REPUBLIC OF ZAMBIA
Ministry of Energy and Water Development

COOPERATION
REPUBLIC OF ZAMBIA
FEDERAL REPUBLIC OF GERMANY

FEDERAL REPUBLIC OF GERMANY
Federal Institute for Geosciences and Natural Resources

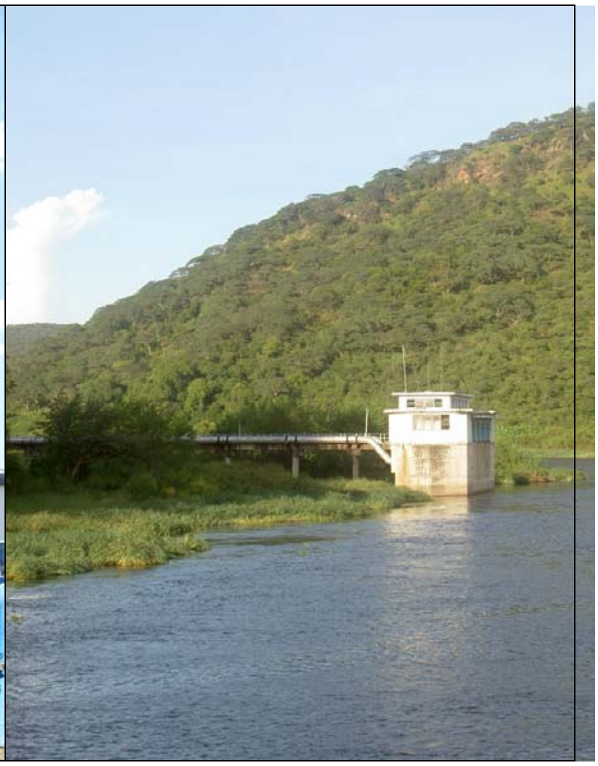
BGR

Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

REPORT NO. 2

DESK STUDY & PROPOSED WORK PROGRAM REPORT

Roland Bäumle & Simon Kang'omba



Lusaka, October 2009

Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

Desk Study & Proposed Work Program Report

Authors (in alphabetical order):	Dr. Roland Bäumle (BGR) Simon Kang'omba (DWA)
Commissioned by:	Federal Ministry for Economic Cooperation and Development (BMZ: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung)
Project Numbers:	BMZ PN 2003.2024.2 (Phase I) BGR 05-2315-01
Implementing Agencies:	Ministry of Energy and Water Development, Department of Water Affairs, Lusaka Federal Institute for Geosciences and Natural Resources (BGR: Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover)
Pages:	101
Place and date of issuance:	Lusaka, October 2009

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABBREVIATIONS

A	Groundwater Abstraction
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BTEX	Benzene, toluene, ethylbenzene, and xylene
CU	Commercial Utility
DEM	Digital Elevation Model
DNAPL	Dense Non-aqueous Phase Liquids
DTF	Devolution Trust Fund
DWA	Department of Water Affairs
EC	Electrical conductivity
ET	(Actual) Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GDC	German Development Cooperation
JICA	Japan International Co-operation Agency
K	Hydraulic Conductivity
LCC	Lusaka City Council
LWSC	Lusaka Water and Sewerage Company
m asl	Meters above sea level
m bgs	Meters below ground surface
MAR	Mean annual rainfall
MEWD	Ministry of Energy and Water Development
MLGH	Ministry of Local Government and Housing
MoL	Ministry of Lands
NWASCO	National Water and Sanitation Council
PET	Potential Evapotranspiration
q	Specific Capacity of a Well
Q	Aquifer or Well Yield
Q_b	Groundwater outflow or baseflow
Q_d	Direct runoff (overland flow and interflow)
R	Groundwater Recharge
R%	Groundwater Recharge Rate (in % of Rainfall)
RAM	Relative plant available moisture
SRTM	Shuttle Radar Topographic Mission
S_y	Specific Yield (effective porosity)
T	Transmissivity
TDS	Total dissolved solids
ΔS	Change in groundwater storage

1 Introduction and Background

1.1 Project Objectives

In May 2005, the Project “Groundwater Resources for Southern Province “ was launched and implemented by the Department of Water Affairs (DWA), Ministry of Energy and Water Development, Zambia with support from the Federal Institute for Geosciences and Natural Resources (BGR), Germany. The main objectives of the project are to facilitate an effective groundwater resource planning and management and to strengthen the capacities in the Zambian water sector.

Continued funding for the program was granted during the bilateral negotiations on development co-operation between the Republic of Zambia and the Federal Republic of Germany held during December 2008. Both sides agreed to carry on their support to the development of a national groundwater database and hydrogeological maps, and to support the implementation of the Water Resources Management Bill, once enacted. The coverage area will be extended to include the Lower Kafue and Chongwe catchments with emphasis on the significant Lusaka groundwater systems. It was decided to develop a groundwater management strategy for the highly vulnerable groundwater resources in the Capital’s urban and peri-urban areas.

In April 2008, the Ministry of Energy and Water Development (MEWD) with support from the BGR convened a two-day planning workshop, and together with all relevant stakeholders in the sector developed a basis for the proposal of the extension of the project. Based on proceedings of the workshop (Bulwani 2008), it is reasonable to conclude that the Development of a Groundwater Information System and Management Program for the Lusaka groundwater systems will be making a significant contribution to the national water and sanitation vision for 2030 through provision of relevant information for decision making by various stakeholders in the Lusaka Region. The outcome and outputs of the project are by and large in conformity with those of the Fifth National Development Plan (FNDP) on water and sanitation. Specifically, the Project will contribute towards water resource management information system and water resource assessment programs. It was furthermore stated that the Project is expected to make a significant contribution to the goal that MEWD and other key stakeholders within the project coverage area will manage groundwater resources efficiently and in a sustainable manner.

Between the 9th and 17th September 2009 a project review led by an external evaluator has been organized to assess the first phase of the project, to contribute to the conceptual design of the second phase from 2010 to 2012, and to harmonize procedures of the German Development Cooperation (GDC) by integrating the offer for the next phase in the GDC’s joint Program Proposal (Water Sector Reform Program).

During the review, the project's outputs and outcomes have been assessed against the five OECD/DAC criteria relevance, effectiveness, impact, efficiency and sustainability (Becker et al. 2009). By and large based on the proposal submitted during the planning workshop held in April 2008, a result chain was developed that defines how the project outputs contribute towards the overaching development results defined by Zambia's Vision 2030 and the FNDP (see Figure 1).

The proposed six **outputs** for the next phase that were identified during the planning process read as follows:

1. Groundwater information system is established and regularly updated.
2. The amount of groundwater that can be sustainably abstracted is quantified.
3. Groundwater quality and its vulnerability to pollution are known.
4. Opportunities of awareness building for *Groundwater Advocacy* are evaluated and, if applicable, implemented.
5. Relevant planning authorities are advised in the use of data for the implementation of sustainable groundwater management in development plans.
6. Capacity building measures focusing on critical skills development related to groundwater management are implemented.

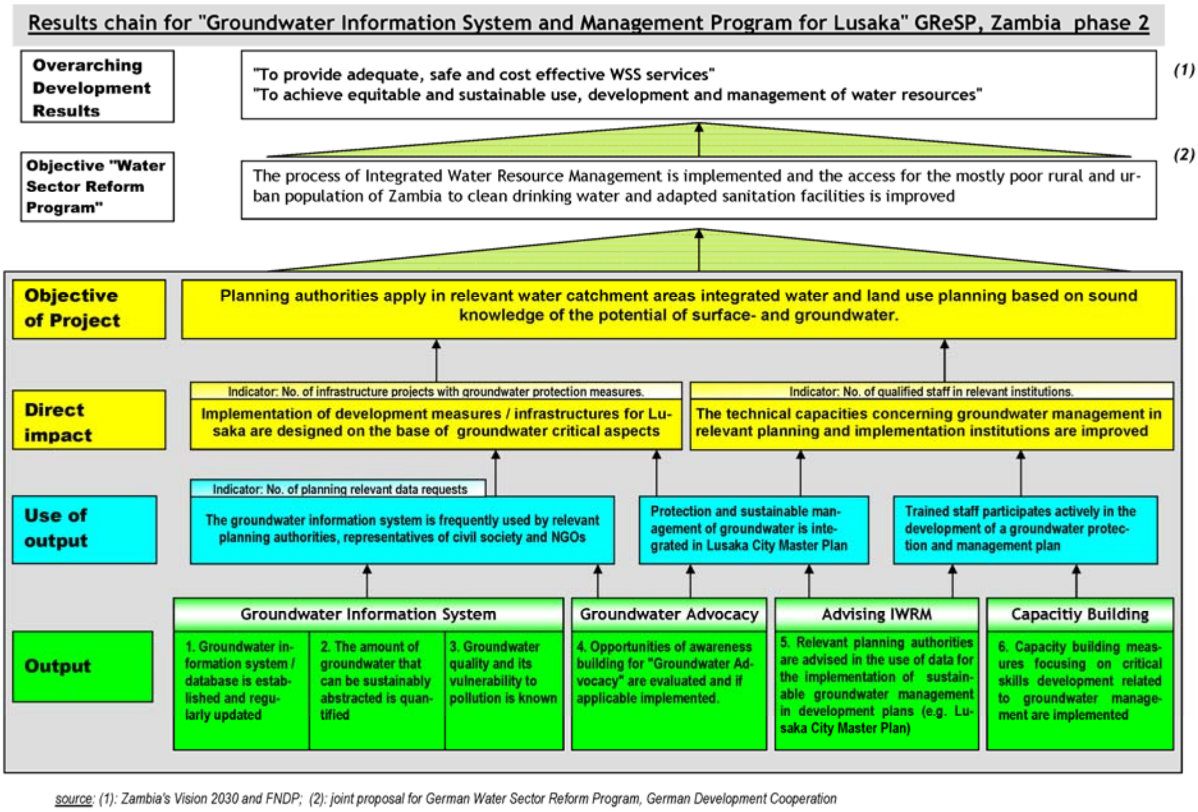


Figure 1 Result chain for the development of a Groundwater Information and Management System for Lusaka (after Becker et al. 2009)

1.2 The Lusaka Aquifer Systems

The Lusaka aquifer groundwater systems comprise (Figure 2):

(1) Main aquifer hosted by the Lusaka Dolomite Formation extending from Mwembeshi in the WNW to the Shantumbu area in the ESE over a distance of about 65 kilometres,

(2) Subordinate aquifers in the crystalline limestone and dolomite of the Cheta Formation located to the north, west and south of the Lusaka Dolomite aquifer,

(3) Minor aquifers developed in the schists, psammites and quartzites of the Cheta and Chunga Formations,

(4) Local aquifers within alluvial deposits, e.g. near the International Airport.

The Lusaka aquifers cover an area of 2,832 km^2 which includes:

- Lusaka Dolomite Formation 580 km^2
- Other carbonate rocks 1,039 km^2
- Schist and psammite 935 km^2
- Quartzite 34 km^2
- Alluvium 244 km^2

The aquifer systems are separated by a major catchment divide. The western and southern portions are part of Lower Kafue sub-cachments whereas the northeastern and eastern portions are located within sub-catchments belonging to the Chongwe river system.

Apart from the development of the Project's new objectives and outputs, preparatory activities were carried out during 2008, including:

- The establishment of a groundwater information system for Lusaka and Central Province.
- Digitizing and compilation of GIS information, including topographic and geological maps and a digital elevation model (DEM).
- Mapping of springs.
- Groundwater contour mapping.
- Reconnaissance sampling and analysis of groundwater chemistry at springs and public water supply wells.
- The development of a preliminary hydrogeological map (scale 1:175,000) for the Lusaka area.

The results of these investigations were used for the detailed planning of the work program and are incorporated in this desk study report.

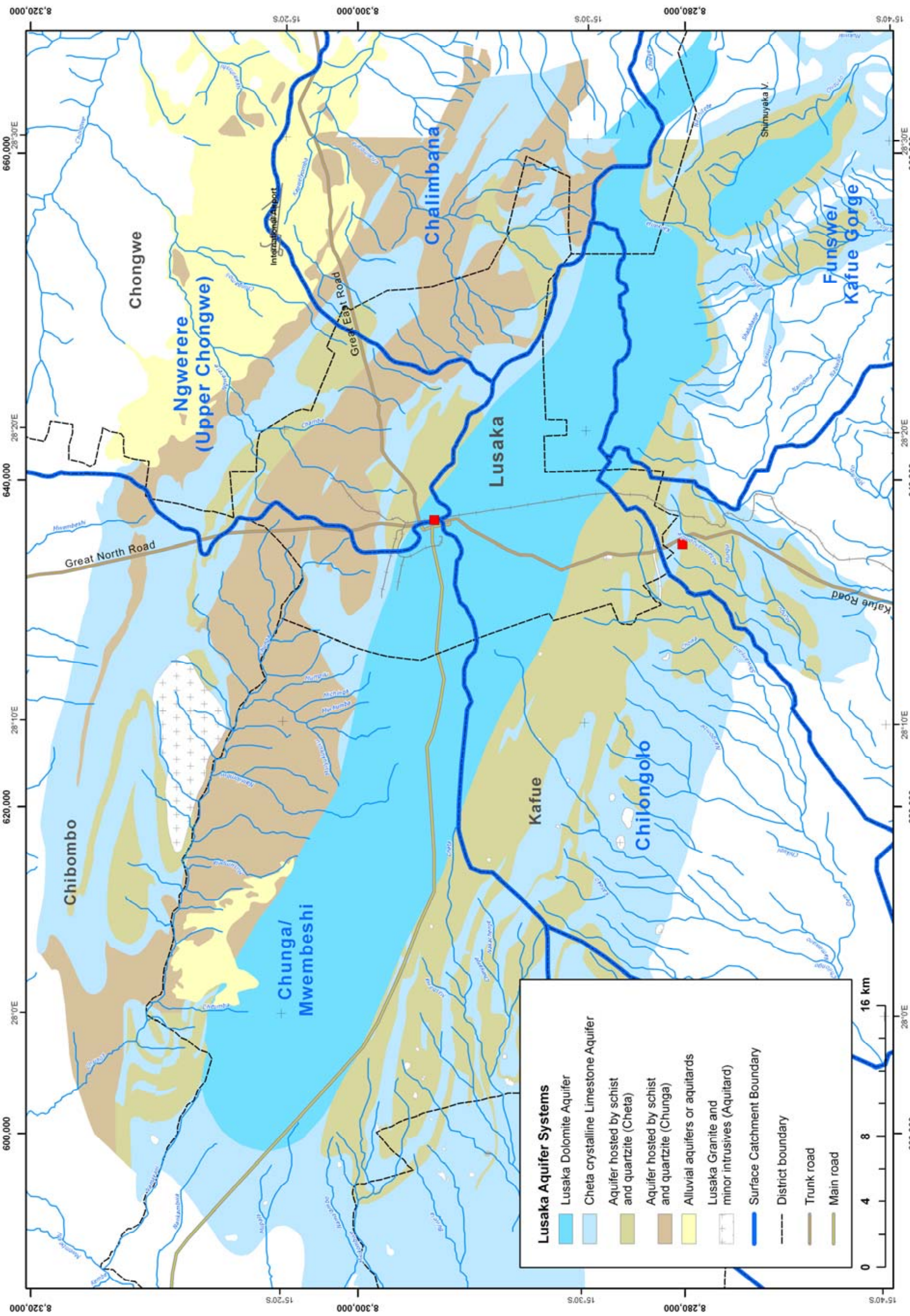


Figure 2 Lusaka aquifer systems

1.3 Structure and Objectives of this Report

Comprehensive investigations on the hydrogeology of the Lusaka aquifer systems date back to the late 1950s and 1960s. Most studies aimed at increasing and sustaining the water supply to the City's growing population. During the last ten years the focus shifted towards the imminent pollution of groundwater. This report summarises the available information on the groundwater resources in the Lusaka area and provides a comprehensive bibliographic reference to individual topics.

It is intended to identify major knowledge gaps with respect to the development of a groundwater management strategy for the Capital. Each chapter or section within a chapter has three components: a summary of available information, an analysis of the quality and comprehensiveness of the information, and a definition of tasks including proposed investigations or activities to be carried out during this Project.

The individual chapters can be linked to the outputs defined in Chapter 1.1. Chapter 2 and 3 describe the availability of groundwater information from previous studies and the status of the on-going collection and analysis of hydrogeological data and maps (**Output 1**).

Chapters 4 to 6 look at the nature of the aquifer systems and their potential for water supply (**Output 2**).

Chapter 7 summarises information on groundwater chemistry and quality as well as pollution risks and vulnerability (**Output 3**).

Chapter 8 deals with planned capacity building measures (**Output 6**) whereas

Chapter 9 explains the steps towards the development of a management strategy (**Outputs 4 and 5**).

The proposed components and associated outputs are combined in the Operational Planning Matrix presented in **APPENDIX 1**.

2 Groundwater Database

2.1 Water Points captured

In the course of the Project, a professional groundwater information system was set up at the DWA for the extended project areas (Lusaka and Central Provinces). The information system consists of the:

1. Groundwater database (using GeODin®)
2. Geographic Information System (using ESRI® ArcGIS)

The Geographic Information System (GIS) is described in Chapter 3.

As for Southern Province, the groundwater database was created using the commercial software package GeODin® (www.geodin.com). The software is based on MSAccess and provides user-friendly data input masks which were modified to meet the specific needs and requirements of the DWA. The database combines general information (e.g. location, type and purpose of water point) with comprehensive and detailed technical information on groundwater hydraulics, borehole design, geology and groundwater quality (Table 1).

The data entered into the database so far were assembled from the following sources:

1. Results of the groundwater resources inventory commissioned by the UNESCO/NORAD Water Research Project and the National Council for Scientific Research (Chenov 1978);
2. A groundwater database established during the mid-1970s in the framework of groundwater and management studies for Lusaka Water supply jointly conducted by the BGR and the Lusaka City Council (von Hoyer et al. 1978);
3. Borehole completion and construction reports from projects commissioned by the MEWD and the Japan International Cooperation Agency (JICA) between 1994 and 1995 for Lusaka Province (Japan Techno Co. Ltd 1994a, 1995a) and for Central Province (Japan Techno Co. Ltd 1994b, 1995b);
4. A groundwater database that was compiled by GIBB Ltd. (1999c) as part of the North-West Lusaka Water Project containing water points and water levels as well as borehole inspections and pumping test data for mainly the western part of the Lusaka Dolomite aquifer;
5. Results from exploration drilling for the establishment of public water supply wells (mainly satellite systems) in the Chelston (GIBB Ltd. 1999a, 2002 a-m), Mass Media (GIBB Ltd. 1999b, 2000, 2002 a-m), Kafue Road quarries (GIBB Ltd. 1999b, 2000, 2002 a-m), NRDC Ranch (GIBB Ltd. 1999a, 2002 a-m), Avondale (GIBB Ltd. 2002 a-m, LWSC 2007a, 2007b, 2008), Marian Shrine (GIBB Ltd. 2002 a-m), Buckley (GIBB Ltd. 2002 a-m), Kamwala South (LWSC 2007a, 2007b, 2008) and Waterworks areas (LWSC 2007a, 2007b, 2008);

6. Borehole completion reports from the DWA box files from boreholes drilled in the Lusaka area between 1999 and 2008, largely compiled and assessed by Mpamba (2008) as part of a PhD thesis;
7. Other sources such as the Environmental Council of Zambia, or Consultants (e.g. JBG-Gauff Ingenieure, new boreholes in Kabwe District, pers. comm. Between Nov. 2007 – Feb 2008, Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd., 2008, recently drilled boreholes in the Lusaka Forest Reserve area);
8. Data, in particular GPS readings and groundwater quality data, collected or updated by this project.

The project has also obtained borehole data for Lusaka and Central Provinces from the Ministry of Local Government and Housing (MLGH). This data set is based on the water point questionnaires collected by the Water Point Inventory Community Management & Monitoring Unit (CMMU) between the early and mid 1990's under supervision of the two line ministries in the water sector, namely the MEWD and MLGH, and has since been updated by the MLGH. The data has not been fully incorporated into the groundwater database as yet since further data verification (e.g. location of water points) is required.

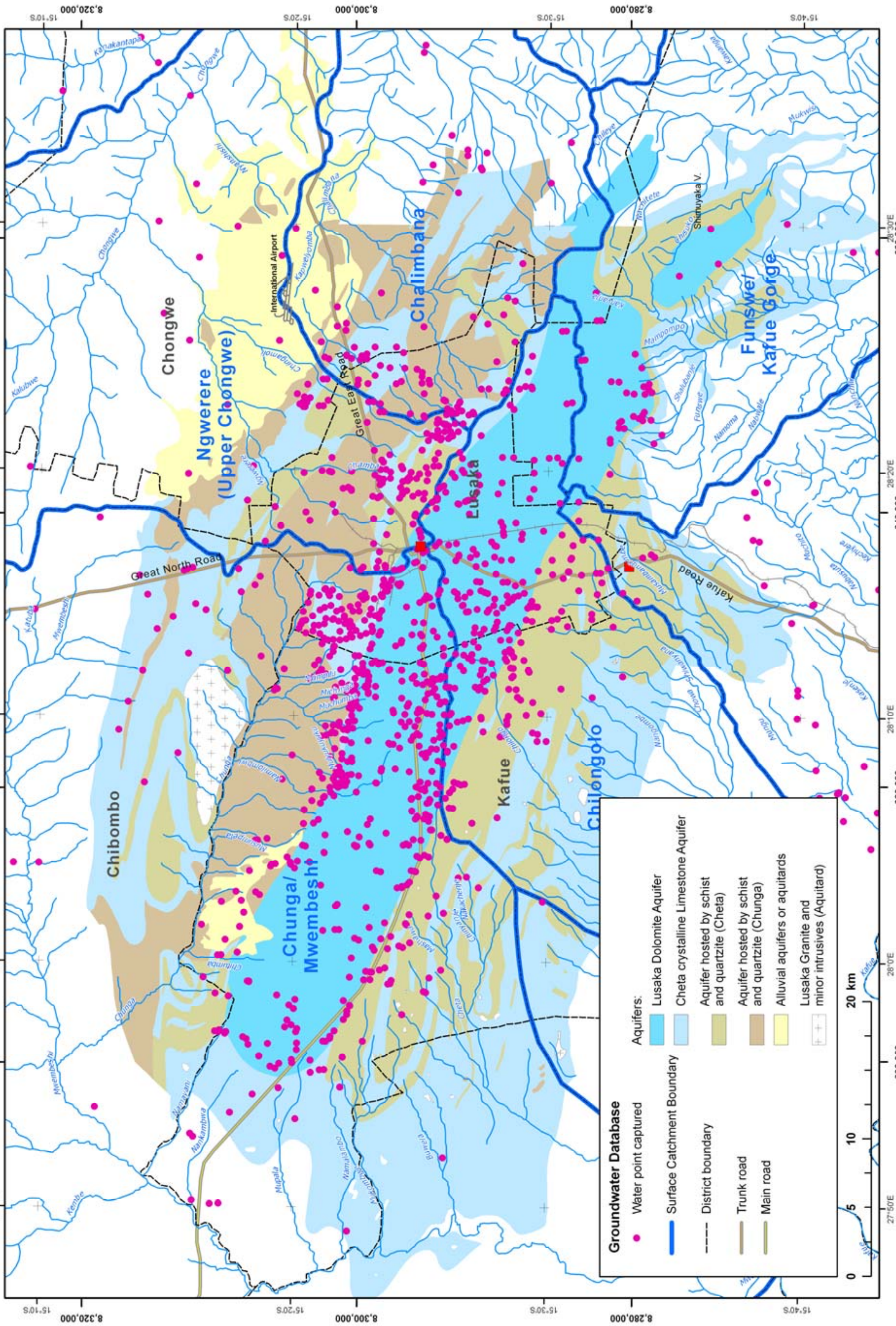


Figure 3 Distribution of water points incorporated into the groundwater database by January 2009

Table 1 Type of information held in the GeODin database

General information	
Location	Borehole name and no. Geographic coordinates Elevation Location with regard to drainage catchment Location with regard to administrative/political unit
Drilling	Drilling/completion dates Drilling contractor Water point funding
Status	Type and purpose of water point Usage
Hydraulics	
Aquifer	Borehole and aquifer depth and thickness Aquifer type Static water levels (single values or time-series)
Hydraulic (Pump-) testing	Hydraulic test summary Hydraulic test data Hydraulic characteristics (yield, permeability)
Borehole Profile	
Geology	Lithological and stratigraphical log
Design	Position of casing, screens, etc.
Groundwater quality	
Chemistry	Water chemistry Comparisons to drinking water standards Water type and quality

The groundwater database for Lusaka Province to date contains over 1200 water points with the bulk being supplied by the BGR/LCC, GIBB Ltd./LWSC, Japan Techno Co. Ltd. and DWA sources (Figure 3). The Central Province database has currently over 200 entries.

2.1.1 Springs

As natural occurrences of groundwater springs are of particular interest to this study and included in the database. They can be considered discharge points of groundwater systems and are thus an important component in the groundwater balance. They can also provide “integrated” information on groundwater chemistry and pollution over their catchment (see Chapter 7.1). For these reasons a separate study was carried out during 2008 in order to locate major springs of the Lusaka groundwater systems and to identify their groundwater chemistry. The study report (Museteka & Bäumle 2009) also includes a thorough review of previous investigations on the Lusaka springs.

The BGR study report (Von Hoyer et al. 1978) describes 25 spring locations and includes estimated discharge during the season. The highest flows observed this 1976/1977 rainy season did not exceed 10 L/s according to this source.

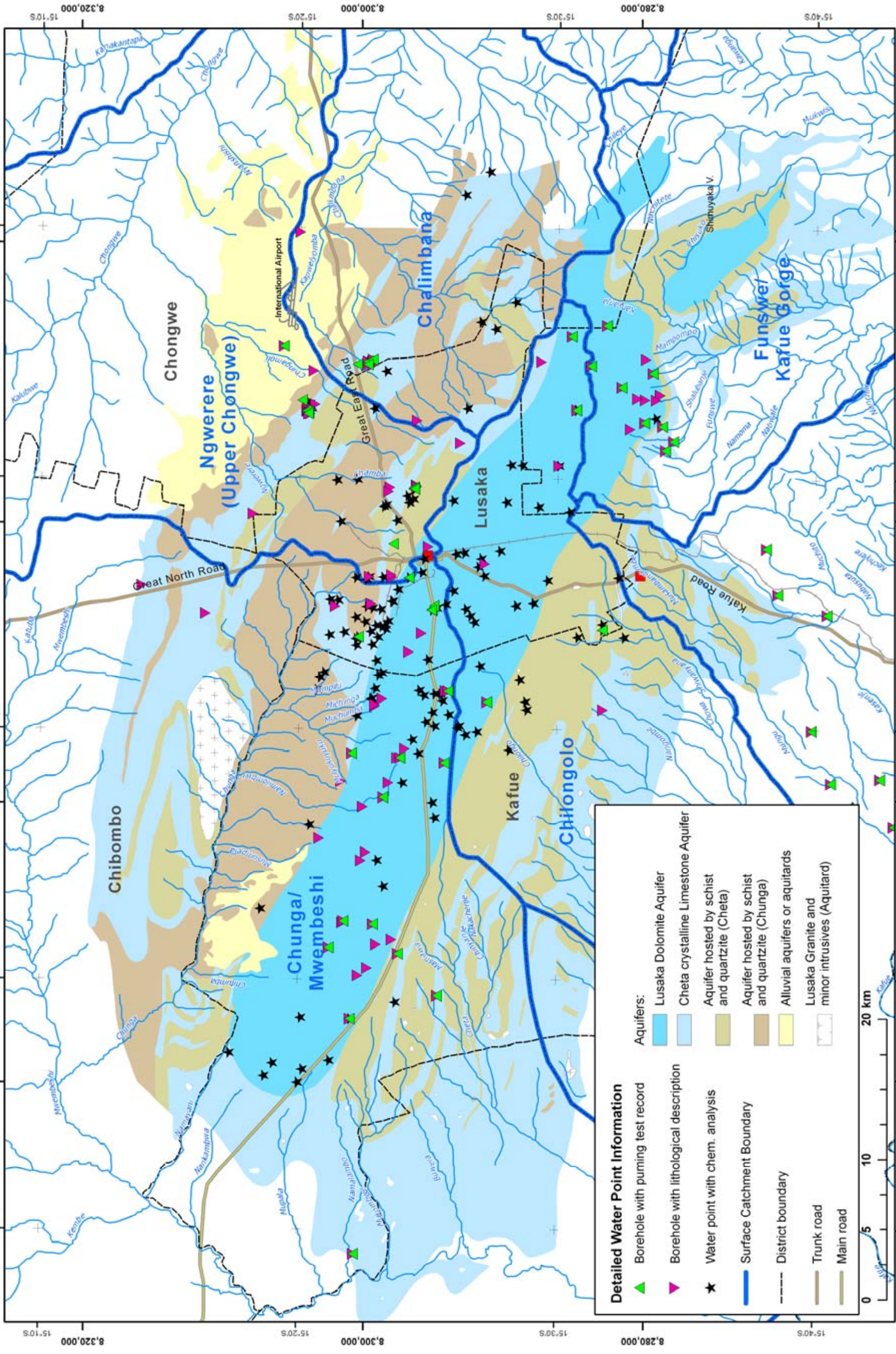


Figure 4 Water points captured in the DWA groundwater database with hydraulic test data, geological borehole logs or reliable chemical analyses results. (Date: January 2009)

The spring inventory by GIBB Ltd. (1999c) includes numerous springs in the western portion of the Lusaka Dolomite Formation. Many of the smaller springs are water filled karst clefts that overflow during the rainy season. These karst features are commonly widened and used as natural wells by residents. According to this inventory the average discharge of the larger springs discovered is about 5 L/s.

During 2008, 28 springs were found and their locations mapped. Most of the springs are associated with the karstified dolomite and limestone aquifers of the Lusaka and Cheta formations with minor springs discharging groundwater within the schists. Major spring drainage zones were identified in the NW around Mwembeshi, in Lusaka west along District Road D170 (Mungwi Road), to the East in the Chalimbana Catchment, and in the South and Southeast (Makeni and Shantumbu areas. 15 out of the 28 springs are assumed to be perennial. Results from previous studies mentioned above suggest that a few additional springs exist that were not found during the recent field visits.

2.2 Water Point Classification and Numbering

The **water point numbering** applied at present state still follows the system proposed for Southern Province in Nkhoma & Bäumle (2007), i.e. the first three of the seven digit identifier represents the Province and the district in which a water point is located. Mpamba (2008) proposed a national system for water point numbering. The proposed number is made of catchment code, sub-catchment number, indexed borehole number, water point type, and the year of construction. Based on this proposal, a numbering system is currently developed at the DWA. It is likely that a numbering system similar to the following type will be adopted:

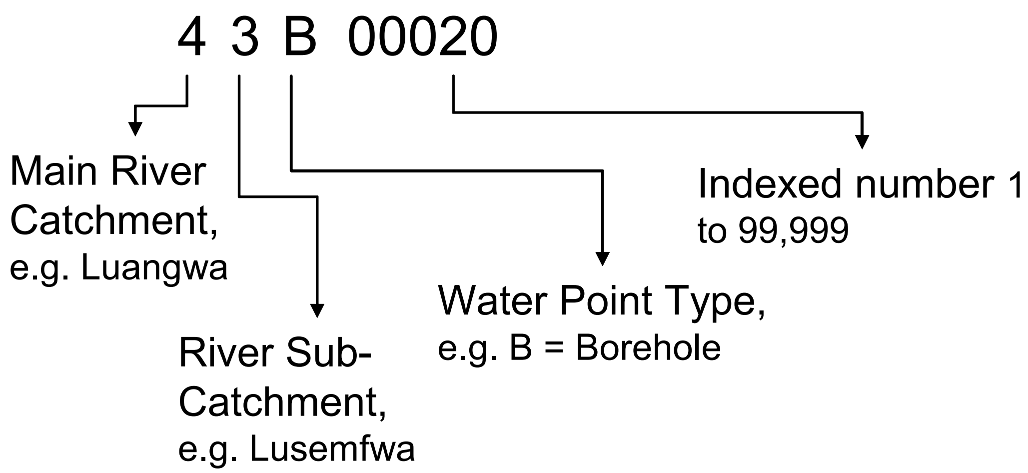


Figure 5 Proposed water point numbering system, currently developed at the DWA

ANALYSIS

Due to the significance of the Lusaka groundwater systems, a number of comprehensive hydrogeological investigations were carried out and their results documented. As a result, information on a considerable number of water points could be assembled for this area. For the rural areas of Lusaka and Central Province, however, there is considerable less information on boreholes.

Mpamba (2008) reports of 1800 boreholes that are available at the DWA as hard copies in box files, but only 117 have GPS coordinates. It is therefore likely that many more (in particular private) boreholes exist.

