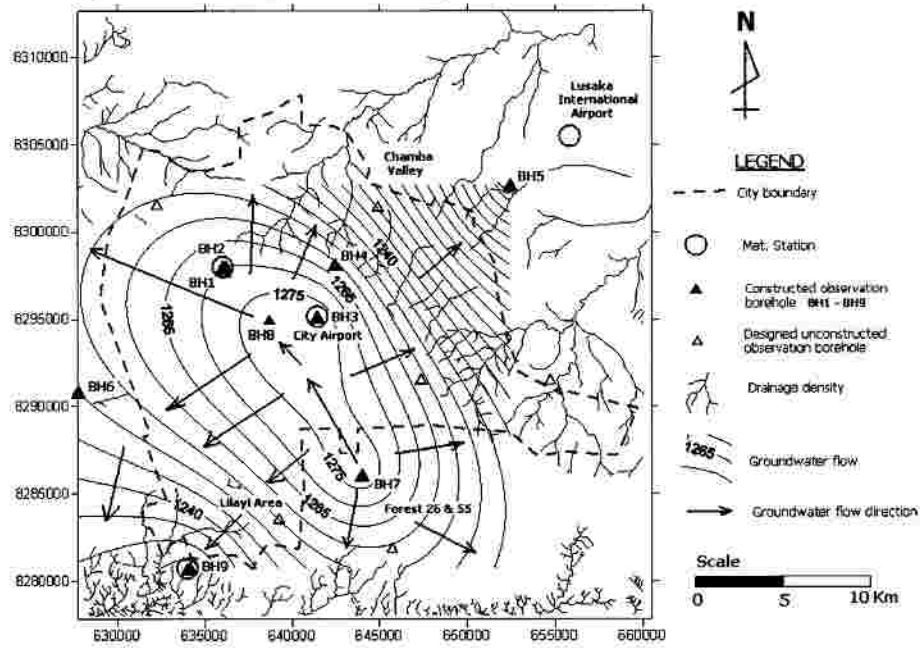


Figure 4.29 Map showing groundwater flow direction: 16 January 2008

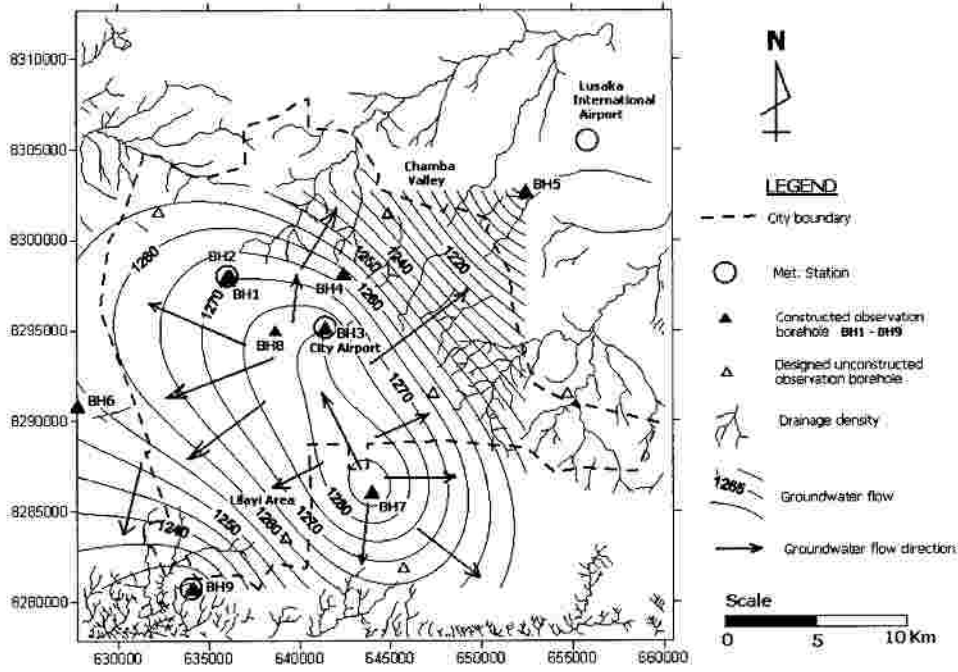


Figure 4.30 Map showing groundwater flow direction: 20 February 2008

Similarly, graphical representation of groundwater level rise (Figure 4.32) captured in table 4.20, shows that recharge is more in Forest 26 (**BH7**) than in other areas. Further evaluation of groundwater level rise for the 2007/2008 rainy season (Figure 4.32) supports the argument to consider the Lusaka Plateau as a groundwater system and an aquifer system (Section 4.2.13). Firstly, groundwater flow from Lusaka Dolomite into the Cheta Formation may be unrestricted in the north-west direction, indicating a high hydraulic connectivity. Secondly, Lusaka Dolomite has for a long time considered to have a higher recharge and groundwater potential than the Cheta Formation (JICA Report, 1995), but the latter equally has a small change in the water table during the dry season despite a high number of production boreholes. This scenario may also suggested a high groundwater potential in the Cheta Formation that requires further investigation to establish the exploitation potential.

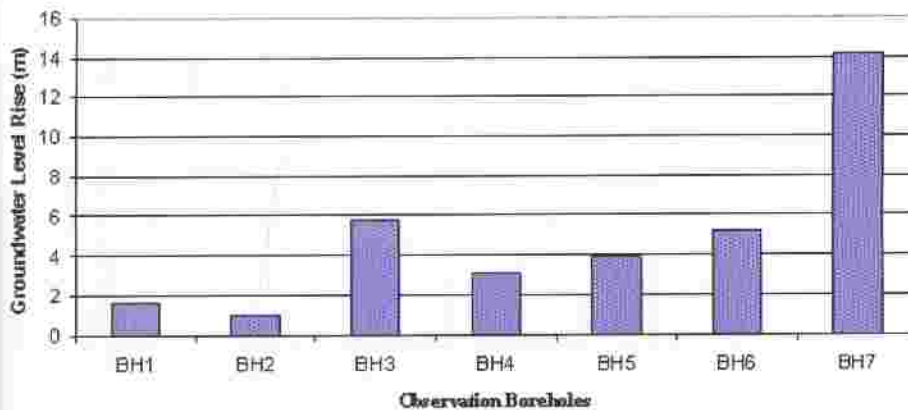


Figure 4.31 Groundwater level rise during 2007/2008 rainy season; October 2007 to January 2008

Table 4.20: Data on groundwater level drop and rise at observation boreholes for Lusaka Plateau: May 2007 to January 2008

Station	Aquifer Lithology	Change in water table (m)				Remarks
		31/05/07 ~ 23/10/07	23/10/07 ~ 27/11/07	31/12/07	31/01/08	
BH1	Schist	0.42	-0.58	1.67	1.62	Responded quickly to rains received in October and November 2007. Suitable to use for early warning and forecasting.
BH2	Carbonate	0.14	-0.64	1.21	0.98	Responded quickly to rains received in October and November 2007. Suitable to use for early warning and forecasting.
BH3	Schist	2.11	0.21	3.32	5.77	Delayed in responding to rains received in October and November 2007.
BH4	Carbonate	0.93	0.33	1.56	3.16	Delayed in responding to rains received in October and November 2007.
BH5	Alluvium	0.77	-0.14	2.8	3.94	Responded quickly to rains received in October and November 2007. Suitable to use for early warning and forecasting.
BH6	Carbonate	3.47	-1.52	2.95	5.26	Responded quickly to rains received in October and November 2007. Suitable to use for early warning and forecasting.
BH7	Carbonate	4.04	0.99	4.01	14.15	Delayed in responding to rains received in October and November 2007.
BH8	Carbonate					Borehole was drilled in December 2007 and measurements started on 16 th January 2008.
BH9	Carbonate					Borehole was drilled in December 2007 and measurements started on 31 st December 2007.
Cumulative rainfall (mm)				489.8	881.53	October to December 2007 cumulative rainfall (489.8mm) that caused rapid aquifer recovery and full recovery by January 31 st January 2008 (881.53mm).

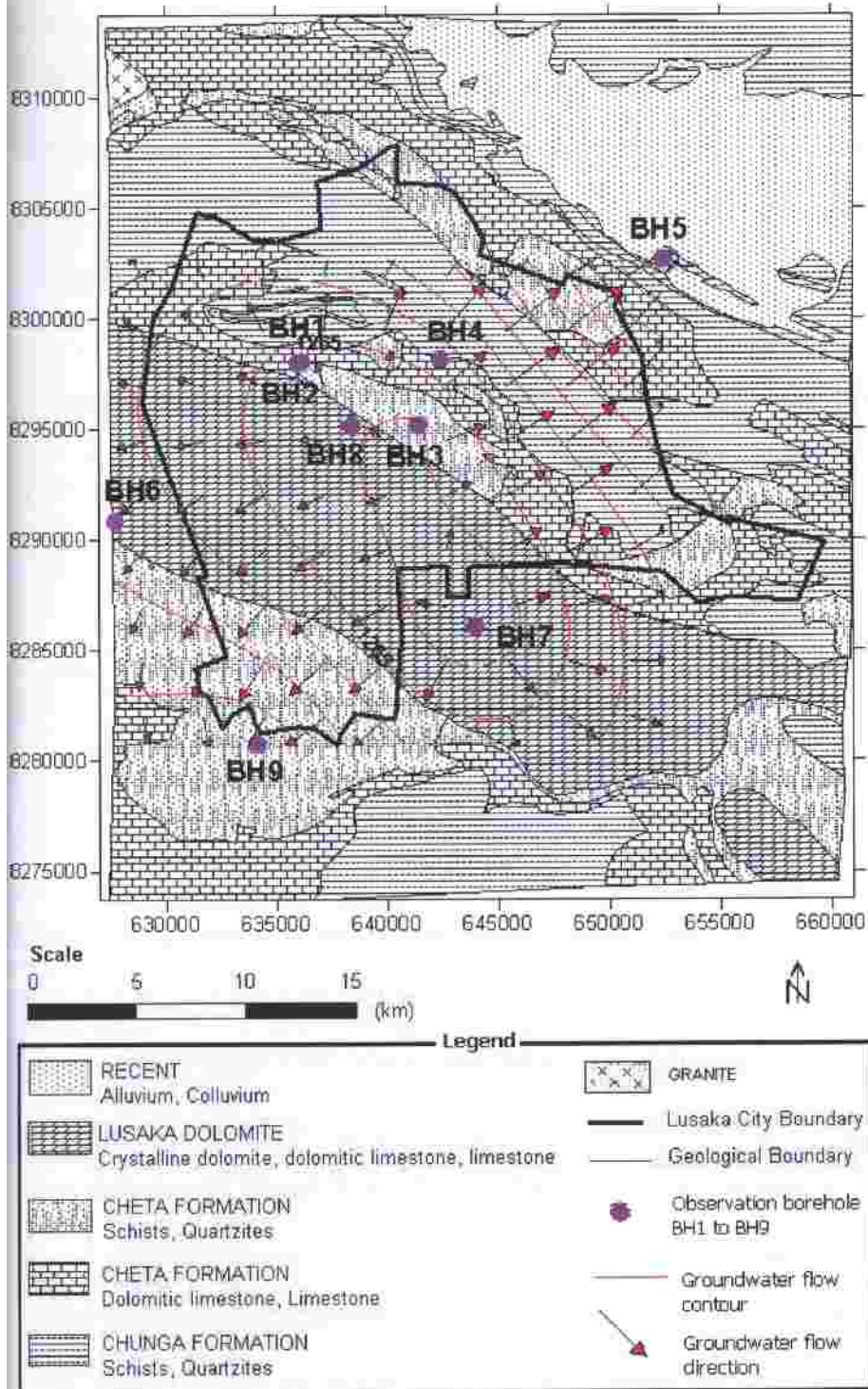


Figure 4.32 Map showing groundwater level rise and flow direction: 2007/2008 rainy season

Lusaka South Forest Reserve has a total estimated surface area of 82.7Km², out of which 52.6Km² is occupied by Forest 26 and 30.1Km² by Forest 55. Based on the groundwater level rise observed by 31st December 2007 and 31st January 2008 (Table 4.20), it is estimated using equation 4-1 (Section 4.2.1.1) that Forest 26 generated groundwater recharge in the order of:

Min. recharge = Main recharge area × depth of water rise × Effective porosity.

$$= 52\,600\,000\text{m}^2 \times 4.01\text{m} \times 0.025$$

$$= \underline{5.273 \times 10^6 \text{ m}^3}$$

Max. recharge = Main recharge area × depth of water rise × Effective porosity.

$$= 52\,600\,000\text{m}^2 \times 14.15\text{m} \times 0.025$$

$$= \underline{18.607 \times 10^6 \text{ m}^3}$$

Recharge generated in Lusaka South Forest Reserve could be estimated also using methods such as Water Table Fluctuation (WTF), Cumulative Rainfall Departure (CRD) and the Equal Volume (EV), which have been successfully used in Southern Africa's semi arid areas (Bredenkamp *et al.*, 1995; Xu and Beekman, 2003). Water Table Fluctuation method [Equation 4 – 2] is an indirect way of determining recharge from Water Table fluctuations (Simmers *et al.*, 1997). According to Simmers *et al.*, (1997), the method is dependent on the value for specific yield, which is difficult to measure, but usually estimated from the lithology of the zone in which the water table fluctuates or from pumping tests.

$$R_r = S_y \Delta S + Q_a + \Delta Q_l$$

Equation 4 – 2

Where: R_r = recharge,

S_y = specific yield,

ΔS = change in water table elevation,

Q_a = groundwater abstraction during the considered period,

ΔQ_l = the difference between lateral subsurface outflow and lateral subsurface inflow during the considered period.

When equation 4 – 2 is used with specific yield of 0.05, change in water table elevation of 4.01m and 14.15m, groundwater abstraction during the considered period being zero, the difference between lateral subsurface outflow and lateral subsurface inflow during the considered period being zero, the volumes generated by 31st December 2007 and 31st January 2008 is about $10.55 \times 10^6 \text{ m}^3$ and $37.22 \times 10^6 \text{ m}^3$ respectively. The other important observations at BH7 from 31st May to 27th November 2007 are that the 14.15m groundwater level rise in 65 days gives 0.22m/day as the rate of rise due to recharge and 0.028m/day as the rate of groundwater level drop (5.03m drop in 180days) due to aquifer discharge. This indicates that a large volume of groundwater recharge is generated in Forest 26 and most likely distributed to all the aquifers on Lusaka Plateau. Therefore, Lusaka South Forest Reserve and in particular Forest 26 has more influence on water resources on Lusaka Plateau than any other place. Hence, environmental highlights and key features on Forest 26 are that:

- the area sustains groundwater flow to surrounding areas as well as most of the base flow in the surrounding streams and rivers.
- it has a high potential to transmit pollution to a larger portion of aquifers on Lusaka Plateau in the event that pollution is introduced in the area.
- reduction of recharge in Forest 26 has the implication on reducing the natural ability of the aquifer to dilute pollution load and flush out pollutants resulting mainly from on-site sanitation and other anthropogenic activities.
- unsustainable development in the area that may reduce recharge, introduce pollution and over look good waste management are potentially likely to lead to severe environmental impact and damage to a large part of the aquifer.
- One of the protective measures for Forest 26 is to turn it into a recreation park.

It is important to also mention that rainfall amounts on Lusaka Plateau vary from one rainy season to the other. Therefore, it becomes an important factor when evaluating groundwater recharge and groundwater resource management. Hence, observation stations are ideal for early warning in planning for groundwater utilisation and abstraction control. Providing information for years of low and high recharge at the end of each rainy season would greatly benefit the farming community that depend on groundwater for irrigated agriculture.

4.2.2.3 Evaluation of the factors affecting Effective Recharge on the Lusaka Plateau

Field observations in the month of December 2005 and January 2006 during rain storms as an empirical approach indicated that most rain storms of less than 10mm depth (Table

4.21) that occurred on Lusaka Plateau did not result in ponding and runoff on most areas covered by carbonates. Most of the rainfall directly infiltrated into the ground, except on schist and quartzite covered areas. However, temporal ponding on most of the carbonate areas resulted from rainfall events of more than 10mm depth, but water disappeared from the ground surface after a few minutes or hours mainly through infiltration. Ponding of rainwater lasted for a few days in areas covered by layers of clays. Sealed off surfaces such as tarred roads, roofs and concrete pavement usually generated high runoff in most areas of Lusaka urban resulting in temporal flooding due to poor urban drainage network.

Table 4.21: Correlation of rainfall amounts received at Sheki-Sheki DWA Met. Station with infiltration situation on the carbonates in Lusaka urban (after Siwale, 2006)

December 2005				January 2006			
Date	Rainfall (mm)	Cumulative Amount from start of rain season (mm)	Total Rain Days	Date	Rainfall (mm)	Cumulative Amount from start of rain season (mm)	Total Rain Days
01-Dec-05	11.4	117.5		03-Jan-06	35	435.1	
02-Dec-05	47.2	164.7		05-Jan-06	10	445.1	
03-Dec-05	50	214.7		06-Jan-06	4	449.1	
04-Dec-05	19	233.7		09-Jan-06	5	454.1	
05-Dec-05	7.7	241.4		10-Jan-06	1	455.1	
06-Dec-05	2.5	243.9		12-Jan-06	3	458.1	
07-Dec-05	3.2	247.1		16-Jan-06	29	487.1	
08-Dec-05	1.5	248.6		17-Jan-06	2	489.1	
09-Dec-05	7.0	255.6		18-Jan-06	24	513.1	
14-Dec-05	24	279.6		19-Jan-06	18.2	531.3	
17-Dec-05	5	284.6		22-Jan-06	65	596.3	
21-Dec-05	1.5	286.1		23-Jan-06	7	603.3	
22-Dec-05	31	317.1		28-Jan-06	9	612.3	
25-Dec-05	58	375.1		29-Jan-06	9	621.3	14
29-Dec-05	25	400.1	15				

High recharge on Lusaka Plateau has been associated with high rainfall amounts (Von Hoyer *et al.*, 1978; Maseka, 1994; JICA Report, 1995; Nkhuwa, 1996). However, critical examination of groundwater level measurements in Appendix C2 using Figure 4.33 led to

the following assumption and interpretation regarding groundwater recharge resulting from rainfall on Lusaka Plateau:

- The combined effect of rainfall amounts, rainy days and rainfall distribution control the amount of effective recharge that contributes to sustainable groundwater levels during the dry season.

An attempt was made to relate and interpret the combined effects of the three factors (rainfall amounts, rainy days and rainfall distribution) on effective recharge. Understanding the interplay of these factors on water resources management on Lusaka Plateau was essential. Figure 4.33 indicates that during the five years of groundwater level measurements at BH1 and BH2, high rainfall amounts of above 830mm shown in table 4.14 (Section 4.3.1) did not necessarily result into high effective recharge when compared to rainfall received from October to December 2007 shown in table 4.15 (Section 4.3.1). Therefore, the interplay of rainfall amounts and rainy days as factors was suggested (Table 4.22). Furthermore, the two factors could not adequately explain yearly variations in effective recharge observed during high rainfall years. Hence, rainfall distribution with regard to the main recharge area (Figures 4.34 to 4.38) was suggested as another important factor that is linked to effective recharge. In brief, when the rainy days-rainfall period ratio is more than 0.4 on the Lusaka Plateau, effective recharge is high and aquifers recover regardless of the rainfall amount received. The opposite is also true, when the rainy days-rainfall period ratio is less than 0.4, effective recharge is low and aquifer recovery is poor and slow regardless of the amount of rainfall received.

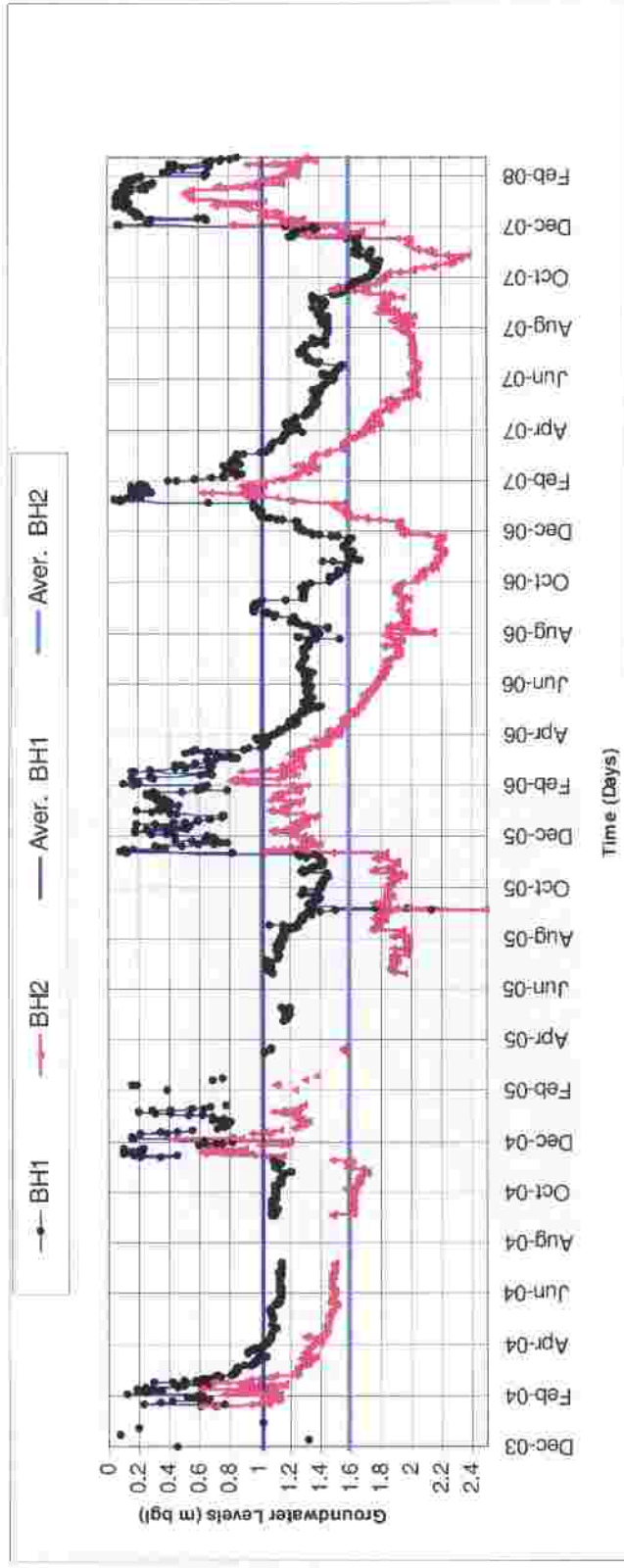


Figure 4.33 Groundwater fluctuation at DWA Sheki-Sheki office: December 2003 to February 2008

How to read the graph:

- i) Zero reading represents the ground surface.
- ii) Groundwater level readings between 0 and 2.5m indicate the distance from the surface of the ground to the water surface (water table).
- iii) The horizontal lines indicate the average depth to the water table for each aquifer lithology: BH1 (schist) and BH2 (marble)

Table 4.22: Average Rainfall – Rainy days relationship for Lusaka Plateau

Hydrological Year/ Period	Average Ratio of Rainy Days to Rainfall Period	Average Rainfall Amounts (mm)
2002/2003	0.51	846.33
2003/2004	0.43	848.73
2004/2005	0.35	731.43
2005/2006	0.47	930.75
2006/2007	0.30	520.08
Oct-Dec07	0.50	489.80
Oct 2007-Jan 2008	0.57	881.53

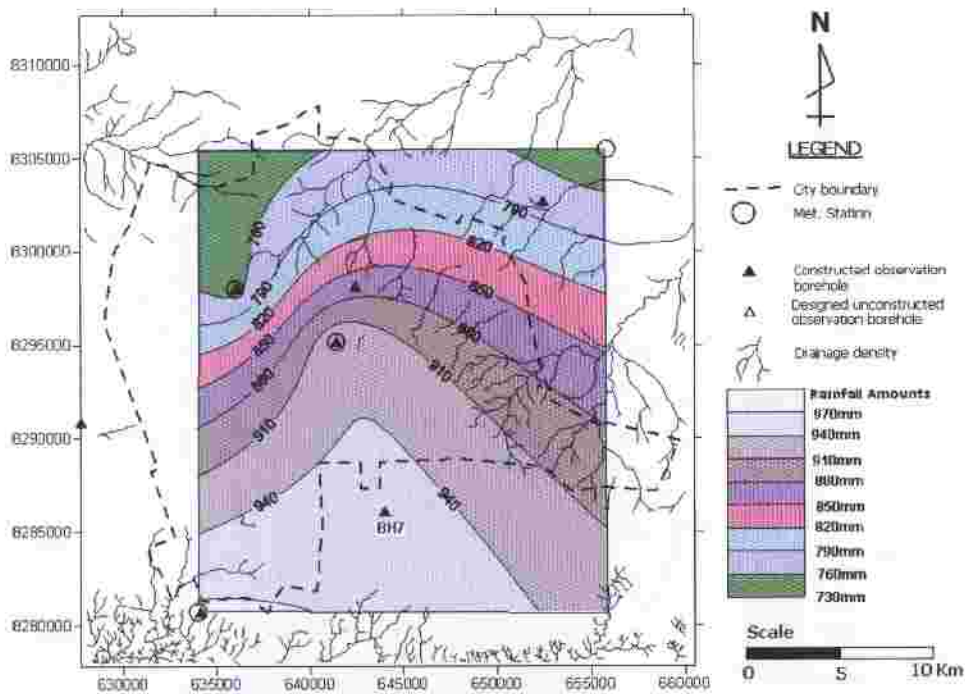


Figure 4.34 Rainfall distribution on Lusaka Plateau: 2003/2004 rainy season

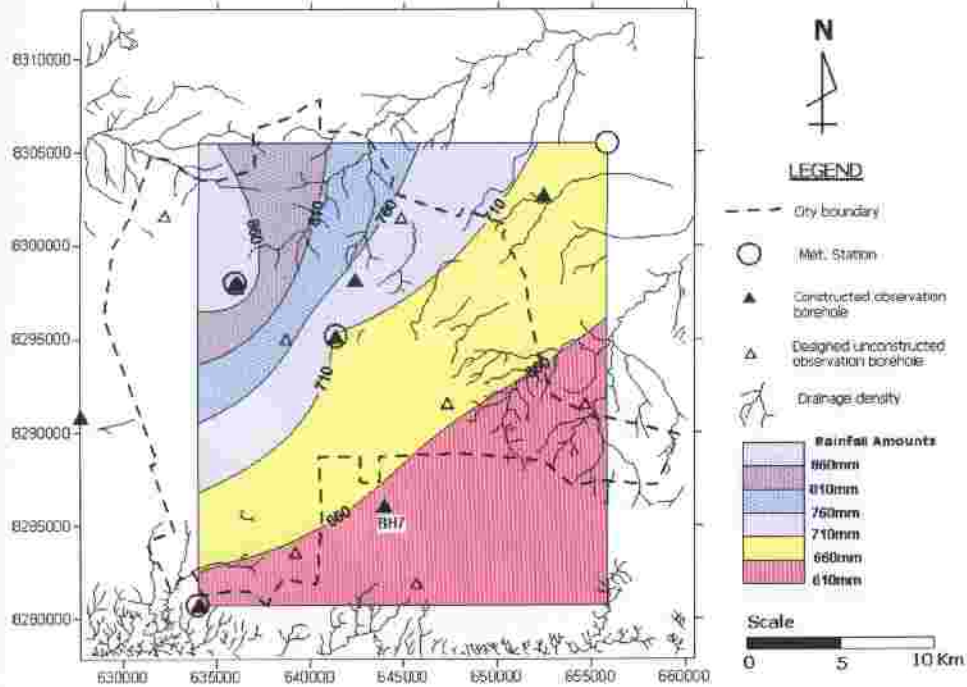


Figure 4.35 Rainfall distribution on Lusaka Plateau: 2004/2005 rainy season

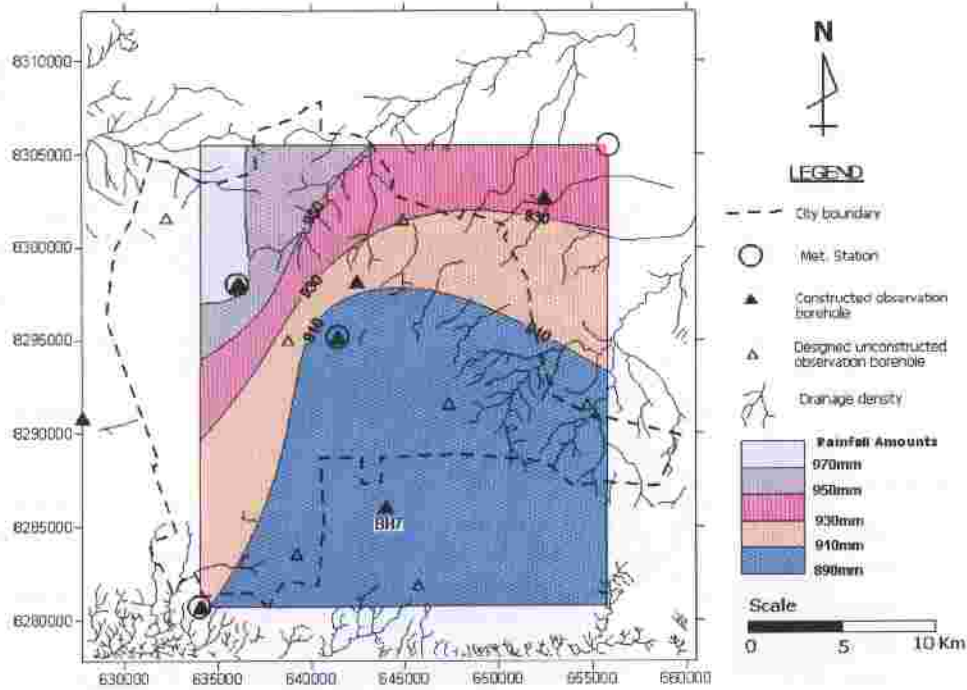


Figure 4.36 Rainfall distribution on Lusaka Plateau: 2005/2006 rainy season

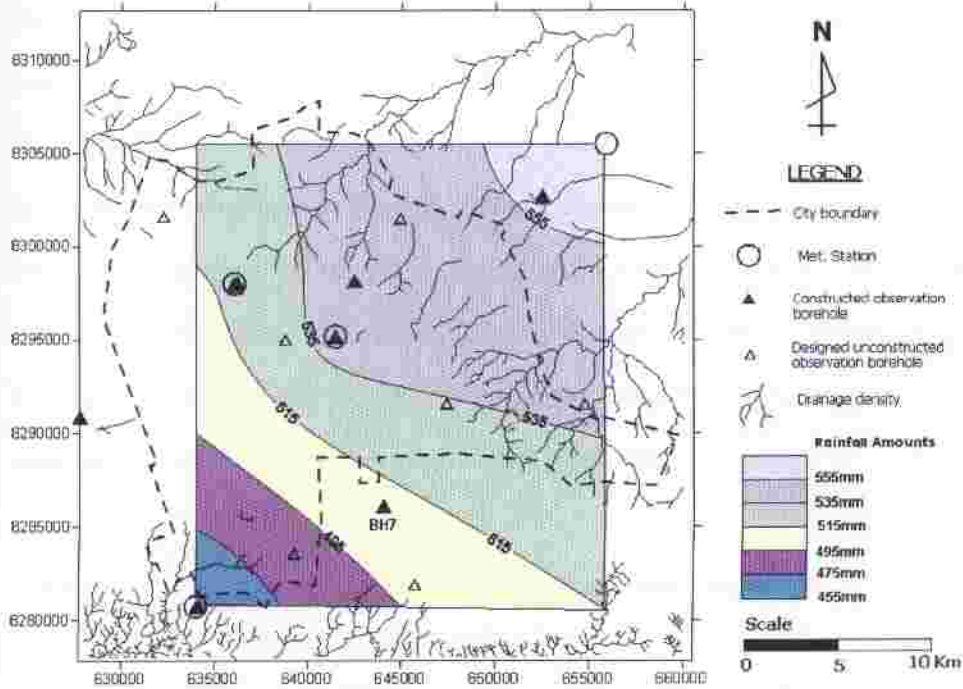


Figure 4.37 Rainfall distribution on Lusaka Plateau: 2006/2007 rainy season

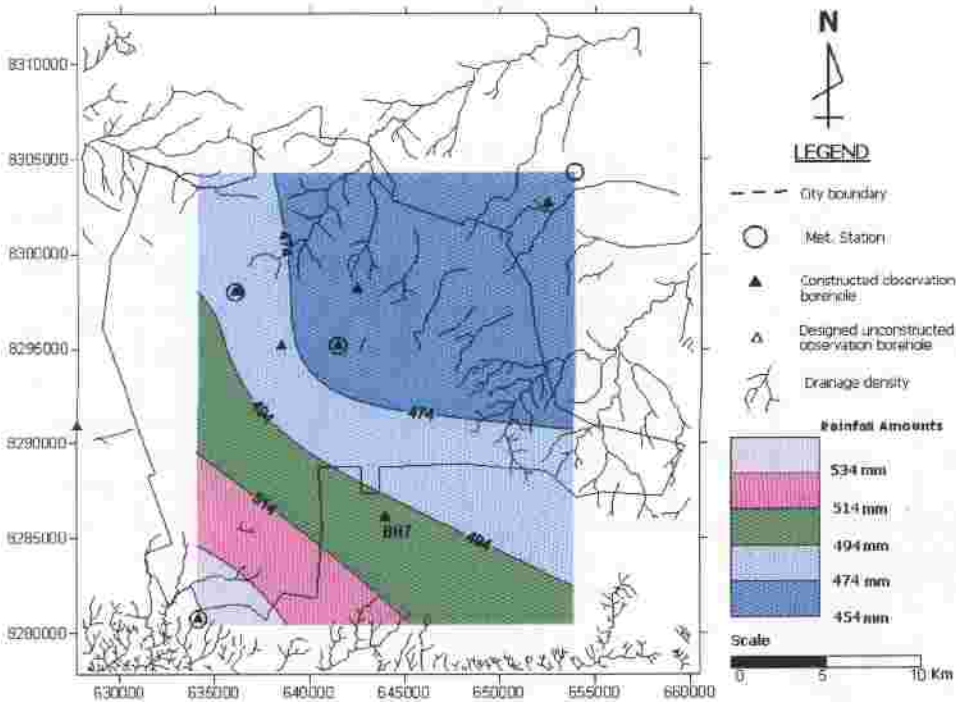


Figure 4.38 Rainfall distribution on Lusaka Plateau: October to December 2007

Table 4.22 indicates rainy days-rainfall period ratio of more than 0.4 for 2007/2008 rainy season (October 2007 to January 2008) at all the meteorological stations than from 2003/2004 to 2005/2006 rainy seasons. This explains the rapid groundwater level recovery observed in aquifers and subsequent flooding that occurred in 2007/2008 rainy season by December 2007 (Figure 4.39), which was not the case for 2003/2004 to 2005/2006 rainy seasons with higher rainfall amounts. Draining of the flooded areas in Kamwala and Msisi by pumping was not effective because water came out from the ground in form of springs (Figure 4.40).

Table 4.23: Rainfall – Rainy days relationship for Lusaka Plateau

Hydrological Year/ Period	Ratio of Rainfall Amounts to Rain days (mm/day)				Ratio of Rain Days to Rainfall Period			
	DWA	City		Int.	DWA	City		Int.
	Sheki	Airport	Mt. Makulu	Airport	Sheki	Airport	Mt. Makulu	Airport
2003	11.43	13.61	11.88	7.85	0.49	0.45	0.55	0.53
2004	12.69	16.46	13.92	10.62	0.39	0.38	0.47	0.46
2005	17.47	16.08	11.65	11.44	0.34	0.29	0.37	0.40
2006	16.02	13.28	11.39	13.31	0.41	0.45	0.53	0.47
2007	9.96	11.31	12.03	13.39	0.35	0.32	0.25	0.28
Oct – Dec 2007	14.88	12.81	16.76	11.35	0.46	0.51	0.46	0.56
Oct 2007- Jan 2008	15.25	14.52	17.02	13.87	0.51	0.59	0.53	0.67



Figure 4.39 Flooding in Kamwala area due to high groundwater table and subsequent accumulation of rain water on Lusaka Plateau: October to December 2007.



Figure 4.40 Draining of floods in Kamwala area on Lusaka Plateau by pumping and construction of emergency drains: December 2007 to February 2008.

4.2.2.4 Water Balance and Recharge Estimation

When evaluating groundwater recharge for Lusaka urban, it is inevitable to pay attention to the importation of water by LWSC, from Kafue River. Unaccounted-for-water from the LWSC water supply network is about 50% of the daily total production of about $210,000\text{m}^3$ (NWASCO, 2005; Mtine & Chikama, 2006-*personal communication*). Additionally, wastewater that finds its way into the sewerage network system is less than the expected figure due to leakages. Furthermore, a large number of residential areas use on site sanitation such as septic tanks and pit latrines. Peri – urban areas entirely depend on septic tanks and pit latrines to dispose of domestic wastewater generated on a daily basis. Moreover, adjacent areas are involved in irrigated agriculture during the dry season from May to October.

In view of the above, the following are the suggested principle sources of recharge or inflow into the aquifers on the Lusaka Plateau:

- Rainfall (October to April)
- Unaccounted for water from the water supply network (through out the year)
- Wastewater from leaky sewerage pipes (through out the year)
- Septic tanks and pit latrines (through out the year)
- Irrigation (May to October)

Similarly, drainage through streams and rivers, natural aquifer drainage and groundwater abstraction comprises the outflow from these aquifers. Outflows are listed as:

- Abstraction (through out the year)
- Drainage density as streams and springs (through out the year)
- Natural aquifer drainage as local and regional out flow (through out the year)
- Evapotranspiration (through out the year)

The water balance can therefore be expressed as:

Inflows – Outflows = Change in groundwater storage

$$A - B = \Delta S$$

Equation 4 – 3

Quantification of individual components is only possible when detailed information is available. However, it is important to mention that it is possible to measure and

quantify most of the listed components with the exception of natural aquifer drainage whose quantification largely depend on the measurement of other components. Therefore, the water balance in the study area comprises of inflows from sources such as rainfall, septic tanks, pit-latrines, irrigation water and unaccounted for water from the water supply network of LWSC. On the other hand, outflows constitute abstraction, natural aquifer drainage, Evapotranspiration, stream and spring flows.

