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Final Report February 2013

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

Final Report

Key Recommendations and Findings

Simon Kang'omba & Roland Bäumle (eds.)

Lusaka, January 2013

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

KEY RECOMMENDATIONS AND FINDINGS

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Abbreviations

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BMZ	Bundesministerium für Wirtschaft und Internationale Zusammenarbeit (Federal Ministry for Economic Cooperation and Development)
DANIDA	Danish International Development Agency
DEM	Digital elevation model
DWA	Department of Water Affairs
DWASHE	District Water Sanitation Hygiene Education
Eta	Actual evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GReSP	Groundwater Resources Management Support Programme
GWR	Groundwater recharge
IWRM	Integrated Water Resources Management
LCC	Lusaka City Council
LWSC	Lusaka Water and Sewerage Company
m asl	Meters above sea level
m bgs	Meters below ground surface
MLGH	Ministry of Local Government and Housing
MMEWD	Ministry of Mines, Energy and Water Development
MSZ	Mwembeshi Shear Zone
P	Precipitation
PI	Protective cover (P-factor) and infiltration conditions (I-factor)
Q	Surface runoff
SRTM	Shuttle Radar Topography Mission
TDS	Totals dissolved solids
TIN	Triangulated irregular network
UNZA	University of Zambia
WARMA	Water Resources Management Authority
WEAP	Water Evaluation and Planning
ZEMA	Zambian Environmental Protection Agency

List of reports compiled by the project in Phase II

Date	Authors	*Title*	Type
Apr. 2009	Museteka L. & R. Bäumle	*Groundwater Chemistry of Springs and Water Supply Wells in Lusaka - Results of the sampling campaigns conducted in 2008*	Report No. 1
Oct. 2009	R. Bäumle. & S. Kang'omba	*Development of a Groundwater Information & Management Program for the Lusaka Groundwater System: Desk Study and Proposed Work Program Report*	Report No. 2
March 2010	Hahne K. & B. Shamboko-Mbale	*Karstification, Tectonics and Land Use in the Lusaka region*	Report No. 3
Oct. 2010	Mayerhofer C., Shamboko-Mbale B. & R.C. Mweene	*Survey on Commercial Farming and Major Industries: Land Use, Groundwater Abstraction & Potential Pollution Sources-*	Report No. 4
Aug. 2012	Hennings V.	*Assessment of annual percolation rates in the Lusaka region*	Report No. 5
Dec. 2012	Maßmann J.	*Numerical groundwater flow model of the Lusaka region*	Report No. 6
Dec. 2012	Shamboko-Mbale B., Siwale C., Bäumle R. & T. Krekeler	*Water Balance Estimates for Sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka region*	Report No. 7
Feb. 2008	Bäumle, R. & J. Nkhoma	*Preliminary Assessment of the Hydrogeological Situation around Lusaka South Local Forest Reserve No. 26*	Technical Note No. 1
Nov. 2010	Tena, T. & A. Nick	*Capacity Building and Awareness Raising Strategy for Phase 2 (2010-2012)*	Technical Note No. 2
Nov. 2010	Nick A., Museteka L. & R. Kringel	*Hydrochemical Sampling of Groundwater in the Lusaka Urban Area (April/May 2010) and Preliminary Findings*	Technical Note No. 3
Feb. 2011	Bäumle R.	*Results of pumping test evaluation and statistical analysis of aquifer hydraulic properties*	Technical Note No. 4
Apr. 2011	Kringel R., Fronius A., Museteka L. & A. Nick	*Assessment of CVOC- and BTEX-contamination level in Lusaka ground-water in 2010 based on developing and testing a method to sample and analyse groundwater containing organic volatile substances after extended storage*	Technical Note No. 5
Aug. 2011	Nick A.	*Compilation of a vulnerability map according to the PI- method – A documentation and manual*	Technical Note No. 6
Dec. 2012	Krekeler T. & C. Siwale	*Discharge measurements and rating curves of the rivers Chalimbana, Chilongolo, Chongwe, Chunga, Kapwelyomba, Mwembeshi, Ngwerere and Laughing Waters Spring*	Technical Note No. 7
June 2012	Bäumle R., Anscombe, J., Siwale C. & A. Nick	*Results of drilling and test pumping at three selected sites in Lusaka, Kafue and Chibombo Districts*	Technical Note No. 8
Aug. 2012	Hennings, V., Willer, J., Sokotela, S., Bwalya, A. & T. Tena	*Regionalization of soil physical parameters in the Lusaka region*	Technical Note No. 9

Summary

Authors: Simon Kang'omba & Roland Bäumle (eds.)

Title: Final Report: Key recommendations and findings

Key words: groundwater management, vulnerability, water budget, groundwater quality, groundwater protection, sustainable yield, capacity building

This report summarises the main findings and recommendations of Phase 2 of the groundwater management support programme GReSP that was carried out between January 2010 and March 2013. The programme was implemented by the Department of Water Affairs (DWA) under the Ministry of Mines, Energy and Water Development with technical support provided by the Federal Institute for Geosciences and Natural Resources, Germany (BGR). The programme overall aimed at strengthening the capacities in the Zambian water sector and at making a significant contribution to enable the DWA and other key stakeholders within the project area to manage groundwater resources in a more efficient and sustainable manner and to provide safer water to the Zambian people.

The report consists of two parts. Part A focusses on major outputs of the study and the recommendations developed concerning the sustainable future use and required measures to better protect groundwater resources in the Lusaka area. Part B summarises the key results of individual components of the study such as the hydrogeological investigations conducted, the groundwater information system established and the implemented capacity building and awareness raising activities.

Executive Summary

Phase 2 of the groundwater management support programme GReSP was carried out between January 2010 and March 2013. The programme was implemented by the Department of Water Affairs (DWA) under the Ministry of Mines, Energy and Water Development with technical support provided by the Federal Institute for Geosciences and Natural Resources, Germany (BGR). Financial support to the programme was granted by the Federal Ministry for Economic Cooperation and Development (BMZ) of the Federal Republic of Germany under its priority area program "Water and Sanitation". Under GReSP, a wide-ranging hydrological and hydrogeological investigation programme was carried out covering the Mwembeshi and Chongwe catchments including the Lusaka Plateau. The area hosts very productive and extensively used carbonate aquifer systems which arguably form one of Zambia's most significant groundwater reserves.

The report includes the key recommendations to future groundwater usage, management and protection and summarises major outputs of the Programme and key findings of the individual investigations completed.

The key recommendations are as follows:

1. A specific unit should be established under the Water Resources Management Authority (WARMA) responsible for groundwater management and protection.
2. A Human Resources Development Strategy for the WARMA and subordinate authorities on catchment and sub-catchment level should be developed that explicitly recognises the capacity requirements of new institutions with respect to groundwater. It is also recommended to look into possibilities of providing additional hands-on training for groundwater management to institutions as well as to develop an undergraduate/diploma course in the field of hydrogeology in Zambia.
3. The Department of Water Affairs should continue to convene the Technical Forum established under the Programme and further strengthen its functions such as information sharing among stakeholders and providing technical input to matters related to groundwater management.
4. The current groundwater abstraction in Lusaka of about 90 Mm^3 per year is considered sustainable and can hence be maintained despite considerable remaining uncertainties regarding abstraction and recharge. These uncertainties are mainly attributable to climate variability and very complex hydrogeological conditions. It is recommended to continue to use groundwater in combination with surface water for water supply in order to minimize dependency on just one resource and thus increase the security of supply.
5. Groundwater recharge varies strongly with rainfall and availability of groundwater may be significantly reduced under persisting drought conditions. Continuous and comprehensive monitoring therefore plays a crucial role in analysing the relationship between rainfall and recharge and evaluating changes in water tables. The existing hydrometric and groundwater monitoring network in Lusaka is adequate and should be professionally maintained. Collection of abstraction data from large public and private wells, however, is currently insufficient and hence needs to be incorporated in monitoring procedures. New monitoring data should be used for validation of the groundwater model results and water budget analysis.
6. According to results of the numerical groundwater model abstractions could be increased further presuming long-term average rainfall conditions prevail. The sustain-

able yield of the Lusaka aquifers is probably between 140 Mm^3 and 150 Mm^3 per year.

7. Large volumes of additional groundwater should only be pumped from areas at sufficient distance from the City and existing wells in order to avoid a big drawdown in the water tables. Five areas at distances ranging from 10 to 30 kilometres from the City Centre that are considered favourable for groundwater exploration are given in the report.
8. It is suggested to calculate the capital and operations and maintenance costs of groundwater supply from the five suggested additional well field areas and compare them to costs of surface water supply.
9. Sanitation provision must focus on high-density peri-urban areas; greatest attention should be paid to sustainable sanitation supply in extreme and highly vulnerable areas.
10. The choice of the sanitation systems to be applied must consider the karstic nature of the underground with the containment of excreta being the most important criterion. Examples are biogas systems, dry toilets and sewerage as long as they provide sufficient protection against leakages.
11. In the highly vulnerable setting of Lusaka, sanitation cannot remain in the responsibility of the individual household. Water and sanitation suppliers as well as the Lusaka City Council (LCC) must take the matter into their own hands and provide the necessary resources required for this.
12. Water supply wells should be protected by a zoned approach of land-use restrictions. The establishment of groundwater protection zones is one of the legal instruments prescribed by the Water Resources Management Act of 2011. For improved groundwater protection zoning, flow velocities need to be determined through tracer tests. Groundwater protection measures in the form of land-use restrictions should be put in place in city planning, infrastructure implementation and on-going activities.
13. City planners and decision makers in the local authorities and commercial utilities are advised to use the vulnerability map to prioritize interventions of groundwater protection for different areas.

The authors express their wish that the Water Resources Management Authority under the Ministry of Mines, Energy and Water Development together with the Zambian Environmental Management Authority and Local Authorities will attach the necessary importance to matters of groundwater management and protection.

PART A

KEY RECOMMENDATIONS

Prepared by Simon Kang'omba, Roland Bäumle & Andrea Nick

1. INTRODUCTION

Phase 2 of the groundwater management support programme GReSP[1] was carried out between January 2010 and March 2013. The programme was implemented by the Department of Water Affairs (DWA) under the Ministry of Mines, Energy and Water Development with technical support provided by the Federal Institute for Geosciences and Natural Resources, Germany (BGR). Financial support to the programme was granted by the Federal Ministry for Economic Cooperation and Development (BMZ) of the Federal Republic of Germany under its priority area program "Water and Sanitation". Under GReSP, a wide-ranging hydrological and hydrogeological investigation programme was carried out covering the Mwembeshi and Chongwe catchments including the Lusaka Plateau (Figure 1). The area hosts very productive and extensively used carbonate aquifer systems which arguably form one of Zambia's most significant groundwater reserves.

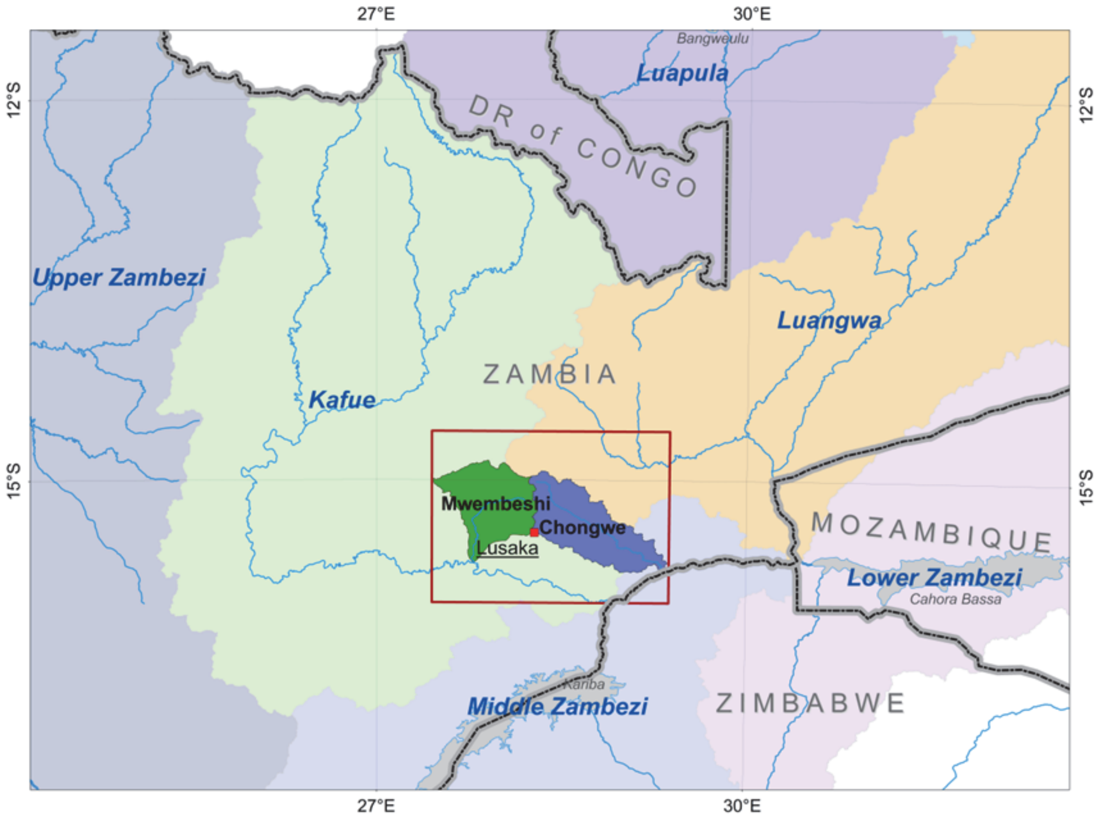

Figure 1 The study area of Phase 2 of GReSP

GReSP overall aimed at strengthening the capacities in the Zambian water sector and at making a significant contribution to enable the DWA and other key stakeholders within the project area to manage groundwater resources in a more efficient and sustainable manner and to provide safer water to the Zambian people.

The programme comprised five main components intending to:

[1] The GReSP project was launched in May 2005 and the acronym "GReSP" originally stood for "Groundwater Resources for Southern Province". The focus of interest has shifted from Southern Province to the Lusaka area during Phase 2. The title of the Project has recently been changed to "Groundwater Resources Management Support Programme" as it intends to focus on groundwater issues in various parts of Zambia.

1. establish a groundwater information system for the pilot study areas (as part of a national system) encompassing a groundwater database and a Geographical Information System (GIS) for the purpose of mapping of groundwater resources;
2. estimate the sustainable yield of the Lusaka groundwater systems;
3. determine the status of the quality of groundwater and identify pollution risks;
4. build capacity focussing on critical skills related to groundwater management and raise awareness of the importance of groundwater management and protection with respect to both economic growth and public health;
5. develop a groundwater management and protection strategy for the Lusaka area and open the way for a stakeholder dialogue intended to initiate its implementation.

During Phase 2 a multi-fold scientific investigation program was conducted to improve the knowledge of Lusaka's groundwater occurrences and to assess the potential of these aquifers for further development. The following studies were accomplished:

- collection of borehole and groundwater information,
- extension and maintenance of the hydrometric and groundwater monitoring network,
- analysis of the tectonic settings of the Lusaka area,
- remote sensing analysis for delimiting karst features, major fault and fracture zones and land use types,
- exploration drilling (3 sites), hydraulic testing and analysis of pumping test data,
- detection of springs and groundwater contouring,
- categorising of aquifer potential,
- hydrogeological mapping,
- groundwater recharge assessment,
- water budget analysis,
- groundwater quality analysis (inorganic and organic compounds),
- groundwater vulnerability mapping.

The results and major findings of the individual studies are summarised in Part B of this report.

2. MAJOR OUTPUTS OF THE PROGRAMME

The Programme during Phase 2 yielded numerous new achievements such as closing existing knowledge gaps, extension of monitoring and information management infrastructure, capacity development and advisory services provided to the sub-sector.

Important outputs of the various activities implemented under GReSP include:

1. Three new rainfall gauges (at Mwembeshi, Ten Miles and ZAWA Park) and two new stream gauges (at Chunga River and Laughing Waters spring) were constructed and seven new groundwater monitoring boreholes were drilled in Kafue, Chibombo and Mumbwa districts. Currently, the DWA observes groundwater levels in the study area at 25 wells using digital probes (see Part B, Figure 25). Readings at 10-days interval are taken at 21 additional points. Regular groundwater quality monitoring is carried out at 11 locations.
2. The groundwater database combines data from Southern, Lusaka, Central, Eastern and North-western provinces. Currently over 12,000 water points are captured.
3. The numerous findings of the scientific investigations are described in detail in seven project reports and nine technical notes. The documents are available online under the following address: www.bgr.bund.de/zambia .
4. Under the Programme three thematic maps were developed and published including the hydrogeological map 1:250,000 of the Chongwe and Mwembeshi catchments (Bäumle & Kang'omba 2012a), the hydrogeological map 1:75,000 of the Lusaka region (Bäumle & Kang'omba 2012b) and the vulnerability map 1:75,000 of the Lusaka region (Nick et al. 2012).
5. The DWA produced the Hydrological and Hydrogeological Yearbook of the Chongwe/Mwembeshi catchment areas for the 2010 and 2011 water years (Siwale & Bäumle 2012).
6. A sub-unit at DWA dealing specifically with topics related to groundwater management is fully functional. From 2010 to 2012 the sub-unit replied to and documented 252 data requests from various institutions and distinguished professionals and researchers.
7. A Technical Forum for groundwater resources management was established among partners and stakeholders involved in groundwater issues. The forum is highly appreciated among those attending for continuous sharing of information and technical experiences. Six meetings were held since 2010.
8. Capacity building activities at four levels were implemented under the Programme, which included
   i. continuous on-the-job training of four counterparts and additional intermittent on-the-job training of staff in selected tasks,
   ii. development and offering of three training modules for a 8-weeks course with 20 participants at the IWRM-Centre of the University of Zambia (UNZA),
   iii. training courses for government personnel and researchers in groundwater database and information management using GeODin® targeting district administration (82 participants), 10 members of staff at Lusaka Water and Sewerage Company (LWSC) and 15 MSc students at UNZA,
   iv. two international bursaries for hydrogeological studies at MSc level.

9. Numerous awareness raising activities were conducted including two major workshops on groundwater management, sustainable sanitation and city planning, presentations to key stakeholders such as LWSC and LCC as well as participation in the exhibitions for World Water Day, Zambia Water Forum and Exhibition (ZAWAFE) and annual fairs in Lusaka and Ndola. Advocacy activities for the general public are estimated to have reached more than 650 people.

3. RECOMMENDATIONS

3.1. GENERAL RECOMMENDATIONS

3.1.1. Establishment of a groundwater unit at WARMA

Groundwater management and in particular protection of groundwater has not received much attention in Zambia in the past, one of the reasons being that groundwater was not regulated or protected under the Water Act of 1948 (GRZ 1948). This Act has since been replaced by the Water Resources Management Act of 2011 (GRZ 2011). The new Act gives the mandate to implement groundwater protection measures to the Water Resources Management Authority (WARMA) with collaboration of other institutions directly involved, such as the Zambian Environmental Protection Agency (ZEMA) and the Ministry of Local Government and Housing (MLGH) through its local authorities.

With this recent positive development, the authors recommend that the Water Authority sets up a specific unit that will tackle issues of groundwater management and protection. This unit then needs to develop concrete by-laws on groundwater usage and protection. These can be based among other things on recommendations listed below.

3.1.2. Capacity development

Capacity in the field of hydrogeology in Zambia is still limited. It is recommended to continue to implement hands-on training measures at relevant institutions in the fields of groundwater information management, development and protection. Furthermore, it is essential to develop a Human Resources Development Strategy for the WARMA and subordinate authorities on catchment and sub-catchment levels that explicitly considers capacity requirements of the new institutions with respect to groundwater. It is also recommended to look into possibilities to develop and install an undergraduate/diploma course in the field of hydrogeology in Zambia.

3.1.3. Stakeholder dialogue via Technical Forum

The Technical Forum established under Phase 2 of the Programme strengthened cooperation between relevant authorities regarding groundwater. It is therefore recommended that the Technical Forum continues to fulfil its tasks such as sharing of information and technical experiences and providing technical input to matters related to groundwater management. The role of the Forum should be further strengthened as it can provide valuable input to the development of sustainable management guidelines and by-laws on groundwater usage and protection under the new Water Resources Management Act.

3.2. USE OF GROUNDWATER RESOURCES

3.2.1. Sustainability of groundwater usage

According to the study results, long-term average recharge in the Lusaka area is estimated to be about 250 mm per year. Average recharge is therefore higher than most previous studies predicted. During years with below average rainfall, however, recharge will drop significantly. Total combined groundwater abstraction in the four catchments discharging the Lusaka City over a total area of 2,247 km^2, namely Ngwerere, Chalimbana, Chilongolo and Chunga streams, currently amounts to about 90 Mm^3/a which translates to a recharge of 40 mm per year (Shamboko-Mbale et al. 2012). Consequently, total groundwater abstraction is still fairly small compared to recharge under average meteorological conditions. In some areas such as the upper parts of the Ngwerere, Chalimbana and Chunga catchments however, groundwater abstractions exceed 100 mm per year due to combined abstractions from public water supply wells and private boreholes. Locally, groundwater resources may therefore come under stress especially during prolonged dry conditions.

