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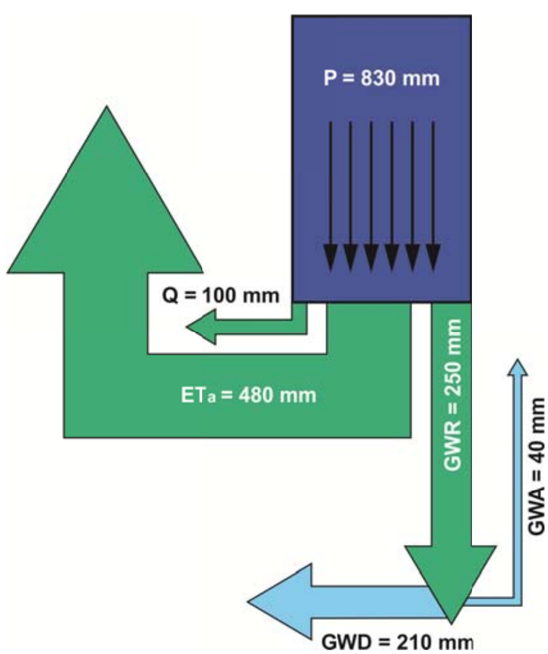
Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

REPORT NO. 7

WATER BALANCE ESTIMATES FOR SUB-CATCHMENTS OF THE CHONGWE AND MWEMBESHI RIVERS IN THE LUSAKA REGION

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



Lusaka, December 2012

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WATER BALANCE ESTIMATES FOR SUB-CATCHMENTS OF THE CHONGWE AND MWEMBESHI RIVERS IN THE LUSAKA REGION

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Abbreviation

A	Abstraction (surface water & groundwater)
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
DWA	Department of Water Affairs
ETa	Actual Evapotranspiration
ETp	Potential Evapotranspiration
GReSP	Formerly: Groundwater Resources for Southern Province, now: Groundwater Resources Management Support Programme
GWA	Groundwater abstraction
GWD	Groundwater (subterranean) discharge
GWR	Groundwater recharge
h	*W*ater table height
JICA	Japan International Cooperation Agency
K	Recession index in stream flow/hydrograph analysis
k	Residence time (or turnover time) of groundwater
LCC	Lusaka City Council
LWSC	Lusaka Water and Sewerage Company
MLGH	Ministry of Local Government and Housing
MMEWD	Ministry of Mines, Energy and Water Development
NWASCO	National Water Supply & Sanitation Council
P	Precipitation (rainfall)
Q	Stream flow (total runoff)
Q_b	Base flow
Q_d	Direct runoff
S_y	Specific yield (effective porosity)
SWA	Surface water abstractions
Ufw	Unaccounted for water
WTF	Water Table Fluctuation- Method
ZARI	Zambian Agricultural Research Institute
ZMD	Zambian Meteorological Department

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
Nov. 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 II (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
2012, in prep.	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: Beauty Shamboko-Mbale, Roland Bäumle, Chisanga Siwale, Torsten Krekeler

Title: Water balance estimates for sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka Region

Key words: Water budget, water (hydrological) year, actual evapotranspiration, groundwater abstraction, groundwater recharge, soil water balance, groundwater modelling

Comprehensive hydrological and hydrogeological investigations were carried out in order to establish reliable estimates of groundwater recharge and the water budget of catchments discharging the Lusaka Plateau. Average annual rainfall for the area is 830 mm; actual evapotranspiration amounts to 480 mm and characteristic surface discharge is roughly estimated to be 100 mm/a although areas covered by carbonate rocks are characterised by a lack of surface streams and discharge. The total groundwater abstraction including public water supply, private abstractions and abstraction for irrigation and industrial purposes currently totals about 90 Mm^3/a, which equals 40 mm/a. Groundwater recharge was determined by various methods including water budget analysis, a soil water balance method and numerical groundwater modelling. As a result, a value of 250 mm/a is considered a reasonable estimate of long-term average recharge in the area. During years with higher than average rainfall such as the 2009/2010 season the recharge may exceed 400 mm/a. In drier years such as the 2010/2011 season, however, recharge may be below 100 mm/a.

Extended Summary

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

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 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 from all major streams and groundwater levels from 25 monitoring boreholes. 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 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.

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 form 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.

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.

Groundwater recharge was estimated using five different approaches including:

- Base flow recession method
- Water table fluctuation method
- Water budget method
- Soil water balance approach (WEAP/MABIA module)
- 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 results comparable to other methods. The results of the other three other 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.

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.

1. INTRODUCTION

In the framework of Phase 2 of the GReSP Project[1] a comprehensive and on-going investigation program was launched in the Lusaka area during 2010. The program comprises – among other components - monitoring and thorough analysis of rainfall, surface water runoff and groundwater levels as well as remote sensing studies to determine the land use distribution and a soil water balance approach to estimate groundwater recharge and numerical groundwater modelling.

Groundwater constitutes a major source of water for the City's drinking water supply as well as for private and commercial use. One of the main goals of the GReSP program was therefore to increase overall knowledge on the water budget of the area and in particular to assess whether current groundwater usage is sustainable and could be further intensified in the near future.

The program largely benefitted from existing monitoring programs and studies obtainable from various institutions. Data and information that proved to be of particular value in this regard included records of existing groundwater monitoring and hydrometric stations that were made available through the respective sections at the Department of Water Affairs (DWA), meteorological data obtained from Zambian Meteorological Department (ZMD), extensive information on current groundwater abstraction and consumption in Lusaka provided by Lusaka Water and Sewerage Company (LWSC) as well as information on soil physical properties acquired from Zambian Agricultural Research Institute (ZARI) .

The investigations under GReSP focussed on the surface water catchments draining the Lusaka Plateau, namely the catchments of the Ngwerere, Chalimbana, Chilongolo and Chunga rivers. These rivers form sub-catchments within the larger basins of the Mwembeshi and the (Upper) Chongwe rivers. A previously unmatched amount and quality of hydrometric and hydrogeological data has been collected in this area for the two water years October 2009 to September 2010 and October 2010 to September 2011. The data collected and analysed includes:

- Meteorological data from three stations run by ZMD,
- Rainfall data from three automatic rainfall gauges,
- Surface runoff data from six gauging stations,
- Groundwater levels at over 30 monitoring boreholes and abstraction wells,
- Average abstraction data from the majority of wells operated by LWSC
- Information on water consumption of administrative units ("water districts") in Lusaka

The **objective of this report** is to summarise the findings regarding the water budget components for the years 2009/2010 and 2010/2011 and to compare the characteristic hydrological situation prevailing during these two years with long-term (secular) rainfall and runoff conditions in the area. A specific effort is made to provide a reliable estimate of the groundwater recharge in the investigation area. Furthermore, the calculation of the water budget for selected sub-catchments will be presented.

[1] The GReSP project was launched in May 2005 and 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.

The findings of this report are based on works described in previous project reports such as the report on land use and groundwater abstraction (Mayerhofer et al 2010), results of remote sensing studies (Hahne & Shamboko-Mbale 2010) the assessment of annual percolation rates (Hennings 2012, in prep.) and the technical note on discharge measurements (Krekeler & Siwale 2012). This report does not intend to quote or comprehensively summarise results of previous studies focussing on water budget and groundwater recharge as this was extensively covered in the desk study report compiled during initial stages of this program (Bäumle & Kang'omba 2009).

2. WATER BUDGET

A 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:

Equation [1]

Precipitation P =	Actual evapotranspiration ETa + Runoff Q (surface & groundwater) + Abstraction A (surface & groundwater)	± Changes in storage ΔS (surface & groundwater)

Evapotranspiration may comprise evaporation losses from land surfaces and reservoirs (open water). Total runoff from a stream or river can be divided into "direct runoff" Q_d (overland flow and interflow) and "baseflow" Q_b (groundwater runoff). Changes in water storage can usually be neglected over long enough periods.

An aquifer is a groundwater storage reservoir in the water cycle. The groundwater recharge may be determined by a water budget analysis of the recharge area using:

Equation [2]

Groundwater Recharge GWR =	Precipitation (plus irrigation) P
	– Actual evapotranspiration ETa
	– Direct runoff Q_d
	– Surface water abstractions SWA

The groundwater recharge term accounts for entries from rainfall (**direct recharge**) as well as from influent seepage from rivers ("losing streams"), unlined canals or excess irrigation water (**indirect recharge**).

2.1. RAINFALL

2.1.1. Long-term rainfall variations

The Zambian Meteorological Department operates three meteorological stations in and around Lusaka. At all three stations, meteorological records including daily rainfall data well exceed 30 years (Table 1). The following observations regarding the long-term (secular) variations of rainfall in the Lusaka area can be made:

1. The long-term average of annual rainfall is very similar for all three stations varying between 824 mm and 845 mm. With values ranging from 776 mm to 802 mm, the median of annual rainfall is generally below the mean implying that for over 50% of the recorded years the area receives rainfall slightly below the mean.
2. Annual rainfall totals vary over a wide range from below 500 mm to over 1200 mm (Figure 1). The obvious succession of years with dry, average and wet conditions can be statistically expressed by means of the standard deviation that amounts to about ±200 mm at the three stations.
3. Rainfall variability in the area during individual years is also high despite the similarity in terms of long-term average. Since 1975, the differences in annual rainfall measured at the three stations ranged from 50 mm to (in the 1979/80-season) over 400mm averaging 170 mm.

Table 1 Statistics of annual rainfall in mm

Station	Start of records	*n* [1]	Mean	Median	Min.	Max.	σ [2]	*CV* [3]
Lusaka City Airport	1950	54	824	796	405	1364	207	25
Mt Makulu Agromet	1961	50	830	802	566	1285	177	21
Lusaka Int. Airport	1975	35	845	776	430	1282	214	25

1) Available number of records (years with rainfall measurements)
2) Standard deviation
3) Coefficient of variation, defined as the ratio of the standard deviation to the mean, in %

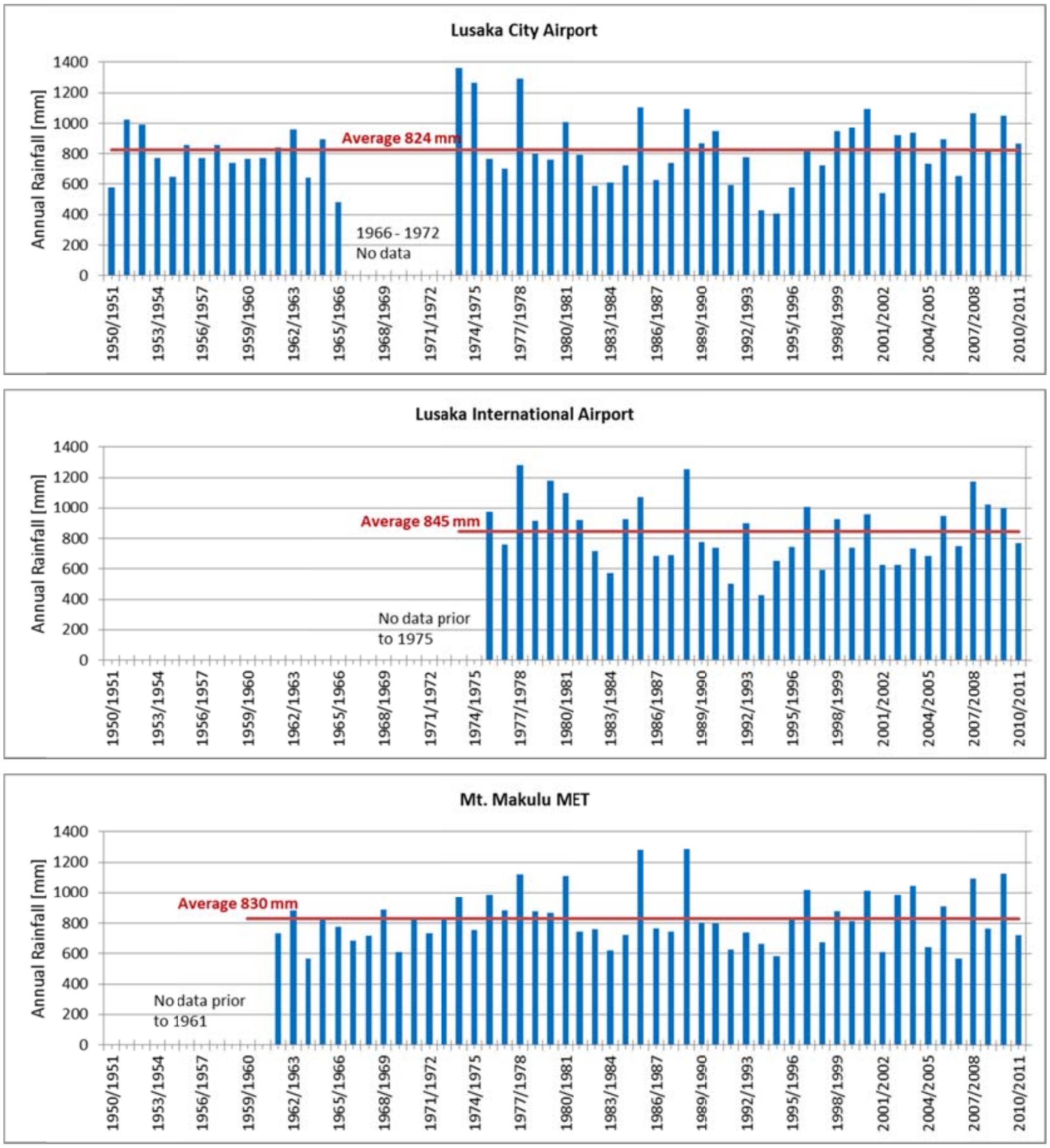

Figure 1 Long-term annual rainfall at three stations in the Lusaka area showing average and temporal variations (Source: Zambia Meteorological Department)

2.1.2. Rainfall during 2009/2010 and 2010/2011 seasons

Three additional automatic rainfall stations were established in 2009 to provide more information on spatial and temporal rainfall variability in the area. Rainfall at these stations is recorded hourly. The existing rainfall recorders are summarised in Table 2 and their location is shown in Figure 2.

Table 2 Meteorological stations and automatic rainfall gauges established during 2009 in the Lusaka area

Station	Operator	Longitude	Latitude	Altitude
Chikumbi	DWA	E 28.26655	S 15.27008	1194
Mwembeshi	DWA	E 27.92956	S 15.32222	1101

Station	Operator	Longitude	Latitude	Altitude
ZAWA Park	DWA	E 28.34267	S 15.52381	1304
City Airport	ZMD	E 28.31992	S 15.41615	1284
International Airport	ZMD	E 28.42040	S 15.34787	1173
Mt. Makulu	ZMD	E 28.24841	S 15.54698	1231

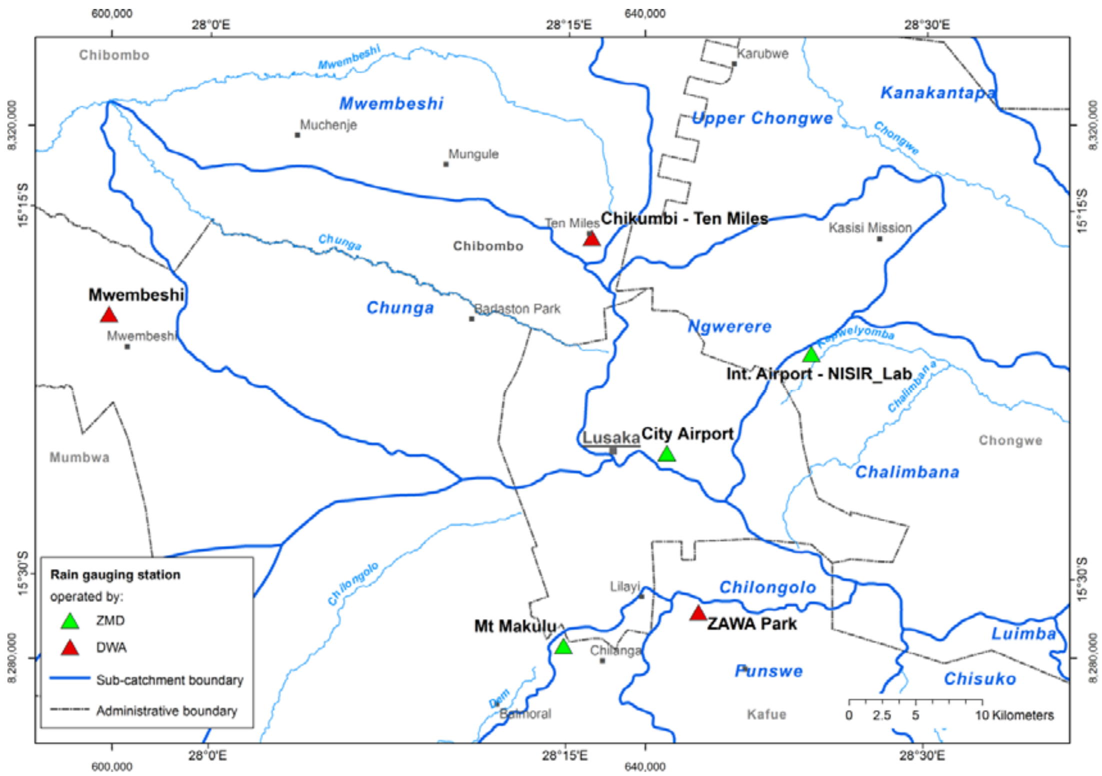

Figure 2 Location of meteorological stations operated by ZMD and automatic rainfall gauges

Table 3 contains observed monthly rainfall at the six stations available. Unfortunately, the records at Chikumbi and Mwembeshi are discontinuous due to repeated clogging of the tipping mechanism caused by maize pollen and insects. Some monthly and the annual totals could therefore not be calculated.

Annual rainfall during the 2009/2010 rainy season varied between 959 mm at ZAWA Park and 1126 mm at Mt. Makulu with an average of 1034 mm. This year has to be considered “wet” compared to long-term average conditions.

During 2010/2011 annual rainfall at International Airport, Mt. Makulu and ZAWA Park was very similar amounting to about 720 mm. With 870 mm a considerably higher rainfall was observed at the station located near City Airport. Despite this, the area apparently received overall below-average rainfall during this hydrological year.

Table 3 Monthly rainfall in millimetres during the hydrological years 2009/2010 and 2010/2011 at six stations in the Lusaka area (Sources: Zambia Meteorological Department & Department of Water Affairs)

Hydrological Year	Month	City Airport	Int. Airport	Mt Makulu	Chikumbi	Mwembeshi	ZAWA Park
2009/10	Oct	0	0	0	0	1.6	2.7
	Nov	181.5	198.9	265.9	n/a	238	205.3
	Dec	188.7	175.7	100.9	n/a	144.3	91.4
	Jan	145	174.4	246.7	113	130.9	224.9
	Feb	393	288.6	331.7	267	214.9	295.2
	Mar	140.5	165.3	117.8	113.7	106.2	121.8
	Apr	0	0	63.1	10.8	10.5	17.2
	May	0	0	0	0	0	0.2
	Jun	0	0	0	0	0	0.1
	Jul	0	0	0	0	0	0.1
	Aug	0	0	0	0	0	0
	Sep	0	0	0	0	0	0
	TOTAL	**1049**	**1003**	**1126**	**n/a**	**846**	**959**
2010/11	Oct	0	0	0	0	0.1	0
	Nov	93.8	75.9	166	43.6	55.3	67.4
	Dec	203.3	319.5	222.6	253.6	151.7	252
	Jan	244.4	205	138.2	130.1	n/a	116.7
	Feb	137.4	32.4	83.2	75.6	72.2	68.2
	Mar	156.4	114.1	83.1	74.2	137.4	139.7
	Apr	34.6	25	31	8.6	8.9	75.5
	May	0	0	0	0.1	0	0
	Jun	0	0	0	0	0.3	0.8
	Jul	0	0	0	0	0	0
	Aug	0	0	0	0	0	0
	Sep	0	0	0	0.8	0.1	0
	TOTAL	**870**	**772**	**724**	**587**	**n/a**	**720**

Like elsewhere in this region rainfall in the Lusaka area is controlled by a clear distinction between the wet season during summer and the dry winter. The wet and dry season are separated from each other by a short pre-rainy season (September-November) and post-rainy period (April-May). Based on long-term rainfall data measured at the City Airport almost 95% of the total annual rainfall occurs during the five-month period from November to March, and 73% during the three-month period from December to February. The highest average monthly rainfall occurs in January with monthly totals averaging 218 mm followed by December (203 mm) and February (182 mm). The winter months from June to August are practically without rain.

In Figure 3, monthly rainfall during the 2009/2010 and 2010/2011 seasons are compared with long-term monthly rainfall averages. The figures show that rainfall distribution during both seasons differed from the general pattern: During 2009/2010, the area received unusually high pre-season rainfall with monthly totals during November ranging from 182 mm to 266 mm. Furthermore, rainfall during February was exceptionally high totalling between 215 mm and 393 mm. During the 2010/2011 season, relatively high rainfall was observed during December with values between 152 mm and 320 mm whilst precipitation during February was extremely low with values below 85 mm at all stations apart from Lusaka City Airport (Table 3).

Figure 3 Monthly rainfall during 2009/2010 season (left column) and 2010/2011 season (right column) compared with long-term monthly rainfall average at three meteorological stations in Lusaka (Source: Zambia Meteorological Department)

According to records of the Zambia Meteorological Department daily rainfall is equally variable and often exceeds 50 mm/d during a rainy season. The highest ever observed daily rainfall amounts to 292 mm at Mt. Makulu on November 5, 1972. During the 2010/2011 season Lusaka International Airport encountered the highest daily rainfall ever recorded at this station amounting to 162 mm. The maximum daily rainfall values recorded at the six stations during the 2009/1010 and 2010/2011 seasons are given in Table 4.

Table 4 Highest daily rainfall recorded during the 2009/1010 and 2010/2011 seasons at stations in the Lusaka area (Sources: Zambia Meteorological Department & Department of Water Affairs)

Station	Date	Daily rainfall [mm]
City Airport	02/12/2009	79.5
Int. Airport	07/12/2010	162.3
Mt Makulu	01/02/2010	84.1
Chikumbi	08/12/2010	68.3
Membeshi	21/11/2009	60.9
ZAWA Park	24/03/2011	62.6

2.2. EVAPOTRANSPIRATION

2.2.1. Potential evapotranspiration

Spatial distribution of potential evapotranspiration *ETp* can be assumed to be fairly uniform over the investigation area due to the smooth topography and overall comparable climatic conditions.

ETp herein defined as FAO's Grass Reference Evaporation was calculated for the 1989/90 and 1983/84 hydrological years from five daily meteorological input parameters at Lusaka International Airport, namely minimum temperature, maximum temperature, mean humidity, mean wind speed, duration of sunshine (Hennings 2012). The 1989/90 season is considered to represent "reference rainfall conditions" with a fairly typical seasonal rainfall distribution and a total of 776 mm. With an annual precipitation of 571 mm, the 1983/84 season represents a distinctive "dry year". Annual sums of *ETp* at International Airport are 1908 mm in 1989/90 and 1815 mm in 1983/84. During the rainy season, daily values never exceed 6 mm/d while at the end of the dry season in September and October maximum values of >10 mm/d are calculated.

According to the Zambian National Water Resources Master Plan (YEC 1995), *ETp* obtained with a revised version of the Penman equation ranges from 1,530 mm to 1,590 mm for stations situated in the Lusaka area and from 1,394 mm to 1,892 mm in Zambia. In view of the results above, values of *ETp* given in the Master Plan must be considered too low.

2.2.2. Actual evapotranspiration

Hennings (20120 has calculated actual evapotranspiration *ETa* using the MABIA software (Jabloun & Sahli 2011) that was incorporated in the "Water Evaluation and Planning" (WEAP) decision support system developed by the Stockholm Environment Institute (2005). The software applies the FAO 56 dual crop coefficient approach for estimating crop evapotranspiration from soil (Allen et al. 1998). It considers crop-specific water demand and transpiration as well as soil water availability depending on net precipitation and soil physical properties (i.e. soil water capacity). Calculations were performed using 1989/90 daily meteorological data from Lusaka International Airport.

Spatial distribution of *ETa* for the year 1989/90 is given in Figure 4. For non-irrigated areas *ETa* varies between a minimum of just below 400 mm and a maximum of 562 mm. Higher evaporation rates are associated with deeply developed soils and higher available water capacity (>100 mm). Highest values of *ETa* displayed in Figure 4 represent land on commercial farms that is irrigated during the dry winter season from April to September. Evapotranspiration increases by about 650 mm to 700 mm under dry season irrigation resulting in total *ETa* for commercial agricultural land under irrigation of 1100 mm to 1200 mm. The average *ETa* over the area amounts to 477 mm if dry season irrigation would be absent but increases to 535 mm if irrigation on commercial farms is taken into account.

ETa of individual catchments for the reference year is given in Table 5. Catchments with highest *ETa* represent areas with a larger proportion of irrigated land.

Table 5 Actual Evapotranspiration ETa in mm/a for selected catchments in the Lusaka area during the reference year 1989/90 according to WEAP/MABIA model calculations

Catchment	*ETa* without irrigation	*ETa* with dry season irrigation
Chunga	466	483
Upper Chalimbana (station 5-029)	467	528
Upper Ngwerere (station 5-016)	504	504
Ngwerere	490	591
Chilongolo	473	574

It should be mentioned that annual totals for *ETa* given in the National Water Resources Master Plan are based on the Turc equation. This empirical approach assumes that approximate values of *ETa* over a year can be obtained based on mean annual precipitation and mean annual air temperature. The resulting values given in the Master Plan vary between 730mm and 739mm. The results of the WEAP/MABIA model suggest that values obtained from the Turc equation are not accurate mainly because seasonal variability of rainfall in Zambia is too high.

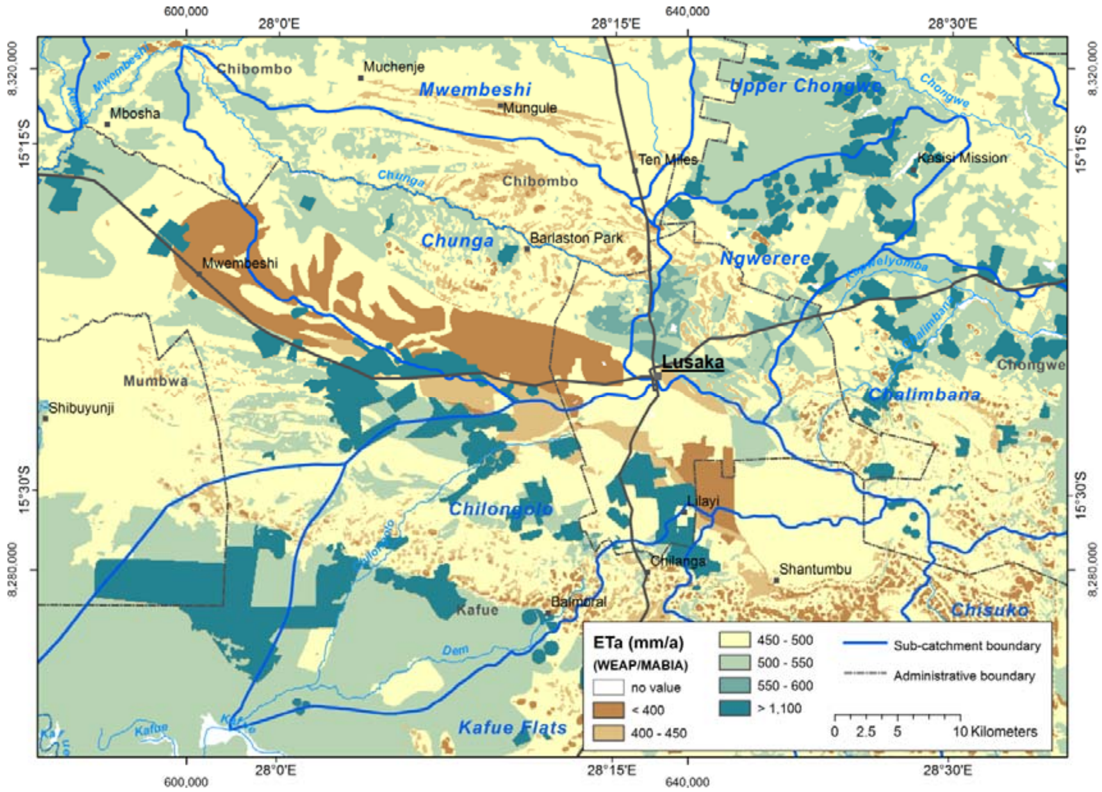

Figure 4 Actual Evapotranspiration *ETa* in mm/a for the Lusaka region in the reference year 1989/90 calculated with the WEAP/MABIA-model using meteorological data from Lusaka International Airport. Areas with *ETa* > 1100 mm represent commercial agricultural land under dry season irrigation (after Hennings 2012).

2.2.3. ETa during 2009/2010 and 2010/2011 seasons

Values of *ETa* for the hydrological years 2009/2010 and 2010/2011 determined by the WEAP/MABIA model are given in Table 6. The annual sums of the two recent seasons and the reference year are in the same order of magnitude ranging from say 460 to 510 mm if effects of dry season irrigation are not taken into account. This indicates that inter-annual variability in actual evapotranspiration is relatively small compared to rainfall.

Table 6 Actual Evapotranspiration ETa in mm/a for selected catchments in the Lusaka area during the 2009/2010 and 2010/20122 seasons according to WEAP/MABIA model calculations

Catchment	*ETa* without irrigation		*ETa* with dry season irrigation	
	2009/2010	*2010/2011*	*2009/2010*	*2010/2011*
Chunga	484	501	498	518
Upper Chalimbana (station 5-029)	492	483	547	547
Upper Ngwerere (station 5-016)	497	452	497	452
Ngwerere	508	495	598	599
Chilongolo	490	500	580	605

2.3. SURFACE RUNOFF

2.3.1. Long-term surface runoff

The Department of Water Affairs maintains three river gauging stations each along the Mwembeshi River and the Chongwe River. Additional stations exist in the upper parts of the Ngwerere and Chalimbana rivers. These two tributaries of the Chongwe River drain the Lusaka plateau in north-easterly and easterly directions. In 2009 an additional station was opened at Chunga River near the confluence with the Mwembeshi River. Measurements at the Kapiriombwa River (also known as "Kapwelyomba"), a smaller tributary of the Chalimbana River located near International Airport has not been operational since 1999. The locations of the gauging stations are depicted in Figure 5.