Furthermore, the quality and amount of data for water points from the individual sources, varies considerably. For many boreholes such as for the CMMU dataset, only general information (type of the water point, GPS coordinates, status and usage of water point) is available. The coordinates of boreholes given in the report by Chenov (1978) are often imprecise and need to be verified in many cases. Many of these old boreholes are believed to be abandoned today. Most valuable sources of water points for this study are reports that contain a detailed description of the geology encountered, borehole design, hydraulic test data and results from chemical analyses, such as the reports by von Hoyer et al. (1978, 1980), Japan Techno Co. Ltd (1994 – 1995), GIBB Ltd. (1999c) and some borehole reports of recent drillings carried out or commissioned by the LWSC, DWA and JICA.

By January 2009, the database contained:

- ca. 85 complete sets of hydraulic test data
- ca. 140 boreholes with lithological description
- ca. 130 water points with comprehensive and reliable hydrochemical data

The distribution of these boreholes is depicted in Figure 4. While there is substantial borehole information in the Lusaka City, Lusaka West and, owing to recent investigation, the Lusaka Forest Reserve areas little detailed information is documented for the aquifers in Chunga River valley and Chibombo District areas, the Cheta Formation aquifers in the West and Southwest and in areas to the far East (Chalimbana Catchment) and Southeast (Upper Funswe/Chisuko Catchments).

Additional results from pumping test analysis are available for a considerable number of additional points yet without the actual water level measurements. Unfortunately, almost all of the hydraulic tests conducted were single-well tests. While providing reasonable results for transmissivity, they are less suitable for determining storage characteristics.

The quality of existing chemical analyses is discussed in detail in Chapter 7.1.

TASKS

All data needs to be further scrutinized and checked for plausibility as part of the on-going activities. In this process, the correct spelling of names needs to be checked and names harmonised, coordinates verified on the map or in the field, and stratigraphical information and measurement data corrected wherever possible and necessary. Throughout the project duration, the database needs to be continuously updated and water points of which the coordinates were found to be erroneous or missing need to be removed from the database.

A complete inventory of private boreholes is likely to exceed the capacities of this Project. It is therefore suggested to concentrate on the identification on major abstraction wells and to carry out a full hydrocensus in a pilot area.

The focus on the data acquisition so far was given to Lusaka urban and peri-urban areas. While the existing data sources for Lusaka have largely been identified and incorporated into the information system, the search for borehole data in rural areas, in particular in Central Province outside of Chibombo District, must be intensified.

Due to its importance for the hydraulic classification of the various aquifers, the hydraulic test data should be re-evaluated.

Once finalised, the national water point numbering system will be incorporated into the database. Since the Lusaka plateau forms the divide between the Kafue and Chongwe catchments, the data for the Lusaka groundwater systems will have to be split into different data sets.

It is also envisaged to further support the DWA in managing and maintaining the developed database for Southern Province at DWA headquarters as well as at Provincial and District levels.

2.3 Groundwater Monitoring

2.3.1 Groundwater Level Monitoring

Early groundwater level measurements exist in Zambia especially from the early 1950s. Table 2 summarises the available groundwater level data from different sources that was entered in the groundwater database.

Von Hoyer et al. (1978) published early water level observations (monthly readings) from the DWA archives at nine boreholes dating back to the years 1952 - 1978. The measurements were taken on a monthly basis over periods ranging from 3 to 16 years. The longest continuous measurements among these monthly records cover the period of 1963 – 1978 and are available for three boreholes (Figure 6, top). During the study water level measurement were taken on an irregular basis at about 260 boreholes and hand-dug wells.

KRI et al. (2008b) present monthly water table records from 1995 to 1999 for public water supply wells. The study team, however, reported inaccuracies and questioned in particular why water levels generally rose over the period observed despite the common assumption that water levels dropped over the last 20 years.

Other water table measurements in the Lusaka area were published by YEC (1995b), GIBB Ltd. (1999c) and Kampeshi (2003) but the records cover only short periods (Table 2). At York Farm which is located in the South of Lusaka along Kafue Road, weekly water level measurements are taken at ten pumped and eight monitoring wells.

Table 2 Water table monitoring in the Lusaka aquifers

Source	Area	Wells	Period	Interval
Von Hoyer et al. 1978	Lusaka Urban	9	1953 – 1978	Irregular, incomplete
	Lusaka Dolomite and adjacent aquifers	260	1976 – 1978	Few, irregular measurements
YEC 1995b	Lusaka Province	10		
KRI et al. 2008b	LWSC wells	52	1995 – 1999	Monthly, but incomplete
GIBB Ltd.1999c	Lusaka West	80	06/98 – 04/99	Few, ± monthly measurements
Kampeshi 2003	Libala Tipping Site	10	12/99 – 02/01	Irregular, up to 5 measurements per month
	Leopards Hill Cemetery	8	12/99 – 07/00	
	Industrial Area	8	04/00 – 01/01	
DWA, Mpamba 2008	Sheki Sheki	2	02/04 on-going	Daily, 12 hrs, with some gaps
	Lusaka Urban and Forest Reserves	18	04/07 on-going	10 days
York Farm	York Farm (Lusaka south)	18	01/00 on-going	Weekly, continuous since 2006

Mpamba (2008) developed a concept of a groundwater monitoring network for the Lusaka aquifers. He recommends that criteria to be considered for establishing a monitoring network in Lusaka should include the distribution of schist and carbonates, drainage pattern, distribution of meteorological stations, security and permanent access to the site and data requirements for planned groundwater models. Based on his criteria the DWA has since 2004 gradually established a monitoring network and currently operates 20 stations. Water level measurements are taken at intervals of about 10 days except for the two boreholes at Sheki Sheki Street where data is collected twice daily (Figure 6, bottom). The location of the existing monitoring boreholes is shown in the conceptual hydrogeological map presented in APPENDIX 2.

2.3.2 Groundwater Abstraction and Quality Monitoring

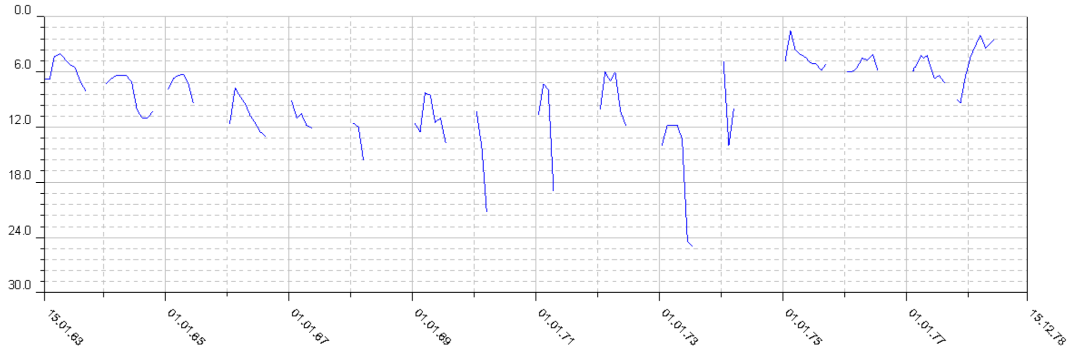
No comprehensive monitoring on water abstraction and water quality exists in the Lusaka area. According to Nkhuwa (1996) existing water quality monitoring programs proved inadequate in that they are irregular and dispersed. Available data of pumped volumes and quality of groundwater is largely linked to individual projects and collected only once or over very short periods. The Lusaka Water and Sewerage Company (LWSC), which is the Commercial Utility (CU) in the City, measures water levels at selected pumped wells twice a year (during the dry and wet season) but plan to take monthly measurements from now on (pers. comm. with Mrs Angela Phiri, LWSC).

DWA GROUNDWATER MONITORING RECORD

Hot Top

WP-No.	District	Ward	East	South	Altitude	Alt. meas. by	Depth [m]	Yield [L/s]	Main Aquifer	Lithological Unit
5040607	Lusaka	Chilenje	28.32888	15.43898	1291.31	SRTM-3 arcsec			Dolomite	Katanga (undifferentiated)

Observed Groundwater Levels [m b.g.s.]



DWA GROUNDWATER MONITORING RECORD

DWA Sheki Sheki 1

WP-No.	District	Ward	East	South	Altitude	Alt. meas. by	Depth [m]	Yield [L/s]	Main Aquifer	Lithological Unit
5040359	Lusaka	Matero	28.26747	15.39379	1271.65	SRTM-3 arcsec	30.00		Schist	

Observed Groundwater Levels [m b.g.s.]

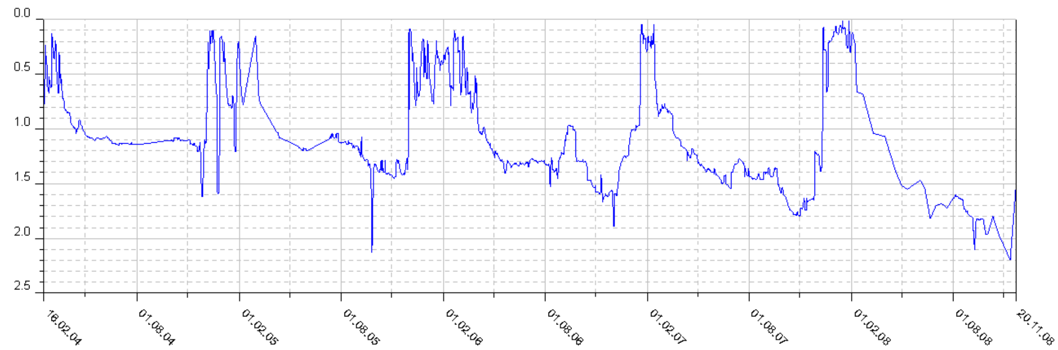


Figure 6 Examples of historical (top) and recent (below) groundwater level data (Sources: Von Hoyer et al. 1978, Mpamba 2008)

ANALYSIS

Groundwater monitoring data in the Lusaka groundwater systems is discontinuous and sparse. Limitations in sustaining the measurements include the non-permanence of observation networks, financial implications, equipment and institutional capacity (Mpamba 2008).

Regarding seasonal variations of groundwater levels distinct periods of groundwater rise from December to March and fall from April to December, with prominent seasonal and intra-seasonal variations, can be observed (Mpamba 2008). Based on data of the 1976/77 and 1977/78 rainy season von Hoyer et al. (1978) conclude that early rains in November bring no recharge, and water levels are expected to be lowest during this month. Peaks are observed during March or April. Seasonal variations of water table depth range from about one meter to over 10 meters depending on location within the catchment and type of aquifer.

Various authors have tried to analyse the long-term trend of groundwater levels, but due to the lack of continuous water level and abstraction measurements, this proves to be a very difficult task and interpretations should therefore be considered preliminary. Making use of data by von Hoyer et al. (1978) and GIBB Ltd. (1999c), Schmidt (2001) compares groundwater levels in the western portion of the Lusaka Dolomite aquifer at the end of dry season 1977 with data from about the same time of the year in 1998. He detected a general drop in water levels of up to 9 m over the period observed, in particular in an area along the southern boundary of the Lusaka Dolomite aquifer stretching from Westwood to approx. 5 km north-west of Makeni. An increase of farming and irrigation activities in these areas was given as a possible explanation for the declining water tables. Mpamba et al (2008a, 2008b) observe a decline in water levels over a period of four years until August 2007 in the DWA boreholes at Sheki Sheki despite above average rainfall during this period. They associate these observations with groundwater mining.

TASKS

Water level monitoring as commenced by the DWA should be supported over the project period. Electronic data loggers should be purchased and installed in selected monitoring wells preferably located in the vicinity of rainfall gauges. About three additional automatic rainfall gauges will be needed for this purpose. Data loggers can be programmed to take measurements at short (one hour, or less) intervals. This is crucial to analyse the response of groundwater levels to storm events. The need and possibility of establishing and equipping additional monitoring wells should be assessed. Areas currently not covered by the monitoring network operated by DWA include (among others) the Lusaka West/Mwembeshi areas and the carbonate aquifers to the Northwest (Chibombo

District). Data could be analysed to confirm or refute the observed long-term drop in water levels and to improve the understanding of rainfall – recharge dynamics.

The LWSC should be urged to monitor groundwater abstraction and pumped water levels on a continuous basis. Major wells for private and commercial use should be identified and the abstraction rates and water levels monitored as further discussed in Chapter 5.5.

For tasks related to capturing additional groundwater quality data see Chapter 7.

3 Hydrogeological mapping & GIS

Hydrogeological maps are considered an essential tool for future management of groundwater resources. This chapter summarises the available GIS information, the status of digitizing and compilation of available map sources, and a proposal of the thematic maps to be developed during this project.

Available information identified includes topographic and geological maps series, soil maps and remote sensing data from aircrafts or satellites.

3.1 Topography

Topographic Map series at scale 1:50,000 and 1:250,000 are available with the Surveyor-General, Lusaka. The Lusaka groundwater systems are covered by 14 map sheets 1:50,000. The sheet numbers and publication date are as follows:

1527B2 (1973), 1527B4 (1980), 1527D2 (1980), 1528A1 (1974), 1528A2 (1972), 1528A3 (1972), 1528A4 (1986), 1528B1 (1990), 1528B2 (1972), 1528B3 (1981), 1528B4 (1972), 1528C1 (1993), 1528C2 (1978) and 1528D2 (1990).

On the more generalised 1:250,000 map series the Lusaka groundwater systems are located in the areas shown in the sheets Lusaka SD-35-15 (Surveyor-General 1986) and Rufunsa SD-35-16 (Surveyor-General 1991). The Lower Kafue and Chongwe Catchments extend into the adjacent map sheets to the north, namely Kabwe SD-35-11 (Surveyor-General 1973, reprinted 1988) and Mulungushi SD-35-12 (Surveyor-General 1974, reprinted 1990).

Rivers, wetlands, administrative boundaries and roads on the 1:50,000 and 1:250,000 maps quoted have been completely digitized during this project except for portions of the Kabwe (SD-35-11) and Mulungushi (SD-35-15) sheets.

Elevation contours were derived from a Digital Elevation Model (DEM) that was compiled using data from February 2000 of the Shuttle Radar Topography Mission (SRTM) distributed by the US Geological Survey. The original grid was smoothed using a low-pass filter five consecutive times in order to eliminate some irregularities and blanks (i.e. grid cells with no data) within the raw data. The developed DEM extends from 14°S to 17°S in N-S direction and from 27°E to 30°E in W-E direction. The DEM grid resolution is approximately 90m by 90m (3 arcsec). Figure 7 depicts a block diagram of the Lusaka plateau that is based on the DEM. The plateau is made of carbonate rocks and surrounded by hilly terrain underlain by schists and quartzites that is intersected by many valleys, with the quartzites forming marked ridges.

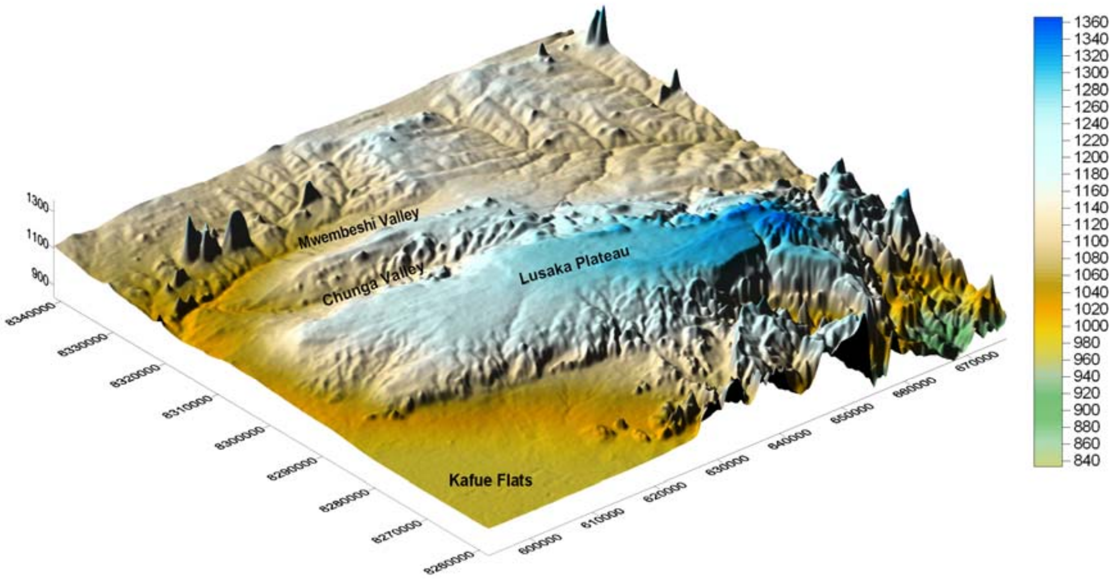


Figure 7 Block diagram of the Lusaka Plateau based on the developed DEM (Vertical exaggeration 26x)

Based on the DEM and the rivers shown on the topographic maps surface water catchments and sub-catchments were delineated. The catchment boundaries are included in the hydrogeological map (APPENDIX 2).

3.2 Soils

At present knowledge there is no detailed (large-scale) soil map covering the Lusaka area. The arguably most detailed map at national scale (1:1,000,000) was developed by the Soil Survey Section Research Branch at the Ministry of Agriculture (1991). The two map sheets have been scanned and georeferenced. Major soil types occurring in the Lusaka area are described in Chapter 7.5.

3.3 Geology

The area of interest is completely covered by the geological map series 1:100,000 distributed by the Geological Survey Department, Lusaka and its predecessor during colonial times, the Northern Rhodesia Geological Survey. Lusaka and its surroundings are covered by the following six sheets: Mwembeshi 1527NE (Simpson 1962), Lusaka 1528 NW (Simpson et al. 1963), Chainama 1528NE (Garrard 1968), Mazabuka 1527SE & Kafue 1528SW (Smith 1963) and Leopards Hill 1528SE (Cairney1967). Adjacent maps to the north and east include Lukanga Swamps 1427SE (1972), Chisamba 1428SW (Moore 1964), Chipembi 1428SE (Arthurs et al. 1995), Luano Valley-1 1429SW (Brandon 1977), Chinyunyu 1529NW (Simpson 1965) and Chongwe River 1529SW (Barr 1997).

The geology of the Lusaka area was also mapped at scale 1:250,000 by Thieme et al. (1984).

All geological maps except for the map sheets Luano Valley-1 and Chinyunyu have been digitised and combined into a seamless GIS layer.

3.4 Satellite Imagery and Land Use Information

Remote sensing techniques have been applied in previous studies to identify surface karst features, wetlands and land use patterns. None of the results, however, were made available in digital (GIS) format.

Von Hoyer et al. (1978, 1980) mapped fracture traces and sinkholes and karstic depressions within the Lusaka Dolomite Formation larger than approx. 15 m using aerial photographs at scale 1:12,000 (1967/1968) and 1:30,000 (Sep 1972). Lineaments and karstic features for the wider areas were also mapped using Landsat-1 images dated September 1972. The results were presented in maps at scale 1:2,000.

In the framework of the “Study on the National Water Resources Master Plan” (YEC 1995c) Landsat Satellite Imagery Interpretation was used to determine the land use distribution nationwide. The approximate scale of the satellite images is given as 1:500,000. The results for the Lusaka district together with totals for Lusaka and Central Provinces are presented in Table 3.

Table 3 Land use distribution in Lusaka and Central Provinces in km^2 based on LandSat satellite imagery interpretation (Source: YEC 1995c)

District or Province	Forest	Grass-land	Sa-vanna	Barren	Agri-culture [2]	Wet-lands	Urban	Water	Total
Lsk Urban	<1	290	<1	0	25	0	125	0	441
Lsk R. [1]	5,107	9,061	3,046	<1	228	254	44	53	17,794
Luangwa	142	2,910	743	14	2	1	4	44	3,859
Lusaka	5,250	12,261	3,790	14	255	255	173	97	22,094
Central	17,823	55,093	16,769	65	2,781	1,744	97	312	94,684

[1] Lusaka Rural: Chongwe & Kafue Districts combined [2] land under cultivation in 1995

Table 4 Land use distribution in Lusaka and Central Provinces in km^2 on Republic of Zambia land use map (Source: YEC 1995c)

District or Province	Fo-rest	Flood-plains	Non-com. farming [2]	Com./gov. farming [3]	Wet-lands	Urban	Lakes	Totals
Lsk Urban	49	0	122	145	0	125	0	441
Lsk Rural [1]	14,324	177	543	2,398	254	44	53	17,794
Luangwa	1,259	2,364	188	0	99	4	44	3,859
Lusaka	15,632	2,541	853	2,543	353	173	97	22,094
Central	58,710	9,702	16,717	7,402	9,702	97	312	94,684

[1] Lusaka Rural: Chongwe & Kafue Districts combined
[2] Non-commercial farming: Land suitable for agricultural purposes, but not necessarily under cultivation
[3] Commercial or Governmental farming: Land suitable for agricultural purposes, but not necessarily under cultivation

The Report on the Master Plan also includes the land use distribution derived from the Republic of Zambia Land use at scale 1:750,000 (Schultz 1972) as presented in Table 4. The results from the two different approaches differ substantially, in particular for agricultural land and forests. One explanation given by the study team is that the MLNRT land use map shows land suitable for agricultural use rather than land actually under cultivation.

The satellite imagery analysis also includes mapping at national scale of geology, geomorphology and drainage, but the produced maps were printed at a very small scale to fit them on the DIN A4 report paper size.

Recent information on land use distribution was compiled under the FAO Integrated Land Use Assessment (ILUA) programme implemented by the Forestry Department with assistance from the Survey Department and the University of Zambia (Kalinda et al. 2008). A wide array spatial land use cover data was generated from Landsat Thematic Mapper satellite imagery of dates ranging from 2000 to 2004.

Maseka (1994) analysed a 60km x 60km SPOT (3 band) image dated September 1986 covering the Lusaka and Kafue areas. He identified areas of active vegetation growth during the dry seasons which he interpreted as presumed seepage zones. These areas include Palabana State Farm, Shantunmbu, Zingalume and Barlaston Park, Leopards Hill Road and an area located NW of NRDC Ranch. Most of these areas can be linked to occurrences of springs (Museteka & Bäumle 2009).

Grelet (2008) used Thematic Mapper Landsat data to detect and map linear structures including tectonic and river lineaments in the Lusaka area (see Chapter 4).

ANALYSIS

Substantial GIS information on topography, geology, river systems and catchments has already been prepared. Of particular value is the availability of detailed geological maps for the whole study area.

Problems occur at the boundaries between adjacent geological map sheets as the individual sheets were prepared by various authors using different stratigraphical classifications. As a consequence, the margins of geological formations do often not match at the sheet boundaries and some lineaments (faults) were not mapped across adjacent sheets.

Little detailed mapped information is available on soils and surface cover.

Available information on roads, distribution of urban and peri-urban areas and land use is considered outdated in view of the rapid growth of the Capital. A suitable system to define land use types for the Lusaka area was proposed by Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) who use the following land use categories: Residential (high, medium, low density), business (central business district and satellite business centres), administration, recreational, institutional, agricultural, forestry and industrial.

TASKS

It is proposed to develop a detailed hydrogeological map for the Lusaka groundwater systems at scale 1:100,000 and a regional map covering the Lower Kafue and Chongwe Catchments at scale 1:250,000. The format of the maps should largely follow the proposed national standard developed for the Southern Province's map series (Nkhoma & Bäumle 2008). The extent of the existing and proposed maps is shown in Figure 8. The conceptual hydrogeological map presented in APPENDIX 2 does currently not yet include all water points and the classification of aquifer potential as the updating of the database and the analysis of aquifer characteristics are on-going activities. Additional thematic maps will be prepared depicting, for example, groundwater chemistry, pollution or vulnerability.

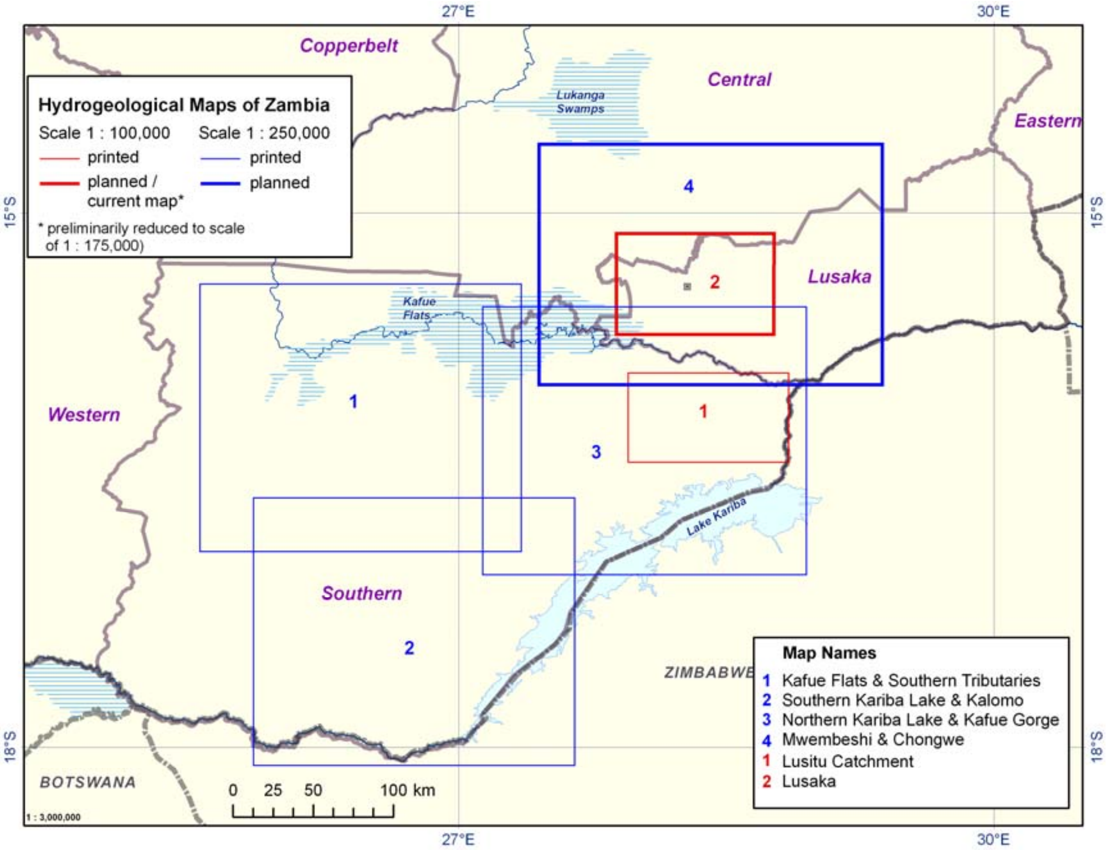


Figure 8 Produced and planned hydrogeological maps

The remaining areas on the topographic (1:250,000) and geological maps (1:100,000) need to be digitised. Depending on the scale of the map, some features such as rivers and roads need to be generalised. Provincial and district boundaries as well as contour lines derived from the DEM need to be checked against the course of rivers and their valleys, and adjusted where required.

It is furthermore proposed to use the Zambian National Projection System for the development of thematic maps. This is the Transverse Mercator projection using the datum "Arc (1950) Zambia" and the "Clarke 1880 Modified" ellipsoid definition.

It is intended to apply remote sensing techniques to obtain updated GIS information on geology, surface cover and land use pattern. The analysis will be based on recent high-resolution, multi-spectral satellite images combined with frequent ground truthing (field observations). For this purpose SPOT images with a resolution of 20m x 20m from July 2007 have been purchased. The remote sensing analysis aims at:

- **The determination of current land use distribution including the scope of urban and peri-urban spreading, and the determination of the area of irrigated land in the Lusaka area;**
- **An update of the road/river/wetland distribution obtained from topographic maps;**
- **The classification and mapping of surface cover and soils;**
- **Correction of geological maps;**
- **Detection and mapping of large-scale lineaments and surface karst features.**

4 Geology

The geology is of major importance to the assessment of aquifer potentials since the lithological (rock) properties and their distribution largely determine aquifer characteristics such as the permeability, storage capacity, natural water chemistry and so on.

One of the first to describe the geology of the Lusaka plateau were Drysdall (1960) and Drysdall & Smith (1960). The Lusaka area was surveyed and mapped at scale 1:100,000 (degree sheet 1528 NW quarter) by Simpson et al. (1963). The adjacent geological map sheets include 1527 NE (Mwembeshi) by Simpson (1962), 1528 NE (Chainama Hills) by Garrard (1968), 1528 SW (Kafue) by Smith (1963) and 1528 NE (Leopard Hill) by Cairney (1967). Mallick (1966) described the geology and stratigraphic succession in the vicinity of the Mpande Dome which is bordering the Lusaka plateau to the south.

Additional early descriptions of the geological setting of the Lusaka area by the Geological Survey Department include Matheson & Newman (1966) and the more local studies by Thieme (1968) who investigated the structure and petrography of the Lusaka granite and Barr (1968, 1970) who described the geology and lithology of the Lusaka South Forest Reserve and adjacent areas.

Turner & Turner (1986) and later Nkhuwa (1996) reviewed the geology of the Lusaka area. Nkhuwa focussed on hydrogeological and engineering geological problems. Recent examinations of the geological sequence on a more regional scale were presented by Porada & Berhorst (2000), John (2001) and Johnson et al. (2007).

The Lusaka area is covered by strongly folded overthrusted metasedimentary rocks of Katanga (Neoproterozoic) age which have been intruded by granitic and basic bodies. The rocks are part of the "Zambezi supracrustal sequence" (Hanson et al. 1994, Johnston et al 2008) within the Zambezi Belt. The sequence is composed of a succession of metasedimentary clastic and carbonate rocks, with a thick sequence of basal volcanics and lavas, and underlain by a variety of Early to Late Precambrian metamorphosed gneisses, quartzites, metasediments and granitoids. By definition the Zambezi Belt is separated from the Lufilian Belt in the North by a prominent dislocation zone within the basement rock, the Mwembeshi shear zone.

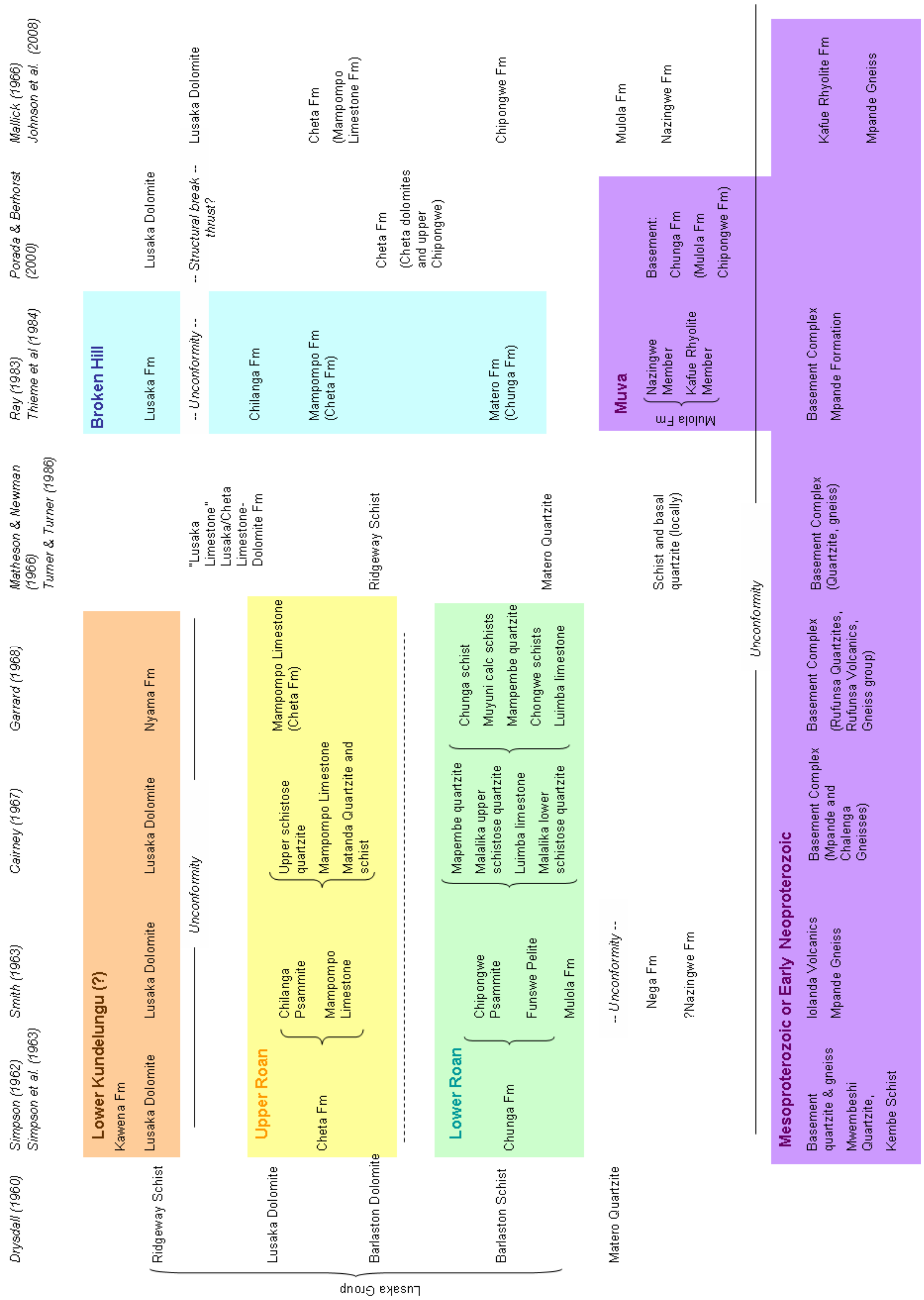


Figure 9 Stratigraphical classification of the rocks of the Zambezi supracrustal sequence and underlying basement rocks according to various authors

Owing to the intense tectonical deformation of the Katanga sequence, the stratigraphic succession and its regional correlation are still not fully clarified. Furthermore, different local names for the rock formations were introduced by the various authors of the geological map sheets. The most widely adopted stratigraphical succession appears to be the sequence proposed by Simpson et al. (1963). Accordingly, the metasedimentary cover can be divided into three formations: the Chunga Formation (Fm) comprising schist and quartzites, the Cheta Fm including schist and carbonates and the Lusaka Dolomite Fm.