The effect of abstraction, natural aquifer discharge and drainage (Table 4.24) were based on groundwater level fluctuations (Appendix C2) for BH1 and BH2. Table 4.24 indicates that effects of abstraction are increasing yearly at both BH1 and BH2 compared to recharge. However, the outflow and inflow for Lusaka Plateau aquifers (Table 4.25 and 4.26) were estimated using equation 4 – 2 based on the 2007 to 2008 groundwater level fluctuations in table 4.19 (Section 4.3.1.1).

Table 4.24: Data on the effect of abstraction and natural groundwater aquifer outflow; and recharge at BH1 and BH2 on Lusaka Plateau

Year	Abstraction and natural aquifer outflows (m)		Recharge (m)	
	BH1	BH2	BH1	BH2
2004	1.08	1.09		
2005	1.34	1.70	1.10	1.37
2006	1.54	1.39	1.34	1.30
2007	1.70	1.76	1.54	1.6
2008			1.70	1.84
Average	1.42	1.49	1.42	1.53

Table 4.25: Estimation of inflows for Lusaka Plateau using groundwater level measurements: February 2007 to February 2008

Recharge from rainfall (mm)		Unaccounted for Water (10 ⁶ m ³)		Leaky Sewers (10 ⁶ m ³)	Septic tanks & Pit latrines (10 ⁶ m ³)	Irrigation (10 ⁶ m ³)	TOTAL INFLOW FROM RAINFALL (10 ⁶ m ³)	TOTAL INFLOW FROM OTHER SOURCES (10 ⁶ m ³)
		Schist	Carbonate					
Formula								
$S_y \Delta S$	80	350	50% of the minimum yearly water production of 76.65 by LWSC	5% of the minimum yearly accounted for water production of 38.33 by LWSC	10% of the minimum yearly accounted for water production of 38.33 by LWSC	Taken as zero due to rain fed agriculture practiced during the rainy season.	207.78	44.08
Q_a	13	38						
ΔQ_i	0	0						
R_r	93	388						

Table 4.26: Estimation of outflows for Lusaka Plateau using groundwater level measurements: February 2007 to February 2008

Abstraction, natural aquifer discharge & Evapotranspiration (mm)		TOTAL OUTFLOW (10 ⁶ m ³)	
		Schist	Carbonate
Formula			
$S_y \Delta S$	40	150	81.34
Q_a	0	0	
ΔQ_i	0	0	
R_r	40	150	

(Most of the measurements at observation boreholes (BH1 to BH7) started in May 2007, two months after the rainy season. Hence the figure is slightly lower than expected.)

According to equation 4 – 3, the water balance for the period February 2007 to February 2008 gives a figure of $126 \times 10^6 \text{m}^3$ as the change in groundwater storage. This is the amount of water that was responsible for the aquifer recovery during this period. The recharge generated from the average rainfall amount (900mm) received by February 2008 was about 10% on the schist and 43% on the carbonates. The 26.5 % average recharge that occurred is in agreement with other estimated recharge figures possible for Lusaka Plateau aquifers (Von Hoyer et al., 1978; Maseka, 1994; Nkhuwa, 1996; Maseka and Nyambe, 1999). Estimation of the long term groundwater recharge for Lusaka Plateau requires groundwater level data of not less than five years, so that the effects of drought years are captured. Although an annual drop in the water table is observed, groundwater level fluctuations in response to rainfall from 2003/2004 to 2007/2008 rainy seasons, suggest that investigated recharge values from 8% to 60% in earlier studies (Von Hoyer, *et al.*; 1978, Maseka, 1994; JICA, 1995; Nkhuwa, 1996; Maseka and Nyambe, 1999) are in agreement. The difference in the values lies in the assessment method employed and the area where the assessment was focused. Forests 26 and 55 contributed about 18% of the recharge generated in 2007/2008 rainy season.

Tables 4.25 and 4.26 indicates that recharge from rainfall is adequate to dilute the current inflows from sources of a polluting nature by more than 50%. It is adequate to also accommodate the outflows. The implication is that Lusaka Plateau has adequate renewable groundwater resources. However, over abstraction is still a concern in some parts of the Lusaka urban aquifers because of the high concentration of production boreholes. On the other hand, studies carried out during consecutive drought years have suggested lower recharge values, whereas those carried out during

the years with normal rainy seasons have suggested higher recharge values. Firstly, recharge occurs over the entire Lusaka Plateau, but also varies widely from place to place. Secondly, a higher recharge potential has been observed in Lusaka South Forest Reserve and lower values in the surrounding areas (Section 4.2.2.2). Hence, Forests 26 and 55 should be declared as the groundwater protection zone for Lusaka Plateau to ensure replenishment of groundwater of better quality for now and the future. Protection of groundwater resources is equally important as the protection of surface water resources (Pietersen, 2004). Therefore, protection and management of groundwater in Lusaka urban and adjacent areas may entail restriction of human activities in the main recharge area (Forest 26 and 55) to preserve the quality of groundwater (Nkhuwa, 1999; Nyambe and Maseka, 2000; De Waele et al., 2004) and the quantity of water entering as recharge. This allows annual flushing out of the aquifer to continue thereby reducing the risk of increased pollution load within Lusaka urban.

4.2.2.5 Hypothesis on Regional Groundwater flow in the Katanga Supergroup

Lusaka Plateau occupies an area of 741km². Evidence of lowering of the water table in the Lusaka urban aquifers due to abstraction has been noticeable in the past 20 years since 1978 (Von Hoyer *et al.*, 1978; Nkhuwa, 1996, Maseka and Nyambe, 1999). However, the rate at which the water table is lowered is periodically counteracted such that even the high recharge on Lusaka Plateau can not account for the recovery of the water table almost to the ground surface, every rainy season. This scenario may be due to high recharge on the Lusaka Plateau or may have the influence of regional groundwater flow regimes.

The average elevation difference between the highest point on Lusaka Plateau in the Lusaka South Forest Reserve where most of the local recharge occurs (Von Hoyer *et al.*, 1978; Maseka, 1994, Nkhuwa, 1996, Maseka and Nyambe, 2000) and the lower parts of the Lusaka Plateau within the study area is about 60m (Section 4.2.1.1). This implies that at a local level, Lusaka Plateau has its own distinct recharge from the immediate surrounding areas. However, Zambia slopes from the north to the south on a regional scale. Hence, to explain the continuous periodical groundwater level recovery, the hypothesis was proposed that groundwater on the Lusaka Plateau may partly be influenced by regional recharge that occurs in the Copperbelt area and beyond (Figure 4.41).

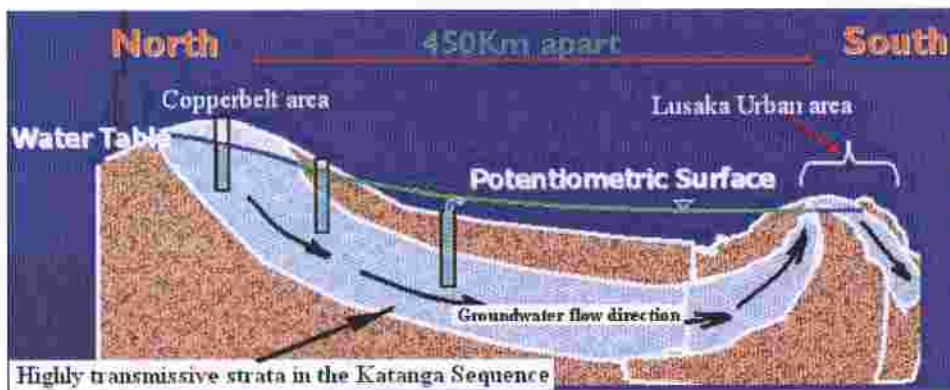


Figure 4.41 Proposed hypothesis on regional groundwater flow that sustain groundwater levels and periodical water table recovery on Lusaka Plateau (section not to scale)

Based on the detailed description of geology and hydrogeology together with the tectonic events for Zambia (Dixey, 1945; Hitchon, 1958; Drysdall and Smith, 1960; Moore, 1964; Matheson and Newman, 1966; Garrard, 1968; Simpson *et al.*, 1963) the following assumptions are advanced to support the hypothesis:

- the Katanga Supergroup transmits groundwater recharged on the Copperbelt area and from beyond through the Lower Katanga Dolomite under confined situation from the northern to the southern parts of the country past Lusaka Plateau (Figure 4.42).
- the Upper Roan Dolomite and its equivalent Lusaka Dolomite are regionally connected and responsible for transmission of groundwater that partly sustains groundwater levels in the Lusaka urban aquifers on the Lusaka Plateau.
- a number of springs on the Lusaka Plateau continuously discharge groundwater through out the year to streams such as the Mutendere, Chunga and the Chalimbana as an indication of a high recharge or large recharge area.
- Davis shaft meant for de-watering the Zinc and Lead mine in Kabwe penetrates the carbonates in the Katanga Supergroup to a depth of about 488m and behaves as an artesian well as deduced from the reported water levels when mining changed from open cast to underground (Jones, 1972). Upon closure of the mines in the 1990s, water levels have attained their natural state after the de-watering activities stopped. Water levels currently fluctuate between a few centimetres in the rainy season below ground surface to about 3m in the dry season. It is inferred that the elevation of the water level supports the assumption that the regional piezometric surface from the Copperbelt and beyond through the Kabwe area lies at an elevation that would partly sustain water levels on Lusaka Plateau.

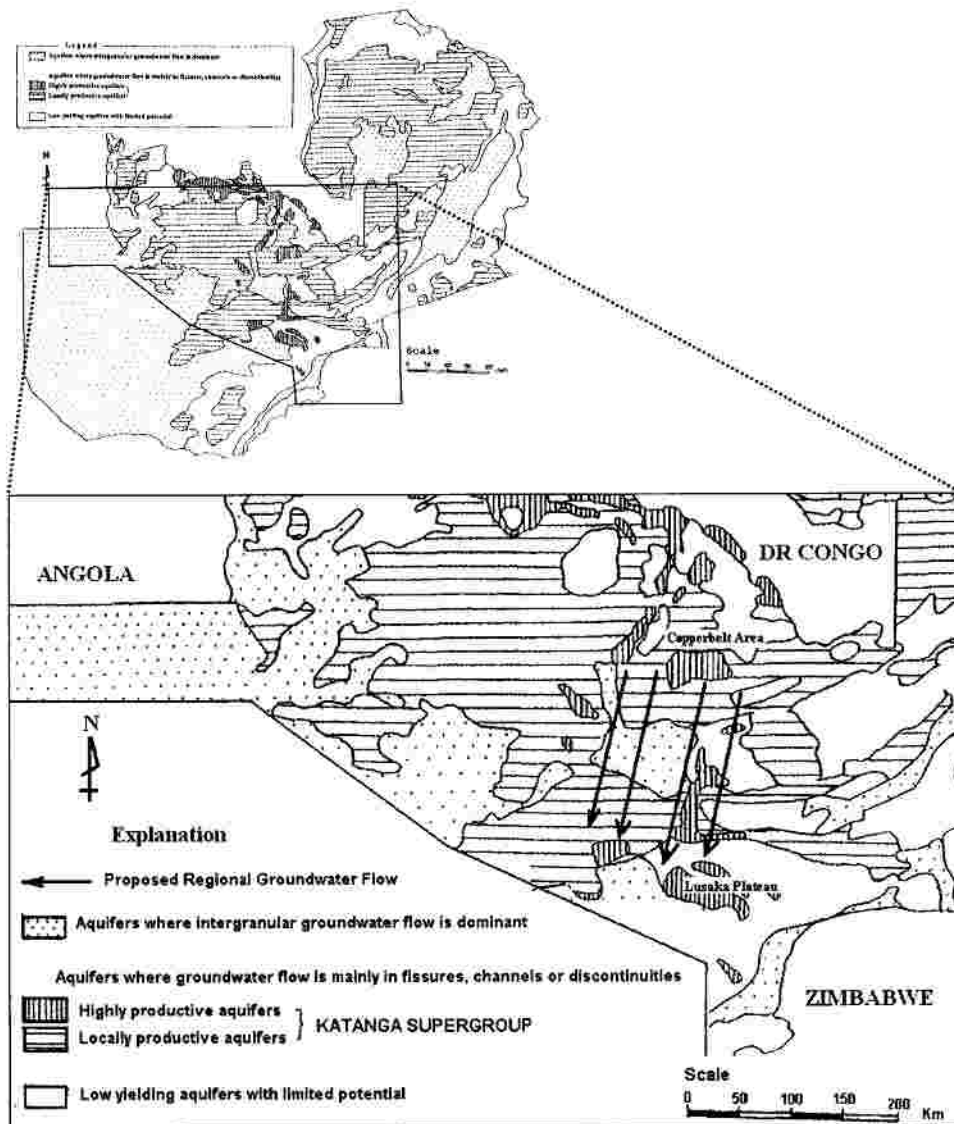


Figure 4.42 Proposed regional groundwater flow direction in the Katanga Supergroup (modified after JICA Report, 1995)

The groundwater flow direction considered in the hypothesis and shown in Figures 4.41 and 4.42 are in agreement with the general groundwater flow direction on the hydrogeological map for Zambia as established in 1977/78 (Chenov, 1978).

4.2.3 Groundwater Quality Data Collection

Evaluation of groundwater quality is an important aspect of groundwater resources assessment. Therefore, groundwater quality data generated during the study at 48 production boreholes (Figure 4.43) on the Lusaka Plateau (Tables 4.27 and 4.28) were interpreted using the Piper diagram, ionic ratios, and water quality standards for drinking water and for irrigation. This was to highlight groundwater quality parameters that exceeded maximum permissible limits for domestic, industrial and agricultural uses, as well as to evaluate suitability of groundwater for various uses.

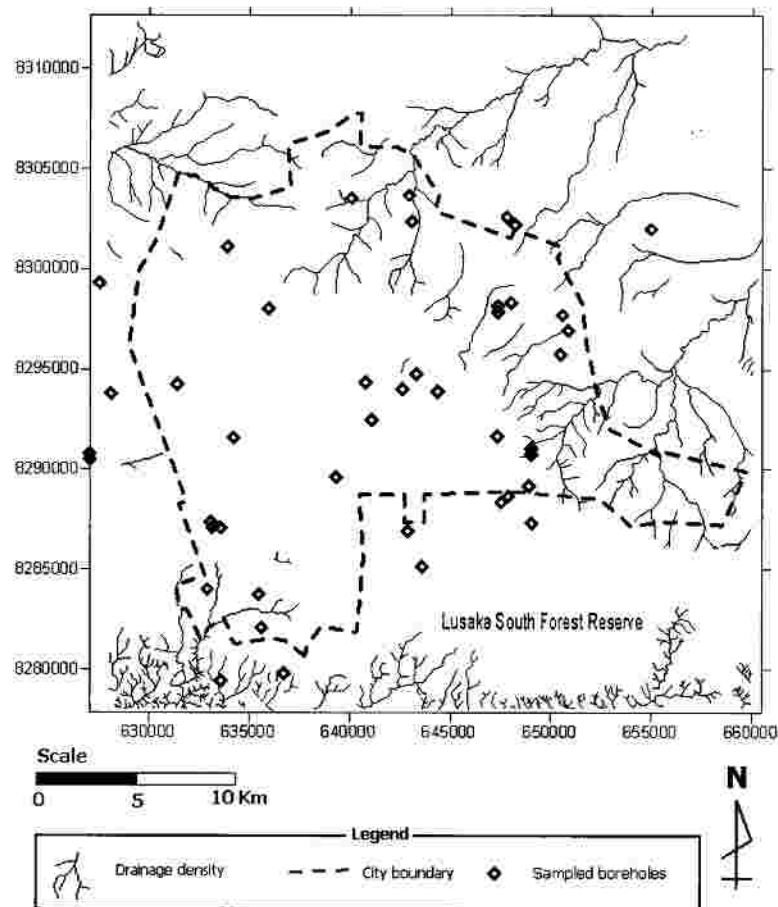


Figure 4.43 Map showing distribution of boreholes sampled for groundwater quality analysis on Lusaka Plateau

Table 4.27: Groundwater quality data for boreholes drilled in Lusaka urban and adjacent areas by the Department of Water Affairs

No.	GPS Coordinates		F	Date Analysed	mg/L										
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ ⁻ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
1	641075	8292462		Oct-03	47.7	65.8	28.8	42.2	2.86	0.53	22.1	0.66	80	86	198
2	647318	8291658		Sep-04	6.82	62.12	76.8	24.5	<0.01	<0.01	5.16	0.18	9	5.4	300
3	636725	8279793		Oct-04	13.5	696.7	20	70.6	0.1	<0.01	2.8	0.08	42	101	452
4	648205	8302194		Oct-04	9.3	Nd	12.8	71	<0.01	<0.01	6.5	Nd	40	11.5	390
5	633145	8287116		Oct-04	6.13	125.4	18.4	52.8	<0.01	<0.01	5.9	0.19	12	35.9	420
6	650453	8295734		Oct-04	5.9	Nd	28.8	2.88	0.26	<0.01	4.9	Nd	27	2.4	130
7	627008	8280783		Oct-04	2.8	66	28	26.4	0.25	<0.01	3.3	0.24	8	<0.01	280
8	650561	8297694		Oct-04	6.4	70.3	58.4	10.6	0.01	<0.01	9.11	0.05	11	26.9	320
9	642619	8294008		Oct-04	1.19	3.26	14.4	30.7	0.31	<0.01	1.0	0.03	7	6.4	326
10	654973	8301976		Sep-04	10.5	190.4	60.8	37.4	0.24	<0.01	12.5	0.11	15	18.2	320
11	648899	8289183		Oct-03	3.4	39.1	64	7.64	2.37	0.1	1.69	0.18	11	11.5	180
12	649024	8287335		Oct-03	8.2	38.4	40	64.3	0.11	<0.01	2.21	0.11	11	20.8	360
13	658647	8306395		Jul-04	23.5	82.9	35.2	88	0.17	<0.01	<0.01	0.15	12	<0.01	136
14	649013	8291038		Jul-04	16	71.2	16.8	17.5	<0.01	<0.01	10.2	0.22	24	<0.01	290
15	643605	8285153		May-04	4.1	11.7	120	7.58	2.87	0.01	16.2	0.24	13	0.7	390
16	635470	8283761		Apr-04	15.4	41.5	60.8	25	3.55	0.02	1.5	0.4	9	4.5	222
17	641970	8312150		Aug-04	10.3	162.1	92	24.5	0.05	0.01	1.9	0.27	78	7	346
18	640758	8294342		Mar-04	17.7	46.2	32	43.20	0.52	0.06	8.5	0.04	30	8.3	120
19	643303	8294775		Mar-04	6.4	63.6	32	81.60	0.21	<0.01	6.7	0.04	35	11.7	384
20	650837	8296927		Feb-04	5.4	23.4	99.2	21.12	<0.01	<0.01	<0.01	0.29	10	21.9	268
21	649004	8290747		Jan-05	5.8	45.2	106	9.60	0.2	<0.01	5.9	0.13	22	3.6	164
22	672940	8313042		Jan-05	35.8	21.9	52.8	15.36	0.16	<0.01	0.1	0.17	2	2.8	172
23	627498	8299299		Dec-04	0.2	12.4	16	7.68	0.27	0.01	3.5	0.12	16	16.9	116
24	632894	8284029		Oct-04	4.5	13.31	14.4	63.40	0.31	0.02	0.3	0.09	11	41.8	284
25	635945	8298009		Jul-03	9.6	43.1	72	79.70	6.58	0.3	0.8	0.26	4	9.6	236
26	628074	8283782		Sep-03	2.4	56	32	34.96	<0.01	<0.01	4.2	0.11	60	18.3	210
27	633270	8287207		Sep-03	37.0	25.8	40	28.80	0.78	<0.01	6.9	0.23	10	5.4	180
28	635963	8311949		Nov-04	8.5	90.8	20	9.60	0.01	<0.01	7.8	0.04	15	52.9	278
29	648013	8296307		Jul-03	4.3	16.8	73.6	29.76	0.19	0.6	4.3	0.78	5	11.3	230
30	633582	8279437		Oct-04	11.5	23.2	31.2	26.90	0.3	0.02	16.8	0.03	16	6.1	306
31	639311	8289615		Mar-04	2.1	35.7	88	3.84	<0.01	<0.01	7.4	0.17	9	<0.01	198

F = Aquifer Lithology / Formation (B-G = Basement Complex - Granite), (B-Q = Basement Complex - Quartzite), (S = Sandstone), (M = Mudstone); Groundwater quality results with values showing as nd = not done. NO₃-N = Nitrate as Nitrogen with maximum permissible limit of 10mg/L. NB all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

Table 4.28: Groundwater quality data for boreholes drilled in Lusaka urban and adjacent areas by the Department of Water Affairs

No.	GPS Coordinates		F	Date Analysed	mg/L										
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ ⁻ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
32	631379	8294244		Apr-05	7.3	21	32	12.80	2.64	0.06	7.0	0.08	4	16.1	290
33	647850	8286649		Apr-05	0.29	3.70	48.00	1.92	<0.01	<0.01	2.90	0.10	8	2.90	320.00
34	644359	8293890		Jun-05	33.1	5.3	42.4	77.8	1.85	0.51	3.02	0.18	34	9.9	220
35	647804	8302562		May-05	21.6	14.3	86.4	37	3	0.04	2.25	0.15	23	42.4	392
36	642944	8303656		Dec-05	4.61	17.9	72	13	0.43	0.02	6.62	0.13	47	33.3	374
37	640065	8303514		Dec-05	9.18	123	15.2	13.4	<0.01	<0.01	3.88	0.08	46	39.2	112
38	642897	8286916		May-05	13.1	6.8	38.8	14.4	0.43	0.02	<0.01	0.43	44	5	138
39	647957	8297851		May-05	3.55	45.2	33.6	38.9	<0.01	<0.01	0.85	0.16	21	9.2	124
40				Oct-03	7.8	38.3	35.2	58.6	0.03	1.4	3.61	0.28	10	33.9	352
41	647529	8286381		Sep-04	6.82	62.12	76.8	24.5	<0.01	<0.01	5.16	0.18	9.0	5.4	300
42	627009	8290494		Oct-04	4.5	13.31	14.4	63.40	0.31	0.02	0.3	0.09	11.0	41.8	284
43	633062	8287384		Mar-04	2.1	35.7	88	3.84	<0.01	<0.01	7.4	0.17	9.0	<0.01	198
44				Apr-04	16.8	41.8	17.6	35.5	2.22	0.02	15.7	0.37	8.0	9.8	80
45				Oct-03	27.2	38.2	60.8	1.92	2.32	<0.01	1.74	0.53	11.0	12.8	160
46				Feb-04	20.4	46.8	75.2	55.7	0.11	<0.01	<0.01	0.27	6.0	<0.01	458
47				Jan-04	<0.03	38.5	81.6	23.04	0.09	0.01	9.4	0.37	5.0	9	360
48				Jan-04	6.7	31.3	38.4	71.04	0.17	<0.01	5.7	0.12	23.0	23	436

F = Aquifer Lithology / Formation [(B-G = Basement Complex - Granite), (B-Q = Basement Complex - Quartzite), (S = Sandstone), (M = Mudstone)]. Groundwater quality results with values showing as nd = not done, **NO₃⁻** = Nitrate as Nitrogen with maximum permissible limit of 10mg/L, **MB** all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

4.2.3.1 Groundwater Type and Hydrogeochemical Characterisation

Characterisation of the ionic ratios calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-) using Stiffs method (Table 4.29, Appendix D1 and Figure 4.44) indicates that groundwater in Lusaka urban and adjacent areas is predominantly Calcium Bicarbonate (CaHCO_3), Magnesium Bicarbonate (MgHCO_3) and Sodium Bicarbonate (NaHCO_3) water types.

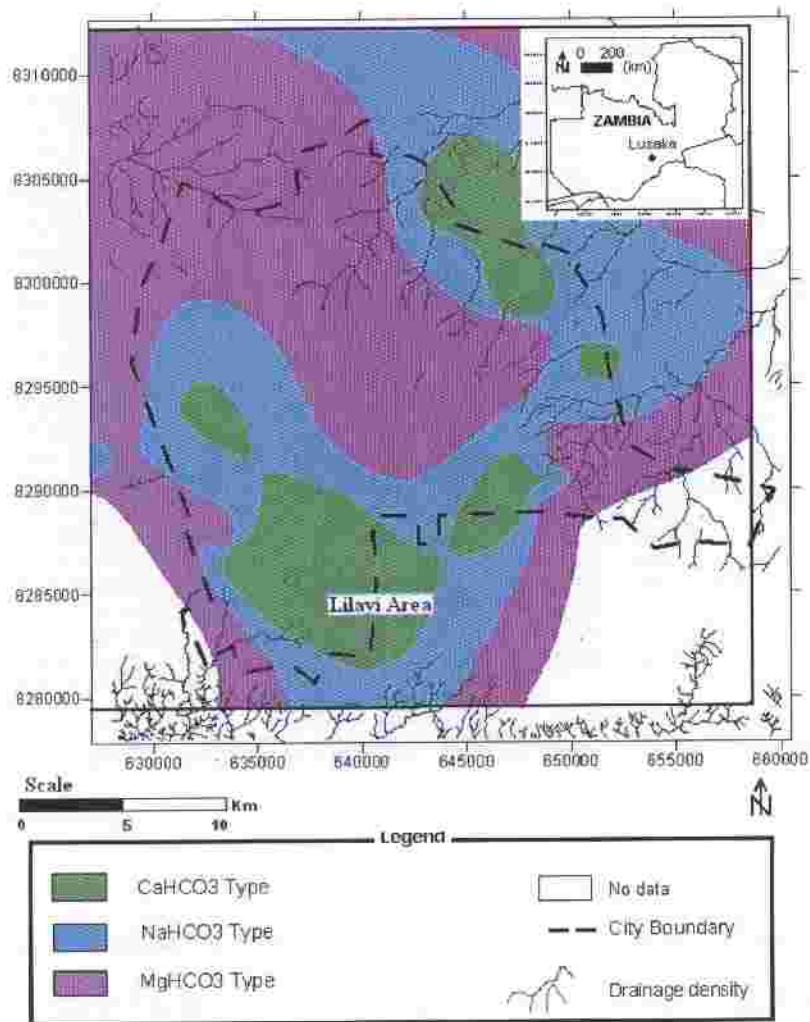


Figure 4.44 Map showing groundwater types in Lusaka urban and adjacent areas

Table 4.29: Boreholes used to show distribution of groundwater type based on classification by Stiffs method

ID	Location	X	Y	Aquifer Lithology	Water Type	Water Type code
1	Hon. Kaplijimpanga	641075	8292462	Schist	MgHCO ₃	5
2	Mr. B. Nkole	636725	8279793	Schist	NaHCO ₃	10
3	Col Ng'ambi	658647	8306395	Schist	MgHCO ₃	5
4	Danish Embassy	641970	8312150	Schist	NaHCO ₃	10
5	Mr. Mwanamwale	632894	8284029	Schist	MgHCO ₃	5
6	Chief Justice Sakala	648013	8298307	Schist	CaHCO ₃	15
7	Mr. Mbula (Kabulonga)	644359	8293890	Schist	MgHCO ₃	5
8	Mr. Mwase Phiri (NRDC)	647804	8302562	Schist	CaHCO ₃	15
9	Ulimi Branch (Ngombe)	642944	8303656	Schist	CaHCO ₃	15
10	Fumbelo Com. Sch. Chazanga	640065	8303514	Schist	MgHCO ₃	5
11	ISST (NRDC)	647357	8297851	Schist	MgHCO ₃	5
12	In Service Training Trust	647356	8298139	Schist	CaHCO ₃	15
13	Co-op. College	647318	8291658	Limestone	CaHCO ₃	15
14	Mr. Musonda	633145	8287116	Limestone	NaHCO ₃	10
15	Mr. Kachinda	627008	8290783	Limestone	NaHCO ₃	10
16	Gen. Tembo	650561	8297694	Limestone	NaHCO ₃	10
17	Mr. Chisanga	654973	8301976	Quartzite	NaHCO ₃	10
18	Dr Kasonde	648899	8289183	Limestone	MgHCO ₃	5
19	Gen Musengule BH 2	649024	8287335	Limestone	MgHCO ₃	5
20	Hon. Maka	649013	8291038	Limestone	NaHCO ₃	10
21	Simoonga	643605	8285153	Dolomite	CaHCO ₃	15
22	Hibajene	635470	8283761	Dolomite	CaHCO ₃	15
23	Muma	647529	8288381	Limestone	CaHCO ₃	15
24	Nalishiwa (Chilanga)	635603	8282098	Limestone	NaHCO ₃	10
25	Mr. P. Mwanfuli (Makeni)	633561	8287083	Limestone	CaHCO ₃	15
26	Mr. Kalichiri (LSK West)	627009	8290494	Limestone	MgHCO ₃	5
27	Mr. Kawatu	633062	8287384	Limestone	CaHCO ₃	10
28	A.E at chancery	640758	8294342	Schist	MgHCO ₃	5
29	A.E Roan Road	643303	8294775	Schist	MgHCO ₃	5
30	Love Mutesa	650837	8296927	Limestone	CaHCO ₃	15
31	Mataka	649004	8290747	Limestone	CaHCO ₃	15
32	Hon. Nawakwi	628074	8293782	Limestone	MgHCO ₃	5
33	Dr. Nsemukila	633270	8287207	Limestone	MgHCO ₃	5
34	Mr. B Luswanga	635963	8311949		NaHCO ₃	10
35	Mweemba	633582	8279437	Dolomite	MgHCO ₃	5
36	Jesus Living Church	639311	8289615	Limestone	CaHCO ₃	15
37	N.H. Mpamba	631379	8294244	Limestone	CaHCO ₃	15
38	Hon. George Kunda	647850	8288649	Dolomite	CaHCO ₃	15
39	Mrs. Chipili (Chilenje_South)	642897	8286916	Limestone	CaHCO ₃	15
40	Sable Company (Makeni)	634198	8291588	Limestone	CaHCO ₃	15

According to Stiffs' analysis, groundwater contains three main Hydrogeochemical facies as follows:

- 1) Mixed (cationic) magnesium dominated bicarbonate types: MgHCO₃, Mg-Ca-HCO₃, Mg-Ca-Na-HCO₃, Mg-Na-Ca-HCO₃ and Mg-Na-HCO₃-Cl.

- 2) Mixed (cationic) calcium dominated bicarbonate types: CaHCO_3 , Ca-Mg-HCO_3 , Ca-Mg-Na-HCO_3 , $\text{Ca-Mg-HCO}_3\text{-Cl}$ and Ca-Na-HCO_3 .
- 3) Mixed (cationic) sodium dominated bicarbonate types: NaHCO_3 and Na-Mg-HCO_3 .

The Piper diagram (Figure 4.45) generated with AquaChem indicates calcium magnesium bicarbonate as the main groundwater type. According to Maseka (1994), calcium magnesium bicarbonate water type is from the dolomites and marble.

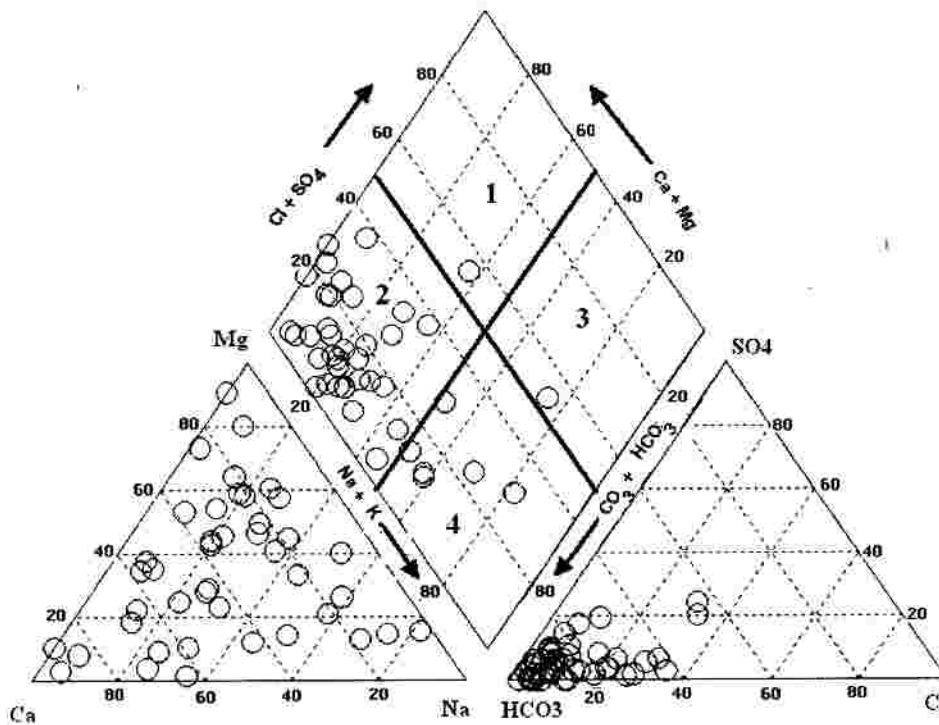


Figure 4.45 Chemical facies of groundwater in Lusaka urban and adjacent areas. ¹calcium magnesium sulphate chloride; ²calcium magnesium bicarbonate; ³sodium sulphate chloride; ⁴sodium bicarbonate

Both the piper diagram and the stiffs analysis show that bicarbonate is the predominant anion, although the chemical composition is highly variable. However,

aquifers in Lusaka urban and adjacent areas contain fresh groundwater resources which according to the groundwater chemistry falls in three main groundwater types with magnesium, calcium and sodium being the predominant cations that have mixed cationic – bicarbonate water types. The most prevalent type is mixed cationic magnesium bicarbonate and mixed cationic calcium bicarbonate types.

Groundwater seems to be highly mixing and characteristics of the groundwater types that are typical of the geological and hydrological conditions obtaining on the Lusaka Plateau. Both the schist and carbonate aquifers have elevated bicarbonate as the predominant anion, indicative of the recharge areas (Freeze and Cherry, 1979). This situation also appears to be favoured by the great depth of the fractures and karstic system in the carbonates, which allows the rise of groundwater enriched with CO₂ resulting in dissolution and increased bicarbonate (Maseka, 1994; Nkhuwa, 1996). The schist seems to receive much of its groundwater from the carbonates that receives high groundwater recharge. Elevated chloride and nitrate values (Figure 4.46) are attributed to anthropogenic pollution with the main sources likely to be septic tanks and pit-latrines.

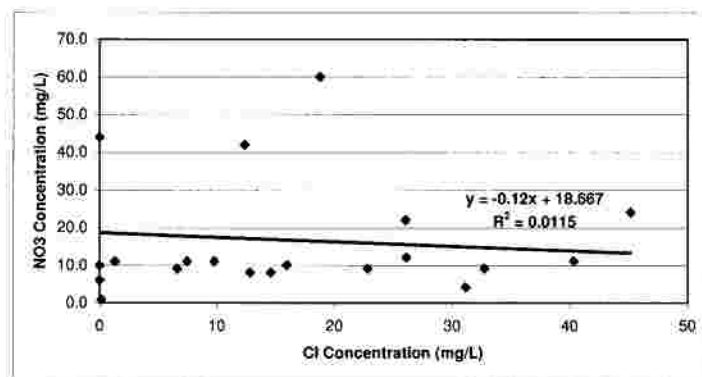


Figure 4.46 Correlation of nitrate and chloride concentration in boreholes on Lusaka Plateau

However, nitrate levels exceeding safe concentration limits for boreholes located within built up areas that depend on septic tanks and pit-latrines are much lower than expected. According to NWASCO (2005a, b), on-site sanitation is the most common form of excreta disposal in low cost and peri-urban areas, whereas planned residential areas use both on-site sanitation and convention system. Therefore, it is suggested that low concentrations of nitrate may be attributed to three factors, namely; reducing conditions due to the presence of pyrites (Wisotzky, 1994; Kraft *et al.*, 2004) as shown in the equation 4 – 4, high dilution effects due to direct recharge in large volume and groundwater of better quality that is recharged in Lusaka South Forest Reserve (Forests 26 and 55) leads to dilution and flushing out of the aquifer system. This implies that some level of natural purification occurs through groundwater dilution and flushing out of the pollutants as well as reduction of nitrates by pyrites thereby reducing the nitrate pollution problem in the aquifer and general increase in pollution load over time.



4.2.3.2 Groundwater Quality Evaluation for Domestic and Irrigation use

Groundwater quality results from the Hydrogeochemical point of view indicate that water from aquifers in Lusaka urban and adjacent areas are generally suitable for domestic uses. However, water quality Constraints are associated with iron (20%), manganese (10%) and nitrate (12.5%) at 48 of the boreholes sampled. Chloride toxicity and Sodium Adsorption Ratio (SAR) values for most of the boreholes are within the recommended range of values when compared to boreholes with magnesium hazard values in the “harmful” class above the recommended value for

long term irrigation (Table 4.31 and 4.32). However, combined evaluation of the three parameters shows that groundwater in Lusaka urban and adjacent areas is excellent for long term irrigation.

