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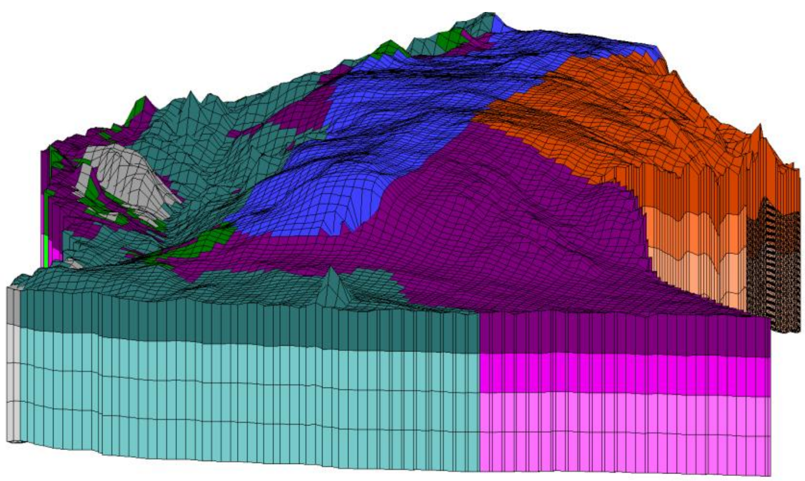
BGR

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

REPORT NO. 6

NUMERICAL GROUNDWATER FLOW MODEL OF THE LUSAKA REGION

Jobst Maßmann



Hannover, December 2012

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Abbreviations

awc	(soil) available water capacity [mm]
BC	boundary conditions
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
DWA	Department of Water Affairs
ET_0	Reference evapotranspiration [mm/yr, mm/month, mm/d]
FDM	Finite-Difference-Method
GW	groundwater
GWR	groundwater recharge
LWSC	Lusaka Water and Sewerage Company
m a.s.l.	meter above the sea level
MABIA	specific name of a simulation model of the soil water balance
MCM	million cubic meter, Mm^3
GMS	Groundwater Modelling System (developed by Aquaveo)
GReSP	Groundwater Resources for Southern Province
K	hydraulic conductivity [m/d]
MODFLOW (MF)	MODular three-dimensional finite-difference ground-water FLOW model (developed by the U. S. Geological Survey)
P	precipitation [mm/yr, mm/month, mm/d]
SRTM	Shuttle Radar Topography Mission
S_s	specific storage [-]
S_y	specific yield [-]
WF	well field

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
2012	Hennings V.	*Assessment of annual percolation rates in the Lusaka Region*	Report No. 5
2012	Maßmann, J	*Numerical Groundwater Flow Model of the Lusaka Region*	Report No. 6
2012, in prep.	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. & Kringel R.	*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.- Ministry of Energy and Water Development*	Technical Note No. 6

2012, in prep.	Krekeler T & C. Siwale	*Discharge measurements and rating curves*	Technical Note No. 7
2012, in prep.	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

Author: Jobst Maßmann

Title: Numerical Groundwater Flow Model of the Lusaka Region

Key words: groundwater flow model, MODFLOW, Lusaka

A transient groundwater flow model of the Lusaka region has been developed for the period from 1976 to 2035. Water table measurements from the water years 2010 and 2011 have been used for the model calibration. Domestic, industrial and agricultural abstractions, recharge, rivers and springs have been considered. A scenario analysis has revealed that the current abstraction scheme is sustainable but new well fields are essential in order to enable additional abstractions, which are needed to meet the future water demand of the region.

Extended Summary

In the framework of the technical cooperation project “Groundwater Resources for Southern Province” (GReSP) the German Federal Institute for Geosciences and Natural Resources (BGR) supports the Department of Water Affairs (DWA), Ministry of Mines, Energy and Water Development, Zambia. In Phase 2 of the GReSP project a comprehensive and on-going investigation program was launched in the Lusaka area in 2011. The program comprises, among other components, the development of a numerical groundwater flow model of the Lusaka region, which is presented in this report.

The model area covers 2,270 km² and contains the Lusaka dolomite and the surrounding areas. The finite difference code MODFLOW is applied to calculate the temporal development of the groundwater table from 1976 to 2035 on a monthly time scheme. The calibration period extends over the water years 2010 and 2011. The model setup is based on earlier reports concerning the hydrogeological properties, the land use and the groundwater recharge. The model considers groundwater abstractions for domestic water supply, industry and irrigation. An important point is the groundwater-surface water interaction at rivers and springs. Based on detailed studies on the recharge behaviour during the calibration period and precipitation data the groundwater recharge has been determined for the entire time period.

In general, the results of comparisons between simulated and observed quantities show a good agreement. Deviations could be explained by inaccuracies in the input parameters and local inhomogeneities due to karst features as fractures, cavities and tubes.

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

The analysis of future scenarios has showed that the current abstraction rates are sustainable in general, even if additional drawdowns up to 7 m can locally be expected at some well fields in the City and in intensively irrigated areas.

However, new well fields outside the City are essential in order to allow additional sustainable abstractions. In a first expansion phase, well fields close to the City and in the Local Forest Reserve area to the southeast should be developed. In a later phase, well fields to the West of Lusaka would be needed. Considering the proposed increase in water demand, a combination of new well fields and new transfer capacities from Kafue are a reasonable solution to assure the supply of drinking water until 2035.

1 Introduction

In the framework of the technical cooperation project “Groundwater Resources for Southern Province” (GReSP) the German Federal Institute for Geosciences and Natural Resources (BGR) supports the Department of Water Affairs (DWA), Ministry of Mines, Energy and Water Development, Zambia, in order to facilitate an effective groundwater resource planning and management and to strengthen the capacities of the Zambian water sector. One part herein is the development of a numerical groundwater flow model of the Lusaka region. This model should compile the data and information on the water resources system from the previous studies in order to improve the general understanding of the hydraulic system and in particular to assess the impact of current and future abstraction schemes.

In 1978, the BGR and the Lusaka City Council have already realized a “Groundwater and Management Study for the Lusaka Water Supply” (von Hoyer et al. 1978). Herein, a numerical groundwater flow model has been developed, which has been revised in 2002 (Schmidt 2002). In contrast to these studies, the work at hand considers a wider area with a higher resolution and includes new investigations, conducted from 2009 to 2011. Furthermore, the prediction period has been extended to 2035.

2 Study area

2.1 General

The study area (Figure 1) is located in the Lusaka region, Zambia, and covers about 4,500 km². It includes parts of the Lusaka and Central Provinces. The topography is dominated by the central Lusaka Plateau (up to 1375 m a.s.l.) sloping down to the edges (975 m a.s.l.). The average yearly precipitation is about 830 mm (1976-2011); 95 % takes place from November to March. The reference evapotranspiration ET_0 is about 1800 mm/year. The irrigated area amounts to about 10 %.

The water demand of Lusaka is satisfied by wells, located in the City and the surrounding area, and a pipeline transferring surface water from the Kafue River.

The Mwembeshi, Chunga, Ngwerere, Chilongolo and the Chalimbana are the most important rivers in the area.

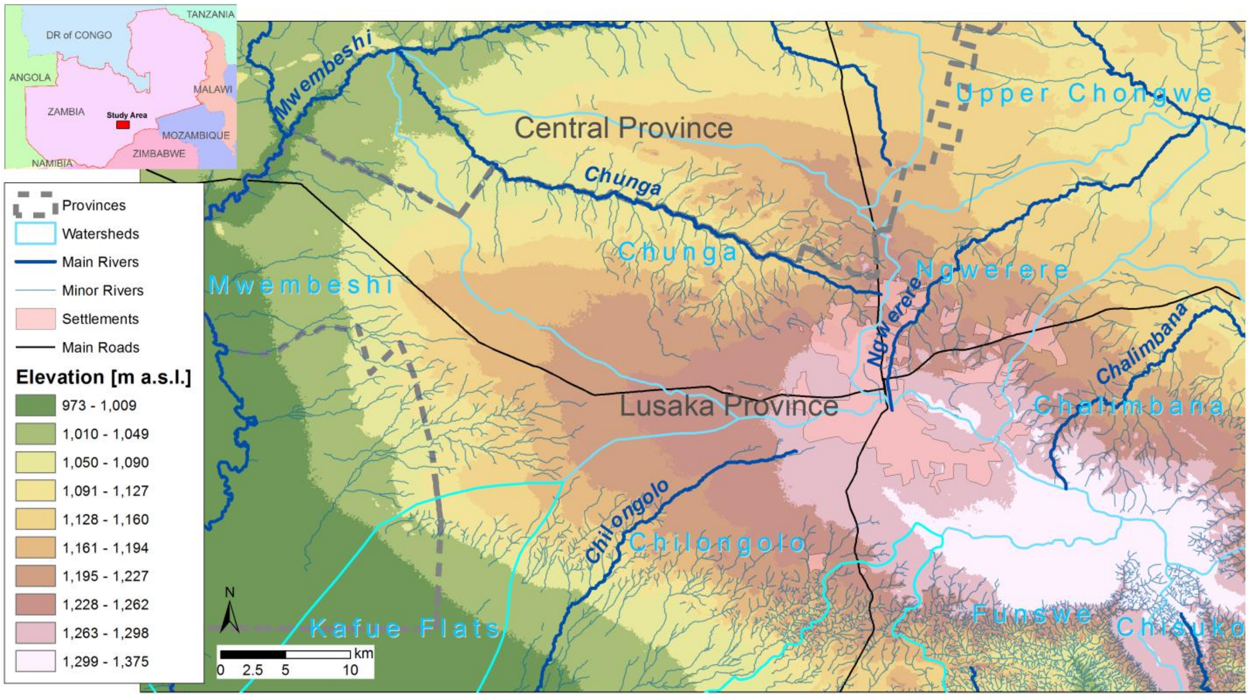


Figure 1: **Study area in the Lusaka region.**

2.2 Hydrogeology

The geology and hydrogeology of the area, including a characterization of the aquifer systems, are described in previous reports (Bäumle & Kang'omba 2009; Bäumle 2011, Bäumle & Kang'omba 2012) and are based mainly on Simpson (1962), Simpson et al. (1963) and von Hoyer et al. (1978). According to these descriptions, three formations can be distinguished in principal (see Figure 2, cf. chapter 3.4):

1) Lusaka dolomite formation (carbonates),
2) Cheta formations (schists and carbonates)
3) Chunga formation (schists and quartzites)

All calcareous units are highly karstified, as described in detail in von Hoyer et al. (1978), von Hoyer et al. (1980), Bäumle & Kang'omba (2009) and Hahne & Shamboko-Mbale (2010).