Nevertheless, the current total groundwater abstraction from the Lusaka aquifers is considered sustainable and can hence be maintained despite considerable remaining uncertainties regarding abstraction and recharge that are mainly attributable to climate variability and very complex hydrogeological conditions. It is recommended to continue to use groundwater in combination with surface water for water supply in order to minimize dependency on just one resource and thus increase the security of supplies.

3.2.2. Hydrometric (monitoring) network

Considering the outstanding importance of the Lusaka groundwater occurrences with respect to public and private water supply and economic development, it is recommended to maintain the established monitoring network consisting of rain gauges, stream gauges, groundwater level monitoring boreholes and groundwater quality monitoring sites[2].

As groundwater recharge varies strongly with rainfall, continuous and comprehensive monitoring plays a crucial role in analyzing the relationship between rainfall and recharge and evaluating changes in water tables. The monitoring data is also needed and should be used to validate the results of the numerical groundwater model and the water budget analysis and to be able to detect water shortages or pollution sufficiently early.

Basic operational rules to maintain the established network are given in Table 1. In addition, the following suggestions for improvement are made:

- Installation of cumulative pluviometers (“rainfall totalisator”) in addition to each automatic rain gauge could be used for verification of hourly measurements.
- Installation of automatic water level recorders at stream gauges (in addition to manual readings) could improve the sampling rate and data security.
- Boreholes where water levels are only taken manually should be equipped with digital probes.

[2] The current number of 46 groundwater level monitoring boreholes could possibly be reduced if financial or logistical constraints exist. This could apply for instance to sites at the University of Zambia campus or the Forest Reserves no. 26 and no. 55.

- Authorities and in particular LWSC must put more emphasis in continuously monitoring abstraction rates and drawn water levels at all major wells for public and private water supply. This recommendation applies at least to wells with abstractions exceeding say, 500 m^3/d.

Table 1 Suggested operational rules to maintain existing monitoring network under the DWA

Type of installation	Current no.	Actions to be taken
Automatic rain gauges	3 1)	- Check function and read out data monthly during rainy season. - Close gauge during dry season. - Clean and check gauge before beginning of rainy season. - Empty and measure accumulated rainfall at totalisator (if available) during each site visit.
Stream gauges	7	- Measure discharge and check if gauge plates and angle irons are fixed well after each rainy season. - Check gauge at least twice a year at the beginning and the end of each rainy season to keep it free from silt deposition, aquatic weeds and debris.
Monitoring boreholes	25	- Check accuracy and read out probes monthly during rainy season. - Check accuracy and read out probes every two months during dry season.

1) Excluding new rain gauge at DWA Sheki Sheki Street

3.2.3. Possible additional groundwater abstraction volumes

A numerical groundwater model was developed for the Lusaka area covering the Lusaka Plateau and surrounding areas to the north and south (Maßmann 2012). The area covered by the model totals 2,270 km^2. The model reproduced observed water tables adequately and is therefore considered a good tool to investigate the current and future water budget considering different water management options. The model was first used to estimate the sustainable yield of the area. The model runs showed that abstractions of 110 Mm^3/a would lead to a minor additional drawdown compared to the current situation. The model, however, predicts a considerable drop in water tables in the Lusaka City area if abstraction near existing well fields is substantially increased. Future exploration would therefore have to focus on areas further away from the City. Scenario calculations incorporating additional well fields on the Lusaka Plateau to the east and west of the City indicated that total abstractions could possibly be increased by an additional 30 to 40 Mm^3/a (total of 140 to 150 Mm^3/a) presuming that long-term average rainfall conditions prevail. Local authorities and LWSC estimate an increase in water demand of about 67 Mm^3/a by 2035. Consequently, groundwater reserves would be insufficient to fully cover the forecasted increase in water demand.

3.2.4. Areas recommended for future groundwater exploration

In order to realize further groundwater abstractions, the development of additional well fields outside of existing abstraction areas are needed. Based on the groundwater modeling results five additional areas are proposed, these being *Mikango* and *Shantumbu* southeast of Lusaka City and *Lusaka West*, *Lusaka West 2* and *Chinyanya* located to the west of Lusaka (Figure 2). The distance of the proposed well fields to the City center ranges from approximately 10 km to 30 km. Areas in Chibombo District covered by carbonate rocks of the Cheta Formation (Mayaba, Musopelo, Mungule villages) may host another productive groundwater reserve. The knowledge on the hydraulic properties of these areas, however, is very limited to date.

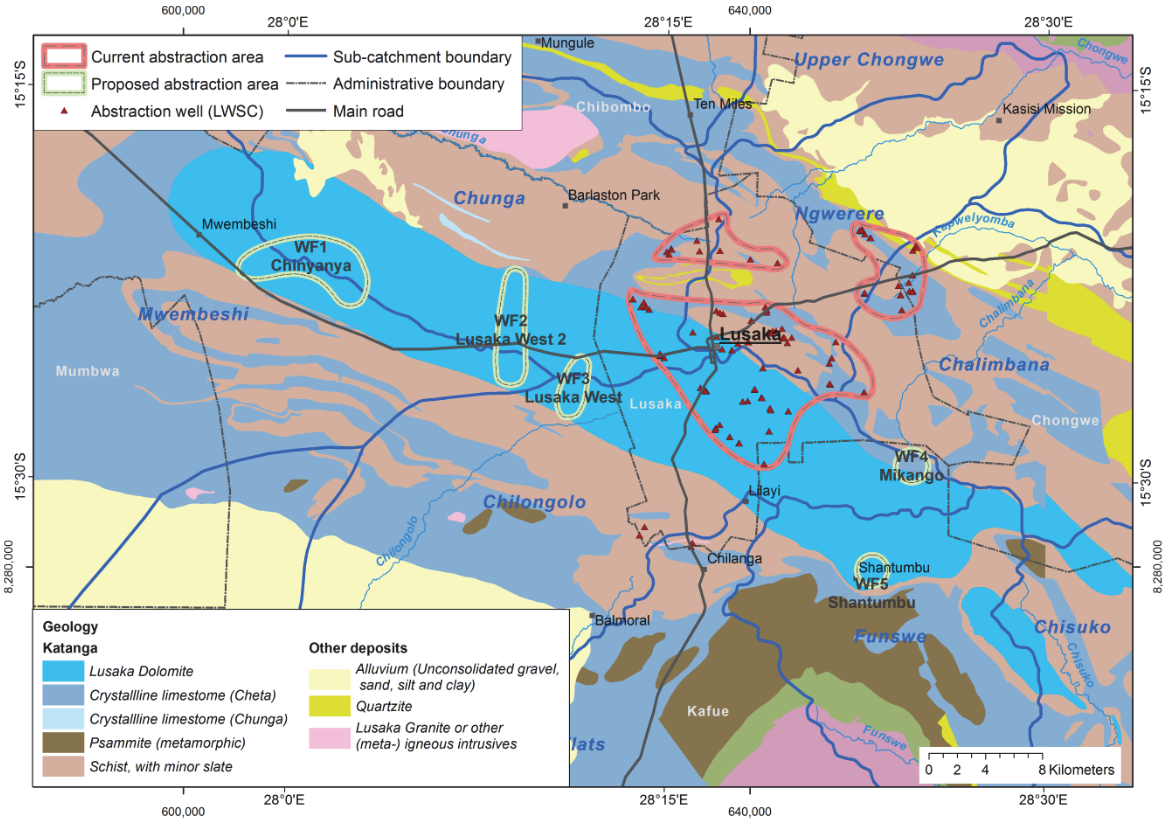

Figure 2 Possible new sites for groundwater exploration on the Lusaka Plateau according to the results of groundwater modeling

3.2.5. Economics of groundwater abstraction

It must be assumed that the Lusaka groundwater bodies are insufficient to supply enough water to cover the increase in water demand predicted for the next 30 years. Compared to the water supply from Kafue River via the Iolanda intake and pipeline system, groundwater presently provides a much cheaper source according to LWSC (presentation by LWSC during 5th Technical Forum Meeting held on May 9, 2012). A higher proportion of supplied groundwater hence offers the possibility to provide water at a more reasonable cost and to minimize the retail price. Producing water from well fields at greater distance from the existing distribution system, however, will result in an increase in overall costs for groundwater supply. It is suggested to calculate the capital, operations and maintenance costs of groundwater supply from the five suggested additional well fields and compare them to costs of surface water supply.

3.3. PROTECTION OF GROUNDWATER RESOURCES

3.3.1. Improved sanitation

The water quality campaigns conducted by the GReSP project indicate frequent **micro-biological and nutrient pollution of groundwater** (Museteka & Bäumle 2009, Nick et al. 2010). This shows that safe sanitation must be provided in high-density peri-urban areas; greatest attention should be paid to sustainable sanitation supply in extremely and highly vulnerable areas. Pollution by organic compounds found in a number of boreholes in April/May 2010 (Kringel et al. 2011) shows that sound handling and disposal practices of solvents and fuel are also required.

The choice of the sanitation systems to be applied must consider the karstic nature of the underground with the containment of excreta being the most important criterion. Examples are biogas systems, dry toilets and sewerage in case they provide sufficient protection against leakages (also see chapter 3.3.3).

In the highly vulnerable setting of Lusaka, sanitation cannot remain in the responsibility of the individual household. Water and sanitation suppliers as well as LCC must assume responsibility and provide the necessary resources required for this.

Sanitation provision is necessary in the whole study area (where human settlements are situated) but in terms of prioritization the southern areas of Lusaka City need to be serviced first. The areas delineated in Figure 3 are derived from the vulnerability map (Nick et al. 2012) and constitute zones of extreme vulnerability (red, priority area 1) and high vulnerability (orange, priority area 2). The areas outlined in red represent places which need to be serviced with highest priority; they include Kanyama, the industrial area, John Laign and Kamwala South as densely populated areas as well as parts of Forest Reserves No. 55 and 26 in the south-east of Lusaka District which need to be declared and kept as protected areas. In the industrial area, emphasis must be put on the treatment of industrial contaminants. The area bordered in orange including settlements like John Howard, Libala and Chilenje stands for second priority but should closely follow priority 1 areas on the intervention schedule. Other areas which have moderate vulnerability degrees but have shown unsatisfying groundwater quality are highlighted with red labels, namely Chunga, Chainda, George and Bauleni. These areas must be provided with safe sanitation as soon as possible.

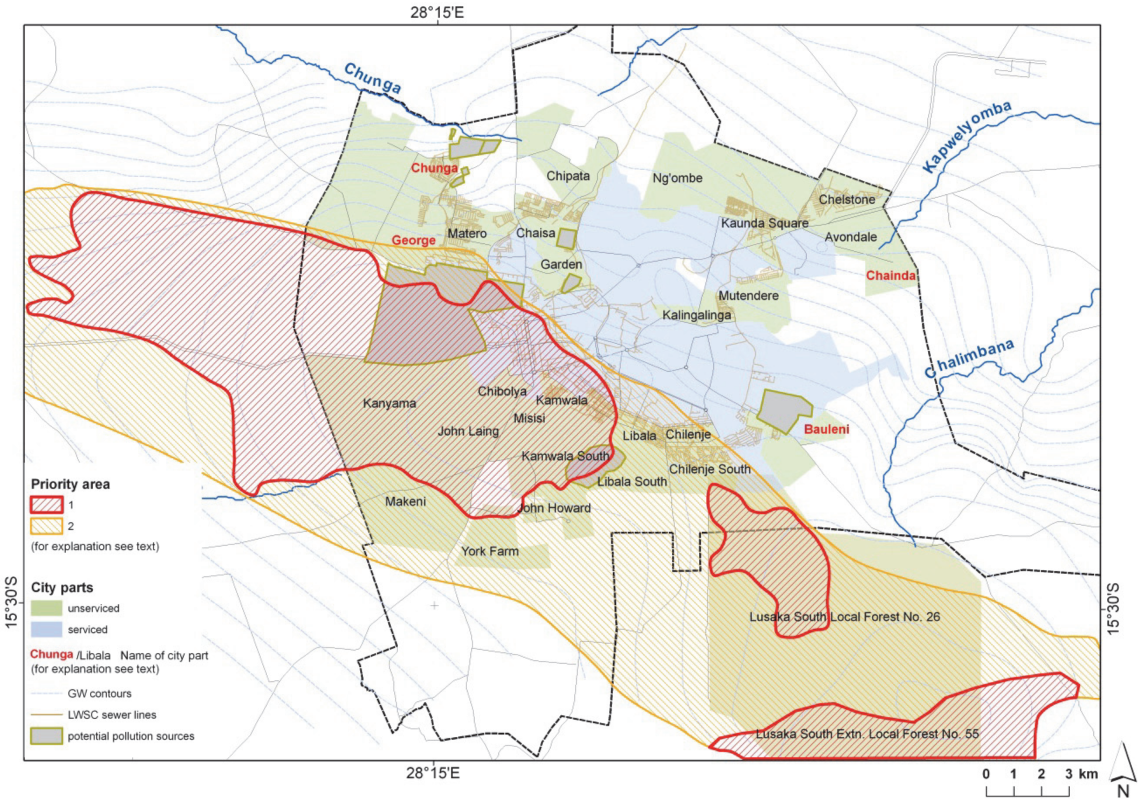

Figure 3 Priority intervention areas for groundwater protection

Most of the areas outlined in the priority intervention map are supplied with water through kiosks, which usually draw water from the local production borehole. Water kiosks as a point of distribution for water supply to those who cannot afford a household connection can be an efficient service facility. However, the water they distribute must be of safe quality. In the highlighted peri-urban areas where high concentrations of coliforms, nitrate and other nutrients were found, water for the water kiosks should not be drawn from local boreholes but should receive its water by the central supply (bulk water supply system). While coliforms can be treated with disinfection methods such as chlorination, nitrate cannot be removed easily and poses a health threat especially to infants. The focus in these areas should be in investing in sustainable sanitation systems which as a consequence, decreases groundwater pollution, turning the local groundwater into a potable resource again. In the meantime, it has to be ensured that residents of peri-urban areas receive safe drinking water from the bulk water supply.

3.3.2. Vulnerability map as a tool

The **vulnerability map** of Lusaka and surrounding areas indicates areas with a high probability of pollution and thus the urgent need for groundwater protection. City planners and decision makers in the local authorities and commercial utilities are advised to use the map to prioritize interventions of groundwater protection for different areas. Figure 3 provides only an excerpt of the full map, concentrating on the urban centre. On the vulnerability map, priority 1 should be given to “extremely vulnerable” areas and priority 2 to “highly vulnerable” areas.

3.3.3. Measures of groundwater protection

Groundwater protection is the first step for a sustainable resource management. The settlements in extremely and highly vulnerable areas (priority zones 1 and 2 in Figure 3) should receive highest priority in the **provision of sanitation services**. Additionally, some **land-use restrictions** should be taken into consideration during planning stages and enforced during implementation and for on-going activities. In prioritized order the measures for groundwater protection to be taken in extremely and highly vulnerable areas comprise:

- **Sanitation systems** need to be lined with material preventing leakage of wastewater into the groundwater and seepage of groundwater into the wastewater containment. Decentralized systems managed by LWSC or LCC (or other institutions or businesses) that take over operation and maintenance from individual households should be given priority over traditional on-site systems. In places where decentralized systems cannot be realized, contained systems like compost or urine diversion toilets should be considered rather than the traditional pit latrine. Where necessary, the pit latrines must have a cement or other forms of lining and should not reach beyond two meters in depth. In areas where groundwater levels are close to the ground surface during the rainy season, sanitation systems which store the waste and allow for later removal and transport out of the area need to be implemented. If sewage collectors or septic tanks are installed, it must be ensured that they are properly constructed and lined.
- All existing residential buildings need to be connected to a sanitation system or have an onsite system as mentioned above.
- **Wastewater treatment** plants should not be built here. If this cannot be avoided, the plants must be protected from groundwater entering from below or flood water.
- If sewers have to cross zones of high vulnerability they have to be double walled or surrounded by an impermeable layer.
- Small-scale **quarries** or mines cannot be allowed as they involve removal of protective soil and rock layers. This is important especially in the largest priority area 1 (Figure 3) which includes John Laign, Chibolya, parts of George and other peri-urban areas where quarrying is a source of income.
- There should be no active **landfills**. Dumping of wastes needs to be prohibited and compliance enforced.
- **Industrial land use** which includes the use of potentially harmful substances, especially liquids, must not be allowed. Where industries are already located in highly vulnerable zones and cannot be given compensation and transferred, ZEMA and WARMA need to monitor water effluents and groundwater quality in the area very intensely and work together with the industries to ensure all possible measures are taken to prevent pollution. These measures must include onsite treatment systems for process water, constructed and maintained by the industries and monitored by ZEMA, as well as lined and regularly inspected storage facilities for potentially harmful substances.
- **Petrol stations** and depots, as well as solvent requiring industries must not be constructed. All existing sites must ensure that their facilities are safe and do not develop leakages. Storage tanks have to be built with the highest standard of containment and the adequate monitoring facilities.
- No **cemeteries** should be allocated in these areas.

- **Agricultural activities** are permitted but only without application of pesticides or other harmful substances. Organic farming provides alternatives to chemical pesticides and fertilizers and should be propagated for these areas. Irrigation water should comply with environmental limits for discharge to streams.
- The application of **sewage sludge** should be restricted to areas of lower vulnerability.
- There should be no **livestock** schemes (> 5 animals) as nitrates and germs from animal faeces pose a similar threat to groundwater as human faeces.
- Within the extremely and highly vulnerable areas **all boreholes need to be capped and fenced off** and entry should be allowed only to personnel of the water supplier. The common practice to grow crops inside the borehole fencing needs to be prohibited or adequate measures taken to ensure that the water source is protected.

3.3.4. Protection zoning

The concept of groundwater protection zoning encompasses a staged zoning around drinking water sources (wells and springs) with increasing land use restrictions closer to the source. The innermost protection zone (zone I) is commonly 10 - 50 m around the source itself. Often the source is surrounded fenced off and only staff of the relevant authority may enter. In karst areas, the inner protection zone (zone II) encompasses areas of high and very high vulnerability, e.g. areas around sinkholes and streams and along structural faults, slopes with runoff into streams or sinkholes and areas with thin soils. In Figure 3, these areas are marked for Lusaka City as priority 1 and 2 areas. The outer protection zone (zone III) should comprise the entire catchment area in karst regions. Therefore, groundwater protection in karst areas requires vulnerability mapping for the delineation of protection zones and hydrogeological investigations, such as tracer tests, for the improved delineation of the catchment area.

The establishment of groundwater protection zones is one of the legal instruments prescribed by the Zambian Water Resources Management Act of 2011. Further legislation has to outline the specifications for the protection zones, the delineation method and land use restrictions for each zone as well as measures and penalties for non-compliance. A coherent system of regulations and clearly defined responsibilities between institutions are essential for a successful implementation. The population has to be informed and sensitized about the installation of protection zones and the associated land use restrictions and the zones have to be clearly marked. For existing facilities that do not comply with new regulations compromises have to be found. Recommended land use restrictions are:

Zone I (innermost zone)

- no activities apart from necessary work related to the water supply
- no wastewater facilities in this zone including
- no sewage collectors crossing this zone
- no handling of hazardous material

Zone II (inner zone)

- no sewage collectors, cesspool or septic tanks. If sewers have to cross this zone they have to be double walled or surrounded by an impermeable layer.

- no wastewater treatment plants
- no industrial land use, landfills or dumping of wastes
- no quarries or mines
- agricultural activities using fertilisers are allowed but application of pesticides is prohibited; irrigation water should comply with environmental limits for discharge to streams.
- no application of sewage sludge
- no livestock
- no new developments or building constructions should be allowed; all existing residential buildings have to be connected to a wastewater treatment plant.
- no new construction of roads

Zone III (outer zone)

- most activities are permitted, but general care should be taken not to contaminate the groundwater resource; operation of industrial and commercial sites should follow environmentally sound practices.
- no underground storage tanks of hazardous substances, but if necessary only with impermeable liner and double walls; above ground storage tanks with double walls and equipped with leak detectors and drainage system
- no discharge of untreated wastewater into the environment, especially industrial wastewater has to be treated.
- no infiltration of strongly contaminated storm water e.g. from petrol stations, high traffic roads or industrial premises; these storm waters should be collected and infiltrated via filtration systems or treated through constructed wetlands.
- landfills have to be constructed with liners and drainage systems to avoid percolation of hazardous leachate into the groundwater
- sewage collectors should be surrounded by soils of low permeability and have to be checked regularly for leakages.
- environmental impact assessments for industrial facilities
- erosion control through natural vegetative cover

At the current stage however, it is not possible to define individual protection zones for production boreholes in Lusaka as reliable figures for mean flow velocities are lacking. Therefore a vulnerability map has been developed to guide protection efforts toward highest priority areas.