Table 4.31: Combined SAR, MH and Cl Toxicity results for boreholes located in aquifers in Lusaka urban and adjacent areas

ID.	X	Y	Cl Toxicity (meq/l)	SAR	MH %	ID.	X	Y	Cl Toxicity (meq/l)	SAR	MH %
1	641075	8292462	2.26	1.82	70.71	21	643303	8294775	0.99	1.36	80.76
2	647318	8291658	0.25	1.58	34.43	22	650837	8296927	0.28	0.56	25.95
3	636725	8279793	1.18	16.41	85.32	23	649004	8290747	0.62	1.13	13.02
4	633145	8287116	0.34	3.36	82.53	24	632894	8284029	0.31	0.34	87.87
5	627008	8290783	0.23	2.15	60.82	25	628074	8293782	1.69	1.63	64.26
6	650561	8297694	0.31	2.22	23.00	26	633270	8287207	0.28	0.76	54.24
7	654973	8301976	0.42	4.73	50.31	27	635963	8311949	0.42	4.17	44.14
8	648899	8289183	0.31	1.23	16.42	28	648013	8298307	0.14	0.42	39.96
9	649024	8287335	0.31	0.87	72.57	29	633582	8279437	0.45	0.73	58.66
10	658647	8308395	0.34	1.70	80.45	30	639311	8289615	0.25	1.01	6.70
11	649013	8291038	0.68	2.90	63.16	31	631379	8294244	0.11	0.79	39.70
12	643605	8285153	0.37	0.28	9.53	32	647850	8288649	0.23	0.14	6.18
13	635470	8283761	0.25	1.13	40.33	33	644359	8293890	0.96	0.11	75.13
14	641970	8312150	2.20	3.88	30.46	34	647804	8302562	0.65	0.32	41.32
15	647529	8288381	0.25	1.58	34.43	35	642944	8303656	1.33	0.51	22.66
16	635603	8282098	1.18	16.41	85.32	36	640065	8303514	1.30	5.54	59.27
17	633561	8287083	0.25	1.13	40.33	37	642897	8286916	1.24	0.24	37.92
18	627009	8290494	0.31	0.34	87.87	38	647357	8297651	0.59	1.26	65.57
19	633062	8287384	0.25	1.01	6.70	39	647356	8298139	0.62	1.13	13.02
20	640758	8294342	0.85	1.25	68.97	40	634198	8291588	1.24	0.24	37.92
Maximum limit			4	10	50	Maximum limit			4	10	50

MH = Magnesium Hazard.

SAR = Sodium Adsorption Ratio

Table 4.32: Groundwater quality results showing boreholes with high Magnesium
Hazard values >50% and those with ≤ 50% values

ID	X	Y	Aquifer Lithology	MH %	ID	X	Y	Aquifer Lithology	MH %
1	641075	8292462	Schist	70.71	25	649013	8291038	Limestone	63.16
2	636725	8279793	Schist	85.32	26	643605	8285153	Dolomite	9.53
3	648205	8302194	Schist	90.13	27	635470	8283761	Dolomite	40.33
4	650453	8295734	Schist	14.13	28	647529	8288381	Limestone	34.43
5	658647	8306395	Schist	80.45	29	635603	8282098	Limestone	85.32
6	641970	8312150	Schist	30.46	30	633561	8287083	Limestone	40.33
7	632894	8284029	Schist	87.87	31	627009	8290494	Limestone	87.87
8			Schist	64.57	32	633062	8287384	Limestone	6.70
9	648013	8298307	Schist	39.96	34	640758	8294342		68.97
10	644359	8293890	Schist	75.13	35	643303	8294775		80.76
11	647804	8302562	Schist	41.32	36	650837	8296927	Limestone	25.95
12	642944	8303656	Schist	22.86	37	649004	8290747	Limestone	13.02
13	640065	8303514	Schist	59.27	38	628074	8293782	Limestone	64.26
14	647357	8297851	Schist	65.57	39	633270	8287207	Limestone	54.24
16	647356	8298139	Schist	13.02	40	635963	8311949		44.14
17	647318	8291658	Limestone	34.43	42	633582	8279437	Dolomite	58.66
18	633145	8287116	Limestone	82.53	43	639311	8289615	Limestone	6.70
19	627008	8290783	Limestone	60.82	44	631379	8294244	Limestone	39.70
20	650561	8297694	Limestone	23.00	45	647850	8288649	Dolomite	6.18
21	654973	8301976	Quartzite	50.31	46	642897	8286916	Limestone	37.92
22	648899	8289183	Limestone	16.42	47	634198	8291588	Limestone	37.92
24	649024	8287335	Limestone	72.57					

MH = Magnesium Hazard.

SAR = Sodium Adsorption Ratio

Spatial distribution of magnesium hazard values (Figure 4.47) shows that a large area occupied by carbonates has low magnesium hazard than those occupied by schist. Hence, magnesium hazard distribution seems to be associated with carbonate dissolution and that its presence in certain parts in schist is in agreement with the earlier suggestion that schist and carbonates are hydraulically connected (Section

4.2.2.1). In terms of agriculture, magnesium hazard sensitive crops should be restricted to areas that do not show such a hazard.

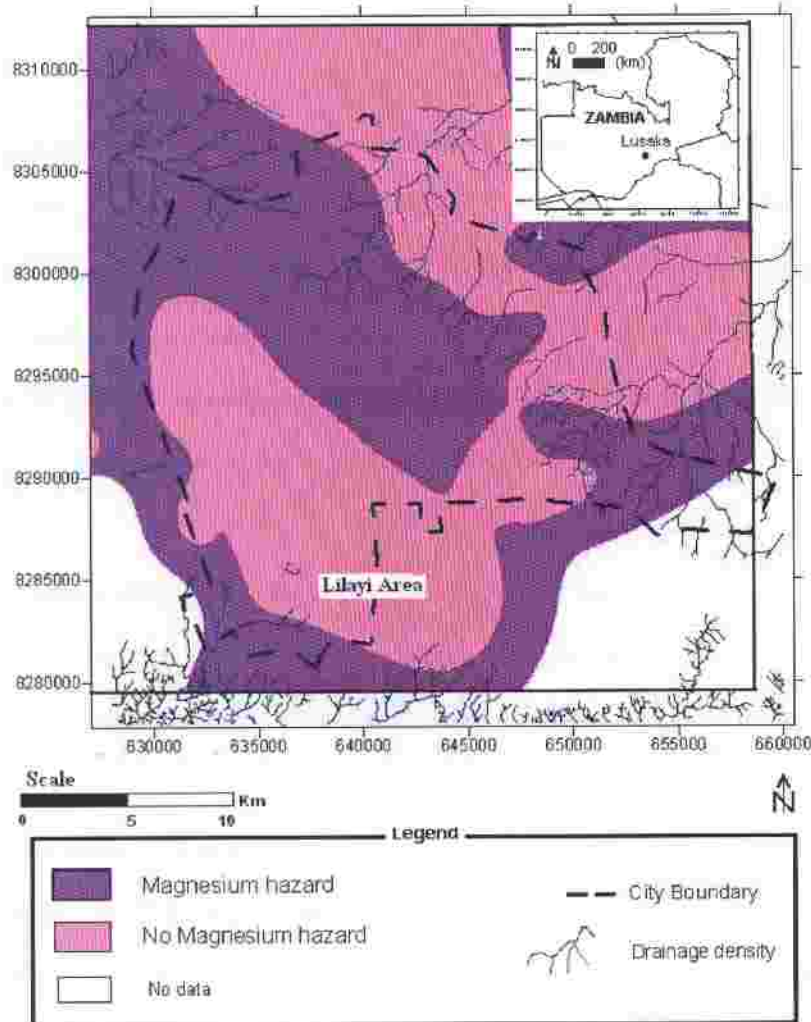


Figure 4.47 Map showing distribution of Magnesium Hazard in aquifers on Lusaka Plateau

4.2.3.3 Groundwater Vulnerability Assessment and Mapping

The term groundwater vulnerability is used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities, depending on the following:

- the time of travel of infiltrating water and contaminants
- relative quantity of contaminants that can reach groundwater
- the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate.

Geological and hydrogeological characteristics are examined and mapped to provide a groundwater vulnerability assessment. This is possible because, travel time, attenuation capacity and quantity of contaminants are a function of geological material and hydrogeological attributes of any area with regard to the subsoil that overlies the groundwater, the type of recharge and thickness of the unsaturated zone (Aller *et al.*; 1987; Rosen, 1994).

4.2.3.4 Vulnerability Assessment of the Lusaka urban Aquifers

Evidence of direct recharge in Lusaka urban aquifers attributed to presences of preferential flow paths such as fractures and sinkholes may be an indication that the aquifer offers little protection from contamination. Groundwater protection zones are also not possible for Lusaka urban because the city covers the entire aquifer (Von Hoyer *et al.*, 1978). However, vulnerability assessment of the aquifers is inevitable. **DRASTIC** is one method most widely used for vulnerability assessment. It has seven factors related to the geological and hydrogeological characteristics that are considered, namely; **Depth to water table**, **net Recharge**, **Aquifer media**, **Soil media**, **Topography**, **Impact of Vadose zone media** and **hydraulic Conductivity** of the aquifer (Aller *et al.*, 1987). This section does not include vulnerability analysis but highlights how **DRASTIC** vulnerability mapping technique may be applied to carry out vulnerability assessment using hydrogeological data for the Lusaka Plateau.

According to Rosen *et al.*, (1994) DRASTIC method has statistical advantages because of a large number of correlated parameters used and thus relevant for groundwater pollution potential assessment. However, it does not account for sorption capacity; travel time and dilution. As such, its result may not be relevant for specific pollutants (Rosen *et al.*, 1994). To assess groundwater pollution potential within hydrogeological settings, numerical ranking based on ranges, ratings and weights are used (Table 4.38 and Table 4.34). Each DRASTIC feature is assigned a weight relative to each other in order of importance; with the most significant being allocated a higher value than the least significant. The DRASTIC index which is the pollution potential (D_i) or vulnerability at any point on the map, is then determined as:

$$D_i = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad \text{Equation 4-5}$$

Where:	r	=	rating
	w	=	weight,
	$D_r D_w$	=	rating value for depth to water table
	$R_r R_w$	=	rating value for net recharge
	$A_r A_w$	=	rating value for aquifer media
	$S_r S_w$	=	rating value for soil media
	$T_r T_w$	=	rating value for topography
	$I_r I_w$	=	rating value for impact of the Vadose zone
	$C_r C_w$	=	rating value for hydraulic conductivity

The computed DRASTIC index identifies areas likely to be more susceptible to groundwater contamination than others. The higher the DRASTIC Index, the greater the groundwater pollution potential. Taking into consideration the geological and

hydrogeological setting on the Lusaka Plateau, the following assigned weights, ratings and ranges were proposed in this study for use with Tables 4.35 and 4.36 as well as information obtained from hydrogeological data (Table 4.37) to perform vulnerability assessment with the DRASTIC method.

Table 4.33: The DRASTIC parameters and their relative weights (after Aller et al., 1987)

Parameters		General weight
D	Depth to water	5
R	Recharge	4
A	Aquifer media	3
S	Soil media	2
T	Topography	1
I	Impact of the Vadose zone	5
C	Conductivity	3

Table 4.34: Ranges and ratings of Aquifer Media in DRASTIC (after Aller et al., 1987)

Aquifer Media Range	Rating	Typical rating
Massive shale	1 – 3	2
Metamorphic/ Igneous rocks	2 – 5	3
Weathered metamorphic / igneous rocks	3 – 5	4
Glacial til	4 – 6	5
Bedded sandstone, limestone and shale	5 – 9	6
Massive sandstone	4 – 9	6
Massive limestone	4 – 9	6
Sand and gravel	4 – 9	8
Basalt	2 – 10	9
Karstic limestone	9 – 10	10

Table 4.35: Assigned Weights for DRASTIC features for the Lusaka Urban Aquifers.

FEATUE	WEIGHT
Depth to Water Table	4
Net Recharge	4
Aquifer media	5
Soil media	5
Topography	3
Impact of Vadose Zone media	5
Hydraulic Conductivity of aquifer	5

Table 4.36: Ranges and ratings for depth to Water Table

Range (m)	Rating
< 5	10
5 – 10	8
10 – 15	6
15 – 20	4
> 20	1

Weight 4

Hydrogeological data collected from the Lusaka urban and adjacent areas, contain information on individual boreholes such as static water level, soil cover depth, soil cover type, aquifer lithology, GPS coordinates etc, which is required in the DRASTIC method. It is therefore possible to carry out vulnerability mapping of the aquifers using the information in tables 4.36 to 4.48.

Table 4.37: Information required from Hydrogeological data in DRASTIC vulnerability technique

DRASTIC mappable feature	Reflection	Information from a Borehole Completion Report
Depth to Water Table	Contaminants easily reach groundwater in shallow water table	Static water level
Net Recharge	The higher the recharge, the more vulnerable the aquifer is likely to be to contaminant. If rainfall is high and soils are permeable, water takes a few days to reach the water table	Soil cover type
Aquifer media	Attenuation characteristics of the aquifer material and mobility of contaminants through the aquifer	Aquifer lithology (Formation of the aquifer)
Soil media	Water holding capacity and influence on travel time of contaminant	Soil cover type and thickness of cover
Topography (slope)	Control runoff and erosion and gradient in the groundwater heads that lead to mobilization of contaminants	GPS coordinates to facilitate location of boreholes on a topographic map or a Digital Elevation Model (DEM)
Impact of Vadose zone	Texture of soil in the unsaturated zone above the water table	Soil cover type
Hydraulic Conductivity of aquifer	Amount of water percolating to reach the groundwater	Soil cover type

Table 4.38: Ranges and ratings for topography

Range (Slope %)	Rating
< 2	10
2 – 10	8
10 – 20	5
20 – 30	2
> 30	1
Weight 3	

Table 4.39: Ranges and ratings for aquifer media

Range (geology type)	Rating
Alluvium/Sand/Gravel/Laterite	8
Karstic Limestone	10
Fractured Limestone/Dolomite/Granite	6
Schist	2
Gneiss	1
Metasediments	1
Weight 5	

Table 4.40: Ranges and ratings for permeability in soil media

Range	Soil media	Rating
High	Gravel	10
Moderate - High	Laterite	8
Moderate	Sand	6
Slow	Schist	4
Very slow	Clay	1
Weight 5		

RECHARGE

The following equation is used to generate a *recharge value*. This value is then grouped into a range of values that are given a rating for use in the final DRASTIC calculation:

$$\text{Recharge value} = \text{Slope \%} + \text{Rainfall} + \text{Soil permeability}$$

Where:

Table 4.41: Factors for the Slope

Range (%)	Factor
< 2	4
2 – 10	3
10 – 30	2
> 30	1

Table 4.42: Factors for the Rainfall

Range (mm)	Factor
> 850	4
830 – 850	3
< 830	2

Based on average annual rainfall at Lusaka City Airport, Lusaka International Airport and Mt. Makulu stations

Table 4.43: Factors for soil permeability for recharge

Range		Factor
High	Gravel	5
Moderate - High	Laterite	4
Moderate	Sand	3
Slow	Schist	2
Very slow	Clay	1

Maximum recharge value = 4 + 4 + 5 = 13

Minimum recharge value = 1 + 2 + 1 = 4

Table 4.44: Ranges and ratings for recharge

Range (Slope %)	Rating
11 – 13	10
9 – 11	8
7 – 9	5
5 – 7	2
3 – 5	1
Weight	4

IMPACT OF VADOSE ZONE

The equation is used to provide a **Vadose Zone Value**, which is then grouped into a range of values that are given a rating for use in the final DRASTIC calculation.

Impact of Vadose Zone = Soil permeability + Depth to Water Table

Table 4.45: Factors for Soil Permeability for impact of Vadose zone

Range		Factor
High	Gravel	5
Moderate - High	Laterite	4
Moderate	Sand	3
Slow	Schist	2
Very slow	Clay	1

Table 4.46: Factors for depth to the water table

Range (m)	Factor
< 5	5
5 – 10	4
10 – 15	3
15 – 20	2
> 20	1

Maximum impact of Vadose zone value = 5 + 5 = 10

Minimum impact of Vadose zone value = 1 + 1 = 2

Table 4.47: Ranges and ratings for Vadose Zone Impact

Range	Rating
8 – 10	10
6 – 8	8
4 – 6	5
3 – 4	2
2 – 3	1
Weight	5

Table 4.48: Ranges and ratings for Hydraulic Conductivity of aquifer

Range	Rating
High	10
Moderate - High	8
Moderate	6
Slow	4
Very slow	1
Weight	5

4.2.3.5 Effectiveness of the DRASTIC Technique on the Lusaka Plateau

Availability of 1,800 borehole records in Lusaka urban and adjacent areas would enable the DRASTIC technique to be used to assess how vulnerable the aquifers are to pollution. However, lack of GPS co-ordinates for most borehole records made them unusable for GIS analysis using DRASTIC technique. Therefore, the following exercise is proposed to be carried out on Lusaka Plateau to facilitate preparation of the DRASTIC index map:

- to take GPS co-ordinates for more boreholes to improve the existing database.
- to establish average groundwater levels for Lusaka urban aquifers for use with DRASTIC technique. This entails measurement of water levels over one year to include the dry and rainy seasons.
- to identify the period during the rainy season when the water table is at its lowest or close to the groundwater surface.

Since Lusaka urban aquifers are fractured and Karstic, DRASTIC technique may have limitations in giving the level of natural attenuation of pollutants, which would require that the method is modified and adopted for the Lusaka Plateau.

4.2.4 Water Planning for the Lusaka Plateau

Water consumption characteristics on Lusaka Plateau are represented by about 30% from surface water sources ($38.33 \times 10^6 \text{m}^3$) and 70% groundwater sources ($65.39 \times 10^6 \text{m}^3$). The current estimated groundwater abstraction of $65.39 \times 10^6 \text{m}^3$ (Section 4.2.1.1) does not include abstractions from most boreholes constructed by private drillers. Hence, 70% groundwater sources are further represented by an estimated 10% (domestic and industrial) for LWSC and 90% for private abstraction (domestic, industrial and agriculture) that occur in the upper aquifer from 0m to 50m. The upper part of the aquifer is highly vulnerable to over abstraction due to high concentration of boreholes in certain areas of the Lusaka Plateau. Over abstraction is evident especially when effective recharge is low for boreholes that partially penetrate the aquifer.

Yearly domestic water demand for a population of about 1,300,000 (CSO, 2000) on Lusaka Plateau could be estimated at about $120 \times 10^6 \text{m}^3$ using per capita consumption of 255 litres/person/day. This figure does not include irrigation and industrial water demands. However, ongoing uncertainty on groundwater availability limits planning for usage and protection. Preliminary results on groundwater flow and groundwater fluctuation – effective recharge relationship established in this study indicates that further groundwater development and abstraction in areas where the private individuals that depend on the upper 50m of the aquifer are not likely to be affected by over abstraction, may be possible and is necessary to control groundwater build up during periods of high effective recharge. Nevertheless, additional studies are required to determine the extent to which groundwater levels could be allowed to drop in the aquifer without affecting the ecosystem on the Lusaka Plateau. The monitoring

network would be also sufficient to facilitate collection of additional data on groundwater level fluctuation.

According to JICA Report (1995), several options are available in meeting the water demand on Lusaka Plateau by government. These are to support LWSC increase the volume of imported treated surface water from Kafue River, exploitation of aquifers on the northern part of Lusaka city and transportation of treated surface water from the proposed Chongwe Multi-purpose Dam once constructed by government. However, the option of increasing transported treated water to Lusaka Plateau would require abstraction of groundwater to continue to avoid build up of the water table and eventual flooding as well as water logging in a number of built up areas within Lusaka city boundary. It should include also development of adequate plans to drain wastewater resulting from excess treated water transported to Lusaka Plateau especially during the rain season.

4.2.4.1 Groundwater Management Strategy for the Lusaka Plateau

The overall groundwater resources availability and the water balance is still unknown. There is need to re-evaluate groundwater recharge for Lusaka Plateau, determine the actual groundwater abstraction for uses such as domestic, industrial and agriculture as well as to urgently put in place groundwater management measures for Lusaka urban aquifers. To achieve this, the following are proposed as management strategies:

- effort must be made to locate, identify according to usage and take GPS coordinates for all existing boreholes. This exercise will facilitate investigation of groundwater availability to determine if the current groundwater abstraction

levels are sustainable for a long time without causing detrimental effects to the aquifer and the environment.

- establishment of a groundwater monitoring network for regular groundwater level measurement and routine groundwater quality evaluation is a must and a priority for Lusaka urban aquifer management.
- groundwater management for Lusaka Plateau must ensure collection of hydrogeological and groundwater quality data for every borehole constructed; as well as submission of a completion report with GPS coordinates.
- Lusaka South Forest Reserve (Forest 26 and 55) must be declared a groundwater protection zone for replenishment of groundwater of good quality to avoid further deterioration of water quality in Lusaka urban aquifers. This should be coupled with stringent solid waste management on Lusaka Plateau.
- a groundwater model and re-evaluation of groundwater recharge is required to investigate and identify areas that need control of groundwater abstraction in the city and surrounding areas.
- the current groundwater abstraction in certain parts of the city need to continue to keep areas such as Msisi, John Laing, Chibolya and Kanyama dry during the rain season to avoid surface flooding and water logging. Furthermore, additional groundwater development and abstraction is recommended to achieve this goal.

The majority on Lusaka Plateau depend on groundwater as an important and valuable resource that requires protection. The risks to groundwater on Lusaka Plateau are twofold. One is that prolonged over abstraction from the upper aquifer (0m – 50m) in certain areas may reduce the water table and so deplete stream baseflow in the three

sub-catchments; Chunga-Mwembeshi, Kafue and Chongwe. It may also cause lower yields and drying up of some boreholes. Additionally, availability of groundwater in the upper aquifers on Lusaka Plateau is highly dependant on rainfall amounts and rain days coupled with rainfall distribution. Abstraction control especially during years of low effective recharge is therefore critical for the upper aquifer, and is proposed to be achieved through the designed groundwater monitoring network.

The second risk is groundwater pollution due to anthropogenic activities in the absence of groundwater protection measures for the entire Lusaka Plateau. Forest 26 and 55 are currently the only sites suitable and available to function as groundwater protection zones to protect the Lusaka urban aquifers from increased pollution load.

4.2.4.2 Exploitation and Abstraction of Groundwater in Lusaka urban Aquifers

There are a number of areas with very high groundwater potential in Lusaka urban and adjacent area, as shown in this study. These are:

- i) Hibex – State Lodge area, specifically around latitudes and longitudes: (UTM Northings 8295000, UTM Eastings 645000), (UTM Northings 8290000, UTM Eastings 645000), (UTM Northings 8295000, UTM Eastings 655000) and (UTM Northings 8290000, UTM Eastings 655000).
- ii) Chamba Valley – Ngwerere area: (UTM Northings 8305000, UTM Eastings 645000), (UTM Northings 8300000, UTM Eastings 645000), (UTM Northings 8305000, UTM Eastings 650000) and (UTM Northings 8300000, UTM Eastings 650000).

- iii) Lilayi – Barclay / Lusaka west area between: (UTM Northings 8285000, UTM Eastings 625000) and (UTM Northings 8285000, UTM Eastings 645000). This is a 5km by 20km stretch.
- iv) The area from (UTM Northings 8300000, UTM Eastings 635000) and (UTM Northings 8295000, UTM Eastings 635000) to (UTM Northings 8300000, UTM Eastings 645000) and (UTM Northings 8300000, UTM Eastings 645000)
- v) The areas on the eastern and southern part of the Lusaka South Forest Reserve (UTM Northings 8280000, UTM Eastings 645000) and (UTM Northings 8275000, UTM Eastings 645000) to (UTM Northings 8280000, UTM Eastings 660000) and (UTM Northings 8275000, UTM Eastings 660000).

The above areas are potential well fields that Lusaka Water and Sewerage Company could develop, although some of these areas are likely to be built up or private land. However, groundwater abstraction has to be controlled using observation boreholes to avoid over abstraction and stream baseflow reduction. Groundwater modelling is therefore required for Lusaka urban aquifers.

A further $120.44 \times 10^6 \text{ m}^3/\text{a}$ ($330\text{m}^3/\text{day}$) and more, but not exceeding $250 \times 10^6 \text{ m}^3/\text{a}$ of groundwater is possible for development and abstraction on Lusaka Plateau (Appendix E1). This is because of the high recharge and radial groundwater flow pattern that would allow withdraw of groundwater around the Plateau without necessarily concentrating boreholes in one area. Forest 26 is an ideal site to be

considered for artificial recharge in the future, because it has a high water entry and flow properties Section 4.2.2.2).

4.2.4.3 Aquifer and Groundwater System on the Lusaka Plateau

Lusaka urban and adjacent areas qualify as an aquifer system and a groundwater system. As an aquifer system, details are as follows:

- the geometry: aquifer saturation thickness of 50m and over an extent of 470km² carbonates and 271km² schist.
- Deeper aquifers at 150m and of the same potential exist in both the Lusaka Dolomite and Cheta Formation.
- the boundary conditions: three flow boundaries exist; flow, head and no flow.
- the aquifer type: unconfined
- hydraulic parameters: porosity for carbonates is 0.5 and for schist is 0.02, whereas permeability varies widely from $1.2 \times 10^{-6} \text{ m}^2$ in the schist to $1.5 \times 10^{-5} \text{ m}^2$ in the carbonates.

Whereas for a groundwater system the following is applicable:

- there is about $600 \times 10^6 \text{ m}^3$ of groundwater in storage in the upper aquifer in the carbonates and the schist. However, the water quality is compromised due to lack of protection zones and presence of on-site sanitation coupled with inefficient solid waste management practices.
- Current observed average annual groundwater fluctuation is about 1.6m in the schist and 5.9m in the carbonates, indicating the effects of recharge and abstraction.

-
- Recharge values vary widely from 8% to 35% of the annual rainfall. However, rainfall is the main source of recharge, although artificial recharge from on-site sanitation structures (septic tanks and pit latrines) and leaky water reticulation is a reality.
 - The carbonate aquifer has the capacity to facilitate abstraction of a certain amount of groundwater in storage. This is because of the high recharge values that would enable re-filling of the space created by over abstraction and is manageable through controlled increased abstraction to the optimum level.
 - Groundwater budget for Lusaka Plateau though not determined is inevitable for control of groundwater abstraction and management.
 - the chemical composition of groundwater is predominantly mixed cationic – bicarbonate water types: $MgHCO_3$, $CaHCO_3$ and $NaHCO_3$.

Hydrogeological parameters established from the study were used as the basis to support the argument to consider Lusaka Plateau as an aquifer and groundwater system (Table 4.49).

Table 4.49: Suggested aquifer systems of Lusaka Plateau

AQUIFER SYSTEM	AQUIFER LITHOLOGY	HYDROGEOLOGIC PROPERTIES	Aquifer geometry		Yield (l/s)	Groundwater storage ($10^6 m^3$)	Rate of groundwater flow (m/d)		Water type
			Average thickness (m)	Area (km^2)			Dry season	Rainy season	
Cheta-Lusaka Dolomite	Carbonate	Regional extension, unconfined to semi-confined, high recharge, uniform karstification, uniformly fractured, high groundwater potential	150	470	0-70	> 600	3.7×10^{-3} to 2.8×10^{-2}	2.0×10^{-2} to 3.7×10^{-2}	CaHCO ₃ , MgHCO ₃ , and NaHCO ₃
	Schist	Hydraulically connected to carbonates, unconfined, not continuous, uniformly fractured, controls groundwater flow from the carbonates	150	271	0-30	-	2.9×10^{-3} to 1.5×10^{-2}	2.0×10^{-2} to 4.9×10^{-2}	CaHCO ₃ , MgHCO ₃ , and NaHCO ₃

Additional hydrogeological work and studies are required to perfect the knowledge on the Lusaka Plateau to effect sustainable water resources management considering that it is a watershed for three small river basins; Chunga-Mwembeshi, Kafue and Chongwe. Measurement of groundwater levels using the 10 days frequency should continue at all the observation boreholes on the Lusaka Plateau for at least two rainy seasons to have sufficient data to re-assess recharge in the schist and carbonates; and determine the average recharge.

The recharge should be investigated using environmental isotopes, groundwater levels and hydrometeorological data. Rainfall variability observed on the Lusaka Plateau and the effect it has on the effective recharge may necessitate establishment of a meteorological station around Forest 26. This would help collect reliable data to use to re-define the role of Lusaka South Forest Reserve, both as the highest point and the main recharge area for the Lusaka Plateau. In addition, protection of groundwater resources is equally important as the protection of surface water resources (Pietersen, 2004). Therefore, protection and management of groundwater in Lusaka urban and adjacent areas entails that human activities have to be restricted in Forest 26 and 55 to preserve the quality of groundwater (Nkhuwa, 1999; Nyambe and Maseka, 2000; De Waele *et al.*, 2004). In brief, it implies that groundwater protection measures need to be in place for the Lusaka urban aquifers, which would ensure that domestic water supply required for a population of about two million people on the Lusaka Plateau is assured. Groundwater protection for almost all boreholes in Lusaka urban is not practical and possible through establishment of protection zone I to III, due to location of industries and settlements (Von Hoyer *et al.*, 1978). Hence, Forest 26 and part of 55 should be declared a groundwater protection zone for Lusaka urban aquifers.

4.3 Gwembe District

4.3.1 Hydrogeological Data Collection

During the study, the Department of Water Affairs constructed 191 boreholes in Gwembe District from where groundwater data and information was captured on borehole completion reports and incorporated in the database (Appendix F1). The 191 boreholes together with the existing boreholes were estimated at about 375 boreholes. Most of these boreholes in Gwembe District are for rural water supply, except for about 4 boreholes, which are used for piped water supply for the township and at private premises. The information collected included GPS coordinates for some existing boreholes and those constructed during the study period. Spatial distribution of the aquifer lithologies, borehole yields and irrigation potential were carried using collected hydrogeological data.

4.3.1.1 Estimation of Groundwater Abstraction and Aquifer Storage

Groundwater abstraction was estimated based on the 371 boreholes for rural water supply (Equation 4 – 6) and the 4 boreholes for piped water supply (Equation 4 – 7):

- i) **Rural water supply boreholes:** Equation 4 – 6

$$\begin{aligned}\text{Abstraction volume} &= 7.5 \text{ m}^3 \text{ day}^{-1} \text{ borehole}^{-1} \times 371 \text{ boreholes} \\ &= \underline{2,782.5 \text{ m}^3 \text{ day}^{-1}} (1,015,612.5 \text{ m}^3 \text{ year}^{-1})\end{aligned}$$

- ii) **Motorized boreholes for piped water supply:** Equation 4 – 7

$$\begin{aligned}\text{Abstraction volume} &= 400 \text{ m}^3 \text{ day}^{-1} \text{ borehole}^{-1} \times 4 \text{ boreholes} \\ &= \underline{1600 \text{ m}^3 \text{ day}^{-1}} (584,000.0 \text{ m}^3 \text{ year}^{-1})\end{aligned}$$

Therefore, the total estimated combined groundwater abstraction is about $1.599 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ in Gwembe District. This figure reflects a very low groundwater abstraction level when compared to $65.385 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ for Lusaka urban and adjacent areas (Section 4.2.1.1).

The 191 borehole records (Appendix F2) show that yields in the mudstones range from $0.1 - 12 \text{ l s}^{-1}$, in the sandstone from $0.1 - 15 \text{ l s}^{-1}$ and in the Basement Complex from $0.1 - 2 \text{ l s}^{-1}$. Average borehole drilling depth is 60m and main water intersection depth ranges from 15m – 40m in most parts of the district, with the exception of Nakasika and Siampande areas near the lake. Borehole depths in the two areas reach 120m and main water intersection depth range from 60 – 90 m in both the sandstone and mudstone aquifer lithology. Spatial distribution of borehole yields in Gwembe District (Figure 4.48) indicates that sandstone and mudstone comprise the best aquifer lithologies in the district. Sandstone is the best in terms of aerial extent.

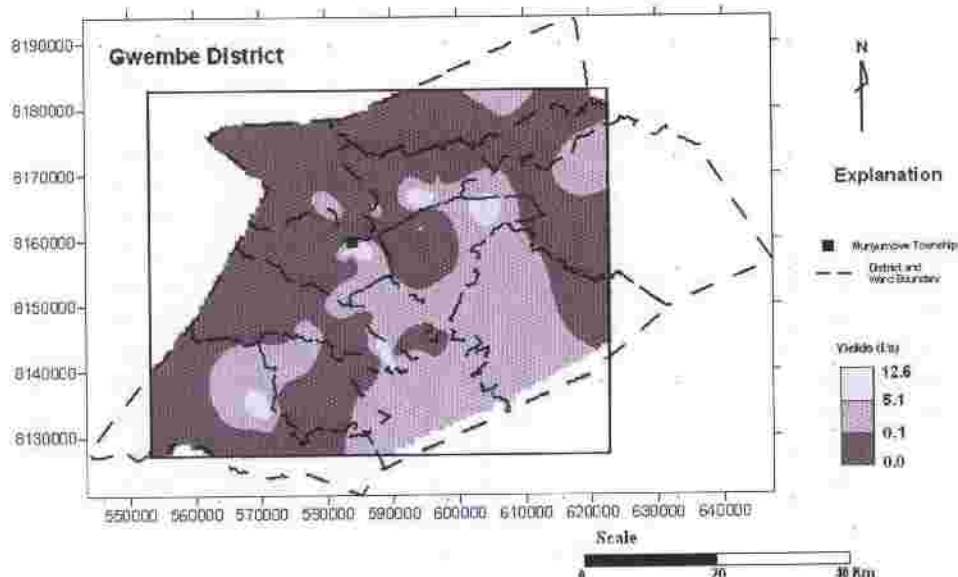


Figure 4.48 Map showing yield distribution in wards in Gwembe District

Most important is that quantitatively, Munyumbwe Township is located on one of the most productive sandstone and mudstone aquifers with yields ranging from 2.5 l s⁻¹ to 13 l s⁻¹ (Table 4.55).

Table 4.55: Data on boreholes located around Munyumbwe Township

No.	X	Y	Aquifer Lithology	Aquifer code value	Static				Soil Cover	Soil Cover code value
					Borehole Depth (m bgl)	Water Level (m bgl)	Yield (l/s)	Main Water Intersection (m bgl)		
1	614300	8162449	M	15	56	6	0.6	30	F	5
2	597130	8169212	M	15	60	6	3	36	F	5
3	586059	8168998	M	15	50	7	0.6	24	F	5
4	577311	8171837	B	5	40	21	0.4	28	F	5
5	586949	8160584	M	15	73.5	12	0.5	49	Clay	10
6	595553	8168510	M	15	73.5	11	0.8	26	Clay	10
7	576374	8172618	B	15	50	5	2	32	Schist	10
8	576642	8169683	M	15	67.5	12	1	49	Clay	10
9	578246	8170746	B	5	52	11	0.6	40	Schist	10
10	574821	8172676	B	5	55.5	19	0.9	24	F	5
11	582335	8161032	M	15	55.5	16	1	34	Clay	10
12	586072	8160615	M	15	62.5	30	0.9	49	F	5
13	597703	8169514	M	15	55	24	0.4	50	F	5
14	584311	8168471	M	15	55	8.4	0.8	22	Clay	10
15	582784	8158461	M	15	40	14.9	12	20	Sand	10
16	580745	8166011	M	15	60	10	5	36	F	5
17	581565	8165854	M	15	52	7	3	38	F	5
18	578234	8164044	M	15	42	4.2	0.6	18	F	5
19	583599	8157579	M	15	45	7	0.5	25	F	5
20	594488	8166194	S	10	42	5	15	30	F	5
21	611107	8177859	M	15	50	4	1	36	F	5
22	583110	8159044	M	15	48	10.5	5	20	F	5
23	580794	8169606	S	10	60	8	1		F	5
24	584931	8158804	M	15	55	5.3	15	36	Clay	10
25	581924	8158655	M	15	43	10	0.3	24	Clay	10
26	587240	8164638	M	15	50	12	4	30	Clay	10
27	592612	8175532	M	15	50	15	0.3	36	Clay	10
28	595794	8174865	M	15	50	8	1	30	Gravel	10
29	594017	8164426	M	15	50	4	1	30	F	5
30	581390	8167238	M	15	55	1	0.3	36	Clay	10
Average					53.3	10.5	2.6	32.3		

F = Aquifer Formation, M = Mudstone, B = Basement Complex, S = Sandstone

Sandstone and mudstone form an intercalation and also function as one unit due to presence of fractures and faults. Static water levels around Munyumbwe Township range from 1m to 30m in most of the areas where the mudstone lithology outcrops. Therefore, further development of this Township must ensure that groundwater protection measures are promoted.

Based on the Hydrogeological data collected in Gwembe District, the average effective aquifer saturation depth is 40.5m in the mudstone, 36.6m in the sandstone and 39.8m in the Basement Complex aquifers. Low effective saturation depth in the sandstone aquifers is attributed to high drainage and shallow drilling depth. Unlike in the sandstone and mudstone aquifers, effective saturation depth in the Basement Complex does not increase with the drilling depth and average yield of the boreholes is about 1 l s^{-1} .

Mudstones are generally considered to be poor aquifers because they are devoid of primary porosity and parting horizons (Lambert, 1961). However, due to high temperatures in the dry season and low temperature in the cool season, mudstones have attained weathering depths of up to 20m and in some cases more. Additionally, tectonic events have also created horizontal and vertical fracturing patterns in the mudstones that allow appreciable storage of groundwater. High yielding boreholes encountered in mudstones during the study period are attributed to weathering and fracturing observed in most of the boreholes drilled in the mudstone-covered areas. Compact and fractured mudstones (Figure 4.49) do not show any signs of swelling and dissolution when in contact with rainwater and as such have a better porosity than the weathered mudstones. However, sandstones provide excellent aquifers compared

to mudstones. The sandstones of Gwembe District are among the good aquifers located in Southern Province and most of the boreholes located in these aquifers are high yielding.



Figure 4.49 Fractures in compact mudstone around Munyumbwe area in Gwembe District

It is important to mention that sandstones and mudstones form an intercalation in the large portion of Gwembe District. This is the reason for commonly encountering high yielding boreholes in the mudstones as well. However the predominant aquifer lithology on the valley floors where human settlements exist is the mudstone. This is common on most valley floors due to the absence of the sandstone strata that is supposed to be on top of the mudstone like in other parts of Gwembe District where tectonic events and erosion have not led to its removal. Effective porosity required to determine aquifer storage in the three aquifer lithologies were not investigated for Gwembe District during the study.

4.3.1.2 Conceptual Hydrogeological Model

The conceptual hydrogeological model (Figure 4.50) for Gwembe District was developed by indicating the permeability coefficient for the main aquifer lithologies on the geological model (Figure 4.51) derived using the 191 borehole records. Figures 4.50 and 4.51 indicate that Gwembe District has two aquifer systems; the Basement Complex and the Sandstone-Mudstone groundwater flow controlled systems. The latter is the largest in aerial extent and is well distributed in most of the wards in Gwembe District. This situation has a good economic implication for the district in terms of availability of groundwater resources, which could facilitate economic growth through industries and agricultural related activities, besides meeting domestic water demands for the rural water supply and township water supply.

