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Groundwater Resources of the Mwembeshi and Chongwe Catchments including the Lusaka Region

A Brief Description of Physiography, Geology, Climate, Hydrology and Groundwater Systems of the Area

Prepared as a technical co-operation project between the governments of Zambia and the Federal Republic of Germany

REPUBLIC OF ZAMBIA
Ministry of Mines, Energy and Water Development
Lusaka, Zambia

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Reviewed by Hans Klinge, Andreas Günther & Volker Hennings

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Foreword

The Groundwater Resources for Lusaka Province project was proposed and implemented by Government of Zambia through the Department of Water Affairs (DWA) with support from the Federal Republic of Germany through the Federal Institute for Geosciences and Natural Resources (BGR). The project started in January 2010 and covered a 36-month implementation period ending December 2012. The project was planned to fulfil the urgent need for groundwater resource assessment in the Chongwe and Mwembeshi catchments, including the Lusaka City area. It was aimed at strengthening the capacities of the water sector in Zambia with special emphasis on groundwater by compiling a groundwater database which contains information on borehole data, geology, yields of boreholes and water quality and hydrogeological maps.

The information generated by the project are useful for regulation of groundwater development, use and management in the study area. Furthermore the project was intended to be a model for groundwater assessment in other catchments in the country.

I am gratified to note that the outputs of the project which include trained manpower, establishment of a groundwater database and hydrogeological maps will be useful to the national planning and regulation authorities, especially in view of the new Water Resources Management Act. I am therefore pleased to launch the hydrogeological maps, technical documents and the brochure produced by the project which will play an important role in the implementation of the Integrated Resource Management Plan to achieve sustainable water resources management and development. This will ensure equitable provision of water in adequate quantity and quality for all competing users, at reasonable cost, with security of supply under varying conditions, supporting economic growth and improving livelihood.

The produced hydrogeological maps, groundwater information, technical manuals, and guidelines for groundwater resource management in the Lusaka region are important for water resource managers, academicians, politicians, water users and other interest groups. However, what remains is the challenge to put it to use and help to achieve the national goal of economic growth and poverty eradication through sustainable development and management of groundwater resources in the country. It is however notable that the limited information on groundwater data was one of the main challenges met during the implementation of the project. In this regard the Government appreciates the continued support of the Federal Republic of Germany through BGR.

Finally, I wish to commend the GReSP Project Team, DWA management and BGR for successfully implementing the project and producing the project documentation including this brochure which highlights various issues addressed by the project.

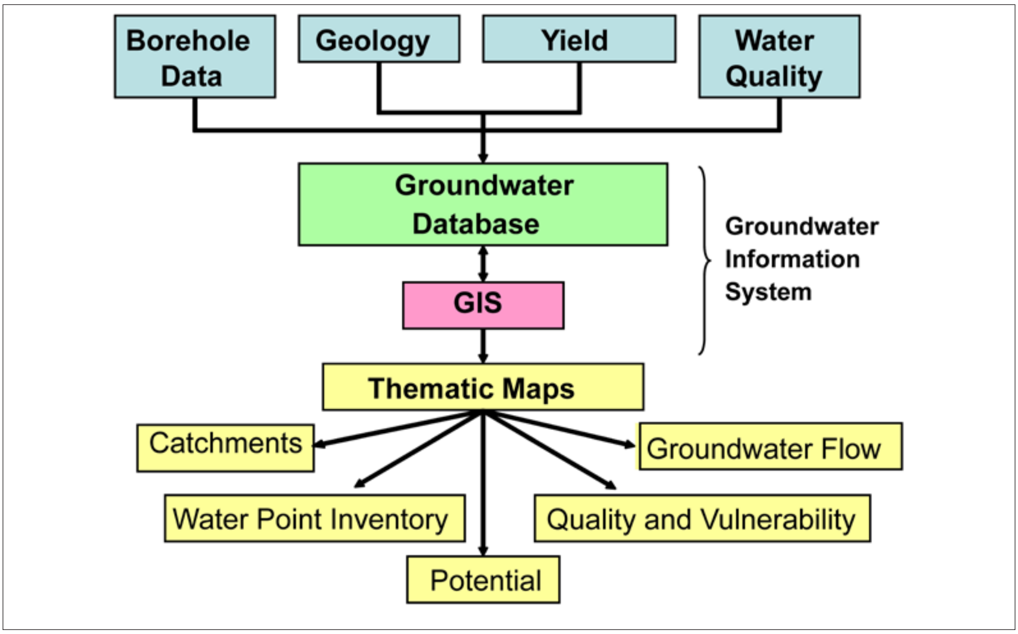
George K. Zulu
PERMANENT SECRETARY
Ministry of Mines, Energy and Water Development

Executive Summary

In order to ensure the sustainable development and use of water resources, an integrated management is needed, including surface water and groundwater as stipulated by the Zambian Water Resources Management Act. The basis of such an integrated management is a sound assessment of the available quantities and qualities of surface and groundwater. The effectiveness of such management strongly relies on the institutional framework and the availability of qualified staff at planning institutions. The main aim of this project therefore is to enable the relevant planning authorities to apply integrated water and landuse planning in the Chongwe and Mwembeshi catchment areas including Lusaka. A professional comprehensive groundwater information system was established at the Department of Water Affairs and capacity was built in the key institutions. Through comprehensive groundwater investigations and surveys the groundwater potential, the current pollution status and potential risks as well as the vulnerability of the groundwater systems were thoroughly assessed.

As part of these investigations one hydrogeological map at scale 1:250,000 and two, more detailed maps at scale 1:75,000 were developed. The design and legend of the maps follow international guidelines and can be adopted as a standard for groundwater maps of other regions. For future studies and exploration drillings, other thematic maps can readily be prepared at various scales from the comprehensive Geographic Information System.

This publication reviews the state of knowledge and provides references for further reading on the geography, climate, geology, hydrology and groundwater in the area comprising the Mwembeshi and Chongwe catchments, and partly beyond. It accompanies the three thematic maps together with a manual which provides detailed explanations on the use of the maps.



Flowchart showing the concept of developing a groundwater information system.

In the Mwembeshi and Chongwe Catchments over 90 per cent of all groundwater is hosted by hard rock including karst formations. The carbonate rocks host abundant groundwater resources that are tapped for commercial agriculture and for domestic and industrial water supply to the City of Lusaka. On the hydrogeological maps the various marbles of the Katanga system were categorised as groundwater systems of "high" or "moderate to high" potential with exceptional permeability and yields. However, since these aquifers are very heterogeneous, groundwater exploration is not a straightforward task, and the importance of modern siting methods is emphasized for further development of these groundwater bodies.

Most other rocks found in the area including igneous rock, gneiss, schist, quartzite and metasedimentary rocks generally form aquifers of limited potential, but locally conditions can be more favorable. The potential of the vast sediments of the Kafue Flats is variable due to different depositional domains and was rated "limited to moderate" in potential.

The overall groundwater quality in the Lusaka region meets most targets of both national and international drinking water standards and hence, is in most places well suitable for drinking water supply. In terms of bacteriological contents, however, groundwater is unsuitable for drinking in most of the high-density urban areas in Lusaka, unless disinfected by chlorination. Another concern is the nitrate concentration in these areas which are equally caused by the lack of safe sanitation services. Poor on-site sanitation facilities are currently the largest threat to groundwater quality in the urban area. The uncontrolled use of agrochemicals, the discharge of industrial chemicals and the negligent handling of leakages from industrial storage tanks are additional pollution risks but often occur locally, as high rainwater infiltration rates dilute contaminants to a high degree.

The need to protect the resource against contamination cannot be over-emphasized, especially in the fast growing City of Lusaka with ever increasing demand for clean water. Areas with extreme and high vulnerability such as the Lusaka Dolomite aquifer that are exploited for the production of drinking water need to be considered for the establishment of protection zones, as the groundwater in these areas is very likely to be affected in the event of pollution. The concept of groundwater protection through restrictions in land-use has to become an integral part of city planning in Lusaka.


Solid waste dumped in Lusaka Dolomite rock

A continuous and extended monitoring of groundwater water tables, abstraction and quality as has been established by the Department of Water Affairs in the course of the project is considered crucial for a more refined groundwater resource assessment and management. Continuous long-term monitoring is essential in order to identify possible impacts of climate change on water resources. Groundwater level observations can be used to identify trends in groundwater recharge, storage and availability. Groundwater quality monitoring can help to detect additional pollution sources or the potential gradual degradation of water quality.

The developed groundwater information system, the groundwater maps and the continuous monitoring efforts will support efforts on exploring, managing and protecting the groundwater resources. It is of hope that the information gathered will be of great use to officials at the ministries on national and district level as well as to technicians of the commercial utilities, city planners, consultants and to the water sector as a whole.

Table of Contents

Foreword 3

Executive Summary 5

Introduction 11

Physiography 14

Geology 21

Climate 27

Hydrology 32

Water Supply and Sanitation 40

Groundwater Resources 43

Groundwater Quality and Protection 54

Groundwater Maps 59

Conclusions and Recommendations 60

References 63

Introduction

Groundwater resources of the Mwembeshi and Chongwe Catchments – A vital and vulnerable resource for the Capital's socio-economic development

The Mwembeshi and Chongwe catchments are located in the central areas of Zambia and cover an area of 4,500 and 5,150 square kilometres, respectively (Figure 2). The Mwembeshi is a north-bank tributary to the Kafue River whereas the Chongwe River flows in southward direction into the Zambezi. Administratively, the catchments include large portions of Lusaka Province as wells as parts of Chibombo and Mumbwa Districts of Central Province.

Open groundwater surface in Lusaka South

Zambia's capital Lusaka is situated on an elongated plateau that divides the subcatchments of the Kafue River (including the Lower Mwembeshi River catchment below the Chunga River) located in west- and southward direction of the City from the Upper Mwembeshi and Chongwe river subcatchments in the east and northeast. Geologically, the plateau is made of very old carbonate rocks of Precambrian age that host a very productive groundwater body supplying water to the rapidly growing population of Lusaka. The abundance of groundwater is also instrumental for agricultural and industrial development. In this sense, the Mwembeshi and Chongwe Catchments arguably share Zambia's most significant groundwater reserve.

Like elsewhere in Zambia, the climate is sub-tropical with a clear distinction between the cool and hot dry season lasting from May to October and the wet season between November and April. Rainfall totals and intra-seasonal distribution vary greatly from year to year. The area receives long-term average annual rainfall in the order of 800 mm to 850 mm. Due to the large seasonal variation, however, the flow of most rivers and streams with the exception of the Chongwe River reduces to a trickle or ceases completely during the dry season despite the relative high annual rainfall totals.

Drinking water for the City of Lusaka and Chongwe, the second largest settlement in the area, is supplied by the Lusaka Water and Sewerage Company (LWSC). In 2011 a total of 88 million cubic meters were produced to supply the population of Lusaka. 56% of this volume was pumped from close to 100 public wells tapping the vast groundwater reservoir whilst the remainder was supplied from surface water through a pipeline from Kafue River.

According to preliminary results of the 2010 national census the population of Lusaka Province has risen to almost 2.2 million. Lusaka and Kafue Districts en-

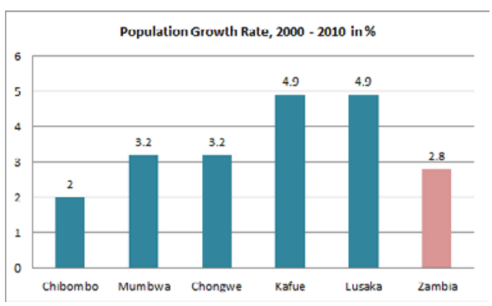


Figure 1 Population increase over the last decade in selected districts of Zambia (Source: [13]).

countered by far the highest population growth of 4.9% over the last decade countrywide [13]. This is generally ascribed to the large increase of Lusaka's urban and peri-urban population. The rapid increase of the City in terms of population number and settlement area will further augment the demand of water. According to the Lusaka Master Plan [29] the water demand is estimated to reach 221 million cubic meters per annum by 2030. With the rapidly growing development there is an obvious need to better protect groundwater from pollution and, in particular, to the provision of safe sanitation.

Commercial farming along the outskirts of Lusaka (York Farm)

Commercial irrigation farming generates the second largest water demand in the area. Extensive irrigation zones within the Mwembeshi and Chongwe catchments are present to the northeast and east of Lusaka along the Chongwe river and its tributaries, namely the Ngwerere and Chalimbana streams, and to the south and west of Lusaka, an area that extends into the adjacent catchment of the Chilongolo stream. An additional irrigation zone has developed in the Chisamba area to the north where a similar carbonate

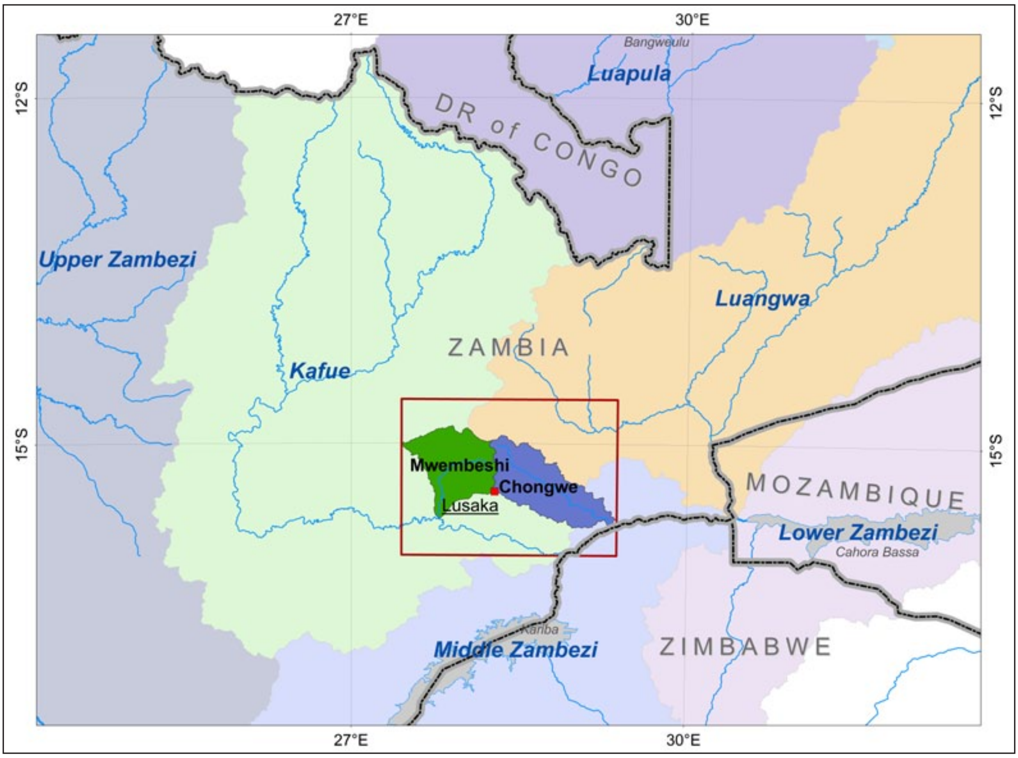


Figure 2 Map Area: Mwembeshi and Chongwe Catchments.

rock formation provides favourable conditions for groundwater production. While some of the water is pumped from larger dams such as the prominent Ray's Dam in the Upper Chongwe and smaller dams along streams, the bulk of water for irrigation purposes is exploited from groundwater reservoirs. It is estimated that the amount of water used for irrigation in the Lusaka area (excluding the Chisamba area) each year is about 25 million cubic meters of groundwater and 15 million cubic meter of surface water [6]. Large amounts of predominantly groundwater are also consumed by industries such as cement producers and the local beverage industry. In addition, groundwater is exploited through private boreholes for irrigation of lawns and gardens.

Outside Lusaka's urban and peri-urban areas and the irrigation belts groundwater constitutes the only reliable and safe water source available throughout the year. The population that inhabits these vast and often remote rural areas live primarily on rain-fed agriculture which is highly undependable.

To ensure the sustainable development and use of the catchments' water resources, the increasing demand for groundwater in agriculture, commercial and domestic use needs to be regulated. This requires an integrated management of the water resources including surface water and groundwater as stipulated by the Zambian Water Resources Management Act. Integrated Water Resources Management has accurately been defined by the Global Water Partnership Technical Advisory Committee [21] as *"a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."*

The basis of such an integrated management is an assessment of the available quantities and qualities of surface and groundwater. An effective management of these resources strongly relies on the institutional framework and the availability of qualified staff at planning institutions.

Against this background, the project "Groundwater Resources for Southern Province" (GReSP) that was launched in 2005 was extended to comprise the Chongwe and Mwembeshi catchment areas including Lusaka. As a major accomplishment of the project, a professional comprehensive groundwater information system was established at the Department of Water Affairs including a water point database and a series of thematic maps showing groundwater usage, potential and vulnerability. Through comprehensive groundwater investigations and surveys the groundwater potential, the current pollution status and potential risks as well as the vulnerability of the groundwater systems were thoroughly assessed. In addition the project implemented various measures to train staff in the fields of groundwater investigations and scientific studies.

The Lusaka Plateau southeast of Lusaka

Physiography

Topography

The topography of the Mwembeshi and Chongwe catchments is visualised in Figure 4 using a Digital Elevation Model (DEM). The elevation of the ground above sea level is displayed at 100 meter intervals.

The upper part of the **Chongwe Catchment** forms a gently dipping overall weakly dissected surface sloping southwards with the elevation dropping from 1,150 to 1,180 meters above sea level (asl) from the Chongwe headwaters to about 1,000 meters asl some 25 kilometres downstream of the Chalimbana confluence. To the east of the catchment the Changala and Chainama Hill ranges rise abruptly from the general surface level with maximum altitudes of just above 1,400 meters asl. These hills locally form the divide between the Chongwe and the Lunsemfwa basins.

Further south, the elevation sharply drops along the **Zambezi graben system** from about 1,000 meters asl to 365 meters asl near the confluence to the Zambezi River. In this river section, the Chongwe and its tributary streams created well defined deep-cut linear valleys undergoing active erosion within a rugged and dissected landscape. With an altitude of 1,412 meters asl the Chinumbwe Hill in the southern parts forms perhaps the highest peak within the catchment.

The **Mwembeshi Catchment** is characterised by an overall relatively flat undulating terrain (peneplain) gently sloping west or south which is broken by isolated hills or low ranges of resistant rock. The maximum altitude of the undulating hills that are typical for the upper catchment range from 1,100 to 1,200 meters asl. Only the hills within the Kawena Forest area located in the far northwest of the catchment reach heights of above 1,200 meters asl. In some areas, resistant quartzites form prominent ridges rising some 50 to 70 meters from the general surface. The southern (lower) catchment area is part of the monotonously flat flood-plains of the Kafue, the so-called **Kafue Flats**. The confluence of the Mwembeshi is at an altitude of approximately 978 meters asl.