4. OUTLOOK

Its underlying groundwater resources are of outmost importance for the City of Lusaka as it draws more than half of its water from them. It is expected that Lusaka - being the capital city of Zambia - will keep growing and expanding both its housing and industrial infrastructure. Therefore it is imperative that planning authorities improve land use and city planning. Special emphasis should also be placed to reduce the amount of water unaccounted for and the implementation of water demand management. It is essential that responsible authorities monitor rainfall, runoff, abstractions and groundwater levels and quality continuously in order to be able to detect over-abstraction and deterioration of quality at the earliest possible stage and to regulate the use of water resources in a sustainable matter in times of increasing demand and possible impacts of climate variability.

The water budget for the Lusaka area is still subject to uncertainties despite the comprehensive work accomplished. Main challenges in this regard include the high variability of rainfall and runoff, difficulties in determining flood peaks and the complex and insufficiently understood mechanisms influencing groundwater-surface water interactions. The availability of information about soil properties is limited, and the representativeness of crop coefficients applied for the determination of percolation rates has to be verified. It has proven particular difficult to fully comprehend and quantify the preferential recharge through karst surface features and evaporation from shallow groundwater bodies and seepage zones as well as drainage from groundwater into streams (i.e. base flow) and vice versa. Further research in these fields is encouraged.

The groundwater vulnerability map is a tool that is envisaged to be of major importance in the allocation of land for different uses. Only when aspects of groundwater protection are given priority the city's expansion programmes can be made more sustainable. Industries, water and sanitation providers as well as local authorities need to work together in order to ensure that their effluents are within the acceptable limits to be defined under the new Water Resources Management Act and the new Environmental Protection Act.

There is need for the Water Resources Management Authority, together with the Zambian Environmental Management Authority, to attach high importance to issues of groundwater protection in order to ensure that groundwater resources can be safely used in the future.

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PART B

KEY FINDINGS

1. GROUNDWATER INFORMATION SYSTEM

Prepared by Rockie Mweene & Tewodros Tena

The Groundwater Information Management System provides instant, easy access to hydrogeological data for groundwater points (such as boreholes, open wells and springs). The database can also be linked to a Geographic Information System (GIS) to visualize groundwater information for stakeholders, policy makers and the public.

Groundwater database design

The groundwater database and information management system was established using the GeODin® software package with special adaptations made for Zambian requirements. It aims to enhance groundwater management through increased access to groundwater information. The information stored comprises of general data like geographic coordinates and name of the borehole as well as comprehensive technical details on borehole design, geological layer data and groundwater hydraulics and quality. Data is stored in a structured database as shown in Table 2.

Table 2 Type of information in the GeODin® database

General information	
Location	Borehole name and number Geographic coordinates Elevation Location with regard to drainage catchment Location with regard to administrative/political unit
Drilling	Drilling /completion dates Drilling contractor Water point funding, etc.
Status	Type and purpose of water point Usage
Hydraulics	
Aquifer	Borehole and aquifer depth and thickness Aquifer type Static water levels (single values or time-series)
Hydraulic (Pump-) testing	Hydraulic test summary Hydraulic test data Hydraulic characteristics (yield, permeability)
Borehole Profile	
Geology	Lithological and stratigraphical log
Design	Position of casing, screens, etc.
Groundwater quality	
Chemistry	Water chemistry Comparisons to drinking water standards Water type and quality

The groundwater database is based on a Microsoft Access database but provides user friendly data input masks. There is a general data input section where general information about the water point is captured. This section consists of three input masks: water point information, additional site information and well information. Several parameters have drop down lists to choose the appropriate parameter in order to avoid spelling mistakes.

Status of database

All available information of groundwater points such as boreholes, open wells and springs in the project area and beyond was collected and incorporated in the national groundwater database. The database combines data from Southern, Lusaka, Central, Eastern and North-western provinces. Currently over 12,000 water points are captured in the database as listed in Table 3.

Table 3 Total number of water points captured in the database (Status: Dec. 2012)

Province	No. of districts	No. of water points captured
Central	5	3,264
Eastern	8	2,585
Lusaka	4	1,833
North-western	5	1,336
Southern	11	3,128
Total		**12,146**

2. CAPACITY DEVELOPMENT

Prepared by Tewodros Tena

Introduction

Capacity building is one of the main activities being implemented in the project. Training activities were aligned to the capacity building and awareness raising strategy for Phase 2 (Tena & Nick 2010). It mainly addressed the critical gaps of the partner organization and key stakeholders that are active in groundwater resource management. A need assessment was conducted to identify the capacity gaps in the counterpart institution Department of Water Affairs (DWA), as well as in Lusaka City Council (LCC) and Lusaka Water and Sewerage Company (LWSC). The following areas for capacity building were identified and considered in the strategy:

– DWA provincial and district offices: conducting and evaluating pumping tests, water quality sampling and drilling supervision. Priority was put on the provincial offices as they support the district offices and can share their knowledge with the districts in their province.

– DWA district water offices: documenting and managing groundwater data.

– DWA water laboratory at national level: water quality analysis procedures and laboratory management.

– LWSC: conducting and interpreting pumping tests as well as groundwater quality analysis and visualization, especially the production of thematic maps with GIS.

– LCC (Public Health Department): water quality monitoring and environmental health related topics, such as sanitation and its effect on groundwater quality.

Conducted Trainings

– ***Technical courses and trainings***

Three **training modules** were prepared in support of an eight-weeks training course on Basic Geology and Hydrogeology conducted at the University of Zambia (UNZA) in 2011 which focus on performing and evaluating pumping tests, water quality sampling and analysis, as well as groundwater information management using GeODin® software. These modules can in future also be held as stand-alone trainings for a target group with basic geo-scientific background (for example provincial or district water officers or water supply utility staff). The course was jointly organized by University of Zambia (UNZA), the Integrated Water Resources Management (IWRM) Programme under DANIDA and GReSP. A total of 20 government officials including drillers and drilling supervisors from the Ministry of Mines, Energy and Water Development (MMEWD), Ministry of Local Government and Housing (MLGH) and LWSC attended the course.

Trainings on groundwater database and information management using GeODin® software were held for DWA district water officers, rural water and sanitation officers of the MLGH and members of the District Water Sanitation Hygiene Education (DWASHE) committees. The training was offered in 14 districts of Southern and Lusaka Province. In total, 82 individuals participated in the training (Table 4). The trained officers are now expected to collect and document field data using GPS hand-held devices, the groundwater database GeODin®, and a standardized process of hydrogeological field investigation. Computers and GPS units were provided to all DWA district offices in Southern and Lusaka Province.

Table 4 Number of participants of database training per district

Province	District	No. of participants
Lusaka	Chongwe	14
	Kafue	9
	Luangwa	6
	Lusaka	7
Southern	Choma	6
	Gwembe	8
	Kalomo	7
	Kazangula	4
	Livingstone	3
	Mazabuka	1
	Monze	5
	Namwala	5
	Siavonga	3
	Sinazongwe	4
Total		**82**

Two days intensive **training on groundwater database and management** was conducted for staff of **LWSC** and students of the **UNZA-IWRM center**. Twenty-five participants (10 from LWSC and 15 postgraduate students from University of Zambia) participated in the training which was accompanied by the handover of full licenses of the GeODin® software to these two institutions.

In addition to the short and long term trainings, GReSP project also implemented **on-the-job training** to the counterparts attached to the project. On-the-job training basically included fields of hydrogeological field investigations (e.g. geophysical methods and test pumping analysis), water sampling, groundwater database management (specifically, GeODin®) and querying, cartographic principles, ESRI ArcGIS® and development of hydrogeological maps, as well as compilation of technical reports. On-the-job training was offered throughout the project duration for the 4 counterparts of the project as well as five laboratory workers, three hydrologists and one geologist.

Two officers from DWA have been sent to Germany to attend **MSc courses** in Hydrogeology. The two candidates have completed their second term study program. After the completion of their course in hydrogeology the officers will strengthen the capacity of the working team of the groundwater section in the DWA.

– ***Awareness Raising Activities***

In addition to the training measures, awareness raising activities such as a workshop on sustainable sanitation, groundwater protection and city planning were included in the project activities. These were regarded as significant in creating awareness on groundwater management and protection issues and in disseminating information to the public. Participation in the exhibitions for World Water Day, Zambia Water Forum and Exhibition

(ZAWAFE) and the annual agricultural show were among the advocacy activities for the general public reaching more than 650 people. Hydrogeological and vulnerability maps, brochures, technical notes and reports produced by the project were distributed to a wider range of stakeholders.

– ***Technical Forum for Groundwater Resources Management***

A technical forum for groundwater resources management was established among the partners of the project and stakeholders involved in groundwater issues. The forum is highly appreciated among those attending for continuous sharing of information and technical experiences. The forum meets regularly three times per year on invitation by DWA. New technical findings, scientific information and products and documents produced by the project such as the hydrogeological and vulnerability maps were presented on a regular basis. Participants of the forum provided valuable inputs and comments on how to improve the groundwater resource management and gave valuable feedback on project activities. There are 30 members of the Technical Forum of mainly water resources experts from the implementing agencies and stakeholders of the project, namely DWA, BGR, LCC, LWSC and from other relevant Ministry offices and research academic institutions concerned with water management issues. Among others the following institutions attended regularly: Ministry of Local Government and Housing (MLGH), Ministry of Agriculture and Cooperatives (MACO), Ministry of Lands (Survey Department), Geological Survey, Meteorological Department, Zambia Environmental Management Authority (ZEMA), National Institute for Scientific and Industrial Research (NISIR), University of Zambia (UNZA), National Water Supply and Sanitation Council (NWASCO), Water Board, and relevant NGOs.

Key reference:

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3. KARSTIFICATION, TECTONICS AND LAND USE

Prepared by Kai Hahne & Beauty Shamboko-Mbale

The focus of this study lies upon groundwater quality and its vulnerability to pollution. For this reason detailed knowledge of possible water flow paths within aquifers as well as the specific distribution of different land use types is essential. As existing maps do not meet these requirements within the study area, the scope of the study was to

- verify currently existing geological data in the field;
- delimit karst features, major fault and fracture zones by various remote sensing methods and to verify them in the field;
- verify and describe karst dimensions in the field, which cannot be detected on remote sensing imagery due to soil- and vegetation cover;
- verify land use information, which was drawn from remote sensing data before.

Multispectral remote sensing methods in combination with field work yielded best results.

Remote sensing was especially helpful in detecting faults and fractures as well as in conducting supervised classifications for land use types in a wide area used as a base for a more refined land use map.

Field work for ground truthing was conducted from 4th to 30th of June, 2009.

Study Area

The working area comprises the coverage of the planned hydrogeological map of Zambia, Lusaka Province, with Zambia's capital Lusaka in the centre (Figure 4).

The main part of the groundwater recharge area is situated on the Lusaka Plateau, expanding from Mwembeshi in the NW to the Shantumbu area about 20 km to the SE of Lusaka. The highest point of the plateau is situated in the SE at 1377 m above sea level (asl). The lowest point is situated in the Kafue flats in the SW at 975 m asl (Figure 5).

One focus of field work was the area NW of Lusaka, as no karst-related field data has been evaluated within this project so far. This area only shows very sparse outcrops and is covered with soil and thick scrubland.

Data used for this study range from satellite images of Landsat Thematic Mapper acquired in May 2002, SPOT acquired July and August 2007 and July 2008, SRTM and Quickbird imagery from 2004 - 2006. The geological maps used were for Mwembeshi 1527NE, Chainama 1528NE and Lusaka 1528NW (Garrard 1962, Simpson 1962, Simpson et al.1963).

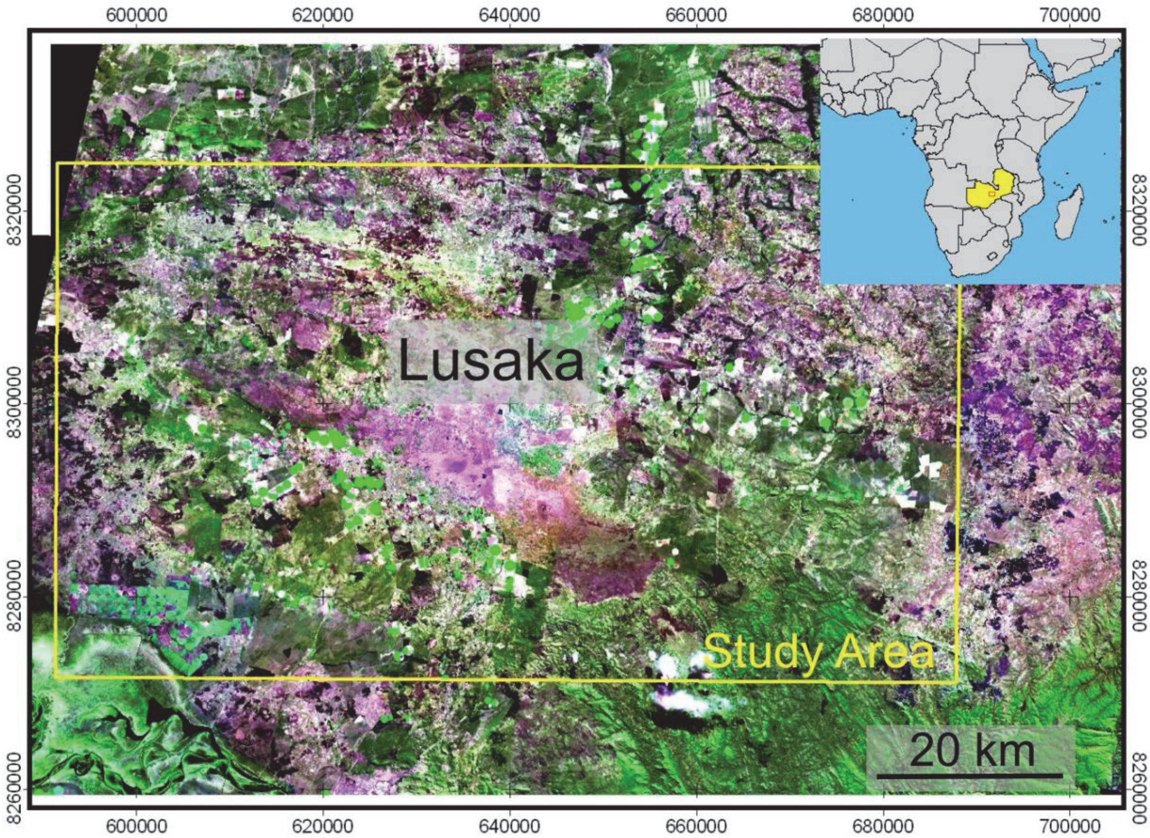

Figure 4 Location of the working area in Zambia marked by yellow frame. SPOT bands 1,2,3 (RGB)

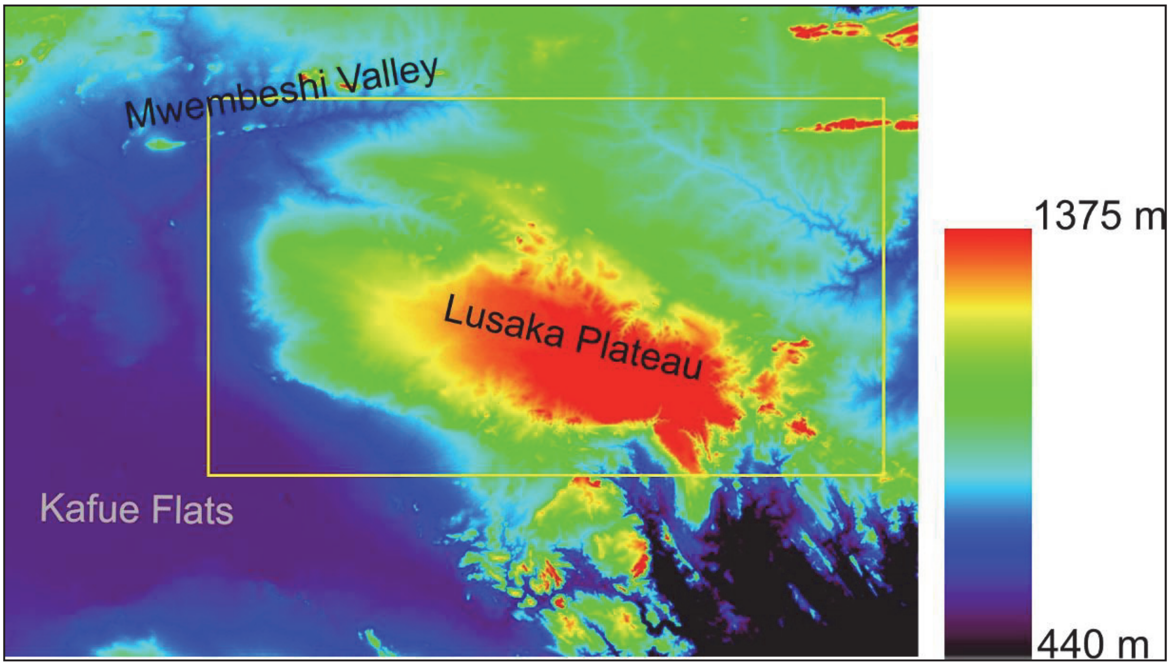

Figure 5 Location of the working area in Zambia in Shuttle Radar Topography Mission (SRTM) DEM with colour-coded altitudes

Conclusions and Recommendations

Tectonics

In terms of tectonics, three major joint directions with distinct sets of orientation exist:

1. Steep dipping (80° - 90° towards the NW and SE) cross joints formed perpendicular to main fold axes, with strike directions between 030° to 060°.
2. Longitudinal joints parallel to the fold trends (strike 110° – 140°, dip 30 – 45° towards the SW as well as a steeper dip of cleavage planes of 75° to 80° towards NE).
3. Diagonal joints striking between 150° – 180° and a minor conjugate set striking between 060° and 080°, dipping 65° to 90° to the east and south.

Joints of calcareous formations appear to be filled with calcite in most locations and thus could be considered to be tight for groundwater migration. The calcite fill of the joints, however, is dissolved relatively fast and acts as a nucleus for the development of karst holes.

Joints of schist formations appear to be open in most locations and thus could be considered to act as pathways for groundwater migration. Both observations were not pursued systematically during field work and could be subject for further investigations.

The types of faults found in the study area were:

- strike direction NW-SE (120°) parallel to main structural trend,
- a further NW-SE (140°),
- probably conjugate NE-SE direction (035° , 045°).

To a minor extent also a NE – SW trend (080°) paralleling the “Mwembeshi shear zone (MSZ) direction” is present.

In satellite images to the W and NW of Lusaka – by influence of the MSZ – almost any fault of all three types shows shear lenses with a fractal pattern. E.g. lenses of 17 km length to a few metres length can be observed.

To the SE, increasing influence of the Zambezi-rift can be observed by NE-striking normal faulting and absence of shear lenses.

On first consideration the transform fault type creating shear lenses appears to be “tighter” for water migration than the fault type of normal faulting depending on the different mechanisms of movement. The first type is “smearing tight” the fault trace; the second type is opening the fault trace by setting off the affected geological formation.

Taking a closer view, the fault-affected lithology type generally appears to stronger control permeability. For example the brittle schists affected by shear lenses are highly permeable for water in these zones. These observations could be subject for further investigations.

Karst features

Karstification is a common feature of all calcareous units of the working area. Karst holes are usually filled with soil. At populated places, the soil cover is often removed to get either soil or limestone for building purposes.

Due to vegetation and soil cover relatively few locations compared with the whole area could be validated in the field. However, all of them were found to be karstified.

As most karst features have formed along strike of geological structures, the lengths of holes are usually larger than widths but cannot be followed in most locations due to thick soil and vegetation cover. For that reason the description of karst dimensions concentrates on maximum widths, ignoring (larger) lengths. This means, karstification must be assumed much higher than verified in the field (Figure 6).

The dimensions of karst holes measured in the working area range from 0.20 m to 5 metres. It appears to be most likely, that all covered calcareous units in the working area are karstified in a similar way as at the checked outcrops.

Vulnerability

Karst aquifers are exceptionally vulnerable to pollution. In the study area, many sources for possible contamination were found (e.g. seepages from gas stations, industry etc.). Local sources included unofficial dumping sites as well as pit latrines.

Land Use

The land use classes defined were: bare soil, small-scale- and commercial agriculture, scrubland, forest, settlement, settlement with garden and surface water (Figure 7). From 2002 to date, the most striking change in terms of land use is the loss of forest and scrubland in favour of commercial- as well as small-scale agriculture and for charcoal production for the local market. Also areas of development are growing rapidly especially in the south of Lusaka.