The Chunga Formation is considered the oldest formation in this sequence; its most common rock type is quartz-muscovite-biotite schist interbedded with psammites, quartzites and minor calcareous horizons. Massive quartz veins occur often standing as small topographic highs.

The Cheta Formation is made up of two calcareous and two schist members. The schists include various rock types dominated by quartzites, quartz-muscovite-chlorite schists and (finer-grained) quartz-muscovite schists.

The calcareous rocks of the Cheta Fm have been described as grey and white, banded dolomitic limestones and dolomite and grey scapolite argillaceous limestone that is thought to have undergone regional metamorphism (Simpson, 1962). The lower and thicker of the two calcareous members is referred to as Mampompo Limestone on map sheets 1528NE and 1528SW. The calcareous rock contains streaks, continuous laminae or lenses of schistose material presumably representing highly modified argillaceous beds.

The Lusaka Dolomite occurs as crystalline banded, grey and white dolomitic limestone. Compared to other calcareous rocks of the Katanga sequence, it appears to be purer and includes a much higher proportion of dolomitic rocks, particular the massive, pink, white and grey varieties. Quartz-muscovite schist is found instead of scapolite-biotite schist within the thin shaly (argillaceous) limestones.

All carbonate rocks within the sequence were commonly referred to as limestone and dolomite. However, as they are crystalline metamorphic rocks, they should be classified as marbles. The metasedimentary carbonate rocks have suffered extreme differential dissolution, resulting in the development of a system of subterranean conduits and solution channels. Some parts of the dolomite are brecciated (see Chapter 6.1).

Three stages of deformation of the Katanga Series have been recognised (Simpson et al. 1963, Matheson & Newman 1966, Nkhuwa 1996):

1. Early large scale recumbent folding with axis trending NW-SE overturned towards the SW.
2. Refolding of the early recumbent structures, forming open folds also with NW-SE axis.
3. Minor refolding with axis trending NE-SW (cross folding, open folds)

Nkhuwa (1996) suggests that probably during the advanced stages of the recumbent folding, repeated (low-angle) overthrusting occurred with the direction of crustal movement from NE to SW. This led to a directional tectonical thickening of the marbles. This could also explain the observed intersection of schists below carbonate horizons (Matheson & Newman 1966).

Three major joint directions with distinct sets of orientation exist (Nkhuwa 1996):

1. Steep dipping (80 - 90° towards the NW) cross joints formed perpendicular to main fold axes, with strike directions of NNE – SSW to NE to SE
2. Longitudinal joints parallel to the fold trends (WNW – ESE to NW – SE, dip 30 – 45° towards the SW)
3. Diagonal joints striking NNW – SSE to N-S

According to Nkhuwa, a good correlation of these results exists with an earlier lineament analysis performed by von Hoyer et al. (1978).

A total of 2497 river lineaments and 347 tectonic lineaments have been mapped in the Lusaka area from Thematic Mapper data from the Landsat 4 and 5 satellite. Through a statistical analysis, the main characteristics of lineaments (orientation and length) were determined. A preferential orientation of tectonic lineaments from south-west to north-east was identified. This set forms the dominant orientation within the Lusaka Dolomite Fm (Figure 10). Another finding was that long lineaments (>6000 m) are rare in the area investigated. Hence, swarms of lineaments which are more likely to be interconnected may be of particular importance to groundwater flow.

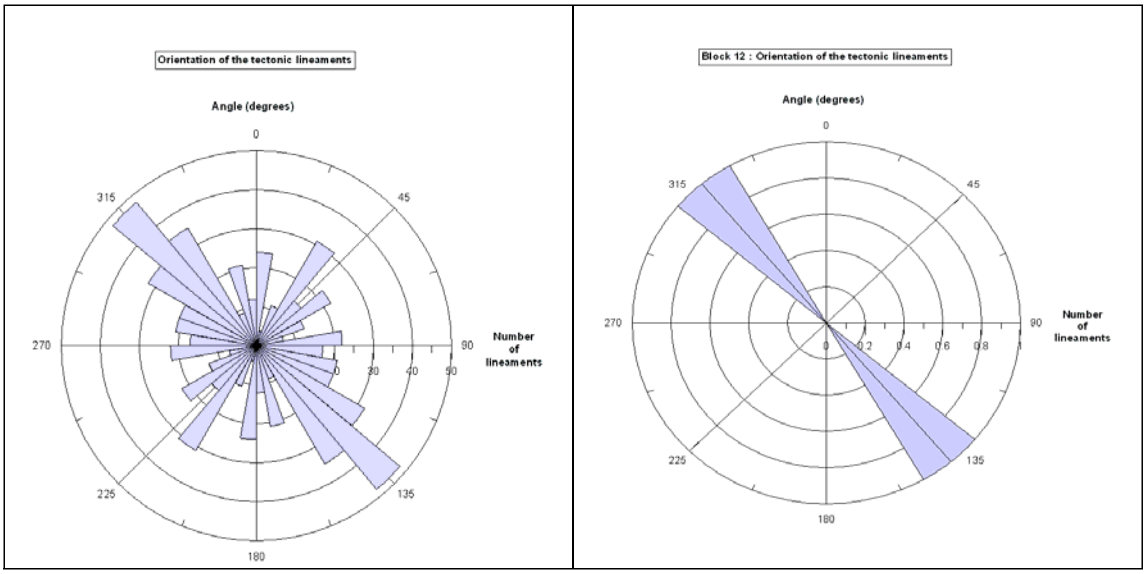


Figure 10 Preferential orientation of lineaments derived from Thematic Mapper Landsat data. Left: Lusaka area across all rock formations. Right: Lusaka Dolomite Formation.

ANALYSIS

The available geological information on the Lusaka area is overall very comprehensive and well documented. The dispute on the correct stratigraphical classification is of minor significance to this study as the aquifer characteristics are mainly related to lithological properties. Due to the absence of deep drilling (>150m) there is little knowledge about the thickness of the rock formations. Available geological profiles and structural diagrams published for instance by Matheson & Newman (1966), YEC (1995c), Nkhuwa (1996) and Mpamba (2008) must therefore be regarded as very schematic. As tectonical banding and large-scale lineaments seem to promote solution weathering and karstification, their location and distribution may largely control the flow of groundwater.

TASKS

Despite the lack of information from deep exploration drilling, an attempt should be made to re-evaluate the available borehole information, to draw updated geological profiles, to perform a structural analysis based on available data, to improve the understanding of the three-dimensional succession of the rock formations and thus, to assess how the stratigraphical and tectonic setting controls the development and nature of the Lusaka groundwater systems.

Valuable additional information on the geological setting could possibly be gained by the planned selective exploration drilling.

A review of available tectonical and structural information should be combined with satellite imagery interpretation to detect lineaments whose location correlate with the occurrence of karst surface features. Interconnected lineaments are likely to act as preferential pathways for groundwater flow.

5 Water Balance

Groundwater plays part in the “hydrologic” or “water” cycle. The hydrologic conditions of an area are largely controlled by the water balance equation:

[1] $P = ET + Q_d + Q_b \pm \Delta S,$

where P is precipitation, ET is actual evapotranspiration, Q_d is direct runoff (overland flow and interflow), Q_b is baseflow (groundwater runoff) and ΔS is change in groundwater storage due to lateral inflow and outflow. Base flow and change in groundwater storage including abstractions from wells are hence of major importance to the groundwater budget.

5.1 Overall Climatic Conditions

Nieuwolt (1971) accurately describes the weather conditions of the Zambian highlands around Lusaka as a **tropical continental highland climate**. Due to the combined effect of low latitude (16 - 18°S), continental position and high elevation above sea level, the climate shows the combination of a clear division into a dry and a rainy season, the predominance of the diurnal cycle over the seasonal, and large daily ranges of temperature.

Tyrrell (1986) distinguishes four seasonal weather types, each with very distinct prevailing circulation and pressure systems, and characteristic distributions of rainfall, wind speed and directions and sunshine. These are the summer rainy season, the winter dry season, the pre-rain hot season and the post-rain warm season.

5.2 Meteorological Data

The Study on the National Water Resources Master Plan (YEC 1995b) is a valuable source of information for meteorological data as it includes nation-wide statistical information from 36 meteorological stations on major climatic parameters including rainfall, temperature, sunshine hours, relative humidity, wind speed as well as pan evaporation and actual and potential evapotranspiration. The climatological data were collected from the Department of Meteorology, Ministry of Transport and Communication, and cover the period from beginning of observation up to September 1993.

The following three meteorological stations are located in the Lusaka area:

1. Lusaka City Airport,
2. Mt. Makulu Agromet, and
3. Lusaka International Airport.

5.2.1 Temperature

The mean annual temperature in Lusaka Province is 19.8°C which is slightly below the Zambian average of 21.0°C. The coldest months are June and July with an average of around 16°C. The maximum monthly temperatures occur in October with a mean of about 24°C.

5.2.2 Precipitation

Rainfall and average number of rainfall days provided by YEC (1995b) at the three meteorological stations in Greater Lusaka are given in Table 5. Annual rainfall for the thirty-year period from 1963 to 1993 averages at 857 mm. Rainfall amounts usually peak during January with monthly totals ranging from 206 to 237 mm (Figure 11). 82% of the total annual rainfall occurs during the four-month period from December to January. The average number of rainfall days is approx. 77.

Variability of both annual and monthly rainfall totals is considerable. YEC 1995 analysed rainfall data from meteorological stations to determine the maximum and minimum probable annual rainfall. According to this analysis, the maximum (minimum) probable annual rainfall with a return period of 10 years at the three stations in Lusaka varies between 1,712 and 1,763 mm (547 and 589 mm). The range of maximum probable rainfall, however, appears rather high since it exceeds the maximum rainfall values observed during the thirty-year period (Table 5).

Table 5 Rainfall statistics and average number of rainfall days at three meteorological stations in the Lusaka area (after YEC 1995b)

Meteorological Station	Altitude in m asl	Start of Recording	Rainfall in mm per annum			Rainfall days per annum
			Average	Min	Max	
Lusaka City Airport	1280	1950	**858**	483	1366	78
Mt. Makulu	1213	1961	**848**	527	1318	77
Lusaka Int. Airport	1154	1967	**865**	530	1299	77

Daily rainfall is equally variable. The highest ever observed daily rainfall (up to 1993) amounts to 292 mm at Mt. Makulu, 190 mm at Lusaka City Airport, but only 105 mm at Lusaka International Airport. Compared with other tropical cities on the continent, however, an unusually small proportion of total rainfall comes from storms of short duration over Lusaka. According to Tyrrell (1986) storms of less than 15 (30) minutes duration account for 27% (52%) of total annual rainfall.

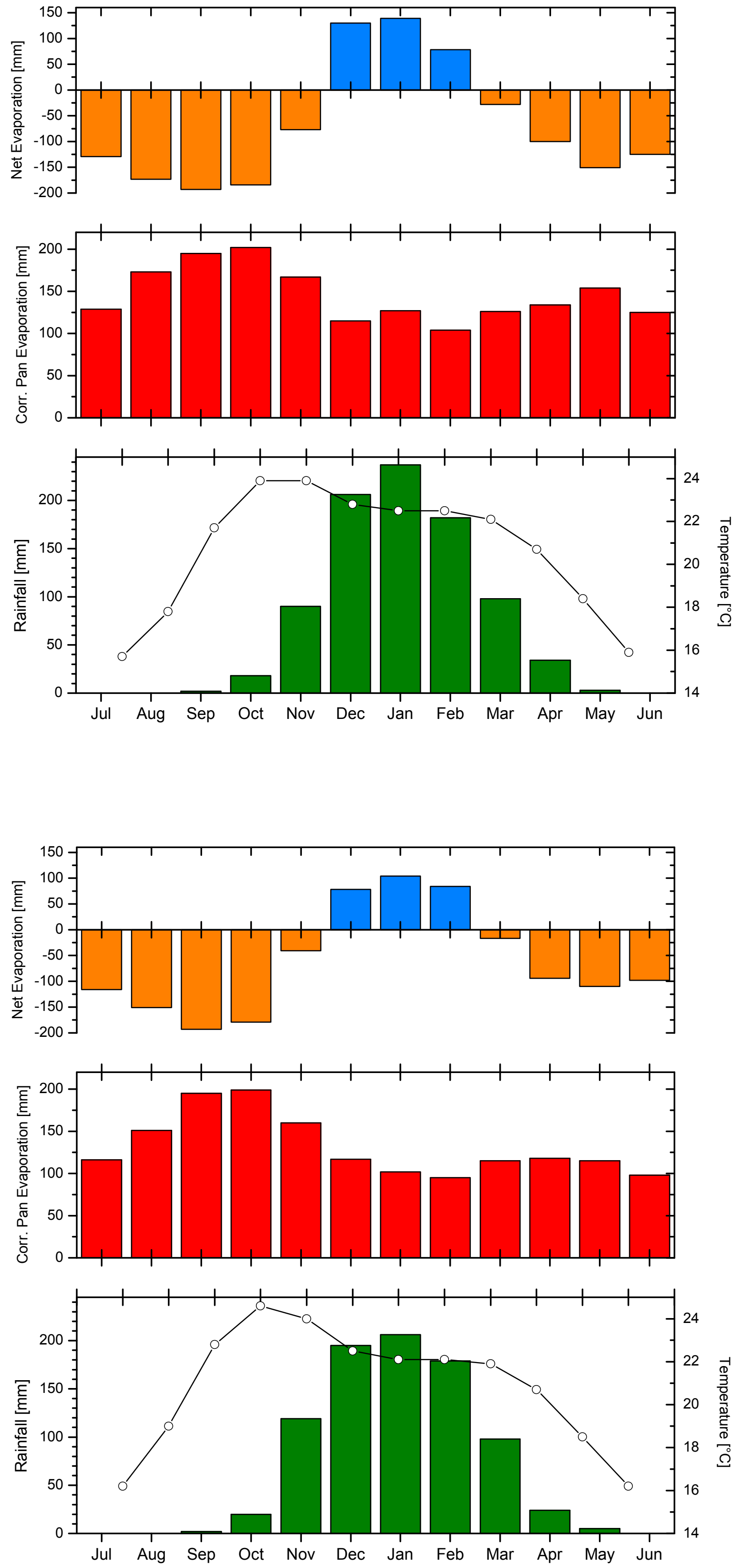


Figure 11 Seasonal variation of monthly mean temperature, rainfall, corrected Class-A pan and net evaporation at Top: Lusaka International Airport (1967 – 1993) and Bottom: Mt. Makulu (1964 – 1993). After: YEC 1995b, data from Meteorological Department.

Nkhuwa (1996) analysed the average rainfall between 1971/72 and 1990/91 for the Lusaka area and obtained a slightly higher mean of 873 mm/a for this period. He identified a particular dry spell between the years 1982 to 1988 with all years except 1986 having below average rainfall.

Analysis of more recent rainfall data was published by Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008). According to this source, the mean annual rainfall (*MAR*) for the years 1995 – 2006 amounts to 832 mm at Lusaka City Airport, 810 mm at Lusaka International Airport and 884 mm at Mt. Makulu. The report also includes tables showing the daily rainfall data observed at Mt. Makulu from 01/1978 to 04/2008 and hourly rainfall values from 05/1959 to 04/1962. Furthermore, rainfall probability statistics were performed using existing daily rainfall data.

5.2.3 Evapotranspiration

Available estimates of potential evapotranspiration (*PET*) are based on pan evaporation measurements, or were calculated using the Penman equation (1948), modified versions of the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith equation (Monteith 1965, Allen et al. 1998) or the empirical Thornthwaite (1948) equation.

Actual evapotranspiration (*ET*) was determined using the empirical equation proposed by Turc (1961) or methods that take the relative plant-available moisture into account.

The available results for annual evaporation are summarized in Table 6.

Von Hoyer et al. (1978) calculated monthly potential evaporation for two consecutive years (Jan. 1976 – Dec. 1977) using the Penman equation. Actual evaporation was then determined by applying the method proposed by Renger & Strebel (1974, in von Hoyer et al. 1978) which takes the relative plant-available moisture (*RAM*, given in %) into account. *RAM* is defined as the ratio actually available to plants at any given time and the maximum plant available moisture (field capacity – wilting point). It is assumed that actual evaporation equals potential evaporation (i.e. $P_{eff} = P$) if *RAM* is above 70% and follows a parabolic relationship for *RAM* below 70%. Average maximum plant available moisture of soil was estimated for forest areas, open bush and cultivated land/grassland at 300 mm, 200 mm and 100 mm, respectively.

The results for the three land use types are presented in graphs on a monthly basis. Unfortunately, totals were only given for calendar years. Actual evaporation for 1976 (*MAR* 898 mm) was determined at 735 mm, and for 1977 (*MAR* 901 mm) at 619 mm. The lower value for 1977 can be explained by the fact that the wet season 1976/77 had a low rainfall of only 682 mm. Actual evaporation is always highest for forests and lowest for cultivated land/grassland due to the assumed differences in maximum plant available moisture.

YEC (1995b) applied a modified version of the Penman equation to obtain values for *PET* varying between 1530 mm and 1590 mm. *ET* calculated using the Turc equation ranges from 730 mm to 740 mm according to this study.

Measured Class-A Pan evaporation at Lusaka International Airport and Mt. Makulu meteorological stations amounts to 2331 mm and 2104 mm, respectively. Other values from stations in Central Zambia are similar to the evaporation measured at Mt. Makulu, e.g. Kabwe 2158 mm, Kabwe Agro. 2051 mm and Kafue Polder 2122 mm (YEC 1995b).

Evaporation from open water bodies such as lakes is often estimated by multiplying the pan evaporation by a pan coefficient of 0.75. Using this value, *PET* at Lusaka International Airport and Mt. Makulu meteorological stations is 1748 mm and 1578 mm, respectively. Depending on season, location and surface cover, however, pan coefficients may vary between 0.35 and 0.85. From comparing these results with values obtained from the Penman-Monteith equation given above, it may be concluded that the pan coefficient of 0.75 applied to Lusaka International Airport data is too high.

Table 6 Potential and actual evaporation in the Lusaka area according to various authors

Source	Method	Station/Area	Period	Value [mm]
Potential Evapotranspiration				
YEC 1995b	Pan coefficient = 0.75	Lusaka Int. Airport	1971-1990	1748
		Mt. Makulu	1967-1993	1578
	Modified Penman	Lusaka City Airport	1963-1993	1533
		Lusaka Int. Airport	1971-1990	1590
		Mt. Makulu	1967-1993	1591
Nkhuwa 1996	Modified Penman	Lusaka	1971-1990	1489
	Thornthwaite		1971-1990	938
Actual Evapotranspiration				
Von Hoyer 1978	Penman & RAM-Renger & Strebel	Lusaka	1976	735
			1977	619
YEC 1995b	Turc	Lusaka City Airport	1963-1993	730
		Lusaka Int. Airport	1971-1990	739
		Mt. Makulu	1967-1993	733
Maseka 1994	Penman-Monteith & RAM	Lusaka	1987/88	412-739
			1988/89	515 -697
Nkhuwa 1996	Penman/Thornthwaite & RAM-Renger & Strebel	Lusaka	1971-1990	518-764
	Turc		1971-1990	732

Maseka (1994) calculated *ET* using a computer program for water balance calculations. Calculations of evapotranspiration are based on the Penman-Monteith equation and a so-called “root constant” which represents soil depth and is hence closely related to the field capacity of soil. Depending on the value chosen for the root constant, he received values ranging from 412 mm to 739mm for 1987/88 and 515 mm to 697 mm for 1988/89.

Nkhuwa (1996) provides monthly and annual evaporation estimates for the period 1971/72 to 1990/91 using a modified Penman and the Thornthwaite equations. Annual values for *PET* of 1489 mm (Penman) and 938 mm (Thornthwaite) were obtained. *ET* for the same period is estimated at 732 mm using the Turc equation. Nkhuwa also used the RAM method originally applied by von Hoyer et al. *ET* according to this method is 764 mm if *PET* is calculated by the Penman equation or 518 mm if *PET* is obtained from Thornthwaite equation.

Monthly variations of *PET* (from pan evaporation measurements) are shown in the diagrams presented in Figure 11. The highest *PET* (190 – 205 mm/month) is encountered during the hot season. Low *PET* (90 – 130 mm/month) occurs during the rainy months due to high humidity and during winter due to low temperatures. Actual evaporation on the contrary can be assumed to peak during the rainy and post-rainy season when surfaces are wet and soils often become saturated with water.

Net evaporation is defined as the difference between mean rainfall and *PET* and may be used as a measure for aridity. Net evaporation is negative (i.e. *PET* exceeds rainfall) for all months except for December to February.

ANALYSIS

Overall, reliable long-term data for rainfall and evaporation is available in the Lusaka area even though an update of existing analyses using data of the last 30-year period would be useful. Due to the high spatial and temporal variability of rainfall events the number of three rainfall stations is considered insufficient with respect to the planned detailed investigations of rainfall – water table interactions. YEC (1995b) lists about 30 voluntary rainfall stations where rainfall readings were taken by the time that could possibly provide the missing information.

Little is known on the influence of urban development, deforestation and overall change in land use on evaporation. An expansion of build-up areas and deforestation are thought to increase urban surface runoff and reduce infiltration and evaporation from land surfaces.

TASKS

Daily and monthly meteorological data over the last 30 years are needed for the recalculation/updating of *PET* using the FAO Penman-Monteith method and to determine *ET* using soil moisture based methods. The meteorological data required includes radiation (or sunshine duration in hour), air temperature, vapour pressure (or relative humidity in %) and daily average of wind speed. New information on urban development and land use can be obtained from remote sensing interpretation, and should be incorporated in the analysis.

Daily rainfall data for the rainy seasons 2008/09 to 2011/12 are essential for the interpretation of groundwater level fluctuations with respect to recharge. The meteorological and rainfall data should be acquired from the Meteorological

Department. The availability of rainfall data from voluntary stations and the necessity for establishing additional rainfall gauges must be assessed. It is planned to establish up to three additional rainfall stations.

5.3 Runoff

The Lusaka plateau forms a 70 km long and 10 km wide ESE-WNW stretching low ridge with an elevation ranging from 1200 to above 1300 meters above sea level (m asl). A major surface water divide runs through the Lusaka area that separates sub-catchments belonging to the Chongwe river system (Ngwerere and Chalimbana rivers) from sub-catchments that are part of the Lower Kafue River (Mwembeshi/Chunga, Chilongolo, Funswe, Chisuko rivers). The divide runs roughly parallel to Great North Road in N-S direction, and turns towards the southeast following the north-eastern edge of the plateau in a NNW-SSE direction (and Figure 12). The catchment areas derived from the DENM are given in Table 7.

Table 7 Catchments and catchment size

Catchment	Included Sub-catchment	Area [km^2]
Mwembeshi		4,504
	Chunga	621
Chilongolo		715
Funswe		458
Chisuko		560
Upper Chongwe *)		2,667
	Ngwerere	298
	Kanakantapa	484
	Chalimbana	658

*) after Chalimbana confluence)

A dendritic and locally very dense river system has developed on areas covered by schist and less permeable carbonate rocks. Quite in contrast, virtually no surface drainage is present on the plateau due to the karstified nature of the Lusaka Dolomite Fm. Dry season surface discharge from the Lusaka Dolomite occurs almost exclusively in spring lines along certain boundaries between Lusaka Dolomite and the lesser permeable rocks of the Chunga and Cheta Fm (GIBB Ltd. 1999c, Museteka & Bäumle 2009). Consequently, smaller streams emerge at the edge of the plateau and feed west- and southwards into the catchments of the Chunga, Mwembeshi, Chilongolo and Funswe Rivers and northeast- and east-wards into the Ngwerere and Chalimbana Rivers.

The DWA operates river gauging stations along the Mwembeshi River as well as along the Chongwe River and its tributaries Ngwerere and Chalimbana. Measurements at the Kapiriombwa River, a smaller tributary of the Chongwe near International Airport were terminated during 1999 after a new owner installed electrical fencing around the farm. A summary of river gauging stations and their current status is given in Table 8.

The GPS coordinates were captured during this study. The location of the stations is shown in Figure 12.

Water level readings are obtained from installed measuring charts and submitted by to DWA headquarters by the gauge readers employed. Readings are usually taken at 06:00, 12:00 and 18:00 hours. Weirs were only constructed at Ngwerere Estate (station no. 5016) and Kapiriombwa (no. 5030). Automatic (analogue type) readers were installed at stations 5025, 5029 and 5030, but none of them is currently in order. Discharge measurements are carried out using current meters by a DWA team consisting of hydrologists and technicians. These measurements, however, are not taken on a regular basis, and the discharge rating curves need therefore updating in most cases. For two stations in the Lusaka area, no discharge rating curves are available. YEC (1995c) has produced updated rating curves for gauging stations at Chongwe (stations no. 5025 and 5025) and Chalimbana (station no. 5029) rivers.

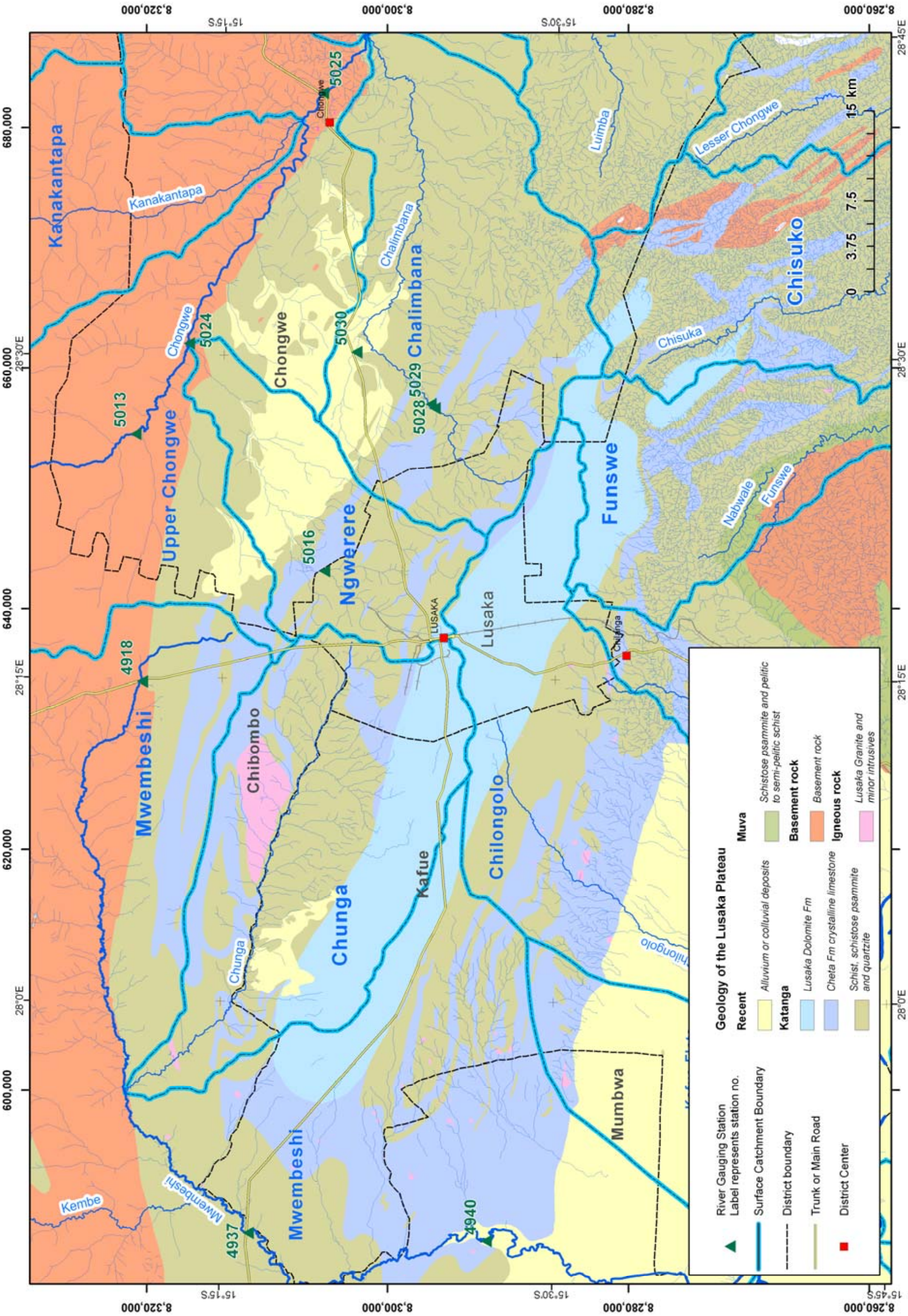


Figure 12 Surface drainage and catchments as well as available river gauging stations on the Lusaka Plateau

As can be seen from Table 9, some of the records started in the mid- 1950s but are often discontinuous. The table also includes the range of monthly and annual runoff data available at the DWA. An example of water level records at Chalimbana is depicted in Figure 13. Towards the end of the dry season, and in particular during years under drought conditions the rivers in the Lusaka area including the larger Chongwe and Mwembeshi rivers reduce to a trickle.

Table 8 River gauging stations and availability of runoff data (Source: DWA, Surface Water Resources Section)

Station No.	River/ Location	Lat (S)	Long (E)	Status
4918	Mwembeshi/ Gr. North Rd Bridge	15.19064	28.24708	Operational, but no gauge reader on duty.
4937	Mwembeshi/ Mumbwa Rd Bridge	15.27200	27.82078	In use; new rating curve required after repairs.
4940	Mwembeshi/ Shibuyunji	15.452	27.815	In use.
5012	Chongwe/ Chongwe North	15.08	28.41	Replaced by no. 5013 after construction of dam.
5013	Chongwe/ Rays dam	15.18458	28.43836	Replaces station no. 5012, no rating curve available.
5016	Ngwerere/ Ngwerere Estate	15.32694	28.33294	Weir; in use.
5024	Chongwe/ Ngwerere Confluence	15.22431	28.50864	In use.
5025	Chongwe/ Gr. East Road Bridge	15.32342	28.70336	Operational, but no gauge reader on duty.
5028	Chalimbana/ Glencraig Farm	15.40914	28.46003	Abandoned, no rating curve available.
5029	Chalimbana/ Rumor Farm	15.40597	28.46300	In use.
5030	Kapiriombwa/ Exchange Farm	15.35008	28.50289	Weir; operational, but currently closed.

Table 9 Minimum and maximum observed annual and monthly runoff (Source: DWA, Surface Water Resources Section)

Station No.-River	Period	Area [2)] [km^2]	No. [3)]	Annual runoff [m^3/s]		Monthly runoff [m^3/s]	
				Min.	Max.	Min.	Max.
4918-Mwembeshi	03/77–12/07	73	22	0.219	4.0	0.11	21.9
4937-Mwembeshi	03/77–06/08[1)]	2,992	0	n/a	n/a	0.002	3.49
4940-Mwembeshi	11/62–05/07[1)]	4,019	24	1.09	4.1	0.13	21.0
5012-Chongwe	01/73–07/02	≈500	25	0.001	5.7	0	16.4
5013-Chongwe	12/02–05/07	551	3	-- No rating curve --			

Station No.-River	Period	Area [2] [km²]	No. [3]	Annual runoff [m³/s] Min.	Annual runoff [m³/s] Max.	Monthly runoff [m³/s] Min.	Monthly runoff [m³/s] Max.
5016-Ngwerere	01/56–01/08	303	43	0.17	1.1	0.095	2.4
5024-Chongwe	01/77–01/08	1,102	24	0.66	2.7	0	10.7
5025-Chongwe	12/68–09/07	1,961	28	1.52	6.1	0	30.7
5028-Chalimbana	12/52–02/72	114	15	-- No rating curve --			
5029-Chalimbana	11/53–09/07	115	41	0.054	1.2	0.014	3.5
5030-Kapiriombwa	10/58–05/99[1)]	61	27	0.072	0.35	0.001	1.9

[1)] Discontinuous data series (major gaps) [2)] Derived from DEM
[3)] Number of years with complete water level records (existing gaps <30 days)

YEC (1995b) determined the ratio of baseflow to mean annual runoff at stations 5-024 (Ngwerere) and 5-029 (Chalimbana) at 22% and 14%, respectively.