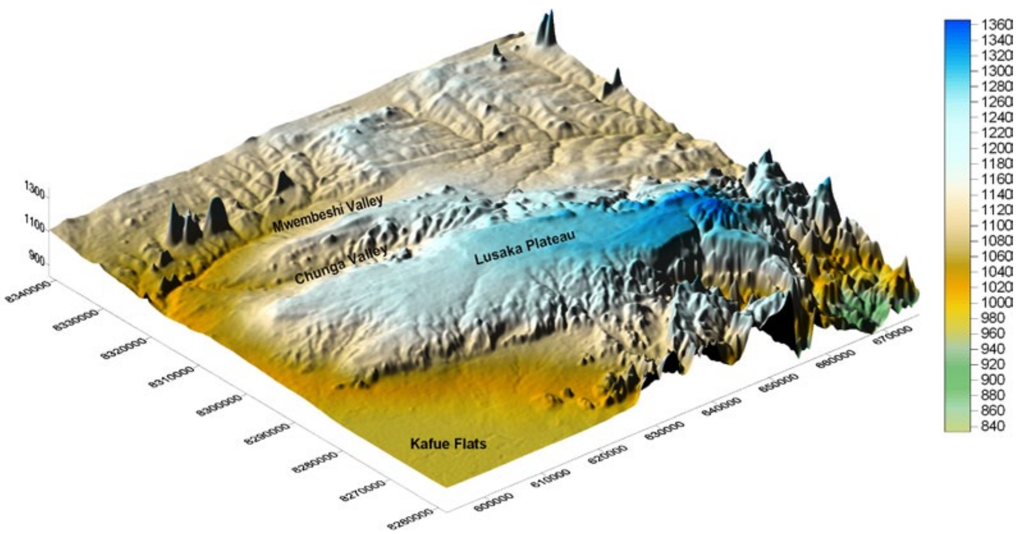


Figure 3 Block diagram of the Lusaka Plateau based on the developed DEM (vertical exaggeration 26x).

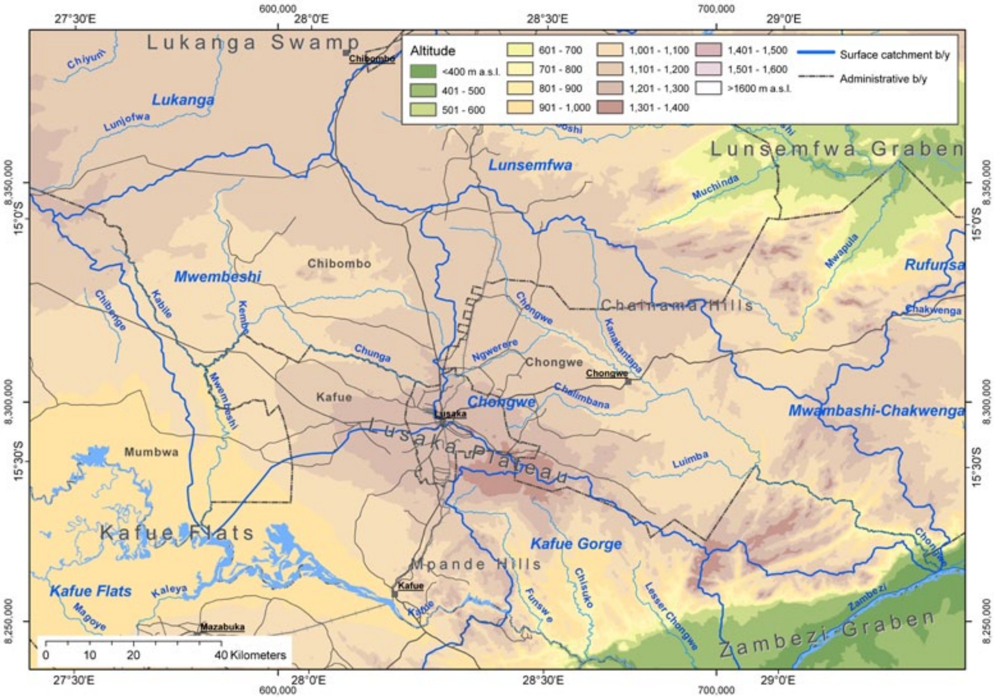


Figure 4: Digital Elevation Model (DEM) with elevation zones at 100 m-intervals.

Located in between the two river catchments, the **Lusaka Plateau** forms a dominant topographic feature in the area. The plateau is an about 70 km long and 10 km wide ESE-WNW stretching low ridge (Figure 3). Its elevation ranges from 1,200 in the west to above 1,300 meters asl in the east with some hills found to the east of the plateau reaching a maximum altitude of up to 1,370 meters asl.

Vegetation

The vegetation is generally strongly linked to the source rock on which the soils have developed. According to the vegetation map of Zambia [47] the most common vegetation types in the area are munga woodland and miombo woodland.

Munga is the prevailing vegetation type in the Mwembeshi Catchment. It is an open, park-like one- to two storeyed savanna woodland with up to 18 meters high individual leave-shedding (deciduous) trees. Munga in fact means “thorn” in one of the local languages. Along the boundaries of the Kafue Flats, on mostly colluvial, poorer drained deposits, the woodland tends to be more open, with Acacia as the predominant species. *Combretum* and *Terminalia* species predominate on higher better drained sites.

Munga woodland near Kanakantapa

Miombo is a type of two-storeyed woodland that usually develops on eluvial coarser-grained sandy to finer-grained sandy-clay soils. It is dominated by semi-evergreen trees (predominantly *Brachystegia* and *Isoberlinia* species) 15 to 21 meters high with a well-developed grass layer under an open or partially closed canopy. The woodland is interspersed by dense, tall grasses growing in seasonally wet dambo soils and clays. Miombo is found on the plateau and adjacent hills as well as down on the escarpment. It is prevailing in most areas of the Chongwe and in the upper regions of the Mwembeshi catchment ([19], [44]).

Hill covered with miombo woodland, Upper Chalimbana Catchment

In the hotter and drier climate of the Lower Zambezi valley the miombo woodland is replaced by **mopane** woodland and scattered baobab and palm trees. This is a one-storeyed woodland with deciduous trees and an open canopy 6 to 18 meters in height. The mopane vegetation zone is typically interspersed by patches of munga woodland.

The carbonate rocks as for example on the Lusaka Plateau often have only a thin soil cover and are typically covered by scrub grassland ([3], [45]). Around Lusaka and in areas with intensive agriculture the natural vegetation has been extensively cleared.

Along the drainage lines grass growing from water-logged soils is predominant. This so-called *edaphic grassland* can be divided into dambo grassland, riverine grassland, and floodplain grassland. These vegetations are associated with the streams and rivers, floodplains of the larger rivers or seasonally flooded swamps. The vast alluvial and colluvial soils of the Kafue Flats and bordering plains support flood-plain grassland.

Soils

Information on the distribution of soils is available from the Zambian exploration soil map at scale 1:1 million [48].

The soil distribution appears to be mainly controlled by morphology (e.g. slope and position) followed by parent material. The three most common soil types in the area are (Figure 5):

1. Leptosols which are very shallow, extremely stony or gravelly and well-drained soils, prevail in the hilly areas of the Chongwe Catchment to the East and along the escarpment to the south.
2. Lixisols, a soil type with high-base status having a higher clay content in the subsoil than in the topsoil as a result of soil forming (pedogenetic) processes, developed on flat or gently sloping areas in the upper regions of the Mwembeshi Catchment to the north-west of the area.
3. Vertisols, heavy clay soils with a high proportion of swelling clays, are found in the poorly drained unconsolidated deposits of the Kafue Flats.

A complete description of all types present in the catchment areas is given in Table 1. The three main soil groups commonly occur in association with other soil variants. On foothills or plateau type terrain leptosols are often interspersed or replaced by acrisols where the parent material is made of acidic basement rock. In less acidic rock leptosols are associated with lixisols. A good correlation can be observed between these two soil types and the occurrence of often carbonaceous schists of Katanga age. Along the partially better drained margins of the Kafue Flats vertisols are found in association with alisols.

Apart from the major soil types described so far there are two notable areas with phaeozem as the predominant soil variant. Phaeozems occur in the flat to gently sloping area near Chisamba and along a 50 km by 8 km wide band to the southeast of the Lusaka Plateau. Phaeozems are dark soils rich in organic matter and particularly fertile. Geologically, the occurrences appear to be correlated with probably colluvial deposits of carbonaceous rocks (Lusaka, Nyama and Cheta formations).

Soil of the Makeni Series (Lixisol) at Mt. Makulu Research Station

On the **Lusaka plateau** and on calcareous horizons of the Cheta Formation leptosols partially in association with lixisols or phaeozems with a shallow or moderately deep thickness varying from a few decimetres to three meters are developed. Locally these soils are known as the "*Makeni Series*". The texture corresponds to sandy loams or clay loam. The soil colour ranges from red to brown and mainly depends on the content of iron oxides. Outcrops of hard rock are frequent. So-called pisoplinthic horizons or layers containing nodules that are strongly indurated by iron can frequently be observed. The soil commonly forms pockets between solution pillars of the carbonate rock that are known as *karrenfelder*.

"Black soil" of the Cheta Series on a transporter at southern Lusaka Plateau

Along dambos or near springs, seepages and streams, in particular along the northwestern edges of the Lusaka plateau, poorly drained dark-grey to blackish, fine-textured and heavy calcareous "vertic" soils occur. This type of soil is locally known as "*Cheta Series*" and normally too wet for cultivation but it contains more clay and humus and is extracted and used as a fertile substratum for gardens [3].

Pisoplinthic indurated nodules found on the Lusaka Plateau

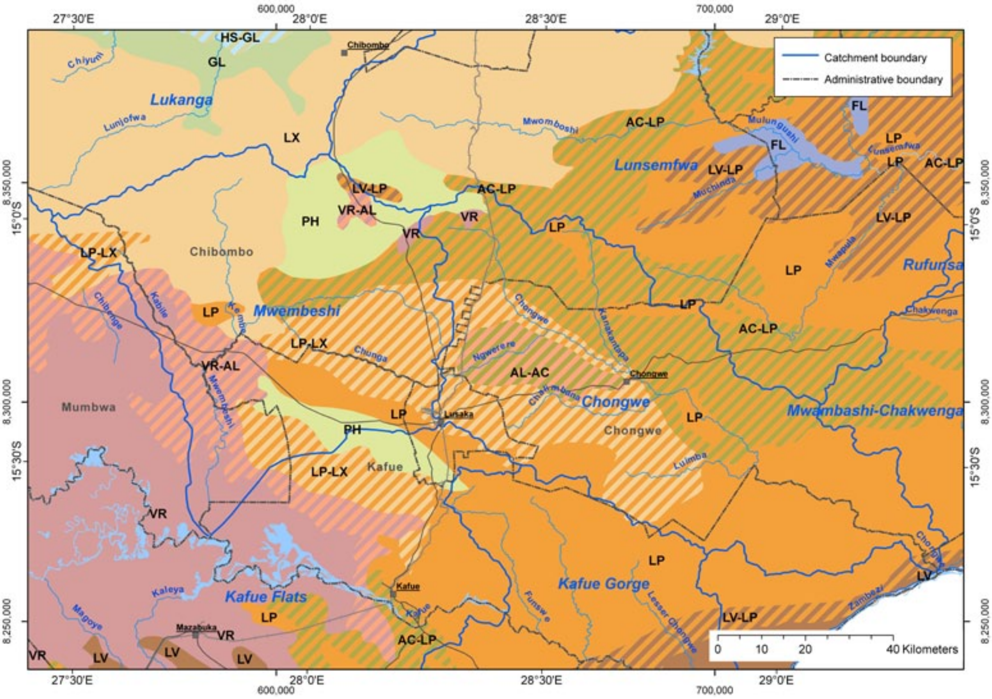
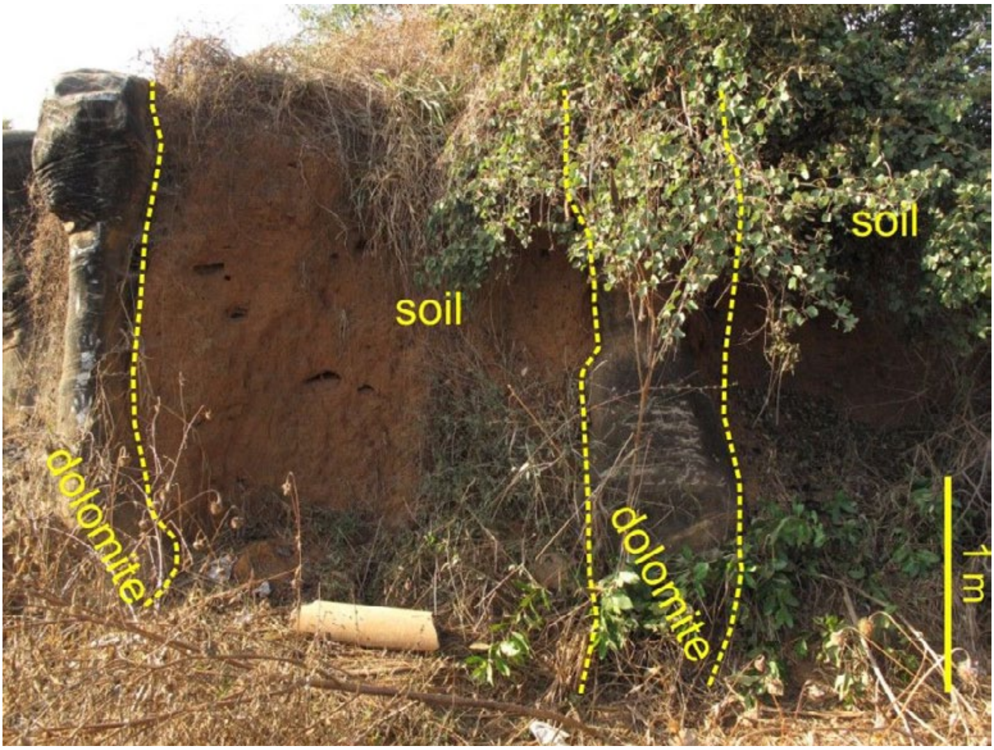


Figure 5 Soils of the Mwembeshi and Chongwe Catchments and adjacent areas. Codes represent individual soil units. Explanations to the soil codes are given in Table 1. (Modified after Zambian Exploratory Soil Map 1:1,000,000 [48]).



Soil forming “pockets” between solution pillars of Lusaka Dolomite

Table 1: Soils in the Mwembeshi and Chongwe catchment areas and the associated morphology and geology. The soil code corresponds to the labels in the map shown in Figure 5. Soil units according F.A.O./UNESCO classification [18].

Soil code	Soil unit	Description	Associated morphology and/or geology	Area coverage in 1 [%]	Area coverage in 2 [%]
AC-LP	Acrisol & Leptosol	Association of acrisols and leptosols; arcisols are acidic 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.	Undulating topography with hilly parts; usually from weathering of acid rocks and strongly weathered clays (Basement gneiss and schist)	7.6	31.6
AL-AC	Alisol & Acrisol	Association of alisols and acrisols; alisols are 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.	Undulating topography or gently sloping hills on unconsolidated material; near Lusaka Int. Airport	--	7.8
FL	Fluvisol	Genetically young soils developed in alluvial deposits.	Alluvial deposits along rivers and lakes	--	--
PH	Phaeozem	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.	Flat or undulating areas with mostly unconsolidated, predominantly basic materials; SE of Lusaka and Chisamba areas	14.5	0.8
VR	Vertisol	Churning, heavy clay soils with a high proportion of swelling clays. These poorly-drained soils form deep wide cracks from the surface downward when they dry out.	Poorly drained depressions; on colluvial and alluvial deposits with high proportions of swelling clays; Kafue Flats	6.2	0.4
VR-AL	Vertisol & Alisol	Association of vertisols and alisols	Along the partially better drained margins of Kafue Flats	14.8	--
HS-GL	Histosol & Gleysol	Association of histosols and gleysols; histosols are soils formed in organic material, i.e. peat	Swamps and marshland (Lukanga Swamp)	--	--
GL	Gleysol	Wetland soils that are saturated with groundwater for long enough periods to develop gleyic colour pattern	Depression areas with shallow groundwater; margins of Lukanga Swamp	--	--
LP	Leptosol	(Including lithosols) Very shallow soils typical for land with strongly dissected topography over continuous rock and soils that are extremely gravelly and/or stony and well-drained.	Land at high or medium altitude with strongly dissected topography, particularly eroding areas; Lusaka plateau, hilly areas and escarpment	6.2	33.6

Soil code	Soil unit	Description	Associated morphology and/or geology	Area coverage in 1 [%]	Area coverage in 2 [%]
LP-LX	Leptosol & Lixisol	Association of leptosols and lixisols	Undulating areas with hilly parts or at transition zone to escarpment; typically schists and psammites	24.0	25.4
LX	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.	Strongly weathered and strongly leached, often finely textured parent materials; schists, psammites, sandstones and gneiss in central plateau and rolling hills areas	26.3	--
LV	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.	Flat or gently sloping areas with usually unconsolidated materials including colluvium and alluvium; Zambezi Valley	--	0.1
LV-LP	Luvisol & Leptosol	Association of luvisols and leptosols	Hilly areas with gently sloping parts; Lower escarpment and Lunsemfwa Graben	0.3	0.4

1 = Mwembeshi Catchment, 2 = Chongwe Catchment

Geology

Geological evolution

The geology is of major importance to the assessment of groundwater 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.

The geological sequence of the area encompasses rocks of large lithological variety which were formed and metamorphosed over a long time range [16]. The oldest rocks associated with the basement have an age of well over 1,000 million years (Ma) and the youngest rocks were formed during the last thousands of years in an on-going process. Most of the rocks exposed in the area are of Precambrian age, i.e. older than 543 Ma, and are assigned to the Katanga Supergroup or the Basement Complex (Figure 7).

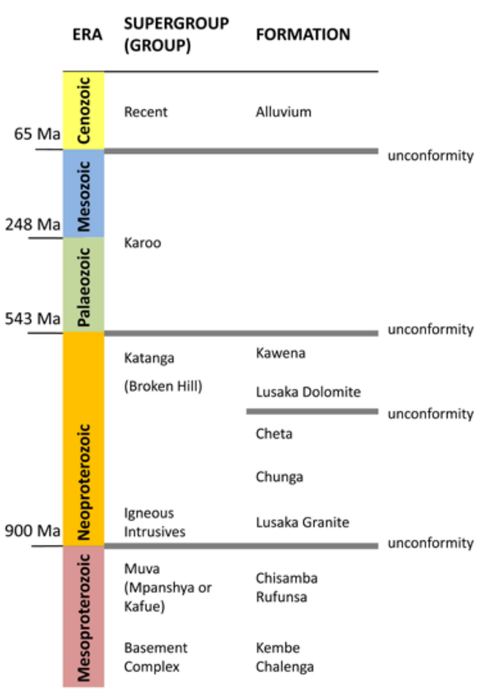


Figure 6 Major lithological subdivision in the Chongwe and Mwembeshi catchments.