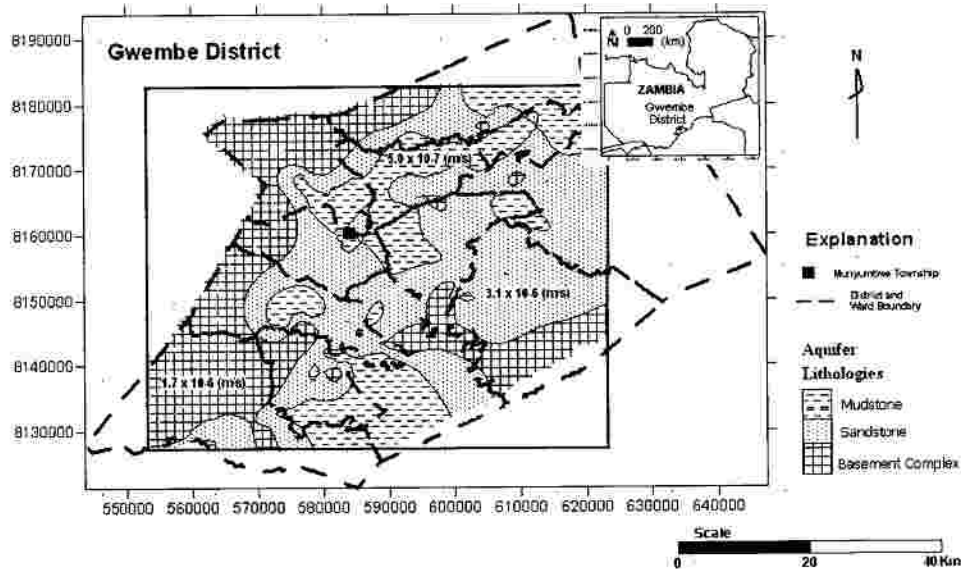


Figure 4.50 Map showing the Conceptual Hydrogeological Model of part of Gwembe District in the studied areas with mudstone, sandstone and Basement Complex

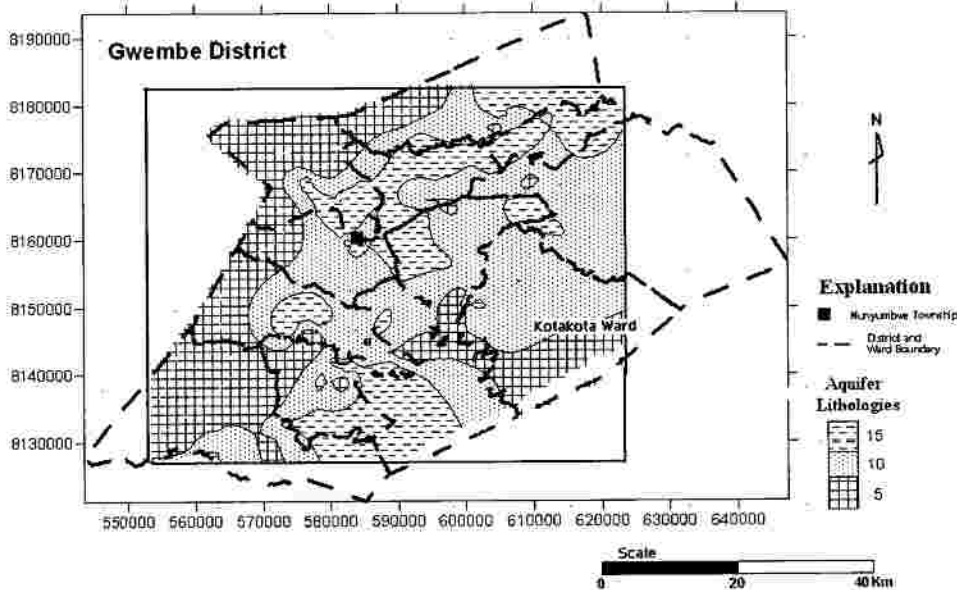


Figure 4.51 Map of Gwembe District showing the main aquifer lithologies of mudstone (15), sandstone (10) and Basement Complex (5) in the studied areas.

Evidence of the two-aquifer systems defined by yields ranging from 0.1 ls^{-1} to 12 ls^{-1} (Section 4.3.1) based on the hydrogeological data collected during the study may suggest that, incorporating aspects of remote sensing and groundwater indicative data in GIS would result in locating boreholes with higher yields (Kellgren, 2002). The results are important for Munyumbwe Township, which has the potential to expand and exert pressure on groundwater resources due to non-availability of alternative water sources such as perennial streams and rivers. At the same time, it should be expected that a number of other places once developed would also exert similar pressure because groundwater is currently the main and best water source option for Gwembe District.

To achieve the analysis described above, spatial distribution of hydrogeological data for boreholes drilled in the study area (Tables 4.56) was carried out by classifying

aquifer lithologies (Table 4.57) and then using Surfer with Kriging as the interpolation method.

Table 4.56: Borehole data used to develop a geological model for Gwembe District

No.	X	Y	F	Aquifer code value	No.	X	Y	F	Aquifer code value
1	591934	8140117	M	15	47	564828	8176544	B	5
2	577476	8147086	S	10	48	590864	8178988	B	5
3	587897	8141858	M	15	49	589202	8180184	B	5
4	590262	8144061	S	10	50	570178	8172544	B	5
5	602040	8145446	S	10	51	586404	8164240	M	15
6	600712	8150120	M	15	52	601954	8174516	M	15
7	553410	8128004	S	10	53	608935	8177315	M	15
8	599998	8152647	S	10	54	572772	8135324	S	10
9	605572	8175860	M	15	55	564898	8132590	S	10
10	613769	8175145	M	15	56	571224	8134324	S	10
11	601605	8170950	M	15	57	559095	8128950	S	10
12	591976	8141853	S	10	58	563355	8128013	M	15
13	609455	8166446	M	15	59	589934	8142716	S	10
14	614289	8160317	M	15	60	583713	8146679	S	10
15	597457	8155806	M	15	61	578109	8147705	M	15
16	603145	8174904	M	15	62	608948	8166995	S	10
17	604855	8177833	M	15	63	613917	8167747	S	10
18	601569	8174564	M	15	64	607433	8176336	M	15
19	606329	8179178	M	15	65	573802	8163633	B	10
20	565826	8177213	B	5	66	601954	8174516	M	15
21	565048	8174887	B	5	67	623129	8182922	M	15
22	563682	8174924	B	5	68	575489	8139666	S	10
23	604553	8176255	B	5	69	585756	8145450	S	10
24	600912	8171042	M	15	70	596446	8164812	S	10
25	612616	8178609	M	15	71	589984	8166817	M	15
26	614811	8173763	M	15	72	585334	8160341	M	15
27	616369	8172411	M	15	73	582911	8152322	S	10
28	597977	8165886	S	10	74	582137	8140585	M	15
29	609303	8166763	M	15	75	586312	8147214	M	15
30	606475	8166104	M	15	76	583320	8146360	M	15
31	589177	8142083	M	15	77	582143	8145557	S	10
32	588891	8143077	S	10	78	580337	8142589	M	15
33	564132	8176917	B	5	79	579580	8138703	M	15
34	564461	8176591	B	5	80	579852	8139023	S	10
35	564471	8178075	B	5	81	584371	8138978	M	15
36	590256	8153671	M	15	82	582450	8140112	M	15
37	599554	8151945	S	10	83	582136	8139973	S	10
38	586378	8146158	M	15	84	582085	8140481	M	15
39	596381	8145961	S	10	85	572688	8132848	M	15
40	596713	8146623	S	10	86	571860	8130746	S	10
41	607893	8154062	S	10	87	569003	8131147	S	10
42	600130	8149724	S	10	88	562638	8131641	S	10
43	599847	8147561	S	10	89	561305	8128539	M	15
44	580025	8149489	M	15	90	562929	8128046	M	15
45	575751	8145682	B	15	91	562159	8126958	M	15
46	574450	8146243	M	15	92	563555	8131647	S	10

*F = Aquifer Formation, M = Mustone, B = Basement Complex, S = Sandstone

Table 4.57: Arbitrary classification used to develop a geological model for Gwembe District

Individual Boreholes GPS		Aquifer Lithology	Assigned Class
Co ordinates			
X	Y	Mudstone	15
		Sandstone	10
		Basement Complex	5

4.3.2 Groundwater Level Data Collection

Observation of groundwater levels was carried out from the month of July 2004 to May 2005 in the aquifer where sandstone and mudstone are intercalated around Munyumbwe area. Although only one observation borehole was constructed, the aquifer with intercalated sandstone and mudstones represent similar areas where most villages are located and boreholes tap their water.

4.3.2.1 Designed Groundwater Monitoring Network for Aquifer Management

There is a strong and positive correlation of groundwater level rise (Table 4.58) due to rainfall that occurs from November to April every rainy season (Figure 4.52). Although rainfall records for Gwembe District for this period were not available and are not plotted on the graph, the period of groundwater level rise due to recharge from precipitation in form of rainfall is quite distinct (December – March). The period of groundwater level fall due to aquifer drainage, Evapotranspiration and abstraction (March – November) is also quite distinct. Since groundwater abstraction levels are still quite low, lowering of groundwater levels during the dry season seems to be affected mainly by aquifer drainage and Evapotranspiration.

Table 4.58: Groundwater level readings in meters for MB – 2 at Makuyu World Vision premises: June 2003 to July 2005

Day of Month	2003			2004			2004			2005			2005								
	June	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Marc	April	May	June	July	Aug						
1								14.74	14.1	15.13	15.18	16	15.23	14.13	14.28	15.00	14.49	20.048	15.48	15.48	15.48
2					13.9			14.78	14.12	15.14	15.1	15.11	15.31	14.23	14.21	15.08	15	20.04	15.48	15.48	17.09
3		12.91						14.71	14.13	15.13	15.16	15.14	15.29	14.15	14.21	15.10	14.48	20.048	15.48	15.48	15.48
4				13.92				15.01	15.1	15.07	15.1	15.13	15.3	14.11	14.18	15.10	14.7	20.061	15.48	15.48	14.48
5								15.03	15.1	15.2	15	15.11	15.3	14.10	14.17	15.10	14.7	20.048	15.48	15.48	
6						14.5		14.81	15	15.12	15.02	15.02	15.6	13.14	14.28	14.50	14.72	15.48	15.6	15.6	
7			13.9					14.77	14.09	15.13	15.09	15.22	15.62	13.18	14.29	14.50	14.91	15.038	15.63	15.63	
8								14.76	14.12	15.15	16	15.32	15.63	13.11	14.29	14.34	14.98	15.049	15.048	15.048	
9				13.91				14.74	14.08	15.15	15.45	15.31	15.64	14.00	13.45	14.42	14.9	15.033	15.48	15.48	
10		12.94						14.74	14.11	15.14	15.16	15.2	15.65	14.00	13.62	14.60	15	15.048	15.48	15.48	
11								14.79	15	15.22	16.03	15.11	15.66	13.17	13.71	15.01	14.48	15.048	15.48	15.48	
12	12.92					13.92		14.78	15.09	15.2	15.1	15.19	14.67	13.11	13.5	14.51	14.91	15.048	15.48	15.48	
13								15.08	15.07	15.2	15.08	15.2	14.69	13.21	13.51	14.51	14.82	15.048	15.48	15.48	
14			13.9					15.06	15.03	16	15.19	15.43	14.69	13.29	14	14.69	14.9	15.049	16	16	
15								14.79	15.09	16.07	15.15	15.49	14.63	13.11	14.11	14.44	14.9	15.05	15.48	15.48	
16					13.92			14.75	15.08	15.00	15.08	15.43	15.63	13.30	14	15.00	14.92	15.061	15.49	15.49	
17		12.92						14.73	15.02	14.49	15.16	15.28	14.64	13.32	13.49	15.01	14.91	15.055	15.49	15.49	
18				13.85				14.71	15.06	15.01	16.03	15.7	15.65	13.49	13.42	14.31	14.6	15.06	15.6	15.6	
19	12.95							14.73	15.07	15.14	15.09	15.38	14.65	13.00	14.08	14.32	14.59	15.062	15.48	15.48	
20								14.71	15.06	15.15	15.08	15.7	14.62	13.01	14.08	14.32	14.91	15.071			
21			13.8					14.71	15.01	15.02	15.09	15.76	14.69	13.11	14.11	14.32	15	15.061			
22								14.79	14.79	15.02	15.49	15.79	14.79	13.08	13.49	14.32	15.5	15.061			
23					13.92			14.79	14.72	15.04	15.16	15.8	14.22	13.18	13.51	15.00	15.02	15.059	15.059	15.059	
24		13.60						14.8	14.65	16.05	15.08	15.81	15.72	14.46	13.39	15.02	15.5	19.011			
25				14.7				14.84	14.78	15.06	15.49	15.51	15.38	13.40	13.42	15.01	15.3	15.6			
26	12.92							14.71	14.71	14.49	15.52	14.4	15.31	13.40	13.45	14.68		16.11			
27								14.61	14.82	15.01	16	14.23	14.21	13.18	14.46	14.69		16.59			
28			13.9					14.7	14.16	15.08	15.03	14.2	15.28	13.49		14.68		15.048			
29								14.72	15.12	15.09	15.14	14.28	14.62	13.15		14.61		15.048			
30				14.4														15.048			
31		12.90							15.14		15.15		14.79	13.42				15.048			

Blank spaces represent data gaps and gaps

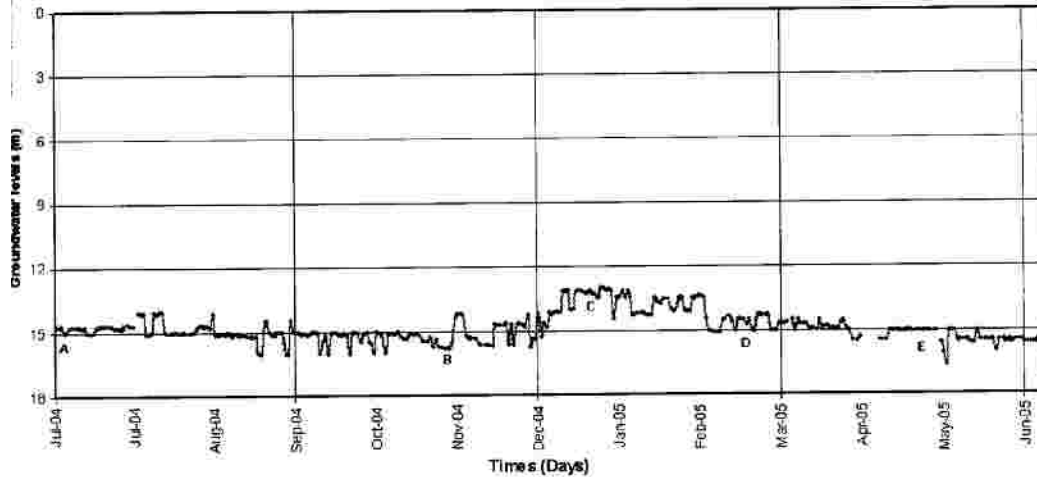


Figure 4.52 Graphing for groundwater level fluctuations at observation borehole MB – 2 located at Makuyu World Vision premises from July 2004 to July 2005

Episodic rise and fall of groundwater levels between points A and B could be attributed to recharge water with regional groundwater flow. The highest groundwater level rise occurs in the month of January and February, whereas Points B to D indicates that the main recharge period for Gwembe District occurs during the rainy season.

In the absence of rainfall data, it was difficult to meaningfully evaluate groundwater level response to rainfall for Gwembe District. Therefore, it is inevitable to establish groundwater level observation boreholes in areas with meteorological stations and at voluntary rainfall stations as the next best option (Mpamba, 2003).

4.3.2.2 Expansion of Groundwater Level Measurement

To provide adequate information on groundwater level fluctuation in the sandstone-mudstone intercalated aquifer that would help in promoting irrigated agriculture using

groundwater, additional observation boreholes to MB-2 in Fumbo ward were proposed for construction in Gwembe District (Figure 4.53). The design was based on the distribution of the Sandstone-Mudstone groundwater flow controlled system in the other wards in Gwembe District (Section 4.3.1.2). Since rural communities entirely depend on rainy feed agriculture, groundwater levels from more observation stations would improve the estimation of groundwater recharge and understanding of regional groundwater contribution. The ultimate aim is to have a specific groundwater monitoring network for use to support irrigated agriculture through sustainable aquifer management around Munyumbwe Township. Target areas suggested for the additional observation boreholes were in the following wards:

- Masanga
- Jumbo/Khoma
- Chisale
- Syampande
- Luumbo
- Chibuwe

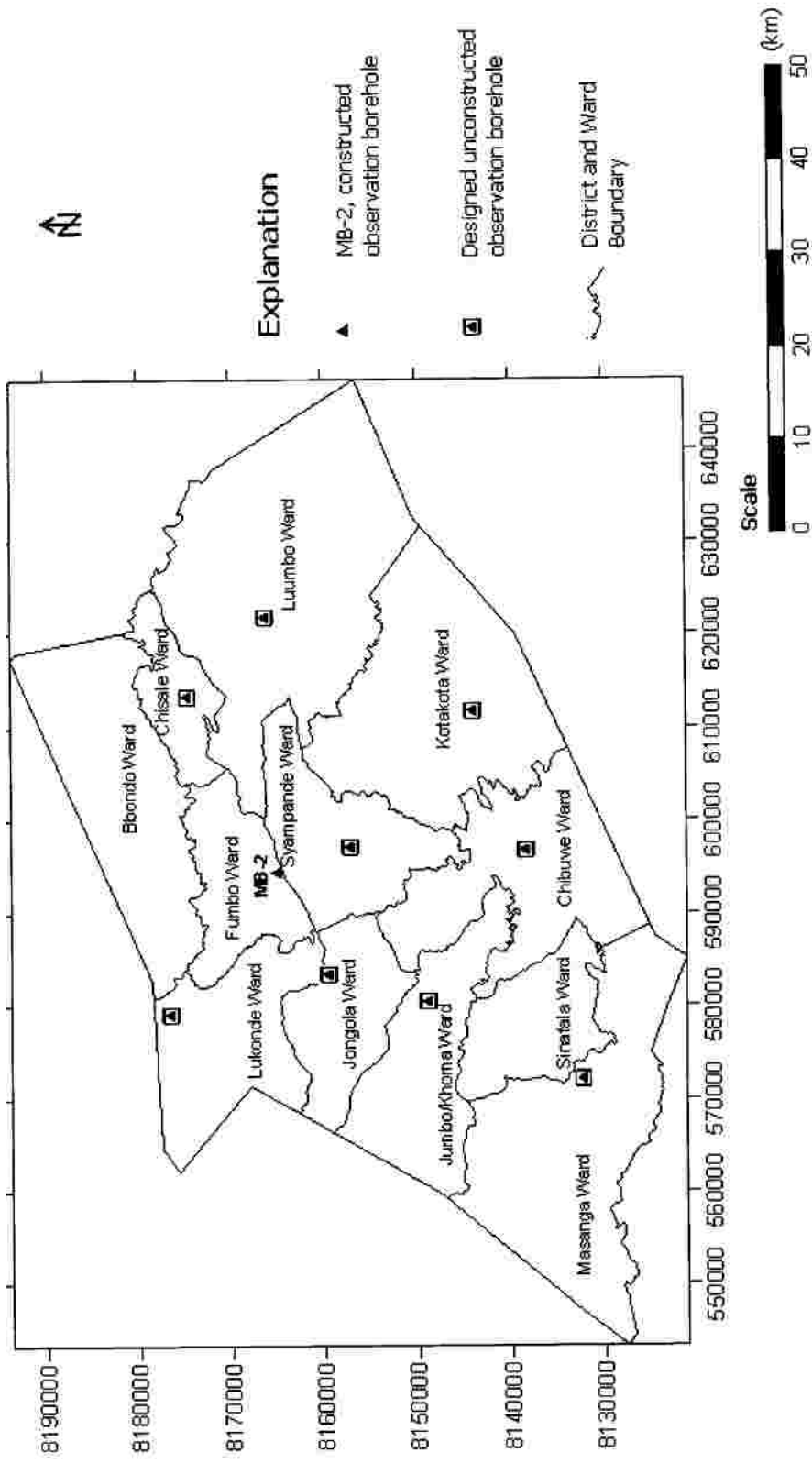


Figure 4.53 Map showing the designed groundwater-monitoring network and wards comprising Gwembe District

4.3.2.3 Water Balance and Recharge Estimation

The areas covered by sandstone are the main recharge areas in Gwembe District and are the largest in terms of aerial extent. However, recharge occurs also in the Basement Complex as well as in mudstone covered areas although their aerial distribution seems limited. Mudstone is overlain by the sandstones in most of the areas, and thus acts as a huge storage lithological unit. Water from springs that drain most of the sandstone covered areas flow for short distances along streams and infiltrate into the ground as well as disappear through evaporation. In view of the low groundwater abstraction estimated in Gwembe District and the presence of non-perennial rivers and streams, the following are therefore suggested to comprise the principal sources of recharge (inflow) for aquifers in the studied area:

- Rainfall (October to April)
- Regional groundwater flow from the plateau (through out the year)
- Springs draining sandstone aquifers and recharge mudstone aquifers (through out the year)
- Streams and rivers recharge aquifers (through out the year)

Similarly, the outflow from the mudstone, sandstone and Basement Complex aquifers comprise the following:

- Abstraction (through out the year)
- Drainage density and springs that feed streams (through out the year)
- Natural aquifer drainage towards lake Kariba (through out the year)
- Evapotranspiration (through out the year)

The water balance for Gwembe District can therefore be expressed as:

Inflows – Outflows = Change in groundwater storage

$$A - B = \Delta S$$

Equation 4 – 8

Not all the components are individually possible to quantify, except for the following:

- Rainfall amount
- Spring discharge
- Evapotranspiration
- Abstraction and,
- Stream flow

Abstraction was the only component possible to estimate for Gwembe District during the study. Further investigations are required in order to determine other inflow and outflow components before the water balance is estimated. Additionally, measurement of groundwater levels at several observation boreholes for at least two rainy seasons is inevitable for recharge estimation.

4.3.3 Groundwater Quality Data Collection

A total of 154 production boreholes were sampled for water quality evaluation; 20 boreholes in the Basement Complex, 93 boreholes in the mudstone and 41 boreholes in the sandstone aquifers. The groundwater quality results obtained were important for further groundwater resources assessment for development and utilisation in the twelve wards of Gwembe District. Groundwater quality evaluation provided details on existing

water quality constraints in the Basement Complex, sandstone and mudstone aquifers, baseline values (Appendix G1) and also facilitated classification of groundwater resources for domestic, agriculture and industrial uses.

4.3.3.1 Groundwater Type and Hydrogeochemical Characterisation

Drilling logs for the study areas in Gwembe District indicate that sandstone and mudstone are stratified and form an intercalation. According to Freeze and Cherry (1979), four geochemical processes are important for groundwater in stratified sedimentary rocks:

- i) cation exchange,
- ii) CO₂ generation below the soil zone,
- iii) Biochemical reduction of sulphate,
- iv) Oxidation of sulphate minerals,

Four cationic dominated groundwater types are identified in the mudstone, sandstone and Basement Complex aquifers of Gwembe District. These are potassium, magnesium, calcium and sodium groundwater types, which are both single and compound groundwater types. The latter is the most prevalent type with mixed cationic – bicarbonate water type, a situation characteristic of many groundwater in stratified sedimentary sequences where Na⁺ and HCO₃⁻ are predominant ions (Freeze and Cherry, 1979). The sodium groundwater types are: NaHCO₃, Na-Mg-HCO₃, Na-Ca-HCO₃, Na-Ca-Mg-HCO₃-SO₄, Na-Ca-Mg-HCO₃-Cl and Na-Mg-Ca-SO₄; the calcium groundwater types are: Ca-Na-Mg-HCO₃, Ca-Mg-Na-HCO₃, Ca-Na-Mg-HCO₃-Cl, Ca-Na-Mg-SO₄-

CO₃-Cl, Ca-Na-Mg-Cl and Ca-Mg-Na-Cl; the magnesium groundwater types are: MgHCO₃, Mg-Na-HCO₃ and Mg-Na-Ca-HCO₃-Cl-SO₄ and; the potassium groundwater type is: KSO₄.

Strong sodium input was observed in the three aquifer lithological units; the Basement Complex (Figures 4.54), sandstone (Figure 4.55) and mudstone (Figure 4.56).

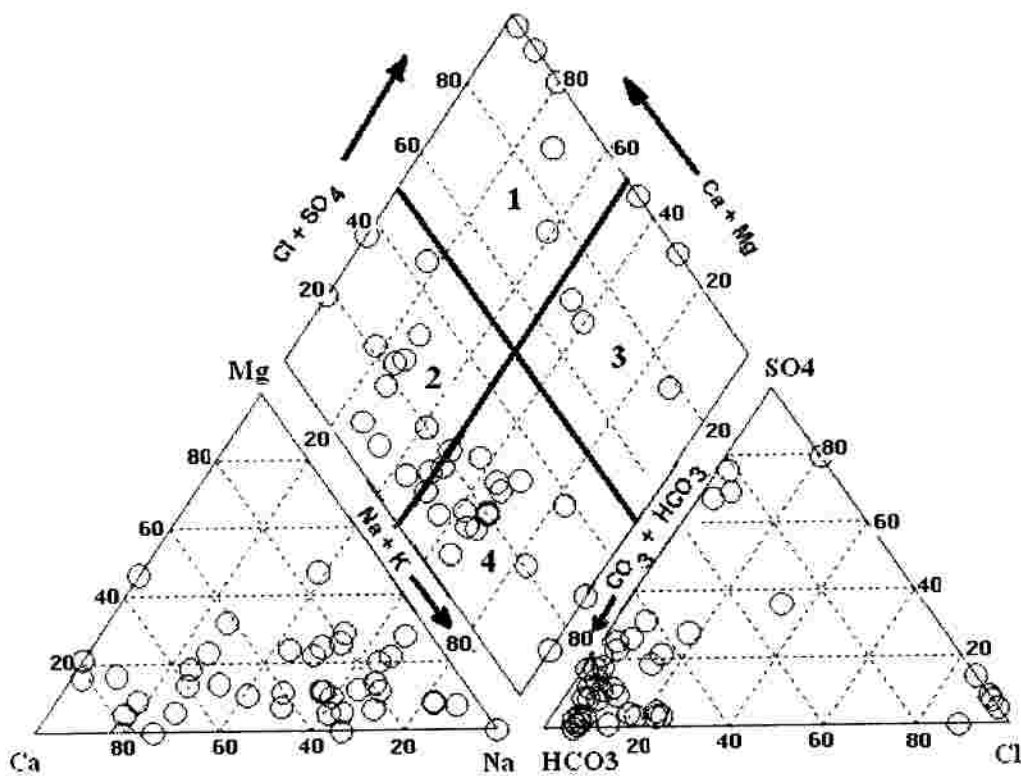


Figure 4.54 Chemical facies of the groundwater in the Basement Complex aquifer lithology of Gwembe District. ¹calcium magnesium sulphate chloride; ²calcium magnesium bicarbonate ; ³sodium sulphate chloride; ⁴sodium bicarbonate

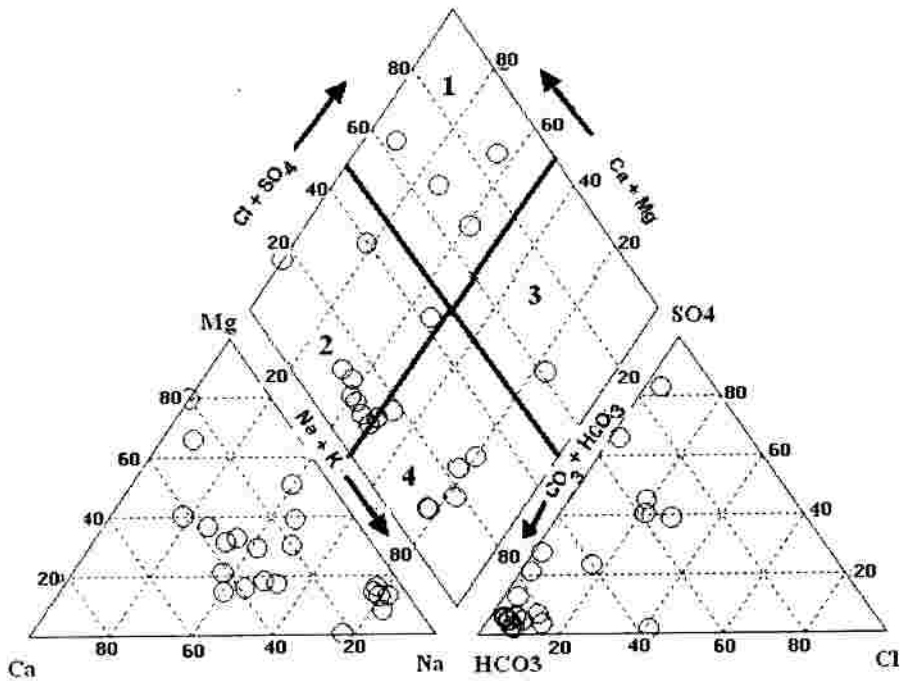


Figure 4.55 Chemical facies of the groundwater in the sandstone aquifer lithology of Gwembe District. ¹calcium magnesium sulphate chloride; ²calcium magnesium bicarbonate; ³sodium sulphate chloride; ⁴sodium bicarbonate

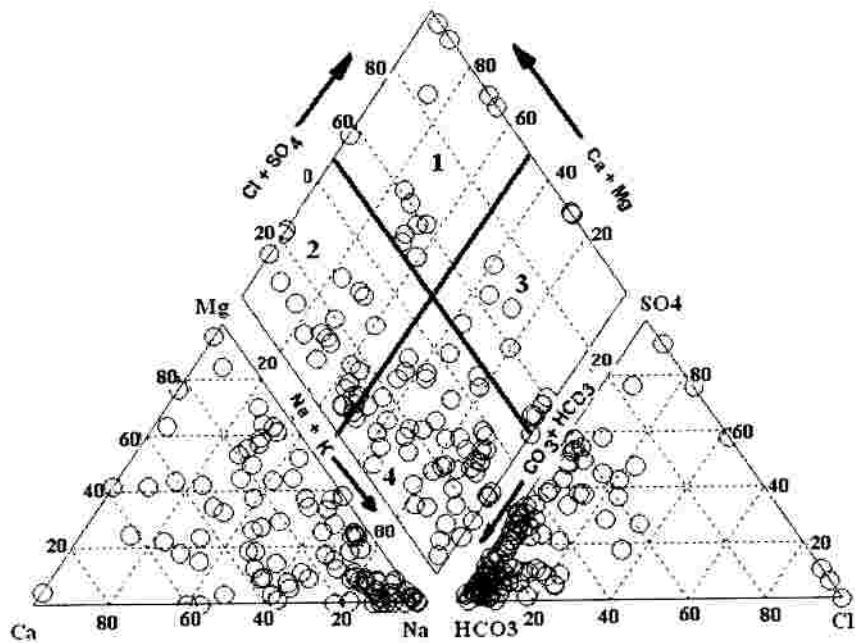
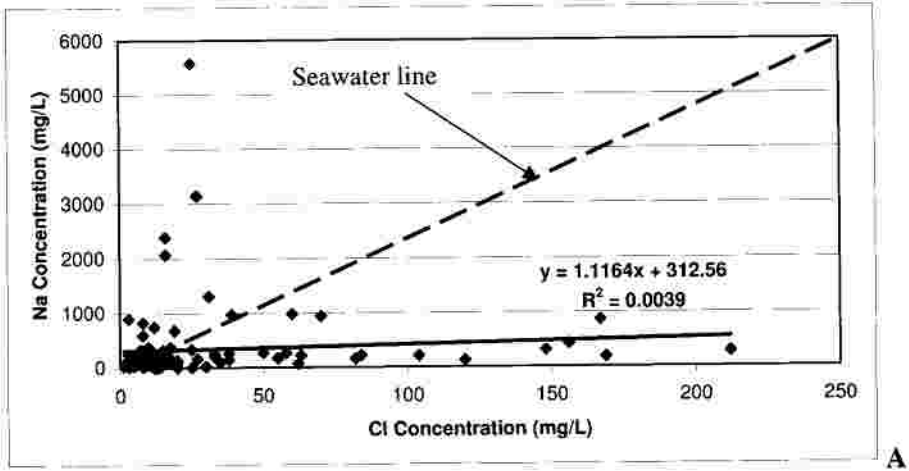


Figure 4.56 Chemical facies of the groundwater in the mudstone aquifer lithology of Gwembe District. ¹calcium magnesium sulphate chloride; ²calcium magnesium bicarbonate; ³sodium sulphate chloride; ⁴sodium bicarbonate

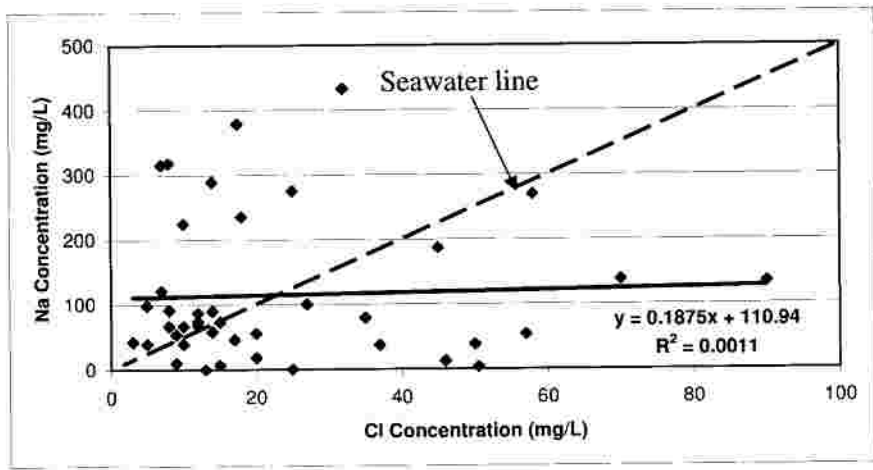
in the Basement Complex and sandstone aquifers, sodium input is attributed to evaporation since it is in low concentrations, whereas in the mudstone where it is most prominent and in high concentrations, sodium input is attributed to both evaporation and geological strata. The process of releasing sodium from the geological strata also leads to an increased HCO_3^- content in groundwater [Equations 4 – 9 and 4 – 10] and eventually sodium cationic dominated groundwater types. High sodium concentrations observed also suggest long groundwater residence time and low groundwater recharge with little flushing of the groundwater system. Biochemical SO_4^{2-} reduction is another process that could lead to increased HCO_3^- content in groundwater in sedimentary regions.



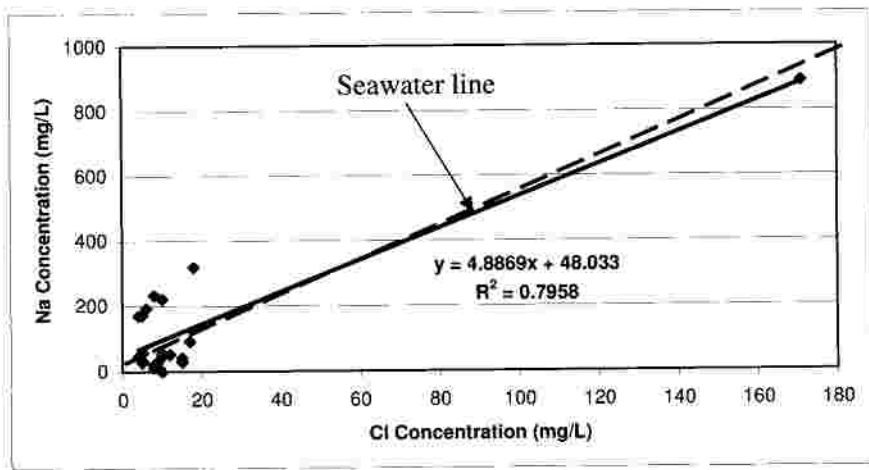
The Na/Cl ratio is higher than the seawater ratio (0.86) for most of the boreholes (Figure 4.57). This may suggest little recharge, high Evapotranspiration and that groundwater in Gwembe District have long residence time. In addition, poor Na/Cl correlation indicates that the sources are different.



A



B



C

Figure 4.57 Na/Cl ratio for boreholes in aquifers in Gwembe District: ^Amudstone (93 samples), ^Bsandstone (41 samples), ^CBasement Complex (20 samples)

3.3.2 Groundwater Quality Evaluation for Domestic and Irrigation use

The Basement Complex, mudstone and sandstone aquifers of Gwembe District generally have groundwater suitable for domestic uses. However, constraints associated with concentrations exceeding recommended limits for water quality parameters, especially magnesium (Mg^{2+}), sodium (Na^+), (NO_3^-), sulphate (SO_4^{2-}), fluoride (F), iron (Fe), and manganese (Mn) (Appendix G) exist in some parts of the district. Elevated Fluoride levels are in the same range as reported in the Groundwater Resources Inventory of Zambia (Chenov, 1978). Elevated nitrate levels (Figure 4.58) for boreholes in Gwembe District are also attributed to natural influence associated with arid and semi arid areas (Fredoux, 2004). Anthropogenic influence is expected to result from livestock and crop farming. Additionally, Figure 4.59 indicates that there is no correlation between high nitrate levels and the borehole depth; further confirming the natural and anthropogenic influence.