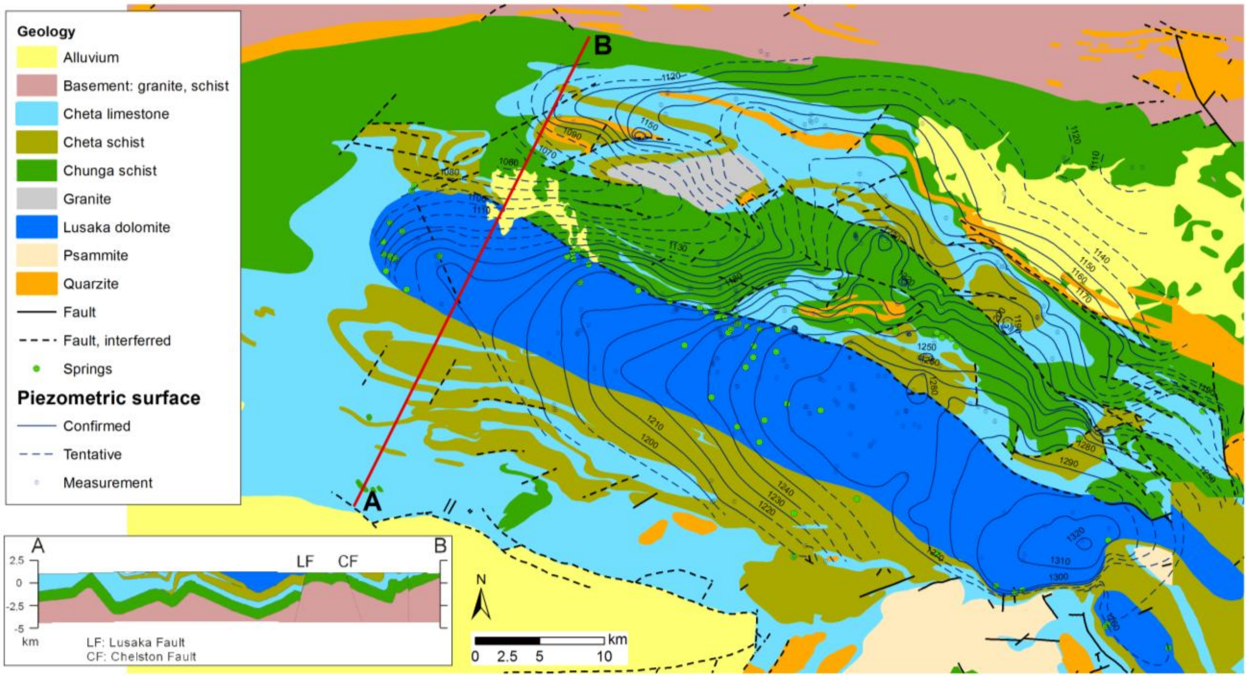


Figure 2: Simplified geological map of the Lusaka region, based on Simpson (1962) and Simpson et al. (1963); cross section constructed using the projected dip data and elevation-registered map information (Günther 2011); piezometric surface in m a.s.l., based on measurements taken in April 2009 (Bäumle & Kang'omba 2012). The location of springs is based on Museteka & Bäumle (2009)

In general, the groundwater system is shallow and the piezometric surface follows the topography. Many springs can be observed, especially in the Lusaka dolomite. The conductivities are dominated by fissures and cavities; consequently, the calcareous aquifers represent the most productive aquifer systems. Considering the frequency and depth of water bearing fissures and cavities (cf. Figure 3), only the uppermost 100 m seem to be hydraulically relevant. However, only minor knowledge about the deeper zones exists.

At large, the aquifers can be assumed to be unconfined.

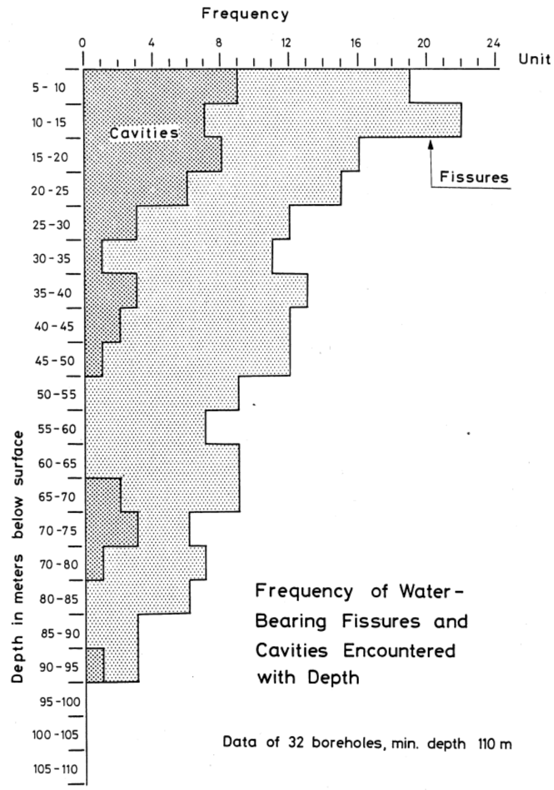


Figure 3: Frequency of water-bearing fissures and cavities encountered with depth (Hoyer et al. 1978)

3 Model setup

3.1 Numerical approach

It is assumed that the aquifer system can be described as a porous medium with sectionwise homogeneous material properties. Thus, typical phenomena observed in karst, as preferential flow, heterogeneity on the small and large scale or turbulent flow, cannot be simulated directly.

The groundwater flow is described by the groundwater flow equation, based on the Darcy flow equation and the conservation of the water volume in the pores:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t} \qquad \textbf{Eq. 1}$$

with the hydraulic conductivities K_{xx}, K_{yy}, K_{zz}, the source term Q, the specific storage coefficient S_s and the time t. The hydraulic head h is defined in relation to a reference height (sea level) as m a.s.l. (meter above sea level). The Finite-Difference-Method (FDM) is applied. The domain is divided into homogeneous cells, so that the differential equation can be transferred to finite differences and be solved. Within a single cell, only one parameter set can be used and only one solution is available. The required input parameters per cell are the hydraulic conductivity, the specific storativity as well as the cell volume and occasionally a source term, which could represent groundwater recharge or well abstraction. The output parameters are the hydraulic head, the flow vector and the storage within each cell.

The software *MODFLOW 2000* (*Harbaugh* et al. 2000) is applied for processing and GMS 7.1 for pre- and post-processing.

3.2 Model area and boundary conditions

Principally, boundary conditions (BC) are needed at all outer boundaries of a numerical model. In order to simulate sinks and sources, BC within the model can be set additionally.

Boundary conditions can be defined as:

- constant/transient hydraulic head (e. g.: river, sea, lake),
- constant/transient flux (e. g.: inter catchment flow, well),
- no flux (e. g.: impermeable layer, groundwater divide) or
- flux, defined as a function of the hydraulic head (e. g.: spring, drainage).

The following aspects have been considered to specify the extent and boundary conditions of the numerical model: the area of interest (main aquifer, well fields), the topography, the groundwater contour lines as well as the rivers and watersheds. In concrete terms (cf. Figure 4):

1. BC in the North: no flow, ground water divide and border of the Chunga watershed;
2. BC in the Northeast: constant head (1140 m a.s.l.), derived from the piezometric surface;
3. BC in the East: no flow, groundwater divide;
4. BC South: constant head (1140 m a.s.l.), derived from the piezometric surface and topography;
5. BC Southwest: no flow, assumed groundwater divide, based on topography;
6. BC West: constant head, the head equals the river stage in the Mwembeshi River. The stage of the Mwembeshi is assumed to be 7.5 m below the elevation, which has been determined by SRTM.

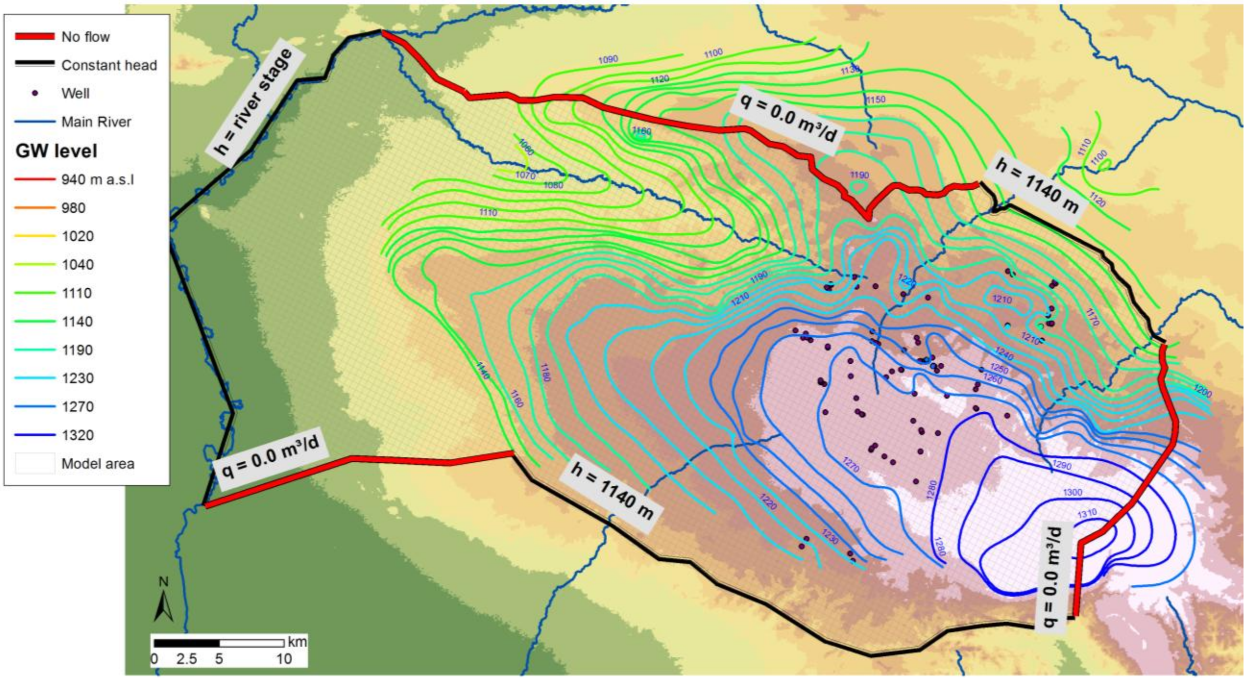


Figure 4: Model area, boundary conditions and piezometric heads in m a.s.l., based on measurements taken in October 2009.