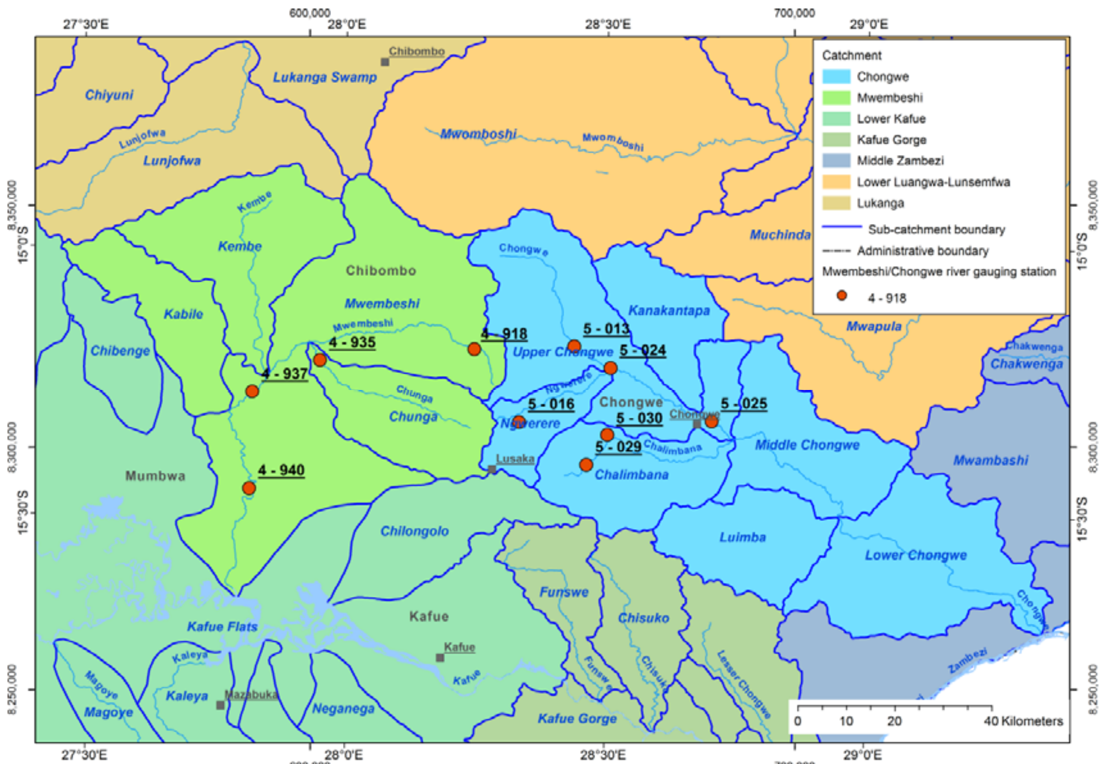

Figure 5 Map showing the Mwembeshi and Chongwe catchments and their associated sub-catchments and existing river gauging stations

The historical gauge readings and calibration measurements were recently scrutinized and stream flow calculations carefully revised. Nevertheless, there remain some uncertainties of the accurateness of the historical data. Flows were calculated only from stream flow data that fall within periods of regular discharge calibration measurements carried out at the respective gauging station. Since 2009 regular calibration measurements were carried out using a OTT ADC (*Acoustic Digital Current meter*) and OTT QLiner (*Acoustic Doppler Current-meter Profiler*) (Krekeler & Siwale 2012). The revised historical (for measurements prior to 2009) and the newly established stage rating curves are summarised in Table 7.

Table 7 Revised historical (for measurements prior to 2009) and the newly established stage rating curves for stations in the Lusaka area.

Rating equation: $Q(h) = B\,(h - A)^c$ with Q := discharge in m³/s
h := stage reading in m
A:= stage at which discharge is zero in m
B:= calibration constant
c := calibration coefficient

Station	Historical rating equation	Current rating equation[1)]
4-918 Mwembeshi (Gr. North Rd. Bridge)	A = 0.01; B = 1.17; c = 1.737 Validity: 1977 – 2004	Not determined
4-935 Chunga (Shandyongo Village)	Only established in 2009	A = 0.19; B = 17.06; c = 1.448
4-937 Mwembeshi (Mumbwa Rd. Bridge)	A = 0; B = 2.84; c = 1.585 Validity: 1976 – 2006	A = 0.08; B = 2.37; c = 1.434
4-940 Mwembeshi (Shibuyunji Village)	A = 0.03; B = 2.00; c = 1.560 Validity: 1962 - 1988	Not determined
5-012 Chongwe (Chongwe North)	$h<0.72$: A = -0.25; B = 3.95; c = 3.588 $h\geq0.72$: A = -0.72; B = 16.11; c = 2.238 Validity: 1973 – 1981	Not determined
5-016 Ngwerere (Estate Weir)	A = -0.10; B = 8.70; c = 2.247 Validity: 1981 - 2005	$h<0.65$: A = 0.24; B = 69.04; c = 3.196 $h\geq0.65$: A = 0.24; B = 12.84; c = 1.471
5-024 Chongwe (Ngwerere Confluence)	A = -0.01; B = 1.39; c = 2.004 Validity: 1977 – 2002	Not determined
5-025 Chongwe (Gr. East Rd. Bridge)	A = -0.42; B = 1.17; c = 2.888 Validity: 1969 – 1995	A = 0.88; B = 12.54; c = 2.051
5-029 Chalimbana (Romor Farm)	A = 0.05; B = 11.57; c = 2.5 Validity: 1974 – 1994 A = -0.15; B = 7.32; c = 2.5 Validity: 1995 – 2004	A = 0.32; B = 4.21; c = 1.507
5-030 Kapiriombwa (Khalamazi Farm)	A = 0.17; B = 1.62; c = 2.5 Validity: 1970 – 2002 (h<0.8 m)	$h<0.74$: A = -0.004; B = 1.75; c = 1.588 $h\geq0.74$: A = 0.17; B = 5.74; c = 2.900

[1)] after Krekeler & Siwale 2012, validity 2009 – 2012

Minimum, mean and maximum value of average annual runoff for the gauging stations are summarised in Table 8. Station no. 4-940 near Shibuyunji and 5-025 at the Chongwe Great East Road Bridge represent the discharge from the Mwembeshi and Upper Chongwe catchments, respectively. The average discharge of Mwembeshi is about 2.1 cubic meters per second corresponding to a runoff of only 17 mm per annum. The average flow of the Upper Chongwe is 5.9 cubic meters per second or 95 mm per annum. Average runoff, in particular from the Mwembeshi catchment, is surprisingly small. The low runoff may be explained by the overall relative flat terrain and high evaporative losses. For the Mwembeshi River it may be assumed that there are sections with “loosing stream” conditions along the watercourse, i.e. indirect recharge of groundwater from the streambeds occurs. In the Chongwe Catchment, a significant number of dams used for irrigation purposes decreases overall discharge. A reliable estimate of total abstractions from dams, however, is not available at this stage.

Average runoff at the stations at Chalimbana and Kapiriombwa rivers amounts to 0.3 m^3/s (82 mm) and 0.2 m^3/s (72 mm), respectively. Runoff from the upper parts of the Ngwerere Catchment is 1.4 m^3/s (415 mm) on average and hence comparatively high. This is explained by the fact that the river collects the stormwater runoff of most parts of the City and significant amounts of sewage discharge into the stream.

Table 8 Annual, monthly and daily runoff observed since beginning of records; only years with verified (calibrated) records are considered (Source: DWA, Surface Water Resources Section & GReSP Project).

Station no. & river	**Start of records**	**No.**[3)]	**Area**[4)] in [km^2]	**Annual runoff** in [m^3/s]			**Annual runoff** in [mm]		
				Min.[5)]	Mean	Max.	Min.[5)]	Mean	Max.
4-918 Mwembeshi	1977	21	73	0.016	0.28	0.67	7	121	289
4-935 Chunga	2009	2	560	--	(2.2)	--		(124)	
4-937 Mwembeshi	1977[1)]	3	2,992	(0.06)	(3.1)	(6.9)	(0.6)	(33)	(73)
4-940 Mwembeshi	1962[1)]	26	4,019	0.29	2.1	5.2	2	17	41
5-012 Chongwe	1973[2)]	9	≈548	(1.1)	(2.1)	(5.6)	(63)	(121)	(322)
5-016 Ngwerere	1956	17	109	0.28	1.4	2.5[6)]	81	415	728[6)]
5-024 Chongwe	1977	18	1,102	0.43	1.9	4.5	12	54	129
5-025 Chongwe	1968	25	1,961	0.94	5.9	20	15	95	322
5-029 Chalimbana	1953	35	115	0.051	0.30	0.99	1	82	271
5-030 Kapiriombwa	1958[1)]	20	87	0.005	0.20	0.51	2	72	185

[1)] Discontinuous data series (major gaps)
[2)] Station 5-012 was closed in 2002 and replaced by 5-013 downstream
[3)] Number of years included in the statistical analysis; these are years with validated runoff data and existing gaps not exceeding one month
[4)] Catchment areas (above station) derived from DEM
[5)] Zero runoff includes periods with negligible flow below measurement limit (trickle)
[6)] Reported annual runoff of 6.8 m^3/s equivalent to 1963 mm during 1980/81 appears to be questionable

As a consequence of the rainfall variability annual runoff undergoes an equally strong fluctuation. Time series of annual runoff at selected river gauging stations are depicted in Figure 6. Considering the complex mechanisms controlling runoff generation and the spatial variability of rainfall during individual years, a fairly strong correlation (correlation coefficient $R^2 \geq 0.6$) between annual rainfall and runoff in the Mwembeshi and Chongwe rivers can be observed (Figure 7).

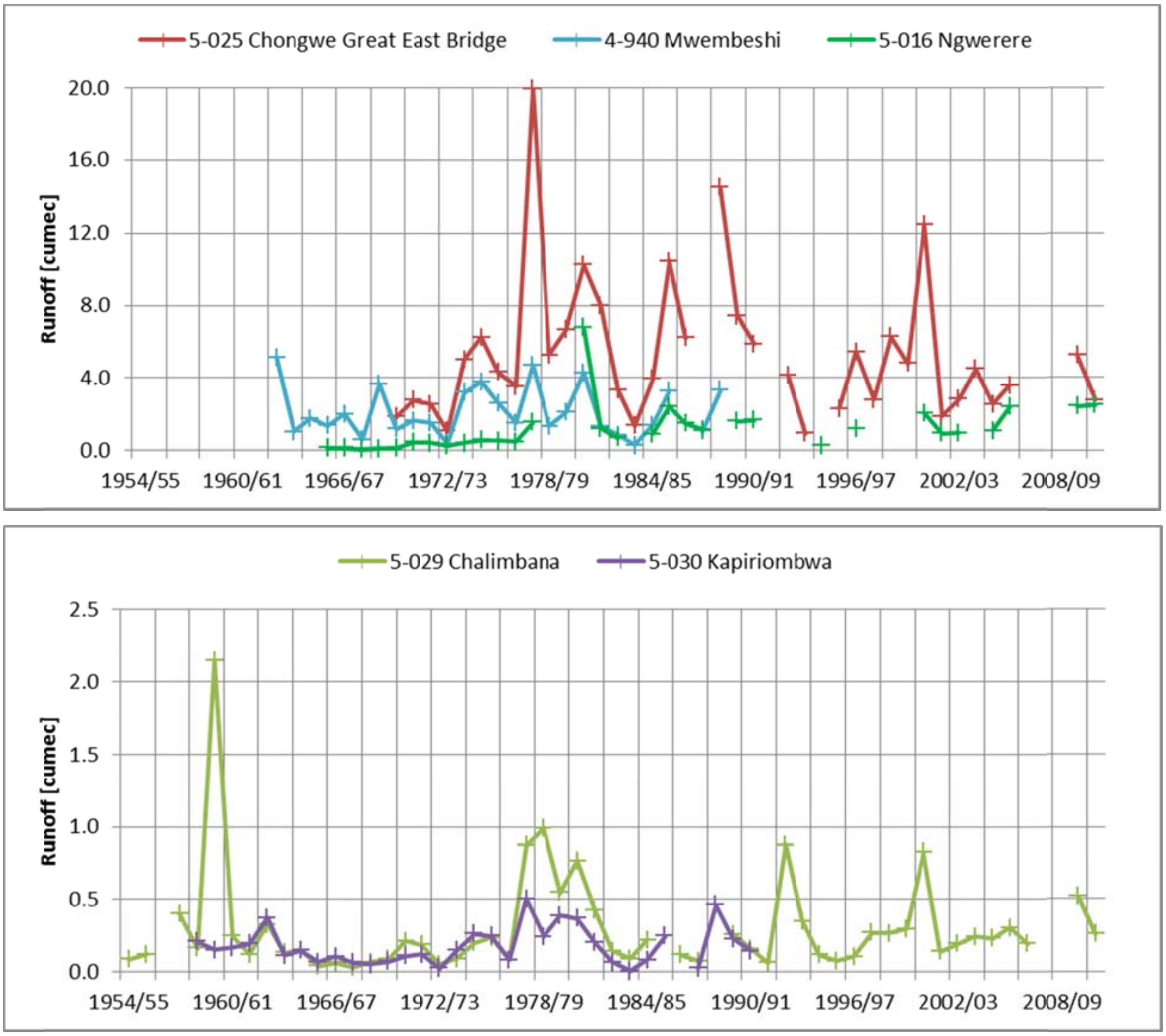

Figure 6 Mean annual runoff at selected stations in the Mwembeshi and Chongwe catchments since beginning of recording (Data Source: DWA, Surface Water Resources Section & GReSP Project).

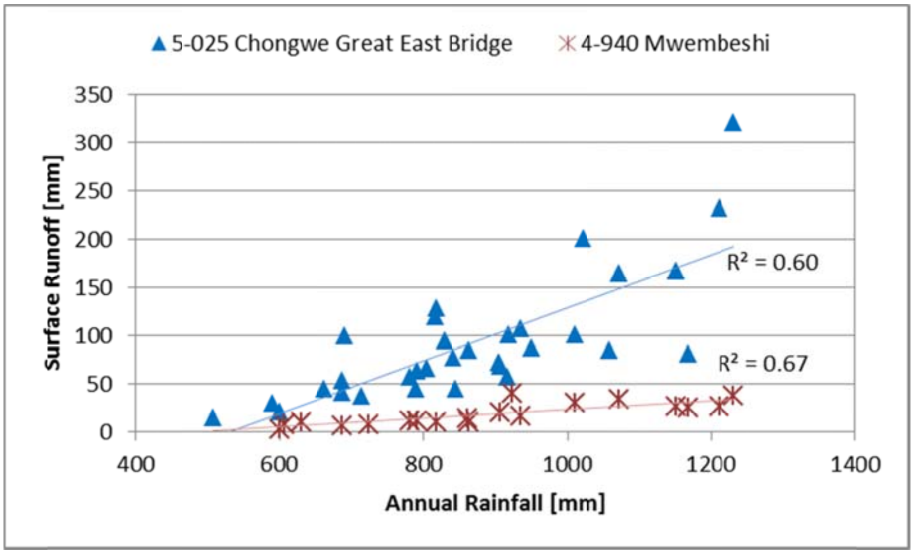

Figure 7 Correlation of annual rainfall (average at stations in Lusaka) and runoff of Mwembeshi and Chongwe rivers.

2.3.2. Runoff during 2009/2010 and 2010/2011 seasons

Monthly and annual runoff in millimetres at selected stations in the Lusaka area for the hydrological years 2009/2010 and 2010/2011 are shown in Table 9.

Table 9 Monthly and annual runoff in millimetres at selected stations in the Lusaka area for hydrological years 2009/2010 and 2010/2011

No.	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Σ
4-935	2009/10	0.2	0.4	5.0	7.5	57.2	34.4	14.0	3.8	2.0	2.6	1.5	0.1	**129**
	2010/11	0.5	0.7	21.8	64.8	12.1	10.3	3.9	1.2	0.7	0.6	0.7	0.8	**118**
5-025	2009/10	0.0	3.5	5.2	5.8	33.2	26.1	5.8	2.6	1.0	0.8	0.3	0.1	**84**
	2010/11	0.0	0.4	5.8	14.2	7.0	9.4	4.6	1.9	0.8	0.9	0.4	0.1	**45**
5-016	2009/10	2.5	47.5	41.9	89.7	178.3	155.3	80.2	52.8	15.9	12.0	11.7	22.5	**710**
	2010/11	12.0	16.0	92.8	186.8	110.1	137.7	56.9	56.0	24.5	14.6	12.7	7.9	**728**
5-029	2009/10	2.8	6.6	6.5	4.5	31.6	39.1	12.6	9.7	8.4	7.7	6.3	6.1	**142**
	2010/11	5.9	4.6	13.6	8.9	6.3	8.4	7.6	2.6	3.1	4.3	3.7	2.3	**71**

The 2009/2010 year is characterized by relatively low to moderate runoff during December and January followed by above-average runoff with exceptionally high discharge during February and March. The Chalimbana maintains above-average flows throughout the dry season. A similar pattern can be observed at Chunga River (station 4-935) where the highest monthly runoff also occurred in February. Overall, the runoff during 2009/2010 exceeded long-term average at Chalimbana (142 mm compared to 76 mm on average), but practically leveled the long-term average of 84 mm at Chongwe for this year.

Runoff during 2010/2011 stayed generally below long-term averages, most notably during the months of February and March. At Chongwe, annual runoff consequently reached only 54% of long-term average. Flow of Mwembeshi at Mumbwa Road Bridge reportedly reduced to a trickle during the dry season. The highest monthly runoff occurred typically during January. At Chalimbana, floods occurred during December. These were produced by downpours observed between the 7th and 8th of December 2010 (rainfall of 162 mm/d followed by 84 mm/d at International Airport).

The Ngwerere River shows very different flow characteristics compared to other streams in the area due to large contributions of urban stormwater runoff and continuous discharge from the wastewater plant. The average discharge of 1.4 cubic metres per second and runoff of 415 mm are exceptionally high. Due to imported water, a significant flow of - on average - over 0.6 m^3/s is maintained even towards the end of the dry season (Figure 9). In both 2009/2010 and 2010/2011 the annual runoff was almost by 75% higher than on average. It should be noted in this context that the Ngwerere River collects urban runoff from large parts of the City area. Of particular importance is the fact that the surface water drains (Bombay and Lumumba drain systems) carry water from large urban and peri-urban areas such as Libala South, Kamwala and Kanyama that are located to the south of the Ngwerere sub-catchment. Due to the specific conditions at the Ngwerere weir however, there is a concern that peak flows may not have been measured accurately in the past which automatically could have led to a distortion of monthly and annual runoff values (Krekeler & Siwale 2012).

No gauge station exists along the Chilongolo River because no appropriate location (hydraulic and logistic) could be found. Discharge from this stream was measured eleven times between the 9th of June 2009 and 31st of March 2010. Discharge ranged from 0.006 m^3/s to 0.44 m^3/s during this period. The measurements, however, included no floods.

In the hydrographs depicted in Figure 8 and Figure 9 below, mean monthly runoff is compared to runoff during the hydrological years 2009/2010 and 2010/2011. On average, maximum discharge is usually observed during February – with a one-month delay compared to the occurrence of the monthly rainfall maximum. Lowest discharge is encountered at the end of the dry season during September/October as to be expected.

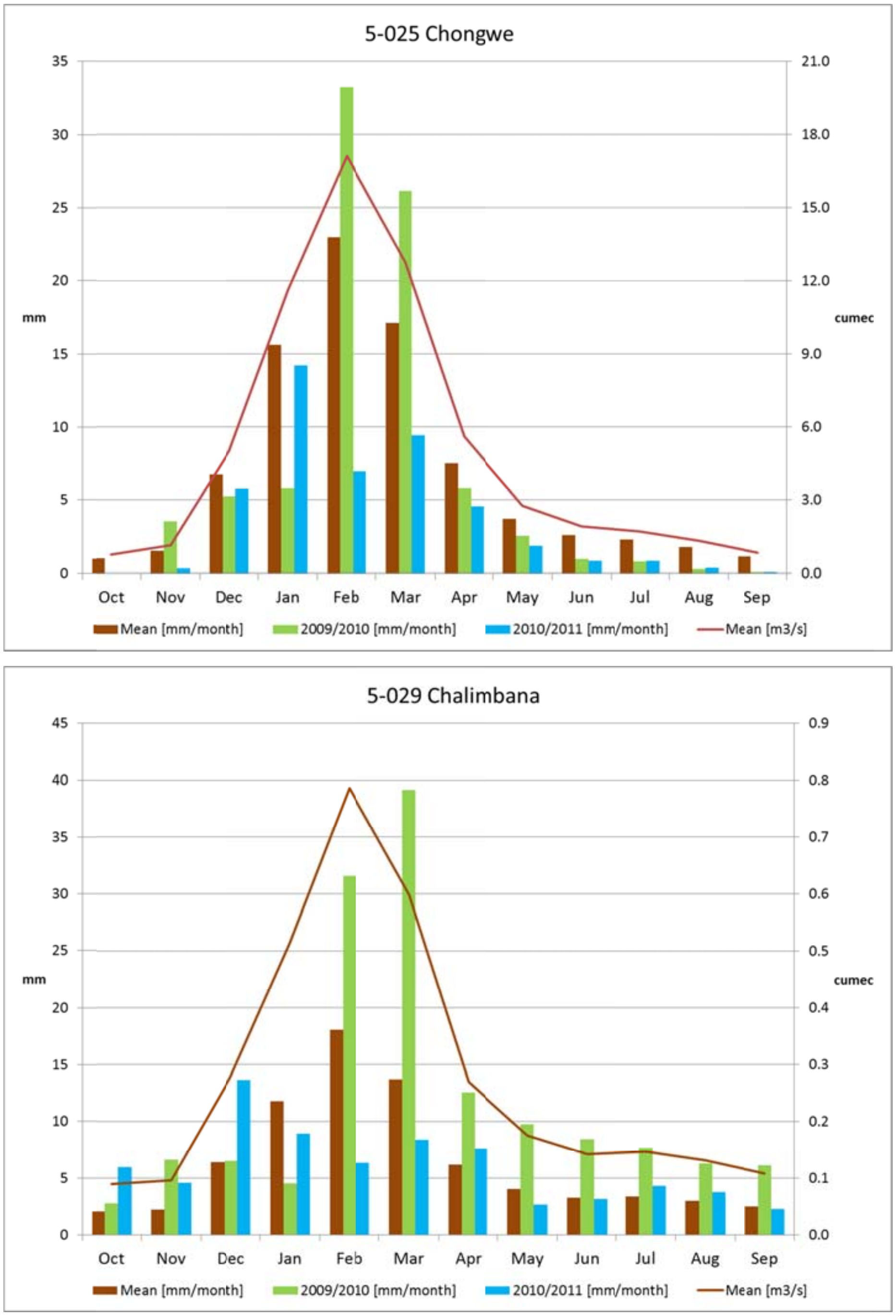

Figure 8 Monthly runoff in millimetres (long-term average and values for hydrological years 2009/10 and 2010/11) and mean monthly runoff in cubic meters per second for the stations 5-025 Chongwe – Great East Rd. bridge and 5-029 Chalimbana (Data Source: DWA, Surface Water Resources Section).

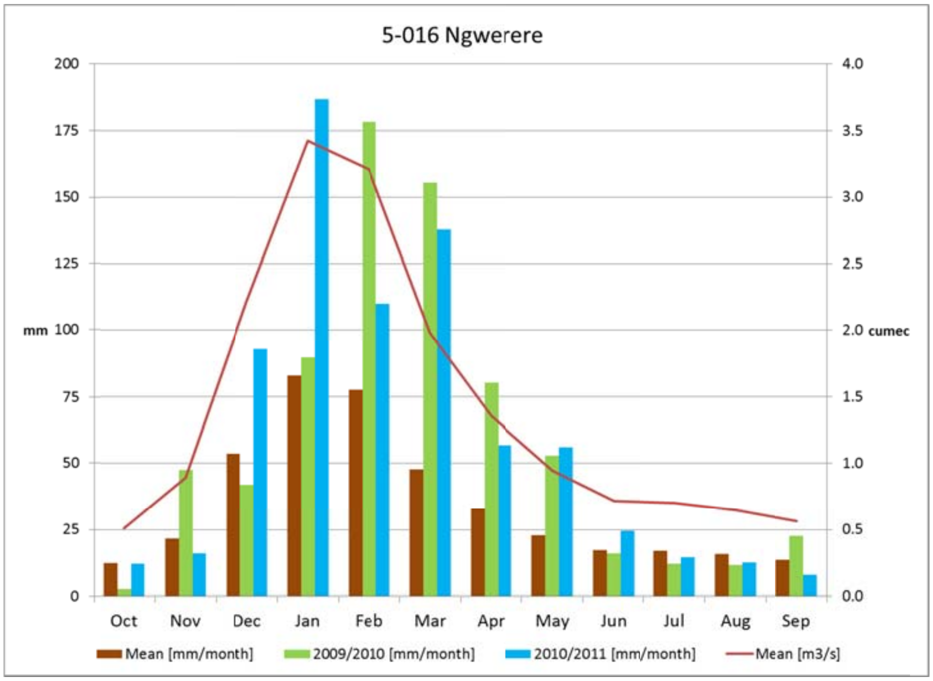

Figure 9 Monthly runoff in millimetres (long-term average and values for hydrological years 2009/10 and 2010/11) and mean monthly runoff in cubic meters per second for the station 5-016 Ngwerere (Data Source: DWA, Surface Water Resources Section).

2.3.3. Dams and reservoirs

Dams and reservoirs may largely regulate the hydrological regime of a catchment since they temporarily store surface water and hence, reduce storm water runoff downstream of the structure. In terms of the water budget, overall surface runoff may be significantly reduced due to evaporative losses from the reservoir and abstraction of stored water.

There are about twenty small earth dams (<1 km^2) to the east and north east of Lusaka in the Upper Chongwe Catchment. The stored water is mainly used for irrigation purposes. Small dams are particularly abundant along the Ngwerere and Chalimbana rivers and some smaller streams. The largest dam in the area is Ray's dam near Karubwe that stores water from Chongwe River over an area of approximately eight square kilometres. The dam is located upstream of the three existing gauging stations (Figure 10). The "Chunga earth dam" is the only significant structure in the Chunga Catchment and was built some 13 kilometres above the confluence with the Mwembeshi River. The private dam is mainly used for commercial irrigation and fishing.

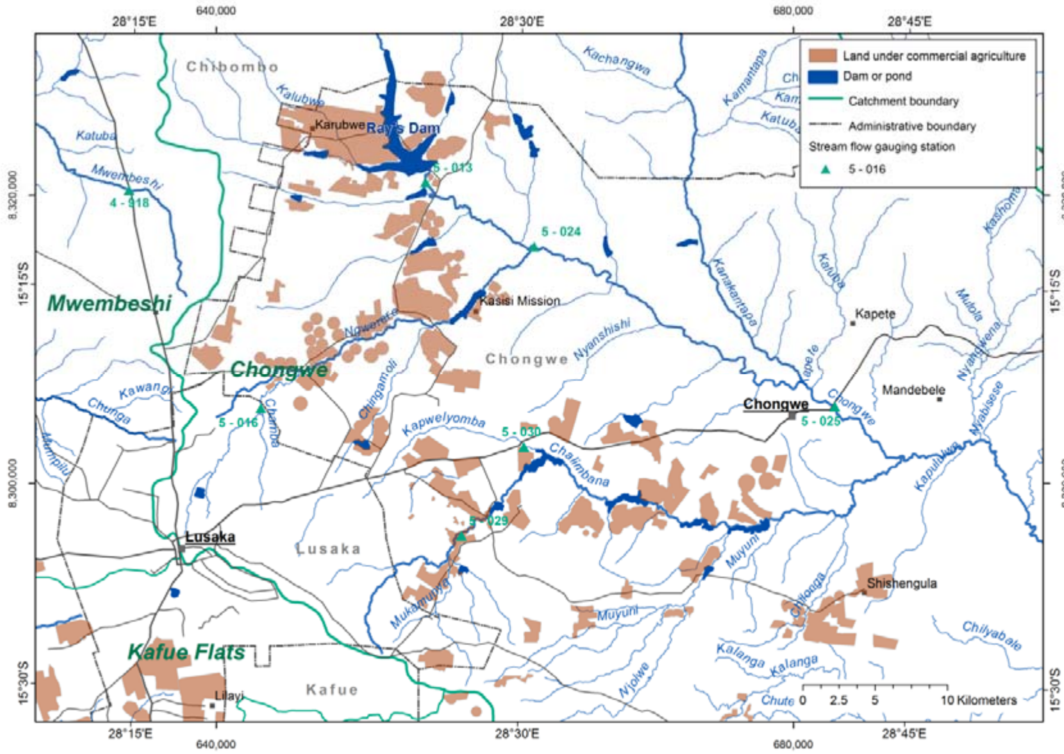

Figure 10 Dams and agricultural areas in the Upper Chongwe Catchment

2.4. SURFACE WATER ABSTRACTIONS

Surface water abstractions in Lusaka and surrounding areas are mainly from two river systems, namely Chongwe with its tributaries Chalimbana and Ngwerere and Mwembeshi with its tributary Chunga. The magnitude of abstractions from these river systems vary depending on the use. The abstractions are mainly for domestic, subsistence and commercial agriculture. The means of abstraction of water (pumping, use of buckets, and impoundments) also correspond to the magnitude of abstraction, flow regime, quality of water as well as the season of the year.

In accordance with CAP 312 of the Laws of Zambia, the use, diversion and impoundment of water must be done as provided for in the Water Act of 1948 (GRZ 1948). The Act recognises three uses of water under the primary, secondary and tertiary categories. For primary use, which is mainly domestic and animal watering, the law clearly states that every person is lawfully entitled to use water for such purposes. In this category, a user can abstract water without a permit or water right. On the contrary, secondary and tertiary users, whose volume abstraction exceeds the primary requirement and is used for commercial purposes, are required by law to obtain a water right to abstract a specified volume of water either by direct pumping or by impoundment. Similar provisions have been incorporated in the new Water Resources Management Act of 2011 under part VII and IX (GRZ 2011). These and related legal requirements on use of surface water are enforced by Water Development Board (WDB), under the Ministry of Mines, Energy and Water Development. The information and data presented in this report is based on the legal provision of the 1948 Water Act.

The quantity of surface water abstracted is thus a sum of primary, secondary and tertiary uses. Since primary water users are not registered and unregulated, the amount of water abstracted by such users is estimated by using approved standards for crop water requirements, per capita consumption and livestock water demand. In the case of the other two categories (secondary and tertiary), the quantity of water that is used is based on granted water rights.

According to the Water Board database, there are 48 registered and valid water users within the project area. These users abstract water using different means which is mainly by direct pumping and impoundment by dam or weirs. According to the WDB database the total volume abstracted is 27,951,600 m^3 per annum. The annual abstraction is equivalent to 10 mm as cumulative water use over a total catchment area of 2,800 km^2. This volume may vary depending on the available runoff and extent of usage in a particular year. In principle, the total abstraction is supposed to be used over a period of 150 days (May to September) according to the water right regulation.