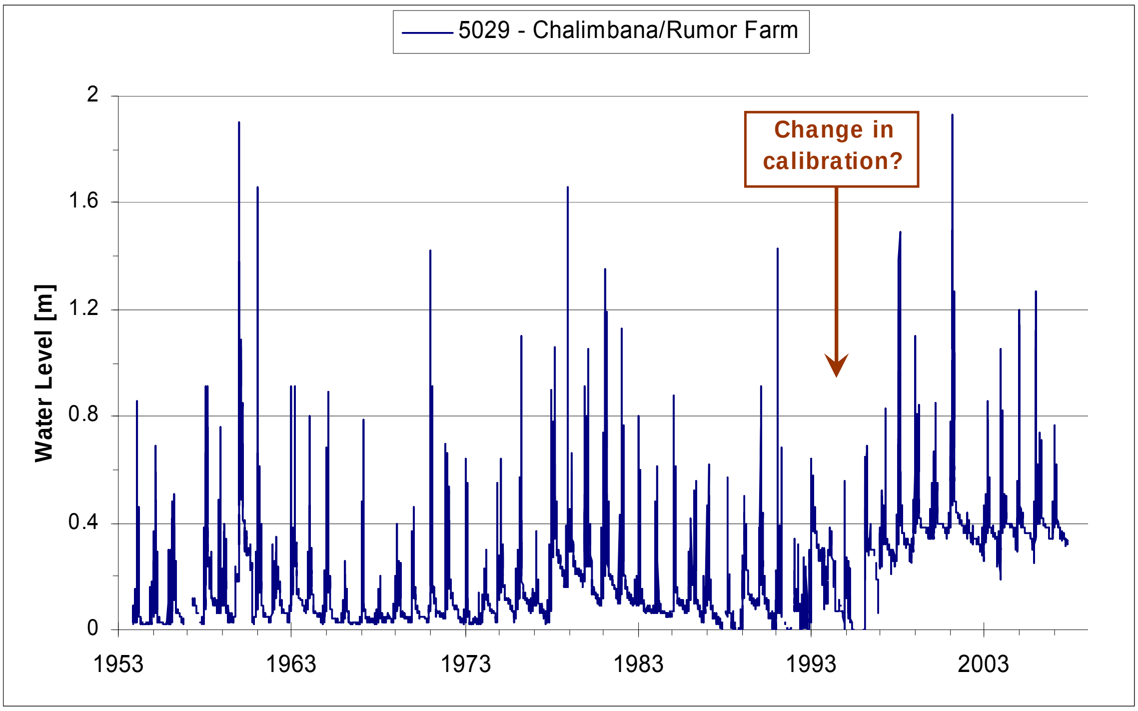


Figure 13 Recorded water levels at Chalimbana/Rumor Farm

5.4 Groundwater Recharge

Principal sources of recharge of the Lusaka aquifers are direct recharge through rainfall, unaccounted for water from the water supply network, septic tanks and latrines and return flow from irrigation of commercial farm land and gardens (Mpamba 2008).

Various estimates of direct recharge, yet with widely varying results are available (Table 10).

Due to its simplicity, a popular approach is to evaluate recharge from groundwater hydrograph data. In this method, referred to as the water table fluctuation method, recharge is determined as the sum of increase in groundwater storage and groundwater outflow (baseflow), as follows:

[2] $R = S_y \cdot \Delta h + Q_b,$

where Δh is the observed (total) rise of groundwater level during the rainy season, S_y is the specific yield of the aquifer and Q_b is baseflow.

If the amounts of groundwater extracted from the area over the period under consideration are substantial the abstracted volumes A (expressed in mm) need to be included in the calculations of recharge:

[3] $R = S_y \cdot \Delta h + Q_b + A,$

Tague (1965) provides estimates of recharge and groundwater reserves of the historical main groundwater reserve and adjacent areas (i.e. Waterworks, Kafue Road Quarries, Old Mumbwa Road, Southern Ridgeway) based on interpretation of borehole logs and water level observations from Nov. 1962 to April 1964. Assuming baseflow to be negligible and a specific yield of 5%, he obtained a recharge of 210 mm (recharge rate, *R%* = 25%) for the rainy season 1962/63 and of 76 mm (*R%* = 10%) for the subsequent rainy season. He furthermore suggests that near zero recharge would occur for *MAR* below 480 mm.

Chenov (1978) estimated the recharge rate for the Kafue Basin at 180 mm (*R%*= 14.3%) over 1977/78 season. Baseflow was estimated from a groundwater contour map using Darcy's Law.

During the Study on the National Water Resources Master Plan (YEC 1995b) the baseflow separation method was used to assess groundwater outflow for major rivers in the country using discharge data from major river gauging stations while water level fluctuations were observed at selected wells over a period of about one year. For Lusaka Province, an average baseflow estimate over the rainy season was produced from hydrograph analysis of various Kafue and Luangwa gauging stations, and the stations at Ngwerere, Chalimbana and Mulungushi rivers. Average baseflow was estimated at 9 mm/a for the Kafue and 12 mm/a for the Luangwa/Chongwe catchments. The rise in groundwater levels was measured at 20 observation wells located in Lusaka Province from May 1994 to March 1995. Measured groundwater level fluctuations in Lusaka Province over this period varied between 0 to 5 m with an average fluctuation of 2.2 m. The specific yield S_y was assumed to be 5% for carbonate rocks and 3% for schists and quartzites. The results were broken down to districts and provinces (rather than catchments). As a result, a relative small recharge of around 70 mm per annum was obtained for both Lusaka Province and Lusaka Urban District corresponding to only 8% of *MAR*.

Table 10 Available estimates of recharge in the Lusaka area

Source	Area	Method	Period	*R* [mm]	*R%*
Tague 1965	Lusaka main well field	*Equ. [2],* $Q_b = 0$	1962/63	210	25
			1963/64	75	10
Chenov 1978	Kafue Basin	*Equ. [2],*	1977/78	180	14.3
YEC 1995b	Lusaka Province	*Equ. [2]*	1994/95	68	7.9
	Lusaka Urban			66	7.7
	Central Province			82	8.7
Nyambe & Maseka 2000	Lusaka main well field	*Equ. [2],* $Q_b = 0$	not spec.	186	27
Mpamba 2008	Forest Reserve 26	*Equ. [2],* $Q_b = 0$	2007/08	707	80
	Lusaka Aquifers	*Equ. [3],* $Q_b = 0$	10/07-01/08	226	26
Von Hoyer et al. 1978	Lusaka Dolomite Fm	*Equ. [5]*	1976/77	202	21
			1976/77	37	5
Nkhuwa 1996	Lusaka Dolomite Fm	*Equ. [5]*	1971-1990	202	23
Maseka (1994)	Schist aquifers	Catchment water and soil water balance	1986/87	40	6
			1987/88	89-310	13-45
	Carbonate aquifers		1986/87	591	47
			1987/88	731-771	57-60

R = recharge, *R%* = recharge rate in per cent of *MAR*, *A* = groundwater abstraction, S_y = specific yield, Δh = rise in groundwater table, Q_b = groundwater baseflow, *P* = rainfall, *ET* = actual evapotranspiration, not spec. = not specified.

Nyambe & Maseka (2000) estimate recharge for the existing well field area of approximately 192 km^2 at 186 mm/a assuming an annual variation in ground-water levels of 6.2 m and an average S_y of 3% for the area.

Mpamba (2008) obtained a very high recharge of 707 mm for the 52.6 km^2 large Forest Reserve No. 26 area during 2007/2008 rainy season based on an rise in water level of 14.15 m in one borehole observed between Oct. 2007 and the end of Jan. 2008, and an assumed S_y of 5% for the carbonate rock encountered in this area. The rainfall over the same period averaged at 882 mm (793 – 943 mm) at the four meteorological stations in Lusaka resulting in a recharge rate of about 80%. An equally high recharge rate of 60% was applied to the Forest Reserve areas by Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) in order to estimate the groundwater potential for the proposed Multi Facility Economic Zone area.

In order to determine the recharge over the same period for the whole Lusaka aquifer systems consisting of carbonate rocks (470 km^2) and schists (271 km^2), Mpamba (2008) applied equation [3] using the following assumptions:

- Average change in water table is 5.9 m and 1.6 m within the carbonate rocks and schist, respectively.
- S_y is 5% for carbonate rock and 2% for schist.

- Groundwater abstraction is 171,000 m^3/d, totalling 20.5 Mm^3 over the four-month period.
- The difference between lateral groundwater outflow and inflow is assumed to be zero.

The result is given as 200 mm in the thesis although recalculation results in 226 mm recharge over the four-month period corresponding to 26% of the average rainfall over the period of 882 mm.

Other available approaches to estimate recharge are based on the water balance equation [1]. Groundwater recharge R can be calculated as:

$$[4] \quad R = P - ET - Q_d - \Delta S$$

where P is precipitation, ET is actual evapotranspiration, Q_d is direct runoff (overland flow and interflow), and ΔS is change in groundwater storage. Note that the water balance equation in this form neglects groundwater abstractions. For annual recharge calculations ΔS is commonly assumed to be zero. This assumption, however, holds only if groundwater levels at the end of each year are in the same order of magnitude. Furthermore, for flat surfaces without surface runoff, recharge can be estimated by the simplified equation:

$$[5] \quad R = P - ET$$

Using this equation, von Hoyer at al. (1978) obtained a recharge of 202 mm (R% = 21%) for the 1975/76 rainy season and of 37 mm (R% = 5%) for the 1976/77 rainy season. Actual evaporation was calculated from the relative soil moisture method described in Chapter 5.2.3. The huge difference between the two years analysed was explained by the fact that the 1975/76 rainy season with a *MAR* of 964 mm was considered as wet whereas rainfall totals of the subsequent rainy season were well below average.

The accuracy of the estimates is approximately ±20% according to the authors. They further concluded from their observations that rains in excess of 700 mm are needed for recharge to be substantial. Keller & von Hoyer (1992), however, pointed out that one short-coming of the method applied is that it does not consider infiltration through open grikes and dolines.

Based on these findings the annual recharge was set at 160mm/a for forest, 180 mm/a for open bush and 200 mm/a for grassland and cultivated land for years with *MAR* of about 820 mm for groundwater modelling purposes (von Hoyer & Schmidt, 1980). For dry years, these recharge rates were reduced by 50%.

Assuming a MAR of 873 mm and ET of 671 mm and zero runoff due to the scarcity of streams, Nkhuwa (1996) obtained an annual recharge of 202 mm (R% = 23%) for the period of 1971 – 1990.

Maseka (1994) used a combined catchment water and soil water balance approach for the two consecutive years from October 1987 to September 1989. He applied an algorithm written by Acworth (1981, in Maseka 1994) which calculates a catchment water balance based upon daily input of meteorological data obtained at Lusaka International Airport. S_y is assumed to be 3% for limestone/dolomite and of 1% for schist. The results proved very sensitive to some of the assumed input parameters, especially the so-called "root constant" which represents the soil depth and inherently field capacity. For the rather dry year 1987/88 (*MAR* 690 mm), he obtained a recharge rate of 40 mm/a for areas covered by schist and, depending on the value selected for the root constant, a recharge rate varying between 89 to 310 mm for limestone and dolomite. For the exceptionally wet year 1988/89 (*MAR* 1254 mm), he obtained overall very high recharge rates of 591 mm for schist and 731 mm to 771 mm per annum for limestone and dolomite. Based on his analysis, Maseka provides the following approximations of average recharge: 300-400 mm per annum for the Ngwerere Catchment, and 500 mm per annum for the Chalimbana Catchment and the area covered by the Lusaka Dolomite Formation.

There are comparatively few studies looking into processes governing recharge. Von Hoyer et al. (1978) observed that usually the water table rises, and hence the recharge process starts, only towards the end of December or January. Mpamba elaborates on the importance of the combined effect of rainfall amounts, rain days and distribution of recharge. According to his investigations, the ratio between the number of rain days and the total days of a wet period proved indicative of recharge, i.e. recharge is substantial even for small total rainfall if this ratio is 0.4 and above. He furthermore observed that rainfall events exceeding 10 mm result in temporal ponding in areas covered by carbonate rocks, but disappears after a few minutes to a few hours indicating direct recharge.

Information on infiltration rates is also sparse. Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) carried out two infiltration tests in the Forest Reserve area to the southeast of the City. The measured (near-steady state) infiltration rates were 566 and 798 mm/hr. The only other reported infiltration test yielded a much lower infiltration rate of 76 mm/hr. (Tague 1969, in Mpamba 2008)

Little information is available on recharge by means of processes other than direct recharge, e.g. by return flow from agriculture and gardening or housing. The loss in the water supply transmission line (bulk water supply system) due to leakages was estimated at 3,000m^3/d or 8% of total capacity during 2002. In August 2007, "Unaccounted for Water" (difference between the quantity of water produced and the quantity of water billed) reached 49% of the supplied capacity, which is much higher than real losses consisting of leakages and storage tank overflows (KRI et al. 2008a). A similar figure (51%) for Unaccounted for Water is provided by NWASCO (2007).

5.5 Groundwater Abstraction

Groundwater from the Lusaka aquifers is extracted for the following purposes:

- public water supply through wells operated by the LWSC
- local public water supply by water trusts

- industrial and commercial use
- irrigation purposes
- domestic use including small-scale gardening
- rural water supply

According to Schmidt (2001), 60% of the aquifer area in the City is affected by the general depletion due to pumping.

5.5.1 Public Water Supply

The Lusaka Water and Sewerage Company provides water through a bulk water supply system, which is the main distribution network consisting of Iolanda Water Works (Kafue) and several boreholes. In addition, there are nine so-called satellite water supply systems and community-based water supply schemes (Water Trusts) to mainly supply peri-urban areas (KRI et al. 2008b). A historical outline of abstraction rates can be found in Mpamba (2008). According to the National Water and Sanitation Council (2007) the water supply coverage (ratio of urban population with access to safe and reliable water) served by LWSC is 64%.

In 1995, 40% of the water supply, 111,500 m^3/d, was provided by groundwater from about 49 production boreholes (YEC 1995b). The total supply then was about 190,000 m^3/d serving a population of 900,000.

According to a survey by KRI et al. (2008b) carried out for August 2007, 133,618 m^3/d of groundwater were pumped from 63 out of 77 available wells. This excludes the wells at George Compound which were not commissioned at the time. The total monitored production by LWSC (surface water from Kafue/Indola intake + groundwater) in 2007 averaged 218,000 m^3/d, which corresponds to 85% of the design capacity. The study report includes graphs showing total monthly abstraction for both groundwater and surface water from 2002 – Aug. 2007 (KRI et al. 2008a).

Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) estimate the total production at 207,000 m^3/d of which 110,000 m^3/d are pumped from boreholes.

Currently, the public service provider operates up to 79 wells throughout the City area. Production from the aquifers from these wells totals 125,000 m^3/d according to recent data obtained from the LWSC (Table 11). Abstraction from the Lusaka Dolomite Fm is about 50% (60,700 m^3/d) from 22 boreholes. The location of the public water supply wells is shown in the conceptual hydrogeological map attached in APPENDIX 2.

The production rates of the wells range widely from <10 m^3/h to over 500 m^3/h. During the dry season, some wells are temporarily pumped at a higher rate than the average values given in Table 11. Some of the strongest wells are found within the Lusaka Dolomite Fm in the area of the Lusaka main well field in the southern parts of the City. The largest amount of groundwater is pumped from Shaft No. 5. According to a personnel communication with the LWSC on 21 Nov 2008, the total production during October 2008 from Shaft No. 5 Pump 1 and Pump 2 was 436,200 m^3 (586 m^3/h) and

353,886 m^3 (476 m^3/h). Other strong boreholes (numbers in brackets refer to current production rates provided by LWSC) in the Lusaka Dolomite are Waterworks (167 and 330 m^3/h), the Roadside wells along Mumbwa Road (75 - 150 m^3/h), Lumumba Road (138 m^3/h) and Lilayi Road (116 and 118 m^3/h). Productive aquifers are also found within the crystalline limestones of the Cheta Fm except where they are compact and massive and show little fracturing and karstification. High yields within this formation were found at Leopards Hill (80 and 188 m^3/h), and on Malo Farm located along Great East Road (94 and 120 m^3/h).

Table 11 Location and average production rates at public water supply wells operated by the LWSC (Source: LWSC)

Name	Long (N)	Lat (S)	Drill Date	Depth [m]	Ø [mm]	Q [m^3/h]	P.D. [h]	Q [m^3/d]
Avondale 1 (DE14 - 9/40)	28.40912	15.37743	1999	50	203	78	24	1862
Avondale 2 (F12 -33W)	28.41079	15.37783	1999	85	152	16	24	387
Avondale 3 (F12 - 33W)	28.41093	15.37726	1999	70	152	29	18	528
Bauleni	28.38013	15.44198	1900	46	150	33	24	785
Buckley 1	28.23663	15.52958	2001	47	152	8	12	91
Buckley 2	28.23287	15.52960	2001	51	152	8	12	90
Chainda	28.40456	15.38948	1995	n/a	150	26	24	622
Chawama 1	28.28520	15.46339	1982	60	250	100	24	2400
Chawama 2	28.28270	15.46538	1982	40	300	95	7	665
Chawama 3	28.28225	15.46655	1984	62	300	119	24	2856
Chelston 1	28.37987	15.38191	1975	55	200	19	6	113
Chelston 2	28.37990	15.38190	1975	61	200	24	24	576
Chelston 3	28.37991	15.38205	1995	62	300	67	0	0
Chilenje South	28.33030	15.45444	1982	38	200	58	24	1382
Chunga 1	28.24972	15.35634	1981	70	200	24	12	282
Chunga 2	28.25199	15.35900	1994	50	150	12	12	144
Chunga 6E	28.25260	15.35382	2002	n/a	0	66	12	792
Chunga 6F	28.25296	15.35438	2002	n/a	0	38	24	919
Freedom Water Trust	28.26772	15.53998	1972	65	150	0	0	0
George 2	28.23478	15.38700	1900	n/a	0	77	11	843
George 3	28.22764	15.38489	1900	n/a	0	55	12	664
George 5	28.23292	15.38964	1900	n/a	0	68	11	749
George 6	28.23836	15.39139	1900	n/a	0	45	22	988
George 7	28.23575	15.38958	1900	n/a	0	32	17	539
Head Office 1	28.30351	15.41307	1900	n/a	150	4	24	96
Head Office 2	28.30379	15.41320	1900	n/a	0	5	24	120
Ibex Hill	28.35872	15.42037	1985	69	200	14	24	344
Int. School 6A	28.31719	15.40446	1995	n/a	300	78	24	1868
Int. School 6B	28.31705	15.40441	1983	81	200	56	24	1350
Int. School 6C	28.31804	15.40483	1995	n/a	300	26	0	0
Int. School 6D	28.31843	15.40455	1982	66	300	118	24	2832
Int. School 6E	28.32184	15.40328	1995	n/a	300	73	24	1742
Int. School 6F (D12-50N)	28.31964	15.40731	2001	n/a	200	45	24	1080
John Howard	28.29182	15.47100	1978	81	250	16	15	239
John Laing	28.27242	15.43989	1995	n/a	150	19	12	225
Kabanana	28.30468	15.36039	2003	n/a	200	47	24	1138

Name	Long (N)	Lat (S)	Drill Date	Depth [m]	Ø [mm]	Q [m^3/h]	P.D. [h]	Q [m^3/d]
Lake Road	28.35715	15.42372	1975	69	200	18	24	439
Leopards Hill 1	28.35772	15.43721	1976	88	300	188	18	3384
Leopards Hill 2	28.35737	15.43689	1995	n/a	250	81	24	1934
Lilayi Road 1	28.31783	15.46738	1995	n/a	300	118	24	2832
Lilayi Road 2	28.31778	15.46739	1985	n/a	300	116	24	2784
Lumumba Rd 4A	28.26719	15.40460	1980	70	300	138	18	2482
Malo Farm 1	28.41143	15.36728	1972	68	300	120	20	2400
Malo Farm 2	28.41101	15.36719	1985	n/a	200	94	24	2256
Marian Shrine	28.40920	15.37061	2001	60	152	22	24	523
Mass Media 1	28.32754	15.40774	1978	70	250	129	24	3101
Mass Media 2	28.32679	15.40738	1980	85	250	50	24	1200
Mass Media 3	28.32631	15.40794	1982	75	250	29	24	701
Mass Media 4 (C5Gs)	28.32589	15.40465	2001	n/a	200	73	24	1752
Mass Media 5 (F1/25W)	28.33217	15.41017	2001	n/a	200	74	24	1766
Mass Media 6 (C3/50W)	28.32589	15.40485	2001	39	200	39	24	936
Mulungushi 6A	28.31571	15.38984	1975	41	150	15	24	360
Mulungushi 6H	28.31475	15.38818	1965	68	200	21	24	494
Mumbwa Rd (Roadside 1)	28.24588	15.41960	1988	50	300	125	24	2990
Mumbwa Rd (Roadside 2)	28.24596	15.41960	1970	38	200	151	24	3624
Mumbwa Rd (Roadside 4)	28.24642	15.41958	1975	61	250	108	24	2592
Mumbwa Rd (Roadside 5)	28.24847	15.42090	1970	39	200	75	24	1800
Mumbwa Rd (Roadside 6)	28.24590	15.41915	1980	65	250	150	24	3600
Ngombe	28.32039	15.37089	1991	73	200	0	0	0
NIPA	28.29294	15.41565	1992	75	250	19	18	338
Northmead 1	28.30566	15.39684	1982	55	250	75	24	1800
Northmead 2	28.30546	15.39679	1995	n/a	250	70	24	1682
NRDC 1 (B6-3/55)	28.38292	15.33976	1999	31	203	19	7	133
NRDC 2 (B10-30N)	28.37993	15.34126	1999	50	254	35	24	842
NRDC 3	28.37634	15.33913	1999	50	152	0	0	0
NRDC 4 (D13/50W)	28.37816	15.33666	1999	45	152	8	0	0
Old P/Station	28.31256	15.44594	1981	n/a	250	73	24	1,760
Parerinyatwa	28.29693	15.41156	1984	80	150	11	24	259
Parks Nursery	28.33654	15.42833	1965	n/a	150	48	24	1,147
Quarries 1	28.27555	15.44175	2001	46	254	35	24	840
Quarries 2	28.27582	15.44194	2001	47	254	51	24	1,224
Quarries 3	28.27630	15.44193	1998	25	254	41	24	984
Shaft 5, Pump 1	28.31463	15.48827	1964	66	200	547	24	13,128
Shaft 5, Pump 2	28.31463	15.48827	1900	n/a	0	507	24	12,168
Showgrounds	28.31563	15.38502	2008	67	200	42	24	1,008
U.T.H	28.31336	15.42714	1995	70	150	23	24	562
Waterworks 1	28.31885	15.45337	1953	65	600	330	24	7,920
Waterworks 2	28.31873	15.43305	1954	70	300	167	24	4,008
TOTAL								**125,091**

Ø= Diameter of well, Q = Average production rate, P.D. = Pump duration, n/a = no information available

5.5.2 Commercial and Private Water Use

Unfortunately, little is known about abstractions from industrial and private wells and commercial farm land.

According to a survey conducted in the early 1990s (YEC 1995b), the largest amounts of groundwater in Lusaka and Central Provinces were abstracted for irrigation purposes (Table 12). With 40% of total usage, groundwater abstraction for irrigation purposes well exceeds the water abstracted for urban water supply (22%) in Lusaka Province according to this study.

Table 12 Percentage of groundwater use by purpose after YEC 1995b

Usage	Lusaka Province	Central Province
Irrigation	40	40
Livestock	26	29
Urban Water Supply	22	5
Rural Water Supply	5	19
Industrial	5	4
Commercial	2	3

De Waele & Follesa (2003) estimated the number of private boreholes in Lusaka at 3,000 to 4,000 and the total abstraction from Lusaka's groundwater systems at 260,000 m^3/d.

Similar estimates for the abstraction from a supposed number of 1,800 private wells were provided by Mpamba (2008). Assuming an average yield of 3.2 L/s and an average daily operation time from one to three hours, private groundwater abstraction would be in the order of 20,000 to 60,000 m^3/d in Lusaka.

Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) estimate the combined abstraction from satellite public supply wells and private boreholes at 80,000 m^3/d.

YEC (1995b) includes estimates of abstractions from boreholes and shallow wells for rural water supply. According to this study the abstraction in Lusaka Rural (Chongwe & Kafue districts) during the early 1990s was about 1,530 m^3/d (Table 13). Respective values for Lusaka Urban could not be provided.

An example of irrigation practices in the Lusaka area is given in Figure 14 which shows the total abstraction at York Farm used for irrigating approximately 220 ha of land. Peak irrigation demand usually occurs between end of March and mid-November. During this period the abstracted volume of groundwater on the farm typically varies between 6,000 and 9,000 m^3/d.

Table 13 Water use for rural water supply after YEC 1995b

District/Province	Borehole			Shallow Well		
	Total no.	Operating	Yield (m^3/d)[2)]	Total no.	Operating	Yield (m^3/d)[3)]
Lusaka-Urban	2,230	n/a	n/a	20	n/a	n/a
Lusaka-Rural [1)]	290	203	1,218	260	156	312
Luangwa	50	50	210	120	72	144
Lusaka	2570	238	n/a	400	n/a	n/a
Central	890	532	3,192	620	324	648

[1)] Lusaka Rural: Chongwe & Kafue Districts combined

[2)] Estimates on groundwater use (yield) are based on following equations:
Total no. of operated boreholes x Unit yield x Operation ratio
(Unit yield = 6 m^3/d, Operation ratio = 0.7)

[3)] Total no. of shallow wells in use x Unit yield x Operation ratio
(Unit yield = 2 m^3/d, Operation ratio = 0.6)

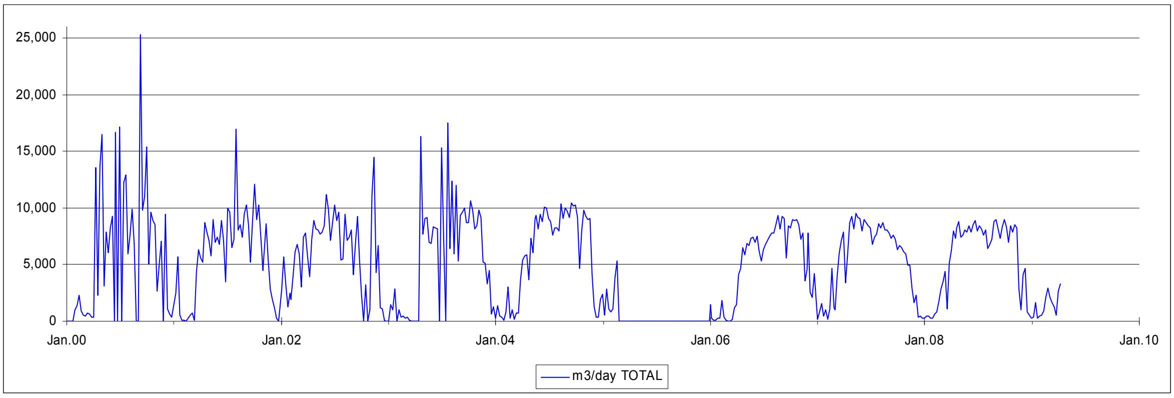


Figure 14 Total groundwater abstraction for irrigation purposes at York Farm in cubic meters per day since 2000 (Data kindly provided by York Farm Management)

Provided that the origin of supplied water is known (i.e. surface water sources can be distinguished from extracted groundwater) approximations of groundwater abstracted for livestock, crops, industrial and private use could possibly be derived from unit water demand estimates.

YEC (1995c) provides the following unit water requirement per head of livestock:

- Beef cattle 40 L/day
- Pigs 20 - 35 L/day
- Sheep/goats 20 - 29 L/day
- Poultry 0.2 L/day.

In the framework of the study on Comprehensive Urban Development Plan for the City of Lusaka, KRI et al. (2008c) developed estimates of the per capita water demand for various housing and land use categories in urban and peri-urban areas (Table 14).

Table 14 Per capita demand estimates for Lusaka urban and peri-urban areas (after KRI et al. 2008)

Housing Category	**Per capita demand [L/c/d]**	
	Zambia Standard for Water Supply System	JICA Study Team
Urban - High cost housing Housing	280	143
Urban - Medium Cost Housing	150	--
Urban - Low Cost Housing	100	60
Informal Cost Housing	40	20

The current industrial water use is estimated at 80 m^3/ha/d by the study team. The estimate is based on figures by the Zambia Standard for Water Supply System which assigns 30 m^3/ha/d to light industrial and 90 m^3/ha/d to heavy industrial areas.

Based on these unit water demand estimates the current (i.e. 2007) water demand could be approximated at about 218,000 m^3/d. The detailed calculation is as follows:

Domestic	85,100 m^3/d
Public	20,300 m^3/d
Commercial	4,700 m^3/d
Industrial	108,000 m^3/d
Total	218,100 m^3/d

This value is considerably lower than an earlier calculation by de Waele & Follesa (2003) who estimated domestic water demand at 360,000 m^3/d (based on a per capita consumption of 180 L/d/c and a population of 2 million), industrial use at 90,000 m^3/d and the total water demand at 450,000 m^3/d.

ANALYSIS

Surface water gauging stations were established at all major streams and rivers in the Lusaka area. Currently, six out of nine available stations are in operation. It is recommended that the measurements at Mwembeshi-4918, Chongwe-5024 and Kapiriombwa-5030 are resumed as soon as possible. For water balance calculations of the Lusaka Plateau additional discharge measurements at Chilongolo and Chunga Rivers are required. The calibration of existing weirs is overall out of date. Since only crude estimates of the discharge of springs are available their role in the water balance can not be determined accurately.

Mpamba et al. (2008) rightly state that there is a great need to establish the actual abstraction and water demand and to verify the correct recharge for aquifers on the Lusaka plateau.

A general weakness is not having exact values for the groundwater abstracted from private wells and from commercial farmers (Schmidt 2001). There is need to identify the abstraction from large irrigation schemes and major industrial water consumers.

While overall reliable information on average abstraction rates from public supply wells is available there is need to monitor groundwater abstraction from at least the major wells on a continuous (hourly or daily) basis.

The determination of reliable estimates for groundwater recharge is essential to quantify the volume of water that can be sustainably abstracted from the Lusaka aquifers. Unfortunately, existing estimates of recharge rates vary between below 10% to over 60% owing to the complexity of recharge processes, the heterogeneity of the rock formations and surface cover and the high temporal and spatial variability of rainfall. Results from previous studies suggest that average recharge rates may be in the order of 20% to 25% except for years with particularly low rainfall. Nevertheless, it is unlikely that recharge can simply be correlated with annual rainfall amounts.

Recharge estimates R based on the water table fluctuation method rely on precise estimates of specific yield S_y since according to equation [2], R and S_y are more or less proportionally linked to each other. It is however difficult to determine specific yield S_y, in particular in fractured and karstified rock. Since values of S_y for limestone may be in the range of 0.5% to 10% this method bears al lot of uncertainty. Furthermore, in fractured and karstified rock, there are often substantial differences in the responses of observation wells. During previous studies the rise in groundwater levels over the rainy season could only be determined from very few groundwater observation points due to the lack of availability of comprehensive hydrograph data. The results provided by Chenov (1978) and YEC (1995b) include large areas outside the Lusaka area that are not characteristic for the karstified and highly permeable aquifers of the Lusaka aquifers. These values are therefore only useful to this study for cross-checking purposes.

Recharge estimates based on the water balance equation neglect direct runoff. This postulation was justified by the absence of a surface drainage system on the karst plateau. This widely used assumption needs to be verified since springs may discharge considerable amounts of groundwater during the wet season. The accuracy of water balance calculations for river catchments in the Lusaka area will greatly rely on the availability of more precise estimates of groundwater abstractions and surface runoff.

Comparatively little is known on the dynamics of groundwater recharge, i.e. the seasonal variation of recharge and the relationship between rainfall duration and intensity and recharge. Similarly, there is very little information on how water moves and how it is stored in the aquifer. A point widely neglected so far is that a considerable amount of recharged groundwater may be drained very quickly, say within days or weeks, through large underground channels and karst springs. Hence, a portion of the recharged water may effectively be not available for water supply throughout the year. Recharge rates could therefore be misleading if not put into relation with mean residence times of groundwater for individual groundwater flow compartments.

It is considered very difficult to quantify water recharging the aquifers through grikes and dolines. It is equally challenging to assess the importance of indirect recharge by leakages from the public supply system.

TASKS

The seasonal variation of discharge at major springs must be measured or at least estimated. It is therefore proposed to install weirs at two to three selected springs. The status of existing runoff gauges at the Mwembeshi, Ngwerere and Chalimbana rivers needs to be checked. Attempts should be made to re-calibrate the gauges and to continuously measure discharge at the three perennial rivers over the project period.