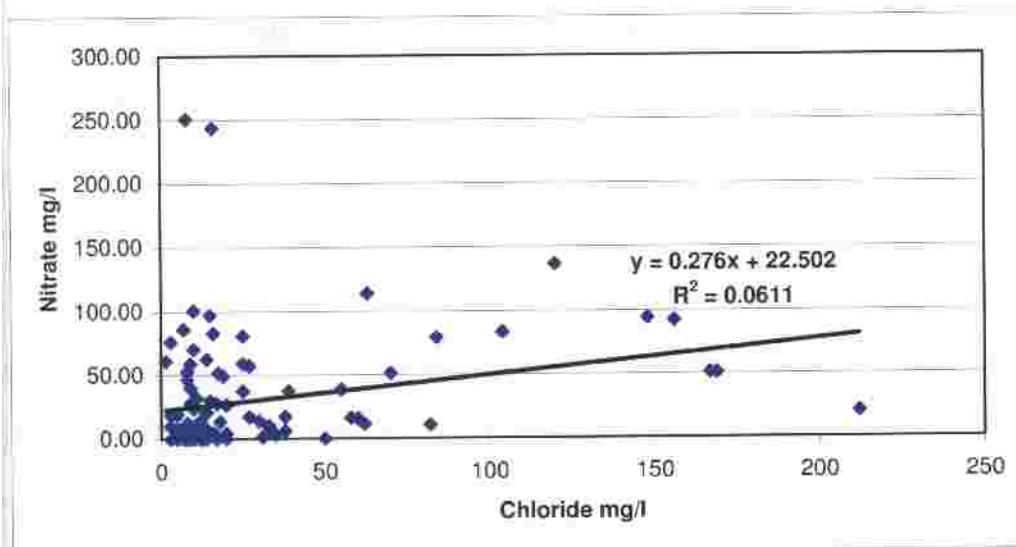


Figure 4.58 Correlation of nitrate and chloride concentrations for boreholes in Gwembe District

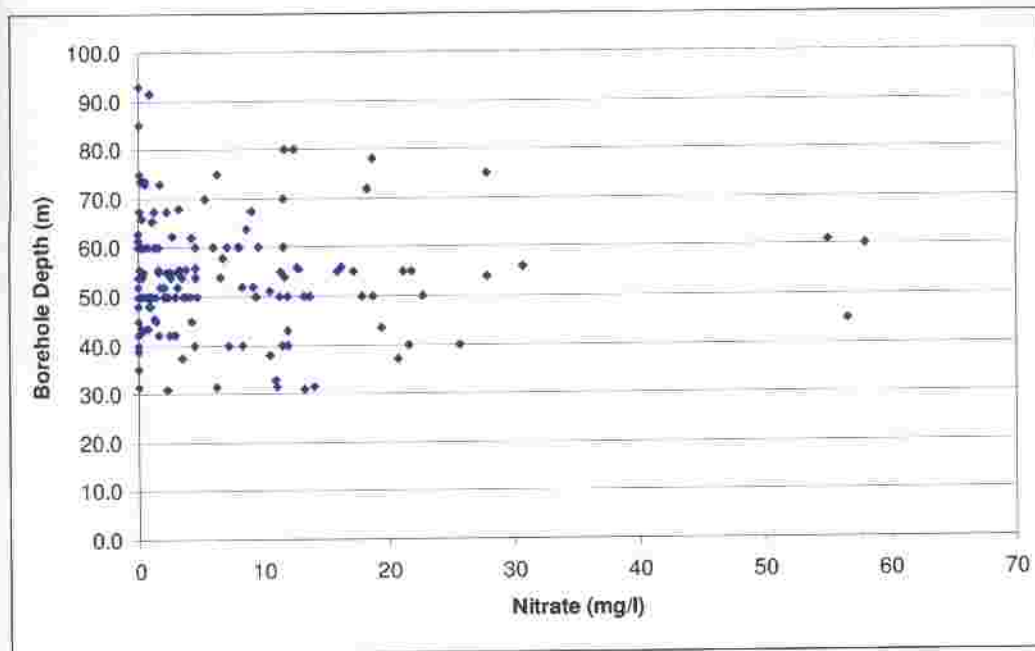


Figure 4.59 Correlation of nitrate concentration to borehole depth in Gwembe District

Geologically, the project area belongs to the Karoo Supergroup (Upper and Lower) and partly the Basement Complex. Hence, natural influence of the geology on groundwater quality is suggested, especially that the sedimentary facies in Karoo Supergroup in the mid-Zambezi Valley are strongly associated with accumulation of organic deposits (Nyambe, 1993).

Water quality results for most boreholes show that groundwater is excellent for long-term irrigation purposes (Tables 4.64 to 4.66). However, care must be taken with regard to Magnesium Hazard (MH), sodium toxicity, commonly referred to as Sodium Adsorption Ratio (SAR) and chloride toxicity for specific boreholes when using groundwater for Irrigated agriculture. Groundwater samples analysed that lie in the “harmful” class of magnesium hazard are about 45%.

ble 4.64: Combined SAR, MH and Cl Toxicity for boreholes in mudstone aquifer

o.	X	Y	Cl			No.	X	Y	Cl		
			Toxicity (meq/l)	SAR	MH				Toxicity (meq/l)	SAR	MH
1	587897	8141858	1.75	1.87	23.57	48	580745	8166011	0.56	0.02	4.63
2	591934	8140117	0.71	0.12	65.65	49	581565	8165854	0.23	17.59	51.54
3	600712	8150120	0.25	1.33	26.48	50	590256	8153671	1.10	27.98	82.56
4	614300	8162449	3.38	2.27	49.30	51	565007	8175870	0.14	1.26	82.16
5	597130	8169212	0.34	6.38	81.63	52	599965	8152991	0.34	28.74	44.31
6	605572	8175860	0.42	8.41	86.08	53	600274	8153265	0.45	92.28	84.20
7	613769	8175145	5.98	2.76	92.28	54	586378	8146158	0.71	10.28	0.98
8	601605	8170950	1.64	6.48	15.08	55	578234	8164044	0.11	1.32	72.78
9	586059	8168998	0.76	3.23	91.87	56	580025	8149489	0.39	2.96	19.80
10	609455	8166446	1.55	5.53	27.81	57	583599	8157579	0.34		75.86
11	614289	8160317	0.85	0.40	91.51	58	579687	8149199	0.23	1.77	1.45
12	601569	8174564	0.39	3.89	83.92	59	572498	8146133	0.08	0.49	52.63
13	576642	8169683	0.28	1.85	74.23	60	574450	8146243	0.39	7.90	49.69
14	595553	8168510	0.14	2.48	81.97	61	576309	8146919	0.34		42.79
15	597457	8155806	0.28	2.12	37.17	62	594017	8164426	0.37		94.89
16	586949	8160584	0.20	2.81	47.00	63	570178	8172544	0.23	36.18	79.80
17	603551	8174352	0.51	2.39	49.19	64	586404	8164240	0.25	8.44	42.00
18	604553	8176255	0.14	13.25	66.39	65	601954	8174516	0.45		
19	604855	8177833	1.07	3.23	73.35	66	604942	8176278	0.71	152.98	93.63
20	603145	8174904	0.45	7.41	78.74	67	608935	8177315	0.08	50.66	73.09
21	606329	8179178	0.93	2.96	91.80	68	611107	8177859	0.14	5.25	53.35
22	605447	8178869	0.93	7.58	86.39	69	563355	8128013	1.41	16.67	26.68
23	586072	8160615	0.39	0.35	46.38	70	583110	8159044	0.08	1.50	0.00
24	582335	8161032	0.23	0.46	28.52	71	578109	8147705	0.48	2.92	36.33
25	600912	8171042	4.71	11.66	79.49	72	607433	8176336	0.23	3.54	99.26
26	597703	8169514	0.20	16865.50	62.21	73	601954	8174516	0.87	70.22	63.35
27	598552	8169811	0.28	16290.84	62.21	74	623129	8182922	0.04	1.77	66.01
28	604926	8179050	0.49	20259.98	62.21	75	572688	8132848	0.34	2.49	27.15
29	606724	8176251	0.28	20259.98	62.21	76	562159	8126958	0.28	2.46	58.45
30	612616	8178609	0.23	11.40	45.64	77	561305	8128539	0.34	0.94	30.07
31	613774	8178904	4.76	2.46	89.29	78	563438	8126594	0.25	7.44	49.69
32	617125	8178394	1.78	12.19	0.00	79	562159	8126958	0.23	7.02	38.99
33	619124	8180611	4.17	6.40	8.99	80	579580	8138703	0.28	5.61	40.33
34	616465	8177436	0.42	15.45	0.00	81	562929	8128046	0.14	2.03	50.85
35	614056	8174975	4.40	32.30	0.00	82	580507	8142609	0.37	10.08	34.10
36	614811	8173763	2.93	14.34	0.00	83	583320	8146360	0.37	4.37	30.40
37	616369	8172411	2.37	13.20	0.00	84	580337	8142589	0.25	9.46	55.25
38	618499	8175384	0.76	197.99	91.60	85	582450	8140112	0.56	5.55	47.06
39	621045	8176731	2.31	2.96	62.04	86	584371	8138978	0.99	3.27	33.46
40	595583	8164053	0.28	16290.84	62.21	87	581390	8167238	0.23	2.70	78.00
41	584311	8168471	0.08	8.92	45.41	88	589984	8166817	0.37	5.66	86.61
42	608477	8166337	1.97	23.18	29.25	89	584931	8158804	0.25	2.94	21.22
43	609303	8166763	0.54	24.62	44.20	90	585334	8160341	0.14	5.25	53.35
44	606475	8166104	1.69	26.73	17.06	91	581924	8158655	0.23	2.57	7.06
45	613448	8167716	0.48	11.14	5.07	92	592612	8175532	0.08	3.15	76.25
46	582784	8158461	0.31	5.62	4.24	93	595794	8174865	0.56	1.64	35.20
47	589177	8142083	0.39	3.71	20.11	94	587240	8164638	0.20	5.24	69.74
Maximum allowable limit			4	10	50	Maximum allowable limit			4	10	50

MH = Magnesium Hazard,

SAR = Sodium Adsorption Ratio

Table 4.65: Combined SAR, MH and Cl Toxicity for boreholes in basement aquifer

No.	X	Y	Cl Toxicity (meq/l)	SAR	MH	No.	X	Y	Cl Toxicity (meq/l)	SAR	MH
1	577314	8171837	0.48	2.17	34.61	11	564461	8176591	0.42	1.60	51.37
2	564171	8173817	0.34	1.73	84.29	12	564096	8176580	0.28	3.62	25.19
3	574827	8164194	0.28	2.12	37.17	13	564471	8178075	0.14	1.59	39.70
4	565048	8174887	0.14	2.03	29.91	14	575751	8145682	0.28		79.82
5	563682	8174924	0.23	0.95	52.17	15	577071	8171995	0.23	8.21	72.50
6	565826	8177213	0.11	1.97	61.31	16	564828	8176544	0.51	11.00	73.50
7	578246	8170746	0.23	0.32	71.75	17	590864	8178988	0.14	7.13	65.84
8	574821	8172676	0.25	0.99	49.69	18	589202	8180184	0.11	7.43	65.66
9	604553	8176255	4.82	19.18	49.66	19	573802	8163633	0.28	1.42	46.86
10	564132	8176917	0.42	1.47	73.38						
Maximum allowable limit			4	10	50	Maximum allowable limit			4	10	50
MH = Magnesium Hazard,						SAR = Sodium Adsorption Ratio					

Table 4.66: Combined SAR, MH and Cl Toxicity for boreholes in sandstone aquifer

No.	X	Y	Cl Toxicity (meq/l)	SAR	MH	No.	X	Y	Cl Toxicity (meq/l)	SAR	MH
1	588333	8142072	1.04	1.07	32.15	20	589934	8142716	0.99	2.17	18.83
2	590262	8144061	1.30	0.33	18.36	21	593484	8142787	0.76	4.07	3.47
3	587535	8140176	1.42	0.09	17.21	22	583713	8146679	0.14	4.12	42.29
4	577476	8147086	1.61	1.34	8.46	23	580794	8169606	0.08	1.14	44.14
5	602040	8145446	1.41	0.89	1.15	24	608948	8166995	0.90	16.32	59.40
6	553410	8128004	1.64	6.48	15.08	25	613917	8167747	0.71	10.44	48.17
7	591976	8141853	1.27	6.18	21.73	26	614593	8168462	0.34	2.71	44.59
8	597977	8165886	0.23	2.98	61.77	27	575489	8139666	0.42	0.36	8.99
9	588891	8143077	0.39	3.13	27.95	28	589325	8142992	0.48	1.98	49.69
10	598946	8147974	0.51	6.09	57.44	29	585756	8145450	0.42	1.99	76.40
11	599554	8151945	0.20	533.33	62.21	30	596446	8164812	0.56	0.59	12.76
12	596381	8145961	0.23	11.40	45.64	31	562638	8131641	0.39	1.58	21.66
13	596713	8146623	0.28	1.11	18.97	32	571860	8130746	0.34	2.14	42.99
14	600130	8149724	0.14	1.06	25.69	33	563555	8131647	0.28	6.18	83.16
15	599847	8147561	0.39	6.68	34.01	34	582143	8145557	0.34	2.88	28.78
16	572772	8135324	0.28	2.95	16.16	35	579852	8139023	0.56	2.12	22.86
17	564898	8132590	0.25	2.16	14.84	36	583856	8141712	2.54	4.09	26.23
18	571224	8134324	0.23	3.52	37.94	37	592482	8143161	1.97	4.82	64.94
19	559095	8128950	0.25	0.54	2.99	38	582911	8152322	0.20	3.48	56.22
Maximum allowable limit			4	10	50	Maximum allowable limit			4	10	50
MH = Magnesium Hazard,						SAR = Sodium Adsorption Ratio					

Evaluation of the distribution of boreholes with good MH, SAR and chloride toxicity in three aquifer lithologies (Figure 4.60) indicates a good aerial distribution of groundwater that would support long-term irrigated agriculture. Sandstones and mudstones are the most productive aquifer lithological units with groundwater suitable for irrigation in Gwembe District.

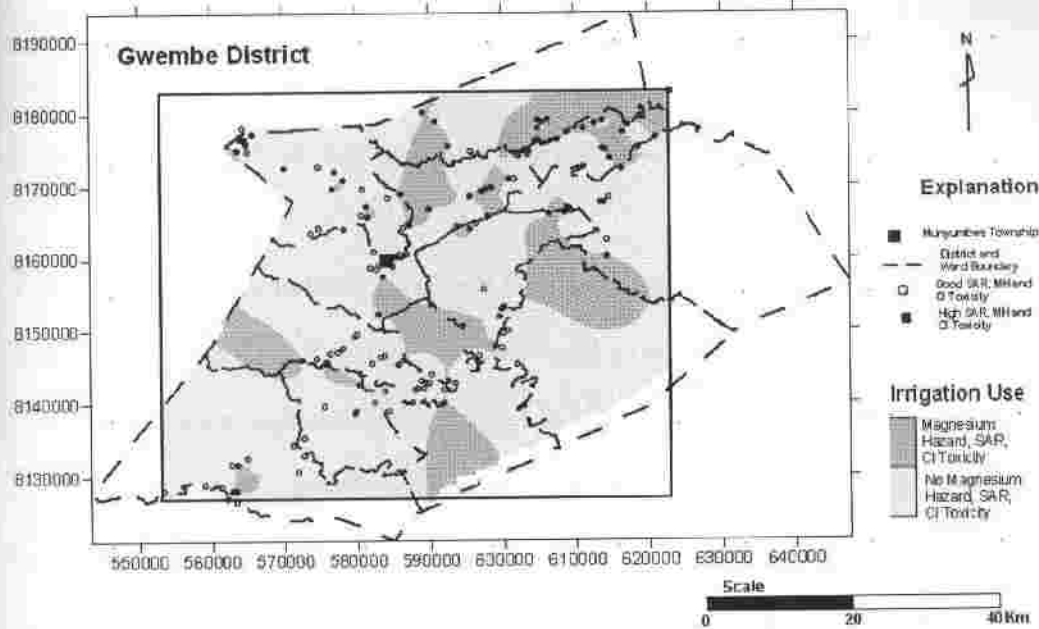


Figure 4.60 Map showing groundwater irrigation potential in wards of Gwembe district

Since Munyumbwe Township is located in an area with excellent groundwater for both irrigation and domestic purposes, abstraction must therefore be controlled to avoid groundwater intrusion from aquifers that do not meet irrigation requirements for SAR, Cl Toxicity and MH.

4.3.3.3 Impact of Groundwater Quality on the Operation and Maintenance of Handpumps

It was observed that hand pump raiser pipes and rods were replaced on a yearly basis at a number of boreholes due to corrosion. The scenario increases operation and maintenance costs of rural water supply facilities. Hence, groundwater quality seems to have an impact on the life span of hand pump facilities. Therefore, groundwater quality analysis should be a prerequisite in the development of groundwater resources projects for rural water

supply. This would facilitate selection of suitable hand pump materials such as stainless steel pipes and plastic pipes with stainless steel rods. It will help also to control the operation and maintenance costs of handpump facilities.

4.3.3.4 Proposed Groundwater usage in Gwembe District

Groundwater usage for irrigation purposes need promotion in most of the wards in Gwembe District to improve food security and offer opportunities for economic growth. In most of the wards, groundwater is suitable for domestic, irrigated agriculture and industrial purposes. However, limitation due to water quality constraints is an indication for the need to promote stringent groundwater management for aquifers in the district. Therefore, the following are the recommendations on groundwater usage:

- high production boreholes for irrigated agriculture are feasible in most parts of Fumbo, Luumbo, Syampande, Jongola Chibuwe, Sinafala and Masanga wards. Boreholes should be drilled to improve food security through irrigated agriculture.
- there is need to establish the recharge and effective porosity for the Basement Complex, mudstone and sandstone aquifer lithologies for the estimation of aquifer storage and groundwater replenishment.
- comprehensive analysis of water quality results in relationship to boreholes with frequent replacement of hand pump riser pipes and rods is required to facility preparation of technical standards and guidelines to support cost effective operation and maintenance of rural water supply hand pump facilities.

- GPS coordinates should be taken for all boreholes together with the water usage and develop a district data base to support sustainable groundwater management and utilisation.

Contrary to the view that mudstones are poor aquifers, the study shows that mudstones are capable of providing high yielding boreholes to support even irrigated agriculture. Groundwater exploitation in Gwembe District should therefore be targeted at both sandstone and mudstone aquifers.

4.3.3.5 Exploitation and Abstraction of Groundwater for Munyumbwe Township

The area with high groundwater potential as well as suitable for exploration and exploitation around Munyumbwe Township is specifically around UTM Northings 8161000 and UTM Northings 8158000; and UTM Eastings 587900 and UTM Eastings 582400. Effective saturation depth in the sandstone-mudstone aquifer around Munyumbwe is about 42m.

Management of groundwater would also be of paramount importance to support management of aquifers by limiting anthropogenic activities that may lead to pollution on the hill slopes. This is also achievable through management of waste for existing human activities. Therefore an area around Munyumbwe Township was delineated (Figure 4.61) based on the Satellite image with the resolution of 90m x 90m (Figures 4.62) and the extent of the sandstone-mudstone groundwater flow controlled system (Section 4.3.1.2).

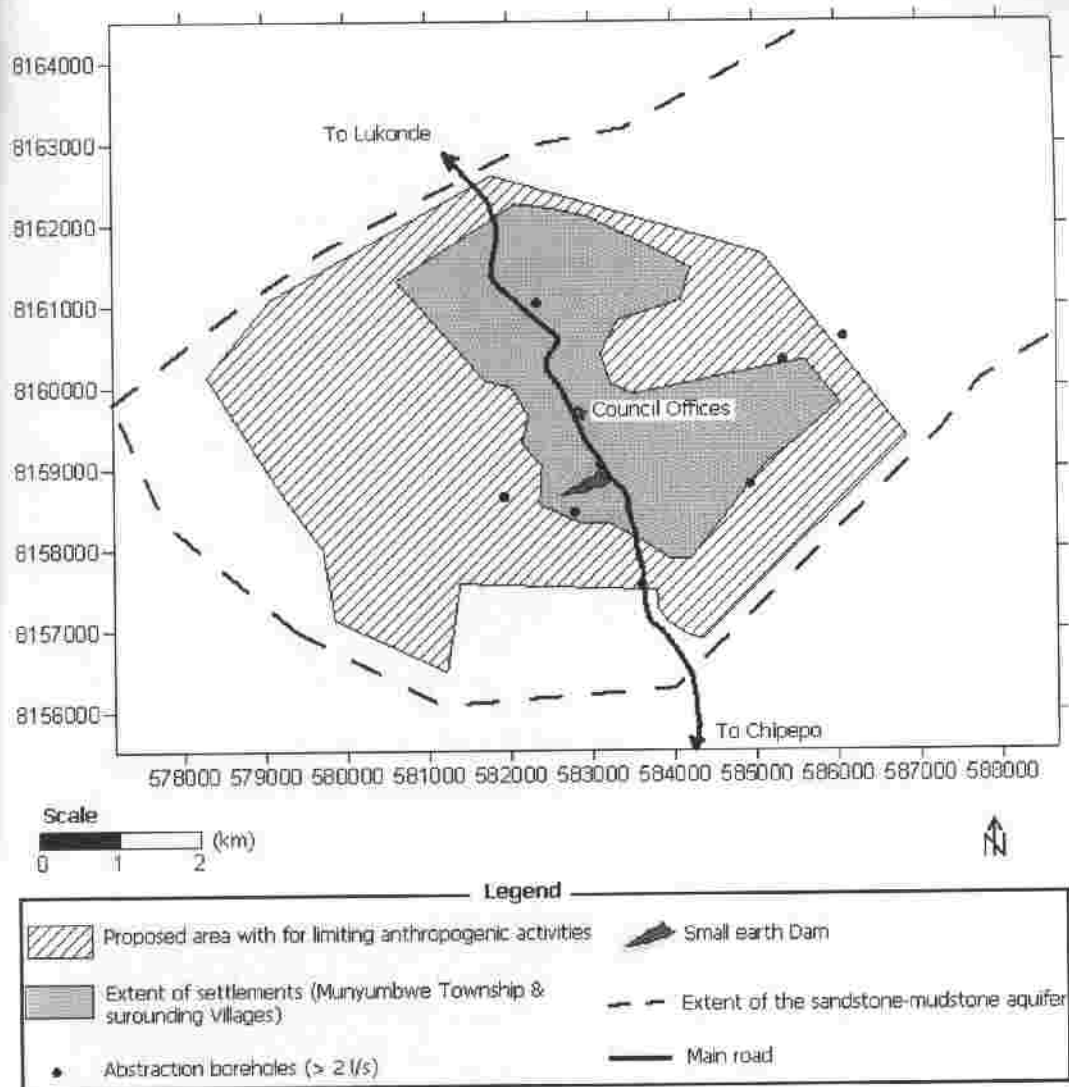


Figure 4.61 Map showing proposed groundwater protection measures around Munyumbwe in Gwembe district

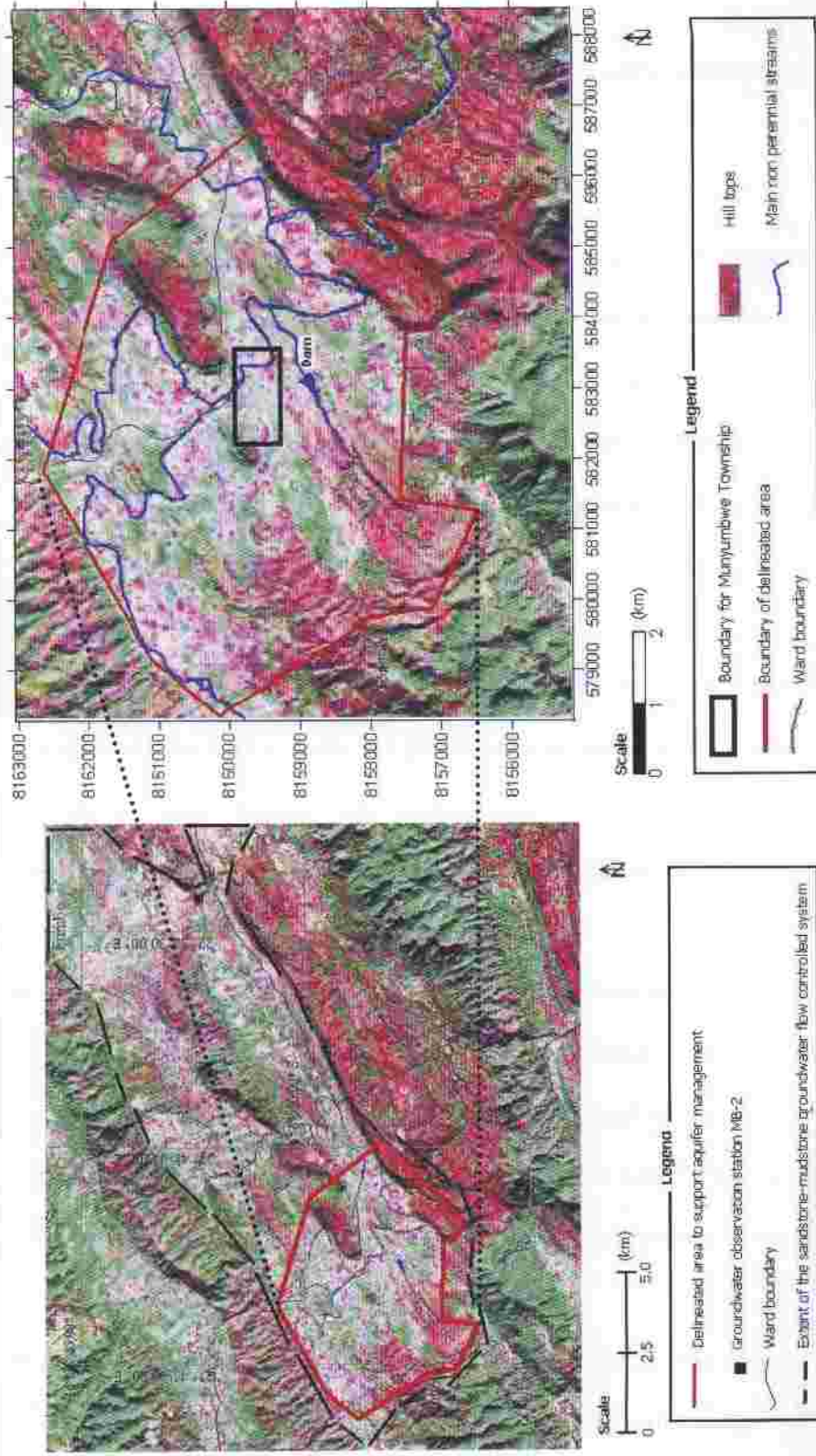


Figure 4.62 Delineation of the aquifer management area for groundwater protection in Gwerembe District (USGS Satellite Image)

4.4 Borehole Numbering

The following were the key issues considered and evaluated when making the proposed borehole numbering system:

- The two main river systems and basin blocks are more stable to use than the provincial and district boundaries when numbering the boreholes.
- The proposed numbering of boreholes must be inline with the water resources management approach of using catchments (basins) and sub-catchments proposed by the Ministry of Energy and Water Development through the Water Resources Action Programme (WRAP, 2003).

The proposed borehole numbering system should therefore enhance sustainable allocation of both surface water and groundwater resources management at country level as well as when dealing with internationally shared surface water bodies and transboundary aquifers. Borehole numbering should be as described below:

- ❖ Boreholes should be numbered according to the two main river basins, which are divided into six catchments (WRAP, 2005), but defined by the 34 basin blocks (JICA Report, 1995) or sub-catchments (WRAP, 2005) and have estimated surface water resources potential figures. Since each borehole will have GPS coordinates, issues of provinces, districts, constituencies and wards are easy to accommodate because of the use of GIS with the database.
- ❖ Maximum average number of boreholes in the smallest of the 34 basin blocks should be taken as 5,000 and as a minimum for basin blocks with a larger surface area. The

5,000 minimum average number of boreholes gives an average borehole density of about 5 boreholes per Km² for smaller basin blocks.

❖ Boreholes should be categorised according to the abstraction levels and usage such as:

- high abstraction and large diameter boreholes (**LB**) of 150mm and above,
- low abstraction and small diameter boreholes (**SB**) meant for rural water supply,
- monitoring boreholes (**MB**) meant for groundwater level measurement and groundwater quality evaluation.

This type of differentiation is important when evaluating abstraction levels, monitoring of groundwater usage and other analysis meant for development and management purposes.

❖ The exact year of construction or a threshold year of construction for boreholes without records should be part of the numbering system in the database. This will help to evaluate progressive impact of groundwater abstraction and make it possible for random registration of boreholes in the database without really following the order of year of construction.

Combining the details from the JICA report (1995) and WRAP (2005), borehole numbering using the six proposed catchments (basins) in Zambia should be as indicated below and as shown in Figure 4.63:

Table 4.68: Assigned catchment codes and number of sub-catchments for Zambia
(after JICA Report, 1995)

Catchments	Catchments' code	Number of Sub-catchments
Zambezi Main River	BZ	9
Kafue River	BK	11
Luangwa River	BL	5
Chambeshi River	BC	2
Luapula River	BP	5
Lake Tanganyika	BT	2

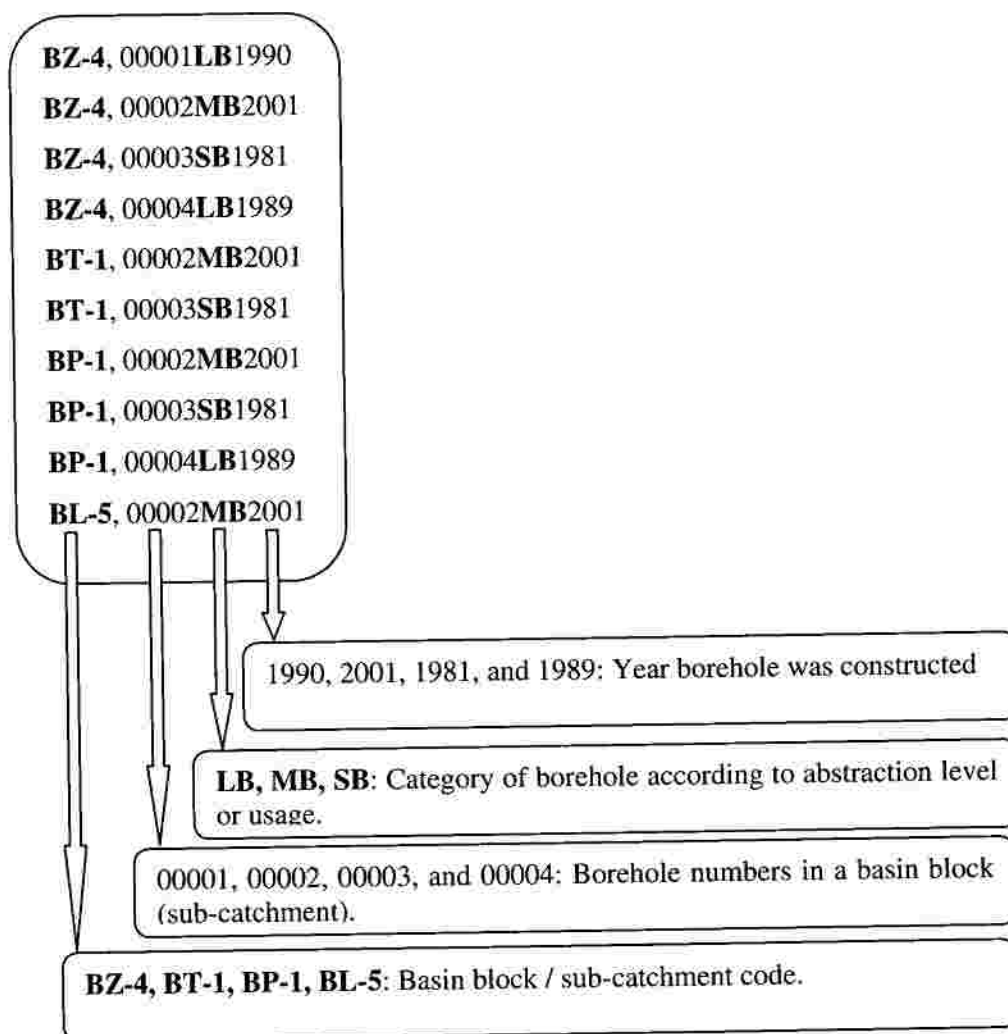


Figure 4.63 Description of the proposed borehole numbering system based on the basin blocks (sub-catchments) in the two main river basins: Zambezi and Congo River systems.

Changes and modifications to the proposed borehole numbering system are possible. However, the principle of using catchments in the two river system is cardinal. Sustainable groundwater abstraction at a block division / sub-catchment need to be compared to the surface block water resources potential in order to avoid over abstraction and eventual stream flow reduction especially in areas with low surface water potential. However, this may not achievable without availability of groundwater data and information, which is crucial in supporting groundwater resources management decisions.

4.5 Strategy for Enhancing Groundwater Exploration in Zambia

The government of the republic of Zambia through the Ministry of Energy and Water Development-Water Affairs Department has been carrying out groundwater exploration on a small scale. However, improvement is required in the collection of groundwater data and information. The following is the strategy aimed at up scaling of groundwater exploration with participation of the stakeholders:

- all boreholes drilled should serve as exploratory boreholes so that accurate and relevant groundwater data and information is collected together with GPS coordinates for submission to relevant government institutions to ensure better planning.
- to build capacity in the stakeholders especially the drillers on the manner and how groundwater data and information need to be captured.
- Groundwater quality analysis must be carried out at the time of drilling for every borehole constructed for the parameters: K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Fe, Mn, NO_3^- , F, Cl^-

, SO_4^{2-} , HCO_3^- , pH, EC and Temperature to facilitate groundwater classification for various uses. This will also provide baseline data on groundwater quality.

- Highly exploited aquifers must have observation boreholes to facilitate regular groundwater level measurement and routine water quality evaluation.
- technical standards and regulations need to be developed to guide groundwater exploration and exploitation in Zambia.

Carrying out of these activities with stakeholder participation will ensure full utilisation of the economic potential of Zambia's groundwater resources and thereby contribute to poverty reduction. Legislation, technical standards and regulations are also inevitable and key to the success of accurate, consistent acquisition of groundwater data and information. Figure 4.64 (Appendix G2) gives details on the proposed data capture.

4.5.1 Hydrogeological and Water Quality Data

Three parties are directly involved in making available the data for public use; the borehole owner, driller and the institution (MEWD) with the mandate to collect water resources data. However, MEWD has an important role to give direction on the type of information to be collected and how it should be done; whereas the driller is the main factor in ensuring that information is collected during borehole construction according to the standard procedure. The following are therefore important to improve to facilitate hydrogeological and water quality data acquisition:

- Drilling contractors are the key stakeholders in the acquisition of hydrogeological data and collection of groundwater samples. They should therefore be sensitised

on the need to use the official borehole completion report and on the importance of water quality analysis to ensure uniformity and reliable data acquisition.

- GPS units, must constitute standard field equipment to ensure inclusion of coordinate readings on a borehole completion report form for both successful and dry boreholes. A Driller for each drilling crew should therefore receive training on how to use the GPS unit.
- Groundwater samples for water quality analysis should be collected during drilling towards the end of well development or pump testing of the borehole. This entails capacity building of the driller to ensure sampling according to standard procedure. A driller through appropriate capacity building could still handle water quality analysis kits for pH, temperature and Electrical Conductivity measurement as well as standard forms for recording information. Collected groundwater samples should only be analysed by reputable Laboratories within or out side Zambia.
- Ministry of Energy and Water Development should start the exercise of borehole numbering to facilitate resource management. Finalisation of the numbering system may require stakeholder consultation.
- Guidelines and technical standards are urgently required to ensure uniformity in borehole construction as well as facilitate data acquisition.

4.5.2 Groundwater Level Measurement and Routine Water Quality Evaluation

MEWD through the Department of Water Affairs is the key institution to ensure countrywide, aquifer specific groundwater measurement, and routine groundwater quality evaluation. Water Utilities that abstract substantial quantities of groundwater for their

water supply are amongst the key stakeholders that MEWD should sensitise to fully participate in aquifer specific groundwater level measurement and routine groundwater quality evaluation. Therefore, the following are important in order to achieve consistent data acquisition:

- Groundwater Observation Boreholes must be constructed at premises of government institutions or sites where security, and permanent accessibility to the facility will be assured. Borehole diameter size should facilitate for measurement of water levels and collection of groundwater samples for routine water quality evaluation.
- Countrywide observation boreholes require rainfall and other meteorological data. Therefore, these must be constructed in towns with met stations.
- Water Utilities should fully participate in groundwater monitoring in specific aquifers to ensure water resources management.

Measurement of groundwater level fluctuation at specifically selected monitoring points for a long time would facilitate management of groundwater resources by controlling or regulating abstraction.

4.5.3 Database for Storage, Analysis and Dissemination

The Ministry of Energy and Water Development is the Institution that must solely undertake the responsibility of data storage, analysis and dissemination of groundwater data and information. This entails developing an integrated water resources data base with a component on surface water and groundwater that should operate as one data

management system. This will facilitate sustainable allocation of both surface and groundwater resource and eventual resource management. However, certain information on groundwater will need to be shared with/submission to the Local Authorities to facilitate smooth implementation of the operation and maintenance of rural water supply facilities. This entails data harmonisation between MEWD and MLGH.

A relevant institution must be responsible for storage of groundwater data and information as hard copy on box files and electronic national database. Effective use of groundwater resources will largely depend on the analysis and dissemination of collected groundwater data and information. The public therefore need information based on analysed data to facilitate informed decision making for socio-economic growth.

4.6 Scientific Contributions of the Study

To make a scientific impact, the thesis has made significant contributions to the field of hydrogeology in Zambia as follows:

4.6.1 Interpretation of Groundwater Abstraction in Lusaka urban Aquifers

The current level of groundwater abstraction in Lusaka urban aquifers is more than the official annual recharge percentage of 8% of the annual rainfall. Interestingly, the current abstraction level seems beneficial in keeping dry most of the residential and other built up areas that would flood during the rainy season or get water logged for most of the time in the year. Therefore, abstraction at about the current level or slightly more need to continue to avoid groundwater build up in good rainy years that would cause surface

flooding of some built up areas. However, this may affect the upper aquifer in some areas in terms of reduced yield and drying up of shallow boreholes during the dry season.