The highest abstraction takes place from Ngwerere and lowest from Chunga River. These results are consistent with the findings by Mayerhofer et al. (2010). The high water demand in Ngwerere is attributed to extensive commercial irrigation. Chalimbana and Chongwe sub-catchments have lower abstraction levels than Ngwerere (Figure 11).

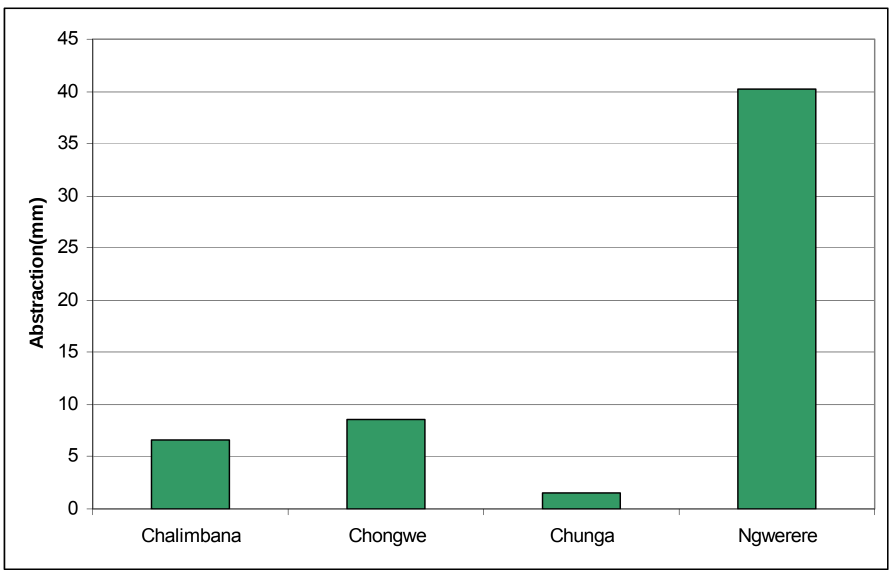

Figure 11 Surface water abstraction by catchment (Source: Water Development Board)

The abstraction levels in Figure 11 represent the entire respective catchment. Overall, the abstractions from the four sub-catchments are small in comparison to the catchment runoff. The runoff figures summarised in Table 8 refer to runoff at existing gauging stations. Figure 12 shows that the stream gauges (basis for runoff analysis) for Ngwerere and Chalimbana rivers are located in the upper parts of the catchment whereas for Upper Chongwe and Chunga sub-catchments, the gauging station is located near the lowest point of the catchment. It should be noted that for Chalimbana and Ngwerere, the majority of the abstractions take place downstream of the gauging station.

Table 10 Surface water abstractions from the project area (Source: Water Board & GReSP Project).

River Catchment	Catchment area [km2]	Total Abstraction(Mm3/a)	Abstraction (mm)
Upper Chongwe 1)	1,230	10.644	8.6
Ngwerere	299	12.040	40.0
Chalimbana	654	4.307	6.6
Chunga	618	0.960	1.6
Total	**2,801**	**27.951**	**10.0**

1) Above gauging station 5-025, excluding Ngwerere sub-catchment

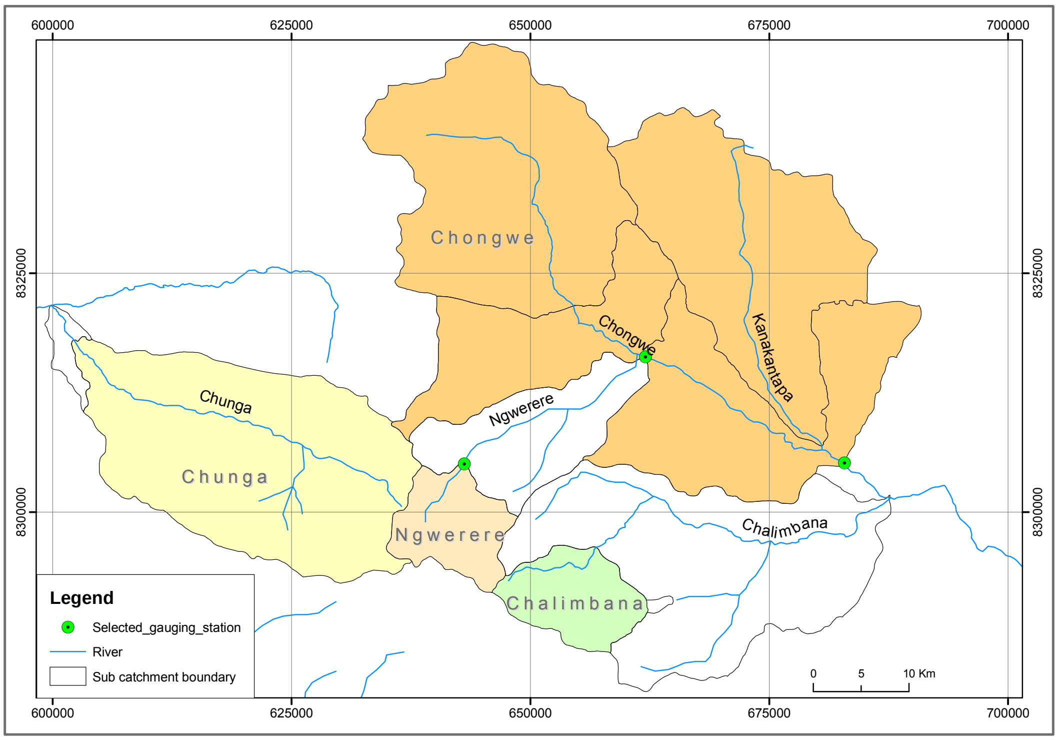

Figure 12 Catchment extents for selected gauging stations

2.5. GROUNDWATER ABSTRACTIONS

The GReSP project in coming up with the water balance for the Lusaka aquifers has collected data on groundwater production/ abstraction for the four main catchments in the project area namely

1. Chalimbana (part of Upper Chongwe)
2. Ngwerere (part of Upper Chongwe)
3. Chilongolo
4. Chunga (part of Mwembeshi) including the sub-catchment of the springs at Laughing Waters;

In terms of domestic water abstraction the main abstractor is the water utility company Lusaka Water and Sewerage Company (LWSC) and hence, data from its production boreholes was collected. The project also obtained consumption data from the water utility company. This data is for two hydrological years (October, 2009 to September, 2010 and October 2010, to September, 2011) which is the project interest period for analysis of the water balance. Historical groundwater production data as well as production data for the water trusts were also collected.

2.5.1. Abstractions for town water supply

LWSC is the water utility company which supplies water to the City of Lusaka. The company previously only provided its services to Lusaka City but has over the years extended its services to the whole of Lusaka Province with Kafue, Luangwa and Chongwe districts now being serviced by the company.

There are two main sources of water which the utility company provides for the City of Lusaka namely;

- Surface water (transmitted from Kafue River at Iolanda Water Works),
- Groundwater production boreholes scattered around the City

According to a previous study under Ministry of Local Government and Housing (MLGH), Lusaka City Council (LCC) and Japan International Cooperation Agency (JICA) on urban development for Lusaka finalised in 2009 (KRI et al. 2009), the average daily water supply of LWSC is estimated to be around 210,000 m^3 per day. Of this, approximately 97,000m^3/day accounting for 46% is drawn from the Kafue River at the Iolanda Water Works by pipeline and 110,000 m^3/day which is 54% from groundwater abstraction

Groundwater production for Lusaka City

During the period of interest, 98 production boreholes were being used by LWSC for its water supply. The boreholes are scattered around Lusaka and fall in the four main catchments of the project area.

The map in Figure 13 shows the spatial distribution of these production boreholes in the four catchments.

In order to get the abstraction per catchment, total groundwater production was calculated and then divided by the total area of the catchment as can be seen in Table 11 for the 2010/2011 hydrological year. Please note that the Chunga catchment was split into its sub-catchments based on the position of the available gauging stations Chunga-Laughing Waters and the rest of the Chunga catchment. In a similar way, the Ngwerere catchment was split into its sub-catchments (Ngwerere at station 5-016 and Ngwerere below station 5-016). The Chalimbana catchment could be subdivided into the sub-catchments above stream gauges Kapiriombwa; station 5-030 and Upper Chalimbana, station 5-029.

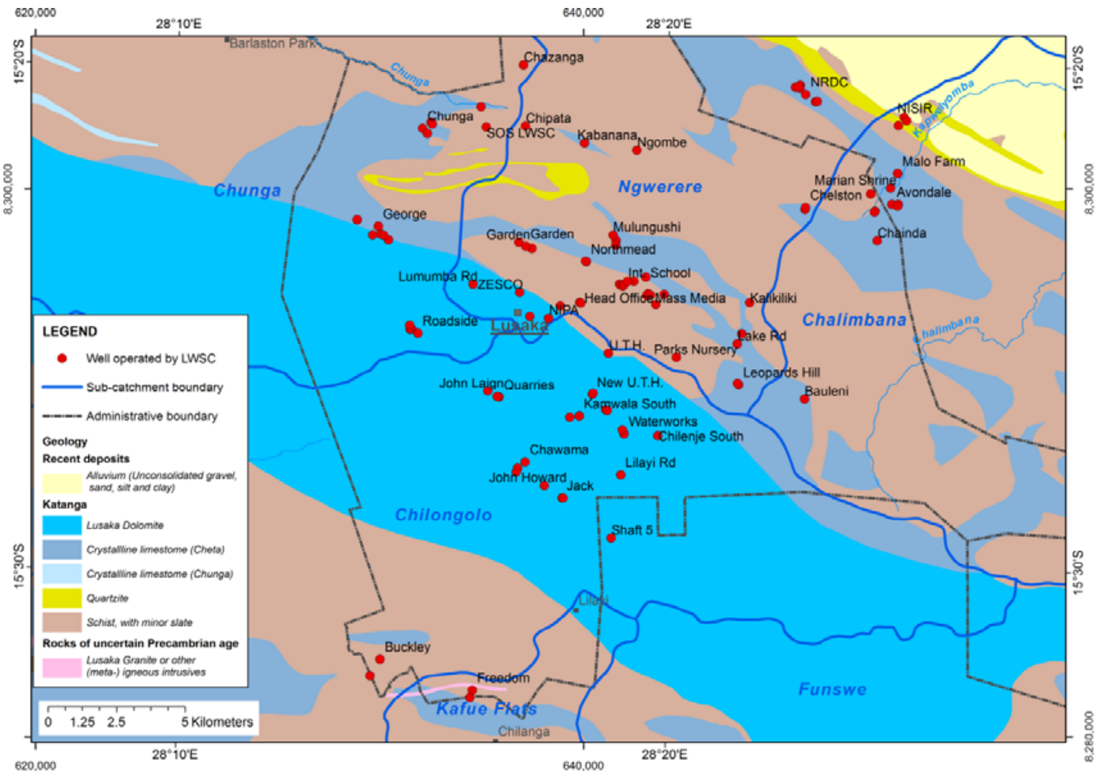

Figure 13 Map showing the distribution of the LWSC boreholes

Table 11 Total abstraction for LWSC boreholes per catchment for 2010/2011 hydrological year

Sub-catchment	Catchment area (km^2)	Abstraction (Mm^3/a)	Abstraction (mm)
Kapiriombwa (Chalimbana)	87	4.402	51
Chalimbana (above station 5-029)	115	0.282	2.5
Chalimbana (below station 5-029)	449	0	0
Ngwerere (above station 5-016)	109	0.988	9.1
Ngwerere (below station 5-016)	190	16.051	84.5
Chilongolo	676	20.052	29.7
Chunga (excluding Laughing Waters)	583	2.809	4.8
Laughing Waters (Chunga)	35	4.975	142.1
Total	**2,247**	**49.559**	**22.1**

There are some gaps in the groundwater production data collected, namely:

- From 02/12/2009 to 31/12/2009 and;
- 14/06/2011 to 15/06/2011.

Total production from these boreholes ranges from as low as 120,000 m^3/day to as high as 145,000 m^3/day. The approximate average daily groundwater abstraction considering the two years under review was 127,800 m^3/day; the total groundwater production for the hydrological year 2010/2011 amounts to 49.6 Mm^3

Of the 98 boreholes owned by LWSC and supplying water to the City, Shaft 5 is by far the largest with its 3 pumps with a total production rate of above 20,000 m^3/day.

In terms of the historical groundwater production, the annual groundwater production for the LWSC boreholes from 2001 up to 2011 was collected in order to ascertain if there was a trend in the groundwater production. Figure 14 shows the graphic representation.

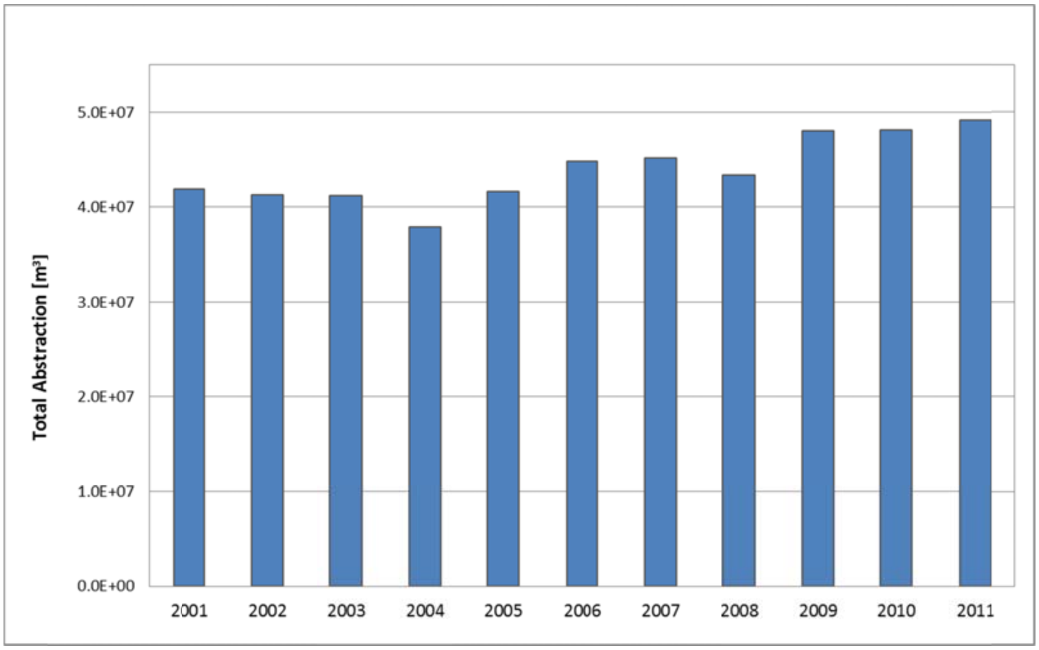

Figure 14 Groundwater abstraction per year from the LWSC boreholes for the last ten years from 2001 to 2011 (Data Source: Lusaka Water and Sewerage Company)

As can be seen from the graph above, there has been an overall increase in the groundwater abstraction by the utility company. This is also supported by the fact that currently, LWSC has augmented its borehole network from the 98 boreholes that were in the network during the study period to over a hundred boreholes.

Groundwater production for the peri-urban areas

The Lusaka Water and Sewerage Company runs a total of nine Water Trusts in the mostly unplanned areas also known as peri-urban areas around Lusaka. These are mostly in the outlying areas of the City and are managed by the Peri-Urban Section of the water utility company. Monthly production figures were collected from these Water Trusts (there were no daily production figures available). They range in cumulative totals of the Water Trusts is from 97,000 m^3/month to 250,000 m^3/month. Total production for the 2009/2010 hydrological year was approximately 2.09 Mm^3 with an average monthly production of 173,830 m^3. This is about 4% of the total production from the LWSC boreholes. It must be stated that there are some months where there are gaps namely for Freedom and Kalikiliki Water Trusts for between October and December 2009.

Total production for 2010/2011 hydrological year was 1.82 Mm^3 with an average monthly production of 151,330 m^3/month. This figure is lower than for the previous season because there are more data gaps during this season (Chaisa, Chazanga, Chipata and Garden Water Trusts have missing data for between July and September 2011 and Kanyama for between April and June 2011).

Figure 15 shows a graphic representation of the total monthly production trend for the year 2010. This was the only period that had no data gaps and hence was the most ideal to illustrate variations in the production.

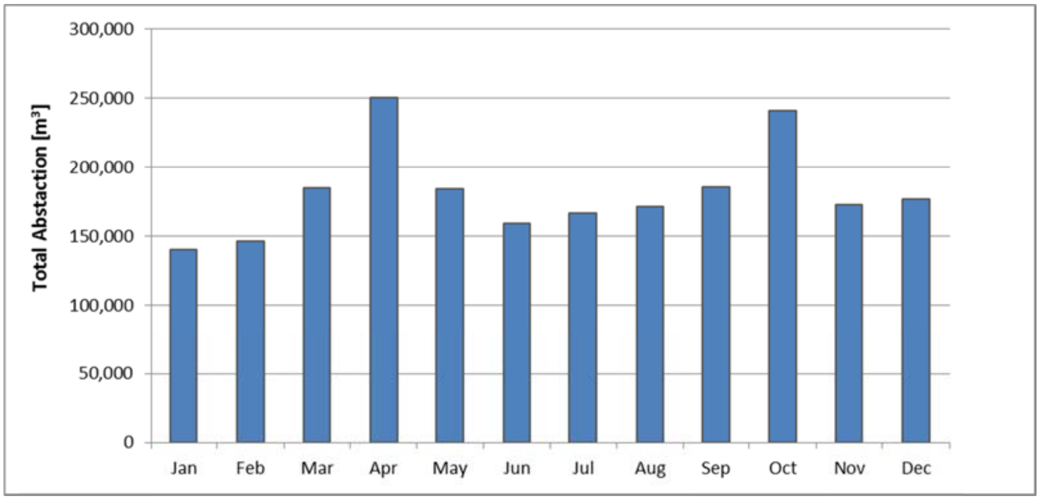

Figure 15 Total monthly production of the 9 Water Trusts for the year 2010 (Data Source: Lusaka Water and Sewerage Company)

Table 12 shows the abstraction per catchment of the Water Trust boreholes for the year 2010. A point to note is that there is no water trust borehole located in the Chalimbana Catchment.

Table 12 Abstraction per catchment of the Peri-Urban (Water Trust) boreholes for the 2010/2011 hydrological year

Sub-catchment	Catchment area (km^2)	Production (Mm^3/a)	Abstraction (mm)
Kapiriombwa (Chalimbana)	87	0	-
Chalimbana (above station 5-029)	115	0	-
Chalimbana (below station 5-029)	449	0	-
Ngwerere (above station 5-016)	109	1.057	9.7
Ngwerere (below station 5-016)	190	0	-
Chilongolo	676	0.096	0.1
Chunga (excluding Laughing Waters)	583	0.124	0.2
Laughing Waters (Chunga)	35	0.539	15.5
Total	**2,247**	**1.816**	**0.81**

2.5.2. Consumption

The estimated current demand for water resources for the Lusaka City is 350,000 m^3/day (KRI et al, 2009). According to the National Water and Sanitation Council (NWASCO, 2011), the water supply coverage by LWSC is 93% with the rest being covered through private boreholes as well as shallow wells to some smaller extent.

The utility company has nine water supply branches namely, Chelston, Central, Kabulonga, Kabwata, Lumumba, Matero, and Peri-urban South, East and West. Each of these branches is headed by a manager. These branches are mainly in charge of the billing of water from the different areas and are made up of a number of metering districts. There are a total of 72 metering districts around Lusaka. A metering district is one that has between 200 and 2,000 connections.

Consumption is categorized into two groups namely;

- Metered consumption – this is from a property that has a meter
- Unmetered consumption - Unmetered consumptions is the water that is billed on accounts/houses that are not metered. This is done by way of water consumption standards as stipulated by Zambia Bureau of Standards according to areas where people live and the estimated number of people per household. In short, consumption for these connections is based on estimations.

It must be highlighted that this consumption data does not include information on consumption for the Water Trusts as these mostly do not have records for consumption. There is data missing for the months of February 2010 and May 2010 for both metered and unmetered consumption. Missing values were arrived at by averaging the values of the preceding and succeeding month.

Annual consumption for 2009/2010 season was 43.9 Mm^3 and 46.7 Mm^3 for the 2010/2011 hydrological year.

The consumption for LWSC was also categorized depending on the catchment the particular metering district was located. This can be seen in Table 13.

Table 13 Annual Consumption for LWSC metering districts per catchment area for the 2010/2011 hydrological year.

Sub-catchment	Catchment area (m^2)	Consumption (Mm^3/a)	Consumption (mm)
Chalimbana	654	5.314	8.1
Ngwerere	299	22.116	74.0
Chilongolo	676	14.400	21.3
Chunga	618	4.903	7.9
Total	**2,247**	**46.733**	**20.8**

Areas for these 72 metering districts displayed in Figure 16 were acquired from the LWSC geographic information system (GIS). Some polygons were modified in order to co-relate with the consumption data i.e.

- Rhodes park East and Rhodes park West were merged and re-named ‘Rhodes park’
- Consumption for SOS was merged with Chipata Township

Using the consumption figures of the 72 metering districts availed by LWSC for the period of interest, as well as the map of these metering districts, the average monthly consumption per area was calculated. The average monthly consumption per area (m^3/month/ha) for the hydrological year 2010/2011 is depicted in Figure 16. In order to put this average consumption into perspective, the result was further analysed on the basis of the distribution of different categories of residential areas namely High density, Medium density and Low density areas.

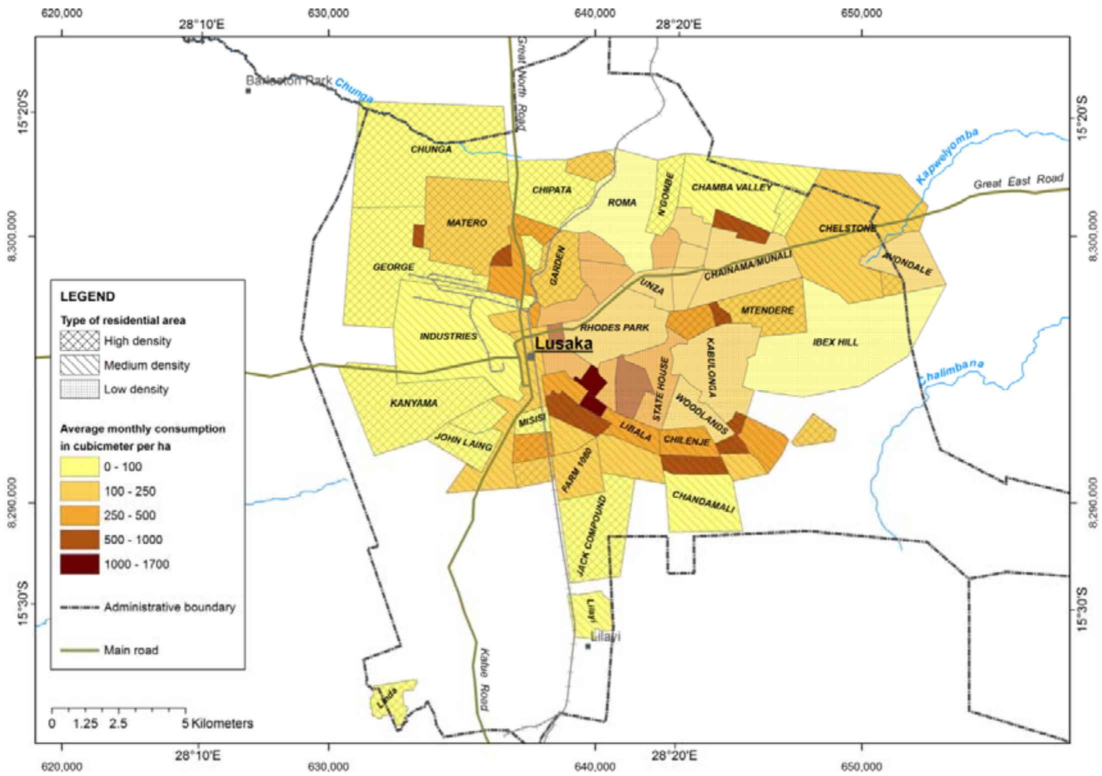

Figure 16 Average monthly consumption for LWSC per area (m^3 per month per ha) for 2010/2011 in comparison to residential type.

From Figure 16, one notices that the high density areas mostly fall in the category with the lowest average monthly consumption of between 0-100 m^3/ha per month. This is accurate as water supply in these areas is through kiosks which open only for a few hours of the day. However, it is difficult to establish a trend for the medium and low density settlements. This needed further information on the number of connections per residential area, which was not done for this study due to the unavailability of this data.

2.5.3. Unaccounted for water (Ufw)

The total water produced by LWSC for the 2010/2011 hydrological year was 84.6 Mm^3 both from groundwater (49.6Mm^3) and surface water from Kafue River (35.0 Mm^3). The total consumption for that hydrological year was about 46.7 Mm^3. Therefore by simple calculation the unaccounted-for water (Ufw) for this hydrological year was 37.8 Mm^3 accounting for about 45% of the total water produced by the utility company. This is even higher than the amount of water piped from the Iolanda station in Kafue which constitutes only 41% of total water produced by LWSC.

The regulator for the water utility companies NWASCO rates the performance with regard to Ufw as 'good' if below 20%; acceptable if between 20-25% and unacceptable if above 25% (NWASCO, 2011).

Causes for the high rate of Ufw include (KRI et al., 2009);

a) Physical leakage from old pipes especially those made of asbestos, steel and galvanized iron and connections in the distribution lines

b) Low number of customer meters installed, human errors and billing system and'

c) Illegal connections / water theft

According to the NWASCO annual report of 2011, there is a high probability that the Ufw will decrease if the metering ratio is increased. The metering ratio of LWSC is currently 67% with a number of 78,394 connections, i.e. one third of total consumption figures is based on estimates.

2.5.4. Abstraction for agricultural purposes

A survey on commercial farmers and major industries was also done by the project to assess land use, groundwater abstraction and pollution sources which covered a total of 43 commercial farmers which are displayed in Figure 17 (Mayerhofer et al., 2010). The survey revealed that these 43 commercial farms cover a total area of approximately 12,830 ha. Of this, 6,150 ha is the total irrigated area, meaning that almost half of the area for commercial farms available for cultivation is under irrigation. Of 6,150ha under irrigation, 3,777 ha solely used groundwater.

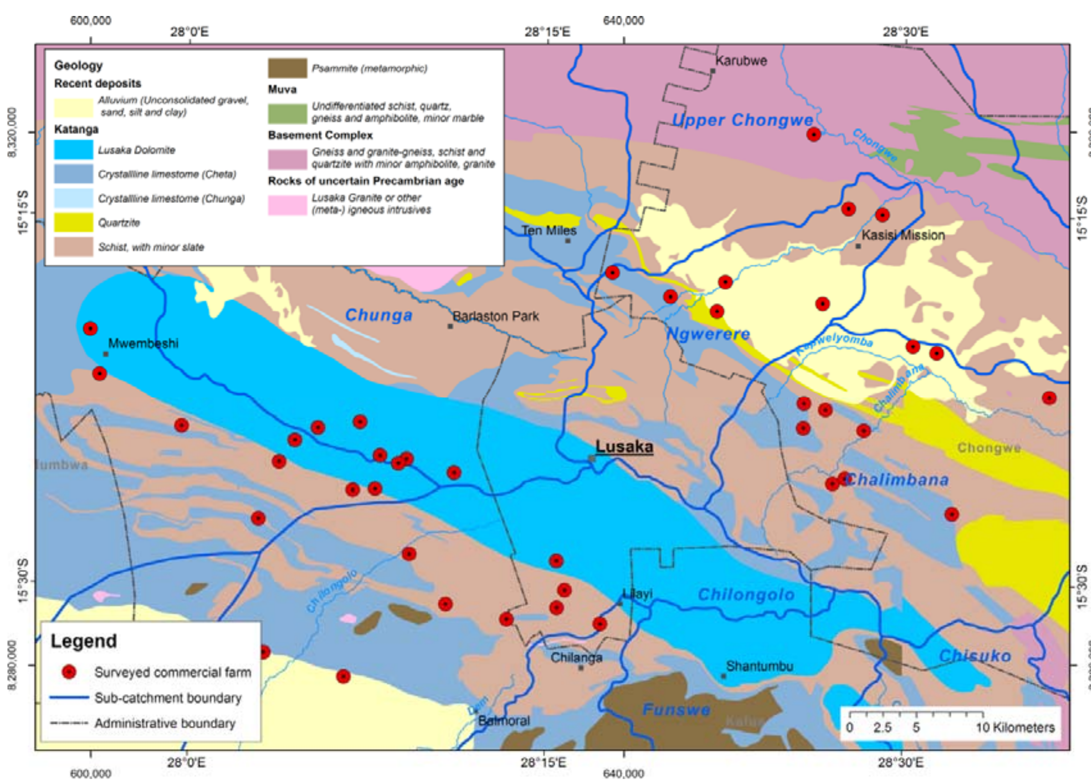

Figure 17 Distribution of the commercial farms visited during the survey (for description of geology see Figure 24)

The amount of water abstracted from the groundwater aquifers for irrigation for all the farms captured during the survey was 24.87 Mm^3/year. This means that an average of 6,585 m^3/ha/year is used for irrigation on a yearly basis with daily amounts ranging between 82,900 m^3/day and 103,600 m^3/day, during the dry months of the year from March to November (Mayerhofer et al, 2011).

Values of total groundwater abstraction for irrigation purposes per catchment are given in Table 14. Please note that some of the farms surveyed by Mayerhofer et al. are located outside the area covered by the selected catchments. The area under irrigation from groundwater in the catchments of interest is 2,451 ha with a corresponding groundwater abstraction of 16.8 Mm^3/year.

Table 14 Annual groundwater abstraction for irrigation by catchment

Sub-Catchment	**Catchment area (km^2)**	**Irrigated land [ha]**[1)]	**Abstraction (Mm^3/a)**	**Abstraction (mm)**
Kapiriombwa (Chalimbana)	87	103	1.23	14.1
Chalimbana (above station 5-029)	115	0	0	0
Chalimbana (below station 5-029)	449	71	0.296	0.66
Ngwerere (above station 5-016)	109	0	0	0
Ngwerere (below station 5-016)	190	265	1.93	10.2
Chilongolo	676	1298	9.35	13.8
Chunga (excluding Laughing Waters)	583	714	3.99	6.8
Laughing Waters (Chunga)	35	0	0	0
Total	**2,247**	**2,451**	**16.80**	**7.5**

1) Under groundwater irrigation

2.5.5. Abstractions from industries

The survey also covered 53 industries of which 70% are located in the Chunga catchment, 17% in Ngwerere catchment and 8% in Chilongolo catchment. Concerning the type of water source, 32% of all industries are connected to the LWSC network and 68% use groundwater from private boreholes. However, industries using LWSC water use only 5% (220,000 m^3/year) of the total water demand of all industries included in this study.