The entire model area covers 2,270 km². It contains all well fields of the LWSC and nearly the whole Lusaka dolomite, despite a small part east of the water divide in the Lusaka Forest Reserve area. In the western part of the model area no water level measurements for calibration exist. Thus, the modeling results in this part come along with higher uncertainties, as discussed in Chapter 4.

3.3 Spatial discretisation

Horizontally, the model area is discretised by 9,109 square shaped elements with an edge length of 500 m. Vertically, four layers have been realized with a depth of about 50 m. A total depth of 200 m is considered sufficient, because the hydraulic relevant zone with cavities and fissures is quite shallow (cf. Figure 3). Only minor knowledge exists about the deeper zones. The four layers allow the consideration of a change in hydraulic properties with depth. The topography of the uppermost layer has been derived from the SRTM elevation model. The MODFLOW mesh is shown in Figure 5.

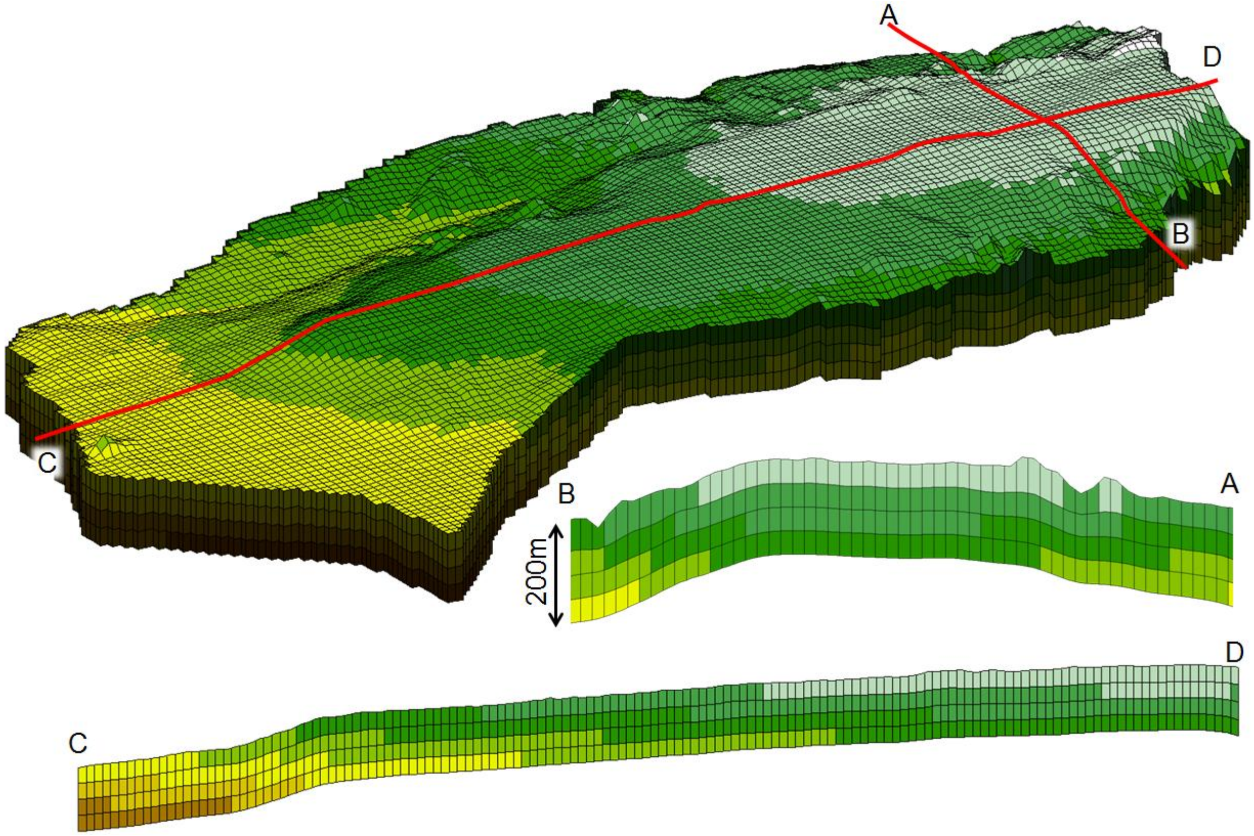


Figure 5: Local discretisation of the model area (MODFLOW mesh). The colors represent the elevation of the top of each cell.

3.4 Temporal discretisation

The temporal discretisation of the numerical model can be distinguished into three periods:

- historical time period: October 1975 to September 2009,
- calibration period: October 2009 to September 2011 and
- future scenarios: October 2011 to September 2035.

Consistent groundwater level measurements are only available for the calibration period.

First model runs have been realized in steady state. Investigations with yearly to weekly timesteps have been performed. It can be stated that monthly timesteps are sufficient for accuracy and comparison with measurements.

3.5 Material groups

Based on the geology, pumping tests (Bäumle 2011, Bäumle et al. 2012), the presence of rivers and streams as well as model calibration, the model area has been divided into material groups, as depicted in Table 1 and Figure 6. Each material group belongs to one parameter set, consisting of hydraulic conductivity, specific yield and storativity, as depicted in Table 2.

The material groups are related to geological units. In general, the geological layers are much thicker than the hydraulic relevant depth and also they are not steep sloped. Consequently, a change of the geological unit with depth can be neglected.

As a result of the calibration process, the Lusaka Dolomite and the Cheta Limestone have been further subdivided. In the South of the occurrence of the Lusaka Dolomite, schists and limestones are alternating, so that a classification of the material group by the uppermost geological layer is not reasonable. Productive wells and the absence of a dense river system in this area are indicators for higher hydraulic conductivities than expected in pure schist (Bäumle et al. 2012).

Table 1: Hydrogeological units and material groups.

	Formation	*Lithology*	*Material Group*	*Colour in Figure 6*	*Groundwater potential*
Katanga	Lusaka dolomite	Dolomites and limestone	Lusaka dolomite 1		High
			Lusaka dolomite 2		High
			Lusaka dolomite 3		High
			Lusaka dolomite 4		High
	Cheta	Dolomites and limestone	Cheta limestone 1		High
			Cheta limestone 2		Moderate
		Limestone/schist alternating	Cheta alternating		Moderate
		Schists and others	Schist		Limited
	Chunga	Schists and others			
		Psammite	Psammite		Limited
Igneous Rocks		Granite	Granite		Limited

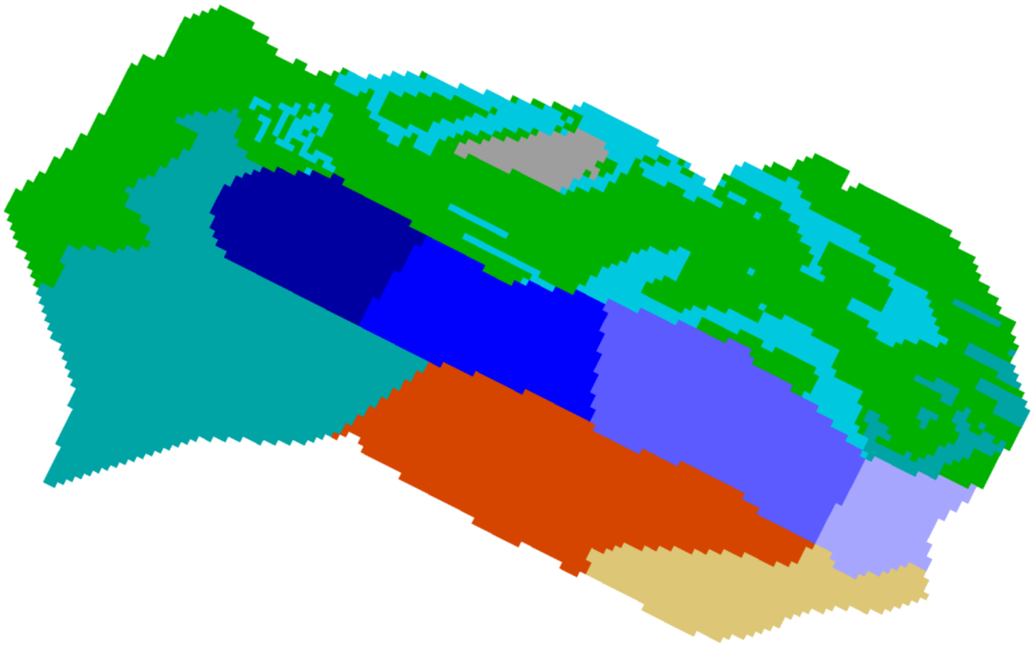


Figure 6: Material groups.

Table 2: Hydraulic conductivities (*K*) and specific yields (S_y).