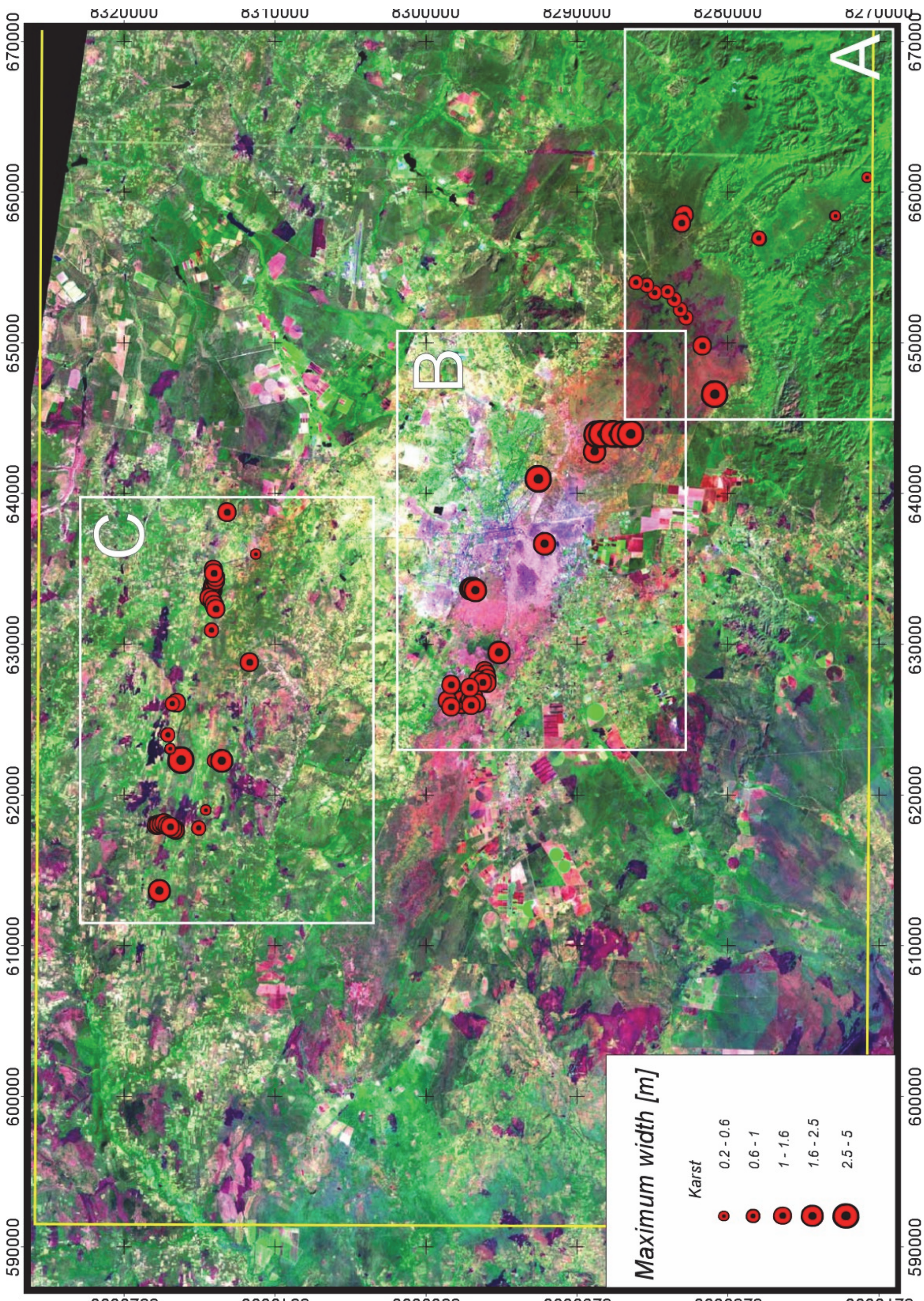

Figure 6 *Overview of karst dimensions and locations of subdivided karst areas A, B and C. Projected into SPOT false colour image (bands 1,2,3 RGB). City of Lusaka in the centre of karst area B (pink colour).*

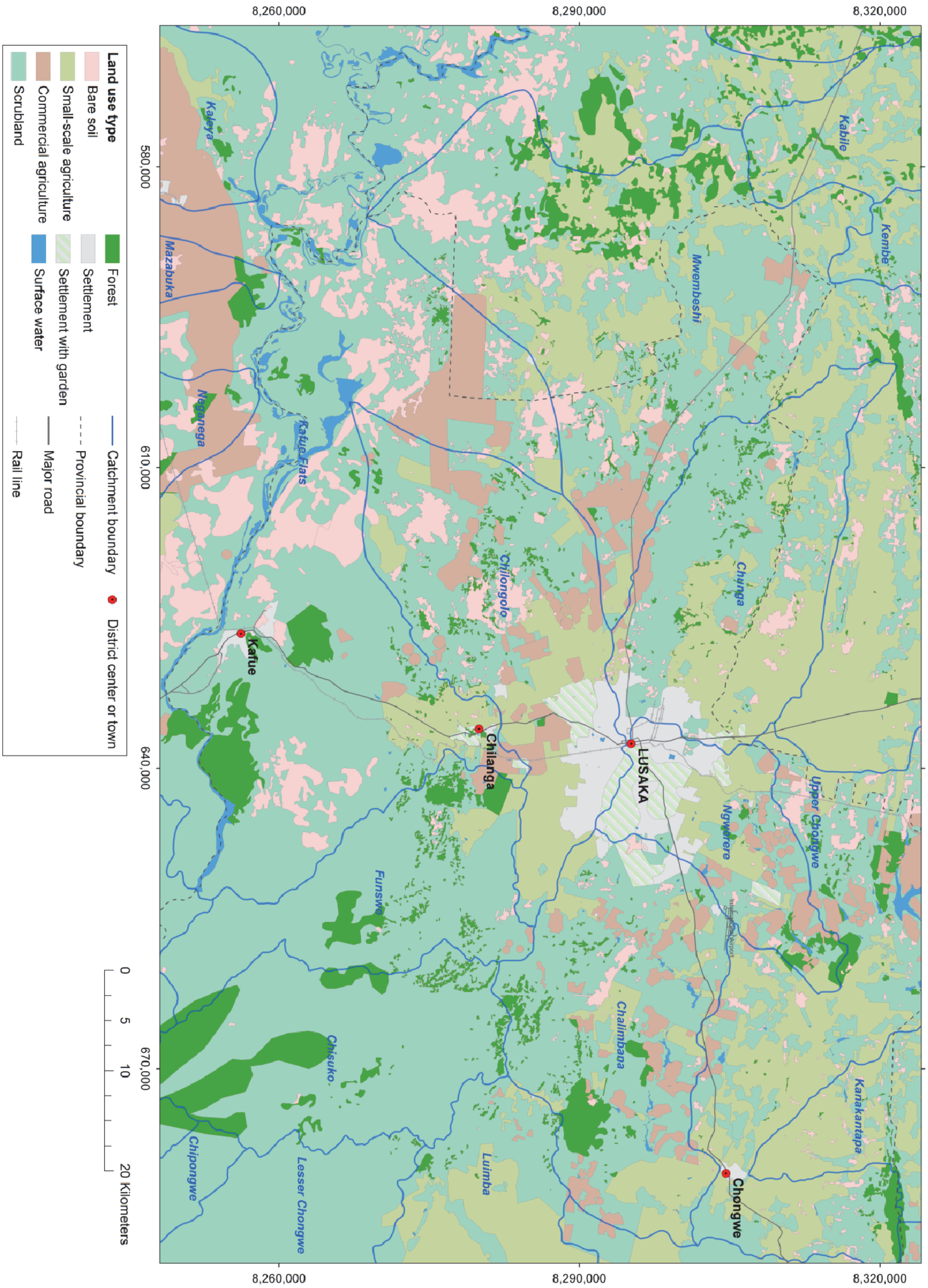

Figure 7 Land use map of Lusaka and surroundings

Drilling sites

Schists are almost impermeable for water migration except in zones of faults and joints where water migration seems to be excellent. Many boreholes equipped with hand pumps were found to be near fault zones of schist areas.

Groundwater table is generally shallow in calcareous formations in the vicinity of schist ridges. This is especially true for locations where stratigraphical layers of calcareous formations are dipping towards the schist ridges channelling the water migration towards the ridges which appear to dam up groundwater.

The likelihood of successful water drilling should increase at locations where additionally intersections of faults or joints are present (Figure 8). Within the calcareous formations successful water drilling should be most likely in synclines and intersections of faults or joints.

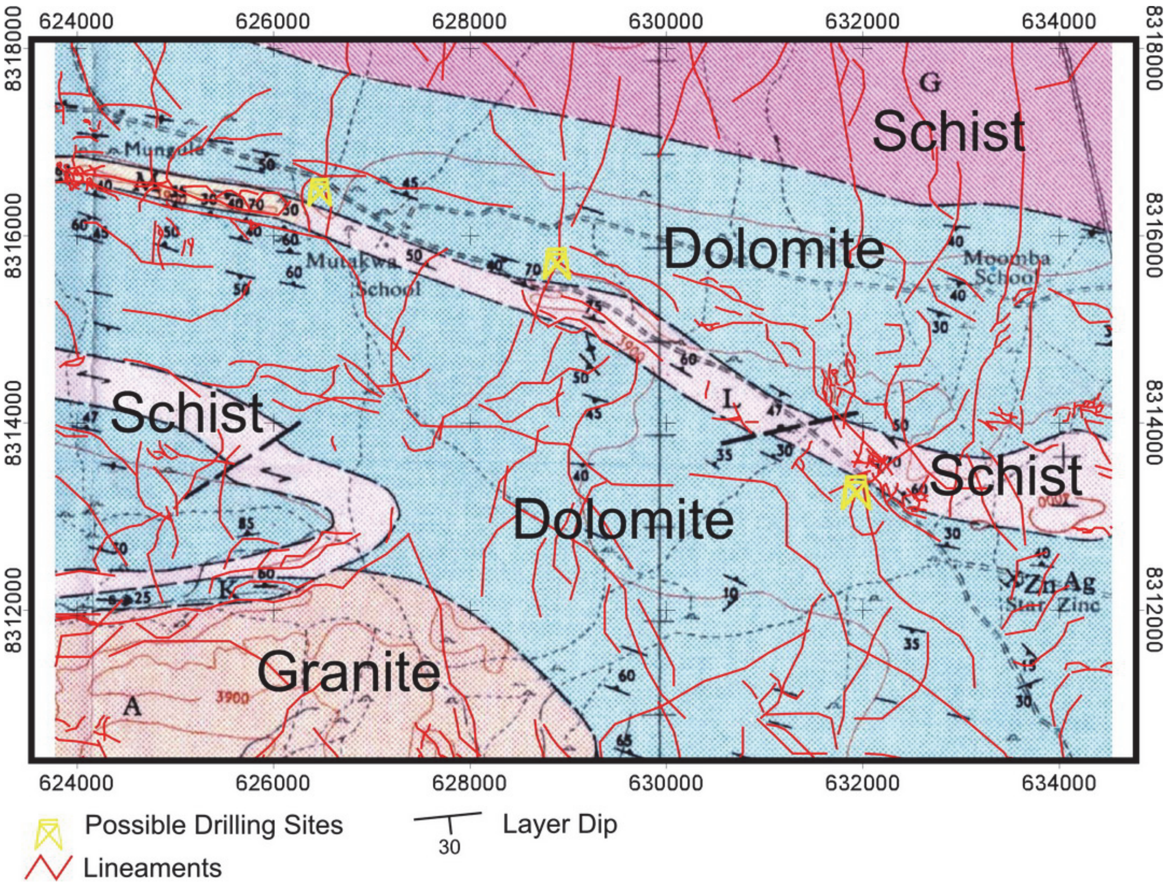

Figure 8 Examples of locations for possible drilling sites projected into modified geological map after Simpson et al. (1963).

Key references:

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

- Hahne K. & B. Shamboko-Mbale (2010): Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems, Report No. 3, Karstification, Tectonics and Land Use in the Lusaka region.- Ministry of Energy and Water Development - Department of Water Affairs and Federal Institute for Geosciences and Natural Resources; 75 pages; Lusaka.
- Simpson J. G. (1962): The geology of the Mwembeshi River area.- Report of the Geological Survey No. 11, Explanation of degree sheet 1527, NE quarter, Northern Rhodesia Ministry of Labour and Mines; 29 pages; Government Printer, Lusaka.
- Simpson J. G., Drysdall A. R. & H. H. J. Lambert (1963): The geology and groundwater resources of the Lusaka area.– Report of the Geological Survey No. 16, Explanation of degree sheet 1528, NW. quarter; Northern Rhodesia Ministry of Labour and Mines; 59 pages; Government Printer, Lusaka.

4. THREE-DIMENSIONAL GEOLOGICAL MODEL OF THE LUSAKA AREA

Prepared by Andreas Günther

A regional structural geological 3-D model for the area of Lusaka (Zambia) at scale 1:100.000 was constructed covering an area of 1,584 km^2 with an outcrop depth of 2 km below ground surface (bgs) on average. To visualise the extremely complex structural geometry of the geology in the outcrop-sparse Lusaka area, only surface datasets consisting of a structural geological map of scale 1:100,000 and a digital elevation model (DEM) with a grid cell size of about 100 m were available. No subsurface information like deep boreholes or geophysical data exists. For model construction, map-based directional information on geological structures was elevation-registered and projected on vertical cross-section planes. Regionally important fault structures were constructed through equidistant projection of elevation-registered mapped fault traceline data. The top surfaces of geological bodies were constructed in 3-D by semi-automated meshing of the structural line data from cross-sections, outcrop and subcrop lines, and cross-cutting with the fault surfaces network and DEM. The final geological model was obtained through a combination of the individual constructed structural planes. The model was outputted as raster, triangulated irregular network (TIN) and vector data and can serve as an important input for simulation of groundwater hydraulics in the future.

Model construction

The structural configuration of the Proterozoic high-grade metamorphic sedimentary and igneous rocks of the Katanga-System (Chunga and Cheta formations, Lusaka Dolomite and Lusaka Granite, Figure 9) in the study area have been visualised using only three surface data sets:

(1) A geological map at scale 1:100,000 compiled from the available geological maps that were harmonized and classified for eight geological model units,

(2) A structural geological map at scale 1:100,000 compiled from available structural geological maps that were harmonized, simplified and error-checked. This data renders spatial and typological information on major fault- and fold hinge trace lines, and

(3) A Digital Elevation Model (DEM) based on Shuttle Radar Topography Mission (SRTM) data with a raster resolution of about 100 m (Figure 9).

Phanerozoic lithostratigraphic units (e.g., alluvial sediments, Figure 9) have not been considered in the modelling. The most important information for subsurface geometry visualization consists of >1000 directional data on different tectonic fabrics (mostly foliation planes) displayed in the geological maps (Figure 9). This data was digitized as dip/dip direction information for planar fabrics, resp. as plunge/plunge direction data for linear fabrics, and elevation-registered with the DEM data.

For model construction, first the positions of five vertical cross sections were defined. Then, the foliation measurements used for individual section construction were selected through a 5 km buffer around each section line. Then, projection linears were calculated using orientations of small-scale fold axes (if available) or fold axis orientations derived from phi-pole constructions for each cross-section. In most cases, these projection linears are very gently dipping (max. 5°) into WNW directions as consistent with the plancylindrical folding style displayed in the synoptic fabric analysis (Figure 9). In the next step, stratigraphic contacts, fold- and fault traces, and the topographic profile were assembled on each section line. Subsequently, the buffer-determined foliation data was projected on the cross-section planes, and structural isodip-domains bordered by fold hinge lines and fault traces were determined. The apparent foliation dip in the cross-section plane was then assigned through mean values of the projected data for each isodip-domain. The projection of fabric data and the assemblage of the map information in each cross-section plane were realized through custom-made GIS tools.

In the next step, the traces of major fault structures (in all cases normal faults) were constructed in each section plane using the hanging wall downthrow information from the geological maps. Since the dip of the faults in the cross section planes cannot be determined, steep (75-80°) inclinations were proposed in each instance. Then, the offset of the stratigraphic units along the fault traces and the thicknesses of the model units in the cross-section planes were determined using the directional- and contact information assembled on the cross-sections following conservative constraints. Since the folded and faulted foliation is oriented parallel to the original sedimentary bedding and represents the most prominent discontinuity set separating different lithologies, it was used for section constructions following common kink-band techniques where the fold hinges were rounded to better represent the fold geometries. Due to the analysis scale, small-scale fold and fault structures have not been considered in the modelling.

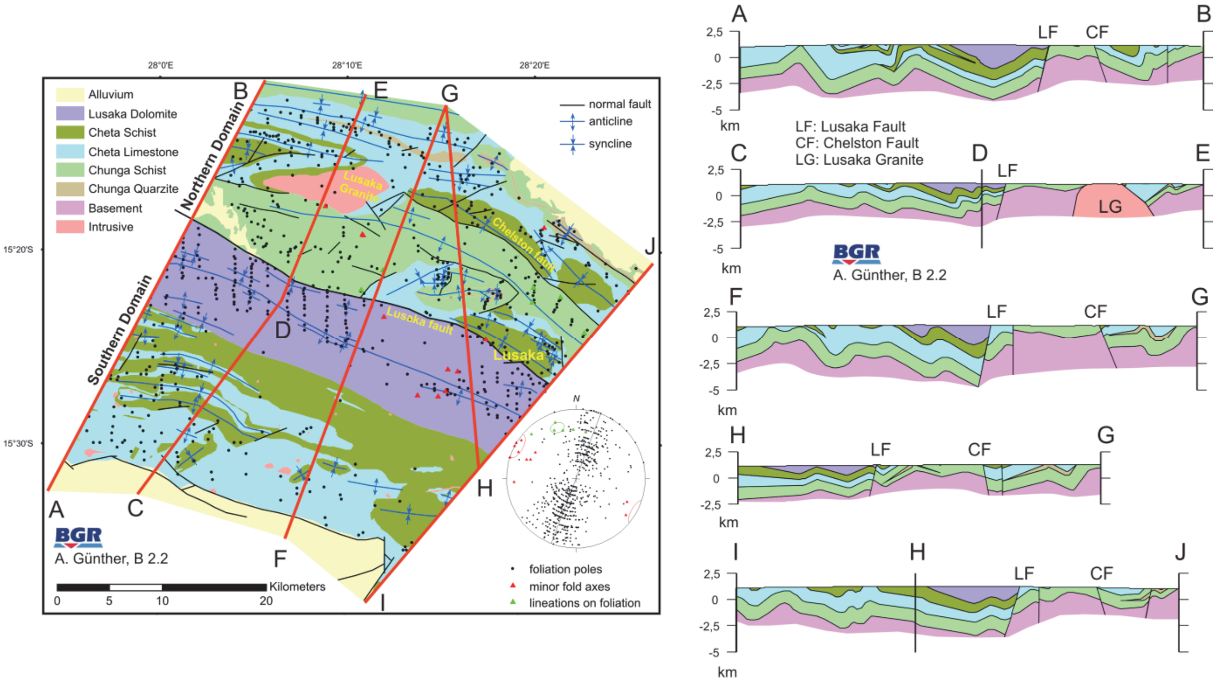

Figure 9 Geospatial information (left) and constructed structural cross-sections (right) used for 3-D modelling

For 3-D modelling, the 2-D information consisting of the five structural cross-sections and the elevation-registered structural features of the geological map (stratigraphic contact lines, traces of normal faults, traces of fold hinges) was transferred into 3-D space (Figure 10). The first step in 3-D modelling consisted in the construction of the planar normal fault array. This was done through equidistant projection of the elevation-registered map traces of the fault lines along projection linears obtained from the orientation of the faults in the cross-section involving interpolations in-between (Figure 10). Then, subcrop lines constraining the contact of the lithostratigraphic units with the fault array or against other units were constructed, together with subsurface fold hinge line data. These operations were conducted in a 3-D GIS environment.

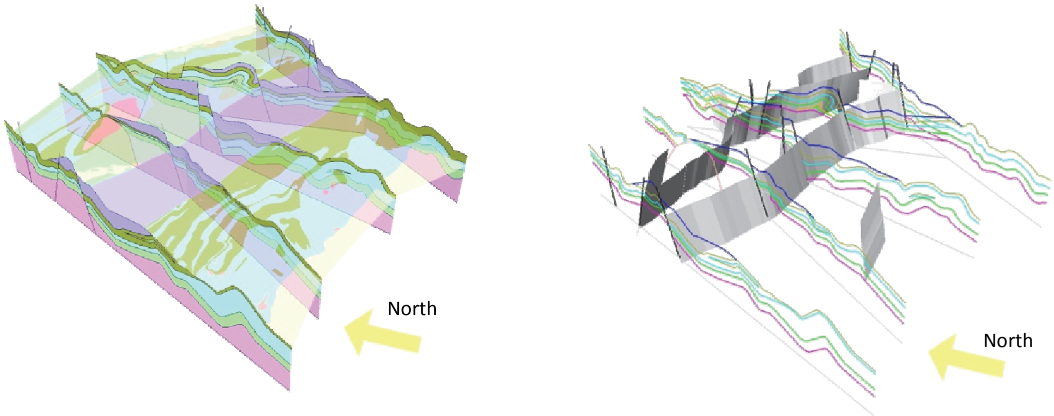

Figure 10 Geological 2-D data (DEM-registered geological map and structural cross-sections) transferred into 3-D space (left) and constructed major normal fault plane array (right)

The final 3-D model construction was performed using the geomodeller gOcad. The GIS-based data was imported into this environment, and structural top- and basal surfaces of the geological bodies were constructed using different surface construction algorithms of gOcad involving the unique DSI (Discrete Surface Interpolation) technique. The constructed surfaces where then cross-cut with the fault plane array and the DEM to achieve a consistently meshed 3-D surface model without voids (Figure 11).