Table 15 shows the main industrial water users, representing 23% of all interviewed enterprises. The survey has shown that these 23% extract 98% (4.42 Mm^3/year) of the total amount of water used by all industries, this being 4,525,000 m^3/year. A minor amount of 106,000 m^3/year (2% of the total demand) is used by the remaining 77% of industries. The cement producer Lafarge, located on Kafue Road 11 km south of the city centre, alone uses 64% of the total water consumption by industries investigated during this survey. The second highest water user with 16 % of the total amount is Zambian Breweries and 5% is abstracted by the third biggest consumer, Zamanita Limited. These “top 3” water users abstract 85% of the total water volume used by industries and utilize groundwater exclusively.

Unlike farms, no seasonal variation in the abstraction of groundwater by industries was identified.

Table 15 Table showing the companies which are major water users and type of industries (after Mayerhofer et al. 2010)

Major Water User	Type of industry	Water consumed m^3/a
Lafarge	Cement producer	2,912,700
Zambian Breweries	Brewery	720,000
Zamanita Limited	Oil Manufacture	240,000
Tombwe processing	Tobacco	165,360
National Breweries	Brewery	116,400
California Breweries	Brewery	62,400
Kembe Meat product	Abattoir	51,782
Midlands Breweries	Brewery	46,800
Manzi Valley	Mineral Water	33,000
Zamleather	Tannery& leather Manufacture	24,960
Verino Poultry	Abattoir	23,360
King Quality meat Producers	Abattoir	21,840

In order to establish the abstraction per catchment in mm, the water use for the industries which are major water users were grouped according to catchments and abstraction per catchment was calculated as shown in Table 16.

Table 16 Table showing the abstraction per catchment of the industries which are major water users (after Mayerhofer et al. 2010)

Sub-catchment	Catchment area (km^2)	Production (Mm^3/a)	Abstraction (mm)
Kapiriombwa (Chalimbana)	87	0.03	0.3
Chalimbana (above station 5-029)	115	0	0
Chalimbana (below station 5-029)	449	0	0
Ngwerere (below station 5-016)	190	0	0
Ngwerere (above station 5-016)	109	0.25	2.3
Chilongolo	676	0	0
Chunga (excluding Laughing Waters)	583	0.91	1.6
Laughing Waters (Chunga)	35	0.29	8.3
Total	**2,247**	**1.48**	**0.7**
Upper Chongwe (at station 5-025)	376	0.02	
Kafue Flats	11,707	2.91	
	Total production	**4.41**	

2.5.6. Private abstractions

Lusaka City includes about 8,900 hectares of low density residential areas (Mayerhofer et al. 2010). These private households commonly use council water and/or groundwater abstracted from private wells for domestic use and to irrigate their lawns and gardens. The number of private boreholes and exact amount of water pumped from the ground has not been assessed to date and hence, can only be estimated. Based on consumption data for low-density residential areas it can be assumed that the water requirements for this land use type is in the order of 3,850 m^3/a/ha or 385 mm/a. As LWSC provides only about 14.5 Mm^3/annum to water districts associated with low density areas, it can be assumed that the remainder of 19.8 Mm^3/a represents private groundwater usage. This corresponds to an abstraction rate of 2,220 m^3/a/ha or 222 mm/a.

Applying this rate, the groundwater abstraction from private boreholes in low density areas can be calculated for individual sub-catchments as presented in Table 17. The Upper Ngwerere Catchments has a relatively high percentage (38%) of low-density areas which includes the city parts Kalundu, Roma, Rhodes Park, Fairview, Longacres, Kabulonga and Twin Palms. Kapiriombwa which forms a part of the Chalimbana Catchment has the second highest percentage of about 12% (mainly composed by Leopards Hill area). Consequently, groundwater abstractions for private use are presumably most substantial in these two sub-catchments.

Table 17 Estimated annual groundwater abstraction from private boreholes in low density areas of Lusaka

Sub-catchment	Catchment area (km^2)	Low density residential area (ha)[1)]	Abstraction (Mm^3/a)	Abstraction (mm)
Kapiriombwa (Chalimbana)	87	1,031 (11.9%)	2.289	26.3
Chalimbana (above station 5-029)	115	163 (1.4%)	0.362	3.1
Chalimbana (below station 5-029)	452	3 (0.0%)	0.007	0.0
Ngwerere (above station 5-016)	190	582 (3.1%)	1.292	6.8
Ngwerere (below station 5-016)	109	4,177 (38.3%)	9.273	85.1
Chilongolo	676	2,613 (3.9%)	5.801	8.6
Chunga	618	304 (0.5%)	0.675	1.1
Total	**2,247**	**8,873 (3.9%)**	**19.699**	**8.8**

1) Number in brackets corresponds to percentage of total catchment area

2.5.7. Total groundwater abstraction

It is clear that among the four main types of usage of groundwater, namely town water supply, private water usage, agriculture and industries, the largest water user is town water supply with over 51.4 Mm^3 per annum (49.6 Mm^3 from the LWSC boreholes and 1.8 Mm^3 from the Water Trusts). This is followed by private abstractions with about 19.7 Mm^3 per annum, agriculture with 16.8 Mm^3 per annum and lastly by industries with only 4.4 Mm^3 per annum.

The average total groundwater abstraction for the whole area amounts to 40 mm/a (Table 18). 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 abstraction is also observed in the small sub-catchments of the Kapiriombwa stream and Laughing Waters spring as well as in the upper parts of Chilongolo River.

Table 18 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**

3. GROUNDWATER RECHARGE

Various estimates of direct recharge, yet with widely varying results are available for the Lusaka area (see references given in Bäumle & Kang'omba 2009). The available estimates suggest that average recharge rates may be in the order of 20% to 25% of annual rainfall, i.e. between 160 and 200 mm. In years with particularly low rainfall, however, groundwater recharge may be considerably lower (von Hoyer et al. 1978).

The following methods were applied under the GReSP project to estimate groundwater recharge in the investigation area:

- Base flow method
- Water table fluctuation method (WTF)
- Soil water balance approach (WEAP-MABIA-Method)
- Groundwater modelling
- Water budget method (see Chapter 4)

3.1. GROUNDWATER LEVEL HISTORY

There has been some concern that groundwater levels in the Lusaka areas have considerably dropped over the last decades due to the significant increase in groundwater production for domestic and public water supply as well as for industrial and agricultural purposes. It is generally known that parts of the built-up areas in Lusaka were originally waterlogged (some still are seasonally). Mapping of the groundwater surface suggests that groundwater levels in the industrial area to the west of the city centre have indeed been drawn down by a few meters due to withdrawals (Figure 18). Some parts such as the university campus and residential areas in the south of the City are known to have been waterlogged in the past.

Unfortunately, no continuous long-term groundwater level records are available that could indisputably verify such a downward trend over the last decades. Continuous recording of groundwater levels started in 2004 at DWA offices at Sheki-Sheki-Street. An extensive groundwater monitoring network was only run from 2009 onwards.

Historical discontinuous data is available from studies carried out during the late 1970s by von Hoyer et al. (1978) and during the late 1990s by Gibb Ltd. (1999). The study by von Hoyer additionally includes a few historic records dating back to the 1950s. Using this data it was possible to compare water levels from before 1980 to levels during the 1990s and recent water levels in about a dozen distinct areas of the Lusaka plateau. Time series showing these water levels are included in Annex 1.

Quite a number of the existing records consist of less than a few measurements over two or three consecutive seasons. Furthermore, a considerable number of values represent drawn water levels with varying and generally uncertain abstraction rates. Unfortunately the precise position of old wells with water level data could not always be re-established. There is also uncertainty whether documented water level measurements were taken from the ground surface or for example, from the well head. Although the topography is generally smooth, no attempt was therefore made to express the historical water level measurements as piezometric levels in meters above mean sea level.

For reasons given above the observed water level trends are not conclusive; yet as a general impression it can be stated that no general or drastic drop of the water table can be detected over the last 30 to 40 years in these areas despite increased abstraction.

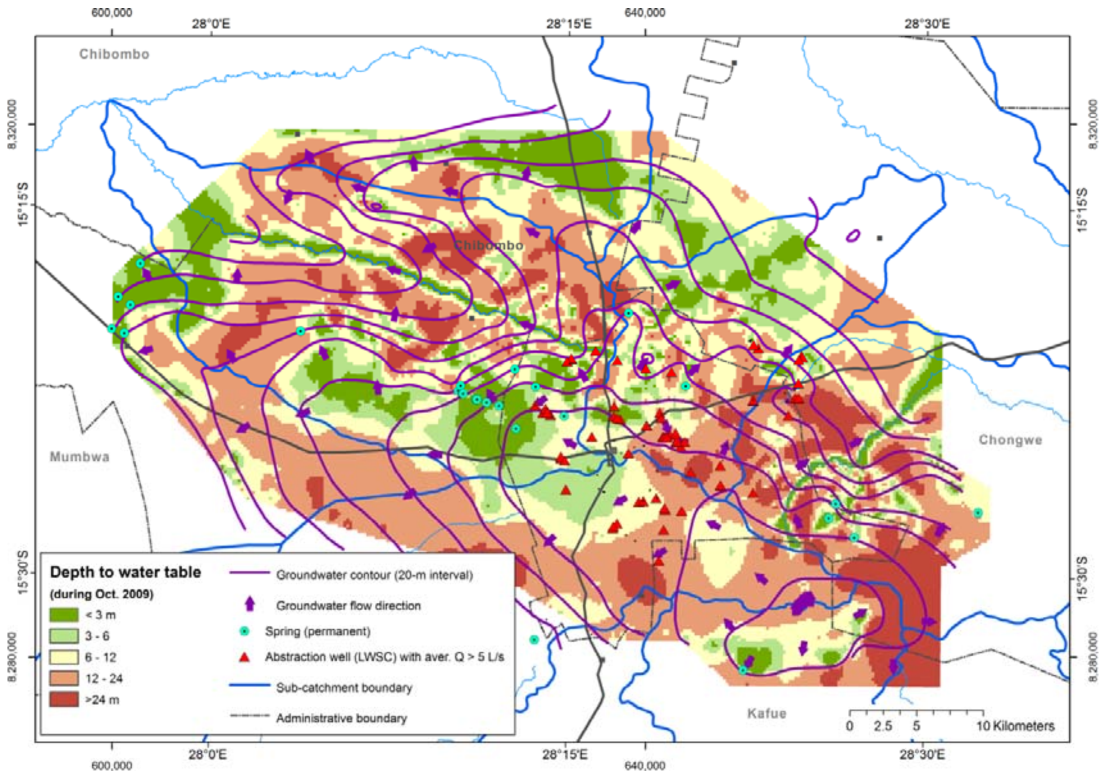

Figure 18 Depth to water table and groundwater flow in the Lusaka Plateau area during October 2009

3.2. BASE FLOW CONSIDERATIONS

River base flow determination is a reliable and commonly-applied method for recharge assessment in humid zones. The base flow method integrates all outflows upstream of the gauging station and therefore provides an integral regional value. The method is based on the assumption that recharge should equal outflow through base flow, i.e. water in a stream that comes from effluent groundwater. It requires that groundwater abstractions are small or otherwise corrected for, and that changes in storage (e.g. by a significant rise or drop in the water table) are minimal over the period of time observed (usually chosen as one hydrological year). It is furthermore assumed that the flow regime of a stream is not disturbed by the presence of surface dams, surface water is not infiltrating into the ground along the stream course ("loosing stream"-conditions) at any time and that recharge is completely drained towards the gauging station, i.e. no bypasses exist laterally or via deeper aquifers. The method is generally not applicable in rivers or streams with seasonal or ephemeral flow where low flow reaches zero.

Base flow is commonly determined by stream hydrograph analysis. The base flow component is separated from total stream discharge using diverse techniques. The recession limbs observed in stream flow records are commonly described as a classical exponential decay function corresponding to the discharge from a linear reservoir:

Equation [3] $Q(t) = Q_0 \, e^{-t/k}$

where Q is the stream flow at time t, Q_0 is the initial stream flow at the start of the recession segment and k is the residence time (or turnover time) of the groundwater system being depleted.

The recession index K is defined as the time required for base flow to recede by one log cycle, i.e. from Qi to 0.1 Qi.

Equation [4] $K = 2.3026\, k$

K is usually expressed in days per log-cycle.

Base flow at stations around Lusaka was independently determined using the USGS software programs PART and RORA (Rutledge 1998). Historical runoff records as described in section 2.3.1 were used as input data. PART provides an algorithm for a base flow separation technique (Rutledge 2007-a). An example of base flow separation with PART is given in Figure 19. RORA applies the recession-curve-displacement method based on works by Rorabaugh (1964) which is quite different from classical base flow separation techniques. The method assumes that the stream flow recession curve is displaced upwards during periods of groundwater recharge (Rutledge 2000, Rutledge 2007-b). In addition, Meyboom's seasonal recession method (Meyboom 1961, in Fetter 2011: pp. 51-52) was applied (Wang 2011). Following this approach, the amount of groundwater recharge that takes place from the end of the seasonal base flow recession in one year to the start of the base flow recession of the subsequent year is determined. An example of the analysis according to Meyboom's method is given in Figure 20.

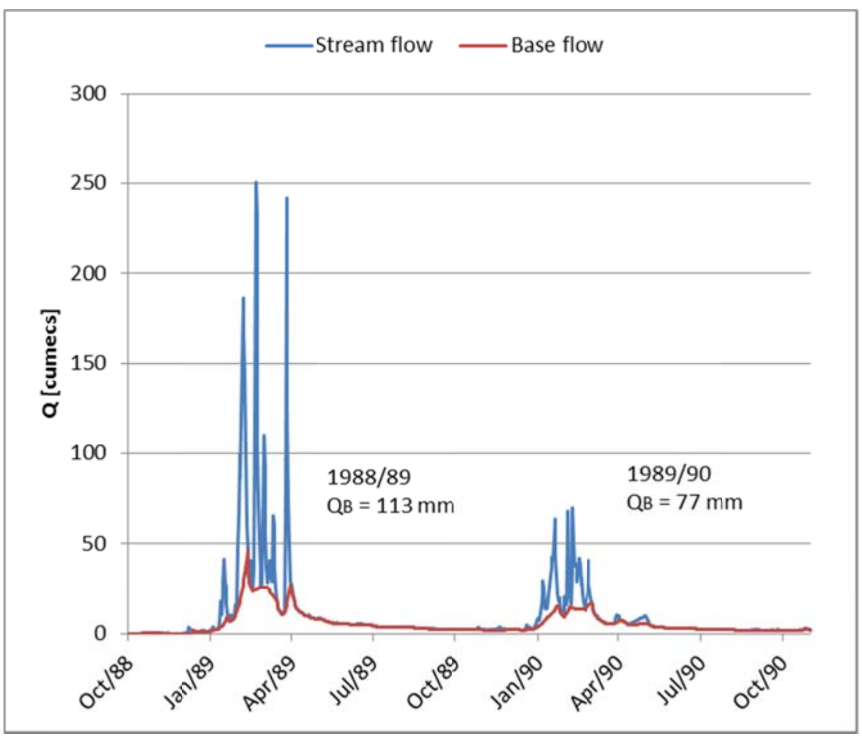

Figure 19 Example of base flow separation with PART (station 5025-Chongwe for hydrological years 1988/89 and 1989/90)

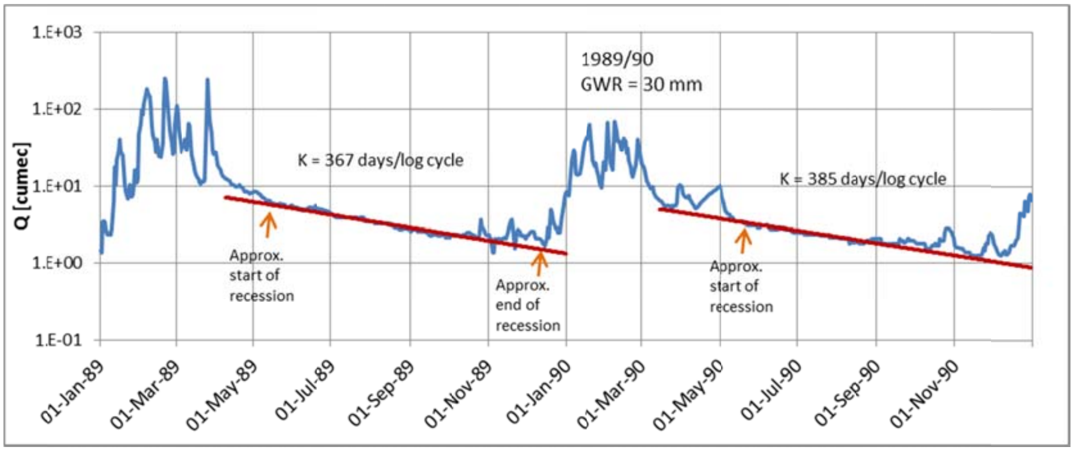

Figure 20 Example of determination of recharge at station 5-025 Chongwe using Meyboom's method

The analysis was applied to stream flow data from stations 5-012, 5-024, 5-025, 5-029 and 5-030 in the Chongwe Catchment and 4-918 and 4-940 in the Mwembeshi Catchment using stage records dating back to the 1960s and 1970s (Chapter 2.3.1). The station at Ngwerere stream was considered not suitable for base flow analysis due to significant amounts of sewage discharge.

The results obtained from the analysis with RORA and PART corresponded overall very well with differences of usually well below 10%. Generally, recession limbs as described by equation Equation [3] could be identified with ease during periods after individual storm events as well as over the dry season from May to October. Determined residence time *k* and recession index *K*, however, varied quite considerably between individual recession segments. It is believed that values of *K* between 65 and 100 days corresponding to a residence time *k* between 29 and 43 days indicate fairly fast base flow ("short-term base flow") such as from shallow groundwater developed within the weathered zone of hard rock (saprolith), epikarst or shallow alluvial sediments. Long-term recession sections that occurred during the dry season were graphically analysed as part of the Meyboom's analysis. Values of *K* determined for these seasonal recession sections often exceeded 300 days and indicate a considerably slower discharge from a (second) less permeable groundwater reservoir ("long-term base flow").

The main outcome of the analysis was that recharge rates determined by base flow methods appeared comparatively small. For station 5-025 at Chongwe River Bridge, for instance, the PART and RORA analysis yielded base flow (i.e. recharge) between 15 mm and 190 mm with an average of 63 mm. Averages of other stations within the Chongwe Catchment ranged from 35 to 85 mm. Annual recharge determined was reasonably well correlated with annual rainfall. Using Meyboom's method annual recharge ranged from below 10 mm to 60 mm only. For station 4-940 at Mwembeshi the various methods yielded even smaller values of recharge.

The small recharge rates determined from the base flow method are a direct consequence of the overall small total runoff from streams and rivers in the area. Total annual runoff at Chongwe River Bridge averages 95 mm according to the statistics presented in Table 8. Average discharge from the Mwembeshi River is assumed to be below 20 mm.

In critically reviewing the overall low base flow of sub-catchments in the Upper Chongwe and Mwembeshi catchments it is likely that base flow is not a suitable approximation of recharge as various assumptions underlying the approach may not be sufficiently fulfilled. The following potential error sources can be mentioned:

- The USGS base flow determination methods applied were developed for conditions prevailing in North America, i.e. a temperate humid climate. The applicability in subtropical conditions with pronounced wet and dry seasons needs to be validated. Furthermore, the authors of the USGS software recommend that the catchment area should not exceed about 1,300 square kilometres. This criterion is not fulfilled for the two lower stations at the Mwembeshi (4-940) and the Chongwe station no. 5-025. Results from these larger catchment areas must therefore be used with caution.
- Inaccurate stream gauging data (poor quality of water level readings and lack of sufficient stream flow calibration measurements) may have negatively affected the accuracy of results.
- Errors may be caused by gains and losses of groundwater through leakage and evaporation (upward rise from the groundwater surface through the capillary fringe), geological heterogeneities, losing stream conditions, storage by dams, spillages from dams or sewage ponds, or high groundwater abstractions.
- If groundwater flow is not perpendicular to the stream, the groundwater discharge bypasses the gauging stations. In this case groundwater recharge as obtained from base flow determination would underestimate actual recharge.

In the investigation area dams and huge abstraction from both surface water and groundwater are well known and form together with the complex geological setup likely error sources. The Mwembeshi River and his tributaries have been described to be seasonally reduced to a series of disconnected pools or stretches of surface water with impersistent flow. Loosing-stream conditions and high evaporative losses are likely to exist which explains its low overall runoff in particular during dry season. In the lower sections of the river, towards the Kafue Plains, the terrain becomes increasingly more flat, and groundwater flow may not be perpendicular to the Mwembeshi river channel.

3.3. WATER TABLE FLUCTUATION METHOD

3.3.1. Estimate of recharge based on regionally drained pore space

In accordance to the seasonal climatic conditions groundwater commonly reaches highest levels towards the end of the rainy season during March – April and drop to lowest levels towards October/November. The monitoring borehole located at City Airport shows such characteristic seasonal behaviour (Figure 21).

Groundwater levels were collected during April 2009 and subsequently during October 2009 in order to determine the groundwater flow pattern over the Lusaka Plateau and surrounding areas during wet and dry conditions (Figure 18). From a total of over 300 visited sites measurements for both April and October are available at about 175 boreholes and shallow wells. With this data it was possible to estimate the total drop in groundwater levels during the 2009 dry-season in the investigation area. If the low groundwater levels are recovered during the subsequent rainy season – which is a reasonable assumption considering groundwater levels observed at monitoring boreholes - it could be argued that groundwater recharge during the rainy season could be approximated by the volume of pore space drained and subsequently refilled over this period. Hence groundwater recharge *GWR* could be expressed as:

Equation [5] $GWR = S_y \overline{\Delta h}$

Where S_y is specific yield and $\overline{\Delta h}$ is the average drop of groundwater levels during the dry season.

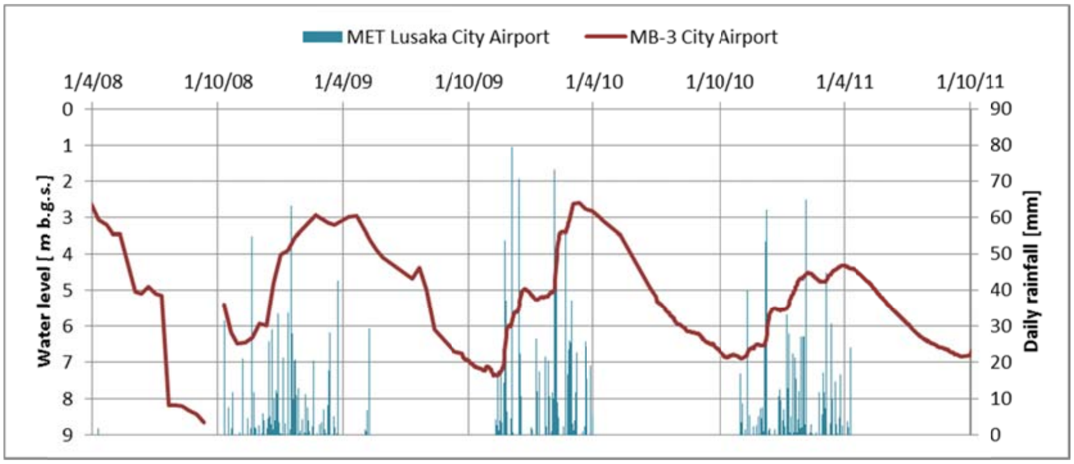

Figure 21 Groundwater level fluctuation at monitoring station MB-3 and daily rainfall during the three rainy seasons from 2008/09 to 2010/11 at location "Lusaka City Airport" (Data Sources: DWA, ZMD).

It must be said, however, that this approach can only provide a crude estimate as it neglects the complex groundwater flow dynamics including recharge and outflow during storm events and groundwater abstractions. Furthermore, regional values of specific yield are difficult to determine for fractured rocks and karst. In addition, the distribution of available water level data as shown in Figure 22 is fairly clustered. Consequently, there are larger areas within the study area with little or missing information on water level changes.

The Lusaka Dolomite Plateau is considered a comparatively suitable area for this analysis as a water table (unconfined) aquifer is developed that - due to its topographic position - is drained laterally and receives no inflows from outside. Furthermore, groundwater abstractions, though considerable in the City areas, are fairly constant over time and commercial agriculture and large-scale irrigation on the Plateau itself are negligible. The regional drop of water level was determined using the Thiessen-polygon and Kriging interpolation methods. Both methods yielded almost identical results for average (regional) drop in water levels over selected areas.

The average water level drop $\overline{\Delta h}$ determined over the 2009 dry season on the Lusaka Plateau was 3.35 meters with an observed range from zero (near springs) to about nine meters (near the highest elevated points) (Figure 22).

Reliable values for storativity in the area are available from test pumping analysis and groundwater model calibrations. The number of reliable test pumping results, however, is still sparse. Von Hoyer & Schmidt (1980) developed a groundwater model for the Lusaka Plateau and applied S_y-values ranging from 0.01 and 0.07 for limestone and dolomite. The authors also referred to results of pumping tests carried out on wells near Lusaka that gave S_y-values of around 0.02. In the recently developed groundwater model for the Lusaka aquifers best calibration results were obtained by choosing a S_y of 0.07 for the top 50 m of the Lusaka Dolomite, 0.05 to 0.07 for Cheta Limestone and 0.05 for other rock types (Maßmann 2012). The analysis of test pumping carried out under the GReSP project at three individual sites in the Lusaka area suggest that storativity of well fractured crystalline limestone is in the order of 0.02 to 0.03 (Bäumle et al. 2012). Previous test results from e.g. the Mass Media and NRDC areas yielded higher values between 0.05 and 0.16. The analysis results of the previous tests were, however, partially questionable due to poor quality of data or interferences from adjacent wells (Bäumle 2011).

Groundwater recharge determined using Equation [5] was calculated as a function of realistic values of specific yield S_y. The results are shown in Figure 23. Assuming a specific yield of $S_y = 0.05$, the groundwater recharge of the Lusaka Dolomite Plateau amounts to about 165 mm/a. For smaller or larger values of S_y groundwater recharge varies proportionally.

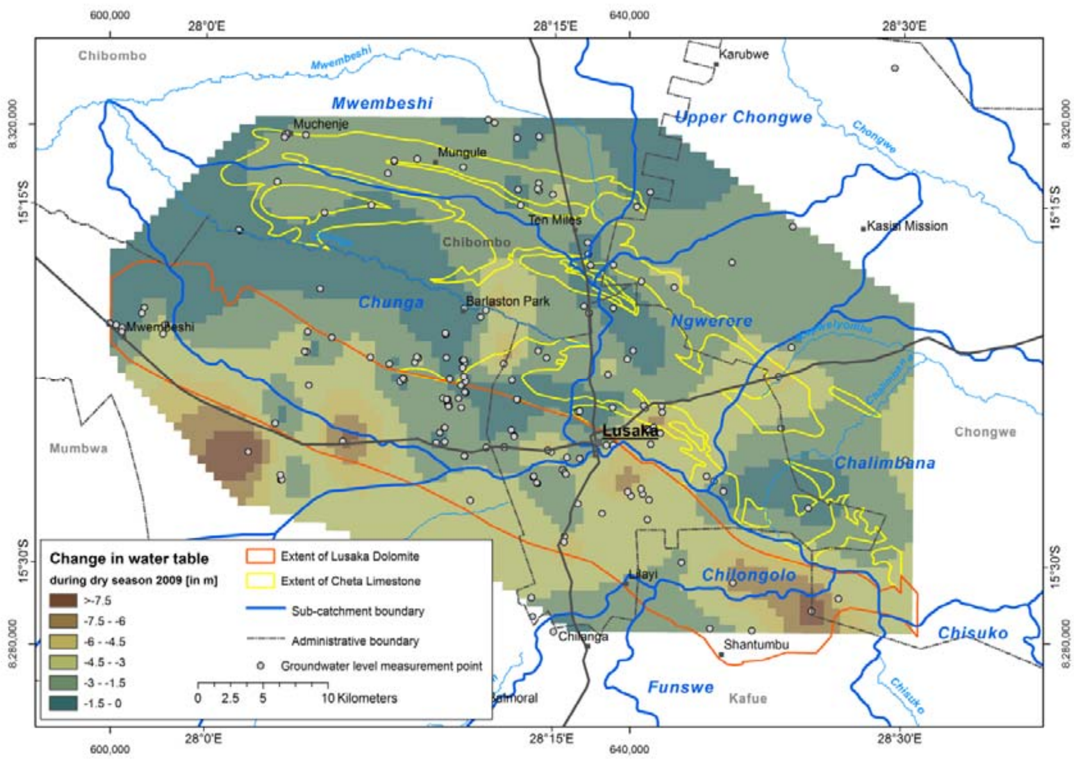

Figure 22 Drop in groundwater tables between April 2009 and October 2009 (based on Kriging interpolation method of point observations)

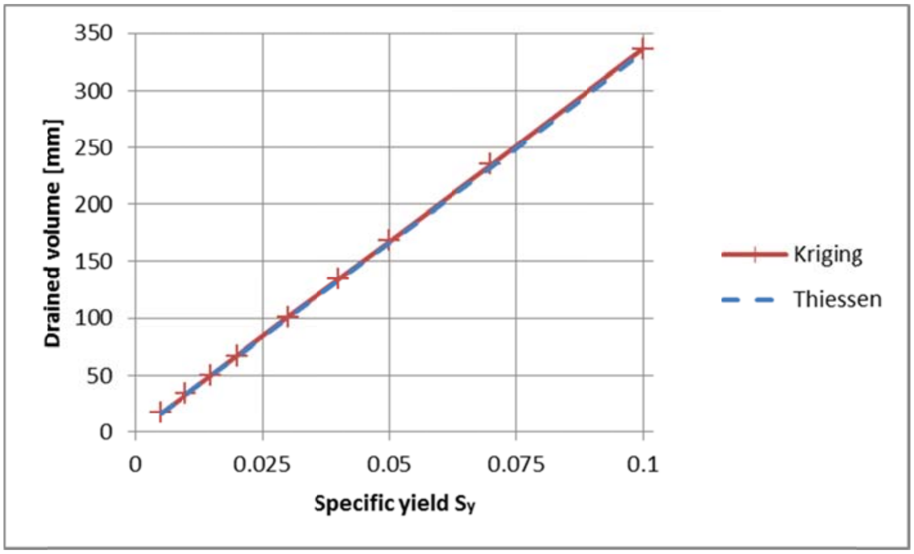

Figure 23 Estimated volume of drained pore space during the 2009 dry season (April to October) for the Lusaka Dolomite Plateau as a function of specific yield S_y; The two different lines show results based on interpolation of point data using Kriging and Thiessen polygon methods.