The following tectonic deformation events were essential in the development of the geological setup in the area ([25], [28], [39], [40]):

1. The continental rifting (separation) of the ancient supercontinent Rodinia about 880 million years (Ma) ago. This was accompanied with thinning of the earth crust and intense magmatic activity.
2. The rifting created a sedimentary basin and led to the deposition of a succession of thick continental clastic basin deposits initially accompanied by volcanism. Further subsidence at the margins eventually allowed the development of a marine lagoon environment or invasion by the sea and the deposition of shallow marine (i.e. carbonaceous) sediments. The basin filled with rocks of the Katanga Supergroup is believed to have developed between 880 and 820 Ma [23].
3. The subsequent complex collision of two ancient tectonic plates, the Angola-Kalahari Plate comprising the Kalahari Craton and the Congo-Tanzania Plate comprising most of the Congo Craton led to the closure of the rift basin. This collision followed after the subduction of a southeast-northwest trending oceanic basin, and was accompanied by intense folding, thrusting, strike-slip faulting and high-grade metamorphism of the Katanga Supergroup and parts of the Basement. This tectonic event is related to the so-called "Lufilian Orogeny". It has been suggested that the Lufilian Orogeny occurred broadly equivalent to the continent-wide Pan-African Orogeny between 560 and 510 Ma ([24], [39], [42]).
4. The final tectonic structural event was the Karoo Rifting associated with the

break-up of Gondwanaland during the Permian (290 – 248 Ma) followed by the opening of the proto-Indian Ocean in the Jurassic (206 – 144 Ma) , and a final episode of rifting related to the initial development of the East African Rift system in late Cretaceous and early Tertiary times. The Precambrian rocks were exhumed under this transtenional or extensional tectonic regime. Normal (vertical) movements on structural contacts took place and segmented the subsurface into a horst-and-graben configuration which can be observed in the area.

Rock formations

The geology of the Mwembeshi and Chongwe Catchments and surrounding areas were mapped and described in detail by a number of geological reports of the Northern Rhodesian and Zambian Geological Surveys ([11], [12], [19], [44], [45]).

As a result of the tectonic structural events described above the area is largely covered by strongly folded overthrusted metasedimentary rocks of Katanga (Neoproterozoic) age which have been intruded by granitic and basic bodies [23].

Basement

The oldest rocks in the area with ages exceeding 1,000 Ma are exposed within the Basement Complex and the overlaying Muva Supergroup (Chisamba and Rufunsa formations of Mpanshya Group). The suite comprises mainly metamorphic rocks like gneiss, paragneisses with intercalated quartzite horizons, schist and minor amphibolite. The basement rocks in the Mwembeshi and upper Chongwe rivers have been named *Kembe Gneiss and Schist* after the Kembe River due to good exposures in some stream sections. The gneisses in the southern parts of the Chongwe River in the Chalenga Hills area are characterised by large lenses (so-called "augen") of quartz and feldspar and known as *Chalenga Gneiss*.

Katanga Supergroup

Rocks of the Katanga Supergroup in the area are associated with the Lufilian Arc and the Zambezi Belt. These Neoproterozoic rocks are between 900 and 543 Million years old and have been deposited in an extensional tectonic setting within a shallow marine environment. Due to major tectonic events after their deposition (Lufilian Orogeny) they have undergone intense deformation and metamorphism of varying degree.

Due to the intense deformation and metamorphism of the Katanga sequence, the stratigraphic relationship 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. A widely adopted stratigraphic classification divides the metasedimentary cover into four formations: the Chunga Formation (Fm) comprising schist and

Outcrop of typical quartz-muscovite-biotite schist of Chunga Formation about 3 kilometers east of Mile Ten. Close-up shows a fine lamination quartzites, the Cheta Fm including schist and carbonates, the Lusaka Dolomite Fm and the Kawena Fm comprising (meta-) sandstone, siltstone and argillite.

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 lower and thicker of the two calcareous members is referred to as *Mampompo* Limestone [12]. The schists include various rock types dominated by quartzites, quartz-muscovite-chlorite schists and (finer-grained) quartz-muscovite schists.

Marble of the Cheta Formation found in the Upper Chalimbana Catchment with a sugary surface and crystalline texture and darker bands

The Lusaka Dolomite Formation 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.

In the Chisamba area north of the Mwembeshi Shear Zone a poorly exposed succession of phyllites, banded slates, quartz-muscovite schists and dolomites is overlain by a thick succession of limestones and dolomites with thin mudstone

Grey and white laminated Lusaka Dolomite with internal folds southwest of Jack Compound, Lusaka South

bands. The two sequences are known as Kangomba Formation and Nyama Formation (named after the Nyama River), respectively. The Kangomba Formation is probably a less highly metamorphosed equivalent of the Cheta and Chunga formations to the south, whilst the Nyama Formation probably correlates with the Lusaka Dolomite Formation [32].

The Kawena Formation occurs in the north-west of the Mwembeshi Catchment and its rocks are the youngest among the Katanga Supergroup in the area. The folded bedrock shows a low grade of metamorphism and is grouped into an upper and a lower member. The lower member (*Kawena Argillite*) consists of fine-grained often siliceous argillite which is a highly indurated mudstone. The upper member (*Kawena Sandstone*) predominately consists of grits - a hard, coarse-grained, siliceous sandstone - and feldspathic and calcareous iron-banded sandstones, and siltstones.

All carbonate rocks within the Katanga 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.

Lusaka Granite/Igneous rocks

The Lusaka granite is located about 20 kilometres north-west of Lusaka. The foliated coarse-grained granite intruded the marble and quartzite horizons of the Cheta Formation to the north and schist and amphibolite of the Chunga Formation to the south about 842 Ma ago. The granitoid rock is a coarse-grained adamellite, a silica rich (>65%) igneous rock with approximately equal proportions of orthoclase and plagioclase feldspars of uniform composition throughout its exposed area [49]. A number of smaller igneous intrusions occur in the areas south and west of the Lusaka Plateau and in the Chisamba areas predominantly as gabbroic plugs.

Karoo Supergroup

The Karoo Supergroup deposits are related to rifting accompanied by the establishment of large-scale graben systems. The rifting is related to the break-up of Gondwanaland and commences at late Carboniferous time (about 300 Ma) and continues until early Jurassic. Although outcrops of Karoo sediments are common along the Zambezi graben system these rocks are not exposed in the Chongwe Catchment.

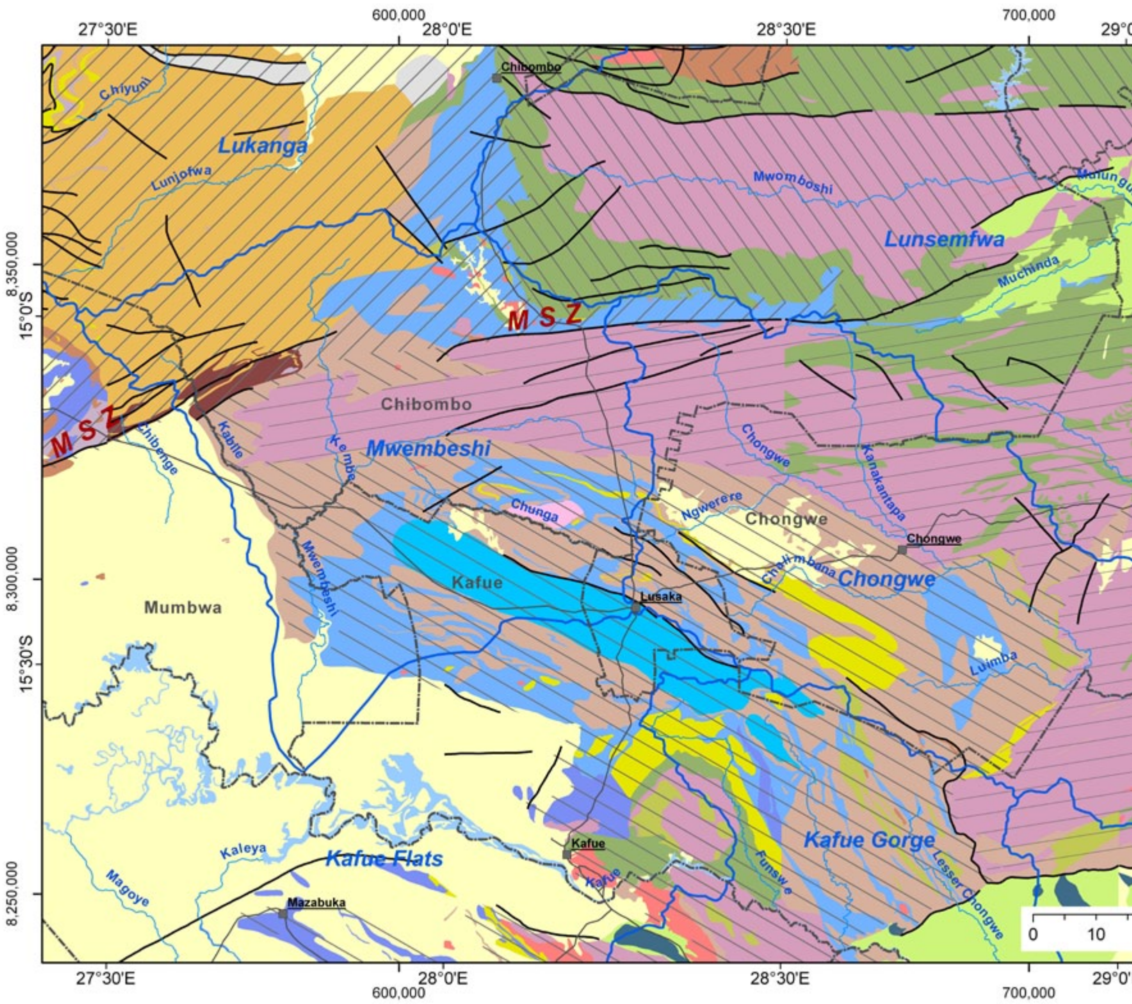
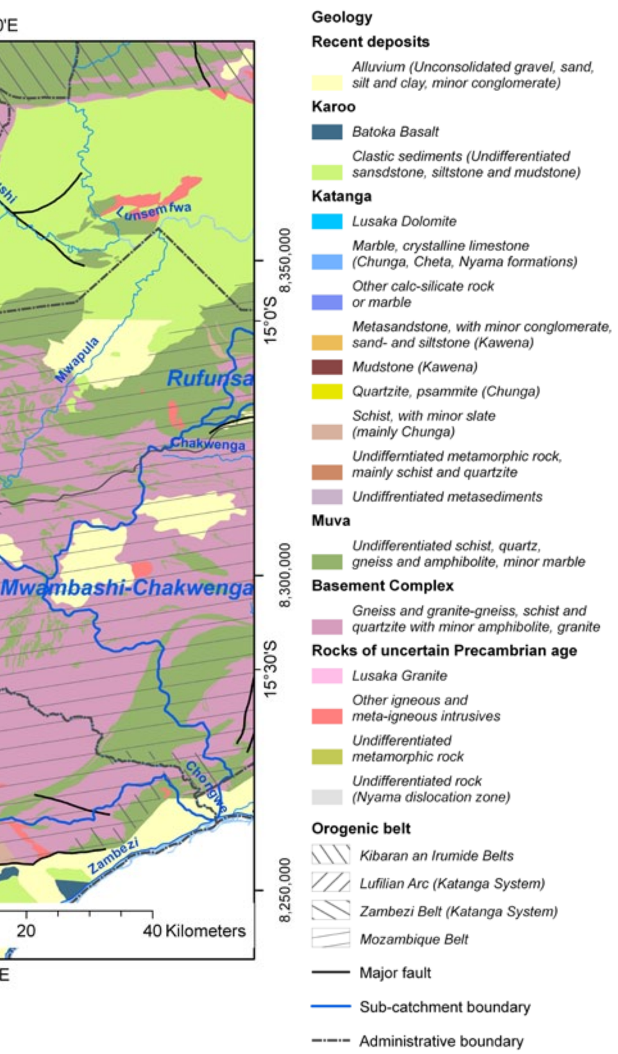


Figure 7 Geological map of the catchment areas with distribution of the main orogenic belts; MSZ = Mwembeshi Shear Zone (Map Source: Geological Map Series 1:100,000, distribution of orogenic belts after [28]).

Cenozoic deposits

With an age of less than twenty million years the Cenozoic deposits are the youngest sediments found in the area. They consist of unconsolidated or semi-consolidated clastic sediments. These include alluvium and colluvium deposits from the Kafue and Zambezi rivers and floodplain material in a large variety of grain size distributions. The Kafue Flats in the south of the Mwembeshi Catchment are covered by thick alluvium and black clay deposits [44].



Subsurface stratigraphy in the Lusaka area

A structural geological model of the subsurface geology across the Lusaka Plateau was constructed at a small scale (1:100,000) from sequential geological cross-sections (Figure 8). These cross-sections were produced using spatial information from geological maps (>2000 mapped geological fabric orientations) and digital elevation models.

From the geological model, the structural geometry of the subsurface geology can be inferred. In the Lusaka area, the structural setting of the lithostratigraphic units is subdivided by the long striking (WNW-ESE) "Lusaka Fault" (Figure 8), a major tectonic fracture system that most probably originated as a thrust/inverse fault during the Lufilian orogeny and was transformed to a normal fault during Mesozoic and Cenozoic extensional tectonics. The steeply SWS dipping "Lusaka Fault" separates the subsurface geology of the Lusaka area into a "northern domain" where the early Proterozoic Basement Complex is situated at relatively shallow depths, and a "southern domain" where the metasediments of the Katanga system reach maximum thicknesses.

The recent structural configuration of the northern domain can be characterized as a horst-and-graben setting with a structural high bounded by the "Lusaka" and "Chelston" normal faults. The Early Precambrian basement is situated at comparably shallow depths, hence the meta-sediments of the Katanga system show reduced thicknesses. In the southern domain, a higher structural level is exposed reflecting thick-skinned (basement-involved) "fold- and thrust belt" tectonics. Here, the early Proterozoic basement is situated in much higher depths (2 km), and the metasediments of the Katanga group reach maximum thicknesses (Figure 8).

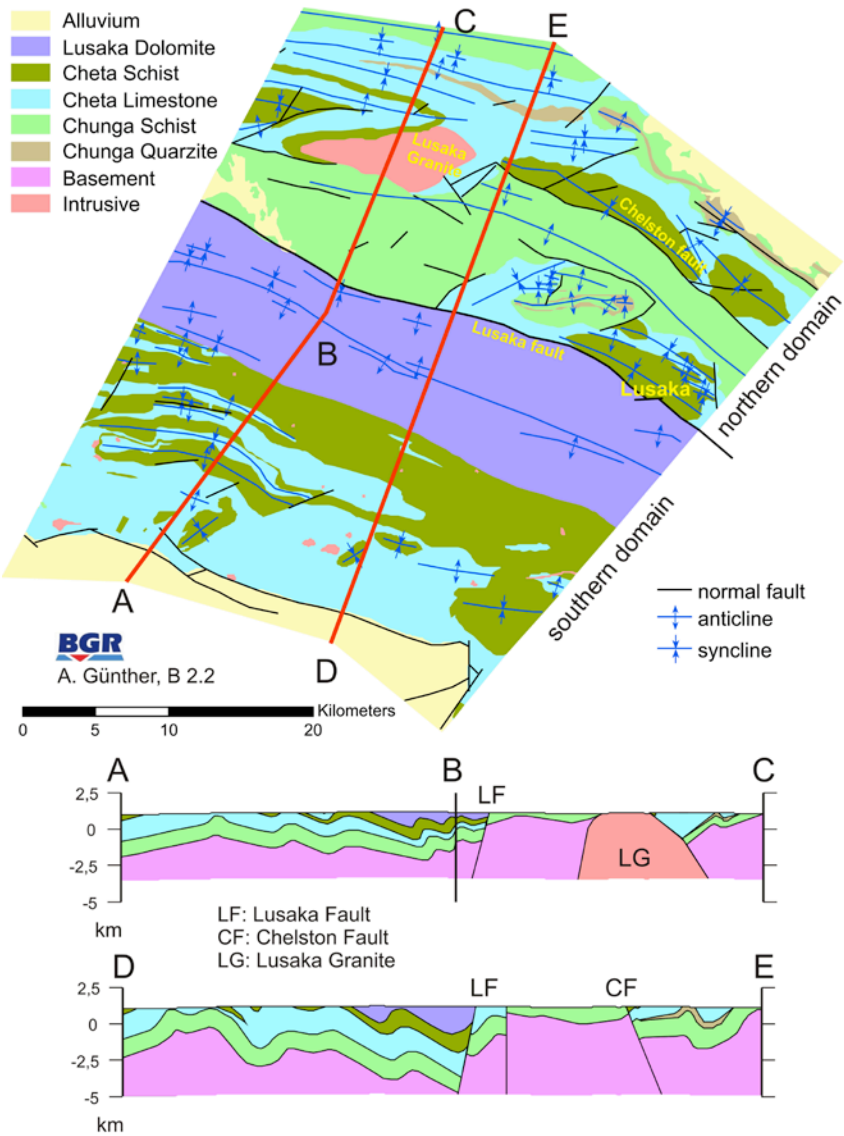


Figure 8 Structural geological map and cross-sections of the Lusaka area.

In general, the basal member of the Katanga system (Chunga formation, schists and quartzites) is the only layer present throughout the modelled area (except for the region covered by the Lusaka granite), and reaches maximum thicknesses of 2.8 kilometres. The hanging Cheta formation (limestones and schists) reaches maximum thicknesses of 3.8 kilometres in the southern domain. The Lusaka Dolomite locally reaches thicknesses of up to 2.2 kilometres south of Lusaka.

Climate

Most of Zambia's climatic conditions can be described as humid subtropical, with dry winters and hot summers, corresponding to Class *Cwa* according to the Köppen-Geiger classification. The Zambezi Valley experiences a hot, semi-arid Steppe climate with higher temperatures and lesser rainfall (Class *Bhs*). The weather conditions of the Zambian plateaus including the Lusaka area have been accurately described as a tropical continental highland climate [34]. Due to the combined effect of low latitude (15 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.

Commonly three seasons are distinguished:

1. Rainy season – a warm wet season from November to April
2. Cold season – a mild to cool, dry season from April to August
3. Hot season – a hot and dry season from September to November.

The rainy season in Zambia is associated with the southward shift of the so-called Inter-Tropical Convergence Zone (ITCZ). During the winter months the ITCZ is situated over the Sahel region at about 15°N. The ITCZ shifts southwards following the apparent movement of the sun. During January the position of the ITCZ over eastern Africa is at 17°S (Figure 9). The trade winds of both hemispheres converge into the low pressure area over the ITCZ. The ITCZ is an area of pronounced convective activity and therefore associated with heavy tropical rain.