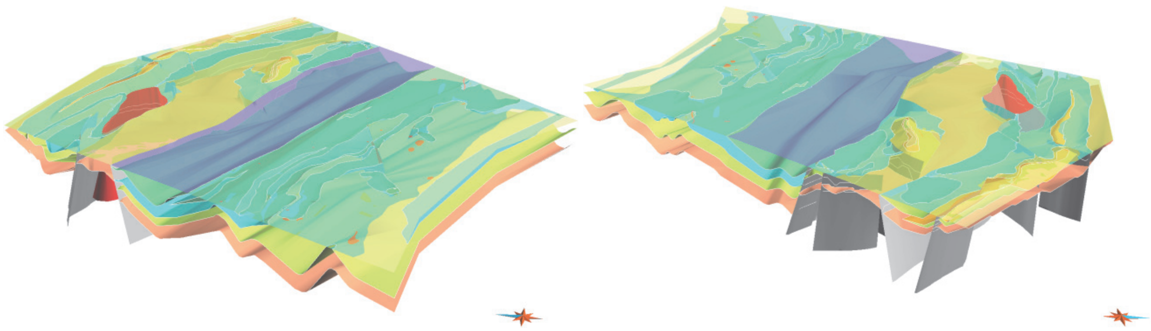

Figure 11 gOcad Snapshots from the final gOcad 3-D surface model. Left: View to Northeast, right: View to Southwest

Key findings from the 3-D model

From the geological 3-D model, several key findings regarding structural geological configuration, kinematic evolution, subsurface stratigraphy and structural control on shallow groundwater flow of the study area can be derived.

Generally, the structural setting is subdivided by the long striking “Lusaka fault” into a “Northern domain” where the early Proterozoic basement complex is situated at relatively shallow depths, and a “Southern domain” where the meta-sediments of the Katanga system reach maximum thicknesses (Figure 9). The major constructed extensional structural elements consist of long, NW-SE striking and steeply SW resp. NE dipping normal faults (in this study: “Lusaka fault” and “Chelston fault”, Figure 9) north of Lusaka. On these faults, considerable dip-slip movements, partly with displacements > 1km, have taken place. Most probably these major structural elements originated as reverse or thrust faults during earlier contractional tectonic movements since they are aligned parallel to first-order fold structures and resemble structural contacts. The folds are nearly plancylindrical, WNW-ESE trending congruent structures with wavelengths of 5 – 10 km. These folds presumably shear off at depths of 3 – 5 km and show a SW facing with long, moderately dipping backlimbs and shorter, more steeply inclined forelimbs in the "Southern Domain". They are presumably associated with regional in-sequence thrust faults which have not been mapped (and hence could not be modelled), but were expected by previous authors. NE-SW fold structures, mostly present in the "Northern Domain", are detaching in shallower depths (1 – 2 km bgs) and are refolding the NW-SE structures resembling dextral shear structures. NE-SW oriented mapped normal faults strike out for some 5 – 10 km and most probably originated as dextral shear bands in a transpressional tectonic regime. 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, the meta-sediments of the Katanga system show reduced thicknesses. In the "Southern Domain", thick-skinned basement-involved fold-and-thrust belt tectonics are exposed.

Based on the structural geometry modelled, some constraints on the pre-Cenozoic kinematic evolution can be inferred, also considering previous work: During Mesoproterozoic orogenies, the whole supracrustal Katanga sequence was intensely metamorphosed and internally sheared resulting in a partly closely spaced foliation. This foliation is oriented sub-parallel to the primary layering of the metasediments and associated with outcrop-scale horizontal internal isoclinal shear folding (F1). The orogen-normal tectonics result in the development of a SW-facing fold-and-thrust belt involving the basement complex, characterized by plancylindrical NW-SE trending first-order detachment folds (F2) and most probable SW directed in-sequence thrusting. In contrast to previous studies, no evidence was found in the field to distinguish the development of F1 and F2 folds for different orogenetic regimes since both are horizontal and related to the same kinematic setting of orogen-normal shortening. These deformations led to an intense tectonic thickening of the supracrustal Katanga sequences towards the SW. During later stages of Proterozoic deformations, transpressional movements corresponding to NNW-SSE shortening result in re-folding and rotation of the F1/F2 folds. Additionally, partially closed ENE-WSW trending folds with shallow detachment depths (F3) developed. The dextral shear exerted by this shortening on the existing NW-SE structures also result in large orogen-parallel, dextral duplex structures, simultaneously with the intrusion of the Lusaka Granite. From early Mesozoic times on, the Precambrian rocks were exhumed in transtenional/extensional tectonic regimes. Normal movements on structural contacts took place and segmented the subsurface into a Horst-and-Graben configuration.

Due to the lack of subsurface data like deep boreholes or geophysical investigations, the lithostratigraphic sequence and the thicknesses of the individual geological units can only be quantified through the 3-D model. As stated above, this model was build using specific construction criteria (congruent folds, conservative thicknesses, avoidance of isolated bodies) and therefore the modelled layer thicknesses and sequence cannot be proved and remain speculative. The depth to the basement complex reflecting the overall thickness of the supracrustal metasediments modelled shows a remarkable differentiation SW and SE of the "Lusaka fault". Maximum thicknesses are reached in the vicinity of the Lusaka dolomite and a NW-SE oriented strip of a major dissected synclinorium. The basal Chunga formation (consisting of schists and quartzites) is built of a basal schist reaching maximum thicknesses from 100 m to 2.8 km which is the only layer present throughout the modelled area (except for the region covered by the Lusaka granite). It is overlain by a locally present Chunga quartzite member (max. thickness 590 m), a wider distributed second schist section (max. 1.4 km) and a top, again locally present quartzite member (max. 840 m). The hanging Cheta formation (limestones and schists) starts with a widely distributed limestone member reaching maximum thicknesses of 3.1 km in the

SW of the area, followed by two isolated patches of schist (max. 760 m) resp. limestone (max 950 m). Above, a widely distributed schist member (max. 2.4 km) is present followed by comparably thin local limestone and schist layers (max. 580 resp. 590 m). The Lusaka dolomite locally reaches thicknesses of max. 2.2 km.

The main aquifers in the studied area are the marbles of the Lusaka dolomite and the Cheta limestone, which show intense and widely distributed karstification down to depths of presumably ~200 m. The schists and quartzites of the Chunga and Cheta formations may be characterized as aquicludes. Main conductive structures are sub-vertical NE-SW resp. NW-SE striking joint systems intensely widened during karst generation; permeability contrasts parallel the folded foliation reflecting lithological contacts. Thus, the deeper groundwater flow directions can be assumed to be controlled by the foliation and the joint sets. The hydraulic characteristics of the major fault structures cannot be determined. From the 3-D model consisting of top surface layers of individual geological bodies, raster-based analyses to investigate some basic characteristics of structurally controlled groundwater flow were carried out. For these instances, simple flow direction and – accumulation determinations were performed using the synoptic geometry of the modelled structure planes reflecting the first-order rock layering (foliation). Although such computations used for surface runoff characterisations cannot be applied to deduce the groundwater flow regime of non-phreatic aquifers, some information on the structural control on shallow subsurface groundwater flow directions may be derived. The distribution of flow directions along folded and faulted foliation surfaces show distinct differences between the Northern and Southern structural domains. North of the "Lusaka fault", maximum flow directions are to the SW-S, whilst south of it maxima to SW-S and NE-N are evident. Important locations of perennial and seasonal active groundwater springs within the study area are always located in close vicinity to model-derived grid cells reflecting high flow accumulation (Figure 12). The remarkable cluster of perennial springs in the centre of the study area is located in an area where the Lusaka Dolomite reaches maximum thickness (Figure 12). This area is considered receiving inflow from various directions and suspected to reflect a high degree of saturation throughout the year.

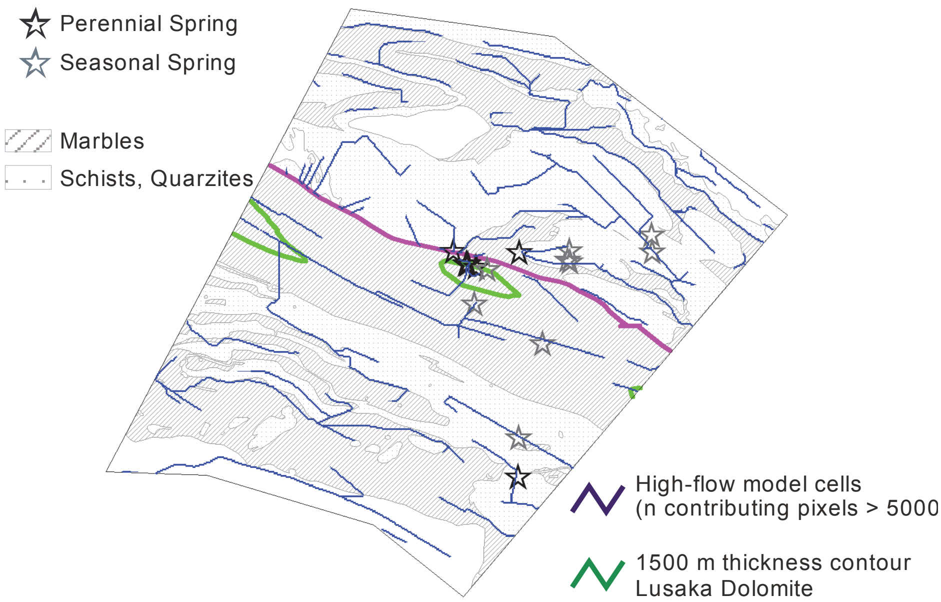

Figure 12 High-flow grid cells of folded and faulted foliation planes, locations of groundwater springs and 1,500 m thickness contour of the Lusaka Dolomite. For the delineation of the groundwater stream network, the areas north and south of the "Lusaka fault" were treated separately

Key references:

- Simpson J. G., Drysdall A. R. & H. H. J. Lambert (1963): The geology and groundwater resources of the Lusaka area.– Report of the Geological Survey No. 16, Explanation of degree sheet 1528, NW. quarter; Northern Rhodesia Ministry of Labour and Mines; 59 pages; Government Printer, Lusaka.
- Smith A. G. (1963): The geology of the country around Mazabuka and Kafue. – Explanation of degree sheet 1527 SE quarter and 1528 SW quarter; Northern Rhodesia Ministry of Labour and Mines; 32 pages; Government Printer, Lusaka.

5. GROUNDWATER QUALITY

Prepared by Andrea Nick, Levy Museteka & Robert Kringel

During the project cycle two major sampling campaigns for groundwater quality were carried out, one between January and October 2008 and one in April and May 2010.

Sampling points were chosen at perennial and seasonal springs (mainly in 2008), water supply wells operated by the Commercial Utility, Lusaka Water and Sewerage Company (in both years), as well as private boreholes on commercial and household plots (only in 2010). The locations covered all main aquifers around Lusaka including the crystalline dolomite and dolomitic limestone of the Lusaka Dolomite and Cheta formations, and the schists of the Chunga formation.

The objectives of the field studies were to

(1) locate and map major springs in the study area,

(2) analyse the groundwater composition and identify the major groundwater types,

(3) assess the extent of groundwater pollution in the urban area in terms of inorganic, organic and microbiological pollutants.

In the 2008 survey, 28 springs were found and mapped within the Lusaka aquifers comprising the dolomite and limestone aquifers of the Lusaka and Cheta formations and minor aquifers in the schists. At current knowledge, 15 out of the 28 springs are perennial. Results from previous studies suggest that a few additional springs exist that were not discovered during the field visits. Both campaigns covered a total of 58 LWSC production boreholes and 34 private boreholes were sampled and analysed.

Analysis of samples was done by BGR laboratory for major and minor water constituents, heavy metals and trace elements as well as chlorinated volatile organic constituents (CVOCs). Micro-organisms were analysed by DWA laboratory using IDEXX® Colilert® equipment in 2010 and Wagtech Ing. Potalab® in 2008.

The water from springs and water supply wells in the limestones and dolomites corresponds to the Ca-Mg-HCO_3 type as was expected (Figure 13). In terms of water hardness, the water is generally hard (>250 mg/L $CaCO_3$) to very hard (>375 mg/L $CaCO_3$). Calcium and magnesium values are typically in the range of 70 -130 mg/L and 15 – 50 mg/L, respectively, and bicarbonate concentrations usually vary between 300 mg/L and 450 mg/L. Calculated ratios of $Mg^{2+}/(Mg^{2+} + Ca^{2+})$ vary between 1:2 indicative of pure dolomite to 1:6 indicating the dominance of calcite. Groundwater hosted by schist can be distinguished from the carbonate springs by overall lower Totals Dissolved Solids (TDS), slightly lower pH, lower HCO_3:SiO_2 ratios as well as much lower hardness and alkalinity (i.e. buffering capacity).

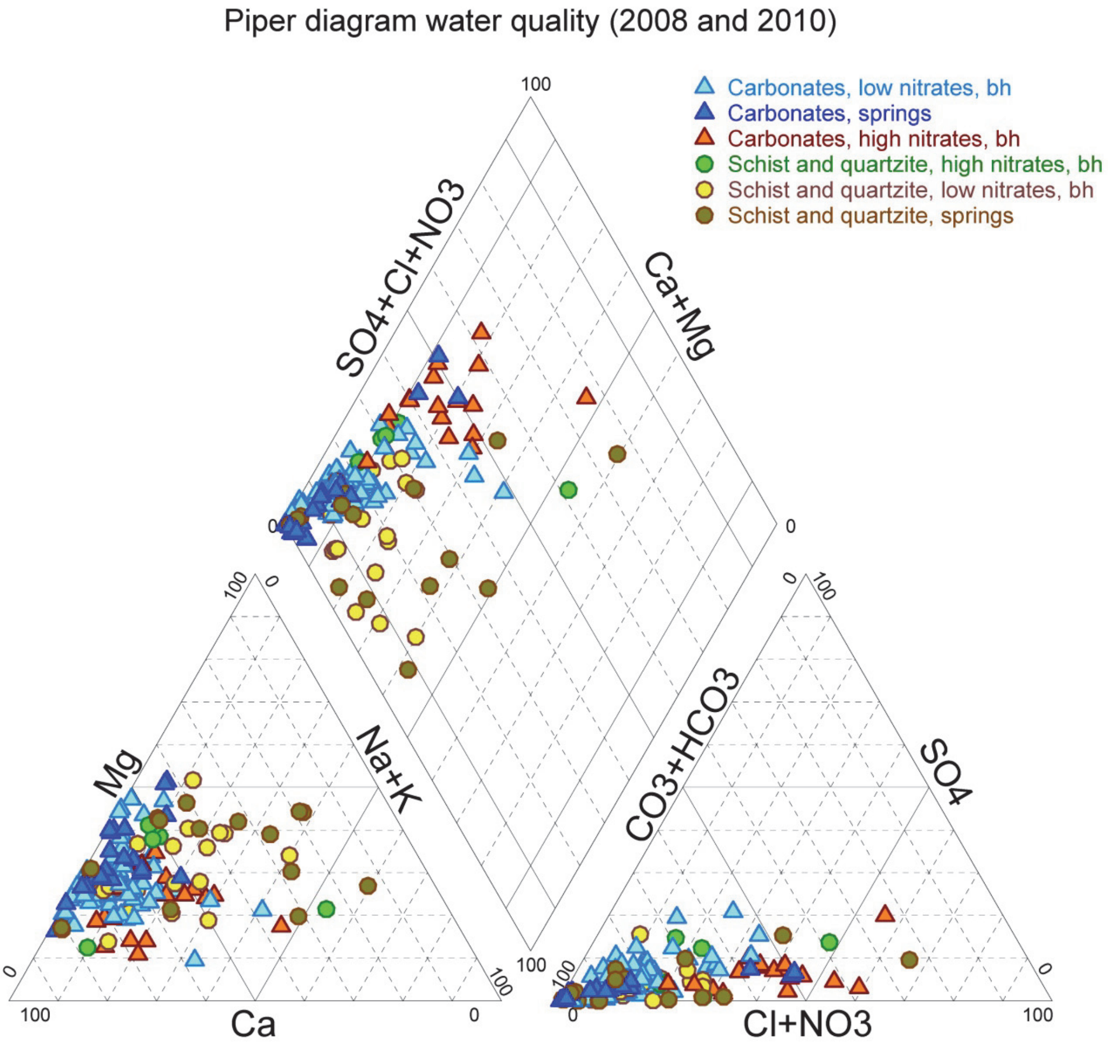

Figure 13 Piper Diagram of the groundwater quality in 2008 and 2010 from boreholes and springs in the study area

The groundwater found in the Lusaka Forest Reserves, Chalimbana springs and Mwembeshi areas was found to be largely unaltered by urban pollution sources. From the chemical analyses it can be concluded that natural (unpolluted) groundwater from the karst aquifers should, with only local exceptions, have an EC of less than 800 µS/cm and concentrations in sodium, chloride, nitrate and sulphate below 10 mg/L. Higher levels in these parameters hence suggest the presence of urban pollution sources.

Groundwater pollution from human activities was apparent in higher levels of EC reaching 1450 µS/cm, sodium contents up to 138 mg/L, chloride levels up to 123 mg/L, and sulphate concentrations up to 172 mg/L. Whilst these values still comply with the Zambian Drinking Water Standard (ZDWS), nitrate levels frequently exceeded the recommended standard of 10 mg/L NO_3-N equalling 44.3 mg/L NO_3 (Figure 14). Nitrate concentrations above 100 mg/L were found at Zingalume and Makeni Burkley springs as well as at Bauleni, Chunga 1 and 2, John Howard, Kanyama, Chibolya and Chawama 1 wells. The highest value was measured at Chainda well with 336 mg/L in 2008 and 260 mg/L in 2010. Chawama, Zingalume, Kanyama, Chibolya, John Howard and Bauleni are largely unplanned residential areas that are exclusively served by pit latrines and septic tanks. The high nitrate loads can be therefore be linked to the overall poor sanitary situation in these areas. In Chunga the same situation is hardened by the neighbouring landfill and graveyard. While the large production boreholes of the commercial utility exhibit nitrate concentrations below the Zambian Drinking Water Standard, it is mainly the boreholes for the local supply of peri-urban (high-density settlement) areas which show considerably higher values.

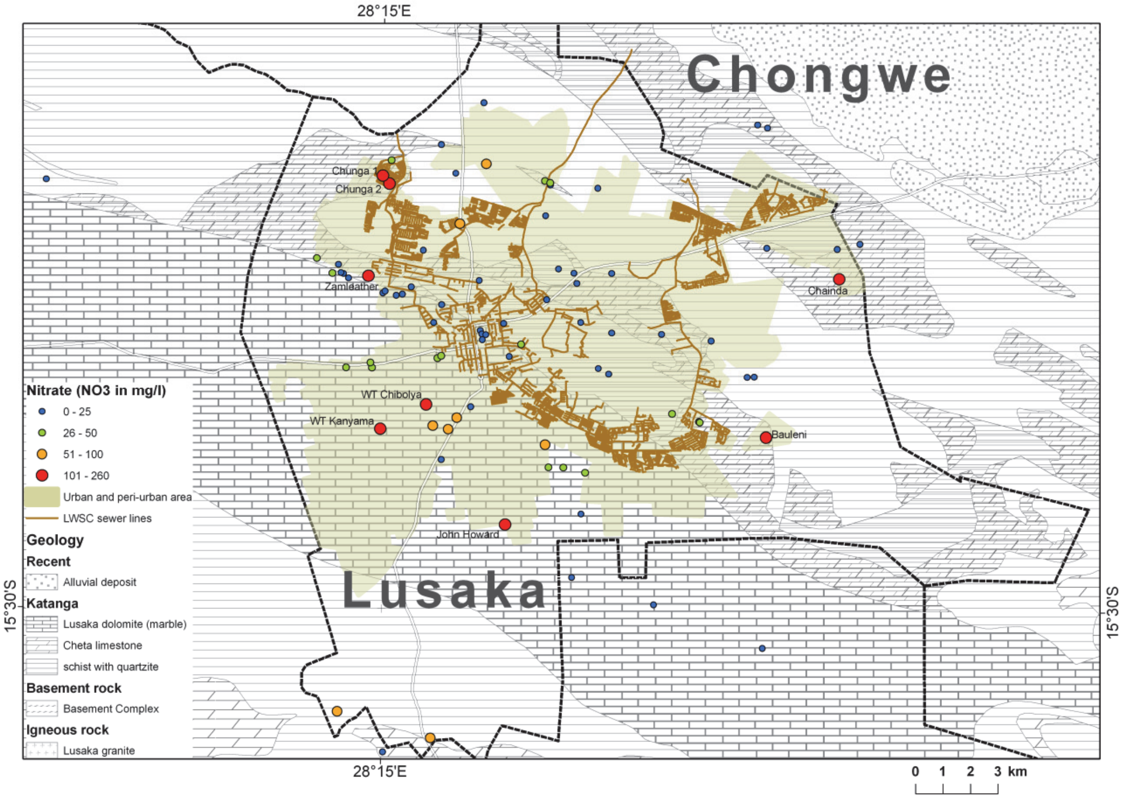

Figure 14 Nitrate concentrations in April/May 2010 in the Lusaka City area

Both studies show that microbiological contamination is widespread confirming descriptions of numerous previous publications. The results from the microbiological analyses from the end of the rainy season in 2010 show that elevated concentrations of E. coli occur much less frequently than of Total Coliforms. Only one third of samples stay below the Total Coliform limit given in the Zambian Drinking Water Standard (most probable number (MPN) = 20). Faecal coliform pollution, indicated by the presence of E. coli, mainly occurs in the high-density settlements. However, the contamination of groundwater with total coliform occurs throughout town, disregarding the service or non-service by sewer lines or septic tanks.