3.3.2. WTF-method

The water-table fluctuation method (WTF) is based on the assumption that rises in groundwater levels in unconfined aquifers are due to recharge arriving at the water table (Healy & Cook 2002). Recharge is calculated according to the WTF method as:

Equation [6] $$GWR = S_y \frac{\Delta h}{\Delta t}$$

Where S_y is specific yield, *h* is water table height and *t* is time.

The main advantage of the method is that it basically requires no other measurements than continuous groundwater level records at one or more stations. A major short-coming is its dependency on reliable estimates for S_y , in particular since the distribution of hydraulic properties of host rock in the Lusaka area is known to be highly variable. It is furthermore assumed that storativity is not changing with depth which is often not the case in karstified rock where cavities are naturally more common and better developed near the surface compared to greater depths. The method requires that the redistribution of water within the aquifer occurs at sufficient time after the recharge event. This is likely to be fulfilled if the recharge events can be identified by a clear and spontaneous rise in the water table after rainfall. In addition, the groundwater levels should not be influenced by groundwater abstractions in the vicinity of the monitoring site.

The DWA at this stage operates 25 monitoring boreholes that are equipped with digital probes for water level measurements (Figure 24). Readings are taken at hourly intervals (Siwale & Bäumle 2012). Nine of these monitoring boreholes are located in urban areas and proved not suitable for the WTF analysis due to interferences with production boreholes. At borehole MB-40 Chinyanya and MB-43 Kacheta, the change in groundwater levels during the rainy season showed a smooth delayed response without any clear correlation to individual rainfall events as can be seen from the hydroisopleths shown in Figure 25. This could possibly be explained by semi-confined aquifer conditions. The assumptions for applying the WTF-method were therefore also not met for these two monitoring sites. Additional examples of hydroisopleths with direct response to rainfall events are shown in Figure 25 for the two stations MB-28 Chikumbi and MB-42 SDA Camp.

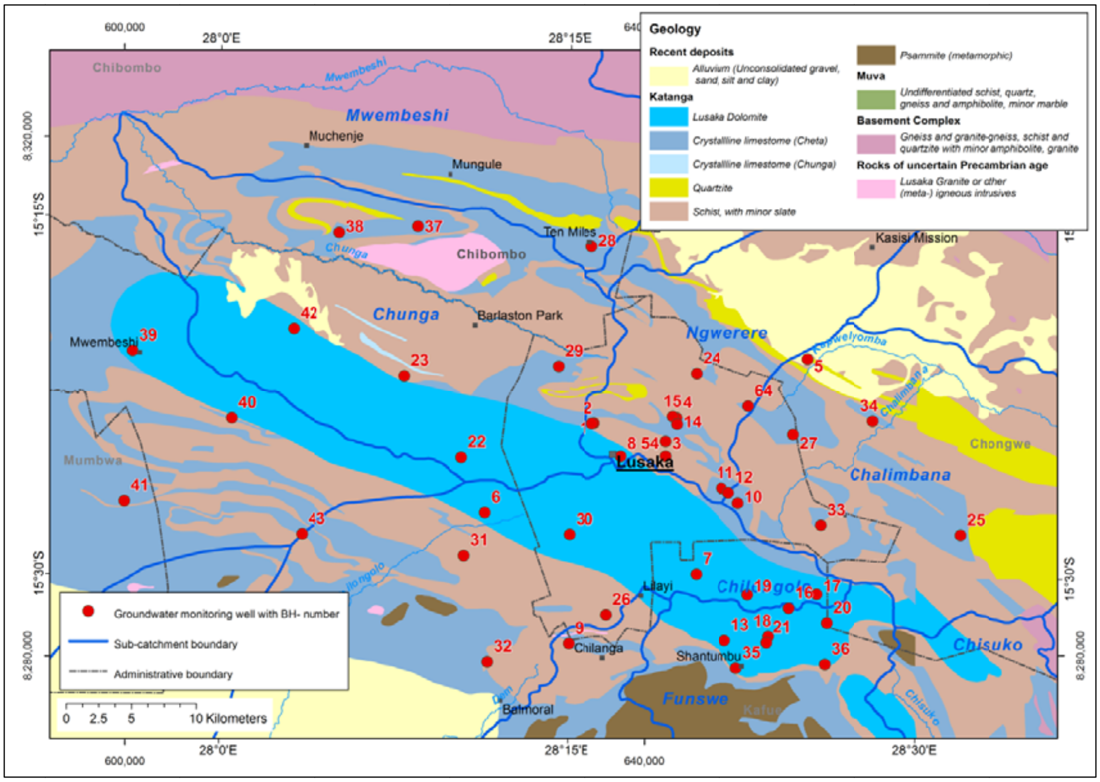

Figure 24 Location of DWA monitoring wells in the Lusaka area

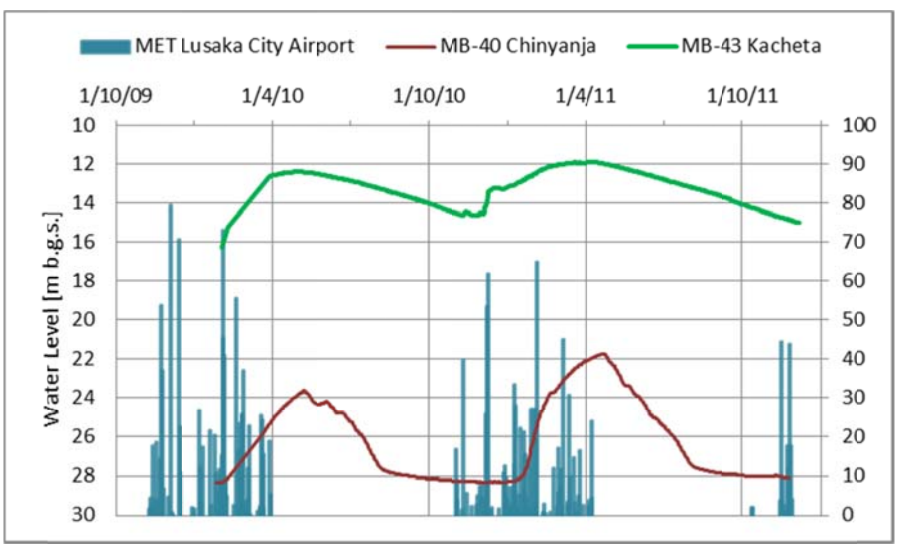

Figure 25 Rainfall and water levels during the 2009/10 and 2010/11 seasons at monitoring stations MB-40 and MB-43 (Source: DWA)

The results for the WTF-method of the remaining 14 stations are given in Table 19 assuming a uniform storativity S_y of 0.05. Unfortunately, quite a number of records are discontinuous and could not be analysed. In particular during 2009/2010 technical problems were encountered with the first batch of digital recorders purchased under the GReSP project. In addition, five monitoring boreholes were only drilled and installed during January/February 2010. During the 2010/2011 season, the seasonal water level variation at ten stations with full daily records ranged from 1.73 m to 3.39 m (average of 2.4 m). Annual groundwater recharge determined for S_y = 0.05 varied between around 60 mm and almost 300 mm. The average recharge at the ten stations according to the WTF-method is 158 mm which is very similar to the results obtained from estimating the drained pore space during 2009 as described in in Chapter 3.3.1.

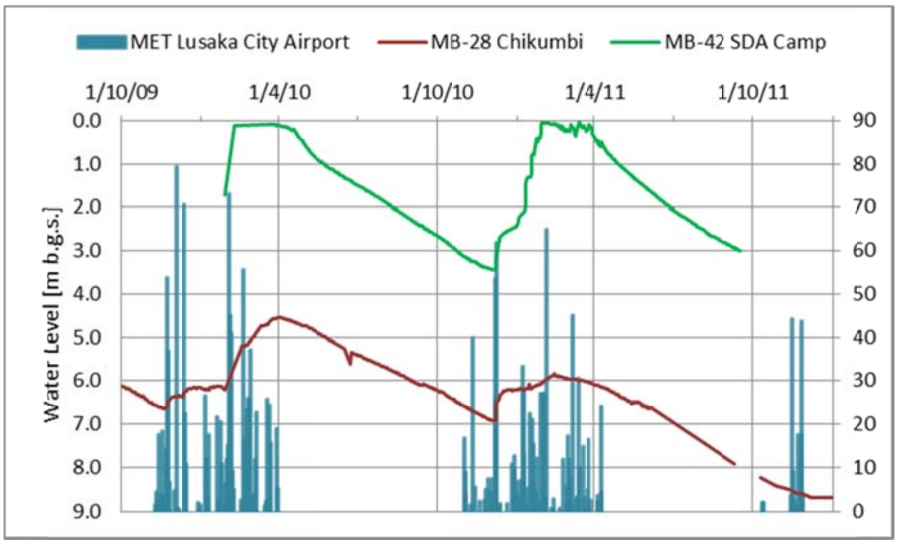

Figure 26 Rainfall and water levels during the 2009/10 and 2010/11 seasons at monitoring stations MB-28 andMB-42 (Source: DWA)

The large variation in the results is largely owing to the complex hydrogeological situation and indicates that storativity differs at each observation site. By modifying assumed storativity values within reasonable limits groundwater recharge according to the WTF-method changes considerably (Figure 27). Closer inspection of the hydroisopleths also shows that water table rises after storm events appear to be smaller during the end of the rainy season when water levels are high. This could be explained by higher porosity/storativity of rocks near the surface or rapid lateral drainage of shallow groundwater towards a nearby spring or stream. The curve representing the monitoring borehole MB-42 at SDA-camp (Figure 26) is a very good example for this observation.

Table 19 Groundwater recharge determined using the WTF-method and daily groundwater level measurements at stations in the Lusaka area for the hydrological years 2009/10 and 2010/11 assuming storativity S_y = 0.05

STATION	BH-No	Fm. [1]	2009/2010			2010/2011		
			h_{Min} [m] [2]	Δh [m] [3]	GWR [mm]	h_{Min} [m]	Δh [m]	GWR [mm]
Chikumbi	MB-28	CL	4.55	2.09	117	5.84	2.85	69

STATION	BH-No	Fm. [1]	2009/2010			2010/2011		
			h_{Min} [m] [2]	Δh [m] [3]	GWR [mm]	h_{Min} [m]	Δh [m]	GWR [mm]
City Airport	MB-3	CS	-	-	-	4.31	2.58	153
Coop. College	MB-10	CL	5.16	6.53	365	-	-	-
Evelyn Hone College	MB-8	LD	-	-	-	1.98	1.86	218
F55 ZAWA Park 4	MB-19	LD	-	-	-	-	-	-
Forest 26	MB-7	LD	-	-	-	-	-	-
Lemyadah	MB-6	LD	-	-	-	2.46	3.20	178
Mayaba (Katete)	MB-37	CL	- [4]	-	-	1.84	1.94	161
Musopelo	MB-38	CL	- [4]	-	-	6.87	1.73	59
Mwembeshi	MB-39	LD	- [4]	-	-	0.40	2.76	299
NISIR	MB-5	CH	-	-	-	5.47	1.55	66
SDA Camp	MB-42	LD	- [4]	-	-	0.04	3.39	234
Shamilimo	MB-41	CL	- [4]	-	-	9.82	2.58	140
UNZA Education	MB-4	CL	2.09	3.77	270	-	-	-

1) Formation: CL = Cheta Limestone; CS = Cheta Schist; CH = Chunga, undifferentiated, LD = Lusaka Dolomite;
2) h_{Min} = Minimum observed water table depth in meter
3) Δh = Observed seasonal range (amplitude) of water table depth in meter
4) Only completed during January/February 2010

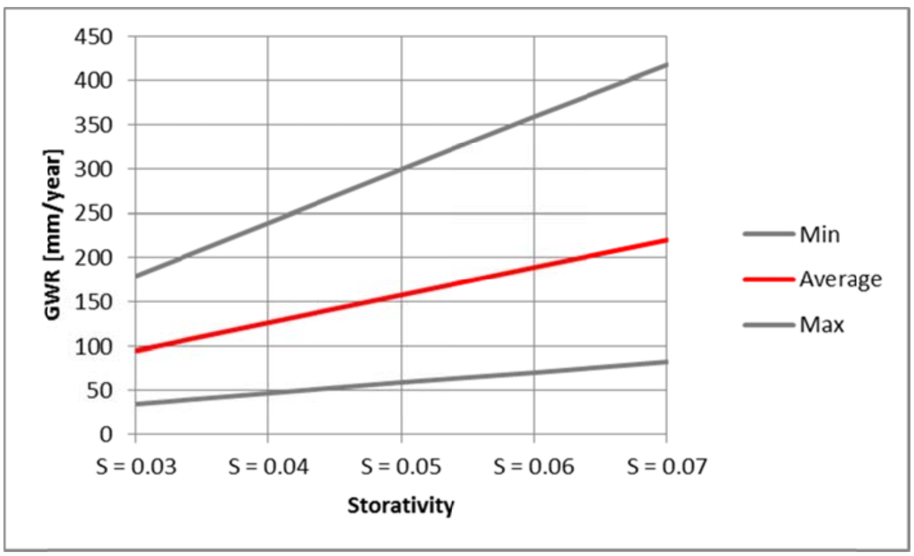

Figure 27 Maximum, average and minimum groundwater recharge *GWR* as a function of storativity S_y according to WTF-method obtained for the 2010/2011 season at ten groundwater monitoring boreholes in the Lusaka area.

3.4. Soil water balance approach

3.4.1. Recharge during reference years

During the on-going groundwater investigations under the GReSP program a soil water balance approach was applied to the Lusaka area in order to establish reliable estimates of the water balance including its major components of actual evapotranspiration and groundwater recharge (Hennings 2012). The method uses the FAO 56 dual crop coefficient approach for estimating crop evapotranspiration from soil as described in Chapter 2.2.2. The method was programmed in form of the MABIA software (Jabloun & Sahli 2011) that was incorporated in the "Water Evaluation and Planning" (WEAP) decision support system developed by the Stockholm Environment Institute (2005).

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

For the hydrological year 1989/90 it was assumed that, of the 780 mm of rain, 40 mm turned into surface runoff on areas with limestone characteristics (karst) and 120 mm surface runoff in areas covered by schist, quartzite or basement. These values resemble average flows observed at the various gauging stations at the Mwembeshi and Chongwe rivers.

Percolation rates as defined by the WEAP/MABIA model are assumed to represent groundwater recharge. Figure 28 shows the regional distribution of groundwater recharge rates as determined by the WEAP/MABIA model for the Lusaka area in the reference year 1989/90. Annual groundwater recharge rates cover a spectrum between below 100 mm and 380 mm. The overall average value, weighted according to spatial proportions of soil and land use classes, accounts for 210 mm. On the Lusaka Dolomite Plateau GWR is overall higher averaging 297 mm which is due to the abundance of soils that generally have a relatively low available water capacity. Lowest values belong to urban areas where larger proportions of sealed surfaces prevent infiltration and therefore reduce groundwater recharge. Outside urban areas, the minimum value of about 130 mm corresponds to non-karstic parent material such as schist or gneiss, higher surface runoff, deeply developed soils with a higher available water capacity and natural woodland vegetation. The maximum values of over 350 mm are associated with karstic parent material (marbles), limited surface runoff, shallow soils with a very small available water capacity and small-scale rain-fed agriculture.

The average values obtained from the WEAP/MABIA method are somewhat higher than estimates from other authors in the past and also compared to the results of the water table fluctuation methods presented in Chapter 3.3 that were based on an assumed uniform storativity S_y of 0.05.

The GWR for individual catchments and sub-catchments for the reference year 1989/1990 according to the WEAP/MABIA calculations are presented in Table 20.

Table 20 Groundwater recharge GWR in mm/a in selected catchments in the Lusaka area during the reference year 1989/90 according to WEAP/MABIA model calculations

Catchment	*GWR*
Chunga	231
Upper Chalimbana (station 5-029)	219
Upper Ngwerere (station 5-016)	175
Ngwerere	184
Chilongolo	224

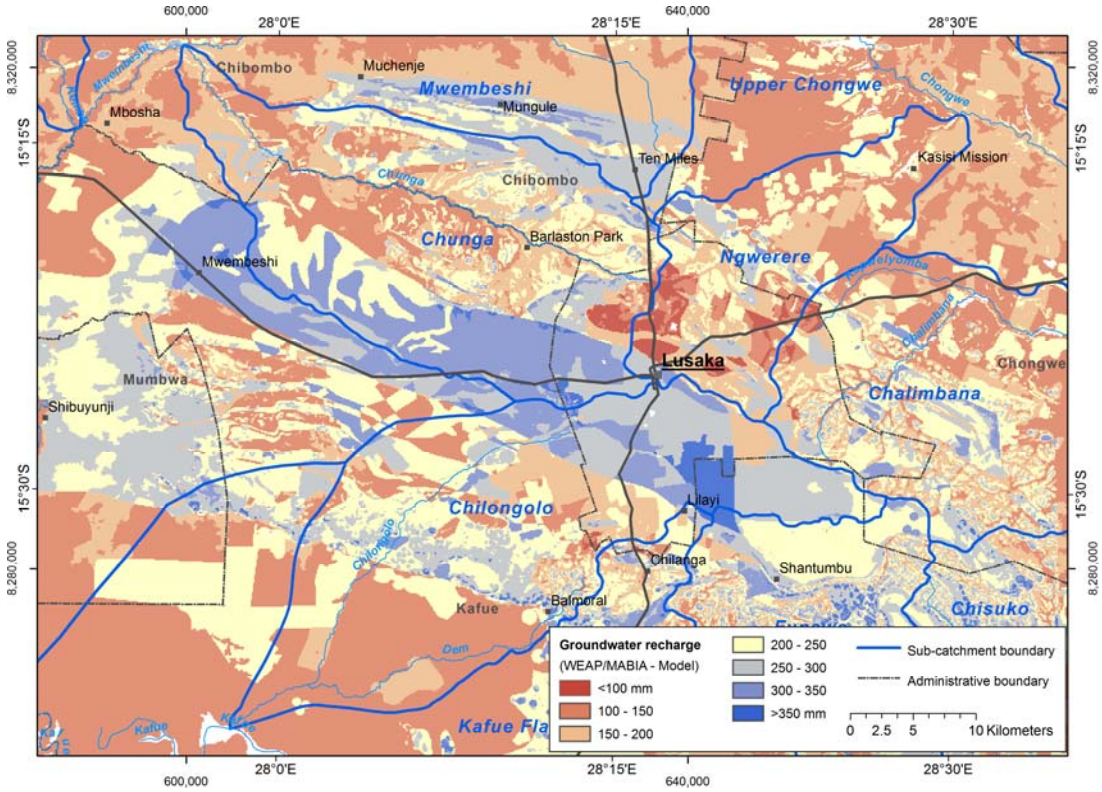

Figure 28 Estimated groundwater recharge rates [mm/a] in the Lusaka region in the reference year 1989/90 (modified after Hennings 2012)

3.4.2. Recharge during 2009/2010 and 2010/2011 seasons

In a second step actual evapotranspiration and percolation rates were determined using the WEAP/MABIA program for the specific climatic and hydrological conditions during the last two seasons 2009/2010 and 2010/2011.

Annual rainfall was assumed to be uniform over the area with 1004 mm during the 2009/2010 and 772 mm during the 2010/2011 season (annual totals at International Airport). The portion of the precipitation which remains in the soil and is available for consumptive use was calculated by subtracting direct (surface) runoff. Based on actual results of stream flow measurements during the years under consideration (Chapter 2.3.2, Table 9) direct runoff was assumed to vary between 60 mm/a and 140 mm/a depending on bedrock. As for the reference year, calculations were performed using daily values of hydro-meteorological input data.

The results of the model calculations for sub-catchments in the Lusaka area are presented in Table 21. Lowest values are generally observed for Upper Ngwerere due to the large percentage of urban areas with sealed surfaces.

Table 21 Groundwater recharge GWR in mm/a for selected catchments in the Lusaka area for the hydrological years 2009/2010 and 2010/2011 according to WEAP/MABIA model calculations

Catchment	*GWR in 2009/2010*	*GWR in 2010/2011*
Chunga	339	135
Upper Chalimbana (station 5-029)	331	141
Upper Ngwerere (station 5-016)	236	73
Ngwerere	287	94
Chilongolo	326	119

Groundwater recharge during 2009/2010 was remarkably high with values exceeding 300 mm/a. The high recharge values can be explained by the overall “wet” conditions during this rainy season and in particular by heavy precipitation during February (Chapter 2.1.2).

Groundwater recharge during 2010/2011 was unusually low according to the WEAP/MABIA model, despite the fact that annual rainfall totals were only slightly lower than during the reference year 1989/1990. Values of *GWR* for selected sub-catchments range from below 100 mm/a to 140 mm/a for this specific year which is only 50% to 65% of *GWR* during the reference year and approximately 40% of *GWR* obtained for 2009/2010. The main reason for the unusually low recharge is perhaps the unfavourable distribution of rainfall during the months of December to March, with above-average rainfall during the start of the rainy season when soils were still dry enough to absorb large portions of rainfall and below-average rainfall towards the end of the rainy season (Chapter 2.1.2).

3.5. GROUNDWATER MODELLING

A three-dimensional numerical groundwater model was developed under the GReSP project with the aim to assess whether current abstraction from the Lusaka aquifers is sustainable and to what extent abstractions could be increased to meet the future water demand (Maßmann 2012). The model was discretized with square shaped elements with an edge length of 500 m. The model boundaries enclose the Lusaka Plateau and areas to the north including the entire Chunga sub-catchment and the urban and peri-urban settlements of Lusaka (Figure 29). The lower parts of the Ngwerere, Chalimbana and Chilongolo sub-catchments are located outside the model area. The model area totals 2,270 km^2.

The model incorporates previous knowledge about the geological structure and hydrogeological setup combined with recent findings, e.g. on the three-dimensional geological structure, groundwater hydraulics, permeability and storativity of rocks and current land use distribution. The model input data include recharge rates defined by the WEAP/MABIA model, rainfall data at meteorological stations and pumping rates from wells operated by LWSC and industrial water consumers as well as estimated groundwater abstraction for irrigation purposes from commercial farms and private gardens. Recharge classes applied in the WEAP/MABIA model that are distinguished based on distribution of land use, soil properties and geology were used to define the surface (recharge) boundary. Some of the recharge classes with very similar characteristics could be combined for the sake of simplicity reducing the number of recharge classes from 90 (in the WEAP model) to 31 (in the groundwater model).

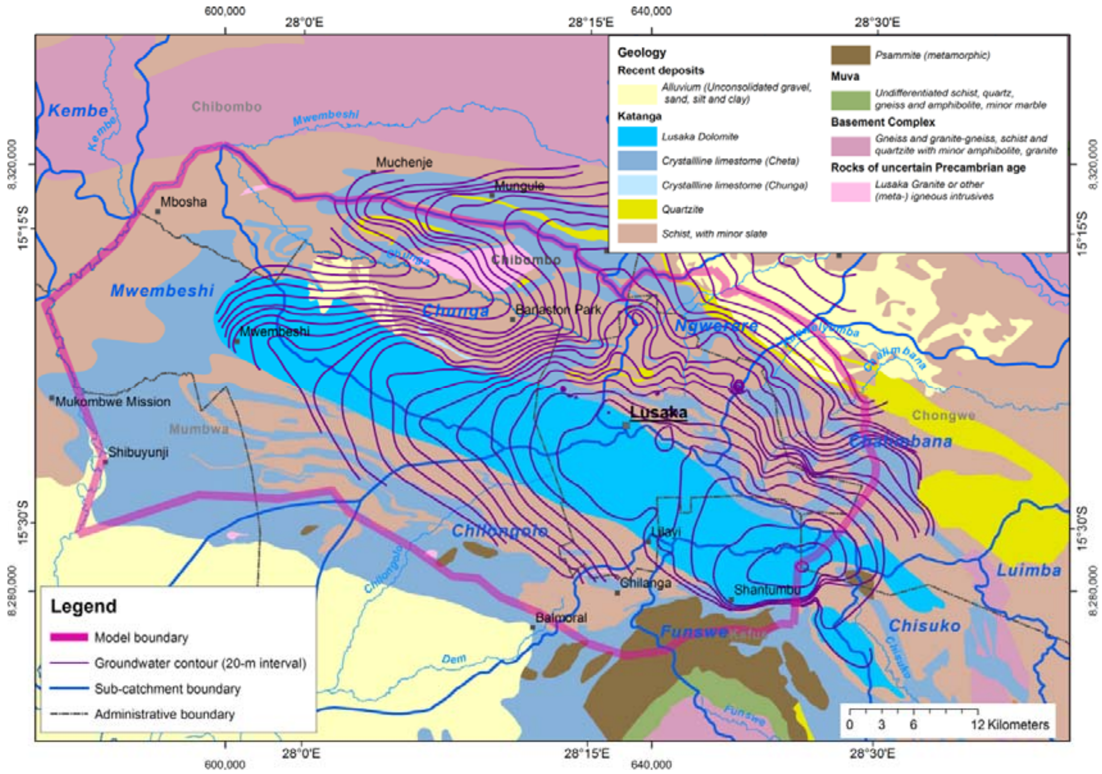

Figure 29 Extent of the numerical model

Recharge rates were determined for each recharge classes using the following approach:

Equation [7]

$$GWR_d = \begin{cases} 0 & if\ P_d < P_{min} \\ GWR_d^{max} & if\ c\,(P_d - P_{min}) > GWR_d^{max} \\ c\,(P_d - P_{min}) & else \end{cases}$$

where GWR_d and P_d are daily recharge and observed daily precipitation, respectively, GWR_d^{max} is the maximal daily groundwater recharge for each class, P_{min} is the threshold for recharge-relevant precipitation and *c* is a calibration factor. The last three parameters were determined for all recharge classes by achieving a best fit between the annual recharge rates calculated by Equation [7] to those established by the WEAP/MABIA model for the hydrological years 2009/2010 and 2010/2011. Using this approach the recharge boundary could be quantified for preceding years and future scenarios for which no WEAP/MABIA calculations were available.

The model was run over a period from the water year 1975/1976 to 2010/2011. Groundwater contour maps for the year 2009 (wet and dry season conditions) and the mapped location of springs were used for the model calibration. In addition, groundwater hydrographs at 47 monitoring sites could be compared with simulated groundwater levels over the “calibration period” covering the last two hydrological years 2009/2010 and 2010/2011. Values of permeability and storativity applied in the model were all in the range of literature and field values. Considering the fact that the knowledge on the heterogeneous rock formations and groundwater-surface water interactions is still limited the model performed well and water tables could be adequately reproduced for the calibration period.

After calibration, recharge rates and water budget figures could be obtained from the model for the entire period covered. Based on the calibration results the long-term average annual recharge over the complete model area for the period 1976-2011 amounts to 284 mm. The recharge rates for selected sub-catchments for the calibration period 2009/2010 and 2010/2011 are given in Table 22. Groundwater recharge during the 2009/2010 season was about twice as high compared to the subsequent year. This finding corresponds to the results described in the forgoing section. Compared to the results obtained from the WEAP/MABIA model groundwater recharge according to the groundwater model is considerably higher during both years, in particular in the Chunga, Upper Ngwerere and Upper Chilongolo catchments and to a lesser degree in the Chilongolo sub-catchment. The main reason for this is that in the groundwater model an additional component was added reflecting preferential (localised) recharge through open karst surface features such as sinkholes to the diffuse recharge component by percolation through the soil. In addition, karst surfaces were assumed to have zero surface runoff as compared to 60 mm/a and the impact of sealed surfaces in built-up areas on recharge is not reflected in the groundwater model.

Table 22 Groundwater recharge GWR in mm/a for selected catchments in the Lusaka area for the hydrological years 2009/2010 and 2010/2011 according to the groundwater model calculations (after Maßmann 2012)

Catchment	*GWR in 2009/2010*	*GWR in 2010/2011*
Chunga	434	214
Upper Chalimbana (station 5-029)	357	169
Upper Ngwerere (station 5-016)	387	178
Upper Chilongolo (406 km^2)	435	221

It should be furthermore mentioned that apart from base flow into rivers and streams, the groundwater model incorporates so-called “drain cells” in order to enable outflow of groundwater if the head reaches the ground surface. This phenomenon is very common in parts of the model area as the groundwater tables are generally shallow. Losses through drain cells represent outflows from springs and small discontinuous seasonal streams as well as evaporation from zones of seepage, wetlands and through capillary fringes above the shallow groundwater table. These losses that contribute to a “negative” groundwater recharge are not considered in the WEAP/MABIA model widely ranging from below 25 mm to well over 200 mm depending on rainfall and specific catchment conditions.

4. RESULTS

4.1. AVERAGE RECHARGE CONDITIONS

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.

Reviewing the long-term averages of the water budget components presented in this report, it can be concluded that

1. Average precipitation *P* amounts to about 830 mm/a (Chapter 2.1.1);
2. Actual evapotranspiration according to the applied soil water balance approach (WEAP/MABIA) is roughly 480 mm/a and fairly time-independent compared to other components (Chapter 2.2.2);
3. Average surface runoff *Q* is a figure not easy to determine, but based on existing data it can be suggested that streams and rivers in the area discharge about 100 mm/a on the average although runoff from karst surfaces is close to zero (Chapter 2.3.1).
4. Base flow Q_b contributes a significant (probably >50%) share to total runoff (Chapter 3.2),
5. Surface water abstractions *SWA* as provided by the Water Board are almost negligible compared to runoff at the gauging stations of interest (Chapter 2.4).

If direct runoff Q_d is roughly set to be 50% of total runoff, applying the water budget Equation [2] yields the following value of average groundwater recharge:

$GWR \text{ (in mm/a)} \approx 830 - 480 - 50 = 300$

This result is quite similar to the long-term recharge of 284 mm/a obtained by the numerical groundwater model. The model calibration, however, indicated that there are areas of smaller groundwater drains, seepages and shallow groundwater that could contribute to a significantly higher (”secondary”) evapotranspiration as determined by the soil water balance approach.

The WEAP/MABIA model yields an average *GWR* of only 210 mm/a for the reference year 1989/1990; with respect to the groundwater modelling area which is smaller and includes a higher proportion of karst surfaces (Table 23) this value increases to 229 mm/a. Groundwater recharge calculated for the karstic Lusaka Plateau using the WEAP/MABIA model is in fact much higher, namely 297 mm/a, due to the abundance of soils that have a relatively low available water capacity. The model results further suggest that values around and above 300 mm/a for the entire area would only be reached under “wet” conditions such as during the 2009/2010 season with an average total annual rainfall of about 1000 mm. Preferential (localised) recharge that may be an important recharge process on karst surfaces, however, cannot be considered by the WEAP/MABIA model.

The presented water table fluctuation methods are considered less adequate to yield reliable results of *GWR* due to limited data and the difficulties to determine the specific yield of hard rock. The available analysis results suggest that the metamorphic rocks must have a fairly high specific yield ($S_y \geq 0.7$) if groundwater recharge rates are between 200 and 300 mm/a.