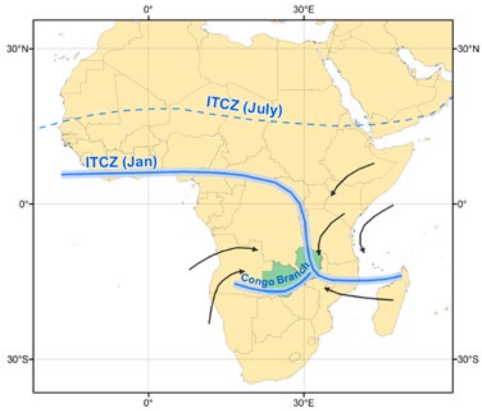


Figure 9 Approximate position of the ITCZ during the Southern Hemisphere winter (dashed line) and summer (thick line) and predominant wind directions during summer (arrows) (simplified after [34] and [41]).

The Zambia Meteorological Department operates three meteorological stations near Lusaka, namely at Lusaka City Airport, Mount Makulu Agromet and the International Airport (Table 2). More distant meteorological stations include Kabwe to the north, Mumbwa to the west and Kafue Polder to the south. Additionally there is a considerable number of voluntary rainfall stations.

Table 2 Meteorological stations in the Lusaka area and the wider region.

MET Station	Altitude [m asl]	Start of records [1)]
Lusaka City Airport	1280	1950
Mt. Makulu	1213	1961
Lusaka Int. Airport	1154	1967
Kafue Polder	978	1957
Mumbwa	1218	1978
Kabwe	1207	1950

[1)] Temperature and rainfall records.

Temperature and Sunshine

The mean annual temperature in Lusaka Province is 20.7°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.

The area receives sunshine similar to the national average. Sunshine duration measured at stations near Lusaka average at 7.7 hours compared to 7.8 hours per day countrywide [53].

Rainfall

The mean annual rainfall in the Chongwe and Mwembeshi catchment areas varies between 750 mm and 880 mm with the lowest values encountered in the lower-lying Kafue Flats and in the Zambezi Valley that lies in the rain-shadow of the escarpment. The rainfall distribution ("isohyetal") map shown in Figure 11 is based on stations with long-term data exceeding 25 years of records including stations from adjacent areas and neighbouring countries.

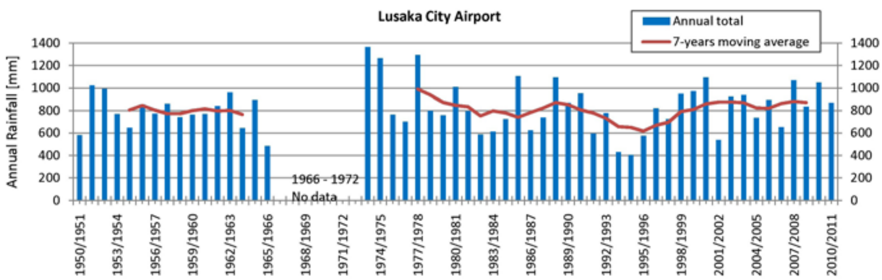


Figure 10 Long-term annual rainfall at Lusaka City Airport showing temporal variations (Source: Zambia Meteorological Department).

Table 3 Mean annual temperature, annual long-term rainfall and evaporation at stations in the Lusaka area and beyond (Source: Zambia National Water Resources Master Plan [53],1962-1993 period, based on data from Zambia Meteorological Department).

Station	Temperature	Rainfall	Rainfall days	Pan Evaporation 100%/75%	PET 3)	ET_{act} 4)	ET_{net} 5)	Runoff Coefficient 6)
	°C	°mm	Day	mm	mm	mm	mm	%
Lusaka City Airport	20.4	858	78	--	1533	730	-675	15
Mt Makulu Agromet	20.9	848	77	1578	1591	733	-743	14
Lusaka Int. Airport	20.7	865	77	1748	1590	739	-725	15
Kafue Polder	21.6	744	68	1592	1776	677	-1032	9
Mumbwa	20.6	900	84	--	1467	756	-567	16
Kabwe	20.7	886	83	1619	1586	751	-700	15
ZAMBIA	21.0	1001	97	1546	1574	816	-573	18

1) Mean annual temperature (1963-1992)
2) Applying a pan coefficient of 0.75
3) Potential Evapotranspiration, calculated using (revised) Penman (1948) equation [38]
4) Actual Evapotranspiration, calculated using Turc (1961) equation [50]
5) Net evaporation = Rainfall – Potential Evaporation
6) Runoff Coefficient = 1 – (Actual Evaporation/Rainfall)

Annual rainfall during the last thirty-year period from the 1980/1981 to 2009/2010 seasons at the meteorological stations in Lusaka varied between 801 mm at Lusaka City Airport, 827 mm at International Airport and 841 mm at Mt. Makulu averaging at 823 mm. Annual rainfall as given in the Zambian National Water Resources Master Plan [53] for the 1963-1992 period is slightly higher (Table 3). According to the same source, the average number of rainfall days per year is approximately 77.

Variability of both annual and monthly rainfall totals is considerable. The annual variation in rainfall at Lusaka City Airport which is the first station established in Lusaka is shown in Figure 10. The highest amount of rainfall ever recorded at the station fell during the 1973/1974 rainy season amounting to 1,364 mm. The lowest recordings ever observed at the stations are 430 mm and 405 mm and occurred during the two consecutive 1993/1994 and 1994/1995 seasons.

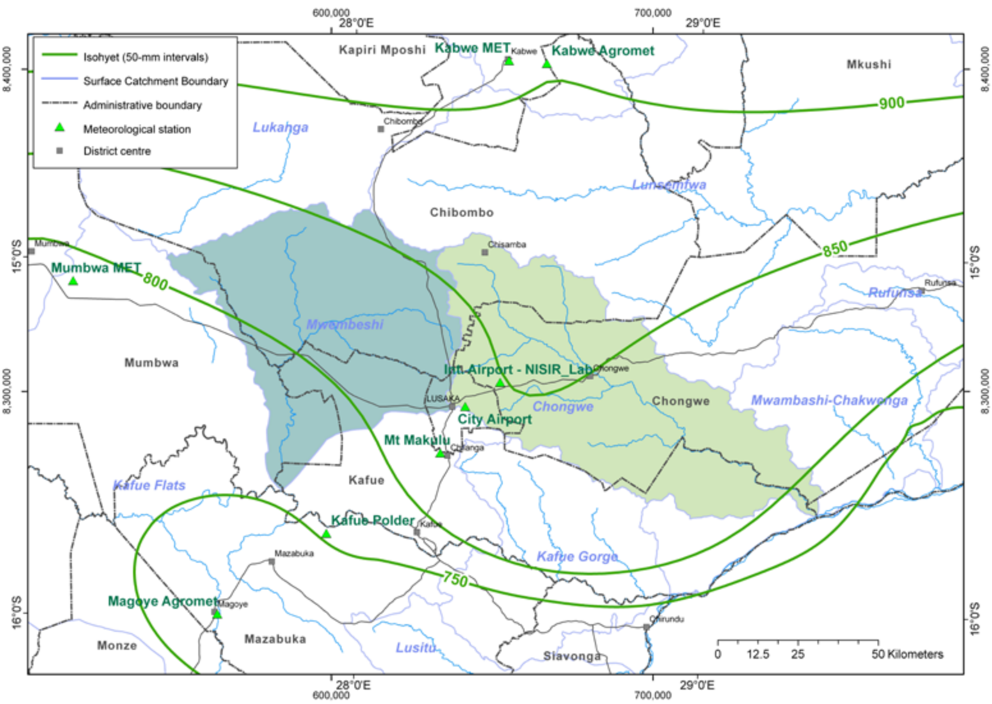


Figure 11 Location of meteorological stations and isohyetal map of annual rainfall (Data Sources: Zambia Meteorological Department).

The annual variation of monthly rainfall is controlled by the clear distinction between the wet season during summer and the dry winter. The wet and dry season are separated from each other by a short pre-rainy season (September – November) and post-rainy period (April-May).

Based on long-term rainfall data measured at the City Airport almost 95% of the total annual rainfall occurs during the five-month period from November to March, and 73% during the three-month period from December to February. The highest average monthly rainfall occurs in January with monthly totals averaging at 218 mm followed by December (203 mm) and February (183 mm). The winter months from June to August are practically without rain.

According to records of the Zambia Meteorological Department daily rainfall is equally variable. The highest ever observed daily rainfall amounts to 292 mm at Mt. Makulu, 190 mm at Lusaka City Airport, and 162 mm at Lusaka International Airport [53].

Evaporation

Table 3 contains available values for evaporation. Potential evapotranspiration (PET) is the amount of water that could be evaporated and transpired if there was sufficient water available. PET is commonly determined using the Penman equation (1948) [38]. In the Zambian National Water Resources Master Plan [53] values for PET obtained with a slightly revised version of the Penman approach range from 1,530 – 1,590 mm for stations situated in the Lusaka area and from 1,394 to 1,892 mm in Zambia.

After [4], using FAO's Grass Reference Evapotranspiration [10], annual sums of potential evapotranspiration are 1,908 mm for 1989/90 and 1,815 mm for 1983/84. These calculations suggest that PET is generally higher for Zambia if the internationally recognised FAO method is applied.

Long-term Class-A pan evaporation at Lusaka International Airport and Mount Makulu meteorological stations amounts to 2,331 mm and 2,104 mm, respectively. Evaporation from open water bodies such as lakes is often estimated by multiplying the pan evaporation by 0.75. Values corrected in such way for the two above mentioned stations result in 1,748 mm to 1,578 mm, respectively.

Actual Evapotranspiration from vegetated land surfaces (quantity of water that is actually removed due to the combined effect of evaporation and plant transpiration) is much lower than PET since surfaces and soils will gradually dry out between individual rainfall periods and markedly during the dry season. According to the National Water Resources

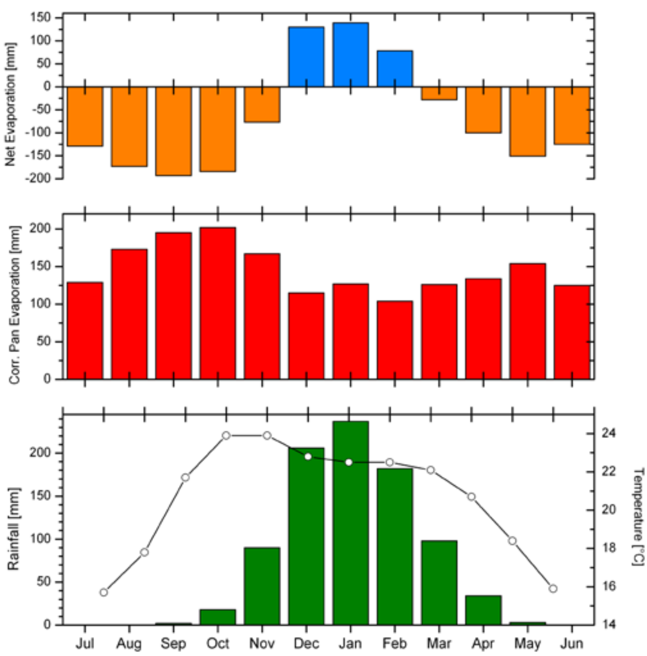


Figure 12 Seasonal variation of monthly mean temperature, rainfall and evaporation at Lusaka International Airport, period 1963 - 1993 (after [53], data source: Zambia Meteorological Department).

Master Plan annual actual evaporation based on the empirical and rather simplistic Turc (1961) equation [50] varies between 730 mm and 739 mm.

A recent, more sophisticated calculation of actual evapotranspiration that considers crop-specific transpiration and soil physical properties results in considerable lower values (<500 mm) for actual evapotranspiration in the area [4]. Results of this recent study are discussed in the chapter groundwater recharge and water balance below.

Net evaporation is defined as the difference between mean rainfall and potential evaporation and may be used as a measure for aridity. Due to high temperatures and the pronounced dry season, the net evaporation in the region takes negative values for all months except for December to February.

The seasonal variation of evaporation and net evaporation together with average monthly temperature and rainfall, temperature, at Lusaka International Airport are depicted Figure 12. It can be summarized as follows:

1. The highest (potential) evaporation (190 – 205 mm/month) is encountered during the hot season. Low potential evaporation (90 – 130 mm/month) occurs during the rainy months due to high humidity and during winter due to lower temperatures.
2. Actual evaporation can be assumed to peak during the rainy and post-rainy season when surfaces are wet and soils often become saturated with water.
3. Net evaporation is negative (i.e. PET exceeds rainfall) for all months except for December to February.

Hydrology


Kafue River some 15 km east of Kafue Bridge

River and streams

The Mwembeshi River drains an area that is part of the Lower Kafue catchment whereas the Chongwe River directly joins the middle Zambezi some 50 kilometres downstream of the Kafue-Zambezi confluence. The catchments areas are given in Table 4.

The total catchment area of the Mwembeshi reaches about 4,500 square kilometres. The streams generally form a dendritic drainage pattern. Three notable sub-catchments can be distinguished: The Kabile and Kembe Rivers are the main tributaries draining the north-west and central north of the catchment, respectively. The Chunga River drains the western part of the Lusaka plateau in west-north-west direction. The source of the Mwembeshi lies in the far east of the catchment within a distance of two kilometres from the village Ten Miles located


Flow in Mwembeshi River near Mumbwa Road Bridge during March 2010

along Great North Road. From there, the Mwembeshi flows roughly west above the confluence of the Chunga River and then south-west above the confluence with the Kabile River before turning south into the flood plains of the Lower Kafue. Because of the low velocity structure of the stream, meandering channels have developed in this section.

Flat headwater dambos and seasonal swamps are quite commonly found especially on schist and gneisses of the Basement Complex. They dry up completely in the hot season so that many streams have impersistent flow. Therefore, some of the larger streams including the Mwembeshi River are described to be seasonally reduced to a series of disconnected pools or stretches of surface water or to dry up altogether [44]. The Chunga River is one of the few watercourses characterised by perennial flow partially because it originates from spring lines encountered to the west of Lusaka. In addition, it collects a steady amount of discharge from Chunga wastewater treatment plant located in the west of Lusaka.

With 5,150 square kilometres the catchment area of the Chongwe River is slightly larger compared to the Mwembeshi. Bigger sub-catchments include the Kanakantapa River in the northeast, the Ngwerere and Chalimbana Rivers which drain the eastern parts of the Lusaka plateau in north-east and eastern directions respectively, and the Luimba River that flows east to join the middle Chongwe. The Upper Chongwe above the confluence of the Chalimbana River has an area of 2,670 square kilometres. This area is of particular interest due to its large proportion of cultivated and irrigated land.

Chongwe above Kanakantapa confluence, February 2012

Dendritic drainage patterns are most common. Gentle gradients predominate in the upper and middle sections of the basin. With a drop in altitude of about 500 meters towards the Zambezi Graben the Lower Chongwe is characterised by steep gradients with deeply incised valleys and a rugged landscape.

The Chongwe and its major tributaries, the Kanakantapa, Ngwerere, Chalimbana and Luimba xx rivers are perennial, i.e. they flow throughout most of the year. The Ngwerere receives large amounts of storm water runoff from the Lusaka City area in addition to discharge of the Manchinchi/Garden and Ngwerere wastewater stabilization ponds of Lusaka Water and Sewerage Company. Like in the Mwembeshi area, smaller rivers and streams often fall dry during the hot season (August to October). During the rainy season the flow of these minor rivers is generally intermittent or driven by rainfall events. Intermittent streams only flow during a few hours or days after a rainfall event.

Table 4 Catchment and sub-catchment sizes.

Catchment	Sub-catchment	Area [km^2]
Mwembeshi		4,504
	Kabile	554
	Kembe	934
	Chunga	621
Chongwe		5,148
	Upper Chongwe *)	2,670
	Kanakantapa	483
	Ngwerere	299
	Chalimbana	654
	Luimba	590

*) below confluence of Chalimbana stream

The Lusaka Plateau forms in some sections the drainage divide between the Chunga, Ngwerere, Chalimbana rivers to the north and the lower Mwembeshi, Chilongolo and Funswe rivers to the south. The plateau is characterized by a striking absence of surface flow. A lack of surface drainage is also characteristic for the ESE-WNW stretching outcrop of Cheta limestone located between the Mwembeshi and Chunga Rivers. This is explained by the high permeability of the parent rock, highly metamorphosed limestone and dolomite that has undergone enhanced dissolution weathering (karstification) near the ground surface. Karstification produced fissures, sinkholes, underground streams, and caverns. This together with the widespread lack of a thick protective soil cover results in high infiltration of rain water into the ground and effective underground drainage.

Surface Runoff

The Department of Water Affairs maintains three river gauging stations each along the Mwembeshi River and the Chongwe River. Additional stations exist in the upper parts of the Ngwerere and Chalimbana rivers, two tributaries of the Chongwe River. In 2009 an additional station was opened at Chunga River near the confluence with the Mwembeshi River. Measurements at the Kapiriombwa River, a smaller tributary of the Chalimbana River located near International Airport has not been operational since 1999. The locations of the gauging stations are depicted in Figure 16.

The historical gauge readings were recently scrutinized and stream flow calculations carefully revised. Flows were calculated only from stream flow data that fall within periods of regular discharge calibration measurements carried out at the respective gauging station.

Gauge plates at Chunga Stream

The average discharge of Mwembeshi is only about 2.1 cubic meters per second corresponding to a runoff of 17 mm per annum. The average flow of the upper Chongwe (at Great East Rd. bridge) is 5.9 cubic meters per second or 95 mm per annum. Flow measurements of Chongwe River near its confluence are not available. Both rivers are considered minor tributaries in terms of runoff. For comparison, the average outflow of the Kafue River from Kafue Gorge Dam is 296 cubic meters per second whereas the average flow of the Zambezi upstream Luangwa River confluence at Feira Boma is 1,762 cubic meters per second [52]. Reasons for the comparatively small run-off from the Mwembeshi and Chongwe catchments include the overall relative flat terrain, high evaporative losses and presumably indirect recharge of ground-water from the streambeds in some river sections. In the Chongwe Catchment, the significant number of dams and abstrac-tions for irrigation purposes may further decrease overall discharge.

Maxima and minima of observed daily, monthly and annual runoff for the water-sheds are given in Table 5.

An example of the variation of annual runoff is given in Figure 13 for Chongwe River at Great East Road bridge. Annual discharge at the station varied from be-low 1 cubic metres per second during the 1993/94 season to almost 20 cubic metres per second during the 1977/78 season.

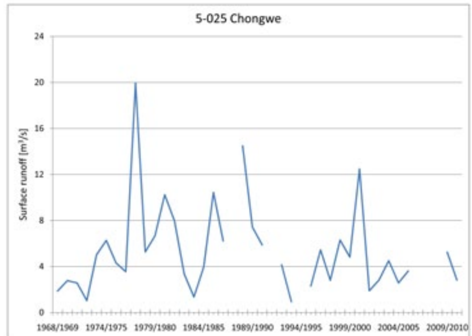


Figure 13 Mean annual runoff at station 5-025 Chongwe – Great East Road bridge since 1968 (Data Source: DWA, Surface Water Resources Section).