	Material Group	***K* [m/d] (0-50 m)**	***K* [m/d] (51-100 m)**	***K* [m/d] (101-200 m)**	***S_y* [-] (0-50 m)**
	Lusaka dolomite 1	20.0	2.0	0.1	0.07
	Lusaka dolomite 2	20.0	2.0	0.1	0.07
	Lusaka dolomite 3	70.0	7.0	0.1	0.07
	Lusaka dolomite 4	40.0	4.0	0.1	0.07
	Cheta limestone 1	60.0	6.0	0.1	0.07
	Cheta limestone 2	10.0	1.0	0.1	0.05
	Cheta alternating	10.0	1.0	0.1	0.05
	Schist	1.0	0.1	0.1	0.05
	Psammite	0.1	0.1	0.1	0.05
	Granite	1.0	0.1	0.1	0.05

Within a hydrogeological unit, the material properties change with depth, which is reflected by decreasing conductivities with depth. The parameters are listed in Table 2. All parameters are within the range of literature values, which are based on pumping tests. A detailed discussion of aquifer properties can be found in Bäumle (2011). Since the entire aquifer is assumed to be unconfined, the specific storage is only of minor importance; a value of 0.0001 m^{-1} is used for the deeper model layers (50 - 200 m).

3.6 Abstractions

3.6.1 Domestic

The LWSC operated 83 wells in 2011; additional 9 wells are operated by Water Trusts. For each of these wells, time series of abstraction rates on a daily time scale with only minor gaps have been provided by the LWSC for the water years 2010 and 2011. For the years 2001 to 2011 total yearly abstraction rates have been provided. In order to estimate the abstraction rates for the historical time series (1976-2009), the drilling date of the wells and abstraction data published in Schmidt (2002) have been considered. The total well abstraction for domestic purpose is shown in Figure 7. Most of the wells are located in settlement areas (cf. Figure 4). Only a small amount (< 0.5 %) of the water abstracted by LWSC wells is used by the industry (Mayerhofer et al. 2010).

The abstraction rates for the future scenarios are described in chapter 4.5.

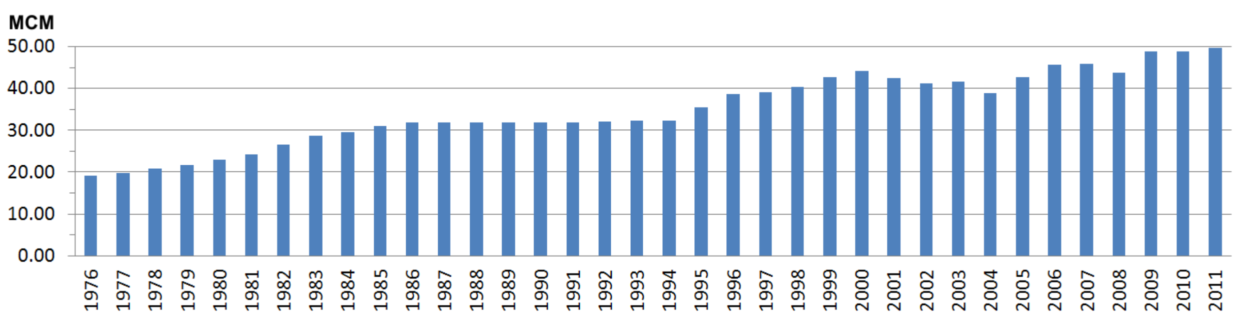


Figure 7: Domestic abstraction rates in MCM.

3.6.2 Industrial

Mayerhofer et al. (2010) have conducted a survey on the industrial water use in the Lusaka area. The most important industrial wells are listed in Table 3 and have been considered in the model for the year 2010. Since no data is available for the preceding years, a linear trend between 1950 (no industrial abstraction) and 2010 (4 MCM) has been assumed. For the future scenarios, no further change in the industrial abstractions is considered.

Table 3: Major industrial water users (Mayerhofer et al. 2010, shortened).

Water User	***Type of Industry***	***MCM/year***
Lafarge	Cement Producer	2.9
Zambian Breweries	Brewery	0.7
Zambian Limited	Oil Manufacture	0.2
Tombwe Processing	Tobacco	0.2

3.6.3 Irrigation

In order to determine the abstraction for irrigation, two earlier reports have been used: The land use map of the Lusaka Region (Hahne & Shamboko-Mbale 2010) and the results of a survey on commercial farming (Mayerhofer et al. 2010). For the areas of small scale agriculture, which cover large parts of the study area (cf. Figure 8) rain-fed agriculture is assumed and hence, no irrigation is applied. Within the study area, the main water source for irrigation is groundwater.

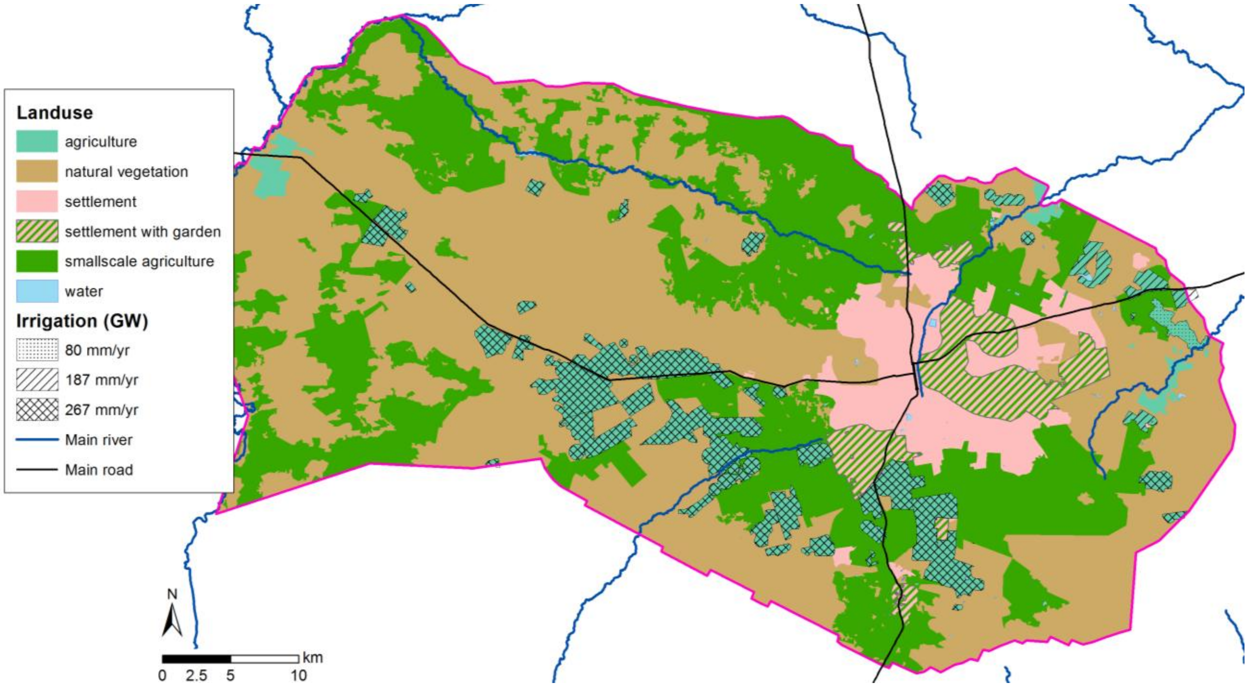


Figure 8: Land use map (Hahne & Shamboko-Mbale 2010, modified) and groundwater abstraction rates for irrigation.

The total commercial agriculture area within the model area amounts to 180 km². The irrigation sources and demands have been determined by a survey (Mayerhofer et al. 2010): 2,674 m³/yr/ha are abstracted in areas, which are 100 % irrigated by groundwater. This value is in good accordance with the results of a functional model, applied by Hennings (2012). Partly, surface water is used for irrigation. As a consequence, lower abstraction rates are applied in the concerned areas. In total, an abstraction of 42 MCM for irrigation purpose is applied for the water year 2009. This amount of water represents the upper limit, because not the total area of commercial agriculture is irrigated.

In order to estimate the long term development of abstractions, a linear increase between 1950 (no irrigation) and 2009 is applied. This linear trend is extrapolated for the future scenarios assuming an annual growth rate of 1.7 %, which results in an abstraction rate of 63 MCM in the water year 2035.

Based on seasonal abstraction data published in Mayerhofer et al. (2010), the annual irrigation demand is split according to Figure 9. In the numerical model, the irrigation demand is considered by negative recharge.

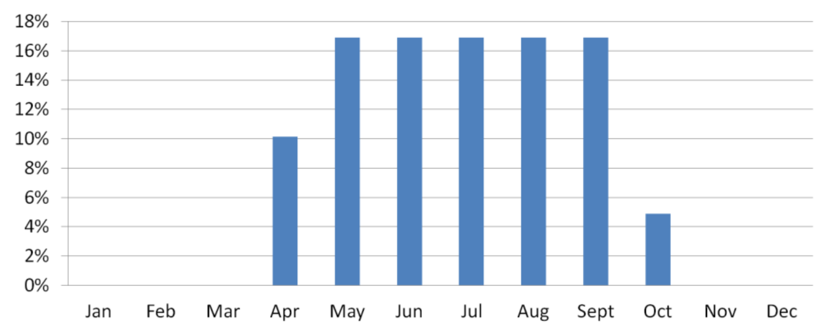


Figure 9: Monthly variation of the irrigation demand (after Mayerhofer et al. 2010).

3.6.4 Private wells (settlement with garden)

Private wells are abundant in the area and represented by the land use class “settlement with garden” (cf. Figure 8). Since no data about these abstractions is available, only a rough estimation is possible. The basis for the determination is the consumption data per township and year for 2009, provided by the LWSC:

- The average water demand in the settlements with gardens, which are 100 % supplied by the LWSC, amounts to 3,837 m³/yr/ha.

- The total area of “settlement with garden” in the model area is 9,000 ha.
- Total consumption in “settlement with garden” yields
  3,837 m^3/yr/ha x 9,000 ha ≈ 34.5 MCM/yr
- By the LWSC only 14.5 MCM/yr are supplied in this landuse class.
- Hence the abstraction by private wells is:
  34.5 MCM/yr – 14.5 MCM/yr = 20 MCM/yr.
- This corresponds to an abstraction rate of 222 mm/yr.

A monthly variation of the water demand in the landuse class “settlement with garden” could not be observed.

A linear trend (growth rate of 1.7 %) is assumed for the historical time period, starting with an abstraction rate of 0.0 MCM/yr in 1950. In the future scenarios, no further change is applied.