All major groundwater abstraction points, including private wells need to be identified and their abstraction measured or at least estimated on a continuous (i.e. monthly) basis. Public wells operated by LWSC with abstraction rates exceeding ca. 3,000 m^3/d should preferably be monitored daily.

It is thought that groundwater abstractions from minor wells can be estimated with sufficient accuracy using up to date maps of land use distribution and unit water demand approximations. This approach could be used to estimate overall abstractions from areas with mainly rural and domestic water supply, from high and low cost housing areas, or from commercial/industrial areas without water-intensive industries. The accuracy of the approximations could possibly be verified by questionnaire-based surveys in selected pilot areas.

Abstractions for commercial irrigation can be estimated by assuming that abstraction during dry periods should roughly equal reference crop water demands. The approach requires that sufficient information can be gathered on the size of irrigated areas, type of crops, irrigation practices and periods and the type of water source.

In order to improve the understanding of recharge processes and to ascertain the reliability of available recharge estimates it is proposed to carry out the following investigations:

1. **Determination of groundwater recharge by baseflow separation at river gauges and selected springs. In the Lusaka area, this method has its limitations due to the inconsistency of river gauging data, the uncertainty about the accuracy of discharge rating curves and the fact that surface flow becomes very small during the dry season. The impact of outflow from sewerage systems and possibly dams must also been taken into consideration carefully. For this purpose the discharge rating curves of rivers discharging the Lusaka Plateau (Mwembeshi, Chalimbana, Ngwerere) need to be checked and updated.**

2. **Integration of satellite imagery, GIS and the CROPWAT model to determine regional evapotranspiration and recharge. The CROPWAT method was developed as a decision support system by the Land and Water Development Division of FAO (Smith 1992). It includes computation of actual evapotranspiration according to the FAO Penman-Monteith method and of crop water requirements. The method can also be used to calculate groundwater recharge using a daily or monthly soil moisture balance of a single soil water store. The soil moisture balance approach to calculate recharge is based on rainfall, evapotranspiration, runoff and the nature of the soil for the growth of crops. If necessary, methods using a more complex soil water store model could be applied.**

3. **Detailed analysis of groundwater and spring hydrographs to assess the mechanisms controlling recharge, i.e. rainfall intensity, duration, cumulative rainfall amounts as well as the characteristics of the soil and vadose zone and epikarst. The analysis can also be used to determine hydraulic properties of the aquifer from spring recession hydrographs based on the equation:**

$$[6] \quad Q(t) = Q_0 \, e^{\alpha(t-t_0)}$$

Where α is the recession coefficient, Q_0 is the discharge of a spring at time t_0 and $Q(t)$ is the discharge at a given time $t - t_0$.

4. **Recharge estimates obtained by applying above methods can be cross-checked by hydrogeological modelling (sensitivity analysis, see Chapter 6.4)**

5. **Infiltration tests (double-ring infiltromter) can be applied in order to determine infiltration capacity of various soil types.**

6. **Isotope studies could be useful for groundwater dating purposes or to analyse rainfall-groundwater-discharge processes. The possible value of isotope studies will be further looked in to.**

6 Aquifers and Aquifer Potential

6.1 Karst

The Lusaka Dolomite Fm is known as a terrain undergoing recent and active karstification processes that hosts abundant groundwater resources (Lambert 1962, von Hoyer 1978 & 1980, Nkhuwa 1996, de Waele & Follesa 2003). On its surface, an **epikarstic zone** has developed with an average depth of 5 m (Lambert 1962) extending to a maximum depth of 25 m below the surface (Nyambe & Maseka 2000, de Waele & Follesa 2003). Epikarst, also referred to as subcutaneous zone, is a horizon at the top of the vadose zone of a karst aquifer characterised by enhanced storage capacity and high porosity and permeability as a result of enhanced weathering (dissolution) near the ground surface. The nature of the epikarst hence strongly influences the distribution and amount of groundwater recharge.

Surface features include pinnacle karst (*karrenfelder*) consisting of residual pillar extending to a depth of 4 m to 7.5 m and hollows or solution flutes filled with pisolitic laterite (residuals) or more rarely soil, grikes developed by solution along a joint plane, and karst clefts. Sinkholes are very frequent ranging in diameter from a few to 100 meters and in depth from one to 10 meters. Karstic depressions with diameters of several hundred meters are also present (Figure 15).

The karst clefts and sinkholes commonly form natural wells. The water table is also visible in several quarries (Figure 16). The laterite may impound a seasonal perched water table although the bed rock is often exposed in the City area by removal of the protective laterite cover in the process of small scale mining.

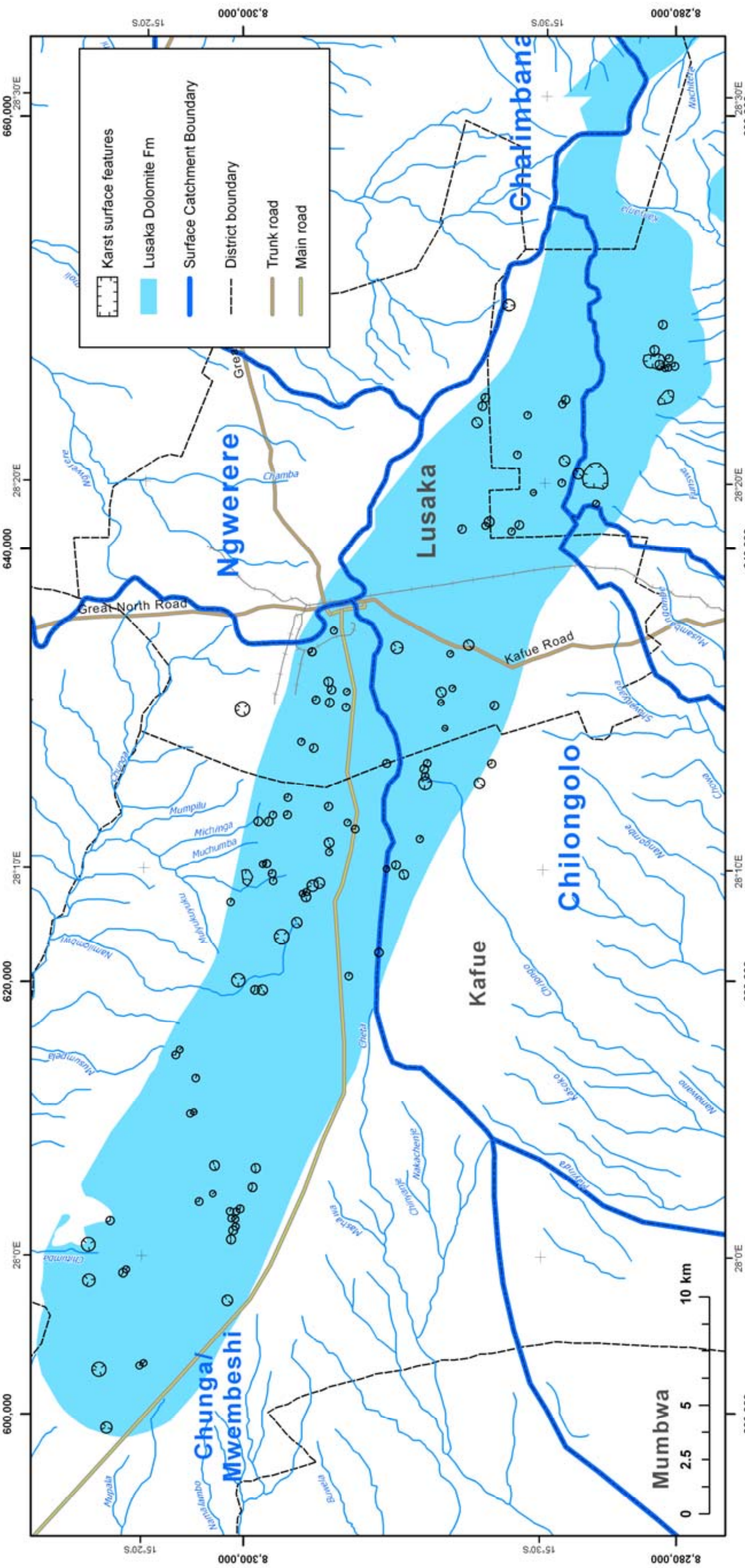


Figure 15 Distribution of Karst surface features detected by aerial photography in the Lusaka Dolomite Fm (after von Hoyer et al. 1978)

Figure 16 Quarry with exposed groundwater table south of Lusaka Chilenje Compound

Nkhuwa (1996) examined the composition and distribution of the Lusaka (meta-) carbonate rocks based on mapping and data by Drysdall (1964), Newman & Matheson (1966) and Barr (1968, 1970) for the City and Forest Reserve areas. He found that 40% are pure marbles (>90% calcite/aragonite) and 20% are pure dolomite (>90% $CaMg(CO_3)_2$) and the remainder are mixtures between the two. Pure dolomite is usually coarser grained. He found that sinkholes are most abundant in areas of calcitic dolomite with calcite content between 70% and 90%, or, locally in the southeast of the mapped area, between 50 – 70%. Areas with fewer sinkholes are associated with pure dolomite which he explained by their coarse-grained texture. Varieties with less than 30% calcite/aragonite form little surface karst. Pure dolomites therefore form bodies of low permeability within the aquifer (von Hoyer et al. 1980).

Solution cavities were reported up to depths of about 150 m although the majority of cavities were found at depths above about 40 m. Lambert (1962) describes cavities in boreholes of 15 cm to 1 m in height, with rare occasions of 2 m to 3 m, but most of the cavities are smaller. The majority of cavities were encountered at depths from 24 m to 36 m. Very little cavitation was found at depths below 45 m in boreholes up to 70 m deep which was interpreted as a product of Pleistocene interpluvials. He suggested that other horizons of late Karoo age could possibly exist at greater depth.

Jones (1971) estimated the vertical porosity distribution based on borehole logs, pumping test results and hydrographs near the “Old Pumping Station”. He concluded that the “maximum” porosity occurs above 18 m depth while “moderate” porosity is found between 18 m to 30m, and that porosity decreases from 30 m to the presumed aquifer base at 60 m. According to von Hoyer (1978) comprehensive analysis of drilling records revealed the following vertical porosity and permeability distribution: “high” from 0 to 25 m, which was described as the zone of maximum circulation, “moderate” from 25 m to 50 m, and “low” and “gradually decreasing to zero” between 50 m to 85 m depth which was consequently defined as the aquifer base at the time

(Figure 17). Laterite fillings in the cavities were encountered even in the deeper sections suggesting hydraulic connections to higher aquifer zones. Based on more recent and deeper drilling records Nyambe & Maseka (2000) identified cavities at 65 m to 80 m and 125 m to 150 m and consider a depth of 150 m as a likely aquifer base. Nkhuwa (1996) assumes that in the geological past, as a consequence of the uplifting of the Lusaka plateau, higher hydraulic gradients with a drainage base level probably situated in the Chongwe and Kafue valleys should have created conditions of accelerated vertical karstification with possible depths of karstification in excess of 350m. He admits, however, that interconnectivity of fractures at such depths could be very poor.

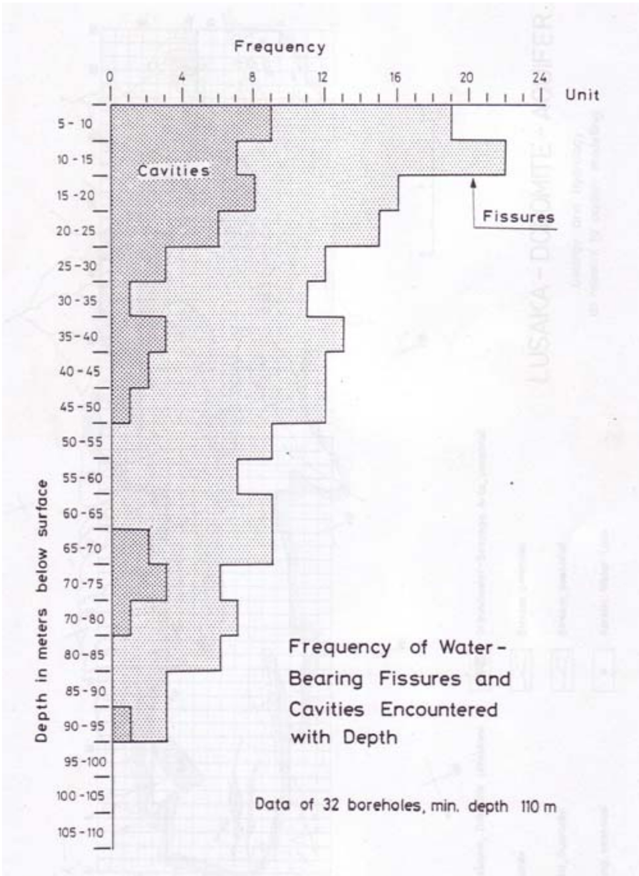


Figure 17 Frequency of water-bearing fissures and cavities encountered with depth after von Hoyer et al. 1978.

A specific feature is the occurrence of fault and collapse **breccias** which were described as up to 400 m long and 5 m to 150 m wide elongated features with their longer axis parallel to the NW-SE strike of the formation. Five occurrences were discovered by von Hoyer et al. (1978) additional to seven collapse breccias originally described by Lambert (1962). The collapse breccias contain calcite, siderite or mud infillings of different ages, with fragments of dolomite and limestone up to the size of blocks, and are thought to represent the rubble fillings of solution cavities of a reactivated palaeokarst system (von Hoyer et al. 1978) or abandoned Pleistocene watercourses (Lambert 1962). Today, some of the collapse breccias represent areas of high permeability due to extensive cavitation and preferential flow paths.

Only few **caves** have been reported, none of which are located in the vicinity of the City (Kaiser et al. 1998, de Waele & Follesa 2003). Of specific interest is Chipongwe cave located 30 km south of the capital as it hosts a subterranean lake corresponding to the local karst aquifer base.

Apart from the mineral distribution and purity of the carbonates, the degree of karstification is controlled by structural properties of the rock formations and the presence and distribution of discontinuities. Von Hoyer et al. (1978) could demonstrate a correlation between zones of high lineament density recognizable on satellite images and the location of karst surface features. Solution cavities are often developed along the planes of tectonical banding, with near-vertical bands promoting the formation of solution cavities from the land surface into greater depths. Folding structures in contrast have apparently only a small influence on overall karstification (Keller & von Hoyer 1992).

According to Nkhuwa (1996) existing karst features in Lusaka have developed preferentially along structures and features of tectonic deformation, e.g. shear zones. Therefore, flowpaths orientated to the SE-NW and NE-SW should predominate. Fracture zones should be concentrated along anticlinal crests which may form zones of good recharge, and synclinal troughs which possibly are areas of converging groundwater flow. He expects good permeability being attributed to faults, factures and major relief forms, especially within prominent NW-SE trending breccia zones. The area covering the Leopards Hill road, Shaft 5, Mumbwa Road and the Old Pump Station probably represents such an area with highly intersected fractures that are “solutionally” enlarged.

6.2 Aquifer Characteristics and Potential

6.2.1 Hydraulic Characteristics of Aquifers

The first comprehensive attempt to classify Lusaka’s aquifers was by Lambert (1962) who grouped aquifers according to the availability of water into the categories “excellent”, “very good”, “good”, “fair”, “poor”, and “very poor”. He also considered the probable success of a borehole site. The aquifers were rated as follows:

1. The Lusaka Dolomite Fm was rated as “excellent” as a yield of >1.3 L/s could be obtained from almost every borehole.
2. Scapolite limestone and dolomites of the Cheta Fm were rated as “poor” with typical yields of >1 L/s, but a lower probability (1:2 to 1:4) to drill boreholes that yield adequate quantities of water.

3. Quartz-muscovite schists and phyllites (Cheta and Chunga formations) were rated as “fair” where they are highly weathered as usually in the top 30 meters, but “very poor” if they are fresh. The probable success rate to strike an adequate water supply is given as 1:2 to 1:3. Calc-biotite and chlorite schists are generally considered very poor aquifers. Successful boreholes typically produce between 0.5 and 1 L/s.
4. Massive quartzites were rated as “very poor”, whilst flaggy micaceous quartzites may yield between 0.6 and 4 L/s. Yields from boreholes drilled in quartz veins are very variable with maxima of about 4 L/s.
5. Granite and gneiss are rated as “poor” with typical yields well below 1 L/s. Yields, however, proved highly variable depending on the degree and depth of the decomposition zone

GIBB Ltd. (1999c) proposed a simplified aquifer classification system. They distinguished the following three types:

1) Shallow (perched) aquifers
2) Aquifers of the Chunga and Cheta Formations
3) Lusaka Dolomite Formation aquifer

Chenov (1978) described the Katanga (Upper Roan) limestones and dolomites as “highly productive aquifer” with yields varying between 1 and 70 L/s. The Katanga (Lower Roan) quartz-muscovite schists and quartzites host “locally productive aquifers” with yields varying from 0.1 L/s to 10 L/s. Hydraulic data from 96 wells and boreholes from this study could be incorporated in the groundwater database. The values for specific capacity *q*, transmissivity *T*, hydraulic conductivity *K* and specific yield S_y were obtained from predominantly single well pumping tests. Table 1 summarises averages and the more meaningful median of these hydraulic parameters from the available data by Chenov.

Table 15 Hydraulic parameters of wells or boreholes in Lusaka Province after borehole database by Chenov (1978)

Aquifer	*n*		*q* [L/s/m]	*T* [m²/d]	*K* [m/d]	S_y [-]
Dolomite/ Limestone	40	Average:	6.4	616	15	0.11
		Median:	1.9	188	4.5	0.12
Schist / Quartzite	56	Average:	2.3	231	6	0.08
		Median:	0.07	6.9	0.12	0.07

Nkhuwa (1996) re-analysed the pumping tests results provided by Chenov from these 96 boreholes and found the following (empirical) near-linear relationship between the transmissivity *T* and specific capacity *q*:

$$[7] \quad T\,[m^2/d] \approx 1.175 \cdot 86.4 \cdot q\,[L/s/m]$$

Von Hoyer et al. (1978) analysed data of pumping tests from archives of the Department of Water Affairs. The specific capacity was calculated for 78 boreholes in schist and 102 boreholes in dolomite. Frequency distribution graphs are displayed in Figure 18. It can be seen that for 41% of the examined boreholes, the specific capacity ranges from 0.03 to 0.08 L/s/m, and for 91% specific capacity is between 0.01 to 0.8 L/s/m. For the Lusaka Dolomite Fm, 88% of all boreholes have a specific capacity between 0.8 and 30 L/s/m. The results reasonably match with the analysis given by Chenov described above. It must be considered, however, that in both studies unsuccessful ("dry") boreholes are not reflected in these statistics.

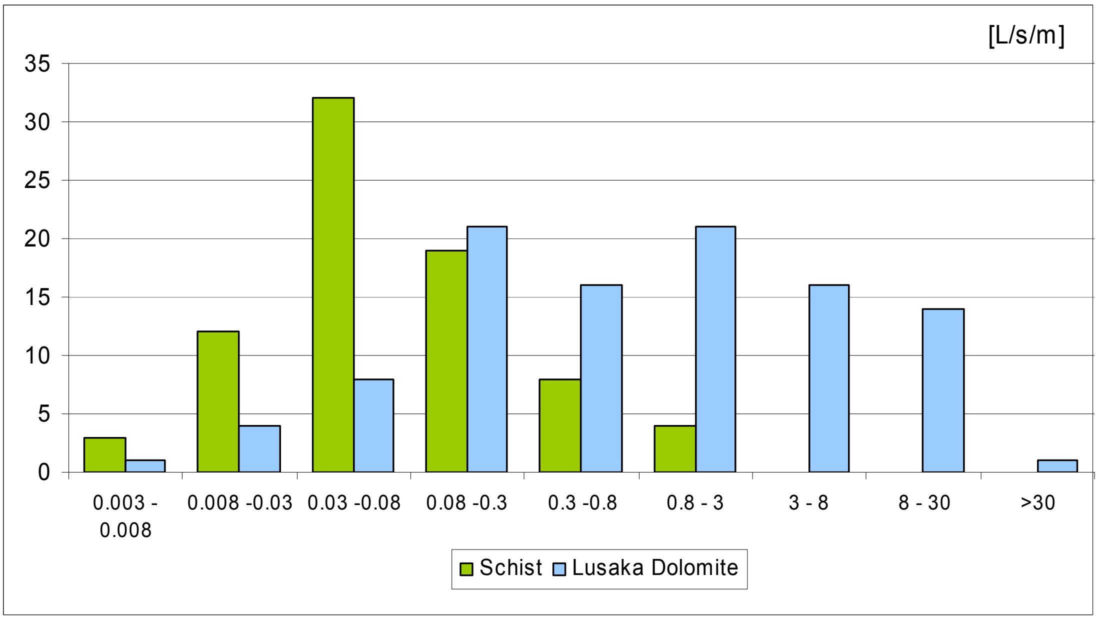


Figure 18 Frequency distribution of specific capacity for 78 boreholes drilled in schist and 102 boreholes in the Lusaka Dolomite Fm (after data by von Hoyer et al. 1978)

Von Hoyer et al. (1978) identified areas with higher and lower permeability within the Lusaka Dolomite Fm. Very high permeability for instance supposedly exist in the Westwood area (near the south-western boundary of the formation) creating good drainage into the schists and subsequently deep water levels. Areas with comparatively low permeability exist in the in far western parts, possibly due to a great number of schist enclosures, and in areas west of Zingalume, Kanyama and within the Namilombwi stream catchment due to specific lithology differences such as the occurrence of massive dolomite bodies.

The limestones of the Cheta Fm do not show the same degree of karstification, and hence their groundwater potential is much lower. As stated by KRI et al. (2008a) the carbonate rocks in so-called "satellite supply areas" that are to a large extent located within the Cheta Fm indeed did not yield the high rates as predicted.

Mpamba (2008) identified four areas with presumably high and currently not fully utilised exploitation potential within the Lusaka aquifer systems. These are the Ibex Hill/State Lodge area in the east, Chamba Valley/Ngwerele area in the north-east, the

Lilayi/Buckley area in the south and the Chaisa/Garden/Kalundu area in the more central parts of the City.

In the framework of the National Water Resources Master Plan (YEC 1995) countrywide borehole data was grouped according to main lithological classes and statistical hydraulic data was prepared for each class. Average yield and specific capacities and the range and median values of hydraulic conductivity and specific yield for limestone/dolomite and schist were provided as presented in Table 16. It is likely that the database incorporates many records from the previous Groundwater Resources Inventory Report by Chenov. Nevertheless, the results for specific capacity, permeability and specific yield on national level are considerably smaller compared to values for Lusaka provided in the Chenov report (Table 15).

Table 16 Hydraulic characteristics of boreholes (countrywide) according to the Study on the National Water Resources Master Plan (YEC 1995b). Top table: results from hydraulic test records; bottom table: results of pumping test analysis

Lithology	*n*	Average Yield of pumping test *Q* (L/s)	Average Specific Capacity *q* (L/s/m)
Limestone & Dolomite	1,267	4.7	0.58
Schist	1,160	1.5	0.049

Lithology	*n*	Hydraulic Conductivity *K* (m/d)		Specific Yield S_y	
		Median	Range	Median	Range
Limestone & Dolomite	57	0.10	0.00040 – 97.5	0.030	$7.8\ 10^{-8}$ – 0.26
Schist	80	0.13	0.0062 – 14.2	0.030	$7.0\ 10^{-7}$ – 0.25

n = sample number

Like Nkhuwa (see equation [7] above), the study team furthermore established a similar approximate relationship between transmissivity *T* and specific capacity *q*:

[8] $T\ [m^2/d] \approx 86.4 \cdot q\ [L/s/m]$,

i.e. *T* roughly equals *q* if expressed in the same units.

The hydraulic conductivity for each borehole was then calculated by dividing the value of T by the aquifer thickness determined as the difference between total borehole depth and static water level from ground surface.

Based on these records and calculations, the following hydraulic values were considered representative and applied to water resources assessments for limestone/dolomite and schist in Zambia:

	Limestone/ Dolomite	Schist
q (L/s/m)	0.58	0.049
K (m/d)	1.3	0.11
T (m^2/d)	50.2	4.2
S_y	0.05	0.03

It is worth noting that the representative hydraulic conductivity determined for limestone/dolomite is about 10 times smaller than the median value obtained from analysis of 57 pumping tests (Table 16, bottom).

For the Lusaka Dolomite Fm, YEC (1995b) provide the following averages:

Thickness (m)	20.8
Yield at pumping tests *Q* (L/s)	12.5
q (L/s/m)	0.28
K (m/d)	8.0
T (m^2/d)	39
S_y	0.068

Unfortunately, the number of boreholes used in this analysis is not stated in the report. Strikingly, specific capacity is only about 4%, and hydraulic conductivity specific yield are about half of the respective value provided by Chenov.

6.2.2 Sustainable Yields

Very few attempts were made to establish the sustainable yield of the Lusaka aquifers. YEC (1995b) estimated the groundwater development potential of Cheta Limestone north of Lusaka based on a crude recharge estimate for the area. Using a (rather conservative) recharge rate of 8% and a MAR of 840 mm the recharge is 14.1 Mm^3/a for the 210 km^2 large area under consideration. Applying the same approximation to the Lusaka Dolomite Fm (580 km^2), groundwater recharge amounts to 39 Mm^3/a. As a comparison, the volume of water stored in the Lusaka Dolomite Fm was estimated by Mpamba (2008) at 598 Mm^3/a considering an aquifer area of 450 km^2, and assuming an average aquifer thickness of 50 m and specific yield of 2.5%.

Based on groundwater recharge estimates and results from hydrogeological modelling, von Hoyer & Schmidt (1980) concluded that under average rainfall conditions (about 820 mm/a), a total of 46 Mm^3/a could safely be abstracted from the Lusaka Dolomite aquifer. Pumping rates could probably be maintained over individual dryer years despite a considerable decrease in direct recharge by pumping from storage. The abstraction by public water supply wells alone from the aquifers investigated by von

Hoyer et al. today is already about 34 Mm^3/a while total abstraction for public water supply is currently 45.6 Mm^3/a (Chapter 5.5.1).

6.3 Groundwater Circulation

It is generally understood that the karst water is under free (phreatic) water table conditions (von Hoyer et al. 1978). The water table is generally shallow and groundwater surface follows the topography of the land surface.

Groundwater flow directions can be established from existing groundwater contour maps by von Hoyer et al. (1978), GIBB Ltd. (1999c) and Mpamba (2008). The maps by von Hoyer et al. show groundwater level contours as well as depth-to-water table and the seasonal water table rise for the City and the Lusaka Forest areas in the southeast for three distinct seasonal scenarios during the years 1976 to 1978. Mpamba (2008) prepared more generalised contour maps covering about the same area using piezometric levels of the 2004 dry season and the 2004/2005 rainy season. These maps were subsequently published by Mpamba et al. (2008a, 2008b).

Groundwater levels documented by GIBB Ltd. (1999c) that were taken at about individual 180 water points between the end of June and August 1998 were used to reproduce a groundwater contour map for this period. The campaign covered only the western portion of the Lusaka Dolomite aquifer from Lusaka West to the Mwembeshi areas. The reproduced map is shown in Figure 19 together with the water level scenario for the dry season 1977 prepared by von Hoyer et al.

A recent groundwater contour plan was prepared during this study which is shown in the conceptual hydrogeological map in APPENDIX 2. Unlike previous maps the contours extend over the whole area underlain by the Lusaka aquifer systems except for the area covered by Cheta limestones in Chibombo District to the northwest. The map is based on groundwater level measurements taken at 126 points throughout the area during November 2008 including dynamic water level data from October 2008 provided by the LWSC.

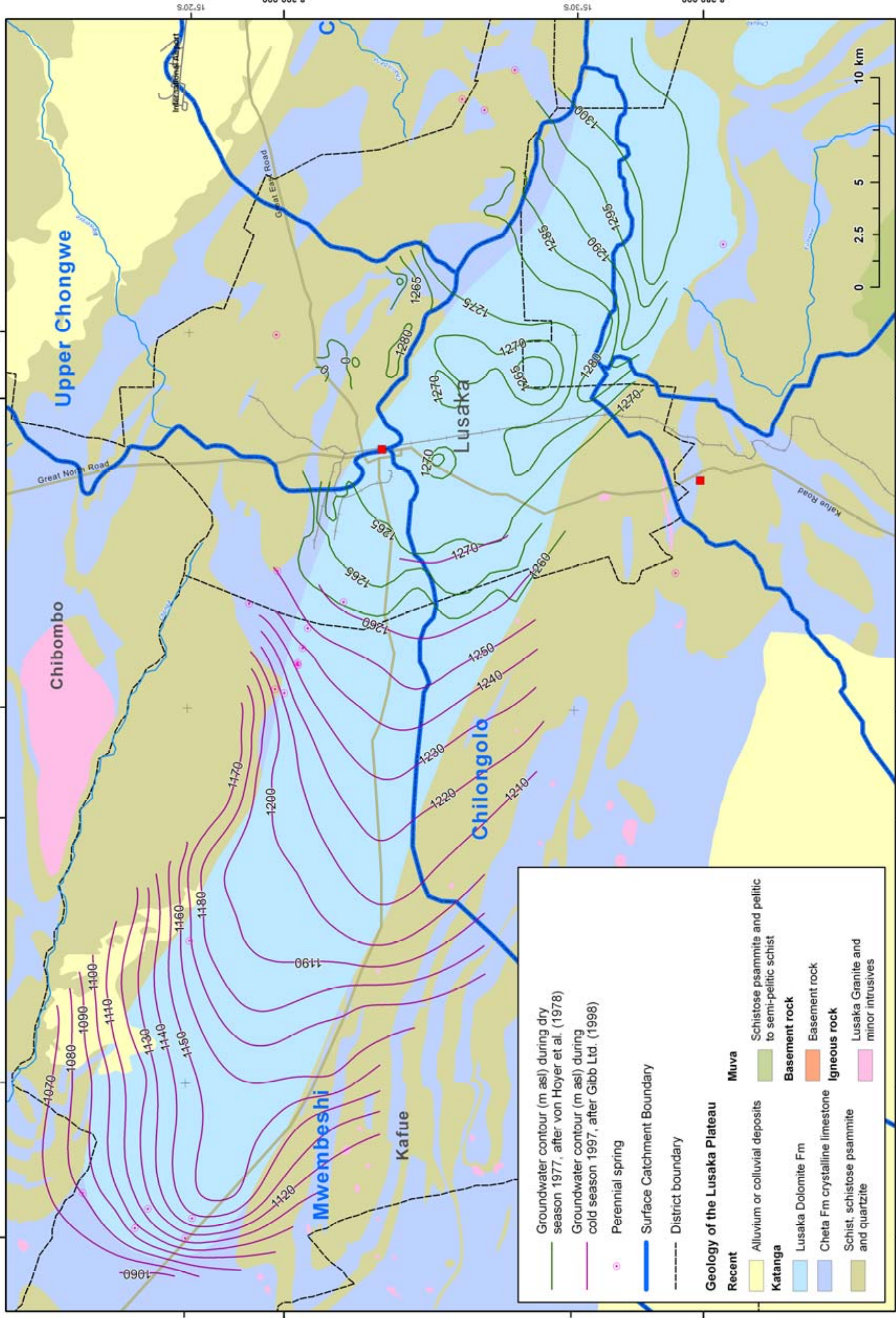


Figure 19 Groundwater contour maps for Lusaka & Lusaka Forest during the dry season 1977 after von Hoyer et al. (1978), and for the Lusaka West/Mwembeshi areas reconstructed from water level measurements taken by GIBB Ltd. (1999c) between June-August 1998.

Similar to the surface water pattern, a groundwater flow divide crosscutting the Lusaka Forest areas can be determined. South of this divide groundwater flows in south- to south-easterly directions towards the Shantumbu area (Funswe River Catchment) whereas to the north the general flow direction is to the northwest with the less pervious schists forming the base level. A second groundwater flow divide is developed along the axis of the dolomite body. The exact position of the divides, however, is difficult to establish due to limited number of observation points. In addition, it may be time-variable depending on the seasonal distribution of recharge and variable abstraction scenarios. Groundwater discharge occurs along certain sections of the schist -dolomite contact in the form of natural springs and seepage areas. Higher elevated schist bodies and quartzite ridges (e.g. Matero, Ridgeway, Woodlands, Ibex Hill) within the carbonate rocks are drained towards the surrounding karst aquifers.

The observed steep dipping set of cross joints with strike directions perpendicular to main fold axes could possibly facilitate a secondary preferential groundwater flow direction in SE-NE direction within the Lusaka Dolomite aquifer. In the eastern parts of town (i.e. the Leopard Hill and Bauleni areas), for example, the contours indicate a groundwater flow to the northeast. The Chalimbana River and tributaries to the Ngwerere River clearly act as drains through areas underlain by the less permeable schists.