Concentrations of heavy metals and iron are low throughout the study area. Under the prevailing pH (median = 7.0, min = 5.8, max = 8.0) in the calcareous geological environment (with its abundance of bicarbonate ions), potentially toxic heavy metals like Pb, Cd or 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 toxic levels in all samples analysed.

Comparison of water chemistry data with available data from the 1970s shows no significant differences although a slightly higher number of samples with increased levels of alkali ions, chloride, nitrate and sulphate were found during the 2008 sampling. Hence, no clear indication was found that the quality of groundwater has worsened or improved over time.

Even though pollution by human activities in the City area proved evident, the overall contamination within the main well field (areas around Shaft 5, Waterworks and Roadside wells) by inorganic pollutants was comparatively small. This may astonish considering the shallow water tables and the general absence of an effective protective cover. An explanation for this could be the comparatively large amounts of direct recharge and the high permeability of the karst aquifers producing a large “turnover” of pollutants. Groundwater of the main well field is possibly further diluted by clean water drawn (through the natural or induced hydraulic gradient) from areas with little human activities such as the Local Forest Reserves.

Based on the results from the 2010 sampling campaign nine production boreholes and one spring were chosen for regular water quality monitoring. Monitoring is being conducted monthly by DWA staff, and has taken place with minor interruptions from November 2010 to date.

The targeted organic groundwater contaminants, mainly chlorinated volatile organic compounds (CVOC’s) like tetrachloroethene, trichloroethane and cis-1,2-di-chloroethene as an indicator of bacterial dechlorination were found in 10 out of 81 groundwater samples (Table 5 and Figure 15). In two wells their concentrations were above the WHO guideline value, namely at Decotex and Chazanga Water Trust (old borehole). Concentrations of trichloromethane (TCM) are less than 1/10 of the WHO recommendation of 200 µg/L. In one well (Mulungushi 6A) aromatic compounds (BTEX: Benzene, toluene, ethylbenzene, xylene) were found in high concentrations over which LWSC had been aware which led LWSC to shut down the pump after discovering the smell. Dissolved manganese in concentrations above the background was found to be an inorganic parameter indicating suspected organic input to the groundwater table (Kringel et al. 2011).

Table 5 Positive results of volatile organic compounds of the BTEX and CVOC-parameter group, Note: negative concentrations designate measurements below the determination limit; bottom line: WHO (2004) Guideline values; all concentrations in µg/L.

sample name	**124TRIMETHYLBENZOL**	**135TRIMETHYLBENZOL**	**BENZOL**	**BROMDICHLORMETHAN**	**CIS_12DICHLORETHEN**	**CUMOL**	**DIBROMCHLORMETHAN**	**ETHYLBENZOL**	**MP_ETHYLTOLUOL**	**MP_XYLOL**
BP Castle	-0.17	-0.15	-0.2	-0.4	0.3	-0.15	-0.5	-0.15	-0.15	-0.16
Decotex	-0.17	-0.15	-0.2	-0.4	29	-0.15	-0.5	-0.15	-0.15	-0.16
MULUNGUSHI 6A	477	191	49	-0.4	-0.3	36	-0.5	126	281	210
Machinery House 5 (George)	-0.17	-0.15	-0.2	-0.4	-0.3	-0.15	-0.5	-0.15	-0.15	-0.16
Mumbwa Roadside 4	-0.17	-0.15	-0.2	3.3	-0.3	-0.15	5.3	-0.15	-0.15	-0.16
Mumbwa Roadside 6	-0.17	-0.15	-0.2	-0.4	-0.3	-0.15	-0.5	-0.15	-0.15	-0.16
NIPA	-0.17	-0.15	-0.2	-0.4	-0.3	-0.15	-0.5	-0.15	-0.15	-0.16
Total Independence Stadium	-0.17	-0.15	-0.2	-0.4	-0.3	-0.15	-0.5	-0.15	-0.15	-0.16
WT Chazanga old	-0.17	-0.15	-0.2	-0.4	6.7	-0.15	-0.5	-0.15	-0.15	-0.16
WT Chibolya	-0.17	-0.15	-0.2	-0.4	-0.3	-0.15	-0.5	-0.15	-0.15	-0.16
WHO Guideline value			***10***	***60***				***300***		

sample name	**N_PROPYLBENZOL**	**NAPTHALIN**	**O_ETHYLTOLUOL**	**O_XYLOL**	**TETRACHLORETHEN**	**TOLUOL**	**TRIBROMMETHAN**	**TRICHLORETHEN**	**TRICHLORFLUORMETHAN**	**TRICHLORMETHAN**
BP Castle	-0.15	-0.14	-0.18	-0.15	-0.13	-0.12	-0.4	-0.2	-0.15	-0.3
Decotex	-0.15	-0.14	-0.18	-0.15	60	-0.12	-0.4	23	-0.15	-0.3
MULUNGUSHI 6A	100	10	137	118	-0.13	22	-0.4	-0.2	-0.15	-0.3
Machinery House 5 (George)	-0.15	-0.14	-0.18	-0.15	0.15	-0.12	-0.4	-0.2	-0.15	0.3
Mumbwa Roadside 4	-0.15	-0.14	-0.18	-0.15	0.7	-0.12	3.2	-0.2	-0.15	1.7
Mumbwa Roadside 6	-0.15	-0.14	-0.18	-0.15	0.3	-0.12	-0.4	-0.2	-0.15	-0.3
NIPA	-0.15	-0.14	-0.18	-0.15	0.13	-0.12	-0.4	-0.2	-0.15	0.7
Total Independence Stadium	-0.15	0.16	-0.18	-0.15	-0.13	-0.12	-0.4	-0.2	-0.15	3.1
WT Chazanga old	-0.15	-0.14	-0.18	-0.15	82	-0.12	-0.4	1.6	-0.15	-0.3
WT Chibolya	-0.15	-0.14	-0.18	-0.15	-0.13	-0.12	-0.4	-0.2	0.2	-0.3
WHO Guideline value				***500***	***40***	***700***		***70***		***200***

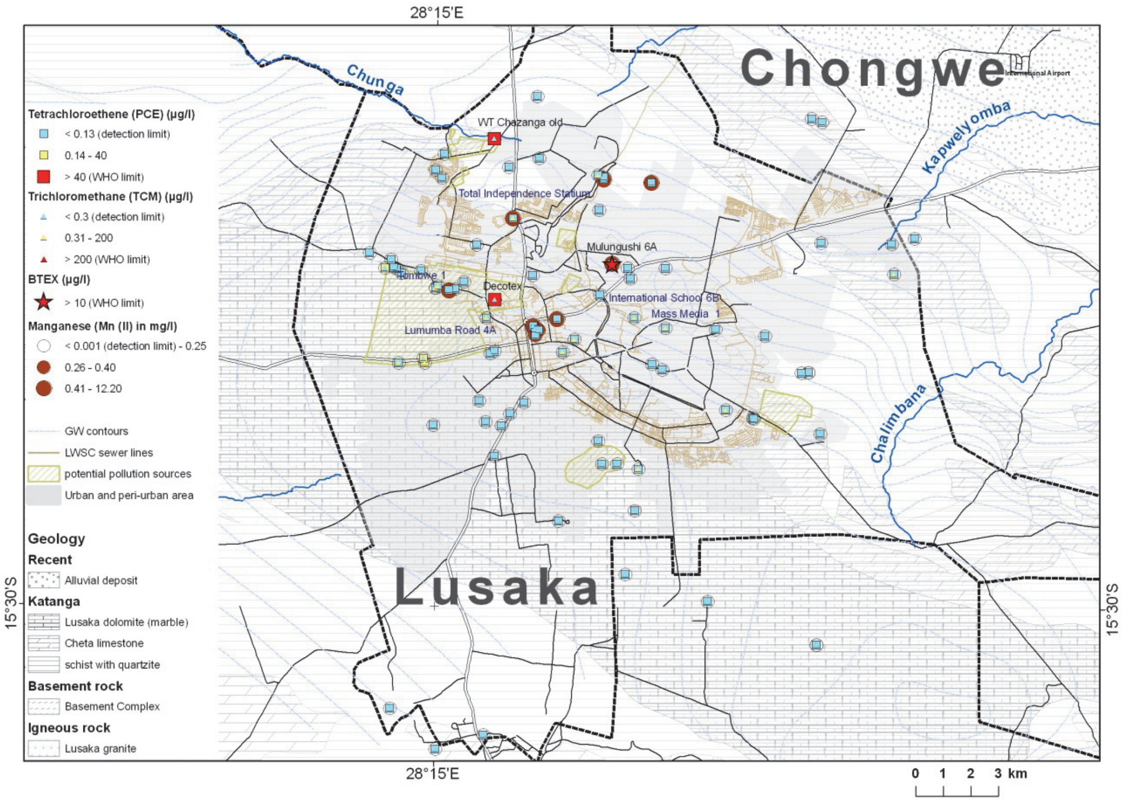

Figure 15 Organic contaminant concentrations in the Lusaka City area as found in April/May 2010

In summary, the following major conclusions were derived from the groundwater sampling campaigns in the Lusaka aquifer systems:

1. Despite high vulnerability and the presence of pollution sources groundwater in the main abstraction areas in Lusaka still complies with national and international drinking water standards with respect to inorganic constituents.
2. Measured nitrate concentrations at Zingalume and Makeni Burkley springs and at Bauleni, Chunga 1 and 2, John Howard, Kanyama, Chibolya, Chawama 1 and Chainda public wells exceed the drinking water standards and are potentially dangerous to infants.
3. Water from Chinyunyu Hot Springs is not suitable for human consumption due to high levels of fluoride (exceeds Zambian Drinking Water Standard by a factor of 8).
4. Pollution from organic constituents is a problem in the urban area with a number of filling stations and fuel storage tanks but also solvent using industries and lacking containment and control structures.
5. A continuous monitoring of groundwater quality at selected sites, in particular for electrical conductivity, nitrate and micro-organisms, has been established, but needs resources and trained staff to deliver continuous and reliable results.

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6. HYDROGEOLOGICAL AND VULNERABILITY MAPPING

Prepared by Andrea Nick, Rockie Mweene, Cornelia Koch & Roland Bäumle

The only hydrogeological map available in Zambia prior to this study is at scale 1:1,500,000 million (MacDonald & Partners 1990). 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 (1978) in the late 1970s and hence, somewhat outdated. The hydrogeological maps developed in the framework under the GReSP 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 16. 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).

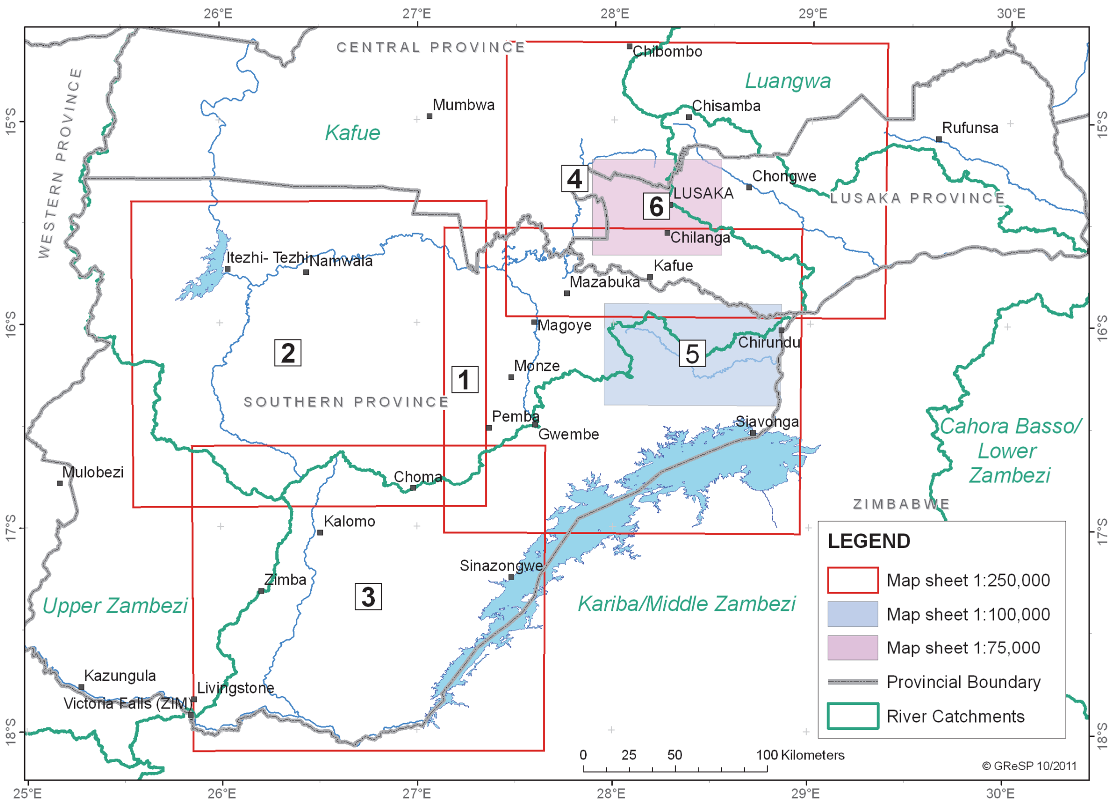

Figure 16 Overview of available hydrogeological map sheets at scales between 1:75,000 and 1:250,000.

The Lusaka plateau is situated on top of the water divide between the Mwembeshi and Chongwe catchments. In order to identify the major aquifers of the catchment areas the groundwater bearing rock formations were differentiated according the 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 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. 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 (aerial distribution > 5%), five major groundwater systems with different lithology can be distinguished in the catchment areas. These are (Table 6):

1. gneisses,
2. schists, which both occur in combination with quartzite and other metamorphic rocks,
3. marbles,
4. metasedimentary clastic rocks (meta-sandstones and siltstones) of Precambrian age (mainly Kawena Formation) which are restricted to Mwembeshi Catchment, and
5. unconsolidated clastic sediments (predominately alluvial deposits).

Table 6 Major groundwater systems of the Mwembeshi and Chongwe catchments and their lithology and occurrence

System	Litho-stratigraphical description	Main occurrence	Area coverage in (1) [%]	Area coverage in (2) [%]
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
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
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
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	--
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

1 = Mwembeshi Catchment, 2 = Chongwe Catchment

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

Each groundwater system was characterised according to their hydraulic properties based on analysis of available pumping tests at over 170 wells and boreholes in the Lusaka and Central Provinces and results of previous studies regarding the potential of the groundwater bearing rocks of the areas (Bäumle 2011). Hydraulic parameters considered include transmissivity *T*, specific capacity *q*, and yield *Q*, which refers to the likely or characteristic yield that a well can produce from a rock formation. Reliable information on storativity was generally very sparse.

The marbles of the Lusaka Dolomite Formation are classified as aquifers of high groundwater potential. 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 aquifers of moderate to high potential. Most other rocks found in the area are considered of limited potential with respect to their productivity. The high permeability of the carbonate rocks is due to karstification. Epikarst features such as dolines, sinkholes and pinnacles ("karrenfelder"), and a subterranean drainage network consisting of solution cavities, channels and shafts are prevalent within all calcareous units of the area.

Hydrogeological Maps

For the development of the hydrogeological maps of the Chongwe and Mwembeshi catchments (Bäumle & Kang'omba 2012a) and the Lusaka area (Bäumle & Kang'omba 2012b) the aquifers were grouped into six different categories depending on their potential to produce water and the type of discontinuities (fractured or unconsolidated rock) (Figure 17). 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. The table 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.

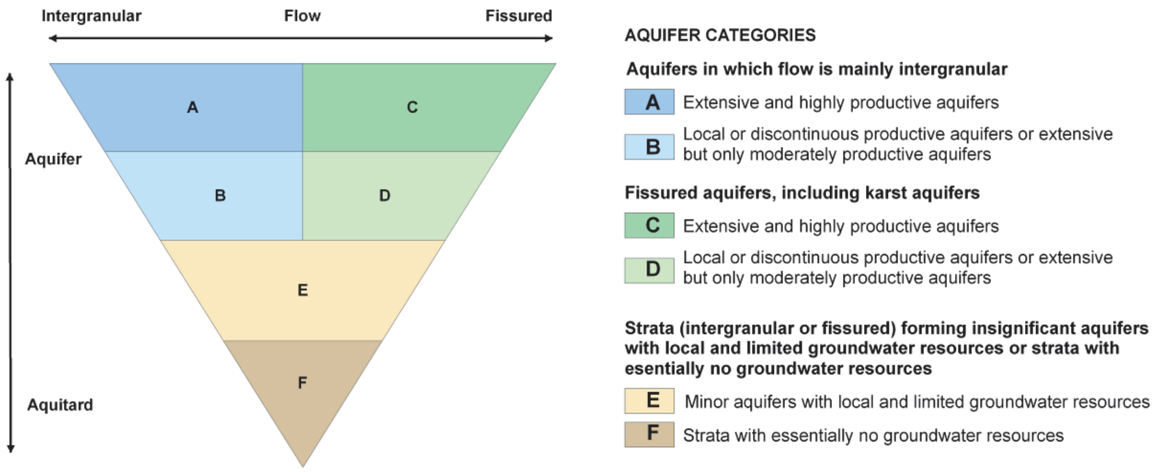

Figure 17 Applied aquifer classification system

Table 7 Hydraulic characterization of the aquifer categories

Aquifer category	Aquifer Type	Trans-missivity *[m^2/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	0.1 – 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 hand pump, private consumption)
F	Undifferentiated	< 0.05	< 0.001	< 0.01	Essentially none: Sources for local water supply are difficult to ensure

Apart from the major classification of aquifers the hydrogeological maps display the location of boreholes, shallow wells and springs as well as contour lines showing the piezometric surface (water levels in meters above sea level) and arrows indicating the general flow direction.

The groundwater contours of the Lusaka Plateau are shown with higher accuracy in Figure 18. The contours were generated based on over 330 water level measurements taken during April 2009. In general the groundwater flow follows the topography and hence is directed towards the stream and riverbeds. Similar to the surface water pattern, a 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.

The depth to the groundwater table is generally moderate to low (Figure 18). Areas of shallow groundwater are 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.