Table 23 Areas considered by the WEAP/MABIA and numerical groundwater models

Model	Total area	Area covered by karst surfaces [1]	
	[km^2]	[km^2]	[%] of total
WEAP/MABIA	4,820	962	20.0
Groundwater Model	2,270	778	34.3

1) Includes mainly Lusaka Dolomite and Cheta Limestone with minor Chunga Limestone

Based on the discussion above 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 *GWA* amount to only 40 mm/a (Chapter 0) which represents 16% of assumed recharge.

4.2. WATER BUDGET FOR SELECTED SUB-CATCHMENTS

Table 24 gives annual water budget components of individual sub-catchments for the two examined hydrological years 2009/2010 and 2010/2012. The table also compares the groundwater recharge rates obtained from the three different methods applied, namely water balance equation, WEAP/MABIA soil water balance approach and numerical groundwater model. It was assumed that precipitation is uniform over the area and groundwater abstractions are equal for both years. The figures generally confirm the "wet" conditions during 2009/2010 with higher rainfall and recharge compared to the "dry" year 2010/2011. Furthermore, it can again be observed that values of *GWR* obtained from the water budget equation and groundwater modelling, respectively, are usually higher than those from the WEAP/MABIA model. The following additional observations can be made:

1. WEAP/MABIA produces particular low recharge for Ngwerere due to larger proportions of sealed surfaces that prevent infiltration and therefore reduce groundwater recharge. During the 2010/2011 season groundwater recharge calculated from the WEAP/MABIA model drops below 100 mm/a. The results of the groundwater model, however, do not support his finding.
2. The water budget for Ngwerere could not be established as exceptionally high surface runoff occurs due to sewage discharge and storm-runoff discharging from the surface drains of most of the Lusaka City area; further investigations in the discharge characteristics of the Ngwerere stream would be needed.
3. Current groundwater abstractions of the four main sub-catchments in the Lusaka area deviate considerably from the overall average of 40 mm/a. Abstractions from Chunga, Ngwerere and Chilongolo vary between 23 mm/a and just over 100 mm/a; groundwater abstractions in the Chalimbana catchment is overall very low (<1 mm/a).
4. The highest total abstraction occurs in Ngwerere catchment. In smaller catchments (Kapiriombwa, Laughing Waters springs) groundwater abstractions relative to catchment area is equally high or higher (Chapter 0). In general, however, abstractions are usually still well below determined recharge rates except for Ngwerere and smaller sub-catchments.

Table 24 Annual Water Budget for selected sub-catchments in mm/a for 2009/2010 and 2010/2011 hydrological years

P := Rainfall ETa := Actual evapotranspiration Q := Surface runoff
GWR := Groundwater recharge GWA: = Groundwater abstraction

2009/2010

Catchment	*P* [1]	*ETa* WEAP/MABIA	*Q*	*GWR* Water Budget [4]	*GWR* WEAP/MABIA	*GWR* GW-MODEL	*GWA*
Chunga	997	484	129 [2]	449	339	434	23
Upper Chalimbana (station 5-029)	997	492	142	434	331	357	6
Upper Ngwerere (station 5-016)	997	497	710	n/d	236	387	106
Ngwerere	997	508	n/d [3]	n/d	287	n/d	103
Chilongolo	997	490	n/d	n/d	326	(435)[5]	52

2010/2011

Catchment	*P* [1]	*ETa* WEAP/MABIA	*Q*	*GWR* Water Budget [4]	*GWR* WEAP/MABIA	*GWR* GW-MODEL	*GWA*
Chunga	735	501	118 [2]	175	135	214	23
Upper Chalimbana (station 5-029)	735	483	71	217	141	169	6
Upper Ngwerere (station 5-016)	735	452	728	n/d	73	178	106
Ngwerere	735	495	n/d	n/d	94	n/d	103
Chilongolo	735	500	n/d	n/d	119	(221)[5]	52

1) Average at available stations
2) At station 4-935 near confluence
3) n/d = not determined
4) Water Budget Approach (Equation [2]) : $GWR = P - ETa - Q_D$, with $Q_D \approx 0.5$ Q and SWA ≈ 0
5) Figure refers to Upper Catchment only representing 60% (409 km^2) of total catchment area

Acknowledgement

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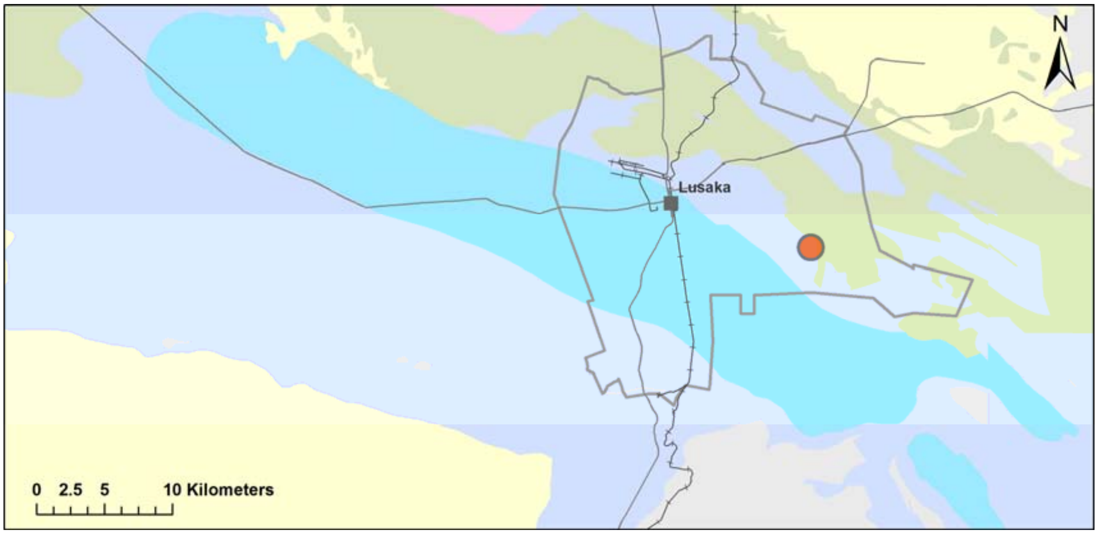
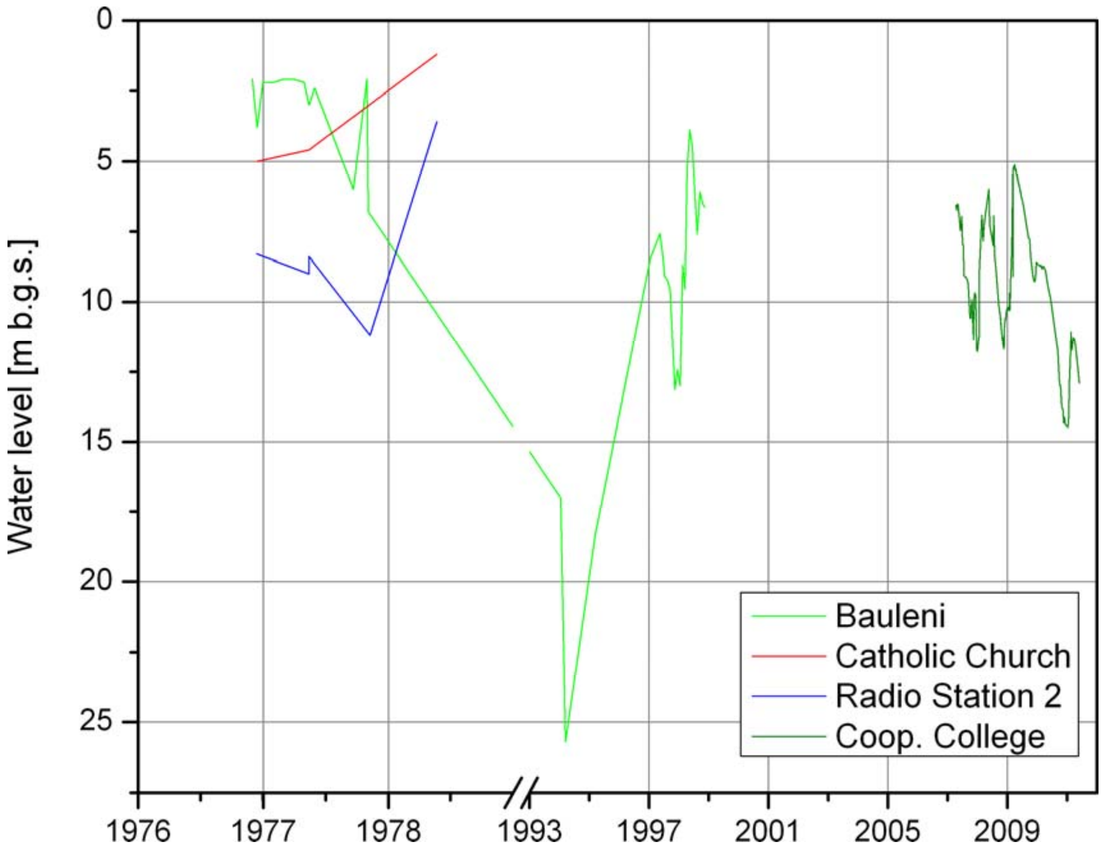
Annex 1

GROUNDWATER LEVEL HISTORY FOR SELECTED AREAS

A1-1 Bauleni Area





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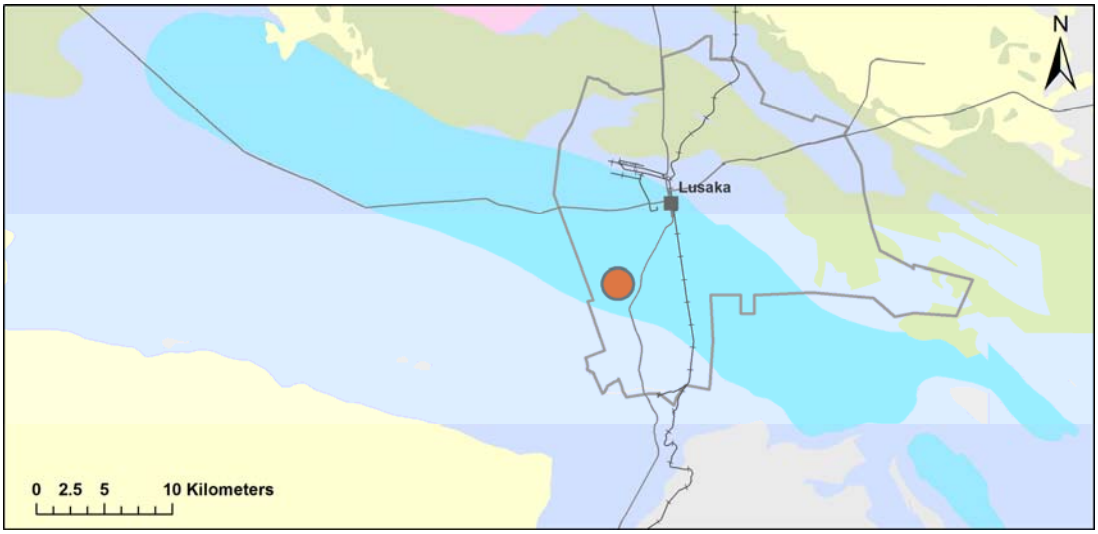

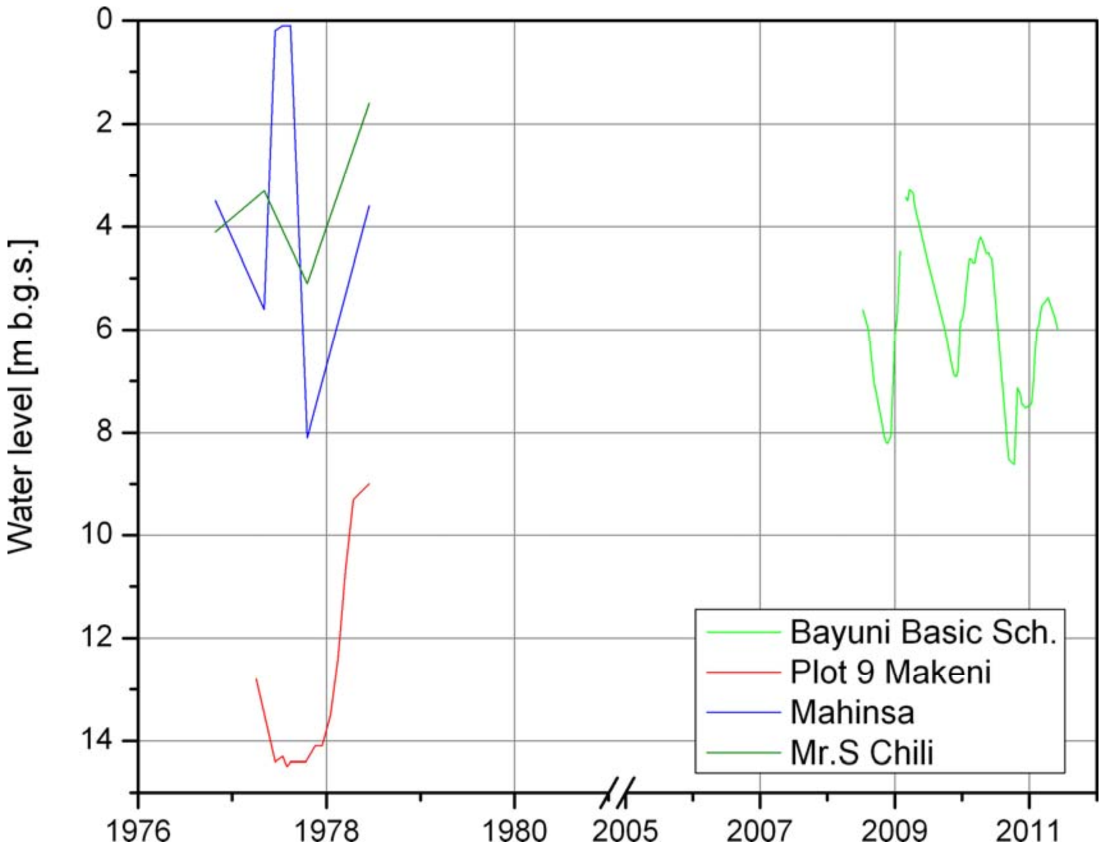

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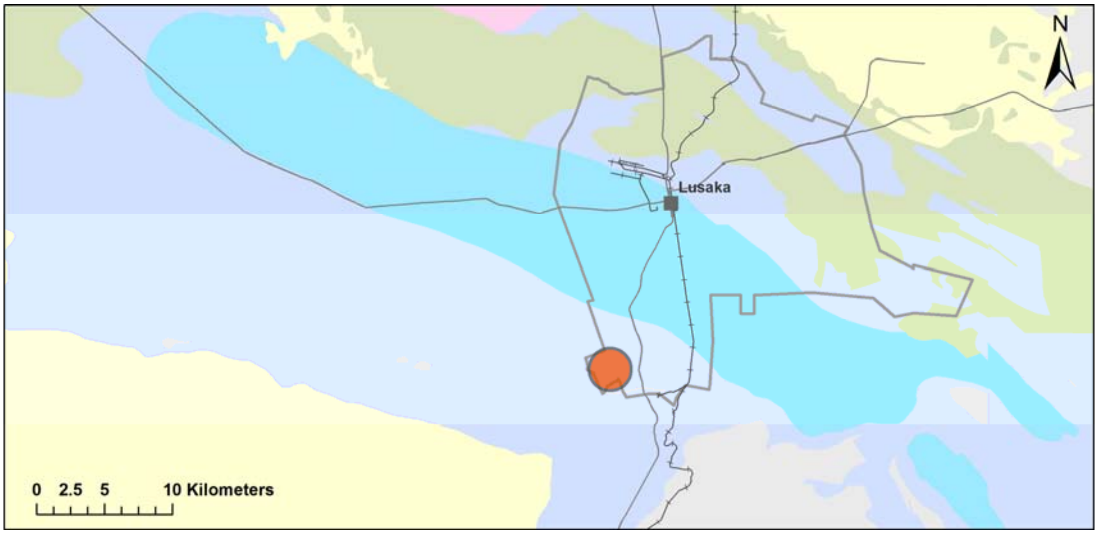

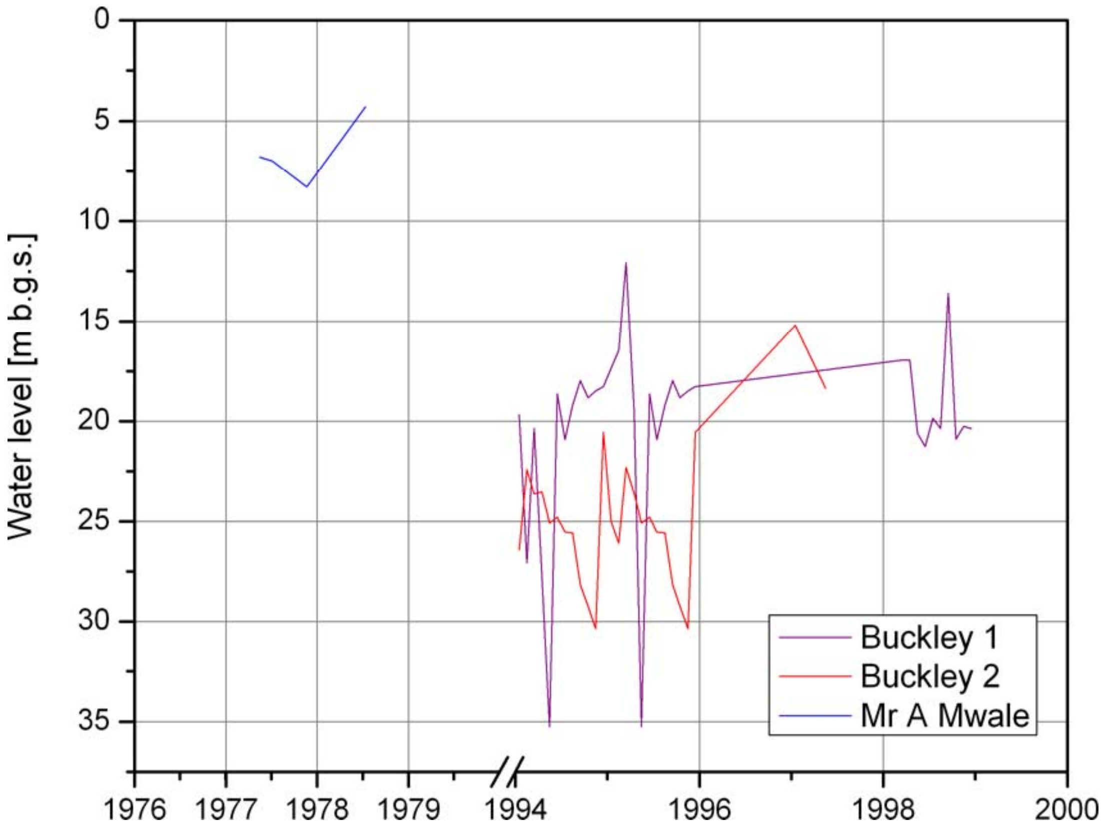

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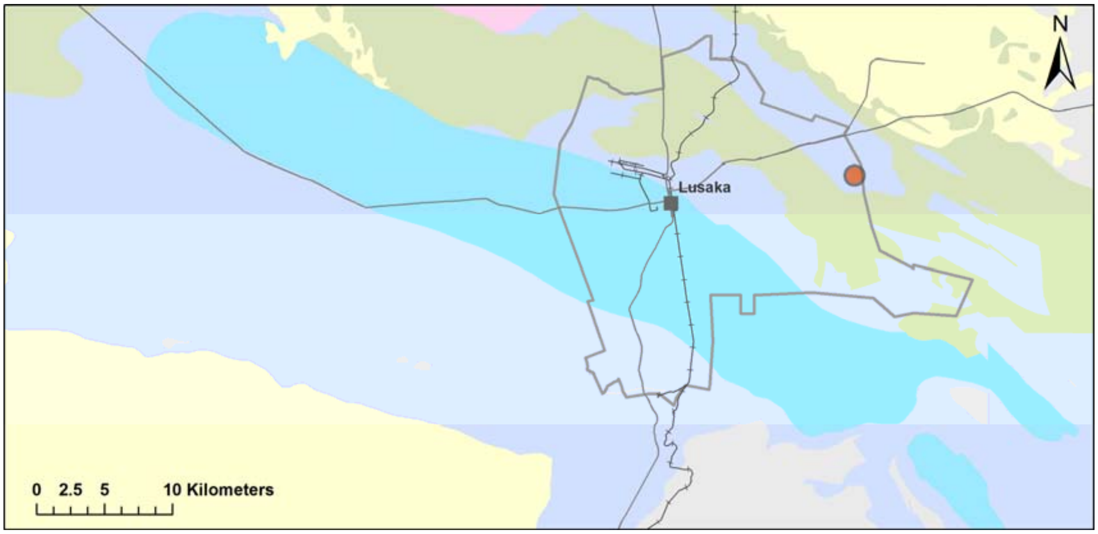

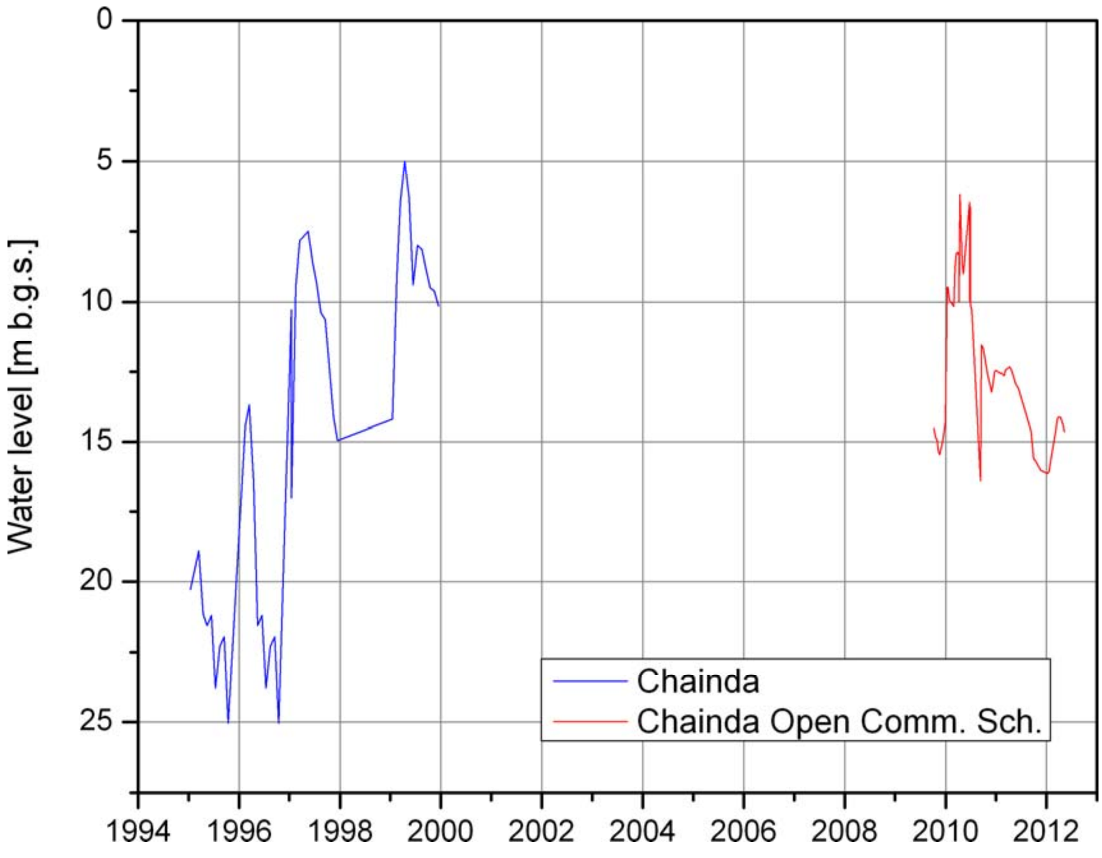

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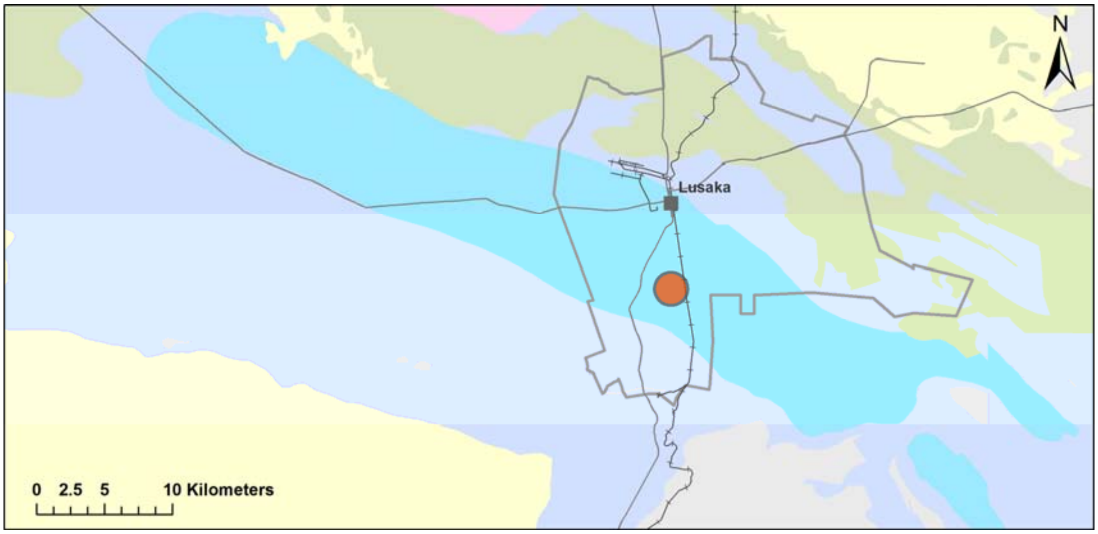

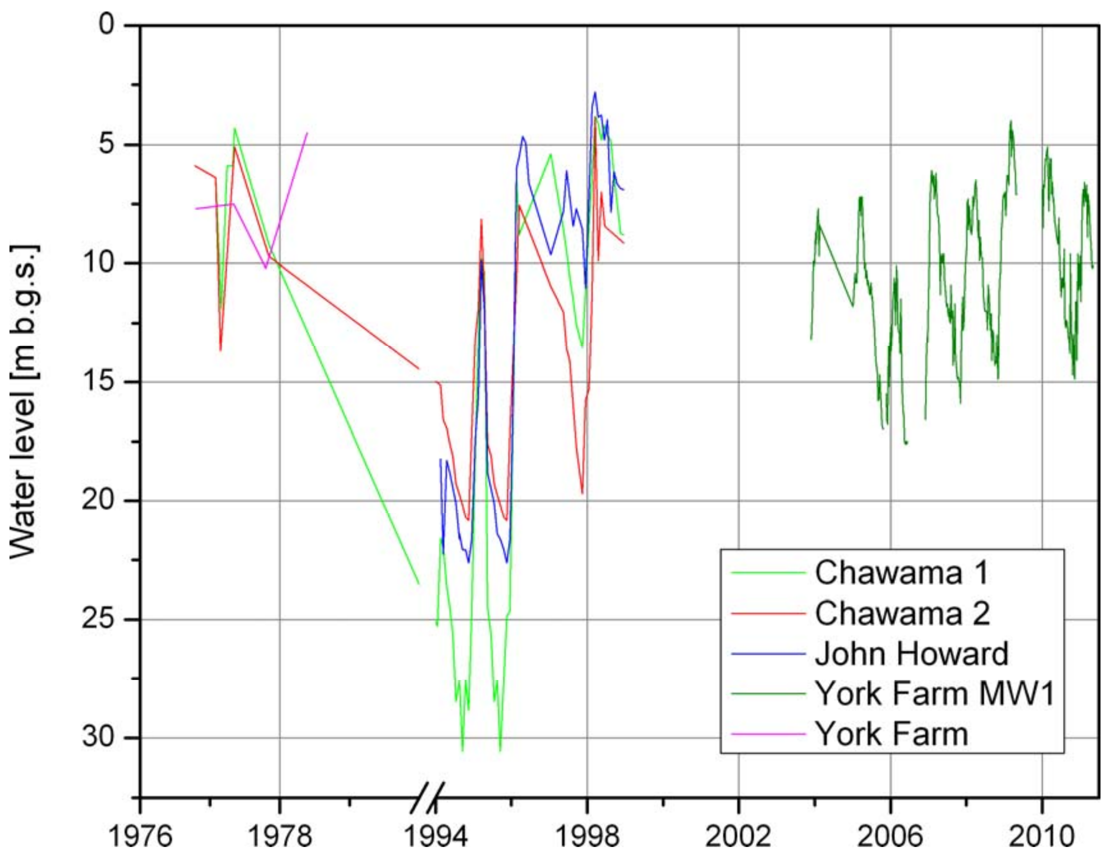

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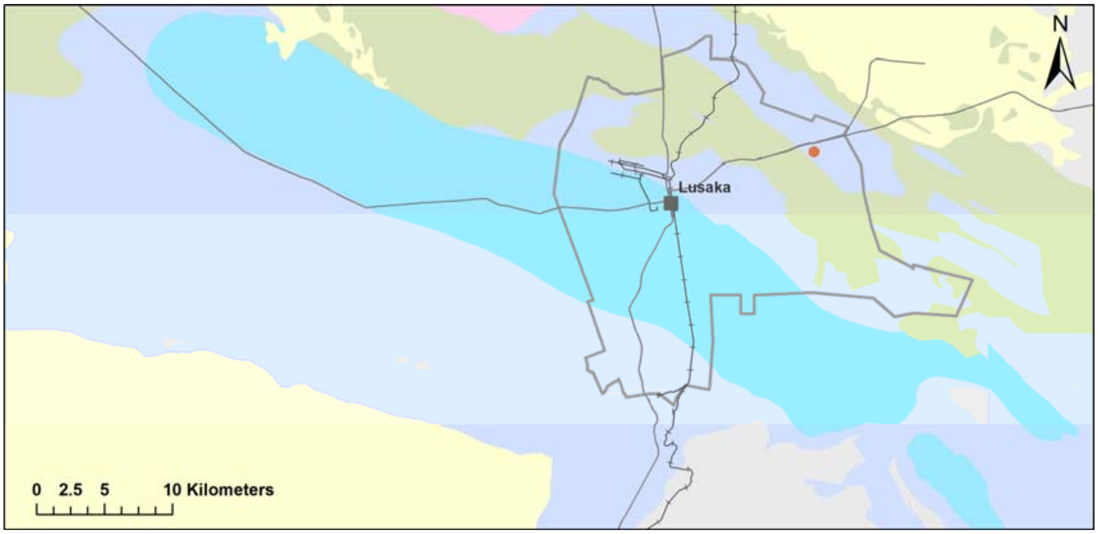