3.7 Rivers

The five main rivers in the study area are: Chunga, Ngwerere, Chalimbana, Chilongolo and Mwembeshi. For the most parts, gaining conditions are met. It is assumed, that these rivers are connected with the aquifer system. Consequently, they are modelled as MODFLOW river cells. As shown in Figure 10, depending on the groundwater head and the river stage, gaining and loosing conditions can be simulated.

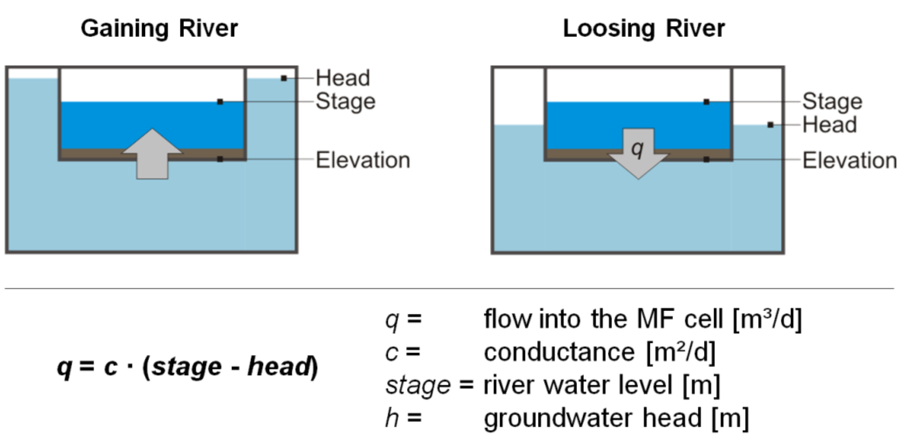


Figure 10: MODFLOW’s river cell concept (after McDonald and Harbaugh 1988).

The river bed elevations and water levels are deducted from the SRTM elevation model and observations as well as assumptions, based on comparison with other rivers. All observations have been made in the framework of the installation of gauging stations within the GReSP project (Krekeler 2011, personal communication). The applied values are listed in Table 4, the used measures are depicted in Figure 11. The river bed conductance is assumed to be large (average: 0.45 km²/d). Hence, the groundwater head equals the water level at the river cells (hydraulically connected). The values have been adapted during the calibration process.

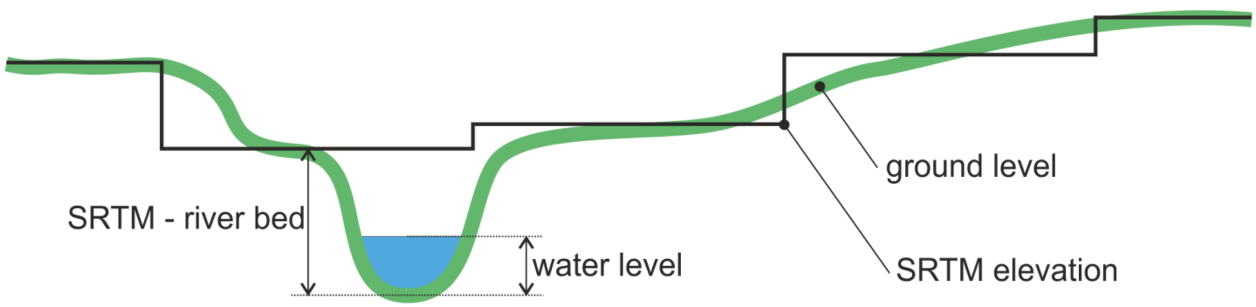


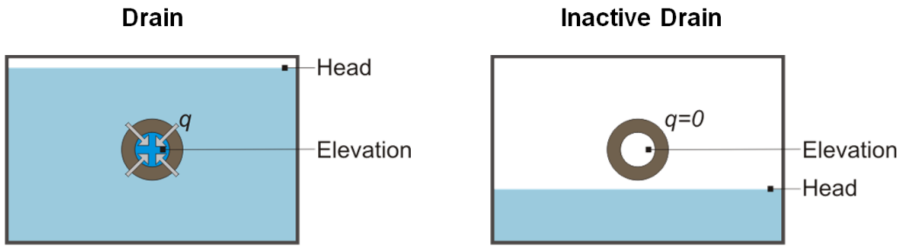
Figure 11: Example for the relationship between SRTM elevation, ground level and river bed.

Table 4: Depths of the river bed in relation to SRTM elevation model and water levels.

River	*SRTM – river bed [m]*	*Water level [m]*	*Data source*
Chunga	12.0	0.4	Measurements at gauging station
Ngwerere	7.0	0.6	Measurements at gauging station
Chalimbana	6.0	0.5	Measurements at gauging station
Chilongolo	6.0	0.3	Assumption
Mwembeshi	9.0	1.4	Measurements at gauging station

3.8 Springs and drain cells

Many springs can be found in the study area. Some of them are mapped in Figure 2. The flow from groundwater to surface proved a decisive factor in this model. In order to enable the outflow of water in dependency of the groundwater head, MODFLOW drain cells are used. The concept is depicted in Figure 12.



$$q = c \cdot (h - elevation)$$

q =	flow from the MF cell [m³/d]
c =	conductance [m²/d]
h =	groundwater head [m]
elevation=	elevation of the drain [m]

Figure 12: MODFLOW's drain cell concept (after McDonald and Harbaugh 1988).

Drain cells may represent springs combined with surface runoff, wetlands, gaining minor rivers as well as loss due to evapotranspiration. In contrast to river cells, the flow is unidirectional pointing always from the groundwater into the stream.

In the Lusaka model, the minor rivers (cf. Figure 1) are simulated by drain cells with an elevation of 1 m below the top of the cell and a conductance of 100 m²/d. Additionally, all cells in the first layer are defined as drain cells with a drain elevation 1 m above the top of the cell and a conductance of 10,000 m²/d. If the groundwater head exceeds the elevation, an outflow is simulated; otherwise, the drain is inactive.

3.9 Recharge

Groundwater recharge due to rainfall is the most important water source for the aquifers in the study area. In preceding reports (Hennings 2012a, Hennings et al. 2012) and ongoing works (Hennings 2012b) soil parameters and percolation rates have been investigated. The functional model WEAP/MABIA (Jabloun & Sahli 2011), based on Allan et al. (1998), has been applied. Land use, soil properties and geology are used to define 90 recharge classes (Hennings 2012).

For the numerical groundwater model, only one value per cell (500 m times 500 m) can be used. A simplification of the highly resolved spatial input data is therefore required. In a first step, the number of classes has been reduced to 31. For this purpose all classes have been neglected, which cover only a marginal area within the modelling domain. The according areas have been assigned to classes with similar available field capacity (awc). Hennings (2012b) has determined the percolation, transpiration and evaporation rates on a daily time scale for each of these classes for the water years 2010 and 2011. Herein, a surface runoff of 60 mm/yr for the dolomite/limestone and 140 mm/yr for all other areas has been applied.

Further adjustments were made in order to be consistent with the definition of material groups: Recharge classes which belong to a lower surface runoff (60 mm/yr) have only been applied in areas, where the material groups “Cheta limestone 1” or “Lusaka dolomite” is defined. In all other recharge classes a surface runoff of 140 mm/yr has been assumed.

In a first approach, the deep percolation as calculated by the WEAP/MABIA model has been used as groundwater recharge. During the calibration process it became obvious, that the groundwater table and its observed increase in the rainy season cannot be explained with these recharge values. Consequently, the following assumptions have been made for the water years 2010 and 2011:

- Restriction of the maximal surface runoff (remainder is direct recharge):
    - areas covered with dolomite/limestone and where streams are absent : 0 mm/yr (former 60 mm/yr)
    - all others areas: 140 mm/yr (no change)
- No special treatment of settlements: recharge/runoff characteristic in the land use class “settlements” and “settlements with garden” equals the land use class “natural vegetation”.

In general, two recharge mechanisms can be distinguished: 1) recharge by deep percolation through the soil and 2) direct recharge by preferential flow and sink holes. Especially in karst, the latter can lead to fast and high recharge and the absence of surface waters. This phenomenon is observed in the study area, where calcareous aquifers are present. Thus, all water from precipitation, which does not evapo-transpirate or increase the soil water storage, is assumed to be groundwater recharge.

In other areas, where the karst features are weaker, streams can be observed and surface runoff takes place. Here, the upper limit of surface runoff equals the values from the functional model with 140 mm/yr approximately.

The landuse classes “settlement” and “settlement with garden” cover a large part of the total model area (about 10 %, cf. Figure 8). Only minor parts of these areas are sealed and so only a small amount from rainfall will be canalized. Furthermore, additional recharge due to leakage of the water supply and sewage network can be expected. Hence, it can be assumed, that only small differences in the recharge behaviour exist in comparison with natural vegetation. This assumption is confirmed by the rapidly increasing water tables in the raining season.

The resulting recharge classes are depicted in Figure 13.