Within the City area, groundwater flow is considerably influenced by the cone of depressions created by public wells. Observed drawdowns, however, are usually less than 10 meters owing to the high permeability of the karst aquifer around the major production wells.

In the western portion groundwater generally follows the main north-westerly direction towards Mwembeshi. Along this flow path, groundwater apparently branches out towards a major groundwater discharge zone located along dolomite/schist boundaries to the north (Chunga tributaries) and towards the southeast (Cheta stream and tributaries). Within the metasediments of the Cheta Fm in the southeast no springs were found, and the water table is fairly deep. This indicates that underground water is well drained owing to the comparatively high permeability of these rocks.

6.4 Conceptual Hydrogeological Model

A conceptual hydrogeological model represents a simplification of the groundwater circulation in a more complex lithological and hydrogeological setting. Despite the simplifications it should adequately delineate the overall hydraulic characteristics and behaviour of an aquifer system. It should comprise the vertical and horizontal distribution of geohydraulic units, i.e. strata with similar lithological and hydraulic properties, distinguish major aquifers from aquitards and hydraulic (impermeable) boundaries, characterise recharge processes and surface - groundwater interactions, and identify major preferential flow paths created by the specific tectonic setting (e.g. faults).

Mpamba (2008) proposed a tentative conceptual hydrogeological model. He distinguishes three lithology classes (limestone, dolomite, schist) with average hydraulic conductivities *K* between 0.1 and 1.3 m/d and specific yield S_y between 2% and 5 %.

Von Hoyer et al. (1978) proposed a two-layer aquifer system for the Lusaka carbonate rocks with a highly permeable, shallow Upper Karst system extending to depths of approx. 50 m and the limestone/schist contact as the likely base drainage level, and a deeper, less permeable Lower Karst system (up to 85 m) with a lower drainage base. They suggest that the Chunga and Mwembeshi tributaries to the west could possibly act as discharge levels for cavities observed at depths below, say 65 m. A tentative water balance for the two-storey aquifer model covering the Lusaka Forest Reserve area (main recharge area) and two main abstraction areas in the City was presented by von Hoyer & Schmidt (1980). It was presumed that recharge *R* should equal groundwater abstractions *A* in the long-term. The water balance estimate for the Upper Karst system reveals a significant surplus of water ($R > A$) for the Forest Reserve and the eastern main abstraction area and a negative balance for the western abstraction area ($R < A$) (Figure 20). According to the authors, the significant differences could only be compensated by vertical flow components between Upper and Lower Karst system. This was seen as a strong confirmation of the vertical zoning within the aquifer. Based on more recent borehole data, Schmidt (2001) later revised the general aquifer base at being at 150 m bgs.

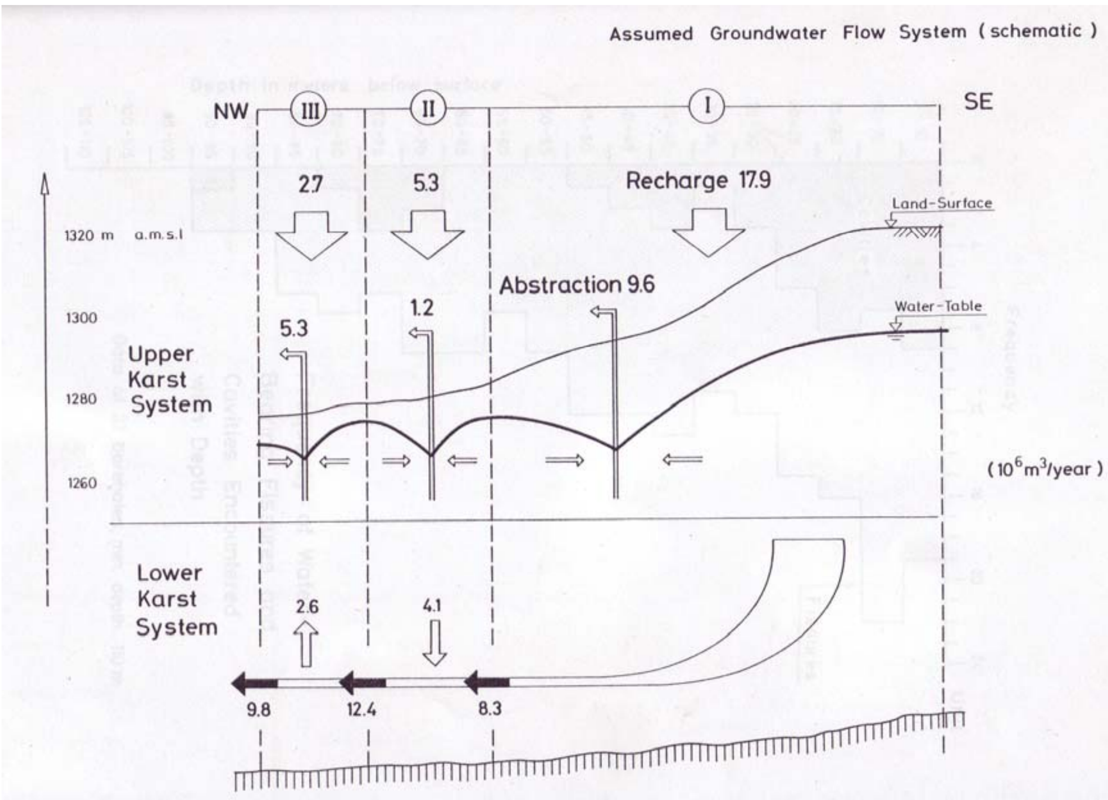


Figure 20 Tentative groundwater balance for the Lusaka well field area. The water table maximum to the right of the schematic profile corresponds to the groundwater divide developed in the Lusaka Forest areas (after von Hoyer & Schmidt 1980).

A two-dimensional horizontal groundwater model developed for the Lusaka Dolomite Fm (von Hoyer & Schmidt 1980) is based on a single-equivalent continuum approach. The rocks of the Lusaka Dolomite Fm together with the carbonate rocks of the Cheta Fm bordering to the north form an aquifer of uniform thickness according to this model while the schists adjacent to the carbonate rocks in the north and south are considered aquicludes forming no-flow (model) boundaries. Within the aquifer, areas with smaller permeability were identified as a result of the occurrence of intercalated schist and quartzite, and of areas with less karstification in impure limestones.

Characteristic values for transmissivity *T* and storage coefficient *S* that were obtained from the model calibrations are given in Table 17. It is worth noting that the transmissivities obtained from the model calibration largely exceed the values reported in the literature (see Chapter 6.2.1).

Table 17 Characteristic values of geohydraulic units within the carbonate rocks of Lusaka (after von Hoyer & Schmidt 1980)

Geohydraulic Unit	*T* [m^2/d]	*S* [-]
Carbonate rocks with intercalated schist & quartzite	1 - 240	$5 \cdot 10^{-4} – 1 \cdot 10^{-3}$
Dolomite	480	$1 \cdot 10^{-2}$
Limestone	840 - >1200	$1 \cdot 10^{-3} – 5 \cdot 10^{-2}$

From the specific statistical distribution of lineaments and their presumed impact on flow and flow directions it is likely that the Karst aquifers show an anisotropic behaviour with expected preferential flow directions in NW-SE and SW-NE orientations.

ANALYSIS

Substantial information was gathered in previous studies on the degree of surface and underground karstification, the hydraulic characteristics and distribution of the rock formations as well as the overall hydrogeological setting in the Lusaka area. While the karst aquifers possess, at least locally, high permeabilities, storage is limited due to the specific characteristics of carbonate rocks (little primary porosity).

Despite these findings, there are still major uncertainties regarding the nature and potential of the aquifer systems owing to the complex geological and tectonic setting and the heterogeneity of the fractured and karstified rock formations. Some of the major knowledge gaps could be identified as follows:

1. Lithological and structural properties and interconnectivity of fractures are controlling the degree of karstification, permeability and preferential flow directions within the carbonate rocks. The distribution and density of discontinuities, however, and their impact on groundwater circulation are not yet fully understood.

2. The maximum depth of the karst aquifer, currently assumed to be about 150 m bgs, and the corresponding drainage base for deep groundwater circulation could not be determined. Little is known of the extent, hydraulic characteristics and the potential of deeper karst zones with respect to water supply.
3. The regional groundwater flow pattern and interactions between schist and carbonate aquifers are not fully established as existing groundwater contour maps exclude portions of the Lusaka aquifer systems.
4. Comparatively little information is available on the Cheta limestones, especially in areas to the north (Chibombo District) and to the south of the Lusaka Dolomite Fm.
5. Hydraulic characteristics of individual rock formations are highly variable. Median values (rather than averages) may be regarded as representative for individual geohydraulic units within the aquifer system. The availability of hydraulic data from pumping tests, however, is too sparse in certain parts of the investigation area for a statistical determination of representative hydraulic values.
6. Reported values on the storage characteristics of rocks in the Lusaka area are largely derived from the analysis of single-well tests in inhomogeneous and anisotropic rock. The accuracy of these values therefore has to be questioned.
7. Large differences exist between the transmissivity obtained from pumping tests analysis and groundwater modelling.

TASKS

The distribution and orientation of lineaments should be analysed for the whole investigation area including areas underlain by Cheta limestones using remote sensing techniques (see Chapter 3). Areas should be identified in which the occurrence of surface features such as sinkholes and depressions correlates with zones of major discontinuities.

More detailed maps showing groundwater contours and depth to water table need to be developed for distinct seasonal periods (dry and wet season). The maps should cover the whole investigation area and be based on a higher density of observation points than existing ones, including where obtainable up-to-date dynamic water levels of major pumped wells. The contour maps should reflect, where applicable, the potential influence of lineaments.

All available hydraulic test data should be re-evaluated. Boreholes drilled during the proposed exploration drilling (Chapter 4) should be pump-tested. Preferably, piezometers should be drilled in the vicinity of exploration boreholes unless existing boreholes can be used as observation points during the pumping test. The exploration drilling could also provide local information on the hydraulic properties of deeper-lying (>100m) aquifer compartments.

Existing statistical analyses of hydraulic parameters should be updated by incorporating all recent hydraulic data.

The groundwater potential should be assessed for the Lusaka aquifers, including areas outside the Lusaka main well fields, based on the established analysis of hydraulic characteristics of the aquifers, and ascertained recharge and water balance evaluations. The regional distribution on aquifer potential should be incorporated into the hydrogeological maps of Lusaka and the surrounding areas.

It is proposed to incorporate all new findings in a revised conceptual hydrogeological model for the Lusaka aquifer system and to develop a numerical hydrogeological model. Besides historical data, continuous rainfall, groundwater level and spring discharge measurements monitored throughout the planned project period (2009/10 – 2011/12) can be used for model calibrations. The model can be utilized to re-assess the groundwater recharge and balance estimates. Sensitivity analyses can be carried out and evaluated in order to determine the level of confidence in the assumptions made in the conceptual model. Groundwater modelling can also be applied to validate groundwater management decisions.

7 Groundwater chemistry and quality

7.1 Overall Groundwater Chemistry

Based on analyses of approximately 80 water samples taken between August 1977 and July 1978, von Hoyer et al. (1978) characterised the overall chemical composition of groundwater hosted by limestone/dolomite and schist. A review of these results was presented by Schmidt (2001). Their findings could be largely confirmed by recent groundwater sampling carried out in this Project (Museteka & Bäumle 2009). About 25 springs and the raw water at 32 public supply wells were tested during this campaign.

Two main water types could be found in correspondence with the geology (Figure 21).

As to be expected, groundwater in limestones and dolomites corresponds to the Ca-Mg-HCO_3 type. The water is generally hard (>250 mg/L $CaCO_3$) to very hard (>375 mg/L $CaCO_3$). The non-carbonate (permanent) hardness is very low. Calcium and magnesium values are typically in the range of 70 -130 mg/L and 15 - 50 mg/L, respectively, and bicarbonate concentrations usually vary between 300 and 450 mg/L. Calculated ratios of $Mg^{2+}/(Mg^{2+} + Ca^{2+})$ varies between 1:2 indicative of pure dolomite to 1:6 indicating the dominance of calcite.

(Na, K, Ca, Mg)-HCO_3 water prevails in groundwater hosted by or originating from schists. It can be distinguished from water in carbonate rocks by overall lower TDS, slightly lower pH, and lower HCO_3:SiO_2 ratios as well as much lower hardness and alkalinity (i.e. buffering capacity).

After interpreting chemical analyses results from sites that are considered largely unaffected by human activities and urban pollution sources such as the Local Forest Reserve, Chalimbana springs and Mwembeshi areas, Museteka and Bäumle (2008) concluded that natural (unpolluted) groundwater from the karst aquifers should, with only local exceptions, have an electrical conductivity (EC) of less than 800 μS/cm and concentrations in sodium, chloride, nitrate and sulphate below 10 mg/L. Higher levels in these parameters could consequently suggest the presence of urban pollution sources.

Comparison of water chemistry between the two data sets from the 1970s and the 2008 sampling showed no significant or systematic differences. Hence, no indication was found that the quality of groundwater has worsened or improved over time.

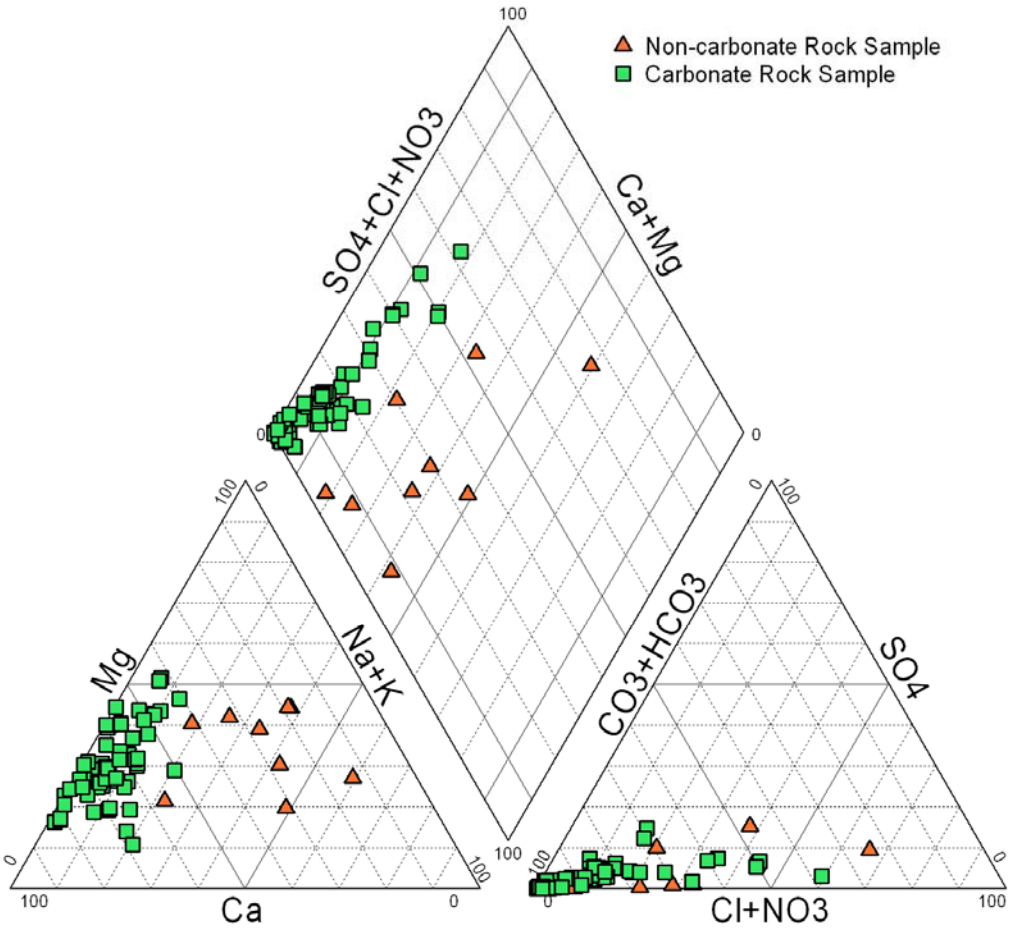


Figure 21 Piper diagram showing the main water chemistry types of groundwater in Lusaka (after Museteka & Bäumle 2009)

Furthermore, no evidence of seasonal changes in water chemistry and quality could be recognized in both studies. Von Hoyer et al., however, detected a relationship between total mineral content and depth to water table suggesting that the solution capacity of percolating water increases with the length of contact with air (enriched with CO_2) in the soil.

Other groundwater sampling campaigns which included all major and most of the minor constituents to determine groundwater types were carried out by Kampeshi (2003), Mpamba (2008) and Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008). The studies made largely use of local water laboratories. Kampeshi (2003) sampled over 150 water samples in areas with suspected groundwater contamination. Mpamba analysed major ion composition, Sodium Absorption Ratio (SAR) and Magnesium Hazard of 48 water samples. Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008) determined major ion composition together with oxygen demand, coliforms and selected metals for 28 groundwater samples. Unfortunately, the error in the ion balance of the majority of these samples was above ±10% indicating critical analytical errors. A conspicuous large number of samples showed unusual high levels of alkali elements (Na>40mg/L, K>10 mg/L) while others showed relatively low bicarbonate contents (<250 mg/L in carbonate rocks) together with a high positive error in the ion balance.

De Waele & Follesa (2003) published analyses from six wells but without specifying the sampling locations.

7.2 Groundwater Pollution

Groundwater pollution through urban pollution sources has been made responsible by numerous investigators for increased EC and contents in total dissolved solids (TDS), elevated contents in sodium, sulphate and chloride, high concentrations of nitrate and the presence of other nutrients, and widespread microbiological contamination.

Von Hoyer et al. (1978) detected higher contents in chloride, sulphate, and phosphate in light industrial areas. High nitrate contents exceeding the recommended standard of 10 mg/L NO_3-N (equalling 44.3 mg/L NO3) were found in low-cost housing areas during the rainy season, sometimes accompanied by high sulphate and chloride values. The distribution of nitrate, sulphate and chloride for two different seasons was presented in maps. Increased contents of pollutants were explained by leaching effect of the rains on surfaces of sewage and waste and locally, flooded pit latrines.

Nkhuwa (1996) examined about 90 water samples taken between 1987 and 1992 from producing boreholes and hand-dug wells. The investigation area covered Lumumba Road, Chawama, Showgrounds, Chunga, George Compound, Mass Media and Malo Farm. Nitrate values of up to 75 mg/L were reported and elevated TDS (>500 mg/L) and EC (>1000 μS/cm) were found locally.

Nyambe & Maseka (2000) reported EC-values of 1000 to 1400 μS/cm coupled with nitrate levels from 70 to 180 mg/L from some suburbs.

In the framework of the Lusaka contamination assessment project (Kampeshi 2003), over 150 water samples were taken in areas with suspected groundwater contamination. The wells include the LWSC public boreholes, commercial water bottlers, golf courses, Agriflora in Avondale and unsewered settlements. Special attention was given to the areas Leopards Hill cemetery, Libala Tipping Site and Lusaka Industrial area. The samples were analysed by the Environmental Engineering and *Alfred H Knight* laboratories. The parameters include main constituents of groundwater, nutrients (ammonia, phosphate) heavy metals and cyanide. Samples at Libala Tipping Site were also partially tested for DDT, the herbicide atrazine, the insecticide malathion and oil and grease, but no details of sampling procedures, analysis method and the laboratory used were given.

The study proved that microbiological (including faecal) contamination and pollution is widespread throughout the City area. High dissolved salt contents associated with EC values from 700 - >1000 μS/cm and elevated levels of sodium and chloride, as well as pollution by nutrients (nitrate, minor: ammonia and phosphates) are also a commonly observed phenomenon. Locally high values of lead were measured, but the author stresses that further investigations are needed to confirm this finding due to potential analytical errors.

De Waele et al. (2004) analysed groundwater from six unnamed wells in the Lusaka area during 2001 and found EC values ranging from 340 to 850 μS/cm, nitrate concentrations between 66 and 177 mg/L, and traces of ammonia in two wells (0.3 mg/L and 0.6 mg/L). In three out of the six wells, concentrations of mercury exceed the WHO guideline of 1 μg/L according to this study. The highest mercury concentration found amounted to 13 μg/L.

Repeated groundwater sampling campaigns conducted in the John Laing and Misisi areas (Nkhuwa 2006) during mid-November 2003, March 2004, and October 2004 showed that faecal contamination is widespread during the rainy season when contaminants are flushed into the groundwater system. High mineral contents (EC>1000 μS/cm) together with high contents in nitrate (20 – 40 mg/L) and chloride (>100 mg/L) were also observed especially during the dry season of October 2004.

Mpamba (2008) found values exceeding permissible limits for iron (>1 mg/L) in 10 out of 48, manganese (>0.3 mg/L) in 5 out of 48 and nitrate (>44.3 mg/L) in 6 out of 48 sampling points. He also reports on magnesium hazard above recommended levels (<50) in 28 out of 48 samples, mainly from boreholes within the schist.

Comprehensive sampling of springs and groundwater from public wells during 2008 (Museteka & Bäumle 2009) showed that groundwater pollution from human activities is apparent in higher levels of EC reaching 1450 μS/cm, sodium contents up to 138 mg/L, chloride levels up to 123 mg/L, and sulphate concentrations up to 172 mg/L. Whilst these values still comply with the Zambian Drinking Water Standard, nitrate levels frequently exceeded the permissible values of 44 mg/L NO_3. Particularly high nitrate concentrations above 100 mg/L were found in largely unplanned residential areas such as Chawama, Zingalume and Bauleni that are exclusively served by pit latrines and septic tanks. The high nitrate loads are therefore thought to be caused by the overall poor sanitary situation in these areas. The highest value was measured at Chainda well with 336 mg/L. Contrary to some of the earlier findings concentrations of heavy metals and iron were low throughout the campaign. This was explained by the overall low solubility of the metal compounds such as siderite ($FeCO_3$) at the prevailing high pH and the abundance of bicarbonate ions. The study furthermore confirmed that microbiological contamination is also prevalent. Mercury, however, was excluded from the analysis, due to the restriction in shipping samples containing the chemical reagent potassium dichromate required for sample preservation.

7.3 Groundwater Pollution Sources

The inappropriate disposal of **sewage** has been identified as one of the main sources of pollution for Lusaka's groundwater (e.g. Nkhuwa 1996, Nyambe & Maseka 2000). Large portions of the high-density townships are only served with pit latrine systems (Chapter 7.4). These correspond to areas with mostly shallow groundwater table and a high risk of seasonal flooding. Open defecation seems to be also common. Septic tank systems are irregularly emptied of sludge from the settling chambers.

Industrial effluents form another pollution source. Unlined surface water drains are increasingly used to dispose industrial effluents. Waste water from car wash centres has also been identified as a problem. Unlined storage of potential groundwater pollutants, chemical spills and underground tanks constitute permanent threats to groundwater quality in particular in the heavy industrial area of Lusaka.

Domestic and industrial waste is poorly stored in the City and is likely to produce leachates that contaminate groundwater. The solid waste disposal is considered a problem by over 80% of the residents in peri-urban and low-cost areas (NWASCO/DTF, 2006). A particular problem in Lusaka is the widespread quarrying and mining activities for building industry (crushed stones and marble) since the protective cover is removed, and abandoned quarries are later often used as refuse dumps.

Commercial farms at the outskirts of Lusaka Urban apply nitrogen-rich **fertilizers** as well as **pesticides and herbicides** that if passing the unsaturated zone could contaminate groundwater.

To many investigators (Nkhuwa 2000, Kampeshi 2003, de Waele & Follesa 2003) the Libala Tipping Site is of specific concern with respect to groundwater protection. Although Libala was originally planned as a temporal (six months) waste disposal site for domestic waste, it was operated from 1994 to 2001 and collected all kinds of waste including industrial waste, medical waste, car batteries, organic matter and building rubble according to Kampeshi (2003). It also received soap stock effluents from the *Amanita Group of Companies*. The site was closed and the waste levelled and covered by soil, but never removed. The site is regarded a major source of pollution due to the fact that it is located over the recharge zone and within a distance of less than one kilometer of the LWSC boreholes to the north and east of the tipping site. According to de Waele & Follesa (2003) Lusaka's waste has been brought in a dump site close to the city of Kafue from 1999 onwards. Kampeshi (2003) discovered a brackish plume of pollutant with EC up to 3000 μS/cm containing high levels of ammonia (up to 10.6 mg/L) and nitrate (up to 82 mg/L), phosphate, sodium, chloride and various heavy metals. Near the Amanita effluent dumping spot, bicarbonate concentrations of over 2000 mg/L were measured.

A high pollution potential has been attributed to the Lusaka Industrial area (Nyambe & Maseka 2000, Kampeshi 2003) which occupies an area of about six square kilometres situated in the Lusaka Dolomite and Cheta Limestone formations. The industrial zone hosts various types of industries comprising transporters, petroleum wholesalers, tannery and leather manufacturers, grain millers, food processing and dairy companies, breweries and drink manufacturers, fertilizer, pesticide and herbicide suppliers and manufacturers, plastic product distributors as well as paint, chemicals and cleaning agent's manufacturers and dealers. As hotspots for potential pollution were identified the Zambia Co-operatives Federation (ZCF-CIDA) who stored pesticides in the open between 1973 and 1993 and the major petroleum industries concentrated between Mungwi and Buyantashi Road. According to Kampeshi (2003) high values of sodium, chloride, and sulphate were detected near the Zambian Breweries, possibly coming from effluents containing cleaning agents and on-site water treatment products. Higher levels of EC (>2000 μS/cm), nitrates, phosphorus, calcium and sulphates were observed in ZCF-CIDA boreholes. Oil and grease was found in wells near petroleum vendors. The highest observed EC (4280 μS/cm) and chromium (2 mg/L) recorded during the study was found near Zamleather. Apart from chromium, no heavy metals were detected.

A possible threat to groundwater quality also comes from cemeteries. Kampeshi (2003) therefore investigated the groundwater quality near the Leopards Hill Cemetery. The two square kilometres large area is build on (partially cavernous) Cheta limestone and Chunga schist. The decomposition of human corpses was given as a possible reason of increased levels of nutrients and salt, and also regarded a potential source of bacteria and viruses in groundwater. But due to the presence of other likely pollution sources such as seepage from sewer effluent from nearby residential areas it was not possible to unambiguously assess the pollution sources.

7.4 Sanitation and Sewerage

According to the Comprehensive Urban Development Plan for the City of Lusaka (KRI et al. 2008a) 35% of 1.2 million estimated inhabitants of Lusaka have access to a sewer system, and about 20% use septic tanks, while the remaining 45% rely on pit latrines to dispose of their sewage and waste water. The same source quotes the Living Conditions Monitoring Survey (2006) conducted by the Central Statistics Office according to which pit latrines are the major toilet facility (66%) followed by flushing (both individual and communal) toilets (28%). Nkhuwa (2000) estimates the percentage of people serviced by a sewer system at 25% whilst 20% rely on septic tanks and 55% on pit latrines. According to de Waele & Follesa (2003) 32% of inhabitants are connected to a sewer service, 43% use septic tanks while only 25% have pit latrines. Recent figures released by NWASCO (2007) show that the sanitation coverage by LWSC's sewer network defined as the ratio of urban population with access to adequate sanitation is only 9%.

The percentage of people without access to proper sanitation is particular high in high-density and low-cost areas. According to the AQUATIS database (NWASCO/DTF, 2006) 96% of households in low-cost areas and 88% in peri-urban areas have no access to any sanitation facility. In John Laing and Misisi compounds, disposal of excreta is mainly through pit latrines with minor systems of open defecation; Pour flush latrines and use of flushing toilets or septic tanks are rare (Nkhuwa 2006). Ground-level pit latrines are often constructed over sinkholes. The insufficient sanitation status in many areas together with inappropriate hygienic practices is considered the main cause for the spread of water-borne diseases.

An overview and assessment of the existing sewerage systems operated by the LWSC is given by KRI et al. (2008a) and Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008). Currently, there are four sewerage treatment facilities in the City: Four stabilization ponds (Ngwerere, Kaunda Square, Chelston and Matero), one trickling filtration plant at Chunga and one combined trickling filtration/stabilization pond system at Manchinchi/Garden. Manchinchi is the largest of the sewerage systems with a maximum capacity of 36,000 m^3/d. The coverage ratio of sewerage system managed by LWSC is about 35% of the City. Effluent water analysis showed that sewerage treatment facilities do not fully meet their water quality targets. The ponds work overall well as measured BOD_5 values are less than 20 mg/L at Ngwerere and Chelston and less than 50 mg/L at Manchinchi/Garden and Kaunda Square in 2006, but the pond's effective volume is largely reduced as sludge has apparently never been removed. The trickling filters at Manchinchi and Chunga, however, are not working well due to damage of some mechanical parts. Chunga receives mainly industrial waste water and observed BOD_5 values regularly exceeded 250 mg/L between 2006 and July 2008. With 66,850 m^3/d corresponding to only 31% of water supplied by LWSC, the sewerage system's total capacity is considered too small. In summary, the treatment was considered insufficient due to lack of equipment, aged facilities and insufficient maintenance.

The drainage system in the City mainly consists of unlined or lined ditches beside roads and locally of an underground drainage system (e.g. Central Business District). Treated sewage and rainwater are hence mainly discharged by gravity. The sewage trunks from the sewage plants and rainwater drains are discharging to the north into the Chunga River (Kanyama, Makeni, Industrial area, Matero, Barlaston areas) and the Ngwerere River (Chilenje, Libala, Kamwala, City Centre, Northmead, Garden) or to the north-east into the Chalimbana River (Ibex, Kabulonga, Kalikiliki, Avondale) (von Hoyer et al. 1978, KRI 2008a).

ANALYSIS

Based on plausibility checks the accuracy of many of the reported water analyses is considered questionable. Results from existing groundwater quality investigations nevertheless indicate a widespread pollution of the Lusaka aquifers due to human activities in the City area. The natural purification capacity must be considered very low due to the characteristics of karst aquifers.

Microbiological pollution and levels of nitrate together with the occurrence of minor nutrients are, at least locally, of major concern to the supply of adequate groundwater. The microbiological contamination has been linked to the poor sanitary and hygienic conditions prevailing in many of the low-cost residential areas. More information is needed on the exact distribution and the seasonal variability of microbiological contamination as well as on the pollution mechanism.

The overall content of dissolved inorganic substances is generally augmented in the City area which can be seen from high levels of EC, and elevated contents in sodium, chloride and sulphate. Considering the shallow water tables and the practical absence of an effective protective cover, the overall contamination within the main well field (areas around Shaft 5, Waterworks and Mumbwa Roadside wells) by inorganic pollutants appears less severe than one could have imagined or feared. The reason for this could be the comparatively large amounts of direct recharge (Chapter 5.4) and the high permeability of the karst aquifers producing a large "turnover" of pollutants. Groundwater of the main well field is possibly further diluted by clean water drawn (through the natural or induced hydraulic gradient) from areas with little human activities such as the Local Forest Reserves.

Reliable information on the heavy metal load of groundwater is overall limited. Existing results indicate that heavy metal concentrations of groundwater within the carbonate rocks are low and non-critical due to the poor solubility of the metal compounds under the prevailing geochemical conditions (high pH). The solubility of trace metals in schist aquifers, however, may be much higher. The preliminary findings need to be confirmed by additional sampling and geochemical modelling (e.g. speciation calculations using PHREEQC)

No substantial information is currently available on contamination by industrial organic chemicals such as hydrocarbons and chlorinated hydrocarbons from industrial areas and waste sites, chemical compounds derived from agricultural chemicals or dumped pharmaceutical products. Unfortunately, national and even regional laboratories lack the capacity to analyse water for most organic chemicals.

TASKS

A groundwater chemistry assessment programme must be developed founded on the results obtained during the 2008 sampling campaign. Besides inorganic parameters the campaign should focus on a semi-quantitative detection of microbiological contaminants in order to assess the distribution of microbiological contamination and its time-variability. Specialised equipment and standardised sampling procedures will be applied to minimise the risk of sample contamination. For this purpose, the QuantiTray® microbiological testing equipment by IDEXX Laboratories will be purchased that can provide easy, rapid and accurate counts of coliforms, *Escherichia coli* and *enterococci*. Despite difficulties regarding sampling procedures and particular sample conservation the Project attempts to sample for and analyse selected organic compounds (selected DNAPL, BTEX). In preparation of such a campaign, suitable water points for sampling have to be carefully selected. Organic samples will have to be shipped and analysed by the BGR laboratories.

Based on the results of the groundwater chemistry assessment program a water quality monitoring program specifying sampling locations, frequency and

parameters to be analysed will be developed and implemented in co-operation with the DWA and the CU.

7.5 Groundwater Vulnerability

Groundwater vulnerability in this context means "*vulnerability of groundwater to contamination*" and is used in the opposite sense to the term "*natural protection against contamination*". In the past 40 years several concepts and methods for vulnerability mapping have been developed. Today *intrinsic vulnerability*, which looks at the intrinsic characteristics of various parts of an aquifer and its protective cover and does not take the behaviour of a contaminant or group of contaminants and the contamination scenario into consideration, is distinguished from *specific vulnerability* which relates groundwater vulnerability to certain contaminants, prevailing human activities or the pollution history.