Stream flow calibration measurement at Kapiriombwa Stream east of Lusaka

Hydrographs of mean monthly discharge are shown in Figure 14. Maximum dis-charge is observed during February at both graphs presented – with a one-month delay compared to the occur-rence of the monthly rainfall maximum. Lowest discharge is encountered at the end of the dry season in October as to be expected. The Mwembeshi River in par-ticular is characterised by very little flow during the dry season. The ratio between mean minimum and maximum monthly discharge is about 1:20 at the Chongwe and 1:60 at the Mwembeshi station.

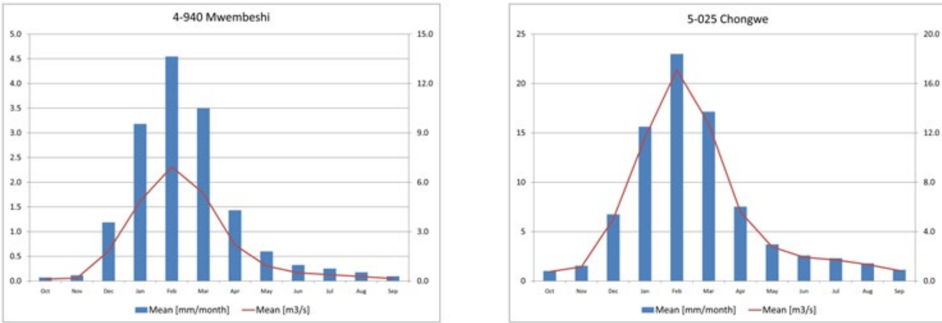


Figure 14 Mean monthly runoff in cubic meters per second and mean monthly totals in millimetres for the stations 4-940 Mwembeshi-Shibujunji and 5-025 Chongwe – Great East Road bridge (Data Source: DWA, Surface Water Resources Section).

The Ngwerere River shows very different flow characteristics due to large contributions of urban stormwater runoff and discharge from the wastewater plant. With an average discharge with 1.5 cubic metres per second, the annual runoff of 440 mm is exceptionally high. Monthly mean runoff is highest in January and February (Figure 15). Generally, a significant flow is maintained even towards the end of the dry season with a ratio of 1:6 between minimum and maximum monthly discharge.

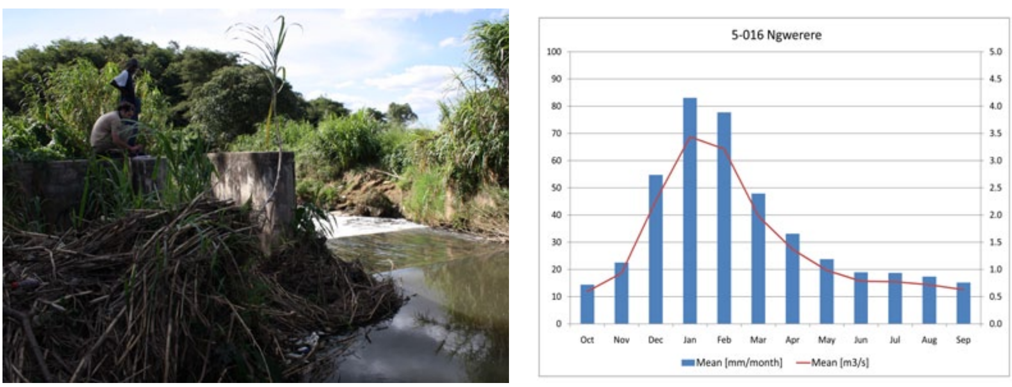


Figure 15 Mean monthly runoff in cubic meters per second and mean monthly totals in millimetres for the stations 5-016 Ngwerere. The relative small catchment of the Ngwerere gauging station (right picture) is influenced by stormwater runoff and a continuous discharge from the wastewater plant (Data Source: DWA, Surface Water Resources Section).

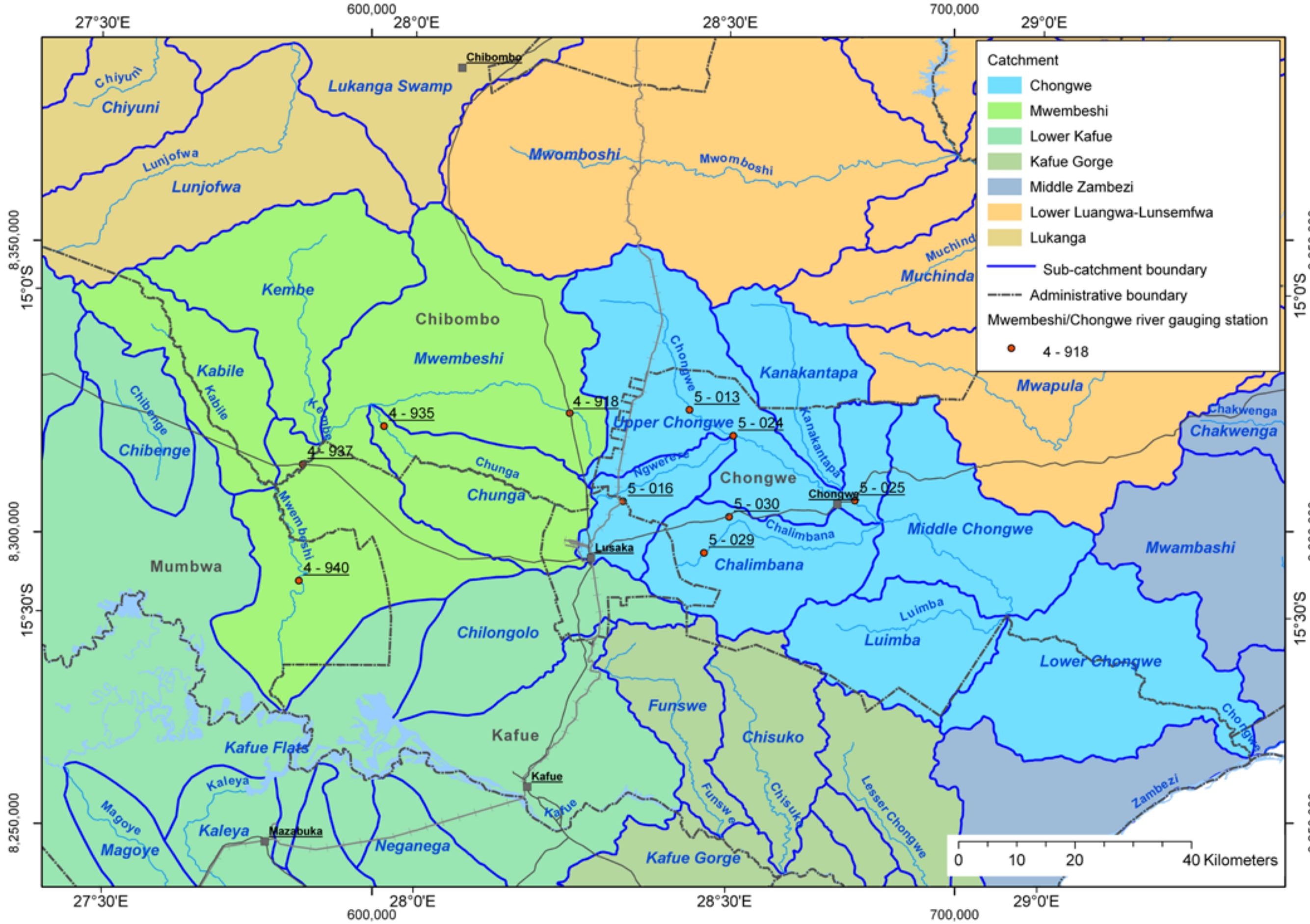


Figure 16 Sub-catchments within the Mwembeshi and Chongwe and adjacent catchments and river gauging stations.

Table 5 Annual, monthly and daily runoff observed since beginning of records; only years with verified (calibrated) records are considered (Source: DWA, Surface Water Resources Section).

Station No. - River	Start of records	No. 3)	Area 4)	Annual runoff [m³/s]			Monthly runoff [m³/s]		Daily runoff [m³/s]	
			[km²]	Min. 5)	Mean	Max.	Min. 5)	Max.	Min. 5)	Max.
4-918 - Mwembeshi	1977	21	73	0.016	0.28	0.67	0	2.3	0	9.4
4-935 - Chunga	2009	2	560	--	(2.2)	--	(0.027)	(14)	0	85
4-937 - Mwembeshi	1977 1)	3	2,992	(0.06)	(3.1)	(6.9)	0	(23)	0	30
4-940 - Mwembeshi	1962 1)	26	4,019	0.29	2.1	5.2	0	18	0	30
5-012/5-013 - Chongwe	1973 2)	9	≈548	(1.1)	(2.1)	(5.6)	(0.004)	(23)	0	56
5-016 - Ngwerere	1956	17	109	0.28	1.5	3.0	0.1	13.1	0.061	77
5-024 - Chongwe	1977	18	1,102	0.43	1.9	4.5	0	18	0	33
5-025 - Chongwe	1968	25	1,961	0.94	5.9	20	0	80	0	251
5-029 - Chalimbana	1953	35	115	0.051	0.30	0.99	0	4.9	0	44
5-030 - Kapiriombwa	1958 1)	20	61	0.005	0.20	0.51	0	2.6	0	8.0

1) Discontinuous data series (major gaps)
2) Station 5-012 was closed in 2002 and replaced by 5-013 downstream
3) Number of years included in the statistical analysis; these are years with validated runoff data and existing gaps not exceeding one month
4) Catchment areas (above station) derived from DEM
5) Zero runoff includes periods with negligible flow below measurement limit (trickle)

Dams and reservoirs

There are about twenty small earth dams (<1 km2) to the east and north east of Lusaka in the Upper Chongwe Catchment in particular along the Ngwerere and Chalimbana River and some smaller streams (Figure 17). The largest dam in the area is Ray's dam near Karubwe that stores water from Chongwe River over an area of approximately eight square kilometres. The water from the dams is mainly used for irrigation purposes.

Chunga earth dam was built some 13 kilometres above the confluence with the Mwembeshi River. The private dam is mainly used for commercial irrigation and fishing.

Chunga earth dam

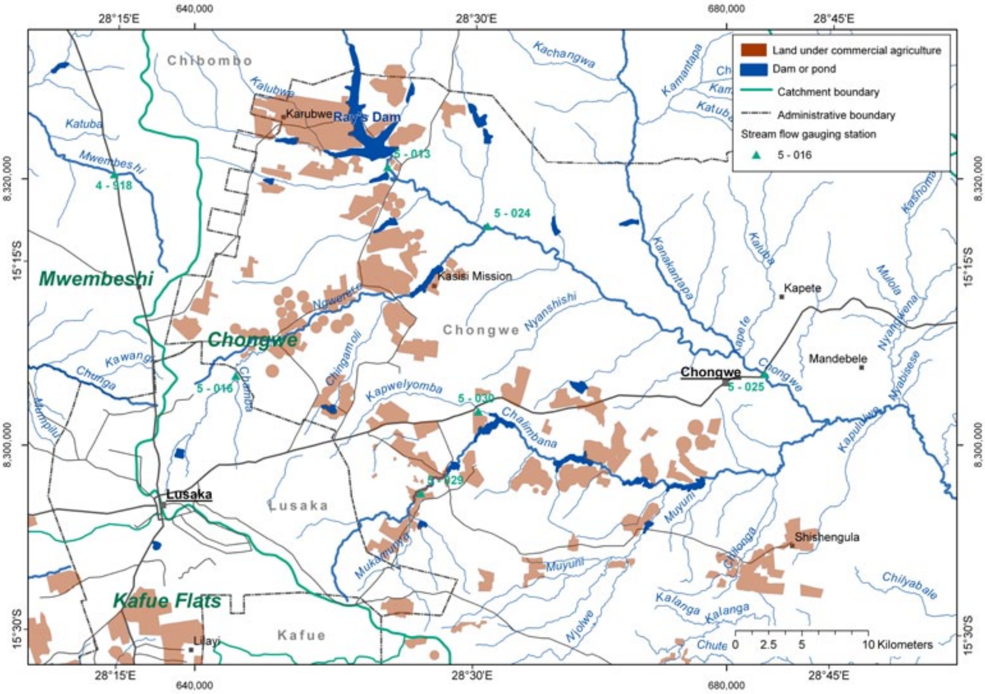


Figure 17 Dams and agricultural areas in the Upper Chongwe Catchment.

Springs

Unfortunately, springs in the two catchments with the exception of the Lusaka area have never been mapped systematically. Springs occurring on or along the margins of the Lusaka plateau were discovered and described by various authors ([7], [20], [51]).

Depending on their discharge behaviour springs can be divided into perennial (springs that flow throughout the year), seasonal (springs that cease to flow during the dry season) and intermittent (springs that fall dry several times a year).

The locations of perennial springs in the Lusaka area are shown in Figure 22. Three separate areas in which several springs emerge can be distinguished, notably the area near Mwembeshi at the western margin of the Lusaka Plateau, the Lusaka West and Barlaston areas at the contact between dolomites and schists and to the east within the upper regions of the Chalimbana Catchment.

Perennial springs in the Lusaka area include Mwembeshi Prison and Kashembe farm springs in the Mwembeshi area, Laughing Waters and Zingalume springs in Lusaka West, as well as Good Hope and Palabana farms springs in the Chalimbana area.

Most perennial springs in the vicinity of Lusaka are used for either drinking, domestic purposes, livestock or small-scale agricultural purposes.

Most of the springs are associated with karstified carbonate rocks and can therefore be regarded as karst springs. This type of spring emerges at the outlet of a subterranean network of conduits formed, to various degrees depending on the maturity of the karst, by fractures, smaller dissolution cavities and large, pipe-like caverns. Sinkhole springs occur where groundwater is under artesian pressure and a subterranean cavern is connected to a shaft that rises to the surface. Karst springs are generally characterised by a pronounced and rapid fluctuation in discharge.

Apart from this, most springs prominent in the Lusaka area can be a assigned to either of the following types: contact springs, fault springs and depression springs [7].

Contact springs in the area occur at the lithological contact of the higher permeable marbles and dolomites with the less pervious rocks typically made of schist. Fault springs are associated with the various fracture and fault systems within the hard rocks. Depression springs are formed along a slope or in a topographical depression such as dambos when the water table reaches the land surface. These springs may fall dry depending on the annual water table fluctuations.

Perennial Karst spring at Zingalume, Lusaka West

Water Supply and Sanitation

Water Supply and Use

Accurate information is required to improve the understanding of the water situation in the country. Zambia's current water resources use cannot be accurately determined since comprehensive water use data is generally not adequate due to poor data records kept by different users as well as the inadequate regulatory capacity to monitor the various water uses. This is true for both surface water and groundwater (which had not been regulated until the enactment of the Water Resources Management Act in 2011 and the start of its implementation in 2012). The previous Water Act empowered Government through the Water Board to control surface water allocations but the Board had limited capacity to enforce the regulations.

Pivot irrigation in the Chongwe Catchment

A survey of the main agricultural and industrial water users in the project area was carried out in 2010 [6]. Commercial agriculture in the Chongwe and Mwembeshi catchments use both surface and groundwater for irrigation. Farms using surface water irrigate approximately 2,400 hectars of land with almost 15 million cubic meters per year. Farms which utilize groundwater for their irrigation abstract approximately 25 million cubic meters per year (68,000 cubic meters per day) on about 3,700 hectars. Groundwater abstraction for irrigation during the dry season can reach more than 100,000 cubic meters per day [6]. In comparison, according to Lusaka Water and Sewerage Company (LWSC) the daily groundwater abstraction rate of the public service provider for the Lusaka City area varies between 120,000 and 145,000 cubic meters per day (Source: LWSC). Industries meanwhile use a total of around 4.5 million cubic meters of mainly groundwater per year in their production [6] which is only one tenth of the annual abstraction of groundwater by LWSC.

Within Lusaka the water supply concept of LWSC is twofold: while the central city area receives piped water supply of a mixture from surface water (brought via pipeline from the Kafue River) and groundwater mainly from 10 large production boreholes (complemented by 63 smaller ones), the peri-urban areas on the fringe of the city are supplied by local boreholes in their respective areas which are mainly unserviced in terms of sanitation.

Local water supply from borehole, Kanyama, Lusaka City

According to the National Water Supply and Sanitation Council (NWASCO), Zambia's regulator in the water sector, 77% of the population living in urban areas have access to safe drinking water while the coverage in rural areas is at 57% [37]. Customers in peri-urban areas complain most frequently about the fact that not enough water is available and that it can only be accessed at certain times when the tap attendant is present.

In rural areas water supplied from groundwater is mostly provided by boreholes with hand-pumps or hand-dug wells that are usually equipped with a bucket and windlass or a hand pump. Common depths of boreholes are in the range of 30 to 100 meters. Hand-dug wells are shallow with depths ranging from a few meters to seldom above 15 meters.


Hand-dug well at Mubanga, Kafue District

Sanitation

For the rural areas, sanitation coverage stands at 38% whereas 54% of the population in urban areas have access to sanitation facilities, which are considered "acceptable" [37]. The facilities considered acceptable are those with connections to the sewer network and septic tanks. Owner of septic tanks often resort to using tanks and soakaways which are constructed to leak. This way groundwater contamination is highly likely to occur. This is further aggravated by lack of enforcement of building regulations by the Local Authorities [37].

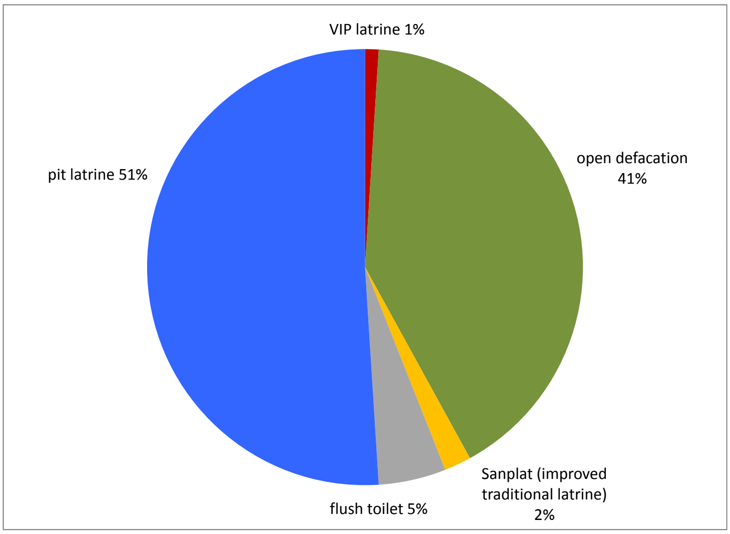


Figure 18 Percent distribution of households in Zambia by type of excreta disposal facility [54].

Unsafe forms of water supply: unprotected shallow well and open groundwater surface used as dumpsite and for water supply

It is estimated that Lusaka produces about 765 tonnes of solid waste daily. Of this quantity, only 76.5 tonnes is actually collected and properly disposed of while the remainder is disposed of elsewhere. For 2005, there were recorded 80,000 tonnes of collected garbage in Lusaka [17], aside from the uncounted garbage that is burnt or disposed in the environment. Wild disposal areas include the limestone sinkholes and crevices [36] posing a big threat to groundwater quality as high recharge takes place in these areas.