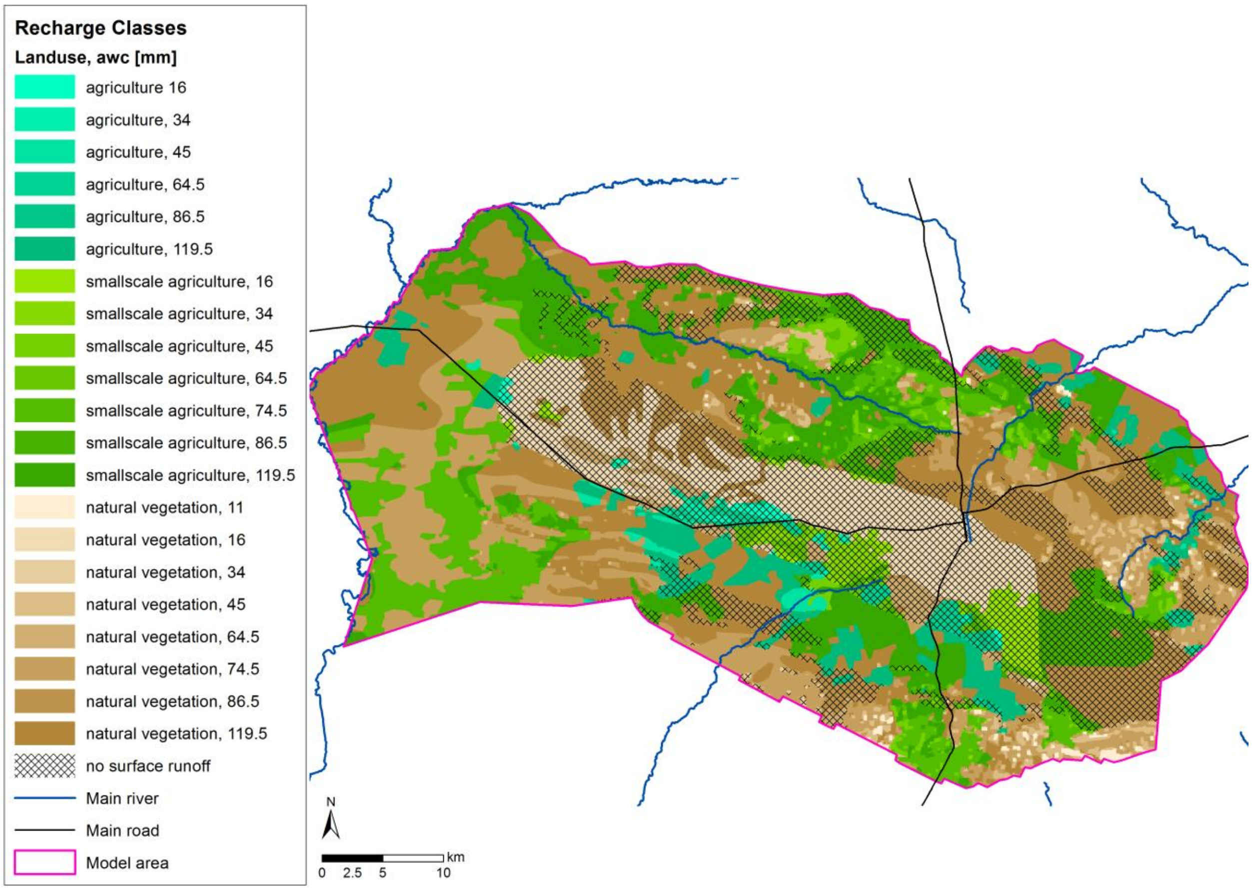


Figure 13: Recharge classes, defined in dependency of the landuse, soil properties (available water capacity (*awc*)) and geology.

Based on the precipitation-recharge relationship in the water years 2010 and 2011 (Hennings 2012b) the recharge values for the historical period have been determined. Whenever possible, the precipitation values from the station “International Airport” have been used. If data gaps occurred, the station “City Airport” was used for the entire corresponding water year. The following equation 2 has been applied to calculate the daily groundwater recharge GWR_d in dependency of the daily precipitation P_d :

$$GWR_d = \begin{cases} 0.0 & \text{if } P_d < P_{\min} \\ GWR_d^{\max} & \text{if } (P_d - P_{\min}) \cdot c > GWR_d^{\max} \\ (P_d - P_{\min}) \cdot c & \text{else} \end{cases} \qquad \textbf{Eq. 2}$$

With the threshold for recharge relevant precipitation $P_{\min}$, the maximal daily groundwater recharge $GWR_d^{\max}$ and the factor c. These three parameters have been determined for all recharge classes separately by comparing of the results of equation 2 with the recharge documented in Hennings (2012b) for the water years 2010 and 2011. A good accordance is reached in the calibration period. The deviations on the yearly scale are below 10 % and the correlation coefficient is about 0.9.

Equation 2 is used to calculate the recharge for the historical period (cf. Figure 14) and the future scenarios.

The long term averaged monthly precipitation (1976-2011) is used to determine the recharge for the future scenarios (Figure 15).

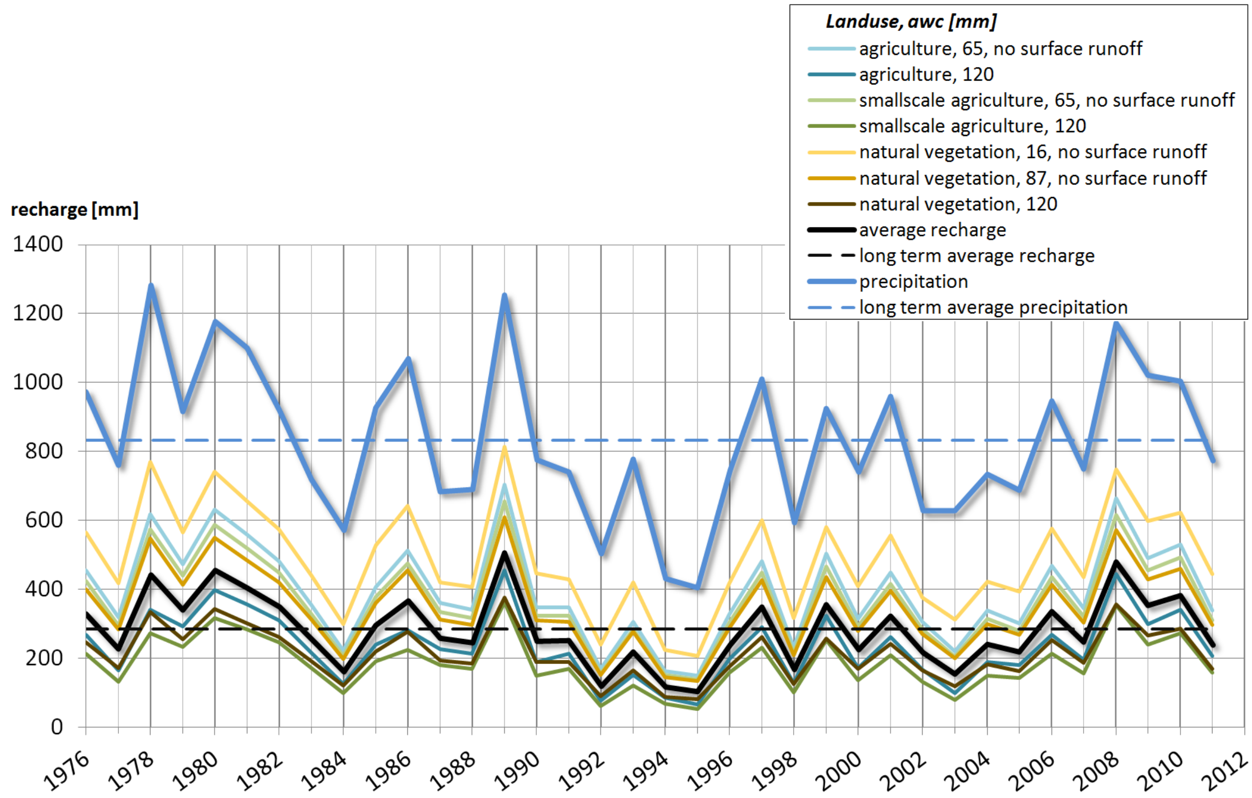


Figure 14: Recharge of selected recharge classes per water year. The long term averaged recharge of the groundwater model area equals 284 mm/yr.

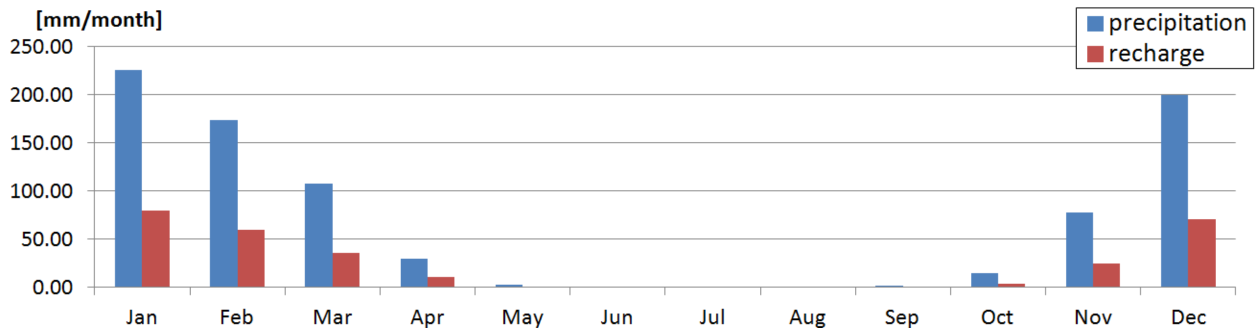


Figure 15: Monthly variation of the precipitation and recharge (1976-2011). These recharge values are applied in the future scenarios.

4 Results

4.1 Calibration

Consistent groundwater measurements are available for the model area for the water years 2010 and 2011. They have been obtained within the technical cooperation project between DWA and BGR. Older measurements that were compiled and presented by Shamboko-Mbala (2012, in prep.) can only be used to get a rough idea of the historical development, but they do not allow direct comparison because the reference heights are not verified.

The following data have been used for model calibration:

- Groundwater contour maps, based on water level measurements
  - April 2009 (294 points)
  - November 2008 (104 points)
  - October 2009 (287 points)
- 47 monitoring wells, starting date: 10/2009, weekly to daily measurements
- Location of 75 springs

The distribution of measurement sites is scattered. The model calibration focusses on the Lusaka Plateau, the Chunga Catchment in the north-west and generally, the settlement area. Consequently, the simulation results outside this area cannot be verified and cannot be used for predictions. Thus, most model results refer to the calibration area (1,593 km²), as shown in Figure 16. This area covers the part within the model area, for which groundwater contour lines have been mapped. Furthermore, a buffer of at least one cell to the constant head boundary conditions has been considered in order to restrict the influence of the boundary condition.