Possible groundwater contaminants and pollution sources were described in the previous chapters. In the following, the term vulnerability always refers to intrinsic vulnerability of the groundwater resource. For mapping of the intrinsic vulnerability, parameters determining the general protective effectiveness of the soil and rock cover, such as thickness of soil, content of clay and organic matter, mineralogical rock composition, degree of jointing and fracturing, porosity and percolation rates are decisive. The thickness of the protective cover is determined by the depth of water table and its seasonal variation.

Superficial deposits in the Lusaka area are largely controlled by the underlying geology (von Hoyer et al. 1978). Schists and quartzites are covered by deposits of red-brown sandy clay and quartz gravel in the vicinity of quartz veins. The Lusaka Dolomite Fm is characterized by a well-developed epikarst zone (Chapter 7.5). Pisolitic laterite mixed with reddish-brown clay is developed in areas underlain by dolomite and limestone. Some occur as pockets filling grikes and karst hollows. Calcareous tufa is found in some streambeds and near springs.

Von Hoyer et al. (1978) mapped soils in the Lusaka dolomite at an approximate scale of 1:200,000 (Figure 22). They distinguish two major soil classes: The "*Makeni*" series are described as shallow or moderately deep to deep, dark brown or dark reddish-brown sandy loams or clay loams. Internationally, the shallow soils would probably fall under the classes "leptosols" whereas the deeper soils would be of the types "luvisols" or "lixisols" depending on the activity of the clay enriched in the subsoil. The "*Cheta*" Series are rather poorly drained dark-grey to blackish, fine-textured and heavy calcareous soils found along dambo and streams and likely belong to the soil class "phaeozem", or possibly "(eutric) vertisol". Apart from the two distinguished soil classes a considerable area is covered by very shallow soils over solid carbonate rock with numerous outcrops.

For a brief description of major soil types according to the FAO world reference base for soil resources (FAO 2006) refer to Table 18.

According to YEC (1995b) major soil types in Lusaka Province include leptosols (lithosols) and cambisols. In Lusaka Urban luvisol-phaeozem type of soils are most prominent.

Table 18 Brief description of most common soils types found in the Lusaka area (simplified after FAO 2006)

Soil unit	Description
Alisol	Soils with low-base status having a higher clay content (with generally low base saturation) in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration). High-activity clay.
Acrisol	Soils with low-base status having a higher clay content (with generally low base saturation) in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration). Low-activity clay.
Cambisol	Soils in an early stage of development with at least an incipient subsurface soil formation.
Leptosol	Very shallow soils over continuous rock and soils that are extremely gravelly and/or stony and characterised by a severe limitation to rooting (incl. “rendzinas” developed on carbonate rock)
Lithosol	Very shallow soils typical for land with strongly dissected topography over continuous rock and soils that are extremely gravelly and/or stony. In the new classification system lithosols are grouped under leptosols.
Lixisol	Soils with high-base status having a higher clay content in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration). Low-activity clay.
Luvisol	Soils with high-base status having a higher clay content in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration). High-activity clay.
Phaeozom	Soils of relatively wet grassland and forest regions with dark, humus-rich surface horizons that have high base saturation in the upper metre of the soil.
Vertisol	Churning, heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out.

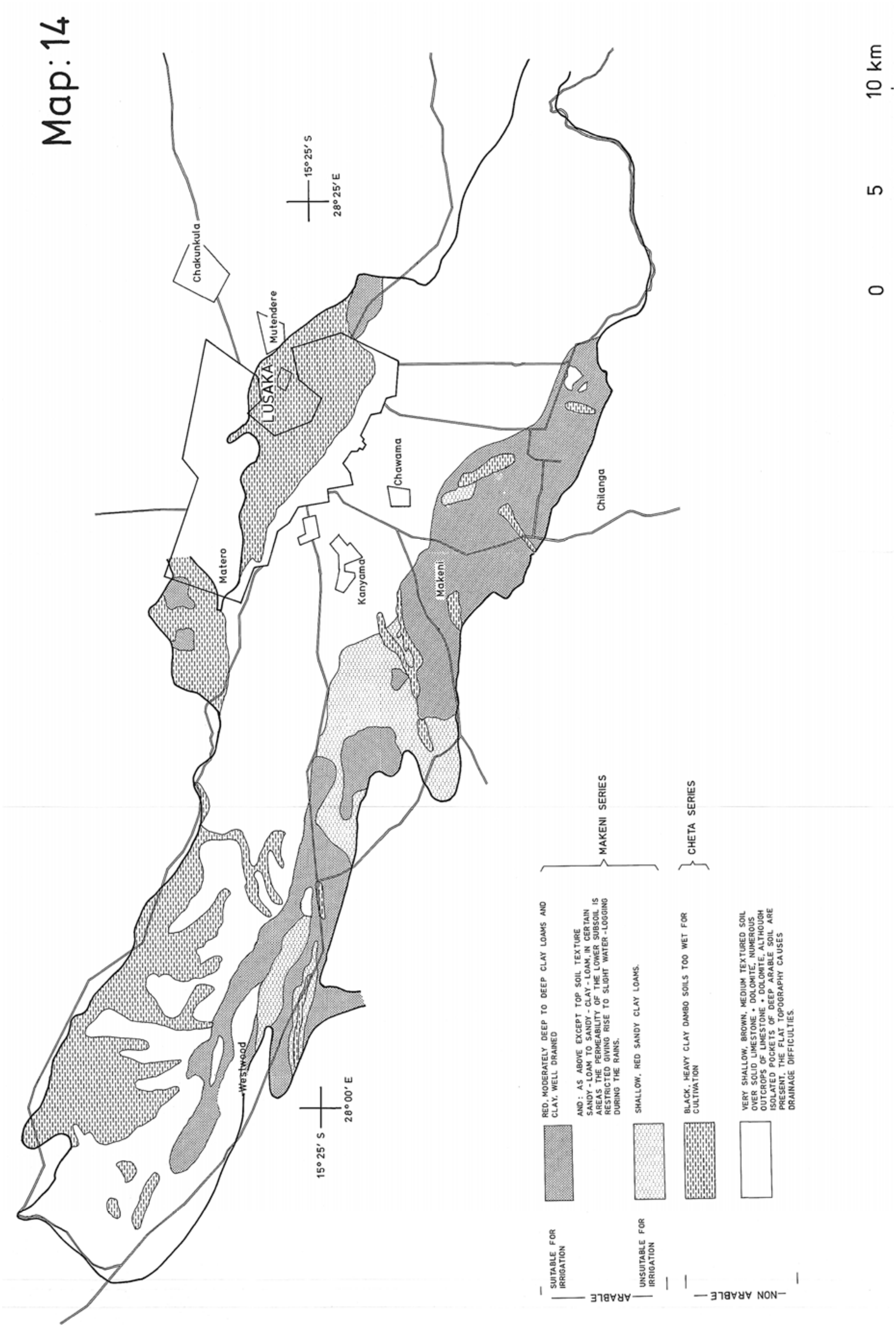


Figure 22 Distribution of soil classes in the Lusaka Dolomite according to von Hoyer et al. (1978)

According to the national soil map (Ministry of Agriculture 1991), the carbonate rocks of the Lusaka Dolomite Fm are largely covered by ortho-eutric leptosols. Areas to the north covered by schist or limestone show ortho-eutric leptosols mixed with chromic-haplic lixosols. Phaeozems, soils with humus-rich surface horizon, occur along the south-western boundaries of the Lusaka Dolomite Fm. In areas along the Great East Road covered by alluvium and schist chromic-haplic acrisols and alisols form the predominant soil types.

In the Lusaka Forest Reserve chromic-haplic lixisols were identified as the major soil type that has developed on limestone and dolomite (Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. 2008). In one case an orthi-eutric leptosol was discovered on biotite schist. The vegetation was characterised as *Miombo* woodland and less common *Munga* woodland, with isolated riparian woodlands along drainage lines.

Interestingly, none of the soils described above corresponds to plinthosols that include laterite soils despite the fact that laterite was described as the characteristic filling material of karst hollows.

A series of economic reports describe the nature and economic potential of limestone, talc and clay deposits in parts of Lusaka (Barr 1970, Drysdall 1964, Hickman 1967, 1968, Newman 1964, Newman & Matheson 1966). The reports contain maps and logs of holes drilled into the surface-near zones and other valuable local information on the sub-surface characteristics.

Large areas of Lusaka aquifers are characterised by shallow (<6 m) or very shallow (<2 m) **groundwater tables**, and hence a thin protective cover. Furthermore, many areas including the Kanyama, John Laign, Misisi, Kamwala South and Kabwata Site and Service compounds are subject to occasional or seasonal inundation. Areas in the limestone/dolomite rocks with a depth to water tables exceeding 10 m are restricted to the south-eastern boundary of the Lusaka Dolomite Fm (Westwood and areas further west) and the Lusaka Forest Reserve areas (von Hoyer et al 1978).

ANALYSIS

Due to the widespread occurrence of outcrops and open water surfaces (quarries), shallow soil types (leptosols), the degree of surface and sub-surface karstification and the general shallow water tables the area must be considered highly susceptible to groundwater pollution. With respect to the regional determination of (intrinsic) vulnerability it must be noted that existing maps showing soil types are not very detailed. Information on thickness of soils and the vadose zone is also limited although the analysis of borehole completion reports and available reports describing the nature and economic potential of surface deposits is yet to be completed.

No approach has been made so far to produce a vulnerability map of the Lusaka area. Mpamba (2008) assesses the possibility of using the DRASTIC technique for vulnerability assessment and mapping. The DRASTIC method is frequently used in the United States. Other methods for groundwater mapping include the GLA-method and its recent modification, the PI-method, used by the German States and Federal Government authorities, the EPIC-method used by the Swiss authorities and the COP-method proposed for use in karst areas of the European Union (see e.g. Margane (2003) for further reference and a comprehensive bibliography on the topic). According to a recent validation of vulnerability mapping methods (Neukum & Hötzl 2008) the DRASTIC and EPIK methods must be used with care in vulnerability assessments of karst areas as they are not able to incorporate the variable distribution and thickness of cover sediments.

TASKS

A regional soil distribution map should be produced distinguishing at least the major soil classes and showing areas of outcrops within the investigation area. Remote sensing techniques combined with selected ground truthing (Chapter 3.4) will be applied. The maps should be created in close co-operation with the Soil and Water Management Division (SWMD) in the Zambia Agriculture Research Institute (ZARI).

In order to estimate the depth and type of soils and the overburden borehole completion reports and available economic reports of the surface-near deposits must be analysed. Depths to water-table maps for specific seasonal situations must be generated from the planned groundwater measurement campaigns (Chapter 6.3) in order to assess the thickness of the unsaturated zone.

The applicability and suitability of available vulnerability mapping techniques must be assessed. Based on this assessment the most appropriate method(s) should be chosen and applied. All required parameters for vulnerability assessment need to be determined or quantified with the best possible accurateness. The location of surface karst features, larger waste sites and quarries will be mapped partially using remote sensing techniques. Furthermore, major potential pollution point sources or areas of potential pollution must be identified. Areas must be distinguished and outlines according to the dominant service delivery mode (sewage disposal). The vulnerability map is considered a major tool for the groundwater pollution risk assessment and the development of a groundwater protection strategy. In accordance to the hydrogeological map, the vulnerability mapping will be at scale 1:100,000.

8 Capacity Building

The brief description of the capacity building status in this chapter does not cover the water and sanitation sector as a whole. Instead, it is by and large restricted to the cooperating partner, the Department of Water Affairs at Headquarters and its provincial and district structures in Lusaka, and to institutions accountable for aspects of usage and protection of the Lusaka groundwater systems, namely the Lusaka City Council and the CU, the Lusaka Water and Sewerage Company.

8.1 Institutional Setup and Capacity

The **Ministry of Energy and Water Development** contains four Departments: the Department of Energy, Department of Water Affairs, Department of Planning and Department of Information and Human Resources and Administration. Its mission is to "*promote sustainable development and management of energy and water resources in order to ensure availability of quality, affordable safe water and energy and enhance national socioeconomic development*" (MEWD 2009). The structure of the Ministry follows recommendations of the 1999/2003 Restructuring Report (Cabinet Office, 1999, 2003).

The **Department of Water Affairs** is vested with the sole responsibility of developing and managing water resources. It is responsible for the provision of sufficient and reliable data on water resources availability and demand in the country to allow for effective planning, utilisation and management of the resource. It is also responsible for overseeing and controlling activities of water resource development and management in order to prevent the indiscriminate tapping of water resources and undertakes the development and management of water conservation.

The DWA has structures present at Headquarters, provinces and district level to provide the required services in water resources management and development.

Headquarters consists of the three following sections: Groundwater Resources, Surface Water Resources and Water Resources Management of which each is directed by an Assistant Director (Figure 23). Each section is further sub-divided into Units. According to a sector capacity study commissioned by the Ministry of Local Government and Housing and the Danish Ministry of Foreign Affairs (Stoltz et al. 2007), the total number of professional staff of the DWA in 2007 was 25 of which 12 had a university degree (BSc or MSc).

This Project runs as one of the programs of the Groundwater Resources Section but has also links to (and trains personnel of) the Water Quality Management and Hydro Informatics Units of the Water Resources and Management Section.

The Groundwater Resources section is divided into the Groundwater Research & Planning Unit and the Groundwater Resources Development Unit. The professional staff of the section includes two principal hydrogeologists and two senior hydrogeologists and seven additional staff members.

The Provincial Water Officer is the head of a **Provincial Office** (Figure 24). The groundwater section at provincial level consists of a senior hydrogeologist, a hydrogeologist, a senior driller and a driller. In a similar way, a senior hydrologist and senior water engineer presides over the hydrology and the infrastructure & development section, respectively. Additional staff includes a hydro-informatics officer, a water resources engineer (demand & supply) and a water quality engineer. In practice, however, a considerable number of the positions are vacant. At Lusaka Provincial Office, the positions of the senior hydrogeologist, the senior hydrologist, the hydrogeologist and the lab technician are currently not filled.

At **district level**, a District Water Officer is backed by a (Water Resources) Engineering Assistant and additional support staff. However, very few of positions at the 76 districts were filled by 2006 (Stoltz et al. 2007). Authority was given in August 2007 to employ more staff as a part of restructuring efforts. In Lusaka Province, currently three out of four district officers are in place. A candidate for the only remaining position for Chongwe district has been nominated and is expected to come on duty in the course of this year.

The **Lusaka Water and Sewerage Company Ltd.** is the main supplier of water and sanitation services to the City of Lusaka's residents. The Company is wholly owned by the Lusaka City Council but for all intents and purposes operates as a private Company. In 2007, 61 (11%) out of a total number of 546 employees had a university degree while 48 (9%) had a diploma (Stoltz et al. 2007). NWASCO uses the ratio "staff per 1000 connections" as a performance indicator for staff efficiency. With a ratio of 13 in 2006/2007, the staff efficiency at LWSC is well above the benchmark of 8 for acceptable staff efficiency and was consequently rated unacceptable by the regulator (NWASCO 2007).

The **Lusaka City Council** has the mandate to develop strategies for water and sanitation, waste management and environmental development through its City Planning Department.

According to the LCC homepage (2009), the Department of City Planning has a total workforce of 75 employees. It is headed by one Director who is assisted by one Deputy Director and two Assistant Directors. In addition, there are five town planners, five building inspectors, five land surveyors and fifty-five, mainly technical, administrative and other supportive staff at different levels or categories.

The LCC is also mandated to execute a yearly water quality monitoring program through its Public Health Department. According to the water sector capacity study, however, there are serious capacity limitations in terms of staff and operational tools and insufficient financial resources to carry out water quality monitoring. The number of samples collected is reportedly very small (Stoltz et al. 2007)

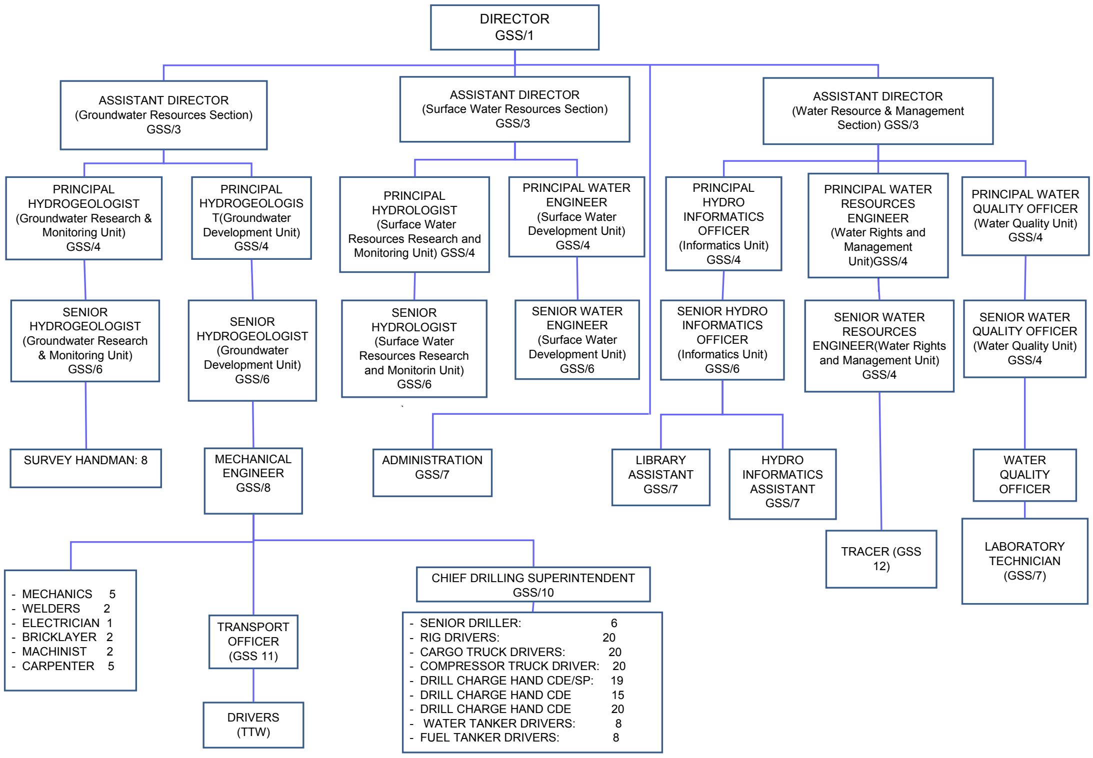


Figure 23 Organisation chart showing the structure and lines of authority of DWA Headquarters (Source: DWA)

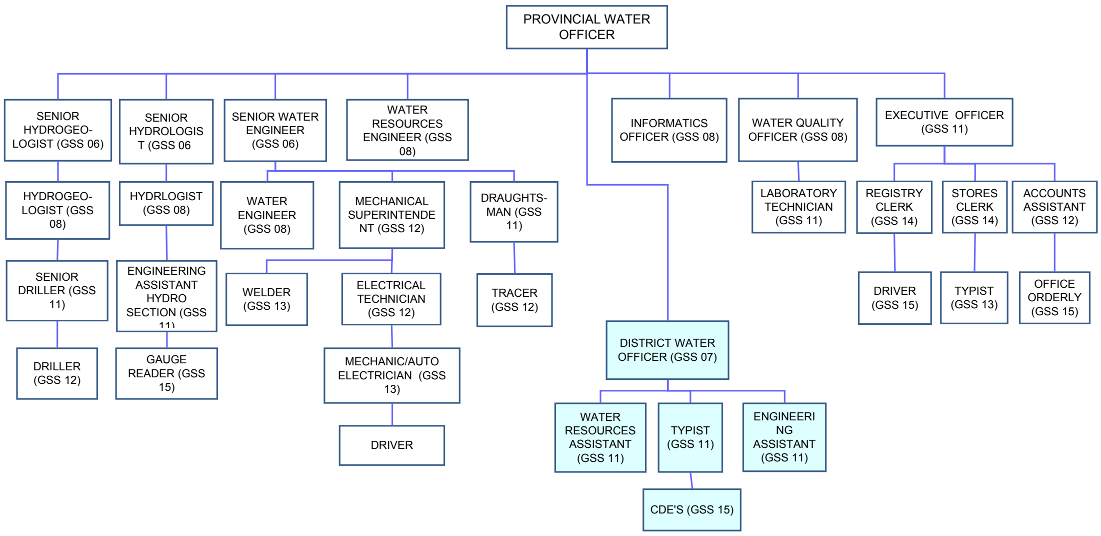


Figure 24 Organisation chart showing the structure and lines of authority of DWA provincial and district offices (Source: DWA, Lusaka Provincial Officer)

It is generally accepted that the capacity for water analyses and water quality monitoring in the present situation is insufficient in Zambia. Details on the institutional capacities of existing water laboratories at UNZA, Food and Drugs, DWA and five Commercial Utilities are provided by Stoltz et al. 2007.

8.2 Previous GReSP Capacity Building Components

The GReSP Project has followed a two-fold strategy to enhance capacities within the DWA. On the one hand, on-the-job training was offered to the counterparts assigned to the Project, which included four officers at headquarters and one at district level. On the other hand, technical courses on selected topics were offered to officers at all levels (headquarters, Lusaka and Southern Province including districts) and students at School of Mines, University of Zambia.

The on-the-job training was conducted in the fields of hydrogeological field investigations and water sampling, groundwater database management, cartographic principles, GIS and development of hydrogeological maps, compilation of technical reports, and others.

The courses on selected topics offered are summarised in Table 19 below. All participants passed the major courses and received certificates.

Table 19 Training courses offered by the GReSP Project

Course Topic	Lecturer	Participant's Institution	Date (Duration)
Working with GeODin groundwater database	T. Fyfe (Fugro)	Headquarters, Lusaka Province, Southern Province	11/2005 (1 week)
Introduction into ESRI ArcGIS, Part 1	K. Kelly (Kelly & Kelly)	Headquarters, Lusaka Province	03/2006 (1 week)
Map projections with practical applications in ArcGIS	U. Philipp (BGR)	Headquarters, Lusaka Province,	04/2006 (1 week)
Introduction into ESRI ArcGIS, Part 2	A. Banda (MoL/ Kelly & Kelly)	Headquarters, Lusaka Province	04/2006 (2 days)
Querying databases in GeODin, ArcMap and MS Access	R. Bäumle	Headquarters	11/2006 (2 days)
Introduction to geophysical field methods and pumping test analysis	F. Schildknecht & R. Bäumle (BGR)	Headquarters, District Officers, UNZA	11/2007 (2 weeks)
Principles in hydrogeology, water sampling and geophysics	R. Bäumle (BGR) & J. Nkhoma (DWA)	DWA and GAUFF Eng., Eastern Province	01/2009 (1 week)

ANALYSIS

The Sector Capacity Study performed in 2007 identified key capacity gaps in the water and sanitation sector. According to the study, the capacity gaps, both in terms of number of staff and their qualifications, are greatest at district level and in the CU's. A particular problem for some of these institutions is the remoteness of the areas together with unattractive remuneration packages.

The study also stresses the lack of required number of hydrogeologists and drilling supervisors with sufficient geological and hydrogeological background, which is likely to affect the two major sub-sector programs, i.e. the National and Urban and Rural Water and Sanitation Programmes, as well as the reform of the Water Resources Management sub-sector.

Furthermore, the study recommends to further support local water laboratories to increase the number and qualification of staff and to establish a National Reference Laboratory responsible for inter-calibrations and quality controls of national water laboratories.

Capacity building measures carried out by the GReSP project have focused on enhancing skills in hydrogeological and hydrochemical methods that are crucially needed according to the sector capacity assessment. A working team has been established within the DWA that is capable of entering, checking and analysing groundwater data, generating thematic maps, planning and conducting hydrochemical sampling campaigns and independently answering the many requests for hydrogeological information from within and outside the Ministry.

Considering the possibilities and limitations of capacity building within this technical cooperation project, the existing two-fold approach – on-the-job training of counterparts and provision of training courses to a larger number of officers – has proved adequate and should therefore be continued and extended. The capacity needs of institutions involved in the collection of groundwater data in the project areas need to be assessed, and respective (additional) training units developed.

The DWA and the Project need to pay more attention to strengthen the links between the CU's, NGO's operating regionally in the water sector and district offices on the one side and headquarters on the other side. This aims at an improved quality of the hydrogeological data collected as well as at an automisation and harmonisation of the collection and transfer of data. It should be the objective to facilitate a continuous update of the established groundwater information system which does not depend on the date of ratification of the proposed Water Resources Management Bill.

The Project has also contributed to develop a standard of data collection by developing date entry sheets for e.g. water sampling and pump testing. Similar data sheets need to be prepared for other purposes and distributed to institutions at all levels.

TASKS

On-the-job training and training courses will be offered throughout the project duration. Additional training components at provincial and district levels are planned in order to support the DWA in managing and maintaining the existing databases.

The capacity needs of the counterpart institution as well as the LCC and LWSC in connection with the practical implementation of groundwater monitoring, management and protection will be (re-)assessed. It will then be specified how the project can contribute to close existing capacity gaps.

Existing standards for the collection of groundwater information during groundwater exploration, monitoring and quality assessment will be reviewed. Based on this assessment recommendations will be prepared in co-operation with the relevant institutions. Additional data (field entry) sheets will be compiled where lacking. Together with the DWA, a strategy will be developed to disseminate the information and materials, to build required capacity, and how to implement groundwater monitoring and management strategies on the ground.

Depending on demand, the Project is prepared to organize one or two training courses per year with duration of between a few days to a maximum of two weeks. Courses could be offered in the following fields:

- **Basic hydrogeology and groundwater inspection**
- **Working with groundwater database**
- **Aquifer mapping, groundwater contouring**
- **Geochemistry, water quality assessment and groundwater sampling**
- **Basics in isotope hydrology**
- **Introduction in groundwater vulnerability assessments**
- **Principles of cartography and GIS**
- **Hydrometric principles (introduction in field measurements)**
- **Introduction in remote sensing techniques**
- **Basics in soil science**

In the future, the Project intends to also work closer together with the Information and Database Section under the Department of Planning and Information which is in charge of maintaining an energy and water information management system and of developing a network to facilitate the exchange of information between Ministry Headquarters. Provided that the ministerial internal network is fully operational, the possibility to allow broad access to the developed groundwater database using the shareware component of GeODin, and to the GIS-based maps using so-called Web-GIS applications will in particular be looked at.

9 Management Strategy

The overall aim of the groundwater management strategy is to manage groundwater efficiently and in a sustainable way, and to preserve the quality of groundwater, particularly for drinking water purposes, for the benefit of present and future generations.

Previously, a City planning and groundwater protection strategy was proposed by von Hoyer et al. (1978, 1980) based on substantial hydrogeological research. The strategy included recommendations regarding water supply, sewerage, refuse disposals and groundwater protection measures. Unfortunately, the strategy was never implemented.

A major component of the strategy included the establishment of three types of protection zones with varying restrictions with regard to prohibited activities:

- Zone I: area comprised within a 20-meter radius around the protection well, which should be fenced,
- Zone II: area comprised within a one-kilometre radius around the protection well,
- Zone III comprising almost the total area covered by the Lusaka Dolomite Fm.

Protective measures in Zone III include (among others) the prohibition of the:

- release of untreated sewage and the development of urban settlements unless fully provided with sustainable sanitation and sewerage systems,
- disposal of poisons, chemicals soluble in water, mineral oils, insecticides or pesticides,
- construction of pipelines carrying substances dangerous to water an human health,
- operation of refuse disposal sites,
- establishment of new cemeteries.

Additional protective measures within a radius of one kilometre around pumped wells (zones I and II) include the prohibition of:

- open air storage of fertilizers,
- storage of oils, petrol, diesel,
- open air quarrying, removal of protective cover,
- drainage ditches draining waste water and industrial effluents,
- pit latrine sanitation, and
- disposal of refuse and industrial waste.

Based on a groundwater contamination assessment Kampeshi (2003) developed recommendations to improve the management and protection of groundwater resources. Measures required include:

- that the Lusaka City Council (LCC) halts the development of unsewered urban settlements in areas covered by the Lusaka Dolomite Fm;

- that existing sewerage facilities are extended and modernised;
- an improved legislation that also enforces the building of monitoring wells by petroleum industries;
- an improved waste management;
- that a water quality monitoring is put in place using easy-to-measure indicators of pollution;
- the decontamination of polluted sites such as the Impala Service Station, the Zamleather grounds and the ZCF-CIDA storage site.

In the same line of reasoning, de Waele et al. (2004) proposed guidelines for the protection and the management of groundwater including:

- the inventory of private boreholes,
- protection zones within 100 meters of production boreholes,
- the protection of major recharge areas such as the Lusaka Forest reserves,
- an improvement of treatment of sewage waters by enlarging sewerage drainage systems,
- the control of waste dumps in recharge areas and the upgrading of existing waste dumps to landfills,
- groundwater quality monitoring,
- the identification of new groundwater resources around Lusaka, and
- measures to improve environmental education.

As major steps towards the establishment of a groundwater management strategy, Mpamba (2008) recommends that all existing boreholes are identified and located, a regular groundwater level and a water quality monitoring is put in place, the amount of groundwater recharge is re-assessed, and that a groundwater model is developed in order identify areas under groundwater stress. He furthermore urges the need of declaring the Lusaka Forest Reserve areas a groundwater protection zone and points out that the current abstraction is needed in certain parts of the City in order to maintain groundwater levels at their present state and to prevent seasonal water logging.

KRI et al. (2008a, 2008c) developed a preliminary groundwater resources development strategy for the City of Lusaka. The study recommends utilising the Kafue River water by 2030 as the main water resource for the City in order to meet the future demand that is estimated to increase to 290,000 m^3/d by 2015 and to 602,000 m^3/d by 2030 from the current estimated demand of 218,000 m^3/d. At the same time, a comprehensive groundwater management program should be developed and the possibilities of developing new groundwater resources or enhancing recharge (e.g. recharge ponds) should be evaluated. The study additionally proposes to step-wise extend the capacity of existing treatment plants and to create a new plant at Kaunda Square by 2030. The drain system should be improved with priority given to areas that are frequently inundated.

ANALYSIS

The successful development of a groundwater management strategy depends on a thorough assessment of the groundwater potential, the current pollution status and potential risks, and the vulnerability of the Lusaka groundwater systems as elaborated in depth in the chapters above. Its successful implementation will largely rely on the institutional framework and capacities.

Specific problems the City faces include the seasonally very wet conditions with very shallow groundwater tables and seasonal inundations together with a high vulnerability of aquifers due to the absence of a thick protective cover, the poor sanitary conditions in many areas, and the abundance of potential pollution sources from unauthorized or poorly managed dumping sites, industrial waste, contaminated soil and unlined sewage, etc. The situation is aggravated by the fact that public water supply wells exist in short distance from industrial areas and unsewered residential areas.

Of major importance to an improved protection of groundwater will be the development of suitable sanitation concepts that take the specific situation in and around Lusaka into account.

Besides this, a major challenge in developing a suitable management strategy for the City lies in the fact that many groundwater recharge areas have already been urbanised, and that existing development can hardly be reversed. Classical protection zoning concepts are therefore not fully applicable, and obviously, a much more flexible and innovative approach must be chosen. Furthermore, economic interests are given a very high priority under the current situation which may be in conflict with interests in protecting groundwater as can be seen from the existing plans of constructing a multi-economic facility zone in the Lusaka Forest Reserve areas.

The timely enactment of the Water Resources Management Bill would certainly strengthen the institutions responsible for developing and managing water resources. In the meantime, however, existing by-laws should be sufficient to implement first steps in an effective groundwater management in the City.

TASKS

The development of the groundwater management strategy for Lusaka will be based on the results obtained from comprehensive groundwater investigations proposed in this work program. As illustrated in Figure 25, it will incorporate findings from the re-evaluation of groundwater recharge and balance, the estimate of groundwater potential of various aquifers, the determining of the groundwater flow system and groundwater - surface water interactions, the assessment of groundwater quality and the susceptibility of the host rock to potential contamination as well as scenario simulations using groundwater modelling.

Steps in developing the management strategy include:

- **Presentation/Discussion of the work program with all relevant institutions; Subsequent reviewing and inclusion of possible amendments;**
- **Regular dissemination of preliminary results (consultative meetings)**
- **Public awareness campaigns at different stages of the study on safe groundwater use and protection;**
- **Incorporation of various findings into an adequate management proposal with major recommendations/guidelines regarding future groundwater use and protection;**
- **Delineate groundwater protection zones**
- **Drafting of report on proposed management strategy and its submission to relevant authorities;**
- **Distribution of report and convening of collaborative meetings with all stakeholders and reviewing.**
- **Finalising of groundwater management strategy for the Lusaka aquifers.**

In order to implement the proposed groundwater management principles it is planned to assess possibilities to cooperate with and support stakeholders from different levels (e.g. the private sector, farmer's unions, NGO's, etc) involved in groundwater use and management. This is to advocate groundwater management "on the ground level" where applicable.