4.6.2 The Role of Lusaka South Forest Reserve

Annual dilution and flushing out of polluted groundwater in the Lusaka urban aquifers is attributed to groundwater from Forest 26 and part of Forest 55 (Lusaka South Forest Reserve), which forms the main recharge area for aquifers on Lusaka Plateau.

4.6.3 Information on Recharge Mechanism and Aquifer System for the Lusaka Plateau

Direct recharge occurs in the carbonates and this facilitates recovery of the aquifers in good rainfall years, whereas the amount of effective recharge that contributes to sustainable groundwater levels in the aquifers on Lusaka Plateau is dependant on the combined effect of rainfall amounts, number of rainfall days and rainfall distribution; as opposed to rainfall amounts only. Rainfall amount as low as 450mm are able to cause aquifer recovery in the same manner as 900mm of rainfall at rainy days to rainfall period ratio of 0.4 and above when observed at the International Airport, Mount Makulu, City Airport and Sheki-Sheki DWA meteorological stations.

Lusaka Plateau is identified to be both an aquifer system and groundwater flow system, comprising of the Cheta-Lusaka Dolomite.

4.6.4 Design and Documentation of the Lusaka Plateau Groundwater Monitoring Network

Design of the groundwater observation sites for Lusaka Plateau for aquifer management in terms of yearly recharge assessment, delineation of protection zones, general aquifer management, early warning to effect abstraction control and plan for groundwater usage. The design was based on information needs targeting quantity and quality, geology and aquifer lithology, drainage pattern and morphology, distribution of meteorological stations, security and permanent access to the installations; and groundwater modelling needs.

4.6.5 Hypothesis on Regional Groundwater Flow

The ever recovering and high groundwater levels observed in Lusaka urban aquifers is attributable not only to direct recharge that is high, but also to the influence of regional groundwater flow in the Katanga Supergroup.

4.6.6 Documentation on the Aquifer Systems of Gwembe District

The Basement Complex and the sandstone-mudstone are the two important groundwater flow aquifer systems with a reasonable potential for groundwater exploration and exploitation.

4.6.7 Documentation on the Aquifer around Munyumbwe Township in Gwembe District

The township of Munyumbwe is located in an area with a good sandstone-mudstone aquifer with high yields and excellent groundwater for various uses.

4.6.8 Documentation of the Borehole Numbering System

The surface water basin blocks in the Zambezi and Congo River Basins are the most appropriate basis for numbering of boreholes to enhance allocation of surface and groundwater resources. This numbering approach recognises interaction of surface and groundwater.

4.6.9 Documentation on the National Groundwater Observation Boreholes

A national network using manual daily measurement frequency is a requirement, in the absence of data loggers. Priority should be given to towns/locations with meteorological stations when considering sites to comprise the national network. Additionally, specific networks are required for monitoring heavily abstracted aquifers.

4.6.10 Documentation on the Data Acquisition Model for Groundwater Data and Information Collection

Equal attention is required on acquisition of hydrogeological, groundwater quality and groundwater level data in both urban and rural areas of Zambia. This forms the basis for assessment of the economic potential of groundwater resources and management of the resource.

4.7 Further Research needs in Hydrogeology in Zambia

Recharge studies and exploitation potential of renewable groundwater resources at different scales is inevitable. Additionally, groundwater vulnerability to contamination, drought and over exploitation are among other issues important for future research. The success of future research depends on the quality of groundwater data and information available in both the urban and rural areas of Zambia.

5.0 CONCLUSION

The proposed data acquisition model demonstrates that Zambia's current groundwater data and information availability could be improved for enhanced resources development and management. Under the present groundwater development practices, groundwater data and information is marginally suitable for the assessment of the quantity of groundwater resources, whereas the assessment of the quality is marginally or severely limited for both the urban and rural areas. The main argument is that the data collection approach outlined in the model aims at improving and putting in place a system for continuous data collection, evaluation and management of groundwater resources inline with the mandate of the Ministry of Energy and Water Development. Additionally, the model is also in agreement with IWRM principles considering the resource management options outlined in the IWRM toolbox training course (GWP, 2006; PAWD, 2007).

A key result of the methodology is the collection and evaluation of groundwater data and information approach to the assessment of groundwater as a strategic resource capable of meeting domestic, industrial and irrigated agriculture water requirements in both the urban and rural areas of Zambia. The opportunity exists to improve on the availability of groundwater data and information for the database through sustainable groundwater resources development and management practices, especially in the rural areas, peri-urban and low-cost areas where water and sanitation services are still low. The emphasis is also on the analysis of groundwater data and dissemination of information for improved socio-economic benefit of Zambia. The identified best drilling practices are suitable inputs for developing regulations and standards, whereas the various drilling methods would save drillers as the drilling guide in the complex geology of Zambia.

6.0 REFERENCES

- Aller, L., Bennet, T., Lehr, J. H., and Petty, R. J., 1987. DRASTIC: A standardised system for evaluating groundwater pollution potential using hydrogeologic settings. US EPA Report EPA/ 600/2-87-035, United States Environmental Protection Agency, 622pp.
- Barr, M.W.C., 1970. Limestone of the Lusaka South Forest Reserve and Adjacent Areas. *Economic Report No. 25. Geological Survey Department, Ministry of State Participation, Lusaka, Republic of Zambia*, pp. 2–6.
- Bredenkamp, D. B., Botha, L. J., Van Tonder, G. J., and Van Rensburg, H. J., 1995. Manual on quantitative estimation of groundwater recharge and aquifer storativity. WRC Report TT 73/95. Water Research Commission, Pretoria. 363pp.
- Burdon, D.J., and Papakis, N., 1963. Handbook of Karst Hydrogeology, F.A.O., Greece
- Boddy, D., and Paton, R., 1998. An Introduction to Management, Prentice Hall, SMALE Consulting Ltd.
- Chenov, C.D., 1978. Groundwater Resources Inventory of Zambia. *Unesco /Norad Water Zambia*, pp. 1–21.

Chola, P., 2003. Historical and current status of Water Resources Management in Zambia. In: WRAP (Water Resources Action Programme), Report on the National Water Resources Action Programme Consultative Forum: The Proposed Institutional and Legal Framework for the Use, Development and Management of Water Resources in Zambia, Ministry of Energy and Water Development, Lusaka, Zambia, pp. 40–51.

CMMU, 1997. Community Management and Monitoring Report: National water point inventory and water point database. Ministry of Energy and Water Development, Lusaka, Zambia.

CSO, 2000. Summary Report for the 2000 Census of population and housing, report 2. Central Statistical Office, Lusaka, Zambia.

DWA, 1982 – 2001. Drilling subject files, annual and Field Trip Reports, Department of Water Affairs, Lusaka, Zambia

De Waele, J; Nyambe, I. A; Di Gregorio, A; Di Gregorio, F; Simasiku, S; Follesa, R., and Nkamba, S., 2004. Urban waste landfill planning and karstic groundwater resources in developing countries: the example of Lusaka (Zambia). *Journal of African Earth Sciences* 39, 501-508.

Dixey, F., 1945. The geomorphology of Northern Rhodesia. *Transactions of the Geological Society of South Africa* 47, 9-45

Drysdall, A.R., and Smith, A.G., 1960. Recumbent folding in the Lusaka Dolomite. *Occ. Pap. Dept. Geol. Surv. Nth. Rhod. 22, pp43-45 (Nth. Rhod., 1958).*

Freeze, R. A., and Cherry, J.A., 1979. *Groundwater*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey 07632, United States of America, pp. 237-310.

Gair, H.S., 1959. The Karroo System and coal resources of the Gwembe District, north-east section. *Bull. Ministry of Mines and Cooperatives, Geological Survey Department, Lusaka, Northern Rhodesia, 1.*

Garrard, P., 1968. The Geology of the Chainama Hills Area. Explanation of degree sheet 1528, NE. quarter. *Report of the Geological Survey No. 24.* Ministry of Lands and mines, Lusaka, Northern Rhodesia, p.57.

Government of the Republic of Zambia, Ministry of Agriculture and Water Development: 1985. Specifications and contract documents for Drilling boreholes for water, Department of Water Affairs, Lusaka, Zambia.

Government of the Republic of Zambia, MACO: 2003. Strategic plan for Irrigation Development, Period 2002-2006, Lusaka, Zambia.

Government of the Republic of Zambia, MEWD: 1993. Implementation review on the project for the Rural Water Supply Development phase III in the Republic of Zambia, JICA Report, Japan Techno CO., Ltd, GRF CR(3) 93-111.

Government of the Republic of Zambia, MEWD: 1994. National Water Policy; and 1949. Water Act.

Government of the Republic of Zambia, MEWD: 2003. Strategic plan for the Ministry of Energy and Water Development. *Period 2003-2007*, Lusaka, Zambia, p. 23.

GWP, 2006. IWRM Toolbox. IWRM/WE planning, Global Water Partnership, www.gwptoolbox.org.

Hadwen, P., 1972. The Groundwater Resources of the Greater Ndola Area together with Certain Aspects of the Surface Resources. Department of Water Affairs, Lusaka, Zambia, pp. 5-85.

Hergert, G.W., and Knudsen, D., 1997. Irrigation Water Quality Criteria, G77-328-A, Cooperative Extension, Institute of Agriculture and National Resources, University of Nebraska-Lincoln, <http://www.p2pays.org/ref/20/19718.htm>

Hitchon, B., 1958. The Geology of the Kariba Area. *Report of the Geological Survey No. 3*. Geological Survey Department, Lusaka, Northern Rhodesia, p.4.

JICA (Japan International Cooperation Agency), 1995. The Study on the National Water Resources Master Plan in The Republic of Zambia. Ministry of Energy and Water Development, YEC. Vol. 1-3.

Jones, M.J., and Topfer, K.D., 1972. The Groundwater Resources of Kabwe Area with Geophysical Notes. Department of Water Affairs, Lusaka, Zambia, pp. 5–103.

Kellgren, N. and Sander, P., 2002. Reports from project group work presented 13 June 2002. *Groundwater Development and Management in Hard Rock Areas Advanced International Training Programme, May 20 – June 14 2002*. Chalmers University of Technology, Goteborg, Sweden, pp. 9–11.

Kellgren, N., 2002. Applicability of Remote Sensing Techniques to Groundwater Exploration in Semi-Arid Hard Rock Terrain, Reports. *A Systematic Approach*. Chalmers University of Technology, Gotenborg, Sweden, p. 98.

Kraft, C; Wisotzky, F., Wohnlich, S; 2004. Untersuchungen in einem Trinkwasserseinzugsgebiet in NRW mit dem Schwerpunkt nitrat.

Lambert, H. H. J., 1961. The Groundwater Resources of Zambia. Department of Water Affairs, Ministry of Lands and Natural Resources, Lusaka, Zambia, pp. 1–23.

Lambert, H. H. J. 1963. *Part 2, Groundwater Resources. In: The Geology and Groundwater Resources of the Lusaka Area*. Explanation of degree sheet 1528, NW quarter. Department of Geological Survey Report, **16**, Lusaka, Northern Rhodesia.

Lerner, D. N., 1961. Surface water-Groundwater interactions in the context of groundwater resources. In: Xu and Beekman et al. (Eds.), *Groundwater recharge*

estimation in Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris. ISBN 92-9220-000-3, pp. 91-105.

Lerner, D. N., Issar A and Simmers I., 1990. Groundwater recharge, Heise, Hannover, 345 pages. ISSN 3-922705-91-X.

Lloyd, J. W., (Editor) 1999. Water resources of hard rock aquifer in arid and semi-arid zones, Unesco, Studies and reports in hydrology 58.

Matheson, G.D., and Newman, D., 1966. Geology and structure of the Lusaka area. Geological Survey Department, Ministry and mines and Cooperatives, Lusaka, Northern Rhodesia, 10 pp. 10-19.

Maseka, C., 1994. A Ground-water Resource Evaluation of Fractured Rock Aquifers at Lusaka. M. App. Sc. Thesis, University of New South Wales, Australia.

Maseka, C., and Nyambe, I.A., 1999. Lusaka's groundwater resources at risk. Environmental Capacity Enhancement Project (ECEP). Canadian International Development Agency, John Devlin (Ed.), 75-90.

Ministry of Agriculture and Water Development, 1983. Running contract for Borehole Drilling, MAWD/71/3/1, Lusaka, Government of the Republic of Zambia.

Money, N.J., Denman, P. D., and Radosevic, B., 1968. Sedimentology of the Lower Karroo rocks of the Siankondobo and Mulungwa areas of the Mid-Zambezi valley. *Rec. Geological Survey Department, Lusaka, Zambia*, 11, pp. 17-27.

Moore, T.A., 1964. The Geology of the Chisamba area. Explanation of degree sheet 1428, SW quarters. Ministry of Labour and mines, Lusaka, Northern Rhodesia, 5.

Mpamba, N.H., 2003. Comparative study to develop a model for Zambia on Groundwater Monitoring in the urban and rural areas as a tool for resources assessment and evaluation. Report No. 1, Groundwater Development Unit, Department of Water Affairs, Lusaka, Zambia., pp. 31-32.

Mpamba, N.H., 2005. Estimation of the effective recharge area for Lusaka Urban and adjacent areas: Report No. 1, Groundwater Development Unit, Department of Water Affairs, Lusaka, Zambia.

Newman, D., and Matheson, G.D., 1966. The Economic Potential of Limestone near Lusaka. Geological Survey Department, Ministry and mines and Cooperatives, Lusaka, Northern Rhodesia, 10 p. 2.

Newton, A.R., 1963. The Geology of the country between Choma and Gwembe. Explanation of degree sheet 1627, SW and SE. quarters. Ministry of Labour and mines, Lusaka, Northern Rhodesia, pp. 3-16.

Nkhuwa, D.C.W., 1996. Hydrogeology and Engineering Geological problems of urban development over karstified marble in Lusaka Zambia. *Mitt. Ing. Und Hydrogeol.* pp. 1–215, Aachen.

Nkhuwa, D.C.W., 1999. Is groundwater management still an achievable task in the Lusaka aquifer? *Proc. XXIX. Conf. Of the Int. Ass. Of Hydrgeol.*, 209–213 pp. Bratislava, Slovak Republic.

Nkhuwa, D.C.W., 2000. Management of groundwater resources in Lusaka, Zambia, and expectations for the future. In: Sililo, et al. (Eds.), *Groundwater: Past Achievements and Future Challenges*. Balkema, Rotterdam, pp. 993-998.

NWASCO, 2005. Urban and Peri-urban Water Supply and Sanitation Sector Report 2003/2004, Lusaka, Zambia, p. 23.

Nyambe, I.A., 1993. Sedimentology, tectonic framework and economic potential of the Sinakumbe Group (?Ordovician to Devonian) and Karoo Supergroup (Permo-Carboniferous to Lower Jurassic) in the mid-Zambezi Valley Basin, southern Zambia. 425pp. Ottawa.

Nyambe, I.A., and Maseka, C., 2000. Groundwater pollution, landuse and environmental impacts on Lusaka aquifer. In: Sililo, et al. (Eds.), *Groundwater: Past Achievements and Future Challenges*. Balkema, Rotterdam, pp. 803-808.

- Pagella, J.F., Drysdall, A.R., 1966. The Coal resources of the Zambezi valley, Siankondobo – The Kazinze basin, *Preliminary report*. Ministry of Mines and Cooperatives, Geological Survey Department, Lusaka, Northern Rhodesia, 13 pp. 1–18.
- PAWD, 2007. IWRM Toolbox training. Facilitation of IWRM/WE planning process in Zambia, Global Water Partnership, *Southern Africa*, pp. 30 – 37.
- Pietersen, K.C., 2004. A decision-making framework for groundwater management in arid zones (with a case study in Namaqualand) PhD thesis, Department of Earth Sciences, University of the Western cape, p. 127.
- Rosen, L., 1994. A study on the DRASTIC Methodology with Emphasis on Swedish conditions. *Ground Water*, Vol. 32, No 2, pp. 278-285.
- Rosenberg, M., 2008. Global Atmospheric Circulation and its Related Effects. *About.com*, Inc., <http://geography.about.com/od/physicalgeography/a/tradewinds.htm>
- SADC, 2001. Development of a Code of Good Practice for Groundwater Development in the SADC Region. *Final Report No. 1, Situation Analysis Report; for SADC Water Coordination Unit*. Groundwater Consultants (Pty) Ltd., Lesotho.

- Scherer, T.F., Seelig, B, and Franzen, D., 1996. Soil, Water and Plant characteristics Important to Irrigation. NDSU Extension Service, North Dakota State University, <http://www.ext.nodak.edu/extpubs/ageng/irrigate/eb66w.htm>
- Simpson, J.G., Drysdall, A.R., and Lambert, H.H.J., 1963. The Geology and Groundwater Resources of the Lusaka Area. Explanation of degree sheet 1528, NW. quarter. *Report of the Geological Survey No. 16*. Ministry of Labour and mines, Lusaka, Northern Rhodesia, pp. 10–56.
- Simpson, J.G., 1965. Two Talc Deposits near Lusaka. Geological Survey Department., Economic Unit; Ministry and mines and Cooperatives, Lusaka, Northern Rhodesia, 9 p. 14.
- Simmers, I., Hendrickx, J.M.H., Kruseman, G.P. and Ruston, K.R., 1997. Recharge of Phreatic Aquifers in (Semi -) Arid Areas. IAH Series No. 19, Belkema, Rotterdam, p.163.
- Siwale, C., 2006. Annual rainfall records for Sheki – Sheki Met. Station from 2002/03 to 2005/06 rain seasons, Ministry of Energy and Water Development, DWA, Lusaka, Zambia.
- Smith, T.R., 1960. The Karroo System and coal resources of the Gwembe District, south-west section. *Bull.* Ministry of Mines and Cooperatives, Geological Survey Department, Lusaka, Northern Rhodesia, 4.

- Smith, A.G., 1963. The Geology of the country between Mazabuka and Kafue. Explanation of degree sheet 1527, SE quarter and 1528, SW. quarters. Ministry of Labour and mines, Lusaka, Northern Rhodesia, 2.
- Taque, M., 1969. Artificial recharge at No. 1 borehole area, Lusaka, WAD, Lusaka, Northern Rhodesia.
- Titus, R., 2003. Hydrochemical characteristics of Namaqualand. Unpublished PhD thesis, University of the Western Cape.
- Tredoux, G., 2004. Nitrate and associated hazard quantification and strategies for protecting rural water supplies. *Water Research Commission (WRC) Report No. 1058/1/04*, Pretoria. ISBN No 1-77005-173-2
- Von Hoyer, Kohler, M. and Schmidt, G., 1978. Groundwater and Management Studies for Lusaka Water Supply. Part 1 Groundwater study, Hanover, Germany.
- Kovalevsky, V. S., Kruseman, G. P. & Ruston, K. R. 2004. *Groundwater studies, An International Guide for Hydrogeological Investigations*. UNESCO IHP-VI, Series on Groundwater, No. 3, UNESCO, Paris. ISBN 92-9220-005-4.
- Warren, G.D., 1972. Aspects of Watershed Leakage in the Upper Kafue Basin. Department of Water Affairs, Data and Planning, Kitwe, Zambia, pp. 15-16.

William, J.D., 1997. Groundwater Chemistry: Fundamental and applications to contamination

Wisotzky, F., 1994. Untersuchungen zur Pyritoxidation in sedimenten des Rheinischen Braunkohlenreviers und deren Auswirkungen auf die Chemie des Grundwassers. – Besondere Mitteilungen zum Dtsch. Gewässerkl. Jb., 58: 153 S.

Wohnlich, S., 1999. Hydrogeologische Modelle: ein Leitfaden für Auftraggeber, Ingenieurbüros und Fachbehörden in der Grundwasserwirtschaft/Arbeitskreis "Hydrogeologische Modelle" der Fachsektion Hydrogeologie in der Deutschen Geologischen Gesellschaft (Hrsg.). – Hannover: Dt. Geologische Ges, pp. 7–36.

World Health Organisation, 1984. Guidelines for drinking water quality. Volume 1, ISBN 92 4 154168 7, World Health Organisation, Geneva, Switzerland

WRAP, 2003. Report on the National Water Resources Action Programme Consultative Forum: The Proposed Institutional and Legal Framework for the Use, Development and Management of Water Resources in Zambia, Ministry of Energy and Water Development, Water Resources Action Programme, Lusaka, Zambia, pp. 2–87.

WRAP, 2003. Groundwater Management in Zambia, *Discussion paper*. Ministry of Energy and Water Development, Water Resources Action Programme, Lusaka, Zambia.

WRAP (Water Resources Action Programme), 2005. Zambia Water resources Management Sector Report for 2004, Ministry of Energy and Water Development, Zambia, pp. 1–37.

Xu, Y. and Beekman, H.E. (Eds), 2003. Groundwater recharge estimation in Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris. ISBN 92-9220-000-3, pp. 81–88.

Zambia Bureau of Standards, 1990. Zambian Standard specification for drinking water quality. Zambia Bureau of Standards, Lusaka, Zambia.

Zulu, J.D.S. and Nyambe, I.A., 2004. Karstified Lusaka Marble aquifer, Zambia: Implications on Groundwater Contamination and community Management in Kanyama Settlement. *In abstract Volume, International Geological Congress*, Florence, Italy.

APPENDIX – A1

Table 3.3: Water Quality Guidelines for Drinking Water (after WHO, 1980; ZBS, 1990)

Water Quality Parameter	Units	Standard/Guidelines	
		Zambia Bureau of Standards (ZBS)	World Health Organisation (WHO)
		- Maximum permissible limit -	- Maximum permissible limit -
Calcium (Ca ²⁺)	mg/l	200	200
Chloride (Cl ⁻)	mg/l	250	250
Iron (Fe)	mg/l	1.0	1.0
Manganese (Mn)	mg/l	0.1	0.3
Magnesium (Mg ²⁺)	mg/l	150	200
Sulphate (SO ₄ ²⁻)	mg/l	400	400
Fluoride (F)	mg/l	1.5	1.5
Nitrates (NO ₃ -N)	mg/l	10	10
Sodium (Na ⁺)	mg/l		200
Potassium (K ⁺)	mg/l		200
Bicarbonate (HCO ₃ ⁻)	mg/l		400

APPENDIX – A2

Table 3.4: *Criteria for Evaluation of Groundwater for Irrigation (after US Department of Agriculture, 1954)*

Water Quality Parameter	Units	Maximum permissible limit
Sodium Adsorption Ratio		10
Chloride Toxicity (Cl^{-})	Meq/l	4.0
Magnesium Hazard (MH)	%	50

APPENDIX – B1

Groundwater level Observation Data Form

REPUBLIC OF ZAMBIA

Form 1S

**Ministry of Energy and Water Development
Groundwater Resources Section**

MEAN DAILY GROUNDWATER LEVELS

GROUNDWATER LEVEL OBSERVATION STATION:-----

REF No:----- **CATCHMENT AREA:**-----

MAP REF:----- **GAUGE ZERO:**-----

	YEAR OF:		UTM Co ordinates			
Date	OCTOBER APRIL	NOVEMBER MAY	DECEMBER JUNE	JANUARY JULY	FEBRUARY AUGUST	MARCH SEPTEMBER
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						

Water levels to be entered against dates / day and respective remarks

Station Observer / Officer

Borehole completion report for observation borehole BH2

REPUBLIC OF ZAMBIA – WATER AFFAIRS DEPARTMENT

BOREHOLE COMPLETION FORM

Grid Reference: UTM 6336180 8298055 Locality: Sheki Sheki DWA Borehole No: 2
 Name of Property: Monitoring Borehole BH2 District: Lusaka Urban Site Selected by: DWA Site No:
 Name of Owner(s) PWD – Lusaka, DWA Province: Lusaka Drill Unit No: GRZ 717 BE Elevation: 1295m

	Depth in meters		Formation	DATE OF
	From	To		
Total depth borehole	36.0			
Depth from surface at which water first struck	4.0			
Depth from surface of main supply	24.0	3.0	Top soil (Clay)	Arrival on site: September 2002
Depth from surface to which water rises	2.4	8.0	Schist associated with Laterite	
Continuous bailer test	hours gave yield of	30.0	Compact Schist	Completion: September 2002
Continuous pump test	1 hours gave yield of	30.0	Compact Schist associated With Limestone	FOR OFFICIAL USE ONLY
Depth of water from surface before test	0.8			Borehole file No.
Depth of water from surface of pump intake	2.4			Schedule No.
Greatest depth to which water was lowered during test	30.0			
Does water return to original level after test? Yes	Recovery 2.4			Office Record No.
Details of Casing in borehole				Borehole Serial
DIAMETER	LENGTH IN METERS			CHARGES TOTAL FOR
Plain	Perforated			Borehole:
300 m	6.0 m			For Casing:
				Warrant No.
Depth from surface to bottom of casing	36.0			REMARKS
Diameter of unlined portion of borehole below casing				
Quality of water (State if fresh, blackish, or saline, etc)	Fresh			
Total distance chargeable	Km at			
Remarks: Borehole fully cased and gravel packed.				

The applicant is required to sign this report after having satisfied himself that it is correct
 Signature of Applicant:

Foreman: P. Chisanga

Date: September 2002

Borehole completion report for observation borehole MB - 2

REPUBLIC OF ZAMBIA - WATER AFFAIRS DEPARTMENT
BOREHOLE COMPLETION FORM

Grid Reference: UTM 594438 8164981 Locality: Makuyu World Vision Chief: Muryumbwe Borehole No: 1
 Name of Property: Monitoring Borehole District: Gwembe Site Selected by: DWA Site No: 1
 Name of Owner(s): Makuyu World Vision Province: Southern Drill Unit No: GR2 717 BE Elevation: 712m

Total depth borehole	42.0	meters
Depth from surface at which water first struck	24.0	meters
Depth from surface of main supply	34.0	meters
Depth from surface to which water rises	13.43	meters
Continuous bailer test	hours gave yield of	
Continuous pump test	1 hours gave yield of	litres per second
Depth of water from surface before test	13.43	litres per second
Depth of water from surface of pump intake	38.0	meters
Greatest depth to which water was lowered during test		meters
Does water return to original level after test?	Yes	Recovery 13.43
Details of casing in borehole		
DIAMETER	Plain	LENGTH IN METERS
	240 m	Perforated
110 mm	18.0 m	
Depth from surface to bottom of casing	42.0	meters
Diameter of unlined portion of borehole below casing		meters
Quality of water (State if fresh, blackish, or saline, etc)	Fresh	
Total distance chargeable	km at	K
Remarks: Borehole fully cased and gravel packed.		

The applicant is required to sign this report after having satisfied himself that it is correct
 Signature of Applicant: _____ Foreman: J. Kachema Date: 10 - 10 - 02

APPENDIX – B3

Table 4.56: Groundwater level readings in meters for MB-3 at Mongu DWA premises

Day of Month	2002					
	March	April	May	June	July	Aug
1	9.98	10.07	10.12	10.20	10.41	10.55
2	9.98	10.07	10.12	10.21	10.41	10.55
3	9.98	10.08	10.12	10.21	10.42	10.56
4	9.98	10.08	10.13	10.22	10.42	10.57
5	9.99	10.08	10.13	10.22	10.43	10.57
6	9.99	10.08	10.13	10.23	10.43	10.58
7	9.99	10.09	10.14	10.23	10.43	10.59
8	9.99	10.09	10.14	10.24	10.44	10.60
9	10.00	10.09	10.14	10.25	10.44	10.60
10	10.00	10.09	10.15	10.25	10.45	10.61
11	10.01	10.09	10.15	10.26	10.45	10.62
12	10.01	10.09	10.16	10.26	10.45	10.62
13	10.02	10.10	10.16	10.27	10.46	10.62
14	10.02	10.10	10.16	10.27	10.46	10.63
15	10.03	10.10	10.17	10.28	10.46	10.63
16	10.03	10.10	10.17	10.28	10.46	10.63
17	10.03	10.10	10.17	10.28	10.46	10.64
18	10.04	10.10	10.17	10.29	10.46	10.64
19	10.04	10.10	10.18	10.30	10.46	10.64
20	10.04	10.11	10.18	10.32	10.47	10.64
21	10.04	10.11	10.18	10.33	10.47	10.65
22	10.04	10.11	10.18	10.34	10.48	10.65
23	10.05	10.11	10.18	10.35	10.49	10.65
24	10.05	10.11	10.18	10.36	10.50	
25	10.05	10.11	10.18	10.37	10.51	
26	10.06	10.11	10.18	10.38	10.52	10.67
27	10.06	10.12	10.19	10.38	10.52	10.68
28	10.06	10.12	10.19	10.39	10.53	10.68
29	10.06	10.12	10.19	10.40	10.53	10.68
30	10.06	10.12	10.19	10.40	10.54	10.69
31	10.06		10.19		10.55	10.69

APPENDIX - C1

Table 4.0: Sample of the excel electronic data base for boreholes located in Lusaka urban and adjacent areas

I.D	Client and Location	Coordinates: UTM - WGS 84		Elevation a (m)	Borehole Depth a (m)	Borehole Diameter r (mm)	Static Water Level Level (m)	First Water Strike (m)	Main Water Strike (m)	Yield (m ³)	Aquifer Lithology	Soil Cover		Pumpin g Depth (m)	Borehole a (m)	Gravel Base		Date Drilled
		South - Y	East - X									Soil Type	Cover Depth (m)			Gravel Bottom from G.L. (m)	Screened Length (m)	
1	Mr. Manjolo (Roma, Extension)	641853	8300433	1277	61.5	150	22	24	54	1.5	Quartzite	Schist	6	54	17.13	42	18	20.11.03
2	Mr. Mwanzanu (Avondale)	643398	8293005	1278	40	150	23	30	36	3	Limestone	Schist	23	36	0.06	27	9	10.11.03
3	USST (NRDC)	647351	8237851	1248	58.45	150	8.13	4.0	54	0.3	Schist	Clay	6	52	42	36	24	28.04.03
4	Mr. Mulera (Avondale)	649328	8239753	1259	55	150	17.35	6	30	2.5	Schist	Clay	1	45	7.27	24	12	26.07.03
5	Mr. Mhanya (Roma, Extension)	640226	8301568	1240	57.5	150	10.62	25	42	1.5	Dolomite	Schist	25	45	21.78	33.5	24	29.02.03
6	Justice Sikulu (Lusaka, East)	653230	8300803	1185	55.5	150	16.24	30	36	3.6	Dolomite	Clay	6	42	10.46	24.5	21	20.03
7	Lt. Col. Chisanga (Airport)	65728	8305256	1163	42	150	2.29	15	18	4	Schist	Clay	18	36	18	24	19	10.03.04
8	Mr. Noel Nkhomo (NRDC, Farm)	648205	8301805	1223	58.75	150	10.22	17.6	24	3	Limestone	Clay	18	25	14.44	18	25.5	20.04
9	Mr. Kwalla (NRDC, Farm)	65332	8302143	1233	45	150	2	2	42	15	Schist	Clay	3	45	22.81	42	16.6	15.09.04
10	Sable Transport BH1 (Airport)	651220	8301864	1236	37	150	3	42	40	40	Schist	Schist	30	30				
11	Sable Transport BH2 (Airport)	649742	8301934	1208	60	150	15	15	42	42	Schist	Schist	35	35				
12	Sable Transport BH3 (Airport)	649742	8301934	1212	42	150	21	21	30	1.4	Schist	Clay	8	35			24	22.07.04
13	Sable Transport BH4 (Airport)	649742	8301934	1204	40	150	2	2	50	5	Schist	Sand	36	54			12	12.04.02
14	Mr. Chwily (Lusaka, East)	643438	8295074	1267	60	150	4.34	4.34	27	21	Limestone	Clay	3	60	35	28	16	27.09.00
15	Chanda Basic Sch. (Avondale)	650005	8238431	1225	103.3	150	3.57	7	36	2	Schist	Gravel	1	24	35	26	12	20.00
16	Chanda Basic Sch. (Avondale)	649665	8239707	1245	40	150	13.37	23	36	7.5	Limestone	Fine Sand	2	34	7.3	33	7	23.10.04
17	Gen. Kazanjo (Avondale)	650962	8237406	1234	43	150	25.63	3.2	25	3	Limestone	Clay	6	42	2.22	23	34	19.10.03
18	Gen. Tombo (Ibesa Area)	649552	8296580	1245	43	150	23.2	3.2	25	3	Limestone	Clay	6	50				
19	Mr. Serina Marika (Ibesa Area)	649110	8334730	1314	23.2	150	22.85	4.2	50	2	Limestone	Schist	36	45	4.24	33	9	10.02.02
20	Mrs. of Finches (H8)	648300	8288834	1310	52	150	27.4	4.2	50	0.5	Dolomite	Schist	3	55	25.24	49.5	18	16.03.04
21	Dr. Kazendo (Leopard Hill)	636148	8291720	1257	38.65	150	10.65	50	57	0.7	Schist	Clay	3	34	8.67	49.5	18	16.03.04
22	Chisanga (Woodlands)	642867	8284630	1298	36.6	150	22.68	16	36	0.6	Schist	Clay	3	34	4.89			
23	Barclay Bank	650454	8295446	1256	53.4	150	28.05	36	33	2	Dolomite	Schist	36	48				
24	Dr. Chipungu (Ibesa Area)	641753	8289838	1302	54	150	28.05	36	33	2	Dolomite	Schist	36	48				
25	Chief Justice Residence	651000	8289630	1300	54	150	28.05	36	33	2	Dolomite	Schist	36	48				
26	Mr. Nkhawa (Ibesa Hill)	649367	8232134	1311	54	150	7.1	18	33	2	Schist	Schist	0	42	2.1	30	18	21.10.02
27	A. Sidianga (Woodlands)	641087	8234017	1311	31.77	150	17.62	18	27	0.7	Limestone	Sand	0	42	26.2	36	18	05.04.03
28	Hon. Kabimpanga (Indep. Ave)	649163	8281527	1314	50	150	16	38	40	7	Limestone	Sand	2	32	16.36	31	6	09.06.04
29	Jays	649163	8281527	1314	50	150	20	38	40	7	Limestone	Sand	2	32	16.36	31	6	09.06.04
30	Hon. Lubinda (Libata South)	649163	8281527	1314	50	150	20	38	40	7	Limestone	Sand	2	32	16.36	31	6	09.06.04
31	Mr. Lovs Mteza	650528	8296324	1227	54	150	3.38	24	30	4	Schist	Clay	12	41	35.74	42	12	16.01.04
32	Mrs. Mhanya (Ibesa Hill)	648671	8234223	1282	85.3	150	11.4	61	78	0.75	Dolomite	Schist	0	31	13.72	31	5	23.06.04
33	Min. of Health (Middle, House)	648671	8234223	1282	85.3	150	11.4	61	78	0.75	Dolomite	Schist	0	31	13.72	31	5	23.06.04
34	Mr. V. Banda (Ibesa Hill)	650273	8281321	1316	50	150	22	37.5	45	2	Dolomite	Sand	3	49	6	6	18	24.01.00
35	Chitete Clinic	649329	8231222	1308	60	150	14.5	18	36	1.8	Limestone	Clay	3	45	38.5	12	12	27.03.00
36	Kabulona Basic Sch.	648249	8234683	1288	79.5	150	9.45	18	25	6	Limestone	Clay	7	54			49	01.03.00
37	Libata Basic Sch.	648095	8287046	1308	60	150	7.1	7	18	2.1	Limestone	Lignite	8	54	5.3	6	5	16.09.01
38	Gen. Muzenqulu	648095	8287046	1308	60	150	16.3	3	24	2.5	Limestone	Lignite	8	54	5.3	6	5	16.09.01
39	Lozaga Serengeti	643401	8234221	1317	105	150	26	26	24	1.2	Limestone	Lignite	2	24	5.3	6	5	16.09.01

Table 4.8: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2002 to March 2003

Day of Month	April 2002		May 2002		June 2002		July 2002		August 2002		September 2002		October 2002		November 2002		December 2002		January 2003		February 2003		March 2003			
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2		
1			0.63																							
2													0.61	1.72						0.53	1.15					
3	0.7					0.62																				
4										0.77																
5					0.81														0.83	1.58						
6															0.13	1.37							0.62	1.28	0.28	1.07
7							0.78																			
8																										
9													0.99	1.88												
10	0.74						0.51																			
11									0.79	1.81																
12					0.86																					
13																										
14										0.81																
15							0.70																			
16																										
17	0.53						0.77																			
18																										
19					0.93				0.74	1.78																
20																										
21										0.83																
22							0.72																			
23																										
24	0.58					0.76																				
25																										
26					0.85				0.79	2.00																
27																										
28										0.88																
29							0.74																			
30																										
31							0.73																			

Blank space represents data gaps.