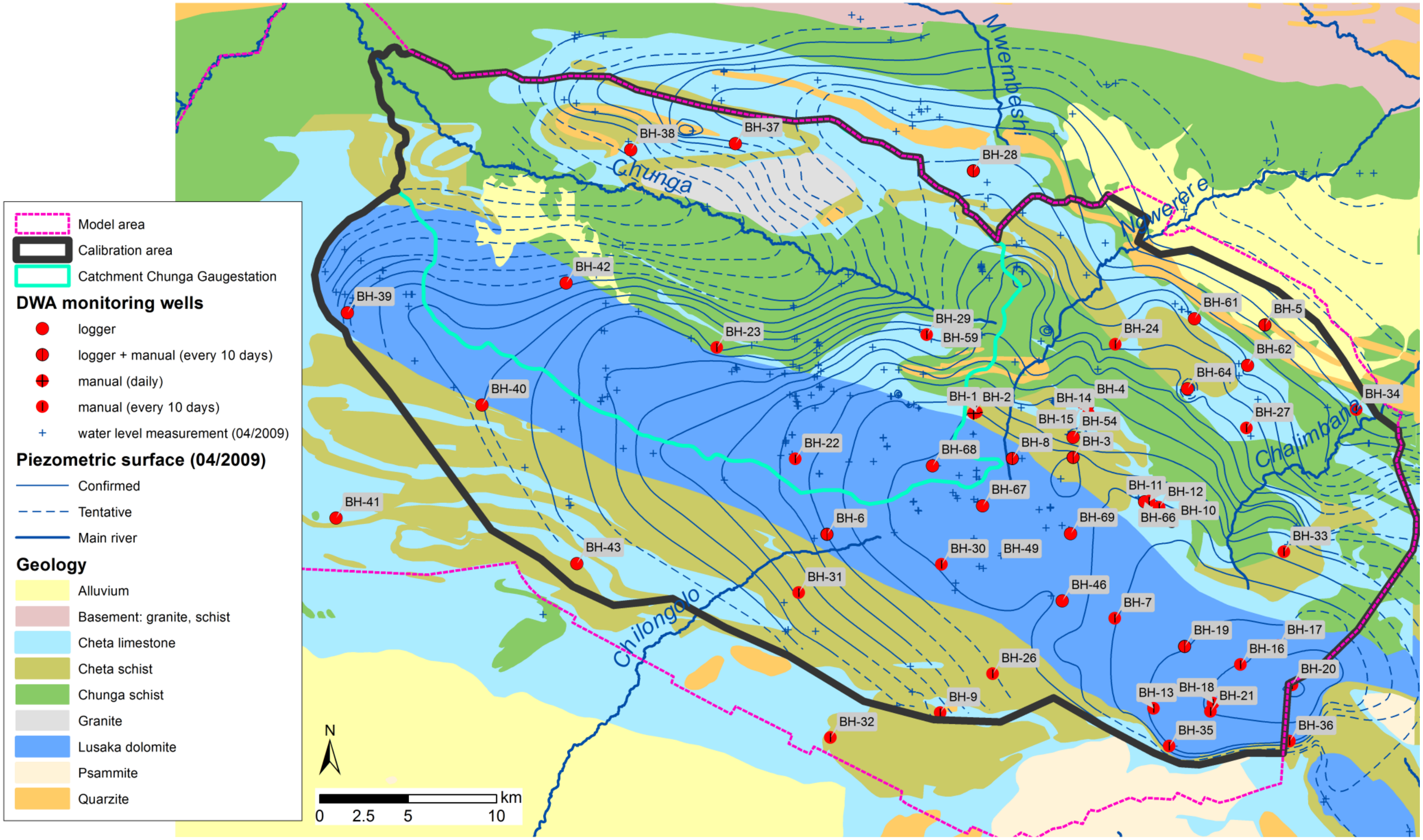


Figure 16: **Calibration area and measurements.**

The first calibration phase of the hydraulic conductivities has been performed with a steady state model, using averaged values for all time dependent input data. The calibration target for this steady state model was an averaged groundwater contour map, based on water level measurements. According to the results, the hydraulic conductivities have been revised. Furthermore, the groundwater recharge has been slightly changed in comparison with data from Hennings (2012b), as described in Chapter 3.9.

In the second phase, transient simulations have been carried out. The starting year for all transient simulations is October 1976. The groundwater contour maps are used to define the initial condition of the hydraulic heads. The calibration target for the transient simulation is the monitored groundwater head in the calibration period, i.e. the water years 2010 and 2011. A comparison with measured contour maps gives a general idea of the model accuracy and can be used to calibrate the hydraulic conductivities. The temporal variations at the monitoring points are used to determine the specific yield. As a result of the calibration process, the material properties are presented in Table 2, page 9.

In Figure 17 the measured and calculated heads are shown for comparison. Additionally, the differences are plotted. The measured heads are based on water level measurements from October 2009. The contour lines have been interpolated on the MODFLOW grid in order to allow a direct comparison.

It can be stated that the general flow regime can be simulated well. Nevertheless, differences in head occur, in some small zones up to 20 m. In the region, where wells are located, only minor differences can be observed. Only in one central area (north-west of the City), differences up to 10 m are calculated. In the Lusaka Dolomite the computed values are slightly to low, in the surrounding schists rather the opposite is the case. It was not possible to solve this discrepancy by variation of hydraulic conductivities as a decrease of conductivities in the schists leads to an increase of heads in the dolomite and in the schists. This would generate many more springs in the schists, which is not observed in the field. Lower conductivities in the dolomite would lead to higher hydraulic heads in the dolomite, which is closer to the measurements, but simultaneously unrealistic high drawdowns at the well fields are observed, leading even to the drying-up of wells.

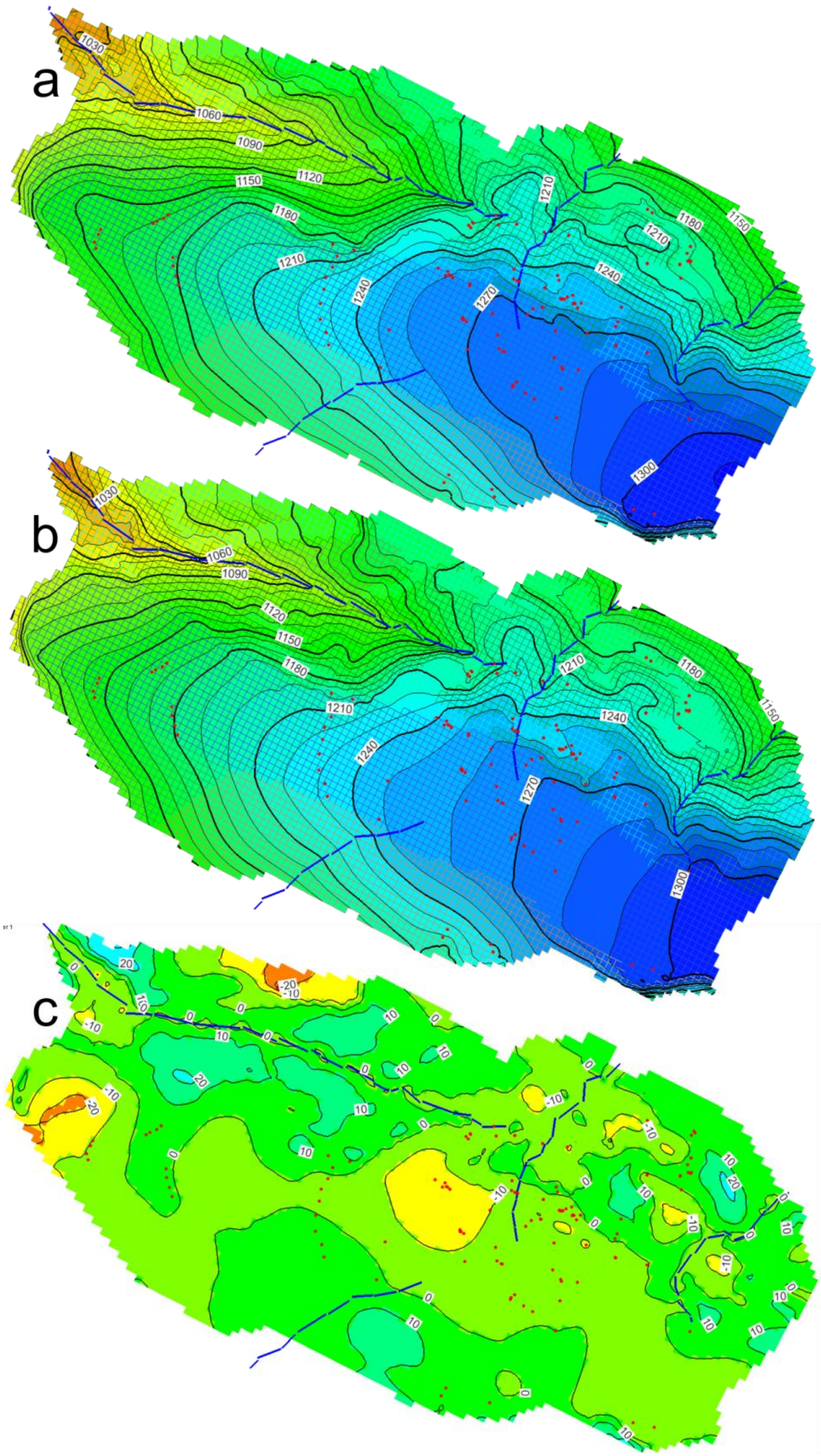


Figure 17: Comparison between measurements and simulation results: a) piezometric surface, prepared using water level measurements taken in October 2009; b) computed heads, c) calculated minus measured values. The red dots are representing existing and proposed well locations.

Figure 18 shows the result of the transient simulation for a specific point in time in comparison with recorded heads from the monitoring stations. The results reflect the same findings as described above: the general trend is predicted well; only within the calcareous aquifers the heads are slightly underestimated.