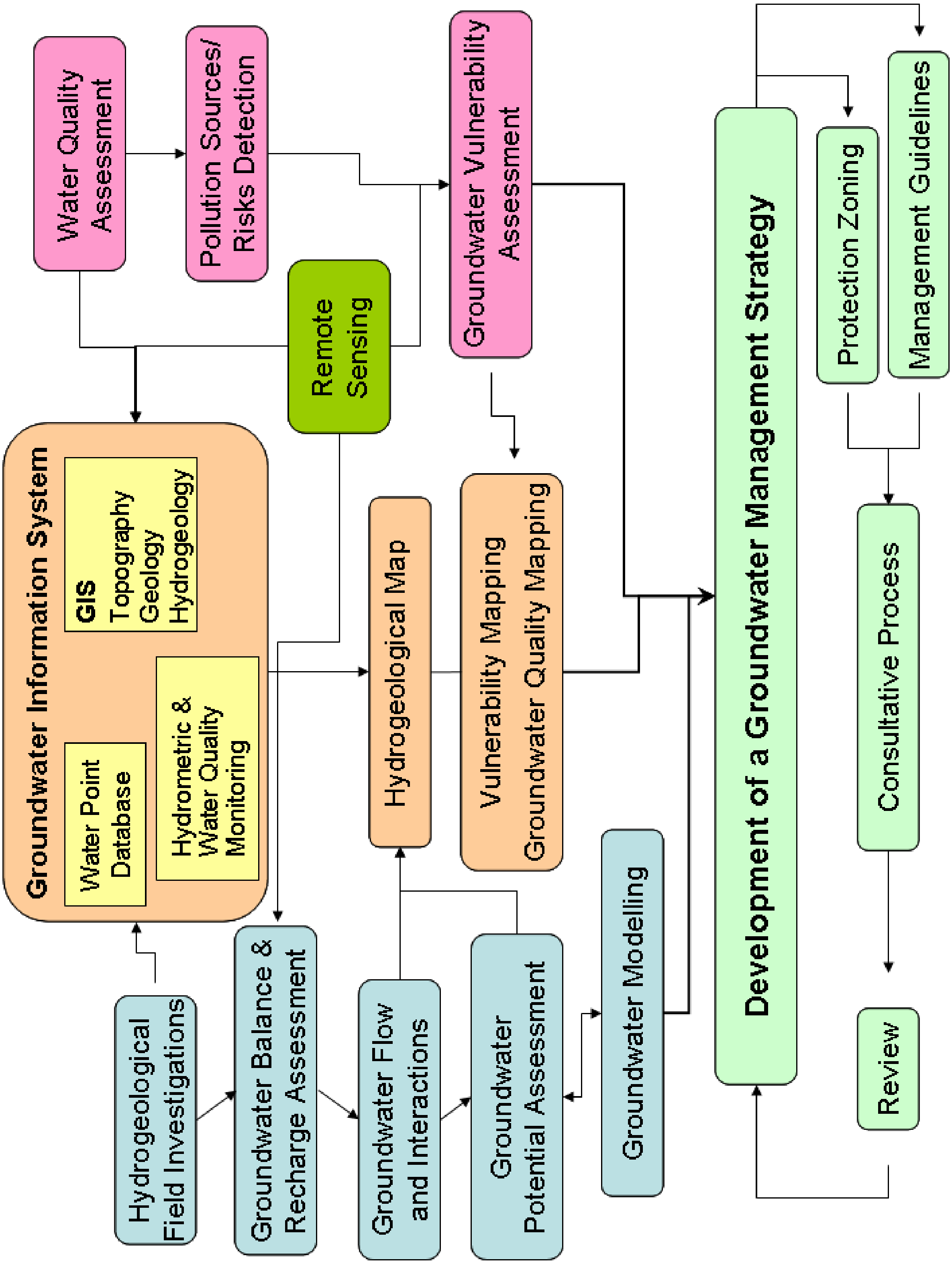


Figure 25 Simplified illustration of the comcept of development of a groundwater management strategy for the Lusaka aquifer systems.

10 References

[1] Allen R. G., Pereira L.S., Raes D. & M. Smith (1998): Crop evapotranspiration – Guidelines for computing crop water requirements.- Irrigation and drainage paper 56; FAO – Food and Agriculture Organization of the United Nations; Rome. www.fao.org/docrep/X0490E/x0490e00.htm

[2] Arthurs J .W , Newman D. & A. G. Smith (1995): Geology of the Chipembi area.- Report No. 58, Explanation of degree sheet 1428, SE. quarter; Republic of Zambia Ministry of Mines and Minerals Development, Geological Survey Department; 37 pages, Lusaka

[3] Barr M. W. C. (1968): Geology and structure of the Lusaka South Forest Reserve and adjacent areas,- Republic of Zambia Ministry of Lands and Mines, Geological Survey Department, Records of the Geological Survey Volume 11, pages 61-68, Government Printer, Lusaka

[4] Barr M. W. C. (1970): Limestone of the Lusaka South Forest Reserve and Adjacent Areas.- Republic of Zambia, Ministry of State Participation, Geological Survey Department; Economic Report No. 25, 10 pages; Lusaka.

[5] Barr M. W. C. (1997): Geology of the Chongwe river area. – Explanation of degree sheet 1529, SW quarter, Republic of Zambia, Ministry of Mines and Minerals Development, Geological Survey Department, Report No. 45; Lusaka.

[6] Becker J., Baier M. & H. Klinge (2009): Project Progress Review: Groundwater Resources in Southern Province, Zambia.- Minutes of Key Findings, 8 -17 Sep. 2009; Unpublished Report Sep. 2009; 9 pages; Lusaka.

[7] Brandon A. (1977): The geology of the Luano valley, The Karoo System.- Report of the Geological Survey No. 61, Explanation of degree sheet 1429, SW & SE. quarter Republic of Zambia Ministry of Mines, pages 28-81; Government Printer, Lusaka

[8] Bulwani G. (2008): Process Report on Planning Workshop, Upcoming Phase: 2009 – 2012: Development of a Groundwater Information and Management Program for the Lusaka Groundwater Systems.- Unpublished Workshop Proceedings; 8 pages; Lusaka.

[9] Cabinet Office, Management Development Division (1999, 2003): Report on the restructuring of the Ministry of Energy and Water Development.- April 1999, updated 2003; Lusaka.

[10] Cairney T. (1967): The Geology of the Leopard Hill area. – Explanation of degree sheet 1528, SE quarter.- Republic of Zambia, Ministry of Lands and Mining, Report of the Geological Survey No. 21; 64 pages; Lusaka.

[11] Chenov C. D. (1978): Groundwater resources inventory of Zambia.- Commissioned by UNESCO/NORAD Water Research Project and National Council for Scientific Research, Zambia; Unpublished Report, 129 pages; Lusaka.

[12] De Waele J. & R. Follesa (2003): Human impact on Karst: The example of Lusaka (Zambia).- International Journal of Speleology, Vol. 32 (1/4) 2003: 71-83.

[13] De Waele J., Nyambe I.A., di Gregorio F., Simadiku S., Follesa R. & S. Nkemba (2004): Urban waste landfill planning and karstic groundwater resources in developing countries: the example of Lusaka (Zambia).- Journal of African Earth Sciences 39 (2004): 501-508; Elsevier.

[14] Drysdall A. R. & A. G. Smith (1960): Recumbent folding in the Lusaka Dolomite.- Northern Rhodesia Ministry of Labour and Mines, Geological Survey Department; Records of the Geological Survey for 1958; pages 43-45; Government Printer, Lusaka.

[15] Drysdall A. R. (1964): The limestones of Morton Limeworks - Geological Survey Department, - Ministry of Labour and Mines, Northern Rhodesian Government Report No. 3, 17 pages; Lusaka.

[16] Drysdall A. R. (1964): The limestones of Morton Limeworks, Lusaka.- Northern Rhodesian Government, Ministry of Labour and Mines, Geological Survey Department; Economic Unit Report No. 3; 17 pages; Lusaka.

[17] Drysdall A.R. (1960): The geology of Lusaka.- Northern Rhodesia Ministry of Labour and Mines, Geological Survey Department; Records of the Geological Survey for 1958; pages 6-25; Government Printer, Lusaka.

[18] FAO – Food and Agricultural Organization of the United Nations, IUSS Working Group WRB (2006): World reference base for soil resources 2006 - A framework for international classification, correlation and communication. World Soil Resources Reports No. 103. FAO, Rome.

[19] Garrard P. (1968): The geology of the Chainama Hills area. – Report of the Geological Survey No. 24, Explanation of degree sheet 1528, NE quarter; Republic of Zambia, Ministry of Mines and Minerals Development, Geological Survey Department; 80 pages; Government Printer, Lusaka.

[20] GIBB Ltd. (1999a): Lusaka Water Supply Rehabilitation Project – Phase 2: Hydrogeological Investigations, Chelston Area.- Unpublished Reconnaissance Study Report; March 1999, 41 pages, Lusaka

[21] GIBB Ltd. (1999b): Lusaka Water Supply Rehabilitation Project – Phase 2: Hydrogeological Investigations, Mass Media and Kafue Road Quarry Areas. Volume 1.- Drilling and Testing of Boreholes - Final Report (unpublished), June 1999; 156 pages, Lusaka.

[22] GIBB Ltd. (1999c): North-West Lusaka Water Project - Final Report on Hydrogeological Investigations and Borehole Inspections, Rehabilitation and Test Pumping; Unpublished Report, Vol. 2 - Appendices, July 1999; 249 pages, Lusaka.

[23] GIBB Ltd. (2000): Lusaka Water Supply Rehabilitation Project – Phase 2:, Hydrogeological Investigations in the Chelston Area.- Drilling of Exploration and Monitoring Wells Report (unpublished); April 2000, 78 pages, Lusaka.

[24] GIBB Ltd. (2002a): Lusaka Water Supply Rehabilitation Project – Phase 2:. Borehole Report, D13/50W gs, NRDC Ranch (Unpublished).- March 2002; 4 pages plus figures & annexes, Lusaka.

[25] GIBB Ltd. (2002b): Lusaka Water Supply Rehabilitation Project – Phase 2:. Borehole Report, C14-4/65 gs, NRDC Ranch (Unpublished).- March 2002; figures & annexes, Lusaka.

[26] GIBB Ltd. (2002c): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, C13 Ves, NRDC Ranch (Unpublished).- March 2002; 4 pages plus figures & annexes, Lusaka.

[27] GIBB Ltd. (2002d): Lusaka Water Supply Rehabilitation Project – Phase 2: Production Wellfield Report, at the NRDC ranch (Unpublished).- April 2002; 11 pages plus figures & annexes, Lusaka.

[28] GIBB Ltd. (2002e): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, B6-4, NRDC Ranch (Unpublished).- April 2002; 3 pages plus figures & annexes, Lusaka .

[29] GIBB Ltd. (2002f): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, C3/50 gs , Mass Media Area 3 (Unpublished).- May 2002; 6 pages plus figures & annexes, Lusaka.

[30] GIBB Ltd. (2002g): Lusaka Water Supply Rehabilitation Project – Phase 2:. Borehole Report, DE 14-9/40gs, Plot 379a / A /Rem (Unpublished).- March 2002; 1 page plus figures & annexes, Lusaka.

[31] GIBB Ltd. (2002h): Lusaka Water Supply Rehabilitation Project – Phase 2: Production Wellfield Report, at 379a / A /Rem (Unpublished).- March 2002; 12 pages plus figures & annexes, Lusaka.

[32] GIBB Ltd. (2002i): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, F12-33w ves, Plot 379a / A /Rem (Unpublished).- March 2002; 4 pages plus figures & annexes, Lusaka.

[33] GIBB Ltd. (2002j): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, F12-0/70 gs, Plot 379a / A /Rem (Unpublished).- March 2002; 4 pages plus figures & annexes, Lusaka.

[34] GIBB Ltd. (2002k): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, QA4, Kafue Road Quarry (Unpublished).- March 2002; 5 pages plus figures & annexes, Lusaka.

[35] GIBB Ltd. (2002l): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, Marien Shrine, Chelston (Unpublished).- March 2002; 4 pages plus figures & annexes, Lusaka.

[36] GIBB Ltd. (2002m): Lusaka Water Supply Rehabilitation Project – Phase 2: Borehole Report, Buckley 2 Borehole (Unpublished).- April 2002; 4 pages plus figures & annexes, Lusaka.

[37] Grelet G. (2008): Analysis of lineaments, tectonic features and structural geology to identify groundwater exploration areas in the vicinity of Lusaka, Capital of Zambia.- Internship Report (unpublished) 42 pages; Hannover.

[38] Hanson R. E., Wilson T. J. & H. Munyanyiwa (1994): Geologic evolution of the Neoproterozoic Zambezi Orogenic Belt in Zambia. – *J. of African Earth Sciences* 18/2: 135-150, Elsevier Science Ltd.

[39] Hickman A. C. J. (1967): Clay Deposits of the Lusaka Area.- Republic of Zambia, Ministry of Lands and Mines, Geological Survey Department; Economic Report No. 18; 46 pages; Lusaka.

[40] Hickman A. C. J. (1968): The Chalimbana Clay Deposit, Lusaka.- Republic of Zambia, Ministry of Lands and Mines, Geological Survey Department; Economic Report No. 21; 46 pages; Lusaka. Simpson J. G. (1965): Two talc deposits near Lusaka.- Republic of Zambia, Ministry of Mines and Co-operatives, Geological Survey Department; Economic Unit Report No. 9; 37 pages; Zambia.

[41] Japan Techno Co. Ltd (1994a): The Project for the Rural Water Supply Development - Certificate of completion of construction works, Stage 2, Lusaka Province. - Republic of Zambia, Ministry of Energy & Water Development, Department of Water Affairs, March 1994.

[42] Japan Techno Co. Ltd (1994b): The Project for the Rural Water Supply Development - Certificate of completion of construction works, Stage 2, Central Province. - Republic of Zambia, Ministry of Energy & Water Development, Department of Water Affairs, March 1994.

[43] Japan Techno Co. Ltd (1995a): The Project for the Rural Water Supply Development - Certificate of completion of construction works, Stage 3, Lusaka Province.- Republic of Zambia, Ministry of Energy & Water Development, Department of Water Affairs, March 1995.

[44] Japan Techno Co. Ltd (1995b): The Project for the Rural Water Supply Development - Certificate of completion of construction works, Stage 3, Central Province. - Republic of Zambia, Ministry of Energy & Water Development, Department of Water Affairs, March 1995.

[45] John T. (2001): Subduction and continental collision in the Lufilian Arc-Zambezi Belt orogen: A petrological, geochemical, and geochronological study of eclogites and whiteschists (Zambia). – PhD Thesis University of Kiel, Germany, Mathematisch-Naturwissenschaftliche Fakultät, 75 pages; Kiel.

[46] Johnson S.P., De Waele B., Evans D., Banda W., Tembo F., Milton J.A., & K.Tani (2007): Geochronology of the Zambezi Supracrustal Sequence, Southern Zambia: A Record of Neoproterozoic Divergent Processes along the Southern Margin of the Congo Craton.-The Journal of Geology. Volume 115; Pages 355-374.

[47] Jones M.J. (1971): The old pump station Lusaka, A hydrogeological study.- Department of Water Affairs, Hydrogeological Report No. 24; Lusaka.

[48] Kaiser T.M., Seiffert C. & T. Truluck (1998): The speleological potential of limestone karst in Zambia (Central Africa) – a reconnaissance survey.- Cave and Karst Science Vol.25, No.1: pages 22-29.

[49] Kalinda T., Bwalya S., Mulolwa A. & H. Haantuba (2008): Use of Integrated Land Use Assessment (ILUA) data for environmental and agricultural policy review and analysis in Zambia.- Food and Agriculture Organization of the United Nations FAO & Forestry Department, Ministry of Tourism, Environment and Natural Resources, Zambia; Unpublished Report, 123 pages; Lusaka; http://www.fao.org/forestry/media/15466/1/20/

[50] Kampeshi Ch. (2003): Lusaka groundwater contamination assessment project, Vol. I (Main report), Final Draft.- Environmental Council of Zambia; 164 pages; Lusaka.

[51] Keller S. & M. von Hoyer (1982): Erkundung von präkambrischen Karstaquiferen im südlichen Afrika.- Zeitschrift der Deutschen Geologischen Gesellschaft 143: 277-290; Hannover.

[52] KRI International Corp, Nippon Koei Co Ltd & Japan Engineering Consultants (2008a): The Study on Comprehensive Urban Development Plan for the City of Lusaka in the Republic of Zambia - Progress Report Volumes 1 & 2 (February 2008).- Ministry of Local Government and Housing, Lusaka City Council and Japan International Cooperation Agency, 289 pages; Lusaka.

[53] KRI International Corp, Nippon Koei Co Ltd & Japan Engineering Consultants (2008b): The Study on Comprehensive Urban Development Plan for the City of Lusaka in the Republic of Zambia - Supplement Report (February 2008).- Ministry of Local Government and Housing, Lusaka City Council and Japan International Cooperation Agency; 76 pages; Lusaka.

[54] KRI International Corp, Nippon Koei Co Ltd & Japan Engineering Consultants (2008c): The Study on Comprehensive Urban Development Plan for the City of Lusaka in the Republic of Zambia – Interim Report (August 2008), Chapter 6: Sector Plan of water supply and sewerage/drainage.- Ministry of Local Government and Housing, Lusaka City Council and Japan International Cooperation Agency, 37 pages; Lusaka.

[55] Lambert H.H.J. (1962) Groundwater Resources.- in: Simpson J. L., Drysdall A. R. & H. H. J. Lambert (1963): The geology and groundwater resources of the Lusaka area.– Report of the Geological Survey No. 16, Explanation of degree sheet 1528, NW. quarter; Northern Rhodesia Ministry of Labour and Mines; Part 2: pp 39-58; Government Printer, Lusaka.

[56] LCC – Lusaka City Council (2009): LCC Homepage.- http://www.lcc.gov.zm/.

[57] Lusaka Water & Sewerage Company Ltd (2007a): Project implementation unit - Kamwala south B 16, borehole completion report (unpublished).- evaluated by H.Manzi, May 2007; 7 pages plus annexes, Lusaka.

[58] Lusaka Water & Sewerage Company Ltd (2007b): Borehole completion reports, Avondale no.1, Avondale no.2, Kamwala South 1080 B16 (unpublished).- evaluated by H.Manzi, May 2007; 8 pages & annexes, Lusaka.

[59] Lusaka Water & Sewerage Company Ltd (2008): Project implementation unit - Lusaka Water Works, borehole completion report, plant 3 (unpublished).- evaluated by H.Manzi, May 2007; 8 pages plus annexes, Lusaka.

[60] Mallick D.I.J (1966): The stratigraphy and structural development of the Mpande Dome, Southern Zambia.- Trans. Geological Society South Africa 69:211-230.

[61] Margane A. (2003): Guideline for groundwater vulnerability mapping and risk assessment for the susceptibility of groundwater resources to contamination.- Arab Centre for the Study of Arid Zones and Dry Lands (ACSAD) and Federal Institute for Geosciences and Natural Resources (BGR); Technical Cooperation Project No. 1996.2189.7 - Management, protection and sustainable use of groundwater and soil resources in the Arab Region, Vol. 4 (April 2003): 177 pages; Damascus.

[62] Maseka Ch. (1994): A ground-water resource evaluation of fractured rock aquifers at Lusaka.- Unpublished MSc Thesis at the University of New South Wales; 131 pages; Sydney.

[63] Matheson G. D. & D. Newman (1966): Geology and structure of the Lusaka area.- Republic of Zambia, Ministry of Lands and Mines, Geological Survey Department; Records of the Geological Survey Vol. 10, pages 10-19; Government Printer, Lusaka.

[64] MEWD - Ministry of Energy and Water Development (2009): Republic of Zambia – MEWD Homepage.- http://www.mewd.gov.zm/

[65] Ministry of Agriculture – Soil Survey Section Research Branch (1991): Exploratory soil map of Zambia, scale 1:1,000,000.- Government of the Republic of Zambia; Lusaka.

[66] Ministry of Lands, National Resources and Tourism (1975): Land use map of Zambia, scale 1:750,000- Government of Zambia; Lusaka.

[67] Monteith, J. L., (1965): Evaporation and environment.- 19th Symposia of the Society for Experimental Biology, Vol. 19: pp 205-234; University Press, Cambridge.

[68] Moore T. A. (1964): The geology of the Chisamba area.– Report of the Geological Survey No. 5, Explanation of degree sheet 1428, SW. quarter, Northern Rhodesia Ministry of Labour and Mines; 32 pages; Government Printer, Lusaka.

[69] Mpamba N. H. (2008): Data acquisition models for groundwater assessment and management in the urban and rural areas of Zambia.- Thesis, Feb. 2008 (submitted); University of Zambia, School of Mines - Department of Geology; 239 pages; Lusaka.

[70] Mpamba N.H., Hussen A., Kang'omba S., Nkhuwa D.C., Nyambe I.A., Mdala C., Wohnlich S. & N. Shibasaki (2008a): Evidence and implications of groundwater mining in the Lusaka urban aquifers.- In: H.H.G. Savenije (ed.): Integrated water resources management - From concept to practice; physics and chemistry of the earth, Vol 33 (2008): pages 648-654, Elsevier.

[71] Mpamba N.H., Nkhuwa D.C, Mdala C. & S. Wohnlich (2008b): Groundwater mining: A reality for the Lusaka urban aquifers?.- In: Adelana S. & A. MacDonald (eds): Applied groundwater studies in Africa, chapter 16: pages 277-289; CRC Press- Balkema.

[72] Museteka L. & R. Bäumle (2009): Groundwater Chemistry of Springs and Water Supply Wells in Lusaka: Results of the sampling campaigns conducted in 2008.- Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany; Unpublished Report; 54 pages, Lusaka.

[73] Neukum Ch. & H. Hötzl (2008): Validation of vulnerability mapping methods by field investigations and numerical modelling.- Hydrogeological Journal (2008) 16: 641-658.

[74] Newman D. & G. D. Matheson (1966): The economic potential of limestones near Lusaka.- Republic of Zambia, Ministry of Mines and Co-operatives, Geological Survey Department; Economic Report No. 10; 26 pages; Lusaka.

[75] Newman D. & G. D. Matheson (1966): The economic potential of limestones near Lusaka - Geological Survey Department – Ministry of Mines and Co-operatives, Zambia; 26 pages; Lusaka.

[76] Newman D. (1964): An occurrence of high grade limestone west of Lusaka.-Republic of Zambia, Ministry of Labour and Mines, Geological Survey Department; Economic Unit Report No. 6; 23 pages; Lusaka.

[77] Nieuwolt S. (1971): Climatic variability and weather types in Lusaka, Zambia.- Arch. Met. Geoph. Biokl., Ser. B, (19, Heft 4): 345-366; reprinted in: Theoretical and Applied Climatology; Springer; Wien.

[78] Nieuwolt S. (1971): Climatic variability and weather types in Lusaka, Zambia.- Arch. Met. Geoph. Biokl., Ser. B, (**19**, Heft 4): 345-366; reprinted in: Theoretical and Applied Climatology; Springer; Wien.

[79] Nkhoma J. & R. Bäumle (2007): Groundwater resources for Southern Province, Zambia – A manual with explanations for the use of the hydrogeological maps.- Department of Water Affairs, Zambia & Federal Institute for Natural Resources; 20 pp; Hannover - Lusaka (Printech).

[80] Nkhuwa D. C. W. (1996): Hydrogeological and engineering geological problems of urban development over karstified marble in Lusaka, Zambia. – Mitteilungen zur Ingenieur- und Hydrogeologie 63, 251 pages; Aachen.

[81] Nkhuwa D. C. W. (2006): Groundwater quality assessments in the John Laing and Misisi areas of Lusaka.- in: Yongxin Xu and B. Usher (eds.): Groundwater Pollution in Africa; pages 239 – 251; Taylor & Francis.

[82] Nkhuwa D.C.W (2000): Management of groundwater resources in Lusaka, Zambia, and expectations for the future.- In Sililo, O. et al. (eds) (2000): Proc. XXXH IAH Congress on Groundwater: Past Achievements and Future Challenges , Cape Town, 26 Nov-1 Dec 2000, 993-998; Balkema, Rotterdam.

[83] NWASCO – National Water and Sanitation Council (2007): Urban and peri-urban water supply and sanitation sector report 2006/2007.- 46 pages; Lusaka.

[84] NWASCO/DTF - National Water and Sanitation Council & Devolution Trust Fund (2006): Aquatis – The urban and peri-urban water supply and sanitation information system (Version 1.0, Jan 2006); www.nwasco.org.zm; Lusaka.

[85] Nyambe I.A. & C. Maseka (2000): Groundwater pollution, land use and environmental impacts on Lusaka aquifer, Zambia.- In Sililo, O. et al. (eds) (2000): Proc. XXXH IAH Congress on Groundwater: Past Achievements and Future Challenges , Cape Town, 26 Nov-1 Dec 2000, 803-808; Balkema, Rotterdam.

[86] Oriental Consultants Co. Ltd. & Yachiyo Engineering Co. Ltd. (2008): The study on the master plan of Lusaka South Multi-Facility Economic Zone in the Republic of Zambia.- Japan International Cooperation Agency (JICA) & Ministry of Commerce, Trade and Industry of Zambia (MCTI); Interim Report (unpublished), Dec. 2008; 468 pages plus Appendices; Lusaka.

[87] Penman H. L. (1948): Natural evaporation from open water, bar soil and grass.- Proc. Royal Society 193 (A): 125-145.

[88] Porada H. & V. Berhorst (2000): Towards a new understanding of the Neoproterozoic - Early Palaeozoic Lufilian and northern Zambezi Belts in Zambia and the Democratic Republic of Congo. - *J. of African Earth Science* 30: 727-771, Elsevier Science Ltd.

[89] Ray A.K. (1983): Lithostratigraphic succession of Zambia.- under the recommendation of the Stratigraphic Committee, Geological Survey Department, Zambia; Lusaka.

[90] Schmidt G. (2001): Groundwater quantification – Validation of groundwater models, Vol. 3: Case Studies, Zambia, Lusaka.- Federal Institute for Geosciences and Natural Resources; pages 29-47; Hannover, Germany.

[91] Schultz J. (1972): Republic of Zambia: Land use.- Government of the Republic of Zambia; Four map sheets at scale 1:750,000, printed by the Ordnance Survey in 1975; Lusaka.

[92] Simpson J. G. (1962): The geology of the Mwembeshi River area.- Report of the Geological Survey No. 11, Explanation of degree sheet 1527, NE quarter, Northern Rhodesia Ministry of Labour and Mines; 29 pages; Government Printer, Lusaka.

[93] Simpson J. G. (1965): The geology of the Chinyunyu area.- Report of the Geological Survey No. 19, Explanation of degree sheet 1529, NW. quarter, Republic of Zambia Ministry of Lands and Mines; 70 pages; Government Printer, Lusaka.

[94] Simpson J. G., Drysdall A. R. & H. H. J. Lambert (1963): The geology and groundwater resources of the Lusaka area.– Report of the Geological Survey No. 16, Explanation of degree sheet 1528, NW. quarter; Northern Rhodesia Ministry of Labour and Mines; 59 pages; Government Printer, Lusaka.

[95] Smith A. G. (1963): The geology of the country around Mazabuka and Kafue. – Explanation of degree sheet 1527 SE quarter and 1528 SW quarter; Northern Rhodesia Ministry of Labour and Mines; 32 pages; Government Printer, Lusaka.

[96] Smith M. (1992): CROPWAT: A computer program for irrigation planning and management.- FAO - Food and Agriculture Organization of the United Nations; FAO irrigation and drainage paper no. 46; 126 pp; Rome.

[97] Stoltz H., Jørgensen, M., Mutale M., Zulu, A., Sijuma R., & W.K. Lumba (2007): Sector Capacity Study Water and Sanitation.- Government of Republic of Zambia, Ministry of Local Government and Housing & Ministry of Foreign Affairs, Denmark, Royal Danish Embassy, Lusaka; Final Report (unpublished) Oct. 2007.; 113 pages; Lusaka.

[98] Surveyor-General, Lusaka (1972-1993): Zambia Topographic Map sheet series 1:50,000, Numbers 1527B2 (1973), 1527B4 (1980), 1527D2 (1980), 1528A1 (1974), 1528A2 (1972), 1528A3 (1972), 1528A4 (1986), 1528B1 (1990), 1528B2 (1972), 1528B3 (1981), 1528B4 (1972), 1528C1 (1993), 1528D2 (1990).- Republic of Zambia; Printed by Government Printer, Lusaka.

[99] Surveyor-General, Lusaka (1973-1991): Zambia Topographic Quadrangle Map, Map sheet series 1:250,000, Numbers SD-35-11 Kabwe, SD-35-12 Mulungushi, SD-35-15 Lusaka, SD-35-16 Rufunsa.- Republic of Zambia; Printed by Government Printer, Lusaka.

[100] Tague. M. (1965) The Groundwater Reserves of The City of Lusaka, Zambia.- Republic of Zambia , Ministry of Lands and Natural Resources, Department of Water Affairs; Hydrogeological Report no. 50, 29 pages; Lusaka.

[101] Thieme J. G. (1968): Structure and petrography of the Lusaka granite.- Republic of Zambia, Ministry of Lands and Mines, Geological Survey Department; Records of the Geological Survey Vol. 11, pages 69-75; Government Printer, Lusaka.

[102] Thieme J.G., Ray A.K. & N.S. Hunjan (1984): Geological map of the Lusaka area.- Government of the Republic of Zambia, Geological Survey Department 1:250,000 Geological Map Series, Sheet No. SD-35-15; Lusaka.

[103] Thieme J.G., Ray, A.K. & N.S. Hunjan (1984): Geological Map Series, Scale 1:250,000, Sheet No. SD-35-15, Government of the Republic of Zambia - Geological Survey Department; Lusaka; Ordnance Survey.

[104] Thornthwaite C. W. (1948): An approach toward a rational classification of climate.- Geographical Review, Vol. 38: 55-94.

[105] Turc L. (1961): Evaluation des besoins d'eau d'irrigation, évapotranspiration potentielle.- Ann. Agron. Paris 12: 13-39.

[106] Turner D. C. & B. Turner (1986): Geology of the Lusaka Area.- in: Williams G. J. (ed.); Lusaka and its environs – a geographical study of a planned capital city in tropical Africa; Zambia Geographical Associations Handbook Series no. 9: 5-18; Lusaka.

[107] Tyrrell J.G. (1986): The climate of Lusaka.- in: Williams G. J. (ed.); Lusaka and its environs – a geographical study of a planned capital city in tropical Africa; Zambia Geographical Associations Handbook Series no. 9: 36-45; Lusaka.

[108] Von Hoyer H. & G. Schmidt (1980): Groundwater and Management Studies for Lusaka Water supply, Part 1: Groundwater Studies, Vol. VI: Revised Aquifer Model.-

[109] Federal Institute for Geosciences and Natural Resources (BGR) & Lusaka City Council; 16 pages; Lusaka.

[110] Von Hoyer H., Köhler G. & G. Schmidt (1978): Groundwater and Management Studies for Lusaka Water supply, Part 1: Groundwater Studies, Vol. I, Text, Vol. III + IV: Annexes, Vol. V: Maps.- Federal Institute for Geosciences and Natural Resources (BGR) & Lusaka City Council; 152 pages; Lusaka.

[111] Von Hoyer H., Köhler G. & G. Schmidt (1980): Groundwater and Management Studies for Lusaka Water Supply – Concluding Report.- Federal Institute for Geosciences and Natural Resources (BGR) & Lusaka City Council; 19 pages; Lusaka.

[112] Vrana S. (1972): The geology of the area south of the Lukanga Swamp.- Report of the Geological Survey No. 28, Explanation of degree sheet 1427, SE quarter; Republic of Zambia Ministry of Mines and Industry; 29 pages; Government Printer, Lusaka.

[113] YEC – Yachiyo Engineering Co. Ltd. (1995a): The Study on the National Water Resources Master Plan in the Republic of Zambia.- Japan International Cooperation Agency & Republic of Zambia, Ministry of Energy and Water Development, Final Report – Main Report, Oct. 1995; Lusaka.

[114] YEC – Yachiyo Engineering Co. Ltd. (1995b): The Study on the National Water Resources Master Plan in the Republic of Zambia.- Japan International Cooperation Agency & Republic of Zambia, Ministry of Energy and Water Development, Final Report – Supporting Volume 1, Oct. 1995; Lusaka.

[115] YEC – Yachiyo Engineering Co. Ltd. (1995c): The Study on the National Water Resources Master Plan in the Republic of Zambia.- Japan International Cooperation Agency & Republic of Zambia, Ministry of Energy and Water Development, Final Report – Supporting Volume 2, Oct. 1995; Lusaka.

APPENDIX 1 Operational Planning Matrix

APPENDIX 2 Concept of Hydrogeological Map of Lusaka