Solid waste in an informal settlement in Lusaka

Groundwater Resources

Groundwater Systems

In order to identify the major groundwater systems, so-called "aquifers", of the area the groundwater bearing rock formations were differentiated according the rock type ("lithology") with respect to their regional distribution.

With over 90% coverage, aquifers hosted by hard rock including karst systems prevail in the catchment areas of the Mwembeshi and Chongwe rivers. Unconsolidated ("loose") alluvial or colluvial sediments covering larger coherent areas are only found in the Zambezi Valley, the area around Lusaka International Airport and the Kafue Flats.

Water-filled karst hole; 2.5 metres deep, in Lusaka West

Groundwater flow in hard rock is related to the occurrence and type of fractures, cavities and fault systems. Taking the predominance of certain rock types into account, four major groundwater systems with different lithology can be distinguished in the catchment areas (Table 6). These are gneisses and schists, which both occur in combination with quartzite and other metamorphic rocks, marbles and metasedimentary clastic rocks (meta-sandstones and siltstones) of Precambrian age (Kawena Formation). The latter only occur in the Mwembeshi Catchment.

In the Mwembeshi Catchment one quarter of the total areas is made up of carbonate rocks. In the Chongwe Catchment the proportion of carbonate aquifers is much smaller with over 85% of the area covered by Precambrian (Basement and Katanga Supergroup) metamorphic rocks like gneiss and schist.

Groundwater Potential

Each groundwater system can be characterised according to their hydraulic properties, including

1. The *transmissivity T*, commonly given in units of m^2/d, which can be considered a measure of the amount of water that can be transmitted through a rock formation.
2. The *specific capacity q*, given in units L/s/m, which is obtained by dividing the discharge of a pumped well by the stabilised drawdown observed during a pumping test.
3. The *yield Q*, given in L/s, which refers to the likely or characteristic yield that a well can produce from a rock formation.

Table 6: Main groundwater systems of the Mwembeshi and Chongwe catchments and their lithology and occurrence.

No	System	Litho-Stratigraphical Description	Main Regional Occurrence	Area coverage in (1) [%]	Area coverage in (2) [%]
1	Acid to intermediate igneous rock	Granitic intrusions and volcanic and meta-volcanic rock	Lusaka granite and smaller intrusions, e.g.in Chisamba area	1.1	0.4
2	Batoka Basalt & other basic igneous rock	Basalt rock of mainly Upper Karoo age	Negligible in this area	--	<<0.1
3	Gneiss & undifferentiated metamorphic rock	Predominantly gneiss and granitic gneiss with minor quartzite, schist, pelite and psammite within Basement and Muva Supergroup	Basement rock in northern parts of study area and of escarpment	15.7	51.4
4	Schist, shale & slate	Schists of the Cheta and Chunga formations	Widespread throughout the catchment areas, in particular in Chunga, Ngwerere, Chalimbana, Luimba and Chunga sub-catchments	31.5	35.2
5	Quartzite	Quartzitic rocks of predominately Precambrian age	Various, Associated with metamorphic and metasedimentary Precambrian rocks	*)	*)
6	Carbonate & calc-silicate rock	Mainly marbles and other calc-silicate rocks of the Katanga Supergroup	Lusaka Dolomite & Cheta Limestone near Lusaka, Nyama Fm in Chisanga and Chibombo areas	25.8	7.7
7	Unconsolidated clastic sediments	Interbedded gravel, sand, silt and clay formed by alluvial deposits	Kafue Flats, area near Lusaka International Airport, Zambezi valley and valley floors	8.4	5.2
8	Precambrian sedimentary and metasedimentary clastic rocks	Sandstone and meta-sandstone of Pre-Karoo age, mainly Kawena Formation of Katanga Supergroup	North-western part of Mwembeshi Catchment	17.6	--

1 = Mwembeshi Catchment, 2 = Chongwe Catchment

*) Coverage cannot be determined; quartzites mainly occur within areas of aquifer categories 3 and 4.

For the development of the hydrogeological maps the aquifers were grouped into six different categories depending on their potential to produce water and the type of discontinuities (fractured or unconsolidated rock). An attempt was made in Table 7 to give practical examples for the possible use of the groundwater resources for each category. Roughly, the categories differentiate aquifers with "high", "moderate", "limited" and "essentially no" potential. Aquifers with a high potential (categories A and C) for example may permit withdrawals of regional importance such as supply to major towns or large-scale irrigation. Aquifers with limited potential (category E) could suffice for the supply of water to rural villages with a handpump. The table also provides characteristic values for transmissivity, specific capacity and approximate probable yield for each category. However, it has to be remembered that hydraulic parameters in individual boreholes vary widely, even in areas with relatively uniform lithology, but particularly in areas where groundwater flow is controlled by zones of intense fracturing and faulting.

Table 7 Hydraulic characterization of the aquifer categories (after [2], and references given therein).

Aquifer category	Aquifer Type	Trans-missivity [m²/d]	Specific capacity [L/s/m]	Very approx. expected yield [L/s]	Groundwater potential
A C	Unconsolidated Fractured/Karst }	> 75	> 1	> 10	High: Withdrawals of regional importance (supply to towns, irrigation)
B D	Unconsolidated Fractured/Karst }	5 – 75	0.001 – 0.1	1 – 10	Moderate: Withdrawals for local water supply (smaller communities, small-scale irrigation etc.)
E	Undifferentiated	0.05 – 5	0.001 – 0.1	0.01 – 1	Limited: Smaller withdrawals for local water supply (supply through handpump, private consumption)
F	Undifferentiated	< 0.05	< 0.001	< 0.01	Essentially none: Sources for local water supply are difficult to ensure

The mapped distribution of aquifer potential displayed in Figure 19 and shown in greater detail on the hydrogeological map series is based on analysis of available pumping tests at over 170 wells and boreholes in the Lusaka and Central Provinces [2] and on results of previous studies regarding the potential of the groundwater bearing rocks of the areas ([14], [51]). The aquifers of the Chongwe and Mwembeshi were classified as follows:

The marbles of the Lusaka Dolomite Formation are aquifers of high groundwater potential, i.e. aquifer category C.

Other carbonate rocks including the Cheta limestones near Lusaka, carbonate rocks of the Nyama Formation in the Chisamba area and limestone in the Luimba area are to be classified as aquifers of moderate to high potential, i.e. aquifer category D-C.

The high permeability of the carbonate rocks is due to karstification, a process of solution and chemical but also mechanical weathering by infiltration of water, whereby surface features such as dolines, sinkholes and pinnacles ("karrenfelder"), and a subterranean drainage network consisting of solution cavities, channels and shafts develop. Karstification is a common feature of all calcareous units of the area. The karstic nature of the Lusaka Dolomite Formation has been particularly well studied

Groundwater reaching the surface filling the space between carbonaceous solution pillars, Shantumbu springs – Forest Reserve Lusaka South No. 55

from the early 1960s by various authors (e.g. [30],[33],[35],[51], and additional references listed in [1]). Solution cavities were reported up to depths of about 150 meters although the majority of cavities were found at depths above about 40 meters. Near the ground zone a so-called "epikarst"- horizon with an average depth of 5 meters extending to a maximum depth of 25 meters is developed that is characterised by enhanced storage capacity and high porosity and permeability as a result of enhanced weathering (dissolution). Measured dimensions of surface karst holes on the Lusaka plateau in the working area range from 0.2 to 5 metres, and it is assumed that similar features occur in all areas covered by calcareous units including the marbles of the Cheta and Nyama Formations in Chibombo District [3].

The metasediments of the Kawena Formation are considered to be of moderate potential (category D) or limited potential (category E) depending on the contents of sandstone versus siltstone and argillite (mudstones). The classification of the Kawena Formation, however, is currently based on very little field data.

Unconsolidated rocks are largely of limited potential (category E) but may locally reach higher potential depending on the content of sand and gravel. The potential of the vast sediments of the Kafue Flats is variable due to different depositional domains and hence rated "limited to moderate" (category E-D).

All other rocks including basement, igneous rock and schist are aquifers of limited potential, i.e. aquifer category E, except for schists of the Cheta and Chunga formations that locally may be considered to be of limited to moderate potential, i.e. aquifer category E-D.

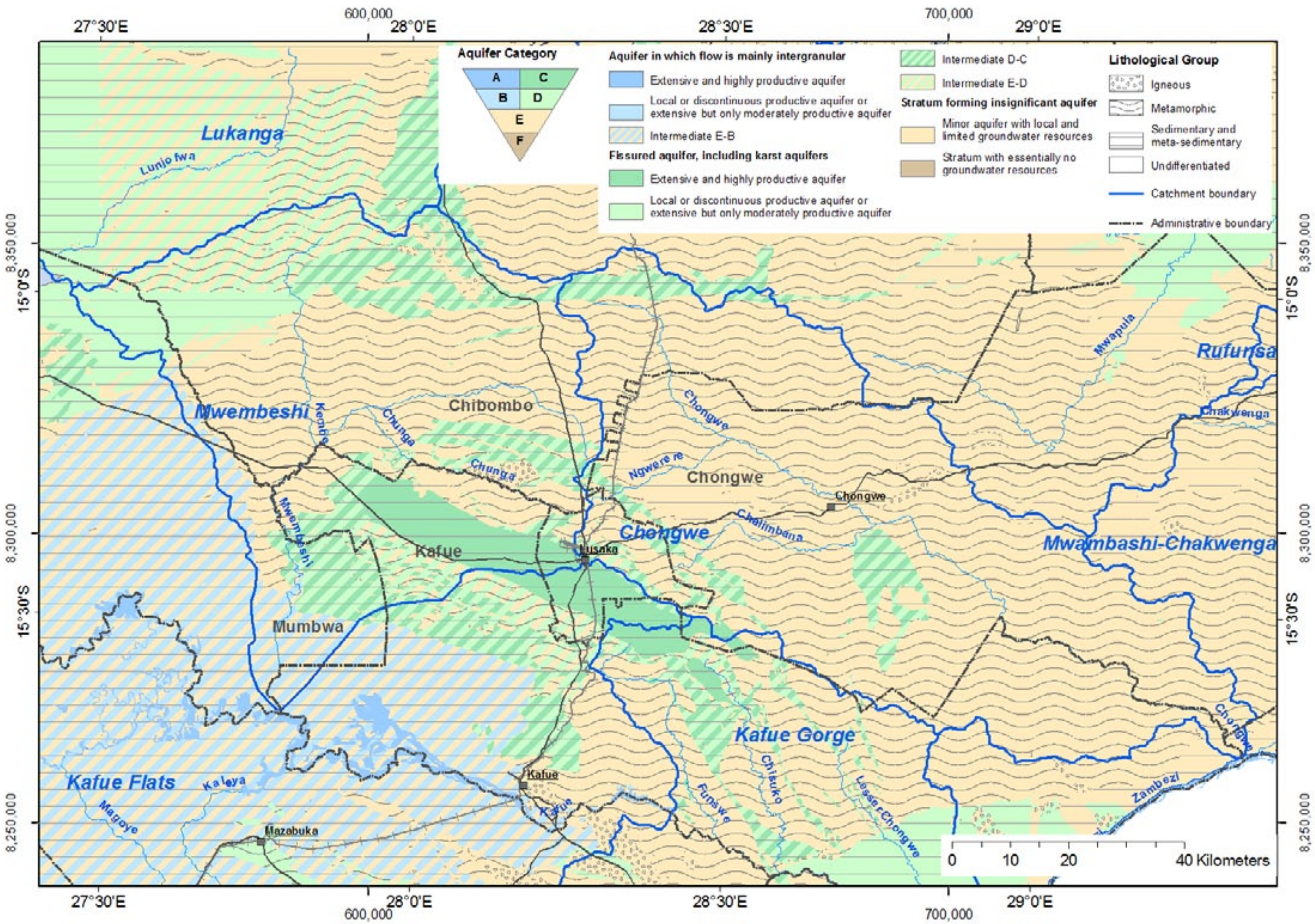


Figure 19 Potential of groundwater systems and aquifer lithology.

Table 8 Descriptive statistics of aquifer characteristics based on test pumping analysis at 174 boreholes (after [2]).

No	System	Parameter	n	Min	Max	Mean	Stdev	CV	Median	Categories
1	Acid to intermediate igneous rock	T	8	0.14	50	--	--	--	--	E
		q	8	0.003	0.28	--	--	--	--	
		Q	8	0.10	1.6	--	--	--	--	
3	Gneiss & undifferentiated metamorphic rock	T	13	0.30	10	4.1	3.0	73	4.0	E
		q	13	0.008	0.35	0.10	0.11	104	0.049	
		Q	13	0.12	1.0	0.50	0.32	64	0.40	
4	Schist, shale & slate	T	17	0.32	563	60	137	228	7.9	E locally E - D
		q	19	0.005	7.4	0.63	1.7	263	0.12	
		Q	10	0.10	3.5	1.1	0.95	88	1.0	
5	Quartzite	T	7	1.5	94	--	--	--	--	E
		q	8	0.025	2.0	--	--	--	--	
		Q	8	0.30	2.5	--	--	--	--	
6	Carbonate & calcsilicate rock	T	56	1.3	8,930	1,402	2,167	155	322	C or D - C
		q	71	0.014	98	13.3	23	173	2.9	
		Q	73	0.20	70	20.6	20.5	96	12	
7	Unconsolidated clastic sediments	T	15	1.2	465	59	121	205	7.2	E or E - B
		q	18	0.013	0.77	0.16	0.21	127	0.056	
		Q	18	0.15	1.8	0.81	0.58	72	0.60	
8	Precambrian sedimentary and metasedimentary clastic rocks	T	3	5.9	142	--	--	--	--	E or D
		q	3	0.124	1.6	--	--	--	--	
		Q	3	0.30	2.5	--	--	--	--	

Explanations:
T: Transmissivity in m^2/d; q: Specific capacity in L/s/m; Q: Borehole yield in L/s; n: sample size; Min: Smallest value observed; Max: Highest value observed; Stdev: Standard deviation; CV: Coefficient of variation defined as the ratio of the standard deviation to the mean given in %; Median: also called 50th percentile, represents the value that divides the higher half of the sample from the lower half.

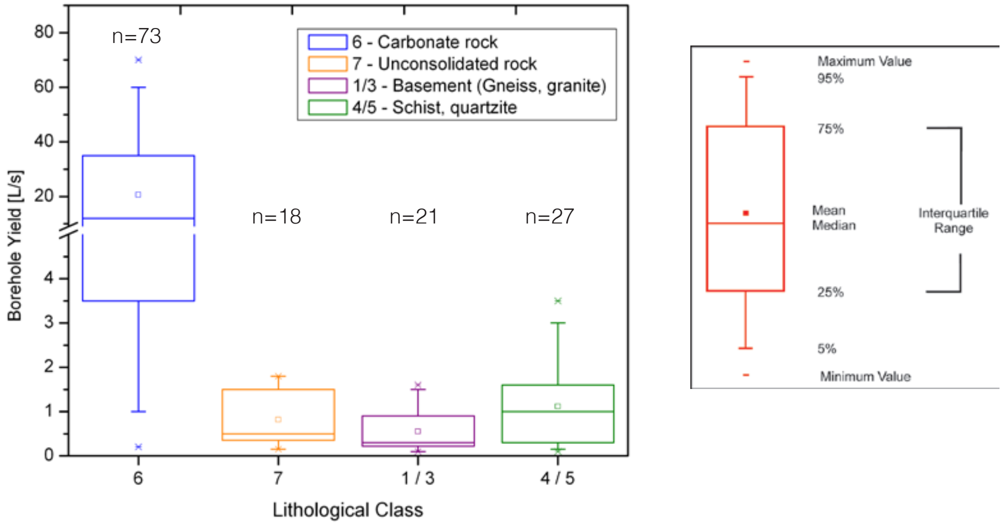


Figure 20 Box charts of borehole yield determined from test pumping analysis for four different lithological classes (after [2]; n being the number of tests analyzed in the respective class).

The range of descriptive statistical values of hydraulic parameters for the major lithological groups determined from test pumping analysis are given in Table 8. As a major finding, the examined hydraulic parameters vary over a wide range even in areas with relatively uniform lithology, but particularly in areas where groundwater flow is controlled by zones of intense fracturing and faulting. This is reflected in the large values (>200%) of the coefficient of variation expressing the heterogeneity of the rock formations.

The exceptionably high aquifer potential of marbles in the area corresponding to high borehole yields is demonstrated in the box charts shown in Figure 20. Values of yield displayed in the charts falling between the 25th to the 75th percentile can be considered typical since they apply to 50% of all boreholes for which the respective hydraulic information is available. For marbles, the 25th and 75th percentile amounts to 3.5 L/s and 35 L/s, respectively, with a median value of 12 L/s. For all other lithological groups typical borehole yields are below 2 L/s. In actual fact, the Lusaka Water and Sewerage Company operates about a dozen boreholes on the Lusaka Plateau that produce yields of around 10 L/s or more. Maximum yields of boreholes tapping the Lusaka Dolomite Formation exceed 50 L/s.

In summary, the Mwembeshi and Chongwe catchments host very productive karst groundwater systems suitable for commercial purposes and to supply large amounts of water to the Capital. Currently, about 50 million cubic meters of groundwater are abstracted annually by the waterworks. Except for the Lusaka City area and the agricultural belts to the north-east and south of Lusaka and in the Chisamba area, however, the groundwater potential of these karstic systems is still not fully exploited.

Most other groundwater systems, especially those formed by granitoidic and metamorphic basement rocks, have only limited potential and are only suitable for smaller withdrawals (e.g. private consumption or local rural water supply through hand pumps). Locally, in particular at contact zones within highly fractured quartzite, or zones of strongly weathered schist, and possibly within metasandstones of the Kawena Formation groundwater may be sufficient to supplement surface water- based irrigation systems along rivers or dams or to facilitate small-scale irrigation.

Apart from this, groundwater can overall be considered a reliable source for domestic and rural water supply for which comparatively small amounts of water (less than two cubic meters per hour) are needed. Groundwater exploration, however, is not without risks due to the heterogeneous nature of most rock formations.

Regional Groundwater Flow

The groundwater contour map depicted in (Figure 21) shows the general regional pattern of groundwater flow in the two catchments. The map contains contour lines showing the water levels ("piezometric surface") in meters above sea level and arrows indicating the general flow direction. Although the contour lines were derived using static water levels at over 2,500 sites available from the groundwater database, it is not suitable for larger-scale study areas due to the overall inconsistent quality of available groundwater level data.

In general, the groundwater flow follows the topography and hence is directed towards the stream and riverbeds. Flow gradients on the plateaus typically range between 4 and 6 meters per kilometre and are particularly low within the alluvial plain of the Kafue River. As a consequence to the similarity between surface slope and groundwater table, rather steep groundwater gradients are characteristic for the escarpment zone in the direction of the Zambezi.