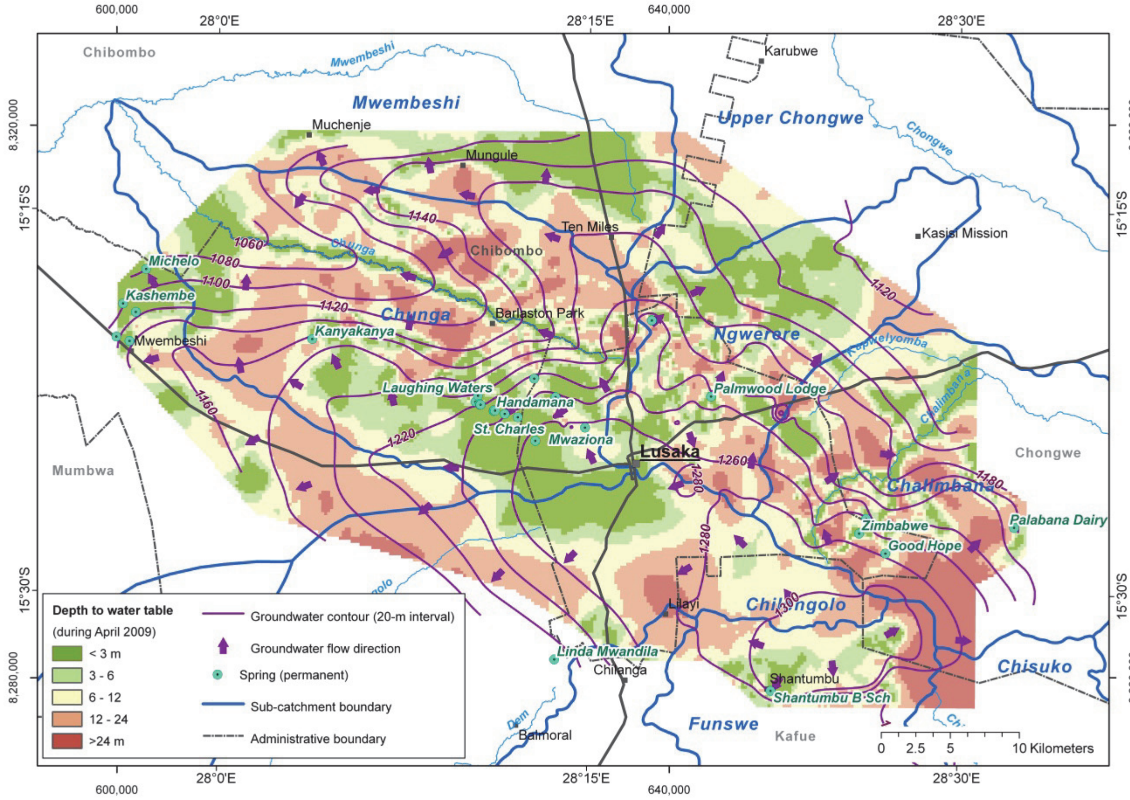

Figure 18 Groundwater flow and depth to groundwater table during April 2009 and occurrences of permanent springs in the Lusaka Plateau area

Vulnerability Map

Groundwater vulnerability describes the sensitivity of a groundwater system to pollution. 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) (Goldscheider 2002). 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 (Nick 2011). The I-factor describes the infiltration conditions, particularly the degree to which the protective cover is by-passed as a result of lateral surface and subsurface flow (Figure 19).

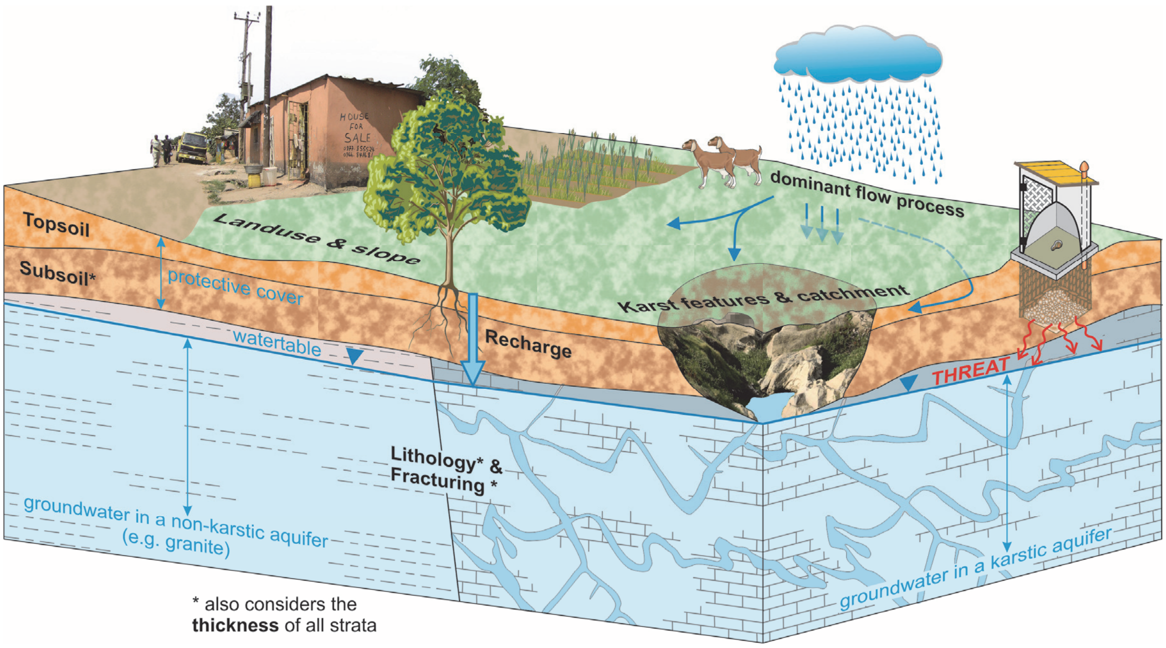

Figure 19 Parameters of PI-method for groundwater vulnerability calculations

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 (Hennings 2012) taking the soil map of Zambia (GRZ 1999) as well as various soil survey reports into consideration. The lithological units were identified based on the geological map of the area (Simpson et al. 1963). The land use was determined from satellite images (Hahne & Shamboko-Mbale 2010). 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 mainly is 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. The vulnerability map (Figure 20) 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 are needed 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.

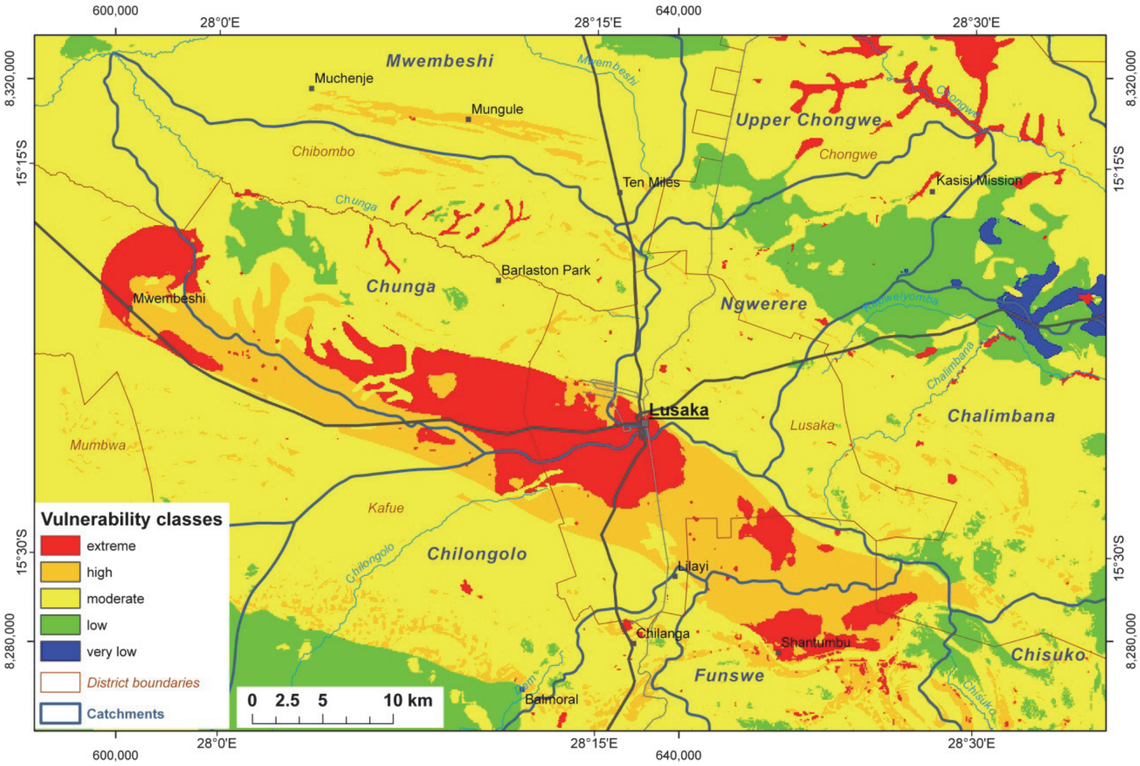

Figure 20 Vulnerability Map of Lusaka

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7. DETERMINATION OF PERCOLATION RATES BY APPLYING FUNCTIONAL SIMULATION MODELS OF THE SOIL WATER BALANCE

Prepared by Volker Hennings

Within the framework of this study the FAO 56 method including the dual crop coefficient concept was applied in the Lusaka region in order to quantify mean annual percolation rates from the soil as part of the groundwater recharge rate. The underlying concept is based on some simple fundamentals:

- actual evapotranspiration is calculated by employing empirical crop coefficients,
- all algorithms originate FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998),
- the soil is regarded as a one-dimensional storage pool,
- deep percolation is calculated as the remaining term of the soil water budget after evaporation and transpiration demand have been satisfied.

This approach was programmed in form of the MABIA software and is available as part of the WEAP system. WEAP ("Water Evaluation and Planning") is a decision support system for quantitative water resources management (Stockholm Environment Institute 2005).

The hydrological year 1989/90 with 780 mm annual precipitation acts as a reference year, 1983/84 with 571 mm annual precipitation was chosen as a typical dry year. Simulations were carried out for five types of land use including small-scale agriculture (rain-fed agriculture with maize as the dominant crop) and large-scale agriculture (irrigation agriculture with non-irrigated maize in summer and irrigated soybeans in winter). Soil hydrological properties such as available water capacity of the root zone were estimated and regionalized with support of digital relief models and digital mapping technology (Hennings et al. 2012). Cultivation of maize under rain-fed conditions on deeply developed soils with an available water capacity of 100 mm/m represents the reference case for model comparisons. Under these general conditions the WEAP/MABIA model leads to 482 mm actual evapotranspiration (ETa), leaving 258 mm percolating water for annual groundwater recharge (GWR) (*Table 8*).

Table 8 Water balance of the reference scenario by application of the WEAP/MABIA model

Precipitation, P	Surface Runoff, Q	Actual Evapotranspiration, ETa	Groundwater recharge, GWR
780 mm	40 mm	482 mm	258 mm

The FAO56 or dual crop coefficient approach respectively is well-established and acknowledged internationally, its results are confirmed by data from experimental sites all over the world. Most of the examples given, do illustrate the robustness of the approach, describe a variety of application options and classify it as a reliable modelling tool to provide accurate results. Under conditions of the reference scenario there is close correspondence between results of an FAO 56-based, functional simulation model (WEAP/MABIA) and a high-sophisticated, process-based mechanistic simulation model such as SWAP (Kroes & van Dam 2003).

In the past, annual groundwater recharge rates within the project area were estimated by several authors. The range of all values derived from soil water balance methods is marked between 100 mm and 200 mm annual recharge. All these former estimates neglect site-specific soil and plant effects. In comparison to existing estimates from the literature results of the FAO 56 approach, or WEAP/MABIA model respectively, look comparatively high. This evaluation is relativized when the whole range of available water capacities of local soils is taken into account; for land-use type “small-scale agriculture” groundwater recharge in a typical year according to WEAP/MABIA varies between minimum rates of approximately 180 mm on deep soils and maximum rates of approximately 330 mm on shallow soils. Both numbers refer to soils developed from schist or gneiss and are based on the same assumption concerning the amount of surface runoff. The long-term estimate of 200 mm for arable land given by von Hoyer et al. (1978) lies within this range. That means that estimates following the FAO 56 approach fit well to estimates that were published as part of the BGR report from the seventies. In comparison to this report Figure 21 is based on regionalized soil properties and contains site-specific information.

All estimates as presented within this study are fraught with uncertainties. Sources of errors are the accuracy of meteorological measurements, the availability of information about soil properties, the representativeness of crop coefficients and several others. Meteorological data have been checked, soil physical properties were analysed in the laboratory and were not obtained by pedotransfer functions, and crop coefficients originate FAO publications or tables FAO offers via its website. One of the most serious deficiencies is the absence of a qualified, fine-scaled isoline map of the groundwater table for areas with very shallow water tables (< 2 -3 m bgs). Because the effects of capillary rise are neglected percolation rates and therefore groundwater recharge rates as shown in Figure 21 have to be evaluated as slightly overestimated for some places.

Annual groundwater recharge rates for 1989/90 as determined by the WEAP/MABIA model (Figure 21) cover a spectrum between 98 and 380 mm. The 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 132 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 380 or 363 mm correspond to karstic parent material such as limestone or dolomite, limited surface runoff, shallow soils with a very small available water capacity and small-scale agriculture, managed by peasants on the basis of subsistence economy and characterized by rain-fed agriculture and monocropping of maize. The overall average value, weighted according to spatial proportions of soil and land use classes, accounts for 209 mm.

In 1983/84 annual (gross) precipitation is reduced by 209 mm in comparison to the reference year 1989/90. Net precipitation however is only marginally reduced because less water is lost for surface runoff. Even in a dry year like 1983/84 deep percolation and therefore groundwater recharge takes place in most parts of the project area. In Figure 22, the dolomite plateau around Lusaka stands out as the most important recharge area. Areas of commercial farms, especially in the Kafue flats southwest of the dolomite plateau, contribute almost no recharge to local aquifers (Figure 22). The overall average, weighted according to spatial proportions of soil and land use classes, accounts for 48 mm. However, under conditions of the reference scenario (soils with an available water capacity of 100 mm/m, rain-fed agriculture and cultivation of maize) the WEAP/MABIA model indicates zero recharge. Differences in estimated recharge to 1989/90 do mostly occur on deeply developed soils with higher available water capacities, e.g. 0 mm against 178 mm in case of small-scale agriculture and 52 mm against 224 mm in case of large-scale agriculture. On very shallow soils with limited available water capacities where less water is provided for water consumption by plant transpiration differences between a normal and a dry year do carry less weight, e.g. 231 mm against 331 mm in case of woodland.

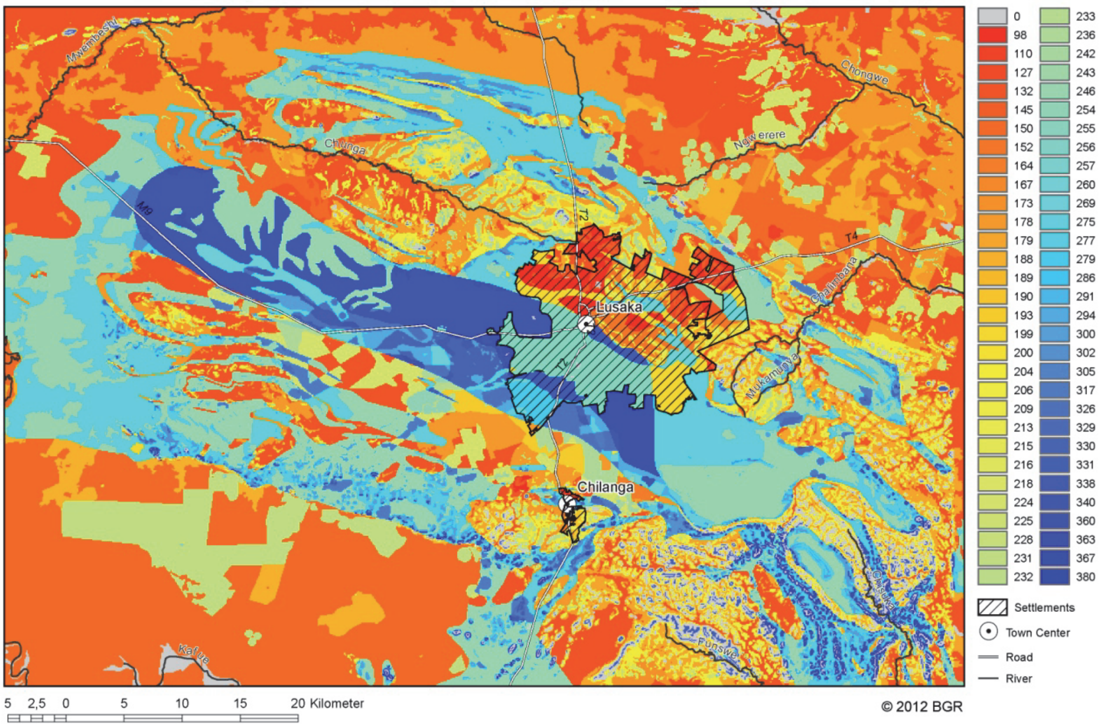

Figure 21 Groundwater recharge rates [mm] in the Lusaka region in the reference year 1989/90

A functional simulation model of the soil water balance such as the WEAP/MABIA model was applied to quantify the amount of groundwater that can be extracted sustainably in a typical year and a dry year. This information can be used by planners and decision makers as well as by local farmers. Due to the lack of existing lysimeters cited estimates cannot be validated against existing measurement results. The only chance to evaluate WEAP/MABIA results offer data from a local farm survey report. When simulated and reported irrigation water demand are compared on the basis of data from 18 commercial farms results for some farms show close correspondence; on the average water demand as simulated by WEAP/MABIA is overestimated by approximately 20 %. However, a final evaluation of all estimates as presented within this study will be possible not until soil-hydrological measurements from the field are available; this remains a future task.

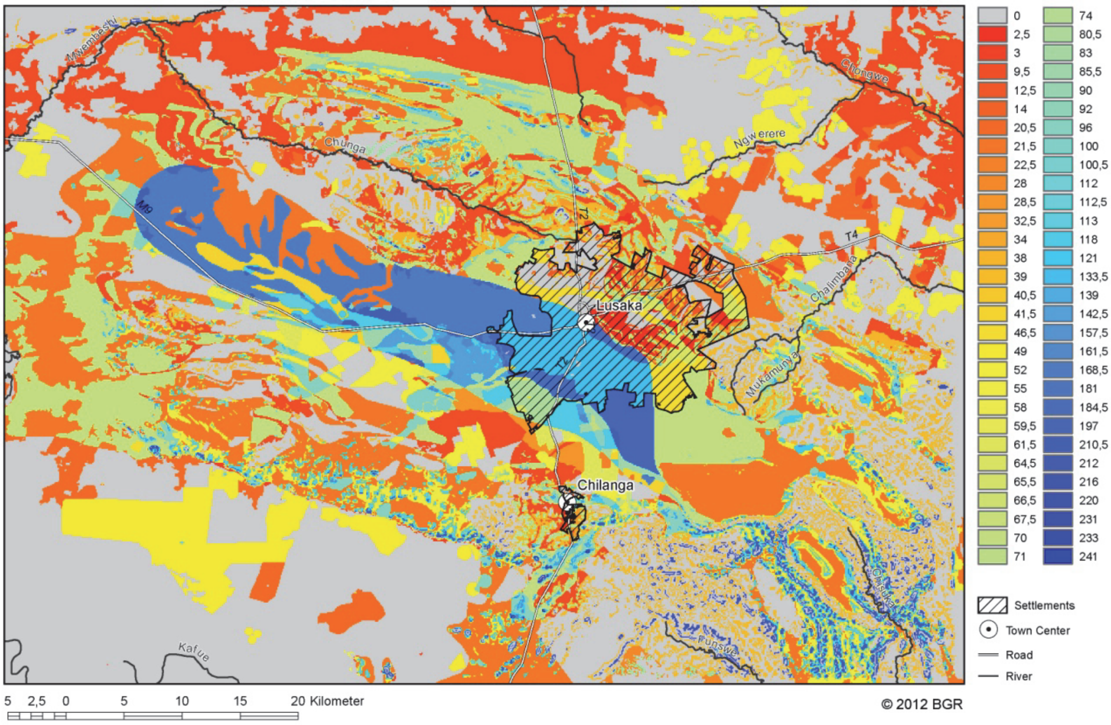

Figure 22 Groundwater recharge rates [mm] in the Lusaka region in the dry year 1983/84

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8. GROUNDWATER MODELLING

Prepared by Jobst Maßmann

In the framework of a comprehensive and on-going investigation program that was launched in the Lusaka area in 2010 under the GReSP, a numerical groundwater flow model has been developed. The model area covers 2,270 km² and contains the Lusaka dolomite and the surrounding areas. The finite difference code MODFLOW was applied to calculate the temporal development of the groundwater table from 1976 to 2035 on a monthly time scheme. The model setup is based on earlier reports concerning the hydrogeological properties, land use and groundwater recharge. The model considers groundwater abstractions for domestic water supply, industry and irrigation. The groundwater recharge has been determined for the entire time period based on long term precipitation data and on detailed studies on the recharge behaviour in the water years 2010 and 2011.

Considering the fact that the numerical model comes along with high uncertainties with regard to aquifer characteristics and boundary conditions, the measured water table can be reproduced well. The good correspondence with measurements after 33 simulated years confirms the estimated recharge and abstraction rates in the historical time period and proves the accuracy and suitability of the numerical model for long term analysis. The calibration is based on 47 monitoring wells in the water years 2010 and 2011. As a result of the calibration process, the domain has been separated in zones of different hydraulic properties.

The deviations between simulation and measurements are mainly characterized by an overestimation of hydraulic heads in the schists and an underestimation in the calcareous aquifers; probable reasons are:

- local inhomogeneities, due to karst features as fractures, cavities and tubes,
- inaccuracies in the abstraction data, especially private boreholes for irrigation and
- inaccuracies in the recharge data.

An implication thereof is that further investigations of the aquifer, especially the groundwater-surface water interaction including recharge, are needed to improve the model's quality.