Table 4.9: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2003 to March 2004

Day of Month	April 2003		May 2003		June 2003		July 2003		August 2003		September 2003		October 2003		November 2003		December 2003		January 2004		February 2004		March 2004	
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2
1																								
2	0.5	1.15					0.95				0.92													
3																								
4					0.92																			
5																								
6									0.94															
7				0.86	1.49										1.28									
8																								
9	0.69	1.23					0.93																	
10											0.98							0.78						
11					0.98																			
12																								
13									0.91															
14																								
15																								
16	0.80	1.29					0.92																	
17											0.99													
18										0.90														
19																								
20																								
21									0.89															
22																								
23	0.85	1.34																						
24																								
25																								
26										0.95														
27																								
28																								
29									0.96															
30	0.85	1.42						0.96																
31																								

Blank space represents data gaps

Table 4.10: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2004 to March 2005

Day of Month	April 2004		May 2004		June 2004		July 2004		August 2004		September 2004		October 2004		November 2004		December 2004		January 2005		February 2005		March 2005	
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2
1	0.85	1.25	1.05	1.40	1.08	1.46	1.13	1.49			1.10	1.48	1.10	1.61	1.10	1.61					0.41	1.205	0.15	1.1
2	0.85	1.25	1.06	1.40	1.08	1.46	1.13	1.49	1.14	1.49	1.08	1.48	1.11	1.62	1.10	1.62					0.55	1.24	0.19	1.125
3	0.86	1.26	1.06	1.40	1.08	1.47			1.14	1.50	1.08	1.49			1.10	1.62					0.21	0.945	0.68	1.27
4	0.90	1.27	1.07	1.41	1.08	1.47			1.14	1.50			1.11		1.14	1.65					0.35	1.03		
5	0.94	1.29	1.07	1.41			1.14	1.48					1.12	1.61	1.13	1.65					0.46	1.08		
6	0.96	1.30	1.08	1.37			1.13	1.48					1.08	1.61			0.21	1.045	0.46	1.08				
7	0.97	1.31	1.07	1.37	1.07	1.48	1.13	1.48					1.08	1.62			0.34	1.13	0.56	1.13	0.78	1.29	0.69	1.295
8	0.97	1.31	1.08	1.31	1.07	1.48	1.13	1.48					1.61		1.14	1.67	0.45	1.16						0.76
9	0.98	1.32	1.08	1.30	1.08	1.49	1.13	1.48							1.14	1.65	0.17	0.96						
10	0.98	1.33	1.08	1.42	1.08	1.49									1.15	1.65	0.10	0.63	0.72	1.225				
11	0.99	1.33	1.08	1.42	1.08	1.49									1.13	1.64	0.22	0.93	0.77	1.23				1.38
12	0.99	1.34	1.08	1.42			1.13	1.48					1.08	1.62	1.14	1.65					0.77	1.26		
13	0.99	1.27	1.08	1.43			1.13	1.48					1.10	1.61			0.10	0.61	0.79	1.285				
14	1.04	1.38	1.09	1.43	1.11	1.51	1.13	1.48					1.09	1.62			0.21	0.88						
15	1.02	1.35	1.09	1.44	1.1	1.50	1.13	1.48					1.08	1.62	1.16	1.67	0.10	0.68	0.79	1.3				
16	1.00	1.31			1.11	1.48	1.13	1.48							1.16	1.68	0.095	0.655	0.78	1.29				
17	1.00	1.31			1.13	1.47									1.17	1.71	0.23	0.905	0.8	1.32				
18	1.00	1.29	1.11	1.43	1.13	1.47							1.11	1.61	1.21	1.71			0.81	1.295				
19	0.92	1.29					1.14	1.49					1.10	1.61	1.30	1.70			0.69	1.24				
20	0.92	1.30					1.14	1.48					1.10	1.61			0.595	1.005	0.73	1.26				
21	0.92	1.30	1.08	1.43	1.13	1.49	1.14	1.48					1.10	1.61			0.655	1.130	0.77	1.28				
22	0.94	1.32			1.13	1.48	1.12	1.48							1.11	1.60	1.12	1.68	0.71	1.165				
23	0.96	1.32			1.13	1.49	1.14	1.48									1.12	1.58	0.75	1.19				
24	0.97	1.32			1.14	1.48											1.12	1.59	0.82	1.205	0.69	0.39		
25	0.98	1.32			1.14	1.48									1.11	1.62	1.10	1.59			0.62			
26	1.01	1.32					1.14	1.50					1.10	1.63	1.10	1.62	1.11	1.58			0.53			
27	1.02	1.33	1.09	1.45			1.14	1.50					1.11	1.63			0.635	1.205	0.41	1.15				
28	1.02	1.34			1.14	1.49	1.14	1.50					1.11	1.59			0.17	0.43	0.31	1.26				
29	1.03	1.35			1.15	1.50	1.14	1.50					1.11	1.57	1.14	1.58	0.16	0.88	0.195	1.09				
30	1.03	1.35			1.15	1.50	1.14	1.50					1.11	1.57	1.10	1.58	0.15	0.81						
31			1.09	1.45													0.155	0.80	0.29	1.16				

Blank space represents data gaps.

Table 4.11: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2005 to March 2006

Day of Month	April 2005		May 2005		June 2005		July 2005		August 2005		September 2005		October 2005		November 2005		December 2005		January 2006		February 2006		March 2006		
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	
1									1.13	1.88	1.19	1.74	1.32	1.79	1.44	1.86	0.82	1.48	0.51	1.23	0.32	1.07	0.28	1.13	
2					1.20				1.12	1.98	1.18	1.75	1.33	1.75	1.44	1.87	0.08	1.30	0.54	1.28	0.33	1.15	0.61	1.21	
3					1.15				1.12	1.98	1.22	1.76	1.33	1.75	1.45	1.96	0.10	1.03	0.19	1.25	0.37	1.13	0.69	1.24	
4									1.12	1.98	1.21	1.75	1.36	1.81	1.45	1.93	0.11	1.08	0.31	1.31	0.30	1.13	0.67	1.22	
5									1.12	1.98	1.26	1.78	1.37	1.81	1.44	1.93	0.17	1.13	0.43	1.23	0.29	1.10	0.65	1.21	
6									1.12	1.98	1.16	1.79	1.38	1.84	1.44	1.93	0.33	1.20	0.51	1.25	0.27	1.13	0.18	1.21	
7									1.12	1.98	1.07	1.79	1.39	1.84	1.44	1.93	0.38	1.24	0.59	1.26	0.26	1.12	0.15	0.88	
8		1.03	1.58						1.11	1.98	1.26	1.78	1.40	1.84	1.29	1.88	0.31	1.37	0.60	1.28	0.25	1.13	0.28	0.99	
9									1.12	1.88	1.25	1.78	1.40	1.84	1.28	1.74	0.49	1.28	0.67	1.28	0.32	1.11	0.28	1.06	
10									1.12	1.88	1.27	1.78	1.37	1.88	1.31	1.75	0.60	1.32	0.68	1.29	0.30	1.18	0.44	1.18	
11		1.03	1.55					1.09	1.96	1.14	1.98	1.27	1.8	1.37	1.83	1.29	1.75	0.70	1.40	0.75	1.31	0.49	1.26	0.51	1.21
12		1.08	1.56					1.08	1.88	1.14	1.99	1.29	1.83	1.28	1.86	1.29	1.76	0.74	1.35	0.75	1.35	0.59	1.26	0.69	1.28
13		1.08	1.56					1.08	1.88	1.14	1.99	1.29	1.83	1.38	1.85	1.34	1.83	0.79	1.30	0.75	1.38	0.79	1.27	0.67	1.29
14		1.08	1.56					1.05	1.89	1.11	1.98	1.29	1.83	1.29	1.85	1.36	1.87	0.44	1.28	0.77	1.39	0.60	1.23	0.44	1.15
15								1.08	1.87	1.12	1.99	1.28	1.76	1.39	1.84	1.37	1.88	0.55	1.31	0.45	1.28	0.62	1.27	0.49	1.22
16								1.04	1.88	1.13	1.98	1.28	1.78	1.39	1.84	1.40	1.88	0.64	1.31	0.41	1.17	0.63	1.25	0.58	1.22
17								1.05	1.87	1.13	1.97	1.28	1.78	1.39	1.84	1.41	1.9	0.71	1.33	0.41	1.18	0.62	1.26	0.68	1.22
18								1.08	1.88	1.13	1.97	1.30	1.78	1.39	1.85	1.42	1.91	0.70	1.33	0.29	1.16	0.65	1.31	0.67	1.21
19								1.08	1.87	1.13	1.97	1.34	1.83	1.29	1.85	1.42	1.91	0.69	1.33	0.19	1.07	0.17	1.21	0.88	1.22
20								1.08	1.88	1.13	1.97	1.32	1.80	1.40	1.85	1.41	1.9	0.66	1.29	0.35	1.08	0.10	0.91	0.65	1.27
21								1.08	1.88	1.15	1.97	1.32	1.83	1.41	1.84	1.42	1.9	0.44	1.23	0.35	1.18	0.20	0.99	0.71	1.25
22								1.08	1.88	1.17	1.98	1.32	1.83	1.41	1.85	1.40	1.78	0.39	1.20	0.33	1.17	0.20	0.98	0.85	1.28
23								1.04	1.88	1.15	1.97	1.40	1.86	1.41	1.83	1.41	1.77	0.29	1.22	0.37	1.16	0.18	0.83	0.82	1.27
24								1.08	1.91	1.16	1.88	1.50	1.89	1.41	1.84	1.40	1.77	0.28	1.21	0.38	1.17	0.17	0.81	0.76	1.26
25								1.04	1.90	1.17	1.93	2.13	2.49	1.4	1.87	1.31	1.83	0.18	1.09	0.47	1.18	0.17	0.84	0.82	1.25
26								1.04	1.88	1.16	1.94	1.98	1.98	1.41	1.88	1.31	1.83	0.18	1.1	0.41	1.19	0.16	0.83	0.80	1.22
27								1.04	1.90	1.16	1.94	1.77	1.90	1.42	1.88	1.27	1.82	0.41	1.08	0.39	1.20	0.30	1.11	0.72	1.25
28								1.12	1.90	1.16	1.94	1.35	1.84	1.42	1.88	1.37	1.83	0.52	1.24	0.37	1.25	0.29	1.16	0.66	1.20
29								1.12	1.88	1.16	1.94	1.35	1.81	1.42	1.88	1.26	1.83	0.26	1.17	0.39	1.26			0.51	1.24
30								1.12	1.88	1.16	1.94	1.32	1.81	1.42	1.91	1.42	1.83	0.39	1.22	0.41	1.25			0.56	1.26
31								1.12	1.90	1.16	1.94			1.42	1.91		0.50	1.26	0.39	1.28			0.67	1.27	

Blank space represents data gaps

Table 4.12: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2006 to March 2007

Day of Month	April 2006		May 2006		June 2006		July 2006		August 2006		September 2006		October 2006		November 2006		December 2006		January 2007		February 2007		March 2007	
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2
1	0.58	1.25	1.23	1.56	1.36	1.71	1.3	1.82	1.82	1.82	1.22	1.97	1.3	1.91	1.58	2.13	1.89	2.18	1.05	1.63	1.05	1.63	0.81	1.32
2	0.9	1.29	1.24	1.56	1.55	1.7	1.35	1.83	1.82	1.22	1.97	1.3	1.91	1.58	2.17	1.89	2.19	1.02	1.6	0.21	0.93	0.8	1.28	
3	0.93	1.31	1.26	1.57	1.34	1.7	1.31	1.81	1.33	1.89	1.23	1.98	1.3	1.9	1.58	2.15	1.59	2.19	1.01	1.58	0.21	0.93	0.77	1.23
4	1.01	1.32	1.2	1.57	1.33	1.7	1.32	1.81	1.33	1.91	1.23	1.98	1.3	1.9	1.58	2.16	1.59	2.19	1.01	1.59	0.2	0.92	0.81	1.28
5	1.02	1.32	1.22	1.56	1.32	1.68	1.29	1.83	1.33	1.91	1.1	1.96	1.3	1.9	1.58	2.15	1.59	2.19	1.01	1.58	0.2	0.92	0.81	1.33
6	1.03	1.38	1.23	1.56	1.32	1.7	1.28	1.83	1.33	1.91	1.1	1.96	1.3	1.92	1.59	2.14	1.60	2.20			0.26	1.03	0.82	1.34
7	1.02	1.4	1.22	1.57	1.31	1.72	1.28	1.83	1.32	1.9	1.11	1.97	1.3	1.92	1.59	2.15	1.61	2.21	1	1.57	0.15	0.88	0.82	1.35
8	1.04	1.43	1.23	1.54	1.32	1.73	1.27	1.83	1.33	1.91	1.05	1.97	1.28	1.9	1.59	2.15	1.60	2.21	1	1.56	0.21	0.92	0.84	1.35
9	1.05	1.45	1.25	1.55	1.32	1.73	1.27	1.82	3.15	1.94	1.03	1.97	1.31	1.91	1.42	2.17	1.52	2.21	1.02	1.55	0.23	0.96	0.85	1.36
10	1.02	1.42	1.26	1.57	1.31	1.72	1.28	1.85	1.53	1.92	1.05	1.98	1.3	1.91	1.49	2.17	1.48	2.18	1.01	1.55			0.83	1.35
11	1.05	1.39	1.26	1.59	1.32	1.73	1.28	1.85	1.38	1.92	0.97	1.93	1.3	1.91	1.67	2.19	1.40	2.11	0.97	1.51			0.84	1.36
12	1	1.36	1.27	1.59	1.33	1.75	1.28	1.85	1.27	1.87	0.97	1.92	1.3	1.91	1.64	2.18	1.36	1.94	0.98	1.51	0.4	1.01	0.84	1.35
13	0.99	1.41	1.28	1.62	1.33	1.74	1.29	1.84	1.26	1.86	0.97	1.93	1.3	1.91	1.62	2.18	1.34	1.96	0.98	1.51	0.46	1.09	0.85	1.36
14	0.98	1.43	1.3	1.63	1.34	1.76	1.29	1.84	1.37	1.83	0.97	1.93	1.34	1.93	1.62	2.19	1.34	1.95	0.97	1.5	0.58	1.13	0.86	1.37
15	1	1.47	1.28	1.62	1.34	1.77	1.29	1.83	1.37	1.84	0.97	1.93	1.34	1.94	1.61	2.18	1.30	1.97	0.97	1.5	0.58	1.16	0.86	1.37
16	1.03	1.48	1.28	1.63	1.34	1.77	1.29	1.84	1.37	1.83	0.98	1.93	1.47	2.03	1.61	2.19	1.29	1.94	0.97	1.55	0.77	1.21	0.9	1.43
17	1.08	1.49	1.29	1.62	1.3	1.77	1.3	1.84	1.4	2.14	0.97	1.93	1.47	2.03	1.6	2.2	1.27	1.93	0.67	1.56	0.77	1.22	1.01	1.44
18	1.09	1.5	1.3	1.63	1.31	1.76	1.3	1.84	1.39	2.14	0.98	1.92	1.47	2.03	1.6	2.2	1.27	1.93	0.67	1.56	0.77	1.22	1.01	1.44
19	1.1	1.52	1.33	1.64	1.32	1.77	1.31	1.88	1.38	2.13	0.97	1.93	1.47	2.03	1.61	2.21	1.26	1.92	0.09	1.22	0.85	1.24	1.04	1.45
20	1.12	1.53	1.38	1.65	1.32	1.78	1.3	1.88	1.38	2.01	0.98	1.93	1.47	2.04	1.62	2.22	1.25	1.92	0.08	1.21	0.89	1.26	1.05	1.45
21	1.12	1.46	1.39	1.65	1.32	1.78	1.3	1.9	1.36	1.96	1.01	1.94	1.47	2.04	1.62	2.22	1.25	1.92	0.04	1.19	0.85	1.25	1.06	1.46
22	1.13	1.46	1.41	1.67	1.31	1.78	1.3	1.91	1.36	1.98	1.01	1.94	1.47	2.05	1.6	2.21	1.25	1.92	0.04	1.19	0.86	1.25	1.07	1.54
23	1.15	1.45	1.38	1.68	1.32	1.79	1.3	1.92	1.45	1.86	1.01	1.94	1.5	2.08	1.58	2.2	1.26	1.93	0.22	1.11	0.82	1.31	1.08	1.56
24	1.15	1.46	1.34	1.67	1.32	1.79	1.3	1.91	1.45	1.85	1.02	1.94	1.51	2.08	1.58	2.19	1.26	1.93	0.13	0.92	0.83	1.32	1.08	1.56
25	1.13	1.46	1.3	1.68	1.33	1.79	1.29	1.91	1.32	1.86	1.18	1.99	1.52	2.07	1.57	2.18	1.25	1.92	0.18	0.95	0.84	1.33	1.08	1.56
26	1.18	1.53	1.29	1.68	1.32	1.81	1.29	1.93	1.29	1.91	1.29	1.99	1.53	2.07	1.57	2.17	1.25	1.92	0.18	1.02	0.78	1.31	1.08	1.56
27	1.18	1.53			1.31	1.8	1.3	1.93	1.26	1.92	1.3	1.96	1.53	2.09	1.57	2.18	1.25	1.92	0.18	1.01	0.79	1.38	1.08	1.56
28	1.19	1.53	1.31	1.68	1.3	1.81	1.3	1.93	1.26	1.97	1.3	1.96	1.53	2.08	1.57	2.18	1.24	1.93	0.17	1.01	0.81	1.39	1.09	1.55
29	1.2	1.54	1.31	1.69	1.31	1.81	1.3	1.92	1.26	1.96	1.29	1.94	1.53	2.08	1.57	2.18	1.16	1.79	0.27	0.62			1.09	1.55
30	1.21	1.54	1.33	1.7	1.31	1.81	1.29	1.91	1.21	1.98	1.29	1.91	1.52	2.08	1.57	2.18	1.12	1.71	0.29	0.68			1.1	1.56
31					1.32	1.7							1.58	2.13			1.08	1.70	0.28	0.98			1.1	1.56

Blank space represents data gaps

Table 4.13: Groundwater level readings in meters for BH1 and BH2 at Sheki-Sheki DWA premises: April 2007 to January 2008

Day of Month	April 2007		May 2007		June 2007		July 2007		August 2007		September 2007		October 2007		November 2007		December 2007		January 2008		February 2008	
	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2	BH1	BH2
1	1.15	1.57	1.31	1.79	1.39	2	1.39	2.03	1.44	2.01	1.4	1.91	1.6	1.68	1.72	2.32	1.24	1.68	0.11	0.92	0.13	0.99
2	1.16	1.58	1.3	1.79	1.4	2.01	1.39	2.02	1.44	2.01	1.4	1.88	1.6	1.71	1.72	2.32	1.24	1.68	0.1	0.92	0.12	0.99
3	1.16	1.61	1.31	1.76	1.42	2.02	1.4	2.02	1.44	2	1.4	1.88	1.61	1.75	1.73	2.32	1.23	1.67	0.06	0.71	0.14	1.02
4	1.16	1.61	1.32	1.77	1.42	2.02	1.36	2.02	1.44	1.99	1.41	1.88	1.62	1.76	1.73	2.33	1.25	1.68	0.06	0.7	0.17	1.03
5	1.17	1.62	1.33	1.77	1.42	2.03	1.34	2.02	1.44	1.98	1.35	1.8	1.62	1.78	1.72	2.38	1.3	1.54	0.12	0.72	0.19	1.09
6	1.17	1.62	1.34	1.78	1.43	2.03	1.32	2.02	1.45	1.97	1.36	1.8	1.64	1.79	1.67	2.23	1.37	1.54	0.12	0.73	0.29	1.13
7	1.17	1.63	1.32	1.81	1.44	2.03	1.32	2.02	1.46	1.96	1.41	1.8	1.65	1.8	1.65	2.16	1.39	1.55	0.14	0.98	0.22	1.13
8	1.18	1.64	1.32	1.85	1.44	2.03	1.32	2.02	1.45	1.96	1.43	1.8	1.66	1.8	1.63	2.14	1.35	1.51	0.13	1.03	0.64	1.24
9	1.18	1.66	1.34	1.87	1.45	2.04	1.32	2.02	1.45	1.95	1.43	1.82	1.68	1.8	1.74	2.13	1.35	1.5	0.12	1.03	0.65	1.26
10	1.19	1.68	1.34	1.86	1.46	2.04	1.32	2.01	1.45	1.95	1.43	1.83	1.7	1.82	1.74	2.11	1.18	1.42	0.05	0.55	0.66	1.16
11	1.19	1.68	1.36	1.87	1.46	2.05	1.31	2.02	1.45	1.95	1.44	1.83	1.71	1.83	1.74	2.12	1.08	0.83	0.05	0.55	0.65	1.17
12	1.29	1.69	1.35	1.86	1.49	2.01	1.31	2.02	1.46	1.93	1.43	1.84	1.73	1.83	1.63	2.04	0.07	0.81	0.06	0.54	0.37	1.19
13	1.21	1.69	1.36	1.87	1.49	2.02	1.28	2.01	1.46	1.91	1.43	1.84	1.74	1.83	1.67	2.05	0.28	1.81	0.06	0.54	0.40	1.2
14	1.22	1.71	1.38	1.9	1.5	2.02	1.27	2.01	1.46	1.96	1.4	1.84	1.74	1.84	1.66	2.04	0.27	1.17	0.12	0.56	0.41	1.21
15	1.24	1.73	1.38	1.9	1.49	2.02	1.27	2.01	1.45	1.98	1.38	1.82	1.74	1.84	1.66	2	0.27	1.17	0.1	0.53	0.42	1.20
16	1.25	1.74	1.39	1.91	1.49	2.02	1.28	2.01	1.45	2.01	1.35	1.82	1.75	1.85	1.65	2	0.28	1.17	0.09	0.53	0.43	1.23
17	1.26	1.71	1.37	1.84	1.43	2	1.29	2.01	1.42	1.99	1.37	1.94	1.76	1.92	1.65	1.98	0.29	1.17	0.08	0.52	0.44	1.23
18	1.26	1.7	1.37	1.83	1.42	2	1.29	2.01	1.41	1.98	1.36	1.88	1.76	2.02	1.65	1.99	0.66	1.28	0.08	0.51	0.50	1.25
19	1.26	1.71	1.37	1.84	1.43	2	1.29	2.01	1.42	1.99	1.36	1.88	1.78	2.01	1.65	1.99	0.64	1.29	0.07	0.51	0.67	1.26
20	1.18	1.8	1.36	1.83	1.42	2	1.3	2.01	1.46	1.88	1.36	1.87	1.78	2.02	1.64	1.99	0.6	1.29	0.12	0.52	0.68	1.27
21	1.18	1.8	1.37	1.86	1.5	2.01	1.31	2.02	1.45	1.95	1.49	1.85	1.78	2.02	1.64	1.99	0.22	1.04	0.15	0.54	0.41	0.92
22	1.18	1.8	1.38	1.94	1.51	2.01	1.31	2.02	1.46	1.91	1.51	1.81	1.78	2.08	1.64	2	0.19	1.01	0.22	0.56	0.44	0.99
23	1.19	1.79	1.37	1.98	1.51	2.03	1.31	2.01	1.46	1.91	1.51	1.7	1.79	2.14	1.64	2	0.21	1.40	0.25	0.56	0.65	1.10
24	1.22	1.72	1.38	1.99	1.51	2.03	1.44	2	1.46	1.97	1.54	1.72	1.79	2.15	1.63	1.99	0.2	1.13	0.26	0.99	0.65	1.19
25	1.22	1.73	1.39	2	1.52	2.03	1.36	2.01	1.46	1.99	1.56	1.69	1.79	2.15	1.65	1.98	0.2	1.13	0.15	0.88	0.69	1.26
26	1.23	1.73	1.39	2.04	1.53	2.04	1.38	2.01	1.46	2.01	1.57	1.62	1.75	2.24	1.58	1.91	0.19	1.11	0.12	0.72	0.74	1.37
27	1.23	1.74	1.4	2.04	1.53	2.04	1.4	2.01	1.4	2.02	1.59	1.5	1.76	2.26	1.2	1.56	0.18	1.40	1	0.73	0.75	1.38
28	1.24	1.74	1.39	2.01	1.54	2.04	1.42	2.01	1.39	1.98	1.55	1.48	1.79	2.27	1.22	1.32	0.16	1.03	0.27	0.92	0.81	1.28
29	1.24	1.75	1.4	1.95	1.54	2.05	1.43	2.01	1.39	1.98	1.53	1.51	1.79	2.28	1.22	1.3	0.15	1.01	0.3	1.16	0.85	1.31
30	1.24	1.75	1.41	1.99	1.55	2.06	1.43	2.01	1.41	1.78	1.53	1.54	1.79	2.28	1.23	1.3	0.15	1.01	0.3	1.15	0.85	1.31
31			1.36	2	1.39	2	1.36	2.01	1.4	1.9			1.8	2.29			0.11	0.93	0.16	1.16		

Blank space represents data ga

APPENDIX – C3

Table 4.16: Sheki-Sheki DWA Met. Station rainfall records for 2003/2004 rainy season (after Siwale, 2006).

October 2003 (2 rain days)		November 2003 (6 rain days)		December 2003 (10 rain days)		January 2004 (15 rain days)		February 2004 (12 rain days)		March 2004 (9 rain days)	
Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
18.10.03	1.3	16.11.03	0.7	09.12.03	4.8	02.01.04	9.3	02.02.04	1.1	01.03.04	6.5
21.10.03	3.3	17.11.03	15.5	12.12.03	7.8	04.01.04	30.0	13.02.04	18.2	02.03.04	19.0
		22.11.03	1.1	13.12.03	90.5	10.01.04	9.0	16.02.04	15.1	03.03.04	21.4
		23.11.03	1.1	14.12.03	27.8	13.01.04	3.5	18.02.04	20	07.03.04	44.5
		27.11.03	13.9	16.12.03	15.0	17.01.04	8.1	19.02.04	26.6	08.03.04	4.6
		30.11.03	22.3	17.12.03	5.0	18.01.04	4.6	20.02.04	3.0	14.03.04	4.1
				18.12.03	3.3	19.01.04	0.9	24.02.04	6.0	15.03.04	20.6
				23.12.03	20.3	20.01.04	2.6	25.02.04	1.2	16.03.04	0.8
				26.12.03	55.6	21.01.04	4.4	26.02.04	10.1	18.03.04	2.5
				29.12.03	35.4	22.01.04	17.4	27.02.04	0.8		
						23.01.04	35.0	28.02.04	1.2		
						24.01.04	12.0	29.02.04	1.9		
						26.01.04	1.6				
						29.01.04	23.0				
						30.01.04	3.9				

Table 4.17: Sheki-Sheki DWA Met. Station rainfall records for 2004/2005 rainy season (after Siwale, 2006).

October 2004 (3 rain days)		November 2004 (7 rain days)		December 2004 (17 rain days)		January 2005 (15 rain days)		February 2005 (4 rain days)		March 2005 (5 rain days)	
Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
12.10.04	3.1	11.11.04	6.9	04.12.04	22.0	02.01.05	4.7	23.02.05	96.0	01.03.05	39.0
13.10.04	1.6	20.11.04	3.6	05.12.04	13.0	03.01.05	23.0	24.02.05	13.0	02.03.05	25.0
14.10.04	3.5	22.11.04	8.9	06.12.04	66.0	04.01.05	23.0	27.02.05	4.0	03.03.05	20.0
		23.11.04	7.7	07.12.04	3.0	16.01.05	6.5	28.02.05	3.5	29.03.05	2.3
		27.11.04	6.2	08.12.04	2.2	17.01.05	1.0			30.03.05	5.3
		28.11.04	1.2	09.12.04	46.0	19.01.05	12.1				
		29.11.04	0.05	10.12.04	35.0	23.01.05	13.0				
				11.12.04	5.2	24.01.05	4				
				12.12.04	15.6	25.01.05	10				
				13.12.04	55	26.01.05	8.5				
				14.12.04	3.5	27.01.05	4.8				
				15.12.04	42	28.01.05	33				
				28.12.04	20.5	29.01.05	5.4				
				26.12.04	71.2	30.01.05	8.9				
				29.12.04	7	31.01.05	4				
				30.12.04	31						
				31.12.04	40						

Table 4.18: Sheki-Sheki DWA Met. Station rainfall records for 2005/2006 rainy season (after Siwale, 2006).

November 2005 (9 rain days)		December 2005 (15 rain days)		January 2006 (14 rain days)		February 2006 (12 rain days)		March 2006 (10 rain days)	
Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
07.11.04	2.5	01.12.04	11.4	03.01.06	35.0	05.02.06	56.0	01.03.06	3.5
08.11.04	1.0	02.12.04	47.2	05.01.06	10.0	06.02.06	16.5	04.03.06	10.0
09.11.04	11	03.12.04	50	06.01.06	4.0	08.02.06	10.0	05.03.06	35.0
10.11.04	9.5	04.12.04	19.0	09.01.06	5.0	14.02.06	10.6	06.03.06	9.5
18.11.04	2.6	05.12.04	7.7	10.01.06	1.0	15.02.06	4.0	07.03.06	15.5
22.11.04	13.5	06.12.04	2.5	12.01.06	3.0	19.02.06	25.2	08.03.06	13.4
23.11.04	3.4	07.12.04	3.2	16.01.06	29.0	20.02.06	20.0	10.03.06	6.5
27.11.04	3.0	08.12.04	1.5	17.01.06	2.0	21.02.06	17.5	12.03.06	4.2
30.11.04	59.6	09.12.04	7.0	18.01.06	24.0	22.02.06	9.0	13.03.06	20.4
		14.12.04	24	19.01.06	18.2	24.02.06	25.0	21.03.06	2.0
		17.12.04	5.0	22.01.06	65	25.02.06	10.7	29.03.06	20.0
		21.12.04	1.5	23.01.06	7.0	27.02.06	13.0		
		22.12.04	31	28.01.06	9				

APPENDIX - DI

Table 4.30: Evaluation of Groundwater Quality Results for the Lusaka Plateau with Stiffs Method

ID	Coordinates: UTM - WGS 84		Date Analysed	Cations				Anions				Water Type by
	South - X	East - Y		K ⁺ (meq/l)	Na ⁺ (meq/l)	Ca ²⁺ meq/l	Mg ²⁺ meq/l	NO ₃ ⁻ meq/l	Cl ⁻ meq/l	SO ₄ ²⁻ meq/l	HCO ₃ ⁻ meq/l	
1	641075	8292462	Oct-03	1.20	2.86	1.44	3.48	0.36	2.26	1.79	3.25	MgHCO ₃
2	647318	8291658	Sep-04	0.17	2.70	3.84	2.02	0.08	0.25	0.11	4.92	CaHCO ₃
3	636725	8279793	Oct-04	0.34	30.29	1.00	5.81	0.05	1.18	2.11	7.41	NaHCO ₃
4	633145	8287116	Oct-04	0.15	5.45	0.92	4.35	0.10	0.34	0.75	6.89	NaHCO ₃
5	650561	8297694	Oct-04	0.16	3.06	2.92	0.87	0.15	0.31	0.56	5.25	NaHCO ₃
6	642619	8294008	Oct-04	0.03	0.14	0.72	2.53	0.02	0.20	0.13	5.34	MgHCO ₃
7	654973	8301976	Sep-04	0.27	8.28	3.04	3.08	0.20	0.42	0.38	5.25	NaHCO ₃
8	648899	8289183	Oct-03	0.09	1.70	3.20	0.63	0.03	0.31	0.24	2.95	MgHCO ₃
9	649024	8287335	Oct-03	0.21	1.67	2.00	5.29	0.04	0.31	0.43	5.90	MgHCO ₃
10	643605	8285153	May-04	0.10	0.51	6.00	0.63	0.26	0.37	0.01	6.39	CaHCO ₃
11	635470	8283761	Apr-04	0.39	1.80	3.04	2.05	0.02	0.25	0.09	3.64	CaHCO ₃
12	641970	8312150	Aug-04	0.26	7.05	4.60	2.01	0.03	4.60	0.15	5.67	NaHCO ₃
13	647529	8288381	Sep-04	0.17	2.70	3.84	2.02	0.08	0.25	0.11	4.92	NaHCO ₃
14	635603	8282098	Oct-04	0.34	30.29	1.00	5.81	0.05	1.18	2.11	7.41	CaHCO ₃
15	633561	8287083	Apr-04	0.39	1.80	3.04	2.05	0.02	0.25	0.09	3.64	CaHCO ₃
16	627009	8290494	Oct-04	0.11	0.58	0.72	5.22	0.00	0.31	0.87	4.66	MgHCO ₃
17	640758	8294342	Mar-04	0.45	2.01	1.60	3.56	0.14	0.85	0.17	1.97	MgHCO ₃
18	643303	8294775	Mar-04	0.16	2.77	1.60	6.72	0.11	0.99	0.24	6.30	MgHCO ₃
19	649004	8290747	Jan-05	0.15	1.97	5.28	0.79	0.10	0.62	0.08	2.69	CaHCO ₃
20	672940	8313042	Jan-05	0.90	0.95	2.64	1.26	0.00	0.06	0.06	2.82	CaHCO ₃
21	627498	8299299	Dec-04	0.01	0.54	0.80	0.63	0.06	0.45	0.35	1.90	CaHCO ₃
22	632894	8284029	Oct-04	0.11	0.58	0.72	5.22	0.00	0.31	0.87	4.66	MgHCO ₃
23	635945	8298009	Jul-03	0.24	1.87	3.60	6.56	0.01	0.11	0.20	3.87	MgHCO ₃
24	628074	8293782	Sep-03	0.06	2.43	1.60	2.88	0.07	1.69	0.38	3.44	MgHCO ₃
25	633270	8287207	Sep-03	0.93	1.12	2.00	2.37	0.11	0.28	0.11	2.95	MgHCO ₃
26	635963	8311949	Nov-04	0.21	3.95	1.00	0.79	0.13	0.42	1.10	4.56	NaHCO ₃
27	648013	8298307	Jul-03	0.11	0.73	3.68	2.45	0.07	0.14	0.24	3.77	CaHCO ₃
28	633582	8279437	Oct-04	0.29	1.01	1.56	2.21	0.27	0.45	0.13	5.02	MgHCO ₃
29	631379	8294244	Apr-05	0.18	0.91	1.60	1.05	0.11	0.11	0.34	4.75	CaHCO ₃
30	647850	8288649	Apr-05	0.01	0.16	2.40	0.16	0.05	0.23	0.06	5.25	CaHCO ₃
31	644359	8293890	Jun-05	0.84	0.23	2.12	6.40	0.05	0.96	0.21	3.61	MgHCO ₃
32	647804	8302562	May-05	0.55	0.62	4.32	3.04	0.04	0.65	0.88	6.43	CaHCO ₃
33	642944	8303636	Dec-05	0.12	0.78	3.60	1.07	0.11	1.33	0.69	6.13	CaHCO ₃
34	640065	8303514	Dec-05	0.23	5.35	0.76	1.11	0.06	1.30	0.82	1.84	MgHCO ₃
35	647357	8297851	May-05	0.09	1.97	1.68	3.20	0.01	0.59	0.19	2.03	MgHCO ₃
36	647356	8298139	Jan-05	0.15	1.97	5.28	0.79	0.10	0.62	0.08	2.69	CaHCO ₃

APPENDIX – E1

Table 4.67: Projected groundwater level readings at observation boreholes for Lusaka Plateau using various increased abstraction scenarios expected in the absence of groundwater control

Station	Name of Location	UTM Co-ordinates		Aquifer Lithology	Elevation (m amsl)	Projected Static Water Level Readings for the month of October (m bgl)					
						Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
						X	Y				
BH1	DWA Sheki sheki	636019	8298008	Schist	1270.1	1.93	2.02	2.27	2.43	2.58	2.93
BH2	DWA Sheki sheki	636180	8298055	Carbonate	1270.7	2.19	2.22	2.31	2.36	2.41	2.53
BH3	City Airport	641420	8295175	Schist	1281.95	8.71	9.19	10.57	11.42	12.29	14.21
BH4	UNZA	642448	8298165	Carbonate	1263.8	5.96	6.22	6.98	7.44	7.91	8.95
BH5	NISIR	652457	8302699	Alluvium	1173.4	8.93	9.09	9.55	9.83	10.11	10.75
BH6	Lemyadah Christian Sch.	627717	8290876	Carbonate	1254.05	9.50	10.22	12.29	13.56	14.86	17.73
BH7	Forest 26	641986	8286102	Carbonate	1297.9	25.82	26.86	29.87	31.71	33.59	37.74
Estimated additional abstraction volume (10 ⁶ m ³ /year)						110.50	136.09	210.20	255.46	301.8	404.28

APPENDIX - F1

Table 4.50: Sample of the excel electronic data base for boreholes located in Gwembe District

I.D	Client and Location	Coordinates: UTM - YQ2 84			Elevation (m)	Borehole Depth (m)	Discharge r (l/min)	Casing Details		Static Water Level (m)	First Water Strike (m)	Main Water Strike (m)	Aquifer Lithologies	Soil Corax		Yield (m ³)	Date Drilled	HANDPUMP INSTALLATION	
		South - X	East - Y	Plain bottom from G.L. (m)				Screened Length (m)	Soil Type					Corax Depth (m)	TYPE			DEPTH (m)	DATE
1	Sianguuze Village	588233	8142072	519	36	100	38	6	13			Mudstone	Sand	18	5	Mar-01	Mark II	30	May-01
2	Mamanzuma Fishing Camp	591934	8140117	503	54	180	48	6	9	24	30	Mudstone	Sand	11	6	May-01	Mark II	30	May-01
3	Siambuwa Village	577476	8147866	566	80	125	85.5	24	31	48	48	Sandstone	Sand	24	6	Jun-01	Mark II	36	Jul-02
4	Stampondo Village	587887	8141868	524	50	100	45	6	19	24	40	Mudstone	Sandstone	6	0.3	Apr-01	Mark II	30	May-01
5	Siamaene Village	597535	8140178	508	56	125	39	18	13	28	38	Sandstone	Alluvium	6	1.5	May-01	Mark II	30	Jun-01
6	Luumba Village	590262	8144061	515	56	125	39	18	28	36	40	Sandstone	Sand	6	3	May-01	Mark II	36	Jun-01
7	Mabuda Village	602040	8145448	521	75	125	57	18	25	36	42	Sandstone	Clay	12	4	Jun-01	Mark II	36	Oct-02
8	Siampando Village A	600712	8160120	515	75	125	57	18	23	30	39	Mudstone	Sandstone	30	3.5	Jun-01	Mark II	45	Oct-02
9	Chizanga Primary School	553410	8128004	553	50	100	32	18	26	18	26	Sandstone	Clay	4	0.3	Nov-02	Mark II	36	Dec-02
10	Siampando Village B	593996	8152647		35	110	27	18	21	25	25	Sandstone			5	Jul-04	Mark II		
11	Hamechis Village - Malaya	614200	8162443	700	56	125	36	18	6	32	30	Mudstone			0.6	Jun-01	Mark II	27	Jul-02
12	Hamechis Village - Bangwe	591330	8169212	702	60	125	39	21	6	24	36	Mudstone			3	Jun-01	Mark II	27	Jul-02
13	Bibondo RHC	609572	8175860	632	58	125	40.5	18	7	14	38	Mudstone			0.4	Jun-01	Mark II	27	Aug-02
14	Mwemba Village	613763	8175145	622	58	125	39	18	7	20	36	Mudstone			1	Jul-01	Mark II	24	Aug-02
15	Chizangano Pr. School	608605	8170950	712	50	125	30	18	7	24	30	Mudstone			1	Jul-01	Mark II	24	Aug-02
16	Hhigona Village A	596059	8168388	770	50	125	30	18	7	24	24	Mudstone			0.6	Aug-01	Mark II	27	Aug-02
17	Chipepo Sec. School	593916	8141853	514	60	125	42	18	11	24	36	Mudstone	Mudstone	29	5	Aug-01	Mark II	24	Sep-02
18	Luumbo RHC	609435	8166446	575	63.3	125	42	21	15	24	24	Mudstone			0.4	Aug-01	Mark II	30	Sep-02
19	Hamentaaga Village	614269	8160317	560	68	125	48	18	46	58	58	Mudstone			0.8	Sep-01	Mark II	54	Sep-02
20	Hama Pr. School	577311	8170837	1088	40	125	24	18	21	28	28	Granite			0.4	Oct-01	Mark II	27	Oct-02
21	Chisebuka Village	587457	8155806	575	55.5	110	37	18	15	12	12	Mudstone	Clay	1	0.4	Nov-02	Mark II	30	Oct-02
22	Chilala Village	586343	8180634	685	73.5	125	54	18	12	49	49	Mudstone	Clay	0.2	0.5	Oct-02	Mark II	30	Oct-02
23	Namukamba Village				50	110	32	18	19	40	40	Mudstone	Clay	2	1	Sep-02	Mark II	30	Oct-02
24	Chimuka Village B	603145	8174904	843	60	110	48	18	11	24	24	Mudstone	Clay	0.5	0.7	Sep-02	Mark II	30	Oct-02
25	Kalanga Village	596953	8163510	707	73.5	110	54	18	11	12	26	Mudstone	Clay	1	0.8	Sep-02	Mark II	30	Oct-02
26	Simweene Village	604835	8177833	840	73.5	110	54	18	7	17	24	Mudstone	Clay	0.1	0.8	Sep-02	Mark II	30	Oct-02
27	Hajanda Village	604353	8176468	677	54	110	35	15	12	24	36	Mudstone	Clay	10	1	Aug-02	Mark II	30	Oct-02
28	Hankuna Village	601669	8174564	643	43.5	110	25	18	7	24	24	Mudstone	Clay	20	1	Sep-02	Mark II	30	Oct-02
29	Muganya Village	605447	8173883	641	60	110	15	35	3	17	26	Mudstone	Clay	30	1	Aug-02	Mark II	30	Oct-02
30	Chimuka Village A	603551	8174362	628	60	110	48	18	3	20	40	Mudstone	Clay	0.2	0.9	Sep-02	Mark II	30	Dec-02

APPENDIX – F2

Table 4.51: Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006

No.	X	Y	Borehole Depth (m bgl)	Borehole yield (l/sec)	Static Water Level (m bgl)	First Water Intersection (m bgl)	Main Water Intersection (m bgl)	Aquifer Lithology
1	588333	8142072	55	1	19			Sandstone
2	591934	8140117	54	5	9	24	30	Mudstone
3	577476	8147086	80	6	31	48	48	Sandstone
4	587897	8141858	50	0.3	19	24	40	Mudstone
5	587535	8140176	56	1.5	13	28	38	Sandstone
6	590262	8144061	56	3	28	36	40	Sandstone
7	602040	8145446	75	4	25	36	42	Sandstone
8	600712	8150120	75	3.5	23	30	39	Mudstone
9	553410	8128004	50	0.3	26	18	26	Sandstone
10	599996	8152647	35	5	21	25	25	Sandstone
11	614300	8162449	56	0.6	6	12	30	Mudstone
12	597130	8169212	60	3	6	24	36	Mudstone
13	605572	8175860	58	0.4	7	14	38	Mudstone
14	613769	8175145	56	1	7	20	36	Mudstone
15	601605	8170950	50	1	7	24	30	Mudstone
16	586059	8168998	50	0.6	7	24	24	Mudstone
17	591976	8141853	60	5	11	24	36	Sandstone
18	609455	8166446	63.9	0.4	15	24	24	Mudstone
19	614289	8160317	68	0.8	46	58	58	Mudstone
20	577311	8171837	40	0.4	21	28	28	Granite
21	597457	8155806	55.5	0.4	15	12	12	Mudstone
22	586949	8160584	73.5	0.5	12	49	49	Mudstone
23			50	1	19	40	40	Mudstone
24	603145	8174904	60	0.7	11	24	24	Mudstone
25	595553	8168510	73.5	0.8	11	12	26	Mudstone
26	604855	8177833	73.5	0.8	7	17	24	Mudstone
27	604353	8176468	54	1	12	24	36	Mudstone
28	601569	8174564	43.5	1	7	24	24	Mudstone
29	605447	8178869	50	1	9	17	26	Mudstone
30	603551	8174352	60	0.9	9	20	40	Mudstone
31	606329	8179178	50	3	6	20.3	30	Mudstone
32			52	0.8	7.2	18	41	Granite
33	565826	8177213	50	2	7	39	43	Granite
34	565048	8174887	65.5	2	5	4	40	Granite
35	563682	8174924	67.5	0.7	21	49	49	Granite
36	576374	8172618	50	2	5	23	32	Granite
37	576642	8169683	67.5	1	12	30	49	Mudstone
38	578246	8170746	52	0.6	11	23	40	Granite
39	574821	8172676	55.5	0.9	19	24	24	Granite
40	582335	8161032	55.5	1	16	26	34	Mudstone
41	586072	8160615	62.5	0.9	30	35	49	Mudstone
42	604553	8176255	50	0.8	8.9	10	37	Granite
43	600912	8171042	70	0.3	7.3	15	15	Mudstone
44	597703	8169514	55	0.4	24	30	50	Mudstone
45	598552	8169811	55	0.9	16.4	18	31	Mudstone
46	604926	8179050	60	0.9	16.4	24	24	Mudstone
47	606724	8176251	55	0.4	7.9	34	34	Mudstone
48	612616	8178609	43	0.4	7.1	6.5	43.5	Mudstone

bgl = Below ground level.