The groundwater contours of the Lusaka Plateau are shown with higher accuracy in Figure 22. The contours were generated based on over 330 water level measurements taken during April 2009. Similar to the surface water pattern, a

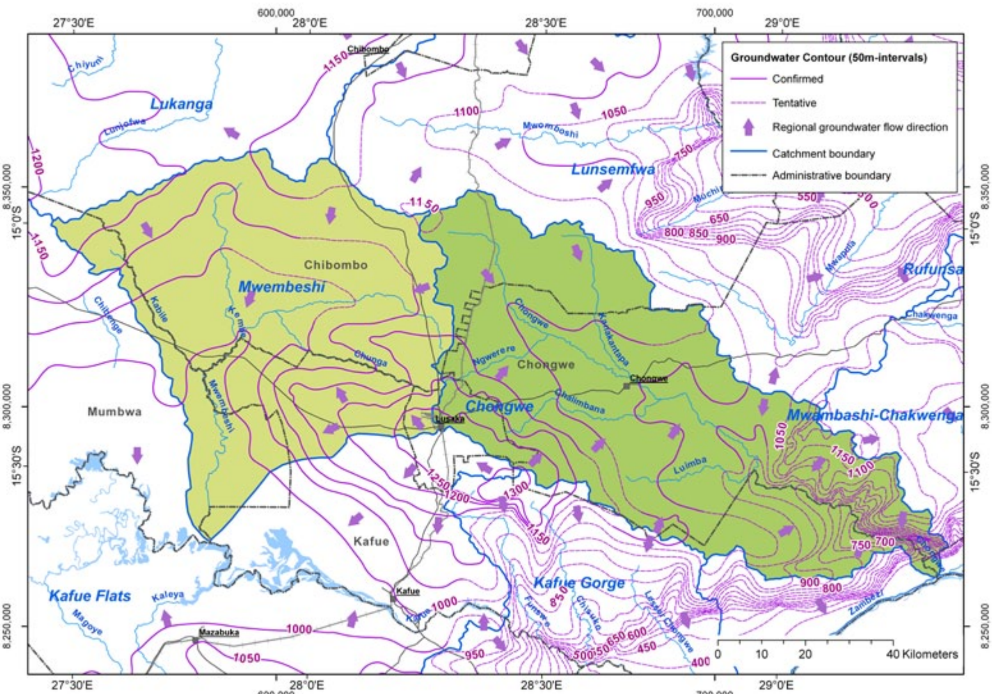


Figure 21 Regional groundwater contour map of the Mwembeshi, Chongwe and adjacent catchment areas with indication of the groundwater flow directions. Water levels are given in meters above sea level.

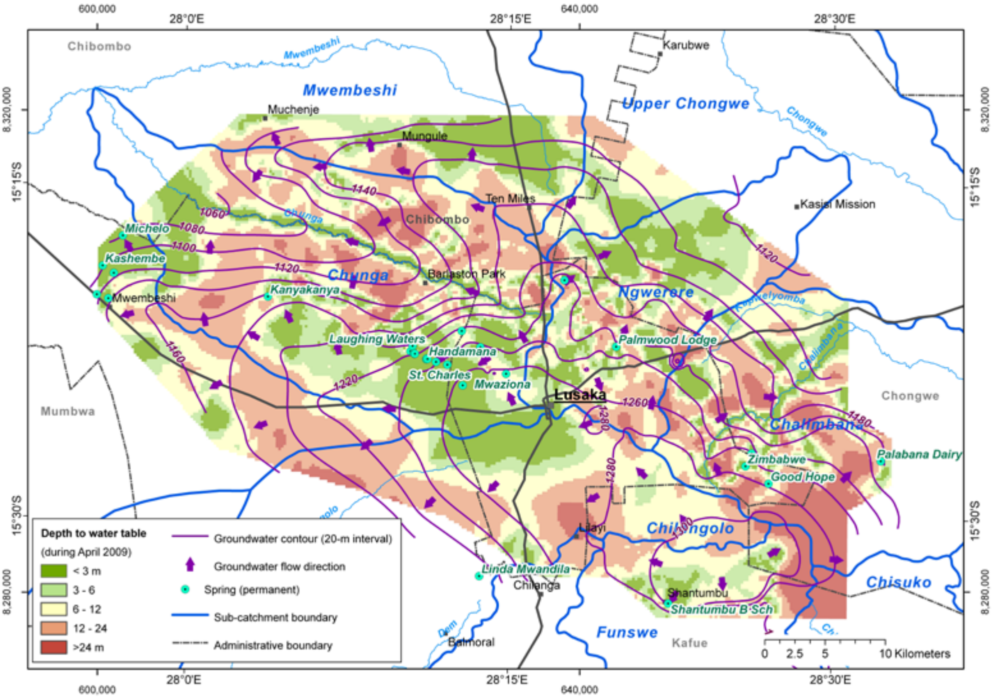


Figure 22 Groundwater flow, depth to groundwater table during April 2009 and occurrences of permanent springs in the Lusaka area.

water divide crosscutting the Lusaka Forest area can be determined. South of this divide groundwater flow is directed south- and south-eastwards towards the Shantumbu area and the Funswe River Catchment whereas groundwater to the north follows a north-westerly direction. In the eastern parts of town (Leopard Hill and Bauleni areas) groundwater flow is directed to the northeast. The Chalimbana River and tributaries to the Ngwerere River clearly act as drainage channels for groundwater through areas of 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 moves generally in north-westerly direction towards Mwembeshi in the far west following the axis of the elongated Lusaka Dolomite body. Along this flow path, groundwater apparently branches out towards a major groundwater discharge zone located along dolomite/schist boundaries to the north (Chunga tributaries).

The depth to the groundwater table is generally moderate to low (Figure 22). Areas of shallow groundwater is encountered to the west and south of Lusaka, below the western margin of the plateau near Mwembeshi and in the Upper Mwembeshi and Lusaka International Airport areas. The townships of Kanyama and Misisi in the southwest of Lusaka are frequently inundated during the rainy seasons due to rising groundwater tables.

Along the south- western margins of the plateau (Cheta and Chilongolo streams) depths to water table within the Cheta Formation are fairly high and accordingly, no springs emerge. This indicates that underground water is well drained in these parts owing to the comparatively high permeability of these rocks.

Groundwater recharge and water balance

Various estimates of direct recharge, yet with widely varying results are available for the Lusaka area (see references given in [1]). The available estimates suggest that average recharge rates may be in the order of 20% to 25% of annual rainfall, i.e. between 160 and 200 mm. In years with particularly low rainfall, however, groundwater recharge may be considerably lower [51].

During the on-going groundwater investigations under the GReSP program a soil water balance approach was applied to the Lusaka area in order to establish reliable estimates of the water balance including its major components of actual evapotranspiration and groundwater recharge [4]. The method uses the FAO 56 dual crop coefficient approach for estimating crop evapotranspiration from soil [10] and was programmed in form of the MABIA software [24] that was incorporated in the "Water Evaluation and Planning" (WEAP) decision support system developed by the Stockholm Environment Institute [46].

In a first step, the water balance was estimated for a situation representing long-term means rather than the budget for one specific hydrological year. Hence, the results presented in this chapter should be understood as a generalized approach to the values in the water balance equation. The hydrological year 1989/90 with 780 mm of rain was considered adequate to represent these long-term "reference" conditions.

The water balance of any area is defined as

$$P = ET_{act} + R_s + GWR$$

where P is precipitation (rainfall), ET_{act} is actual evapotranspiration, R_s is surface runoff and GWR is groundwater recharge.

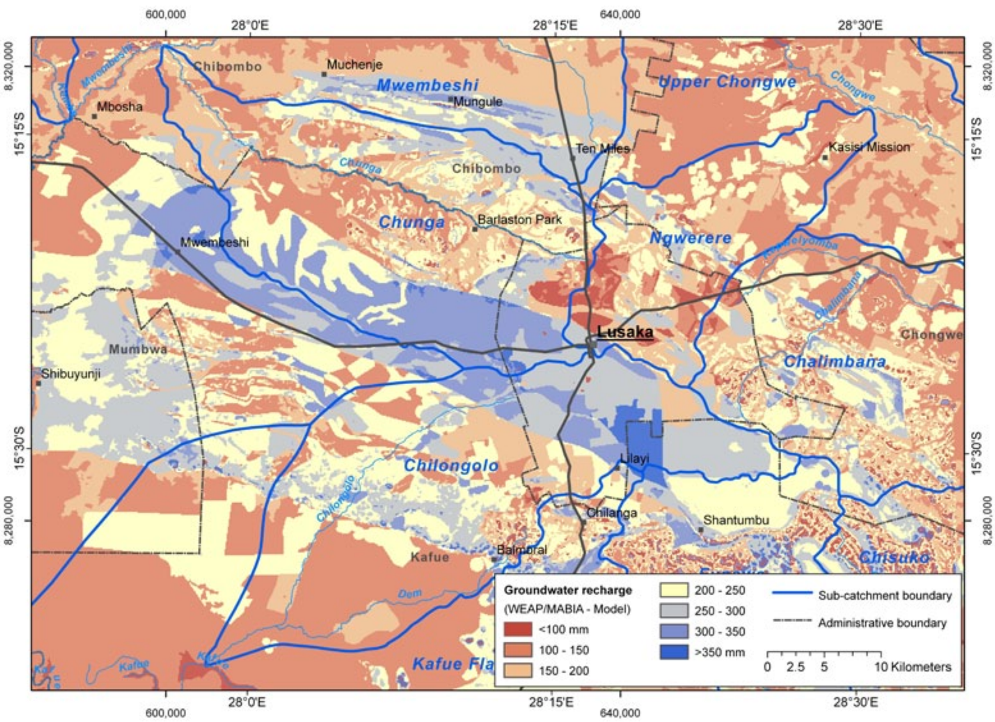


Figure 23 Estimated groundwater recharge rates [mm] in the Lusaka region in the reference year 1989/90 (modified after [4]).

For the hydrological year 1989/90 it was assumed that, of the 780 mm of rain, 40 mm turned into surface runoff on areas with limestone characteristics (karst) and 120 mm surface runoff in areas covered by schist, quartzite or basement. These values resemble average flows observed at the various gauging stations at the Mwembeshi and Chongwe rivers. Water that infiltrates into the ground can be used by plants or evaporate; this amount is summarized in the term actual evapotranspiration (ET_{act}). The value of ET_{act} largely depends on the vegetation or crops grown in the area under consideration and soil type.

Figure 23 shows the regional distribution of groundwater recharge rates as determined by the WEAP/MABIA model for the Lusaka area in the reference year 1989/90. Annual groundwater recharge rates cover a spectrum between about 100 mm and 380 mm. The overall average value, weighted according to spatial proportions of soil and land use classes, accounts for 209 mm. This is slightly higher than estimates from other authors in the past. Lowest values belong to urban areas where larger proportions of sealed surfaces prevent infiltration and therefore reduce groundwater recharge. Outside urban areas, the minimum value of about 130 mm corresponds to non-karstic parent material such as schist or gneiss, higher surface runoff, deeply developed soils with a higher available water capacity and natural woodland vegetation. The maximum values of over 350 mm are associated with karstic parent material (marbles), limited surface runoff, shallow soils with a very small available water capacity and small-scale rain-fed agriculture.

The amount of groundwater abstraction in the area around Lusaka is currently estimated at 100 million cubic meter per year, resulting in a mean value of 20 mm for the total study area. Therefore it can be assumed that the "net recharge" of 189 mm is being discharged underground to downstream catchments or streams.

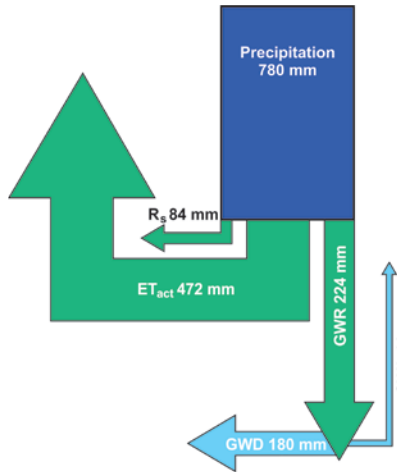


Figure 24 Water balance of the Chilongolo sub-catchment obtained from the MABIA/WEAP model in the reference year 1989/90 (ET_{act} = Actual Evapotranspiration, GWR = Groundwater Recharge, GWA = Groundwater Abstraction, GWD = Groundwater Discharge).

Water balances can be established for individual catchments as well as the complete area. As an example the Chilongolo sub-catchment is described in the following. It was chosen as it is fully enclosed by the investigated area. The water budget of this catchment of an area of 676 square kilometres can be derived from the WEAP/MABIA model as follows: The precipitation remains at 780 mm, while surface runoff that is generated on limestone, schist and alluvial areas is estimated at 84 mm. Land use in the Chilongolo catchment is a mixture of small-scale (rain-fed) and commercial (irrigation) agriculture as well as urban and peri-urban areas. The actual evapotranspiration therefore reaches a mean value of 472 mm and estimated groundwater recharge hence amounts to 224 mm. Of these 224 mm only about 44 mm are abstracted so far by farmers, industries and for urban water supply purposes. The rest (180 mm) is assumed to flow into downstream catchments, i.e. mainly the Kafue Flats (Figure 24).

Groundwater Quality and Protection

Groundwater quality

Overall chemical composition

Groundwater consists of the water molecule as well as the elements that are in solution. These are grouped according to their electrical charge: anions with negative charges and cations with positive charges. The major anions that occur in water are bicarbonate HCO_3^-, sulphate SO_4^{2-}, chloride Cl^- and nitrate NO_3^-. The major cations are sodium Na^+, potassium K^+, calcium Ca^{2+} and magnesium Mg^{2+}. The major ion composition of groundwater in the area of wider Lusaka is typical for continental groundwater of primarily meteoric origin, shown by the accumulation of data in the left quarter (Ca/Mg - HCO_3) of the rhombus in the PIPER-Diagram (Figure 25). The anion composition is strongly dominated by bicarbonate while calcium prevails in the cation composition although in the schists and quartzite rocks higher portions of dissolved magnesium and partly sodium occur.

Chemical water testing

The chemical composition furthermore shows that groundwater occurring in the unserviced areas of Lusaka City is high in nitrates due to lacking sanitation facilities [9].

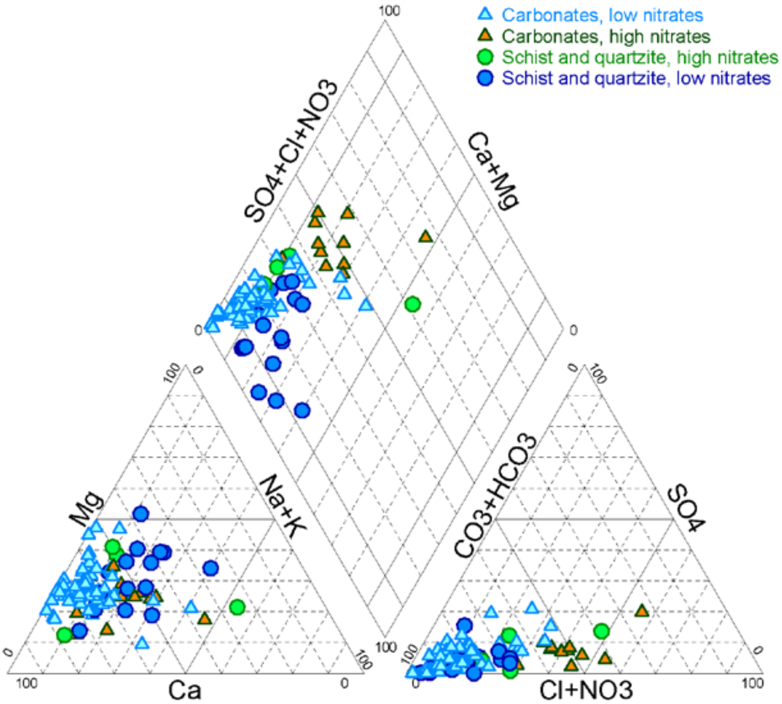


Figure 25 PIPER diagram showing major composition combining anion triangle (right) and cation triangle (left) to a rhombus (top) [9].

The groundwater quality in the Lusaka City area is shown in the map (Figure 25) highlighting LWSC boreholes as well as private boreholes with their measured nitrate concentrations [9]. Nitrate concentrations were above the Zambian Drinking Water Standard of 44 mg/l in 23% of all 91 sampled boreholes (Figure 26). While nitrate concentrations of the large production boreholes of LWSC are well below the Zambian drinking water standard, boreholes for the local supply of peri-urban areas such as Kanyama, Chibolya, John Laing and Bauleni show considerably higher values of more than 44 mg/l, some even of more than 100 mg/l. The percentage of boreholes showing pollution from faecal bacteria (indicated by the Total Coliform concentration) was considerably higher with 60% of all 88 sampled boreholes exceeding the limit given in the Zambian Drinking Water Standard.

Sources of groundwater contamination

The quality of groundwater in the aquifers of the Lusaka region is generally very good unless it is contaminated by poor sanitary conditions, local industrial wastewater outlets or leaking fuel storage tanks. Usually households rely on unlined pit latrines as sanitary facilities or public toilets which sometimes discharge into the same cavities that the neighbouring borehole draws its water from. Poor on-site sanitation facilities are the largest threat to groundwater quality in the urban area. The uncontrolled use of agrochemicals, the discharge of industrial chemicals (e.g. from leather production) and the negligent leaching of storage tanks add to the contamination but occur often locally, as high infiltration rates dilute contaminants to a high degree. The need to protect the resource against contamination cannot be overemphasised, especially in the fast growing City of Lusaka with ever increasing demand for clean water. Once polluted, it is difficult and costly to clean such water to the acceptable standard for drinking. This is of utmost importance in the karstic aquifers in the urban area, as sinkholes present shortcuts for contaminants, and large underground solutions channels provide for fast distribution.

Urban area flooded after rainy season affecting pit latrines and septic tanks

As a consequence of groundwater pollution due to poor sanitary conditions and poor hygiene practices the prevalence of waterborne diseases such as diarrhoea, dysentery and cholera in Lusaka and in the rural areas is very high, especially during the rainy season. In the rural areas that are supplied by surface water, schistosomiasis can occur, especially if stagnant pools of water are used during dry season, as shown in Kafue and Luangwa districts [43].