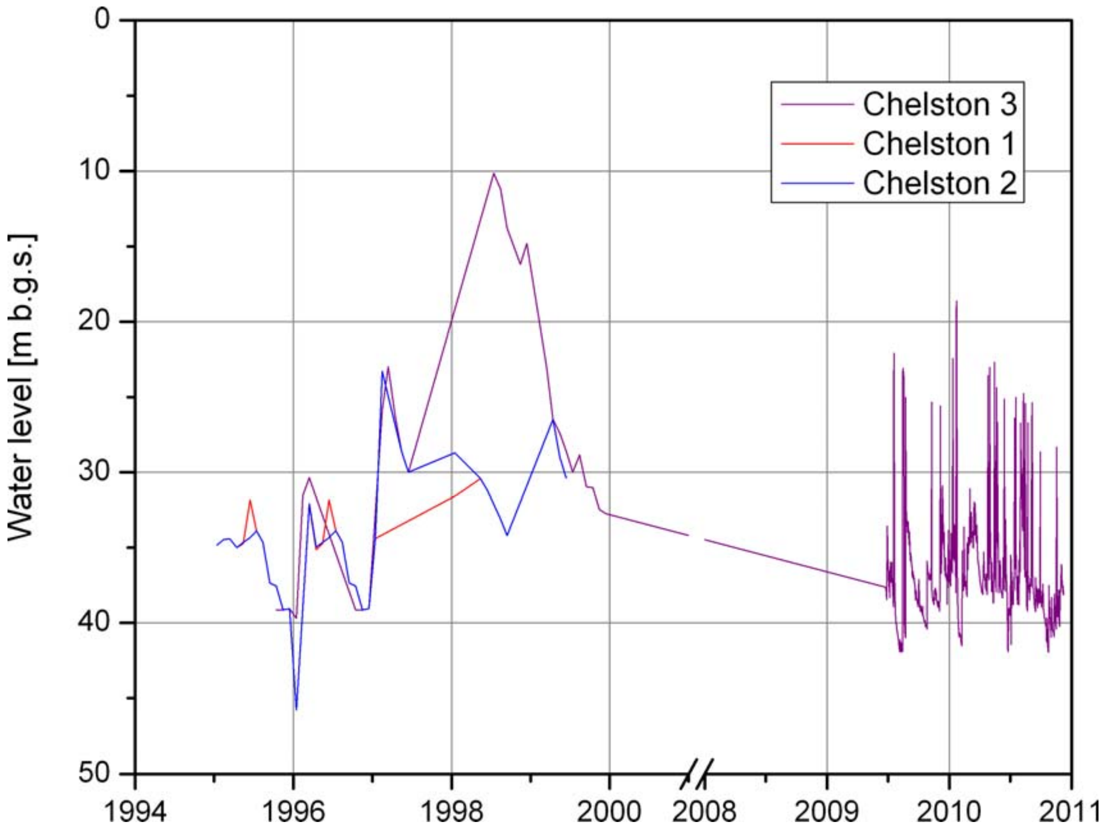

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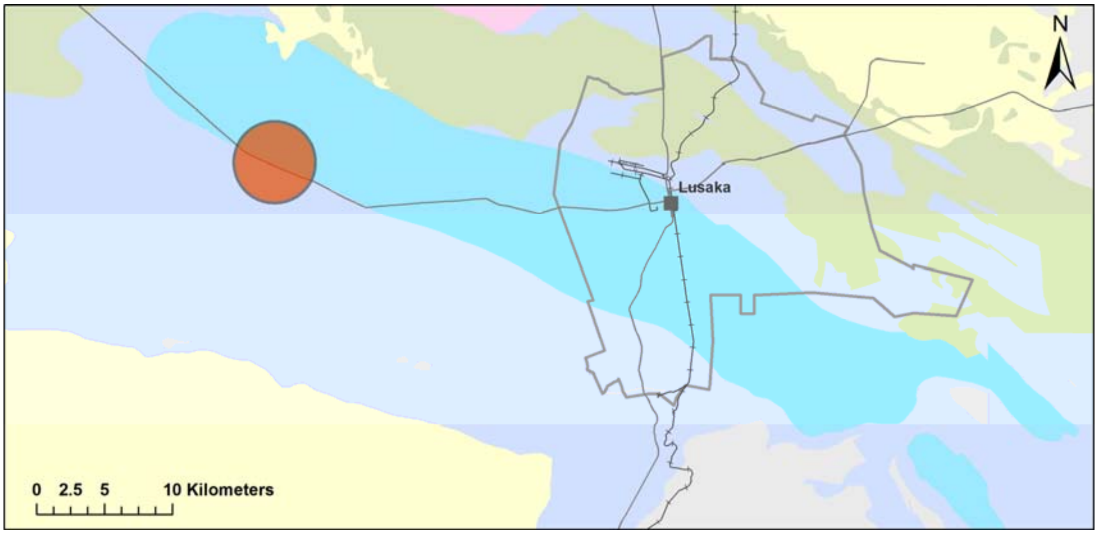

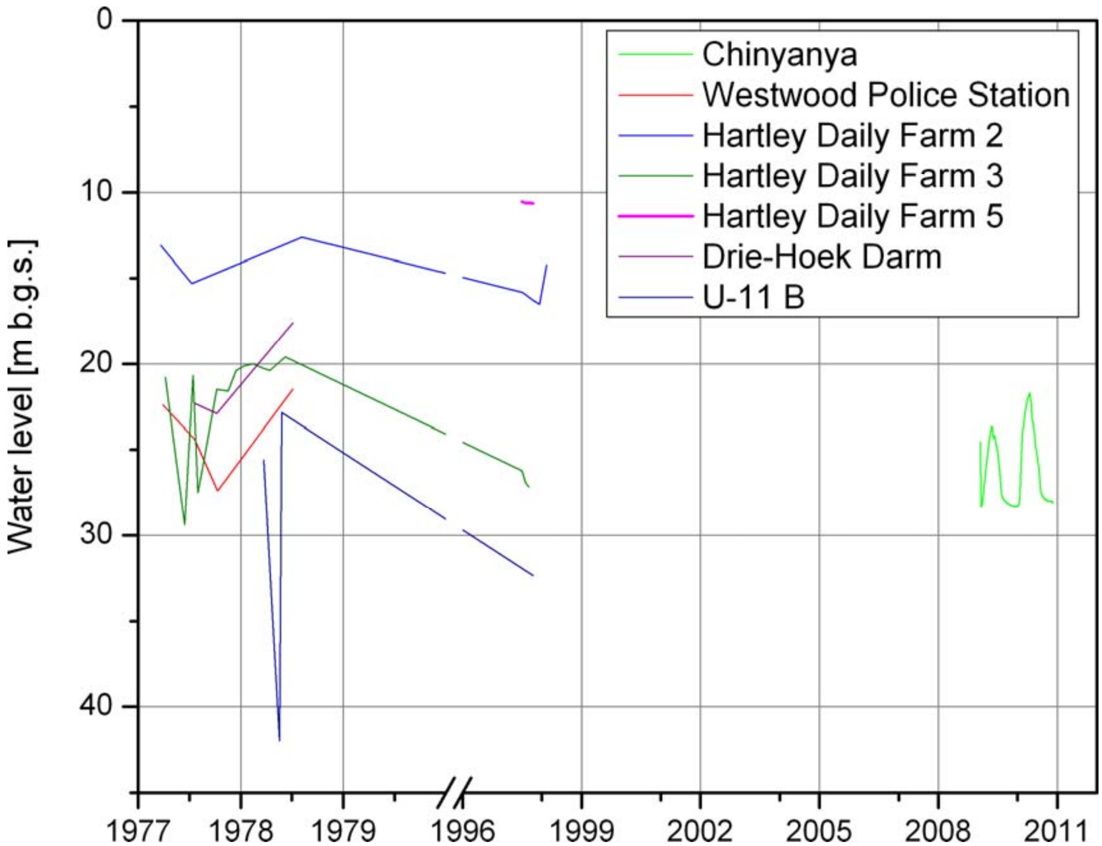

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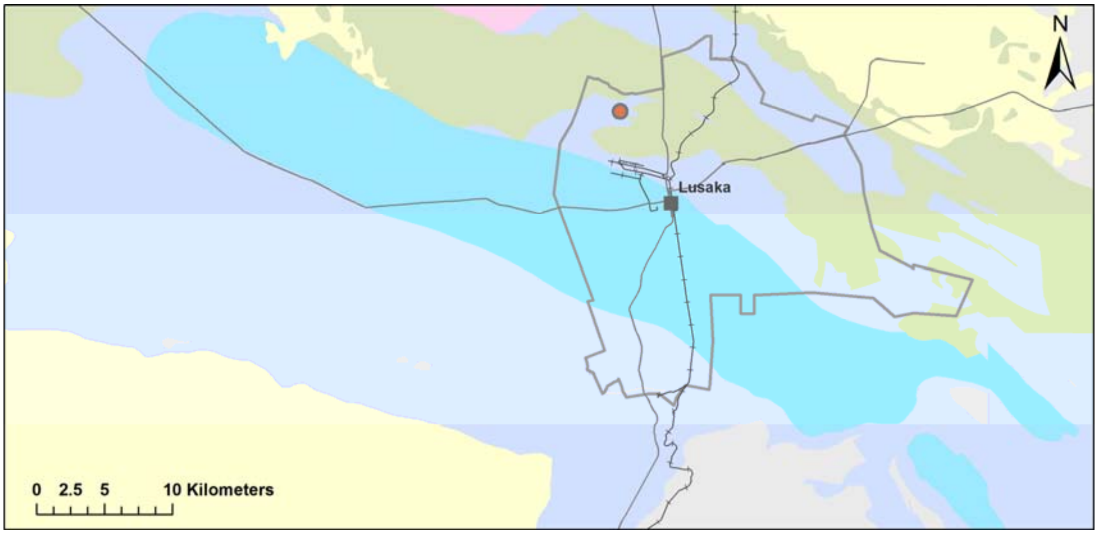

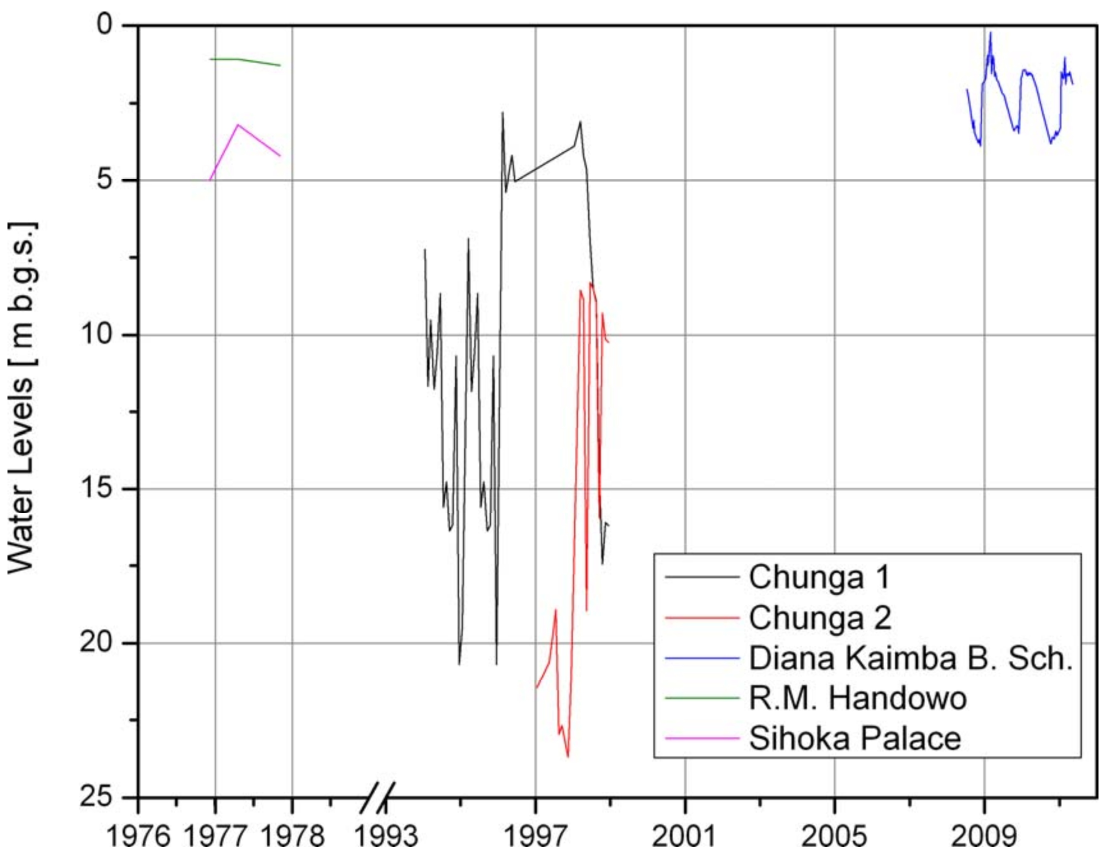

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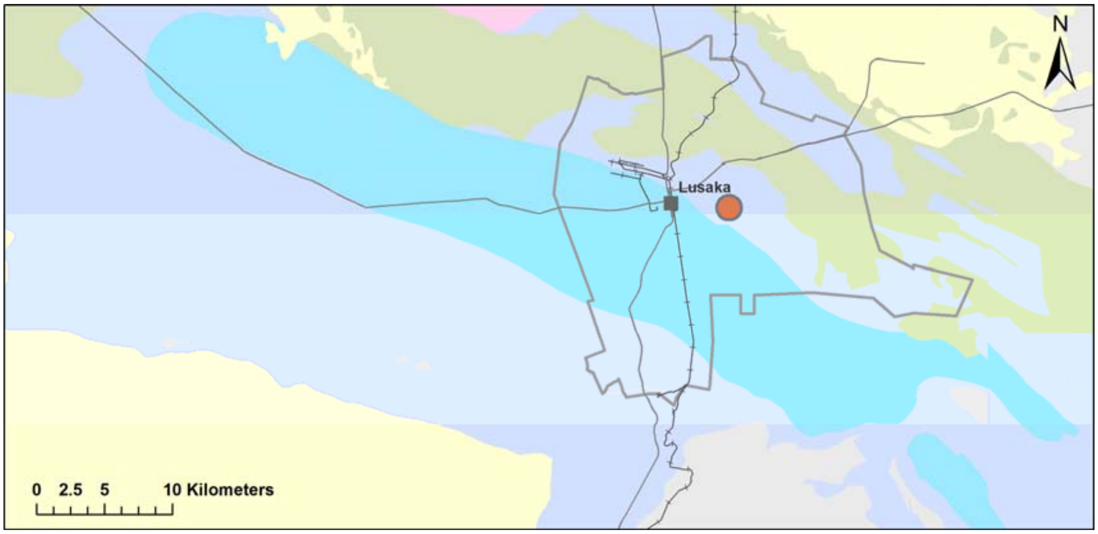

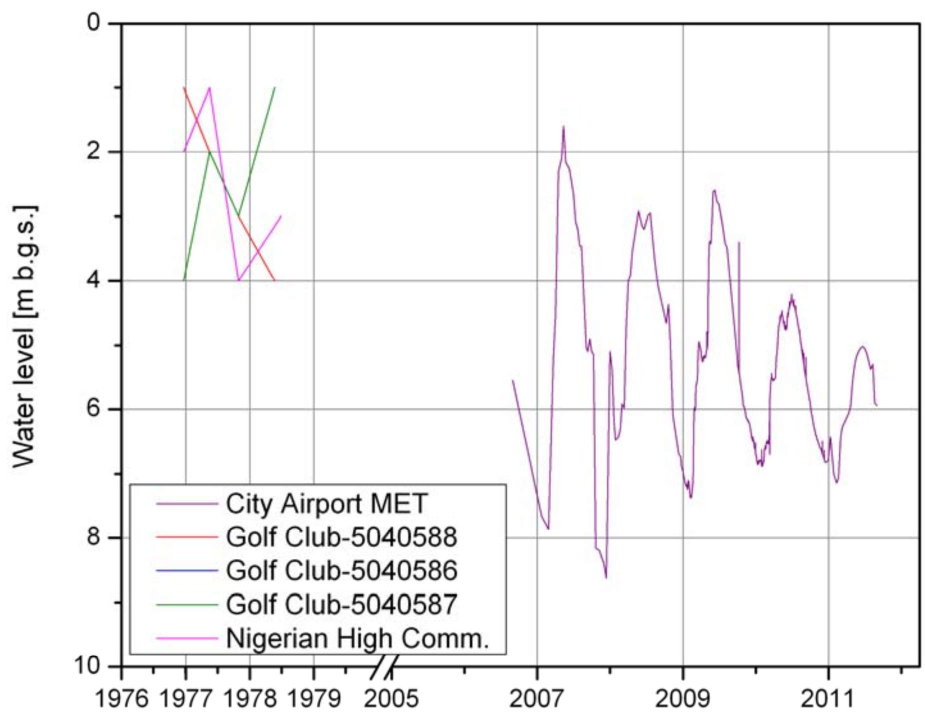

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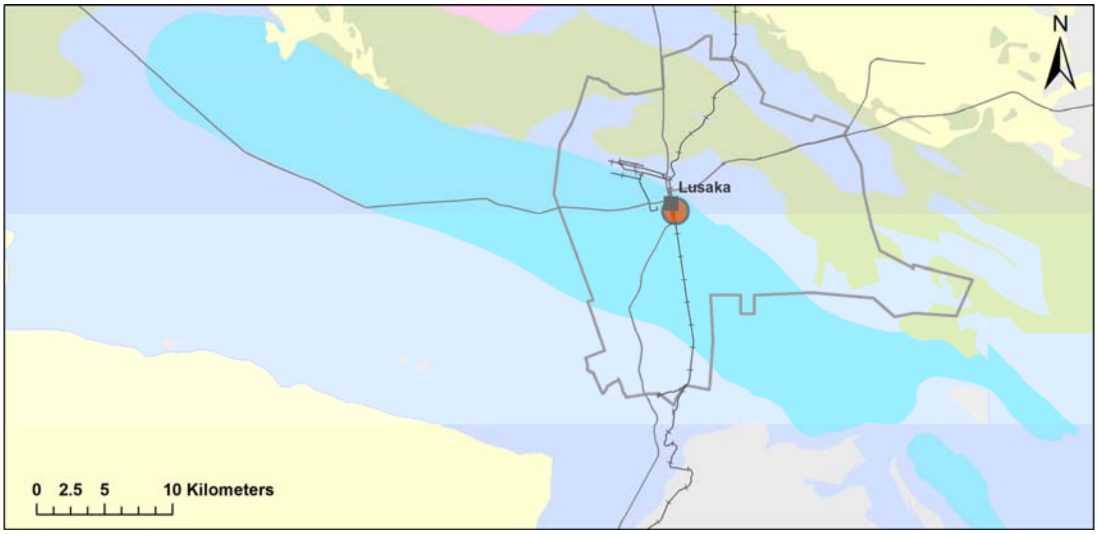

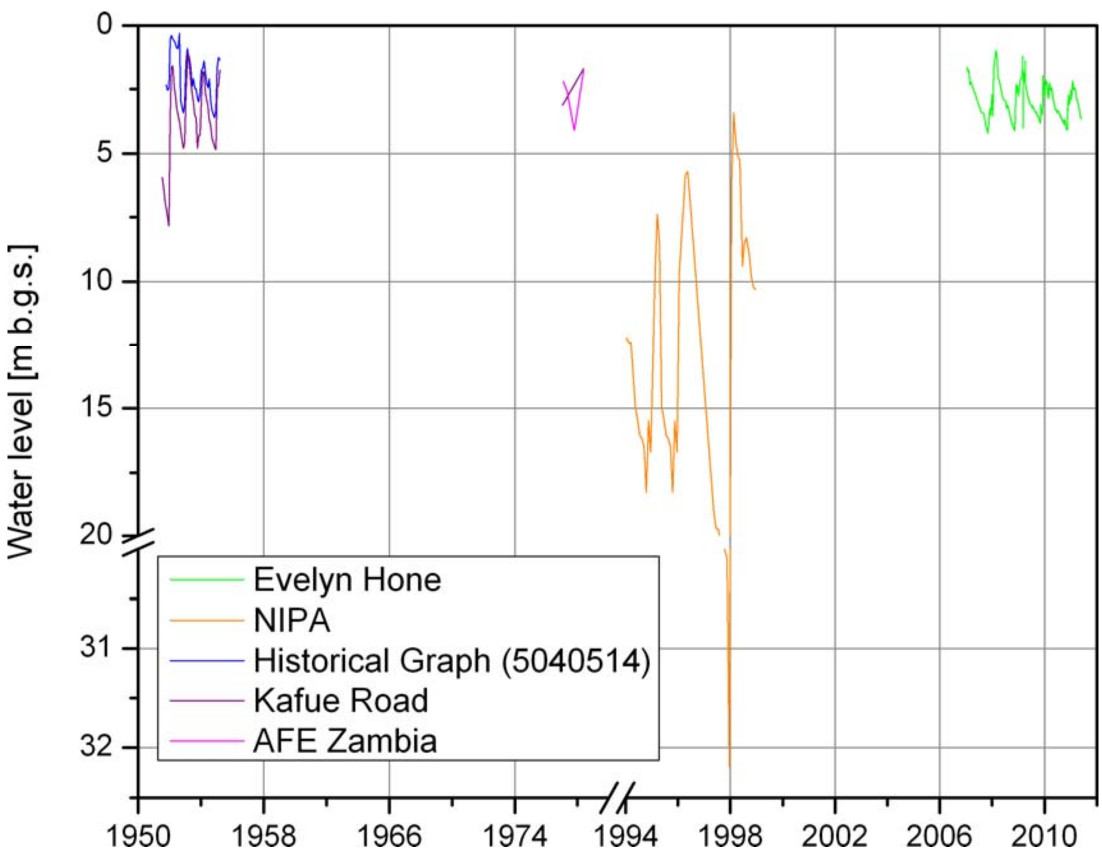

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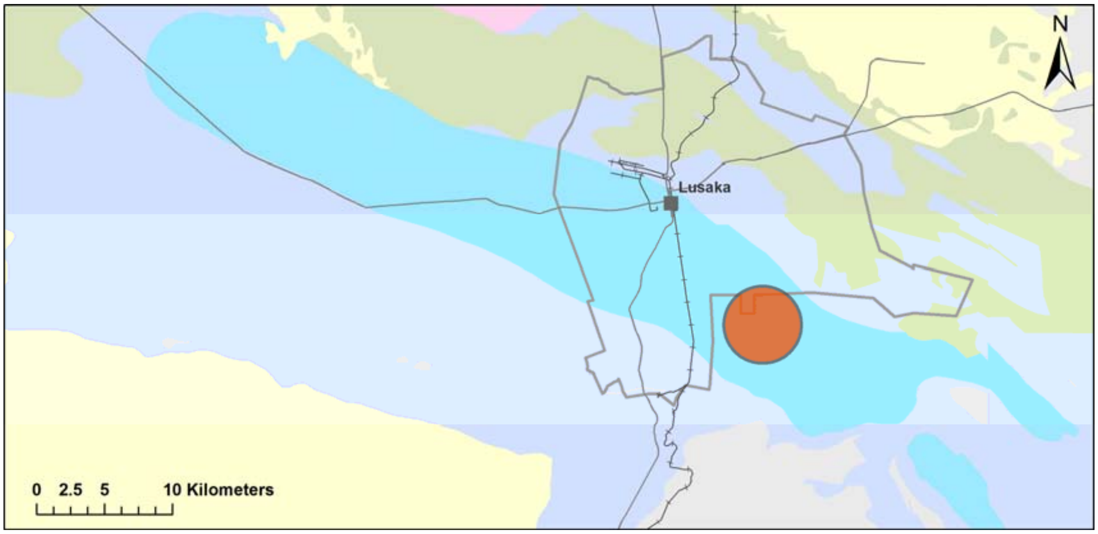

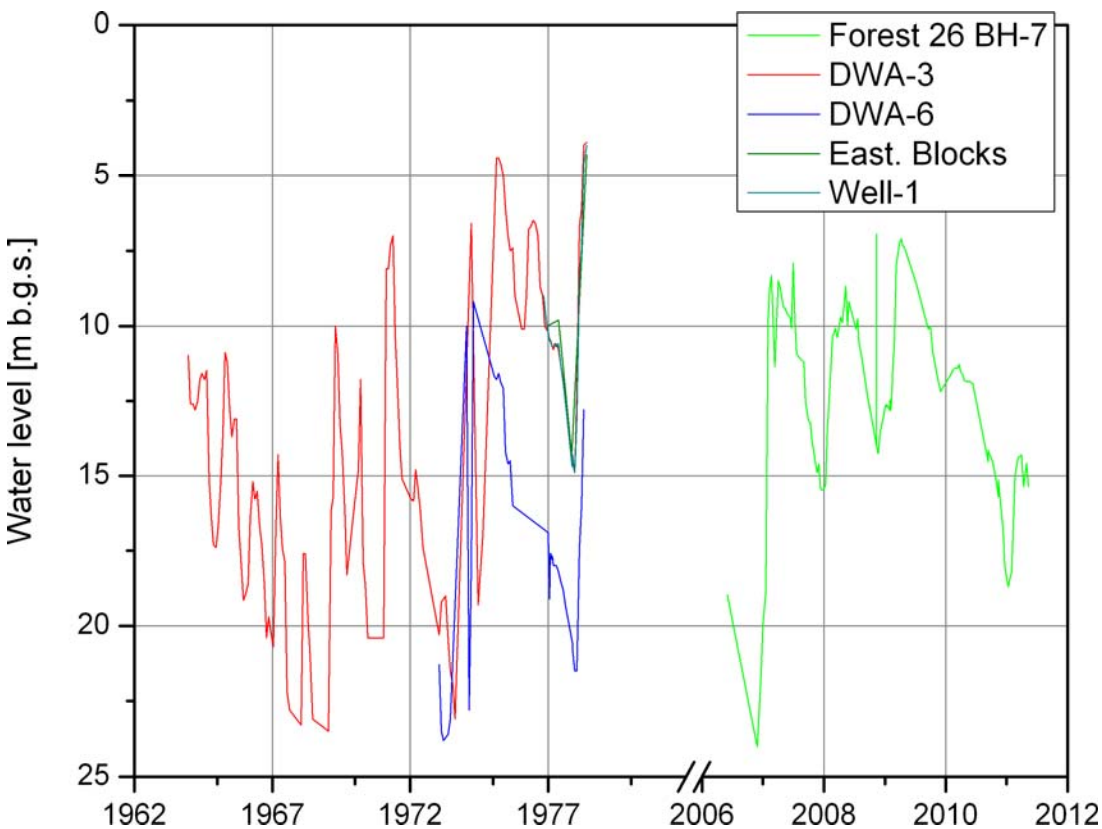

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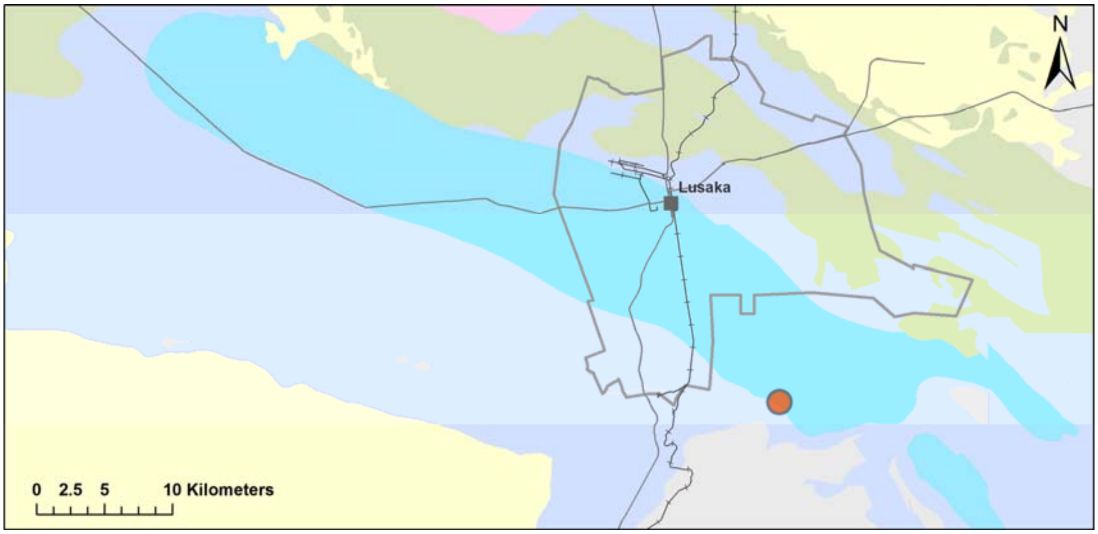