Despite the mentioned shortcomings, the numerical model is a good tool to investigate the current and future water budget considering different water management options. Analysis shows that the current abstraction rates are sustainable. Only at a few well fields additional drawdowns can be expected (e.g. up to 7 m at the well fields "International School" and "Mass Media")

The calculated significant drawdowns at the well fields from 1976 to 2000 are in accordance to the findings from Schmidt (2002). However, for the following years (2000 to 2010) the model produces a further increase in the water table with a stable state predicted during future years (2010-2035) assuming average rainfall patterns and constant abstraction.

Due to socio-economic development (mainly population growth), the LWSC expects nearly a doubling of the water demand from 2010 to 2035 (KRI et al. 2008). Based on this increase, future scenarios are investigated, considering different assumptions on the development of the water abstractions by LWSC. One abstraction scenario is depicted in

Figure 23. In order to allow further sustainable abstractions, new well fields outside the City are essential. In a first expansion phase starting 2014, well fields in the Local Forest Reserve area and in relative vicinity to the City and in a later phase, starting around 2020, well fields in the west of Lusaka are developed. In this scenario, the capacity of all pipelines increases from 35 MCM (2011) to 67 MCM (2035).

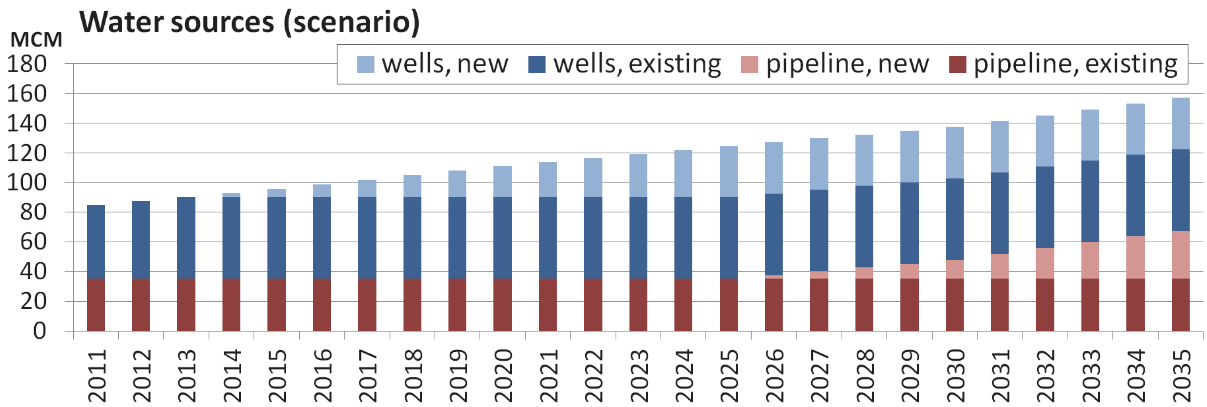

Figure 23 Projected abstraction rates and water sources. New pipeline capacities are developed in 2026 and two well fields are used additionally.

The resulting groundwater tables are presented in Figure 24. The temporal development of the groundwater table emphasizes that a steady state is gradually reached by 2035 and an additional drawdown will only be marginal. In order to realize further groundwater abstractions, the development of additional well fields would be needed.

Concerning the agriculture demand, groundwater is the main water source in the intensively irrigated areas. An increase of abstraction rates for irrigation proposes by 50 % until 2035 would lead to an additional groundwater drawdown of up to 7 m in the irrigated areas.

Summarizing it can be stated that the transfer from Kafue must not be increased until 2025, if enough well fields can be developed. Considering the proposed increase in water demand until 2035, a combination of new well fields and new transfer capacities from Kafue are a reasonable solution to assure the supply of drinking water in combination with sustainable abstraction rates.

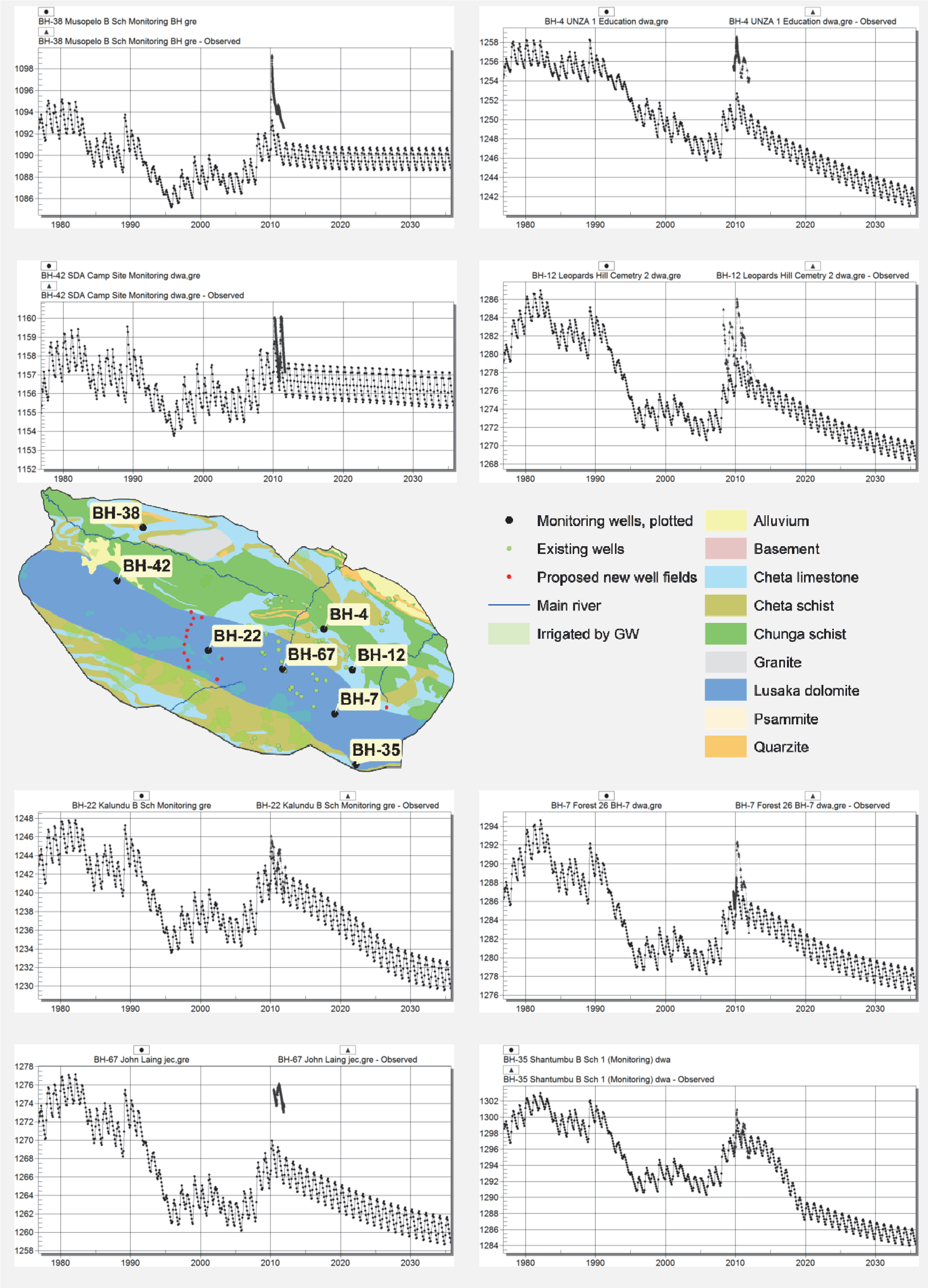

Figure 24 Simulated temporal development of the groundwater table at 8 monitoring stations. Additionally, the measured water tables in the water years 2010 and 2011 are depicted.

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9. WATER BUDGET OF LUSAKA REGION

Prepared by Chisanga Siwale, Roland Bäumle, Torsten Krekeler & Beauty Shamboko-Mbale

In the framework of Phase 2 of the GReSP Project that commenced in 2010, a comprehensive and continued investigation and monitoring program was carried out in the Lusaka area. One of the main objectives of the program was to establish reliable estimates of groundwater abstraction and groundwater recharge and to establish the water budget of catchments discharging the Lusaka Plateau.

The water budget encompasses all inflows into and outflows from an investigated area that take part in the "hydrologic" or "water" cycle. Outflows must equal inflows plus or minus storage. The water budget for a catchment (with no inflows other than from precipitation) therefore reads in a basic form:

Precipitation = Actual evapotranspiration + Runoff + Abstraction ±
Changes in storage

Precipitation

The various studies looked at long-term average meteorological conditions compared to years with dry conditions on the one hand and specifically at the two recent water (hydrological) years 2010 and 2011 on the other hand. The long-term average rainfall at the rain gauges operated by the Zambian Meteorological Department amounts to about 830 mm per year. The median of annual rainfall is about 30 mm below the mean. The hydrological year 1989/90 was considered adequate to represent long-term "reference" conditions as the seasonal distribution of rainfall resembled well long-term averages and the annual total of 780 mm (measured at International Airport) lies within an order of magnitude of the long-term average. Data availability for the two recent years was unmatched in the past as it included continuous daily time series of rainfall from six gauges, calibrated surface discharge form all major streams and groundwater levels from 25 monitoring boreholes (Figure 25). In addition, comprehensive information on current groundwater abstraction could be obtained for this period. During the hydrological year 2009/2010 the area received above-average rainfall totalling 997 mm. The 2010/2011 season was relatively dry with total rainfall of 735 mm.

Actual evapotranspiration

Actual evapotranspiration was determined by employing empirical crop coefficients and algorithms based on FAO's Irrigation and Drainage Paper No. 56. For the reference year 1989/90 actual evapotranspiration is about 480 mm. Inter-annual variations of actual evapotranspiration can be expected to be relatively small.

Runoff

The Lusaka Plateau is partially forming the water divide between the Lower Kafue and Chongwe basins. It is discharged by smaller rivers and streams including the Ngwerere and Chilongolo rivers, which are tributaries of the Chongwe River, the Chunga/Mwembeshi system and the non-perennial Chilongolo stream that runs towards the Kafue Flats. The monitoring network included five existing stations and one additional established under the GReSP project. These are Ngwerere River at Estate Weir, Chalimbana River at Romor Farm, Chongwe River at Great East Road Bridge, Kapiriombwa at Khalamazi Farm, Mwembeshi River at Mumbwa Road Bridge and Chunga River at Shandyongo Village. Discharge at Chilongolo was measured several times, but no gauging station was established there because no appropriate location (hydraulic and logistic) could be found. While historical stream gauging data are subject to an element of uncertainty, the hydrometric installations were in good working order and produced reliable data during the two hydrological years 2009/2010 and 2010/2011 during which existing rating equations were revised and a new rating equation for the station at Chunga was developed. Surface runoff from areas covered by carbonate rocks is almost absent due to their epikarstic nature. The runoff determined at the stream gauges strongly depends on rainfall and varies over a wide range. The long-term average runoff from the catchments of the Lusaka Plateau was crudely estimated to be 100 mm. The runoff at Ngwerere Estate weir, however, is considerably higher as it is largely controlled by runoff from the sewage plant and by storm water runoff from urban and peri-urban areas with a high percentage of sealed surfaces.

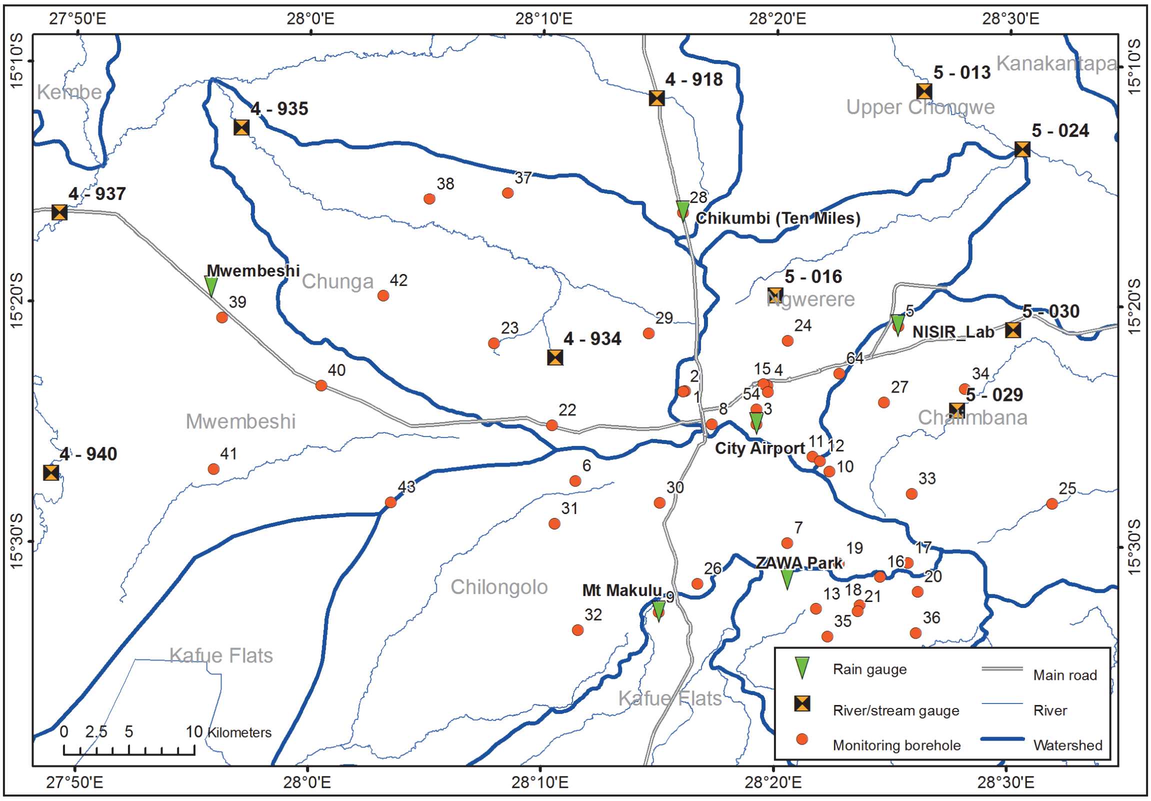

Figure 25 Monitoring network established in the Lusaka area including rain and stream gauges and groundwater monitoring boreholes

Groundwater abstraction

The current groundwater abstraction was determined as follows:

(1) Public/domestic abstractions from wells operated by Lusaka Water and Sewerage Company and Water Trusts were calculated based on comprehensive data obtained from the water utility company. LWSC operates close to 100 wells with a total production of almost 50 Mm^3/a. Abstraction from Water Trust boreholes is comparatively small with 1.8 Mm^3/a.

(2) Private/domestic abstraction from low-density areas was estimated to be 19.6 Mm^3/a based on the distribution and size of the area of this residential type and coarse approximations of water demand for domestic use and the irrigation of gardens and lawns.

(3) Abstraction for irrigation on commercial farms was determined using information on common irrigation practices, crop cycles and crop water demand that was obtained from a survey of 45 commercial farms in the area. The abstracted amount determined for this category is 16.8 Mm^3/a.

(4) Abstraction from industries with 4.4 Mm^3/a is relatively small and was determined from a survey of 53 enterprises in the region.

Hence, the largest water user of groundwater in the Lusaka area is public water supply followed by private abstractions, agriculture and industries. Total current groundwater abstraction according to this study amounts to about 90 Mm^3/a.

The average total groundwater abstraction for the whole area amounts to 40 mm/a. With respect to sub-catchments groundwater usage is – with over 100 mm/a - most intensive in Ngwerere due to high abstractions for both LWSC boreholes and assumed private use. High groundwater abstraction is also observed in the small sub-catchments of the Kapiriombwa stream and the upper parts of Chilongolo and Chunga rivers that include urban and peri-urban areas.

Table 9 Estimated total groundwater abstraction per catchment

Sub-catchment	Catchment area (km^2)	Abstraction (Mm^3/a)	Abstraction (mm)
Kapiriombwa (Chalimbana)	87	7.951	91.4
Chalimbana (above station 5-029)	115	0.644	5.6
Chalimbana (below station 5-029)	452	0.303	0.7
Ngwerere (above station 5-016)	109	11.568	106.1
Ngwerere (below station 5-016)	190	19.273	101.4
Chilongolo	676	35.299	52.2
Chunga (excluding Laughing Waters)	583	8.508	14.6
Laughing Waters (Chunga)	35	5.804	165.8
Total	**2,247**	**89.504**	**39.8**

Groundwater recharge

Groundwater recharge was estimated using five different approaches including:

(1) Base flow recession method

(2) Water table fluctuation method

(3) Water budget method

(4) Soil water balance approach (WEAP/MABIA module)

(5) Numerical groundwater model (MODFLOW 2000/GMS 7.1)

The base flow method proved inappropriate for the specific hydrological conditions in the catchments as the flow of many streams is seasonal or reduces to a trickle during the dry season. In addition stream flow is often strongly influenced by discharge from sewage plants and dams. The water table fluctuation method is considered less accurate as it is difficult to come up with reliable estimates for specific yield, in particular since the distribution of hydraulic properties of host rocks in the Lusaka area is known to be highly variable. Nevertheless, the method produced values comparable to other methods. The results of the other three methods applied are overall similar and considered reliable. According to the analysis, groundwater recharge for years with average climatic conditions varies between 229 mm/a and 300 mm/a. The authors suggest to consider a value of 250 mm/a as a reasonable estimate of long-term average recharge in the area. Current total groundwater abstractions amount to only 40 mm/a which represents 16% of assumed recharge. For the “wet” year 2009/2010 groundwater recharge may be above 400 mm/a whereas for the “dry” year 2010/2011 recharge may fall below 100 mm/a depending on the catchment area and method applied. In catchments with high groundwater abstractions such as the Ngwerere River catchment, groundwater resources may therefore be under stress during prolonged dry conditions.

Water budget

Establishing the water budget for the Lusaka area is still connected with uncertainties despite the comprehensive work accomplished. Main challenges in this regard include the high variability of rainfall and runoff and the complex and insufficiently understood mechanisms influencing groundwater-surface water interactions. It has proven particular difficult to fully comprehend and quantify the impact of preferential recharge through karst surface features and evaporation from shallow groundwater bodies and seepage zones as well as drainage from groundwater into streams (i.e. base flow) and vice versa. In Figure 26, the generalised water budget for the Lusaka region is shown. Please note that the figures given represent long-term average climatic conditions.

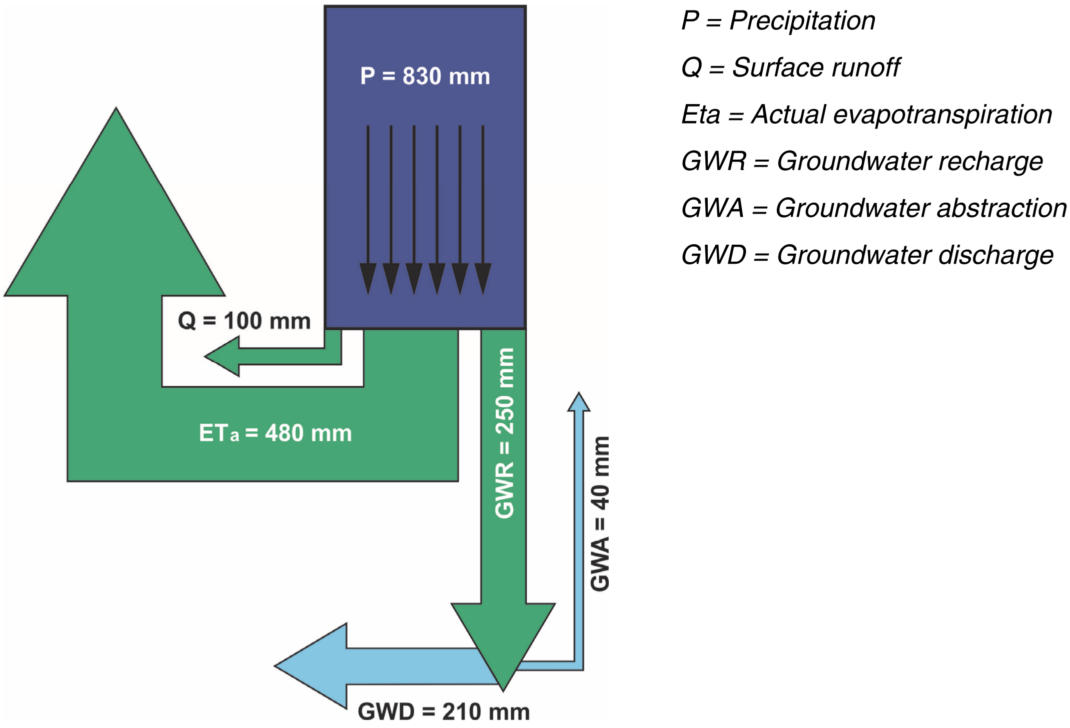

Figure 26 Estimated generalised water budget for the Lusaka region considering long-term average climatic conditions

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