Malfunctioning central wastewater treatment plants discharge their effluents into surface waters like the Ngwerere river. This water is regarded as unsafe for drinking and other uses, but is in fact

Ngwerere River near Kalimba Farm showing foam from high organic/nutrient content

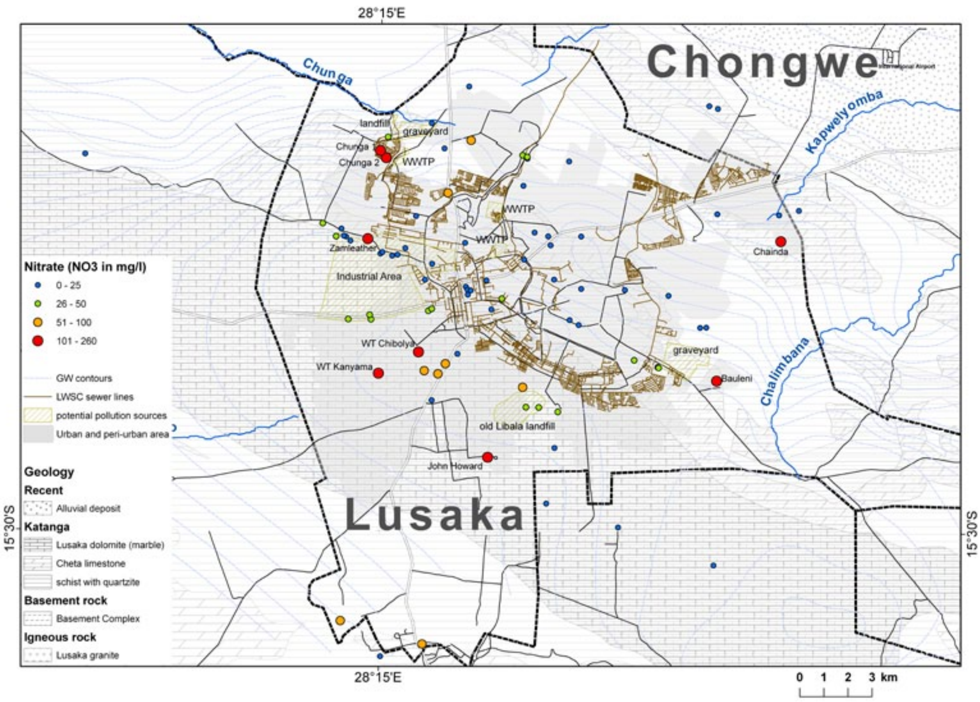


Figure 26 Regional distribution of nitrate in groundwater in Lusaka District and surrounding.

often used for small-scale irrigation of vegetables and fruits by those living on the river banks in the city area. Sanitation concepts that preserve the nutrients in human excreta while sanitizing them to become a safe product exist and need to be put into practice to support urban farmers in gaining their income without compromising the consumers' health. Increased health and hygiene education especially in peri-urban communities is required as well as investments into sustainable sanitation concepts.

Under the prevailing pH (average value of 7.0) in the calcareous environment potentially toxic heavy metals like lead (Pb), cadmium (Cd) or arsenic (As) as well as iron or manganese tend to form hydroxy- and carbonate complexes which are insoluble and can therefore not be found in the water. Concentrations of Pb, Cd and As are far below a toxic level in all samples taken in Lusaka and surroundings [5].

Groundwater vulnerability and protection

Groundwater vulnerability describes the sensitivity of a groundwater system to pollution (Figure 27). Vulnerability maps are tools to assess the ability of the environment to protect the groundwater from contamination. They assist in identifying areas which need additional protection measures, such as restrictions of human activities. By using vulnerability maps for integrated water resources management, groundwater protection and management can be significantly improved.

The PI-method was chosen to describe the vulnerability of the aquifers in the Lusaka area. The acronym PI stands for the two factors protective cover (P-factor) and infiltration conditions (I-factor) [22]. The P-factor describes the effectiveness of the protective cover resulting mainly from the thickness and hydraulic properties of all the strata between the surface and the groundwater table [8].

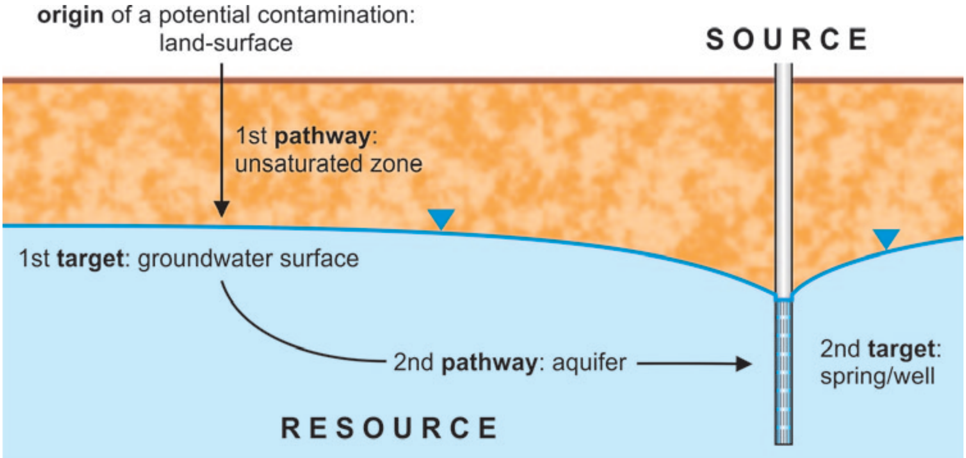


Figure 27 General concept of vulnerability mapping. Resource vulnerability considers target 1 and source vulnerability aims at target 2, after [55].

The I-factor describes the infiltration conditions, particularly the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow (Figure 28).

The estimation of unsaturated zone thickness was based on the regional groundwater table contours which were interpolated from groundwater level point measurements within the Mwembeshi and Chongwe catchments. The thickness of soil and its properties were evaluated [4] taking the soil map of Zambia [48] as well as various soil survey reports into consideration. The lithological units were identified based on the geological map of the area [45]. The landuse was determined from satellite images [3].

The mapped area which is most vulnerable to pollution is on the Lusaka Dolomite Aquifer where extreme and high vulnerability classes prevail, i.e. natural protection is low. In these areas the probability of water quality deterioration is high to very high in the event of a spillage or other hazardous incidents. This is mainly

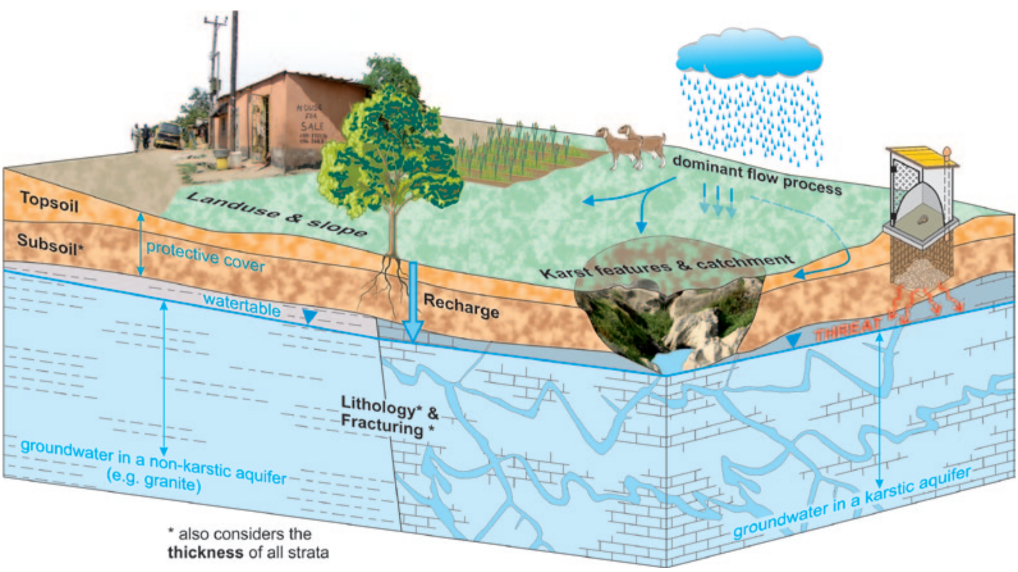


Figure 28 Parameters of the PI-method (after [22]).

Unprotected area on the Lusaka Dolomite with pit latrines, garbage disposal and quarrying around an open groundwater surface.

due to the very thin soil cover which is removed in places, the high groundwater table, and the fast transport channels that exist in this highly fractured and karstic groundwater body.

The largest part of the area is of moderate vulnerability due to less fractured aquifers, more extensive soil cover (Chongwe and Kafue Flats catchments) and/or lower groundwater tables, as for example in the area drained by the Chunga river (Figure 29).

The vulnerability map presents an alarming picture of the risk that is taken if groundwater in the Lusaka area remains unprotected. Especially in the city area, protection measures need to be put in place to prevent resource contamination from potential pollution sources such as industrial activities, storage facilities of harmful substances, wastewater treatment plants and unsafe on-site sanitation, etc. Furthermore, restrictions areneeded for infrastructure planning. New industrial zones for example should be placed on areas of low or very low vulnerability. Protection measures in the extreme and highly vulnerable areas should include (but not be limited to) the ban of unsafe on-site sanitation and dumpsites, restraints on quarrying activities and the prohibition of pesticide application.

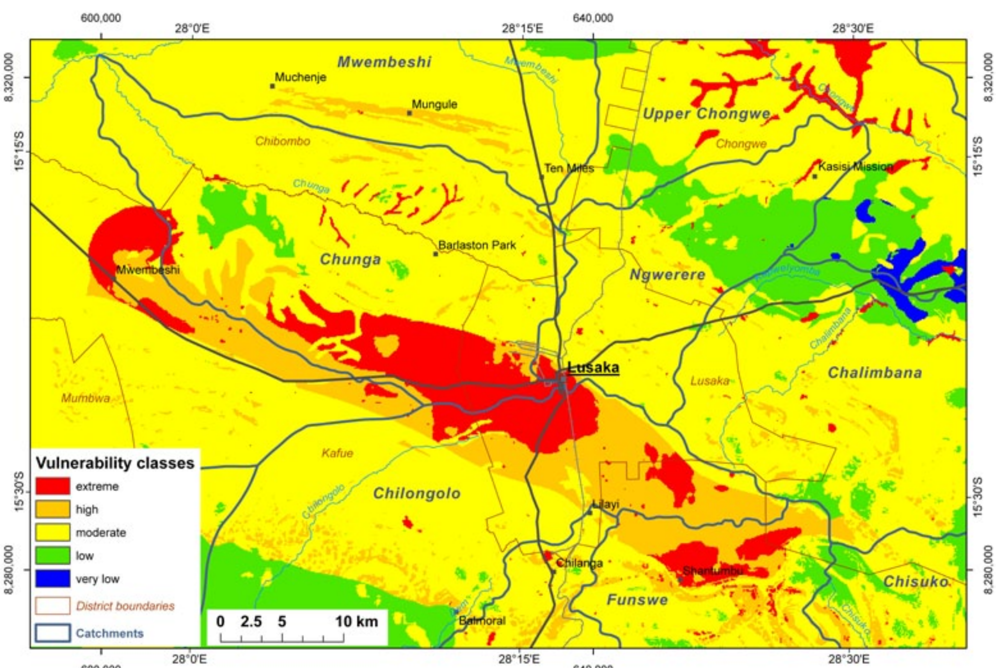


Figure 29 Map of Lusaka and surrounding areas showing the vulnerability to groundwater contamination [8].

Groundwater Maps

The only hydrogeological map available in Zambia prior to this study is at scale 1:1.5 million [31]. This map compiled in 1990 provides an appropriate classification of Zambia's aquifer systems and a very good general idea of overall hydrogeology at national scale. The groundwater information the map is based on, however, is largely taken from studies carried out by Chenov [14] in the late 1970s and hence, somewhat outdated.

The hydrogeological maps developed in the framework of this project are at scales 1:250,000 (four sheets), 1:100,000 and 1:75,000 (one sheet each). The extent of the maps is shown in Figure 30. The information displayed on the maps is drawn from all major groundwater studies that were carried out in the area during recent years. Due to the larger scale compared to the hydrogeological map of Zambia, these maps contain much more detailed information on groundwater related features. They are designed to display the groundwater systems and water points at catchment and sub-catchment scale. All information displayed is available in digitised format (ArcGIS feature classes).

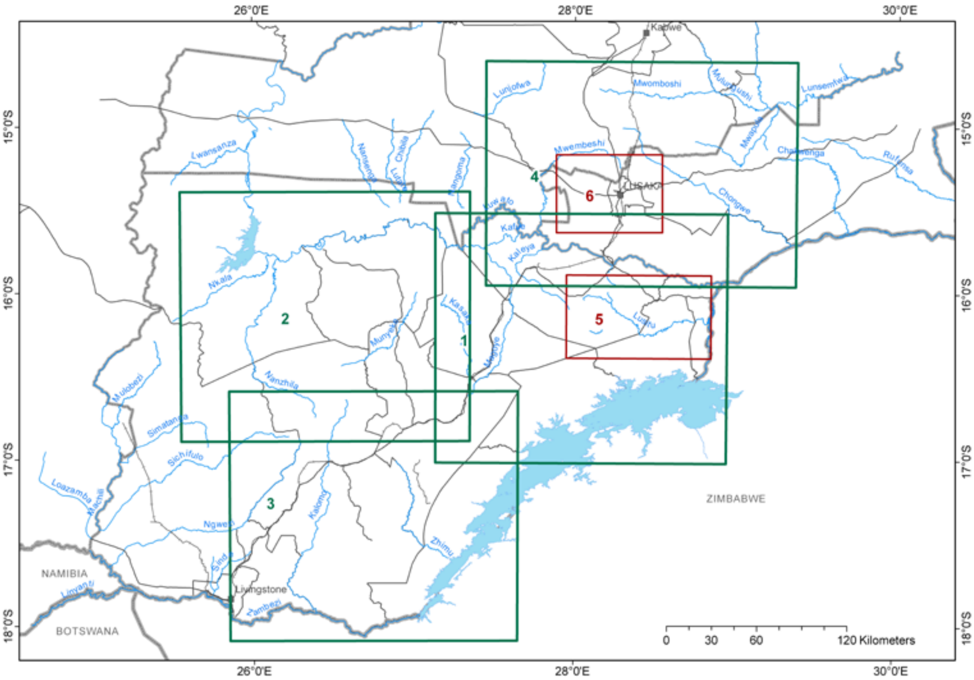


Figure 30 Available hydrogeological map sheets (Scale 1:250,000 unless indicated):

1 Northern Kariba Lake and Kafue Gorge
2 Kafue Flats and Southern Tributaries
3 Southern Kariba Lake and Kalomo
4 Mwembeshi and Chongwe
5 Lusitu, scale 1:100,000
6 Lusaka and surroundings, scale 1:75,000.

Conclusions and Recommendations

In the framework of the project "Groundwater Resources for Southern Province" a professional and comprehensive groundwater information system for the Southern Province and the wider Lusaka area (Lusaka and Central Provinces) was developed at the Department of Water Affairs. The system includes a groundwater database and a Geographic Information System (GIS) for hydrogeological mapping and is expected to be extended step by step to other regions to become a nationwide information system for groundwater resource management.

In the database, detailed technical data on water points in the areas is stored. Statistical information on aquifer characteristics of catchments or administrative units can be obtained straightforwardly and made available to groundwater consultants and planners. The published hydrogeological maps show the location of water points as well as the potential and distribution of major groundwater systems. The vulnerability map of Lusaka and surroundings will serve as a valuable tool for urban and peri-urban planning. On request, other thematic maps showing hydrological and groundwater information can be prepared for individual studies at various map scales using the established GIS.

The available information is considered essential for the planning and preparation of upcoming groundwater investigations. It is therefore envisaged that the information system will be of great use and facilitate a more effective groundwater exploration and management in the near future. Thus, it can back the immediate and effective implementation of Zambia's Water Resources Management Act endorsed in 2011.

During this study, the need of harmonising data acquired during groundwater exploration became obvious. The regular submission of drilling records, water levels and abstraction data must be stronger promoted among stakeholders in the Water Sector. Even if no hydrogeologist or qualified consultant is available at a drill site a minimum set of data could be collected by the person(s) on site including date and location of drilling, a sketch map, GPS co-ordinates, drill depth, borehole and casing diameter, depth of screens installed, static and pumped water levels and pumped yield.

In the Mwembeshi and Chongwe Catchments over 90 per cent of all groundwater

The City of Lusaka as seen from Great North Road is hosted by hard rock including karst formations. Since these aquifers are very heterogeneous, groundwater exploration is not a straightforward task, and the importance of modern siting methods is emphasized. Careful siting using detailed structural analysis and advanced geophysical methods could considerably increase success rates and production rates during exploration drilling. Training of personnel in charge of groundwater development in geophysical field measurements and advanced evaluation methods is hence strongly recommended.

The carbonate rocks of the Mwembeshi and Chongwe Catchments host abundant groundwater resources that are tapped for commercial agriculture and for domestic and industrial water supply to the City of Lusaka. On the hydrogeological maps the various marbles of the Lusaka Dolomite, Cheta and Nyama formations were categorised as groundwater systems of "high" or "moderate to high" potential with exceptional permeability and yields. In some areas such as in the northern parts of the Chunga Catchment, and in areas along the western, south-western and eastern margins of the Lusaka Plateau, the groundwater potential is seemingly not fully exploited.

Recent studies revealed that the overall groundwater quality in the aquifers of the Lusaka region meets many targets of both national and international drinking water standards and hence, is in most places well suitable for drinking water supply. In terms of bacteriological and nutrient concentrations however, groundwater is unsuitable for drinking in most of the high-density urban areas in Lusaka, unless disinfected (e.g. by chlorination). In general water from these areas should not be given to bottle-fed infants due to the risk of blue-baby syndrome. Poor on-site sanitation facilities are currently the largest threat to groundwater quality in the urban area.

The uncontrolled use of agrochemicals, the discharge of industrial chemicals and the negligent handling of leakages from industrial storage tanks are additional pollution risks but often occur locally, as high rainwater infiltration rates dilute contaminants to a high degree.

The assessment of groundwater vulnerability in the area showed that the Lusaka Dolomite Aquifer is extremely prone to pollution as a natural protection cover is largely missing.

The need to protect the resource against contamination cannot be over-emphasised, especially in the fast growing City of Lusaka with ever increasing demand for clean water. Once polluted it is difficult and costly to clean the water to an acceptable standard for drinking.

Areas with extreme and high vulnerability that are used for drinking water production need to be considered for the establishment of protection zones. The concept of groundwater protection through restrictions in land-use has to become an integral part of city planning in Lusaka.

In the framework of the GReSP project existing groundwater monitoring infrastructure in and around Lusaka was substantially extended by the Department of Water Affairs. Water levels are regularly measured at over 40 sites and water quality is monitored at 10 sites. The network does, however, not yet include other zones with high groundwater abstractions such as the Chisamba area.

Additional efforts should also be made to more fully capture the amount of groundwater extracted for water supply as well as industrial and agricultural use. A continuous and extended monitoring of groundwater water tables, abstraction and quality is considered crucial for a more refined groundwater resource assessment and management.

Continuous long-term monitoring is essential in order to identify possible impacts of climate change on water resources. Groundwater level observations can be used to identify trends in groundwater recharge, storage and availability. Groundwater quality monitoring can help to detect additional pollution sources or the potential gradual degradation of water quality.

Suggested Further Reading:

The Technical Reports available at the DWA includes a more comprehensive description of the physiography, climate, hydrology and groundwater systems as well as a full bibliography:

www.bgr.bund.de/zambia

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- Zambia Meteorological Department (ZMD) for comprehensive (daily) meteorological data,

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