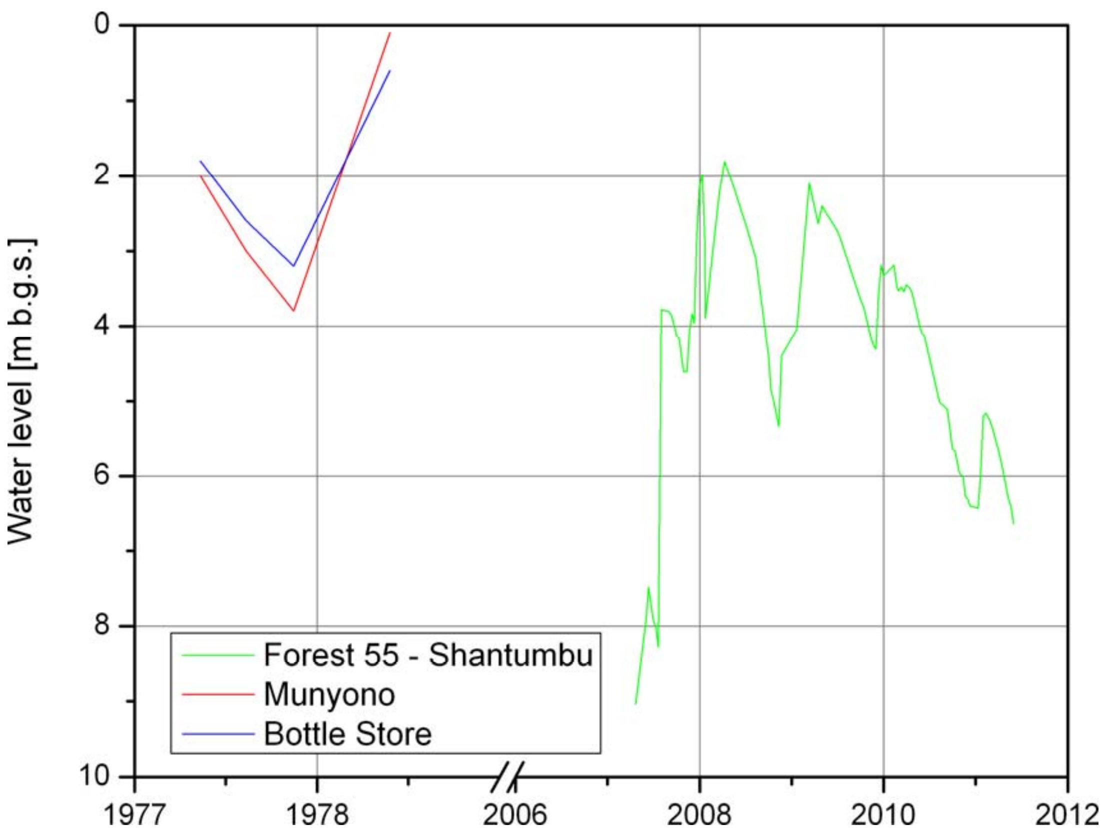

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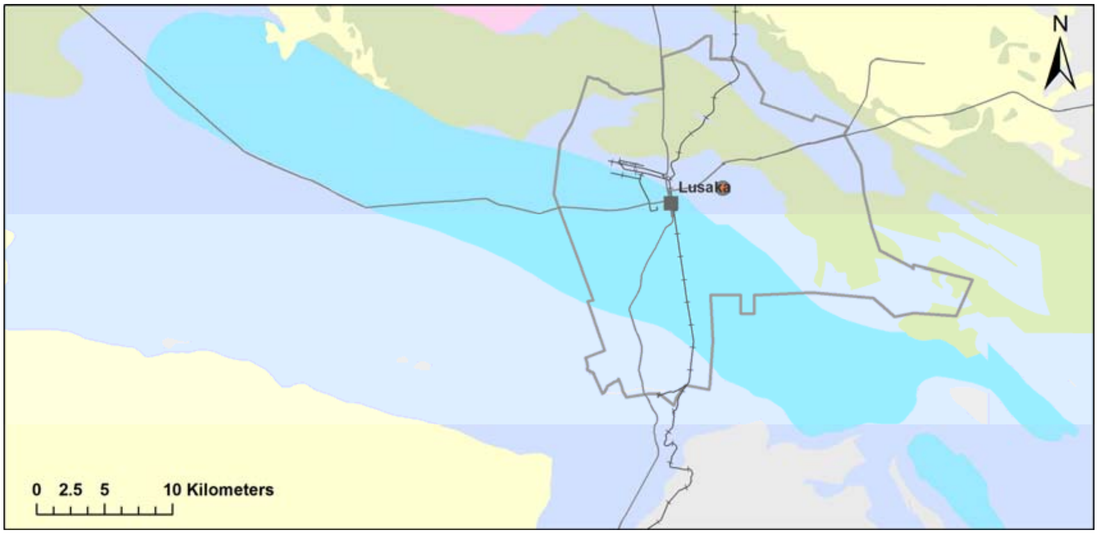

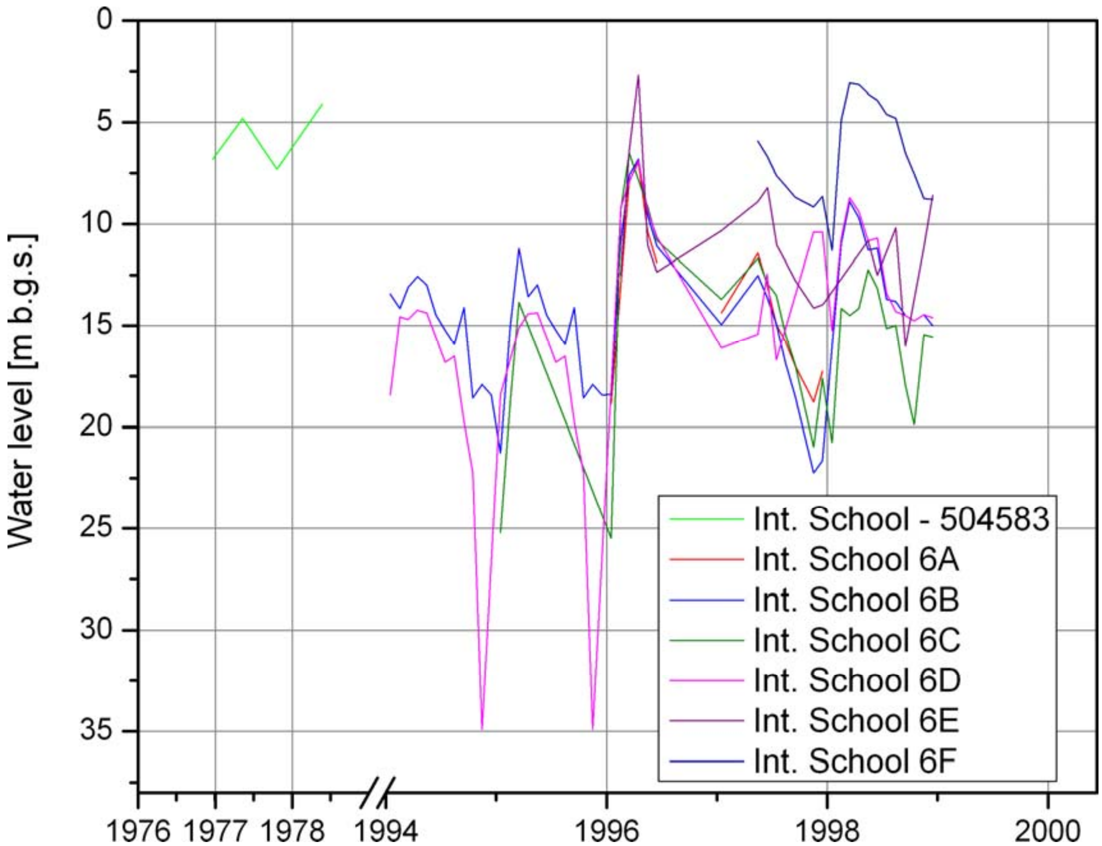

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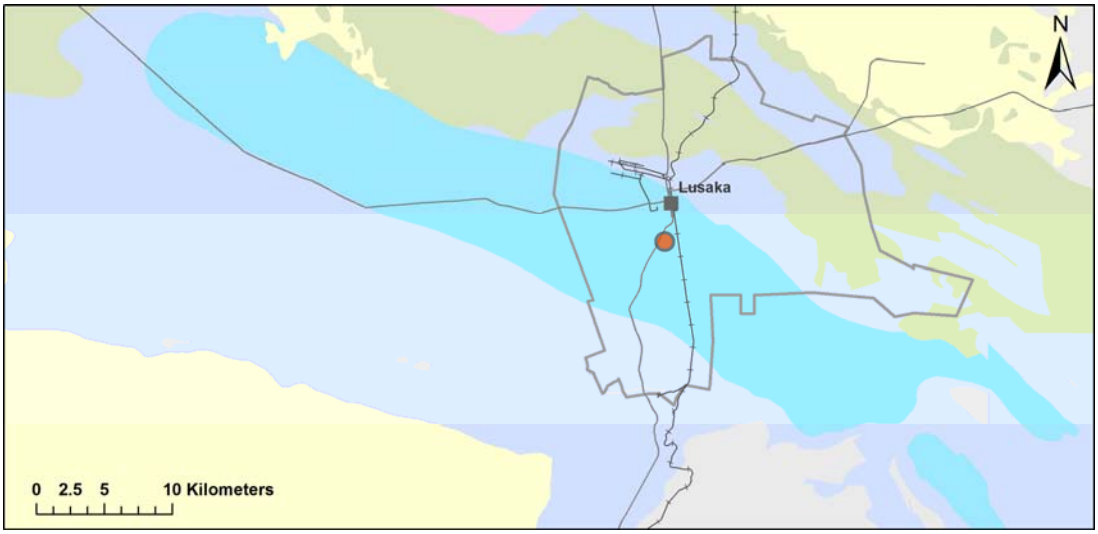

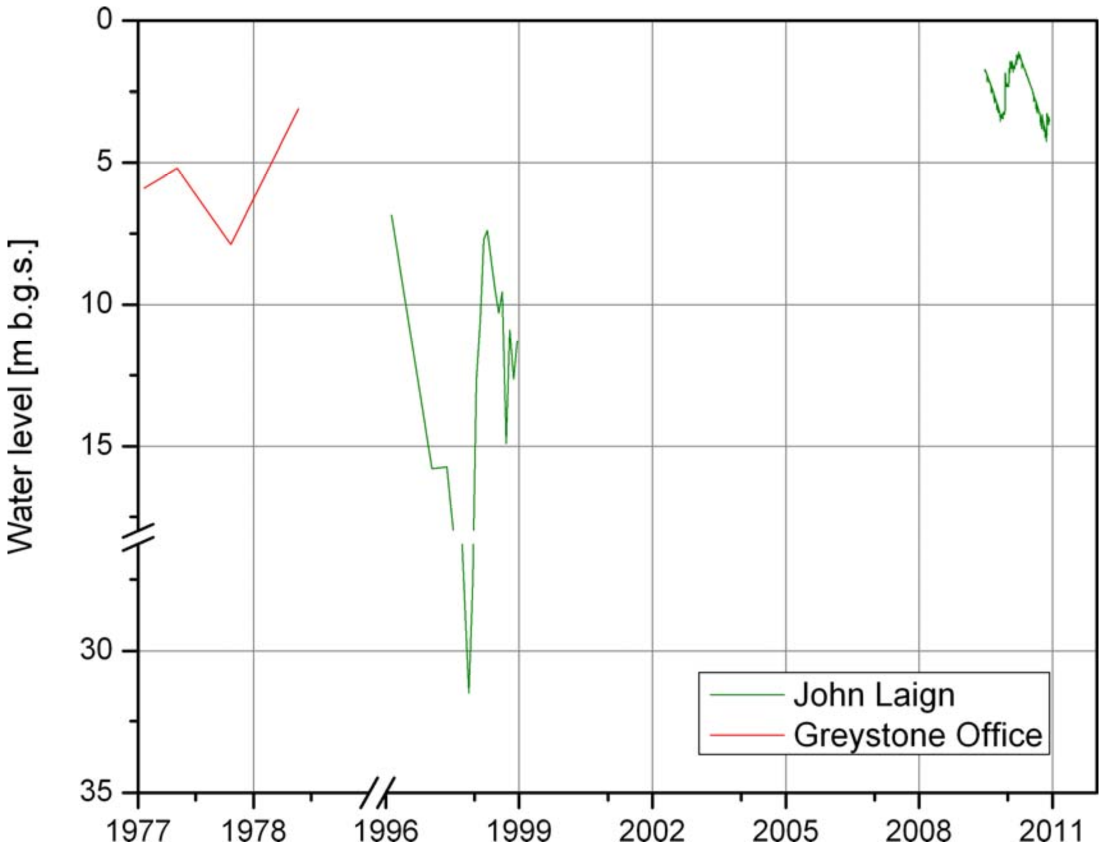

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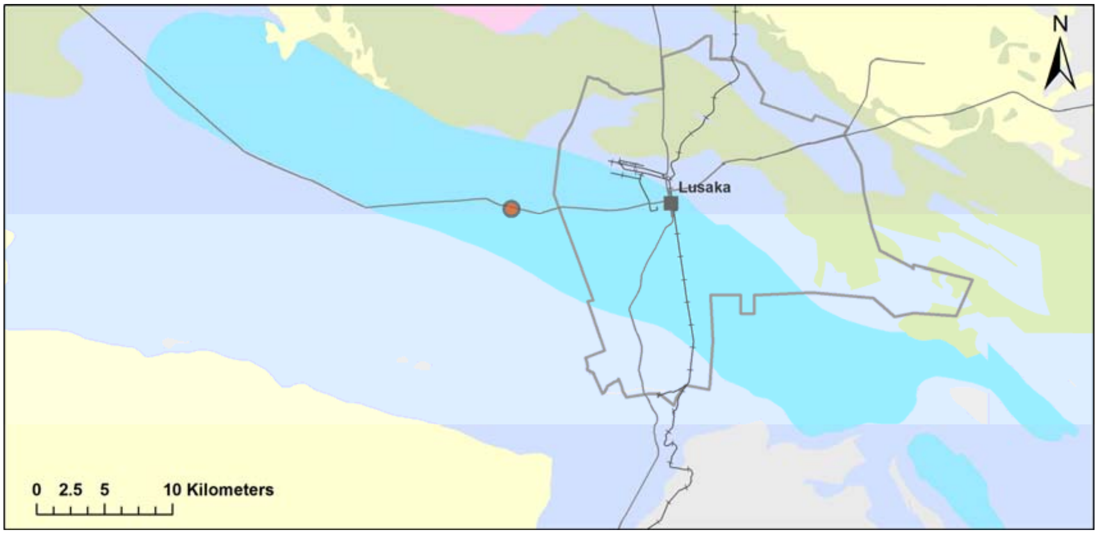

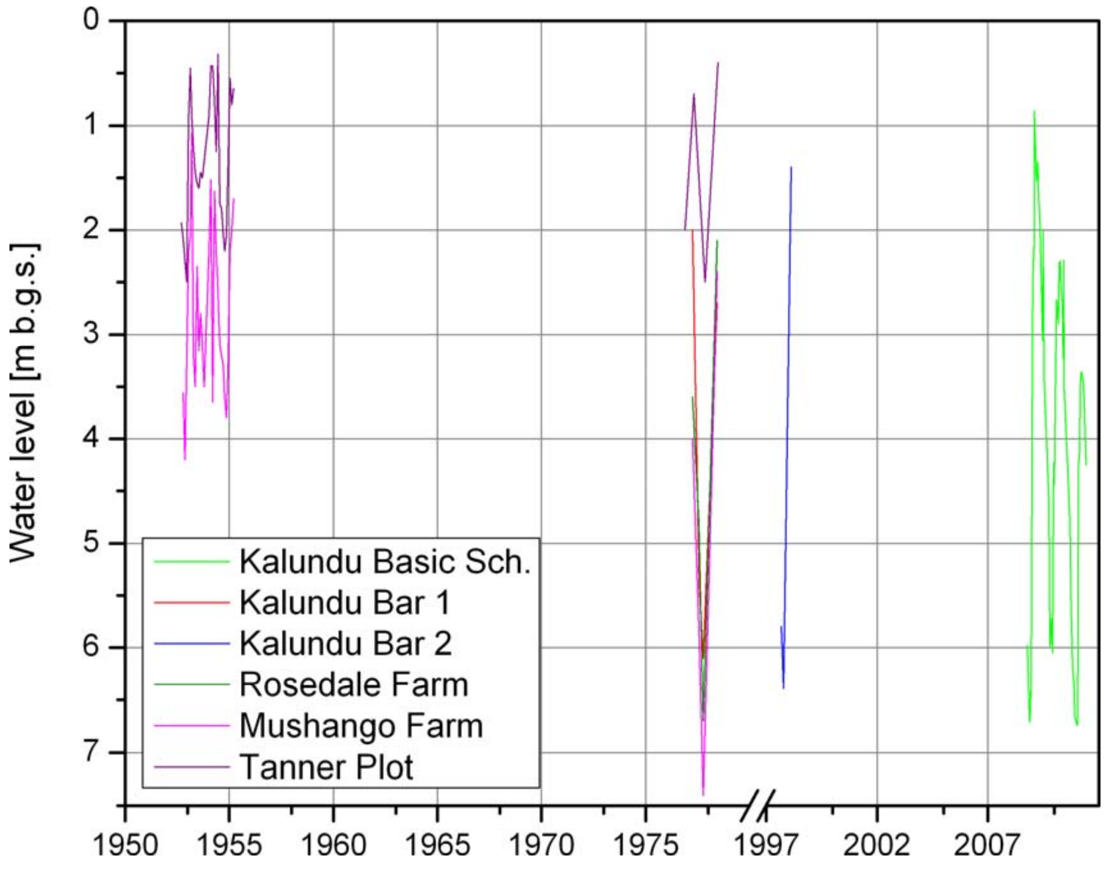

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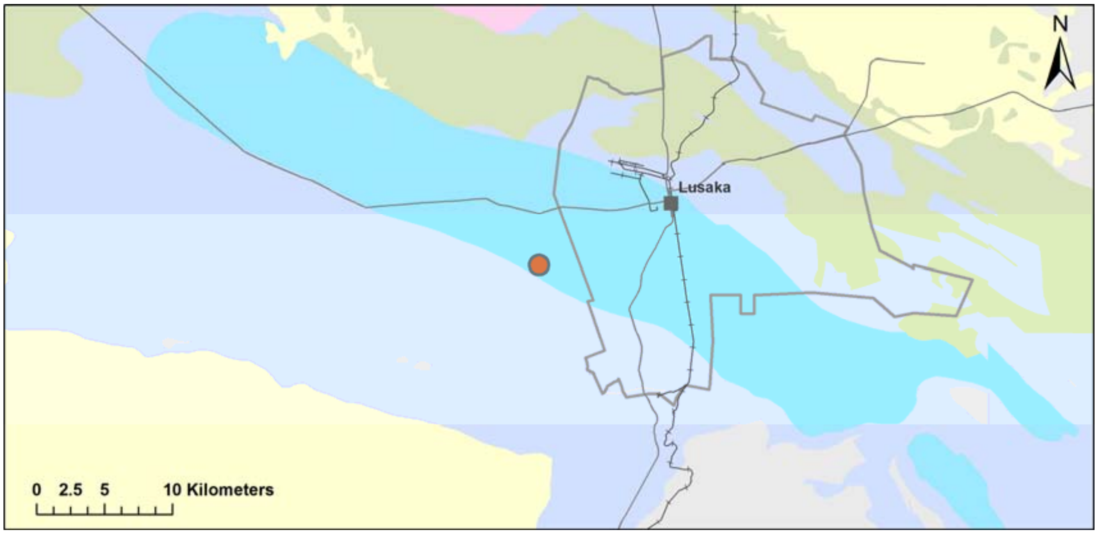

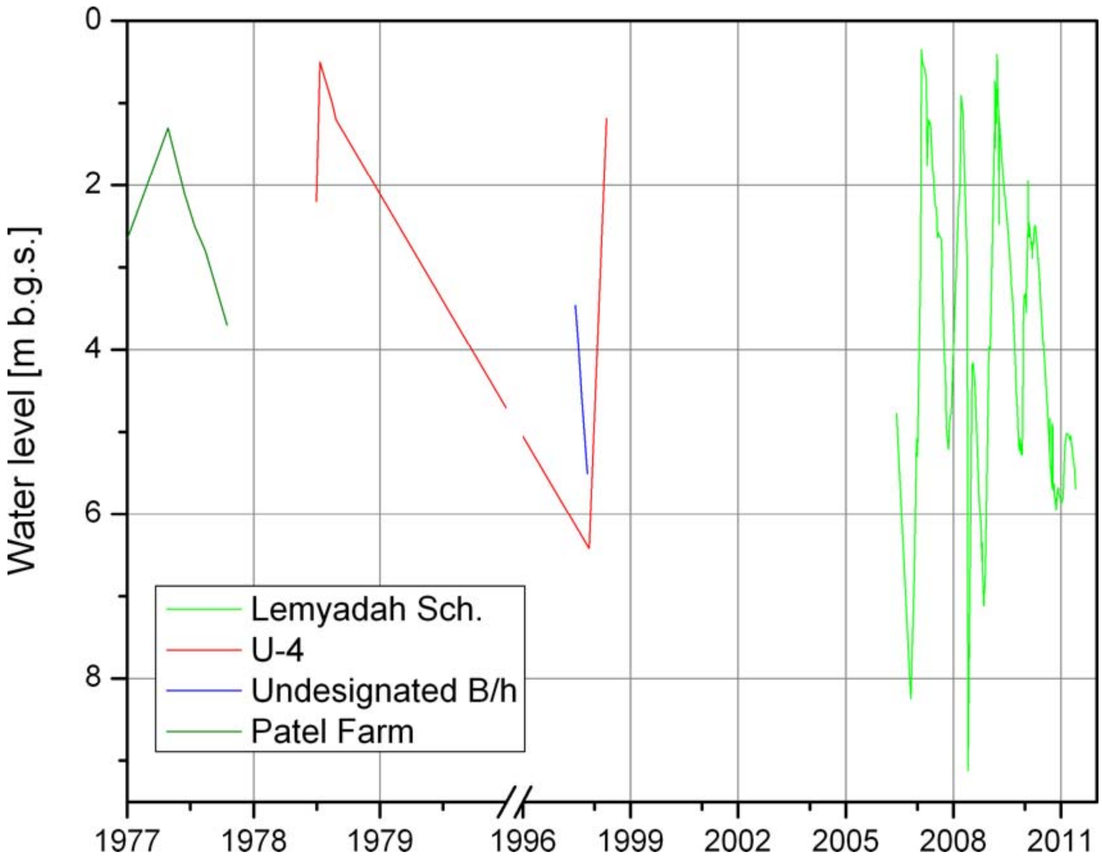

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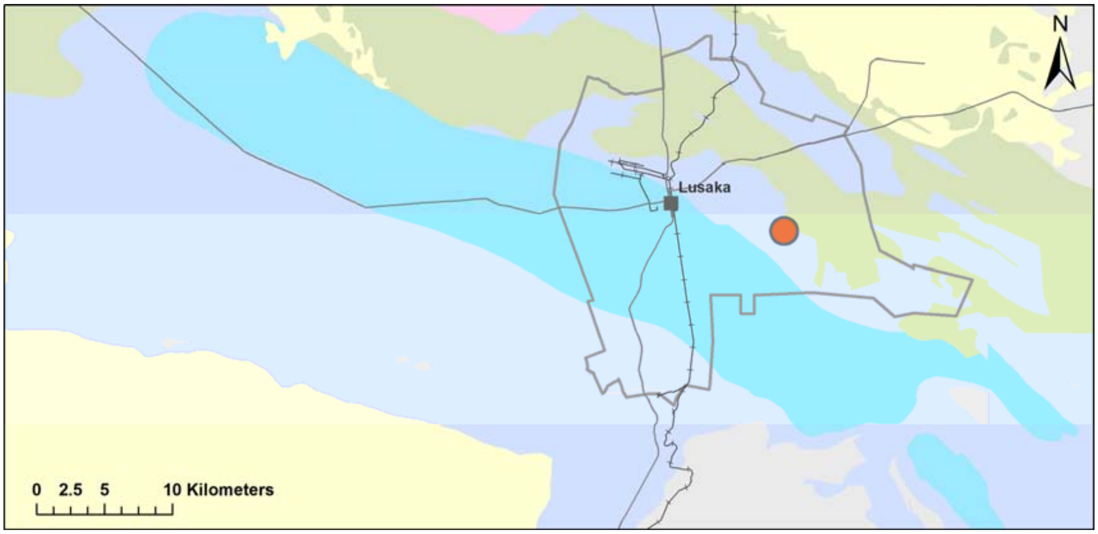

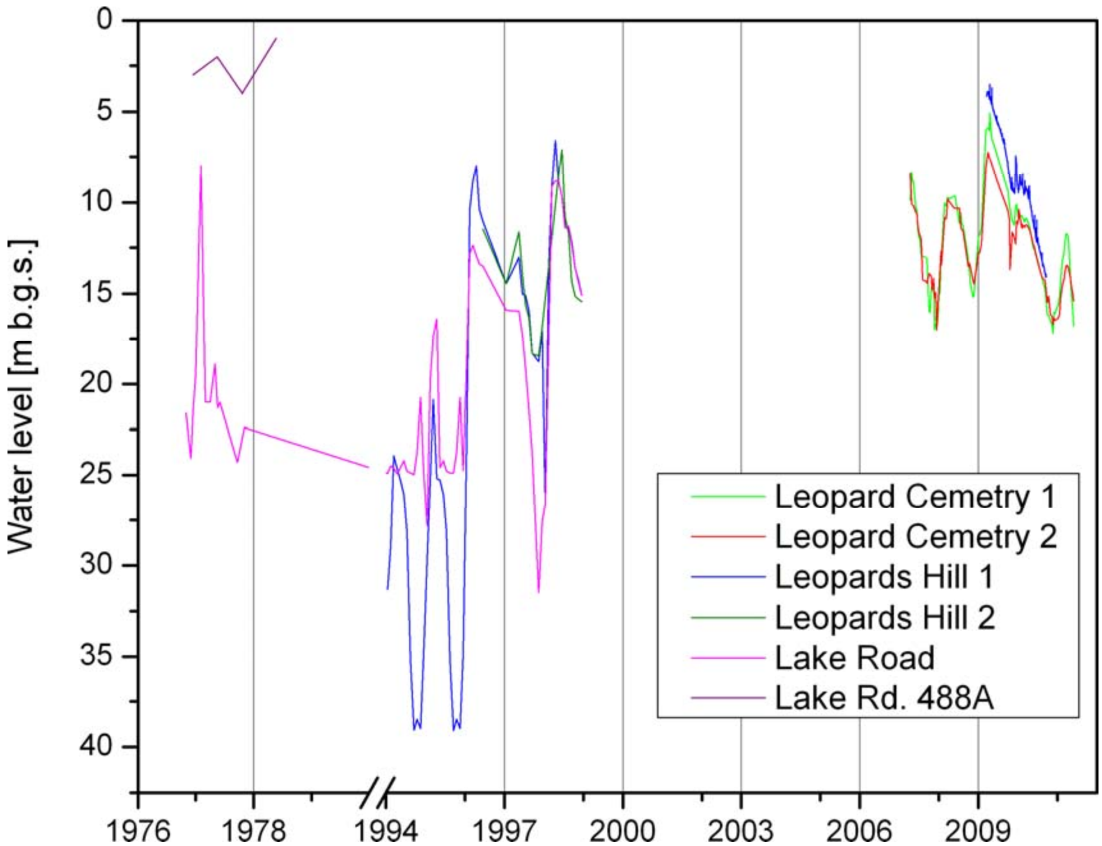

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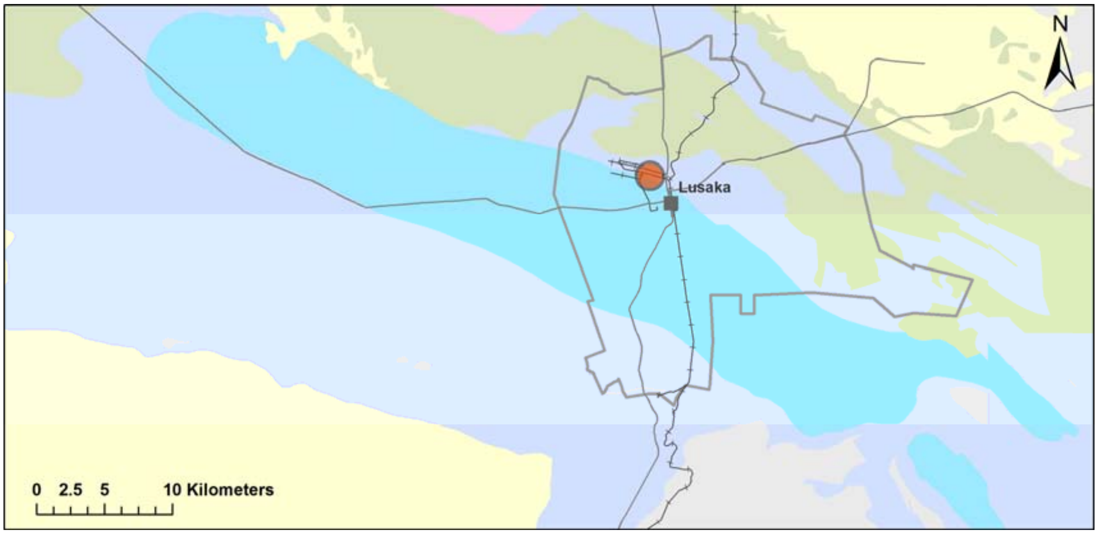

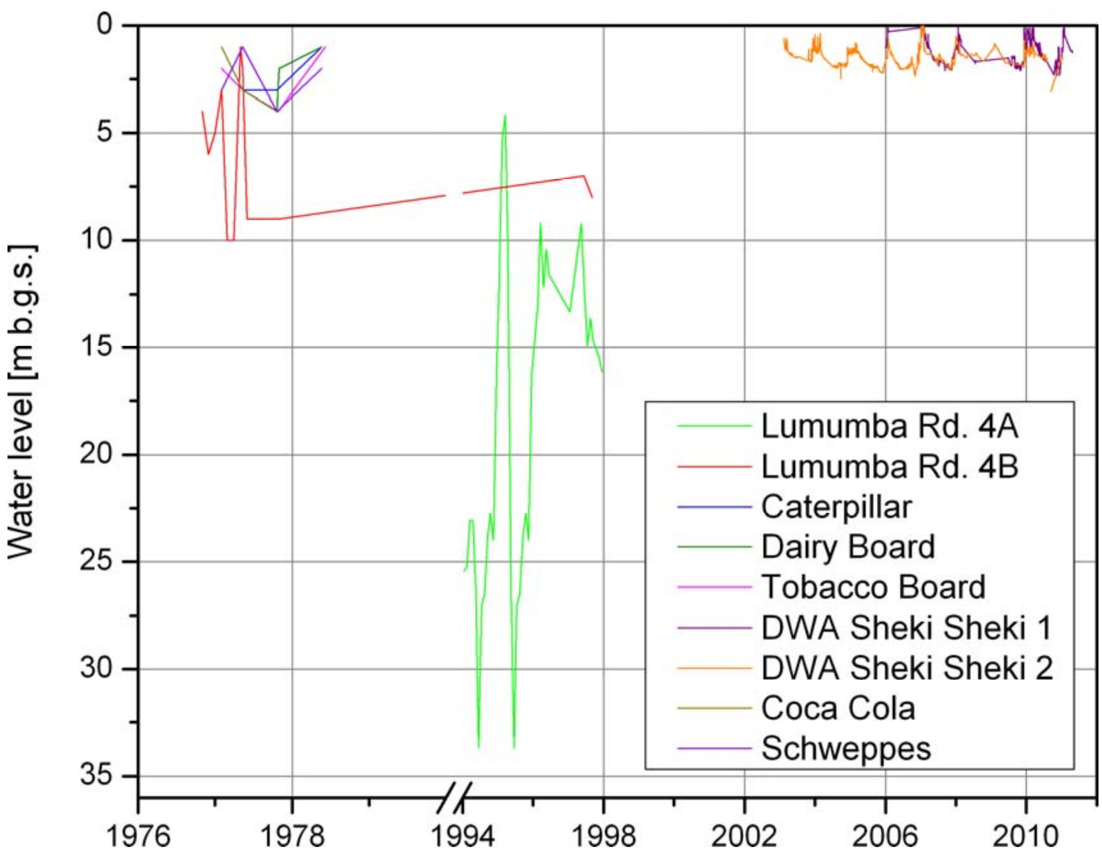

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