Table 4.52: Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006

No.	X	Y	Borehole		Static Water	First Water	Main Water	Aquifer Lithology
			Depth (m bgl)	Borehole yield (l/sec)	Level (m bgl)	Intersection (m bgl)	Intersection (m bgl)	
1	613774	8178904	55	0.8	14.3	15	15	Mudstone
2	617125	8178394	40	0.6	6.32	18	24	Mudstone
3	619124	8180611	55	0.4	8.65	13	30	Mudstone
4	616465	8177436	55	0.7	10.58	13	26	Mudstone
5	614056	8174975	37	2	8.43	12	28	Mudstone
6	614811	8173763	50	0.4	5.5	18	26	Mudstone
7	616369	8172411	50	5	13.23	18	40	Mudstone
8	618499	8175384	55.5	0.3	5.2	18.5	24	Mudstone
9	621045	8176731	50	0.4	10.8	18.5	18.5	Mudstone
10	595583	8164053	31	2	5.4	12	18	Mudstone
11	584311	8168471	55	0.8	8.4	15	22	Mudstone
12	597977	8165886	38	7	12.98	24	24	Sandstone
13	608477	8166337	40	10	10	9	21	Mudstone
14	609303	8166763	31.5	2	4.33	8	24	Mudstone
15	606475	8166104	37.5	8	5.94	12	24	Mudstone
16	613448	81677116	31.5	2	3.8	9	20	Mudstone
17	582784	8158461	40	12	14.9	20	20	Mudstone
18	589177	8142083	52	12	26.5	44	36	Mudstone
19	588891	8143077	52	12	20.7	40	43	Sandstone
20	580745	8166011	60	5	10	22	36	Mudstone
21	581565	8165854	52	3	7	20	38	Mudstone
22	564132	8176917	60	1	7.5	25	50	Granite
23	563493	8176345	60	1.2	2	24	35	Schist
24			54	0.5	2.5	42	42	Granite
25			60	1	4	32	48	Granite
26	564461	8176591	50	2	22	30	48	Granite
27	564096	8176580	50	1	7.5			
28	564471	8178075	60	1.2	13	28	50	Granite
29	590256	8153671	52	3	5	30	30	Mudstone
30	565007	8175870	45	0.5	5			
31	599965	8152991	75	8	47	63.4	63.4	Mudstone
32	598946	8147974	40	3	20	30	30	Sandstone
33	599554	8151945	73	6	38	58	58	Sandstone
34	600274	8153265	61	4	40	53	53	Mudstone
35	586378	8146158	72	5	36			Mudstone
36	596381	8145961	40	2	15	25	30	Sandstone
37	596713	8146623	43.5	3	20			Sandstone
38	607893	8154062	35	6	5	25	25	Sandstone
39	598526	8152466	80	2	27			Sandstone
40	600130	8149724	54	5	25	37	37	Sandstone
41	599847	8147561	42	3	22	36	36	Sandstone
42	578234	8164044	42	0.6	4.2	12	18	Mudstone
43	580025	8149489	31.5	3	10	24	24	Mudstone
44	583599	8157579	45	0.5	7	25	25	Mudstone
45	579687	8149199	31.5	3	4	20	20	Mudstone
46	575751	8145682	50	5	25	30	30	Quartzite
47	572498	8146133	50	10	17	30	30	Coal
48	574450	8146243	50	1	20	30	30	Mudstone

bgl = Below ground level.

Table 4.53: Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006

No.	X	Y	Borehole Depth (m bgl)	Borehole yield (l/sec)	Static Water Level (m bgl)	First Water Intersection (m bgl)	Main Water Intersection (m bgl)	Aquifer Lithology
1	594017	8164426	50	1	4	30	30	Mudstone
2	594488	8166194	42	1.5	5	30	30	Sandstone
3	577071	8171995	60	0.31	30	30	42	Granite
4	564828	8176544	60	0.4	15	30	40	Schist
5	590864	8178988	52	0.3	25	30	30	Granite
6	589202	8180184	62	0.2	35	36	36	Granite
7	570178	8172544	51	0.4	32	42	42	Granite
8	586404	8164240	31	1	9	42	42	Mudstone
9	601954	8174516	78	1	14			Mudstone
10	604942	8176278	40	1	8	30	14	Mudstone
11	608935	8177315	50	1	11	40	40	Mudstone
12	611107	8177859	50	1	4	36	36	Mudstone
13	572772	8135324	40	2	26	34	34	Sandstone
14	564898	8132590	66	3	25	48	48	Sandstone
15	571224	8134324	38.9	10	4.5	27	27	Sandstone
16	559095	8128950	33	0.5	11	24	24	Sandstone
17	563355	8128013	85	0.2	36	64	64	Mudstone
18	583110	8159044	48	5	10.5	15	20	Mudstone
19	589934	8142716	54	1	26	38	38	Sandstone
20	593484	8142787	45	1	26	36	36	Sandstone
21	583713	8146679	63	1	31	55	57	Sandstone
22	578109	8147705	42	0.2	10.4	18	30	Mudstone
23	580794	8169606	60	1	8			Sandstone
24	608948	8166995	60	1	8	24	42	Sandstone
25	613917	8167747	60	1.5	12	12	42	Sandstone
26	614593	8168462	60	1.5	2	18	36	Sandstone
27	607433	8176336	54	1.5	24	18	24	Mudstone
28	573802	8163633	42	0.3	7	18	24	Granite
29	601954	8174516	54	2	4.2	42	42	Mudstone
30	623129	8182922	50	2	6.5	18	24	Mudstone
31	575489	8139666	50	3	6.5	24	24	Sandstone
32	589325	8142992	60	1.5	19	36	42	Sandstone
33	585756	8145450	60	0.3	25	42	46	Sandstone
34	596446	8164812	54	0.3	11	30	36	Sandstone
35	592482	8143161	43	4	5	24	28	Sandstone
36	589984	8166817	50	0.1	1	12	12	Mudstone
37	584931	8158804	55	15	5.3	30	36	Mudstone
38	585334	8160341	48	1	7	18	24	Mudstone
39	581924	8158655	43	0.3	10	18	24	Mudstone
40	582911	8152322	60	5	30	38	38	Sandstone
41	587240	8164638	50	4	12	18	30	Mudstone
42	582137	8140585	73	0.2	10.3		62	Mudstone
43	581390	8167238	55	0.3	1	18	36	Mudstone
44	592612	8175532	50	0.3	15	24	36	Mudstone
45			43	1	7	17	36	Gneiss
46	595794	8174865	50	1	8	20	30	Mudstone
47			45	0.4	13	25	26	Granite
48	577303	8147696	44	0.5	4.2	15	24	Mudstone

bgl = Below ground level.

Table 4.54: Data on boreholes drilled by DWA in Gwembe District from 2001 to 2006

No.	X	Y	Borehole Depth (m bgl)	Borehole yield (l/sec)	Static Water Level (m bgl)	First Water Intersection (m bgl)	Main Water Intersection (m bgl)	Aquifer Lithology
1	586312	8147214	62	1.5	39.6	45	50	Mudstone
2	594038	8150270	79.5	1.5	37.4	66	66	Mudstone
3	583320	8146360	61.5	1.5	35.8	48	52	Mudstone
4	582143	8145557	60	0.4	24.8	38	42	Sandstone
5	580337	8142589	67.5	0.6	38.2	48	48	Mudstone
6	580507	8142609	91.5	1	35	82	82	Mudstone
7	579580	8138703	55.5	1.5	13.2	15	40	Mudstone
8	579852	8139023	54	1.2	7	36	38	Sandstone
9	583856	8141712	50	1.5	11	36	38	Sandstone
10	584371	8138978	43.5	2	13.2	30	36	Mudstone
11	582450	8140112	48	2	9.8	40	42	Mudstone
12	582136	8139973	45	1.5	12	30	32	Sandstone
13	582085	8140481	57	0.6	19.4	36	42	Mudstone
14	572424	8139432	45	0.5	17.1	18	24	Mudstone
15	575559	8144768	80	2	9.5			
16	568127	8133670	85	0.8	26.5			
17	572688	8132848	45	2	11.4	24	30	Mudstone
18	571860	8130746	67.5	1.5	28	36	45	Sandstone
19	569003	8131147	62	2	29.1	46	48	Sandstone
20	562638	8131641	67.5	1	26	48	54	Sandstone
21	561305	8128539	45	2	6.5	18	24	Mudstone
22			70	0.2	28	42	45	Mudstone
23			45.5	1	14.5	24	30	Mudstone
24			50	0.4	6.5	18	30	Mudstone
25	563438	8126594	48	0.6	11.5	36	36	Mudstone
26	562929	8128046	48	0.4	7.2	12	36	Mudstone
27	562159	8126958	48	0.8	11	12	36	Mudstone
28	563555	8131647	73	1	21	60	60	Sandstone
29			50	0.4	3	30	36	Gneiss
30			85.5	1.5	27	72	75	Mudstone
31			91.5	0.2	42	54	76	Sandstone
32			55.5	4	13.4	30	42	Sandstone
33			43.5	2	9.4	18	30	Sandstone
34			60	3	11.5	45	48	Sandstone
35			103.5	0.5	32	36	72	Mudstone
36			50	2	18.2	28	30	Sandstone
37			50	2	9.2	36	36	sandstone
38			55	2	9.4	30	36	sandstone
39			50	2	30	30	30	sandstone
40			67.5	1	18.2	38	48	Sandstone
41			67.5	2	24.5	42	45	Sandstone
42			60	0.5	20.1	36	42	Mudstone
43			43	4	9	12	24	Sandstone
44			43	5	11	15	24	Mudstone
45			48	4	6.5	18	30	Mudstone

bgl = Below ground level.

Table 4.59: Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006

No.	GPS Coordinates		Aquifer Lithology	Date Analysed	mg/L										
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
1	577311	8171837	B-G	Nov-01	4.73	91.5	88	28.3	0.8	<0.01	21.6	1.28	17	14.6	302
2	564171	8173817	B-G	Oct-02	33.2	53	11.2	36.5	<0.01	<0.01	0.09	0.57	12	5.2	240
3	574827	8164194	B-G	Oct-02	30.7	55	32	11.5	2.04	1.1	0.48	2.04	10	6.8	230
4	565048	8174887	B-G	Oct-02	31.8	58	43.2	11.2	<0.01	<0.01	4.59	2.07	5	10.8	290
5	563682	8174924	B-G	Oct-02	42.2	20	16	10.6	1.21	<0.01	<0.01	0.57	8	251.1	50
6	568826	8177213	B-G	Oct-02	26	46	16	15.4	0.58	<0.01	0.19	0.93	4	6.1	100
7	578246	8170746	B-G	Dec-02	4.66	12.8	35	54	0.44	<0.01	3.16	0.22	8	26.6	26
8	574821	8172676	B-G	Dec-02	3.16	32.1	40	24	5.7	<0.01	3.3	0.81	9	17.3	18
9	604553	8176255	B-G	Sep-03	53.6	888	81.6	48.9	0.13	0.1	11.3	0.29	171	455	546
10	564132	8176917	B-G	Mar-04	16.1	29.4	8	13.4	0.92	0.01	8	0.04	15	1.2	36
11	563493	8176345	B-G	Mar-04	25.3	44.5	38.4	15.4	3.59	0.04	9.66	0.07	15	30.5	104
12	564461	8176591	B-G	Mar-04	39.9	40.9	24	15.4	2.8	0.03	12.01	0.06	15	19.8	440
13	564096	8176580	B-G	Mar-04	40.8	221.2	211.2	43.2	<0.01	<0.01	<0.01	0.19	10	441.9	270
14	564471	8178075	B-G	Mar-04	35.4	28.3	14.4	5.76	0.9	0.02	8.17	0.03	5	2.4	52
15	575751	8145682	B-Q	Aug-04	18.8	Nd	18.4	44.2	<0.01	<0.01	0.5	0.17	10	51.2	414
16	577071	8171995	B-G	Oct-04	15.55	233.3	16.8	26.9	<0.01	<0.01	7.1	0.08	8	11.6	254
17	590864	8178988	B-G	Oct-04	53.4	172.9	15.2	17.8	0.16	<0.01	9.2	0.25	5	57.6	256
18	589202	8180184	B-G	Oct-04	52.57	170	13.6	15.8	0.2	<0.01	4.3	0.09	4	80.2	254
19	570178	8172544	B-G	Oct-04	23.1	828	8	19.2	0.61	0.01	10.5	-	8	10.7	354
20	573802	8163633	B-G	Jun-04	4.86	47.4	44.8	24	3.84	0.52	3	0.16	10	13	234
21	588333	8142072	S	Apr-01	6.4	36.7	60.8	17.5	1.42	0.17	3.21	0.45	37	7.5	209
22	590262	8144061	S	Apr-01	12.1	12.1	80.8	11.04	0.3	<0.01	12.8	1.1	46	3.8	Nil
23	587535	8140176	S	Apr-01	0.66	3.4	91.2	11.52	2.11	<0.01	16.3	0.33	50.5	6.8	Nil
24	577476	8147086	S	Jul-01	3.8	53.7	111.2	6.24	<0.01	0.07	12.44	0.148	57	0.20	12.0
25	602040	8145446	S	Jul-01	10.6	37.9	136	0.96	0.86	0.09	27.81	0.159	50	5.10	Nil
26	553410	8128004	S	Jan-03	2.3	269.5	111.2	12	0.2	0.5	3.66	1.59	57.98	11.90	302
27	591976	8141853	S	Oct-01	3.2	187	54.2	9.14	0.11	<0.01	58	0.21	45	10.3	0
28	597977	8165886	S	Sep-04	16.9	91.7	27.4	26.9	1.21	0.05	10.6	0.14	8	42.4	Nil
29	588891	8143077	S	Jan-04	12.1	89.9	44.8	10.56	0.45	<0.01	2.1	0.13	14	12.4	360
30	598946	8147974	S	Jul-05	22.5	235.1	48	39.36	<0.01	<0.01	<0.01	0.5	18	0.4	456
31	599554	8151945	S	Jul-05	40.4	315.5	0.001	0.001	0.65	<0.01	0.4	1.41	7	19.5	240
32	596381	8145961	S	Jul-04	32	318	32	16.32	0.53	0.7	12	0.54	8	14.4	120
33	596713	8146623	S	Aug-05	3.36	39.5	77.6	11.04	0.4	<0.01	0.26	0.05	10	6.2	304

B-G = Basement Complex, S = Sandstone, M = Mudstone, values showing as n/d = not done, NB all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

Table 4.60: Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006

No.	GPS Coordinates		Aquifer Lithology	Date Analysed	Mg/L										
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
34	607893	8154062	S	Aug-04	27.5	Nd	72	38.9	0.02	0.001	0.001	0.18	13	58.9	418
35	598526	8152466	S	Jul-04	29.1	379	0.001	0.001	3.47	0.9	11.6	1.86	17.5	171.9	610
36	600130	8149724	S	Jul-05	1.75	40.1	80	16.8	<0.01	<0.01	6.6	0.12	5	79.2	360
37	599847	8147561	S	Jul-04	35.5	289.1	93.6	29.3	<0.01	<0.01	<0.1	0.12	14	30	382
38	594488	8166194	S	Aug-04	13.2	Nd	42.4	7.68	1.85	0.05	2.5	0.14	25	50.8	186
39	572772	8135324	S	Dec-04	9.6	67	32.8	3.84	<0.01	<0.01	4.54	0.19	10	16.1	198
40	564898	8132590	S	Dec-04	13.6	54.4	40.8	4.32	<0.01	<0.01	0.22	0.2	9	19.8	180
41	571224	8134324	S	Dec-04	11.4	66.6	16.8	6.24	<0.01	<0.01	<0.01	0.28	8	47.7	154
42	559095	8128950	S	Dec-04	6.4	10.1	25.6	0.48	0.31	0.01	10.95	0.24	9	16.2	74
43	589934	8142716	S	Jun-05	1.15	79	81.6	11.5	<0.01	<0.01	3.5	0.09	35	12.3	294
44	593484	8142787	S	Jun-05	0.32	100	44	0.96	1.01	0.4	<0.01	0.16	27	31.9	330
45	583713	8146679	S	Apr-05	3.88	98.3	24.8	11.04	0.12	<0.01	<0.01	0.07	5	52.5	296
46	580794	8169606	S	Apr-05	3.56	43	60	28.8	<0.01	<0.01	<0.01	0.08	3	88	530
47	608948	8166995	S	Apr-05	11.4	433	21.6	19.2	<0.01	<0.01	0.8	0.13	32	1264	466
48	613917	8167747	S	Apr-05	13	275	37.2	15.36	0.08	<0.01	<0.01	0.08	25	162	406
49	614593	8168462	S	Apr-05	4.44	87.1	43.2	21.12	0.13	<0.01	<0.01	0.04	12	76	420
50	575489	8139666	S	Apr-05	6.1	6.8	24	1.44	1.4	0.02	9.49	0.15	15	32.8	80
51	589325	8142992	S	May-05	7.81	46.2	20.8	12.48	<0.01	<0.01	0.48	0.18	17	11.2	366
52	585756	8145450	S	May-05	9.13	73	24	47.2	1.33	0.01	0.16	0.16	15	234	106
53	596446	8164812	S	Apr-05	9.43	18.4	64.8	5.76	1.19	<0.01	27.9	0.16	20	5.9	148
54	562638	8131641	S	Sep-05	4.66	58.1	80	13.44	<0.01	<0.01	<0.01	0.18	14	2.2	326
55	571860	8130746	S	Sep-05	7.6	68.3	44	20.16	<0.01	<0.01	<0.01	0.09	12	4.2	264
56	563555	8131647	S	Oct-05	3.39	224.4	16.8	50.4	0.13	<0.01	1.7	0.21	10	43.4	384
57	582143	8145557	S	Aug-05	6.59	73.7	35.2	8.64	<0.01	<0.01	0.4	0.06	12	83.1	336
58	579852	8139023	S	Sep-05	2.01	55.5	40	7.2	0.89	0.04	0.02	0.08	20	2	220
59	583856	8141712	S	Sep-05	2.84	134	60	12.96	0.19	<0.01	0.76	0.08	90	132	142
60	592482	8143161	S	Jun-05	1.35	137.5	21.6	24.3	1.18	0.41	<0.01	0.18	70	20.9	402
61	582911	8152322	S	Jul-05	4.17	121	40	31.2	<0.01	<0.01	<0.01	0.12	7	216	121
62	587897	8141858	M	Apr-01	3.15	71.9	85.6	16.04	0.88	0.32	2.62	0.66	62	242	265
63	591934	8140117	M	Apr-01	11.6	3.8	24.8	28.8	1.98	<0.01	13.3	0.80	25	4.9	Nil
64	600712	8150120	M	Jul-01	5.6	49.4	76.8	16.8	<0.01	0.23	6.31	0.170	9	0.80	Nil
65	614300	8162449	M	Jul-01	15.9	118.8	104.8	61.92	3.04	0.62	30.78	0.55	120	11.3	
66	597130	8169212	M	Jul-01	5.2	193.6	12.8	34.56	1.31	0.43	1.31	2.11	12	51.8	

B-G = Basement Complex, S = Sandstone, M = Mudstone, values showing as nd = not done, **NB** all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

Table 4.61: Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006

No.	GPS Coordinates		Aquifer Lithology	Date Analysed	Mg/L												
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻		
67	605572	8175860	M	Jul-01	9.3	319.7	15.2	57.12	0.66	0.3	6.77	0.64	15	217.5			
68	613769	8175145	M	Feb-02	11.23	276.2	58.4	42.4	0.6	0.7	4.6	0.29	21.2	229.9	414		
69	601605	8170950	M	Feb-02	2.3	269.5	111.2	12	0.2	0.5	3.66	1.59	57.98	11.9	3020		
70	586059	8168998	M	Feb-02	1.99	156.3	14.4	98.9	0.5	0.2	3.89	0.99	27	1.8	420		
71	609455	8166446	M	Oct-01	2.2	173.4	53.7	12.57	0.03	<0.01	8.7	0.46	55	8.8	438		
72	614289	8160317	M	Feb-02	3.65	21.6	18.4	120.5	0.8	0.2	3.16	0.2	30	13	464		
73	601569	8174564	M	Sep-02	9.9	118	11.2	35.5	<0.01	<0.01	0.09	2.14	14	27.7	330		
74	576642	8169683	M	Oct-02	28.3	58	19.2	33.6	<0.01	<0.01	1.14	0.84	10	13.4	180		
75	595553	8168510	M	Sep-02	14.2	85	16	44.2	<0.01	<0.01	1.69	1.58	5	9.5	300		
76	597457	8155806	M	Nov-02	30.7	55	32	11.5	2.04	1.1	0.48	2.04	10	6.8	230		
77	586949	8160584	M	Oct-02	11.6	115	67.2	36.2	<0.01	<0.01	19.4	1.77	7	50.1	370		
78	603551	8174352	M	Sep-02	31.2	154	160	94.1	0.33	0.6	3.02	0.91	18	14.3	284		
79	604553	8176255	M	Aug-02	15.8	235	8	9.6	<0.01	<0.01	<0.01	1.51	5	16.9	56		
80	604855	8177833	M	Sep-02	41.1	250	120.6	201.6	2.07	5.6	1.39	2.16	38	150.2	244		
81	603145	8174904	M	Sep-02	15	209	12.8	28.8	<0.01	<0.01	1.12	2.21	16	61.7	122		
82	606329	8179178	M	Sep-02	42.1	202	28.8	195.8	0.47	0.3	2.25	1.5	33	270.8	284		
83	605447	8178869	M	Aug-02	32.3	250	11.2	43.2	0.08	<0.01	2.06	1.45	33	282	200		
84	586072	8160615	M	Dec-02	3.46	13.3	59	31	9.14	<0.01	1.62	0.48	14	26.5	Nil		
85	582335	8161032	M	Dec-02	4.11	16.2	66	16	0.9	<0.01	2.8	0.72	8	101.2	26		
86	600912	8171042	M	Sep-03	53.8	862	84.8	199.68	0.16	0.1	11.5	0.22	166.9	458	486		
87	597703	8169514	M	Sep-03	40.4	315.5	0.001	0.001	0.65	0.001	0.4	1.41	7	19.5	240		
88	598552	8169811	M	Sep-03	39.7	304.8	0.001	0.001	1.35	0.001	2.3	1.18	10	94.3	140		
89	604926	8179050	M	Aug-04	29.1	379	0.001	0.001	3.47	0.9	11.6	1.86	17.5	171.9	610		
90	606724	8176251	M	Sep-03	28.4	379	0.001	0.001	3.51	0.3	15.9	1.79	10	172.4	634		
91	612616	8178609	M	Sep-03	32	318	32	16.32	0.53	0.7	12	0.54	8	14.4	120		
92	613774	8178904	M	Sep-03	75.1	180	43.2	218.88	0.14	0.1	11.4	0.44	168.9	353.6	480		
93	617125	8178394	M	Oct-03	20.1	224.3	25.6	0.001	0.47	0.04	25.7	0.14	63	112.2	416		
94	619124	8180611	M	Oct-03	36.6	308.7	160	9.6	0.001	0.001	21.2	0.31	148	418.8	326		
95	616465	8177436	M	Oct-03	30.7	201	12.8	0.001	0.76	0.07	21.9	0.15	15	35.5	548		
96	614056	8174975	M	Oct-03	17.6	420.2	12.8	0.001	0.55	0.06	20.8	0.11	156	247.6	510		
97	614811	8173763	M	Oct-03	24	208.6	16	0.001	0.05	<0.01	18.8	0.06	104	60.3	550		
98	616369	8172411	M	Oct-03	25.8	218.9	20.8	0.001	0.05	<0.01	17.9	0.06	84	55.6	554		
99	618499	8175384	M	Sep-05	8.1	314.3	1.6	10.6	0.03	<0.01	12.9	0.08	27	215.7	858		

B-G = Basement Complex, S = Sandstone, M = Mudstone, values showing as nd = not done, NB all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

Table 4.63: Groundwater quality data for boreholes drilled in Gwembe District by the Department of Water Affairs: 2001 to 2006

No.	GPS Coordinates / Name		Aquifer Lithology	Date Analysed	mg/L												
	X	Y			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	NO ₃ -N	F	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻		
133	601954	8174516	M	Apr-05	7.8	1307	9.6	10.08	0.2	<0.01	0.33	0.08	31	535	530		
134	623129	8182922	M	Apr-05	10.18	76.7	48	56.64	3.57	0.04	13.77	0.09	1.5	113.7	312		
135	572688	8152848	M	Sep-05	7.16	69	42.4	9.6	<0.01	<0.01	<0.01	0.08	12	6.1	356		
136	562159	8126958	M	Sep-05	5.89	71.4	26.4	22.56	<0.01	<0.01	<0.01	0.12	10	6.3	294		
137	561305	8128539	M	Sep-05	6.76	33.8	68	17.76	<0.01	<0.01	<0.01	0.13	12	3.2	240		
138	563438	8126594	M	Oct-05	15.52	180.5	22.4	13.44	<0.01	<0.01	<0.01	0.06	9	21.6	366		
139	562159	8126958	M	Oct-05	7.03	120.6	13.6	5.28	2.97	0.41	56.6	0.05	8	65.5	340		
140	579580	8138703	M	Oct-05	2.9	103	15.2	6.24	4.33	0.53	5.3	0.08	10	114.8	200		
141	562929	8128046	M	Oct-05	6.88	57.1	29.28	18.4	<0.01	0.04	<0.01	0.1	5	7.4	266		
142	580507	8142609	M	Aug-05	6.83	185	16.8	5.28	0.53	0.01	0.9	0.12	13	178	408		
143	583320	8146360	M	Aug-05	7.29	123	41.6	11.04	<0.01	<0.01	<0.01	0.09	13	146	272		
144	580337	8142589	M	Aug-05	6.77	184	12.8	9.6	<0.01	<0.01	9	0.1	9	137	440		
145	582450	8140112	M	Sep-05	2.89	136	24	12.96	1.76	0.05	1.02	0.07	20	17.1	148		
146	584371	8138978	M	Sep-05	4.49	96.6	44	13.44	0.05	<0.01	0.74	0.12	35	12	190		
147	581390	8167238	M	Jun-05	3.27	77.2	13.6	29.3	1.32	0.38	2.61	0.14	8	41.2	450		
148	589984	8166817	M	Jun-05	11.59	151	7.2	28.3	2.57	0.5	0.25	0.21	13	55.6	526		
149	584931	8158804	M	Jul-05	0.27	79.8	44	7.2	0.12	<0.01	1.61	0.1	9	76.8	332		
150	585334	8160341	M	Jul-05	2.02	154	30.4	21.12	0.45	<0.01	0.86	0.09	5	85.3	584		
151	581924	8158655	M	Jul-05	3.49	82.6	72.8	3.36	0.03	<0.01	0.36	0.15	8	32.2	392		
152	592612	8175532	M	Jul-05	7.49	93.93	16	31.2	0.63	0.04	<0.01	0.06	3	144	400		
153	595794	8174865	M	Jul-05	11.33	66.4	80	26.4	<0.01	<0.01	<0.01	0.05	20	246	300		
154	587240	8164638	M	Jul-05	4.54	120	12	16.8	0.96	0.07	<0.01	0.05	7	232	560		
155	Namukama Village		M	Aug-02	22.6	75	11.6	79.7	0.14	<0.01	1.16	1.02	9	19.5	234		
156	Siamukwasa Village		M	Sept-04	11.4	193.3	49.6	1.92	<0.01	<0.01	11.8	0.11	6	15.4	278		
157	Malambo Village B		M	Mar-04	29.3	32.2	64	38.4	0.03	<0.01	4.66	0.05	5	10.6	32.2		
158	Muchenenga Village A		M	Oct-05	6.09	103.7	17.6	22.56	0.96	<0.01	1.3	0.11	14	88.1	282		
159	Syabenzu Village		M	Aug-05	7.45	151	26.4	17.76	0.38	<0.01	3.9	0.21	38	46	424		
160	Hamunali Village		M	Jul-05	10.14	65.7	20	67.2	<0.01	<0.01	<0.01	0.1	8	174	510		
161	Hulumya Village		M	Jul-05	2.36	37.82	48	36	0.11	<0.01	<0.01	0.15	3	71.6	230		
162	Sabenzu Village B		M	Oct-05	4.16	152.4	8	50.88	0.32	<0.01	22.7	0.22	10	4.5	198		
163	Siamulowa Village		M	Aug-05	2.3	41.7	20.8	42.72	<0.01	<0.01	3.2	0.18	12	33.1	250		
164	Luumuno Village		M	Oct-04	58	318.3	16.8	28.3	<0.01	<0.01	<0.01	0.11	18	16.4	228		

B-G = Basement Complex, S = Sandstone, M = Mudstone, values showing as nd = not done, NB all values of <0.01 were set to 0.0001 when calculating SAR, Cl Toxicity and MH etc.

APPENDIX – G2

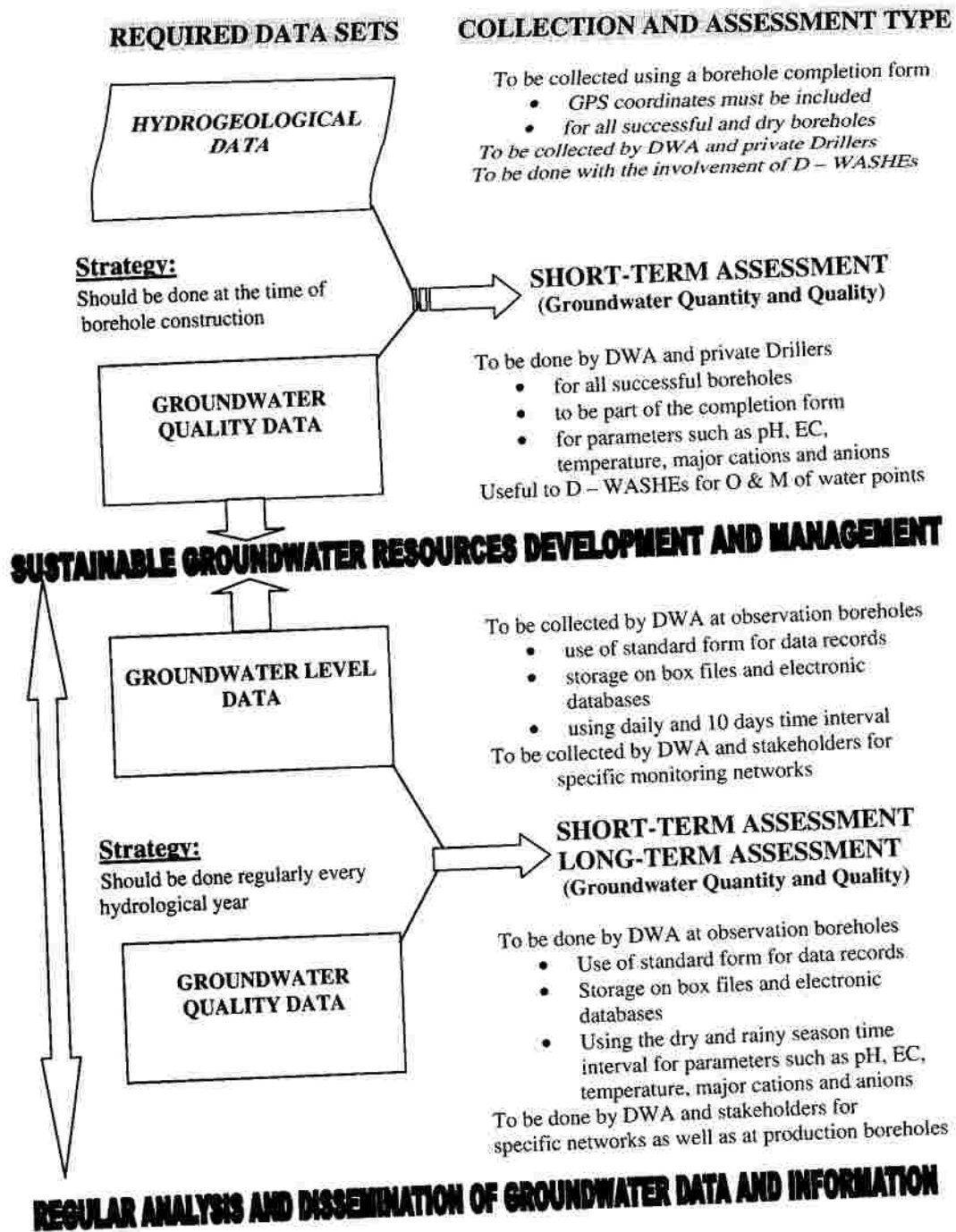


Figure 4.64 Summarised flow chart of the proposed groundwater data and information capture model