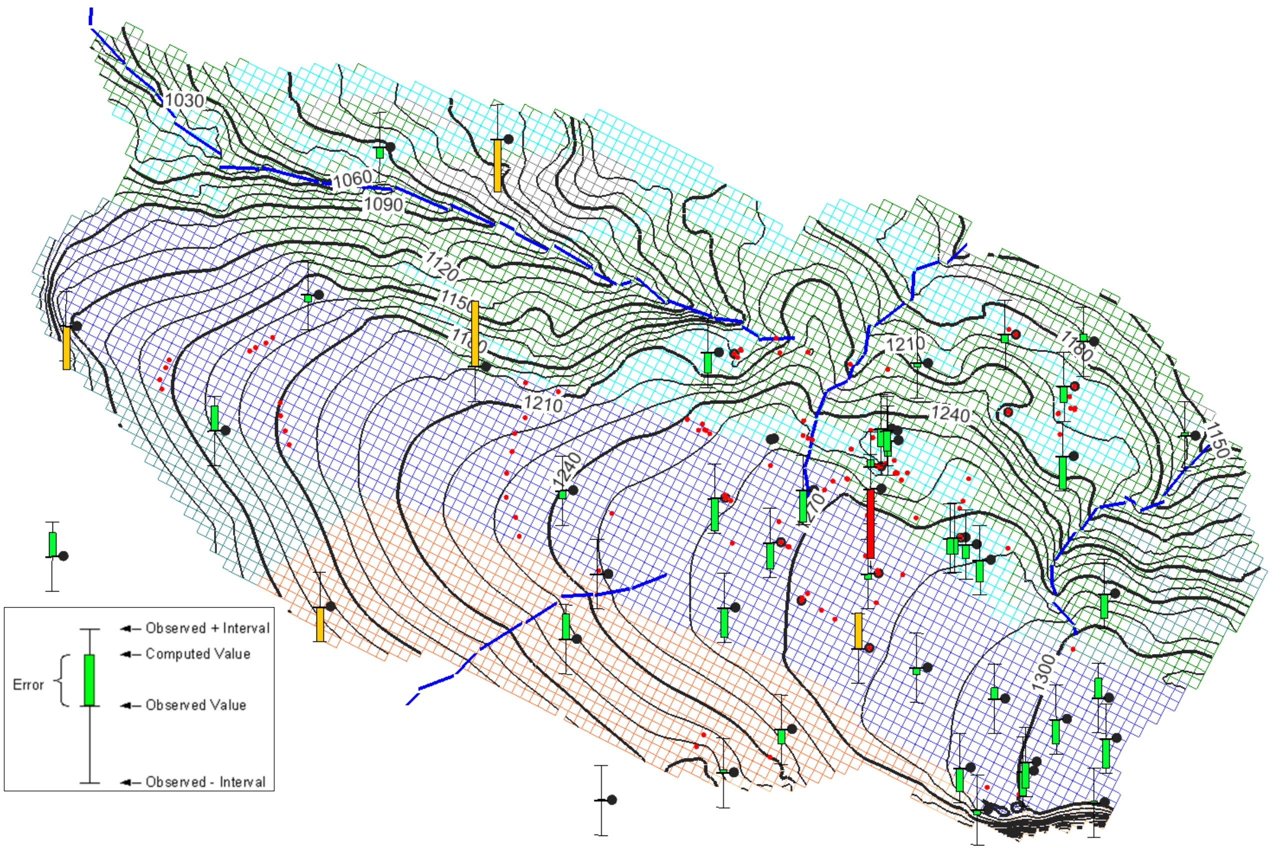


Figure 18: Comparison between computed and monitored heads (April 2011). The interval is set to 10 m. The black lines are representing the computed heads and the red dots existing and proposed well locations. The grid's color corresponds to the material group, as depicted in Table 1.

The foregoing two figures only show temporal "snapshots". In order to investigate the development of the groundwater table with time, the computed heads have been compared to the measurements at all 47 monitoring points over the calibration period of two years. At some monitoring points the comparison is difficult because they are influenced by pumping. As examples, in Figure 19 the temporal developments at 8 points are shown. Please keep in mind that all simulations started in the year 1976 and the presented results represent only a section of the total results.

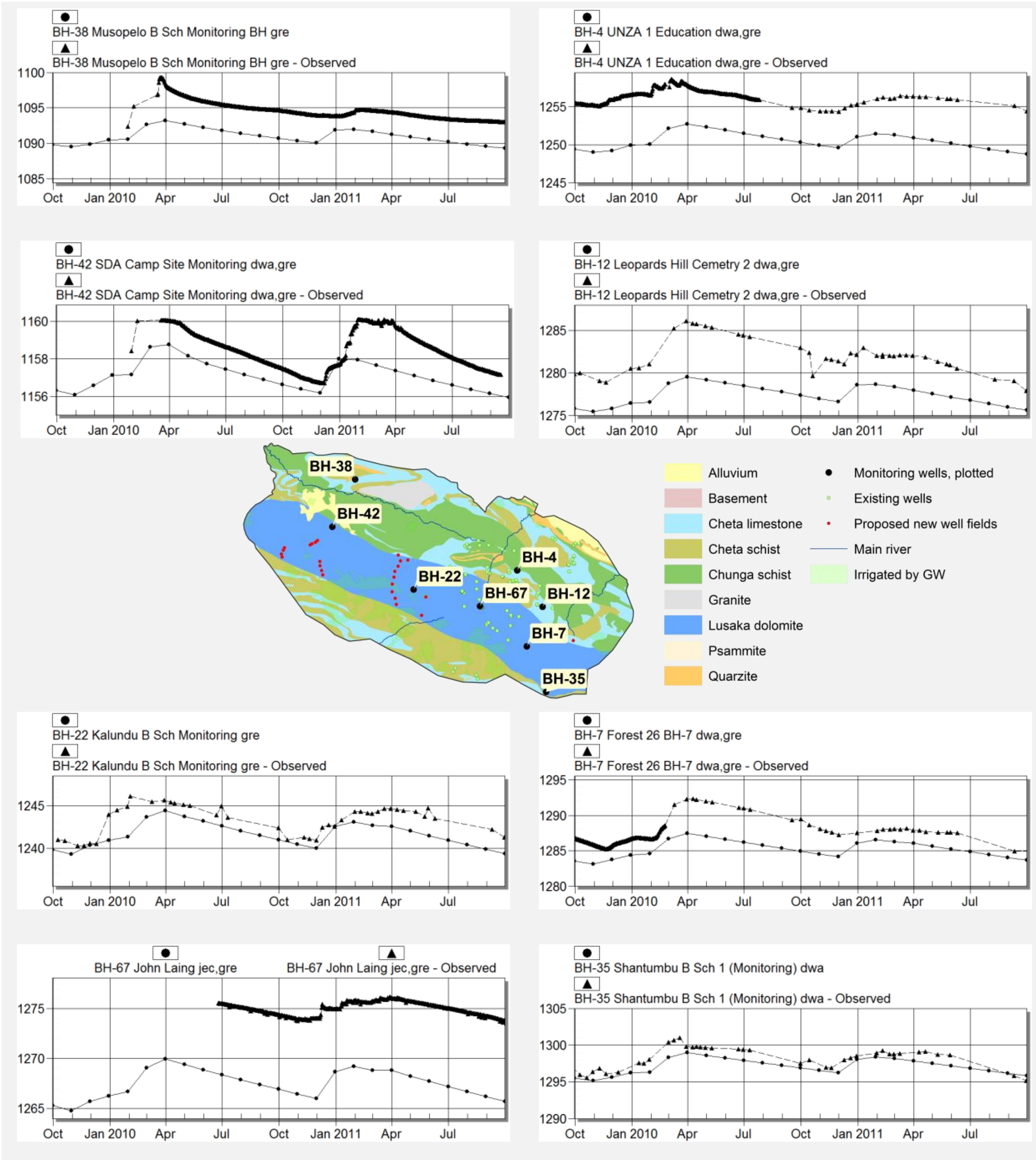


Figure 19: Comparison of the computed transient heads with measurements at 8 monitoring points.

In general, the temporal trend can be computed well. Especially the seasonal decline in the water table during the dry months can be adequately reproduced, which is an indicator for correctly computed storage behavior and a realistic specific storage coefficient. Individual recession segments during the wet months follow after groundwater recharge events during storms, which occur with a high local variation. These storm events are not reflected by the model.

4.2 Discussion of calibration results

Overall, the results of the numerical model show a good accordance with the measurements, even if not all measurements can be simulated. At this point, the shortages of the applied model approach become obvious. The highly heterogenic karstic aquifer is modelled as a homogeneous porous media. Thus, preferential flow paths, such as fractures and pipes, cannot be considered directly. Furthermore, the knowledge of the aquifer system is still limited. Information about the flow velocities and their variations and knowledge about the vertical variations of hydraulic properties are missing or very sparse. It is not analyzed for all systems whether the aquifer is confined or not. It makes no sense to increase the model's complexity as long as the knowledge of the aquifer system is limited to a general picture of the groundwater table and rough estimations of hydraulic properties based on local pumping tests.

Besides the hydraulic and geometric properties of the aquifer, the boundary conditions influence the model results essentially. They are accompanied with uncertainties. Abstraction data from public wells appear to be of the highest accuracy. But even here, questions arise due to the high discrepancies between pumped and supplied water (Shamboko-Mbale et al. 2012). A possible return flow, caused by leakage in the supply and sewage network, has not been considered in the model, because it has not been identified so far. For the determination of the abstractions by private wells, no direct measurements are available. The abstractions have been estimated, based on a farm survey and reasonable comparisons with other areas. It is obvious that this is a relatively rough estimation, which could only give the order of magnitude.

The most important boundary of the model is the ground surface, i.e. the surface water groundwater interaction, including direct recharge by rainfall. Even if considerable effort has been made in order to determine the groundwater recharge, the mechanisms are not completely understood. Spring discharges, evapotranspiration from shallow groundwater tables as well as river – groundwater interactions have not been sufficiently investigated so far.

4.3 Water table and springs

In Figure 20, the observed and computed spring locations are shown, as well as two cross sections, which reflect the location of the water table.

If the water table intersects the ground surface, a spring occurs. The main spring area, located at the northern and western edge of the Lusaka dolomite, can be simulated (e.g. Michelo, Kashembe, Mwembeshi Satellite, Kanyakanya Farm, Laughing Waters, Handamana, Chimbwete, Nsanje Muleke). Since the computed heads in the Lusaka dolomite are underestimated, the springs in the central part of the dolomite cannot be predicted (e.g. Norsaka Farm, Zarnus Quarry, Kasanova, Mwazuna Farm, Kayomba, Makeni Valley).

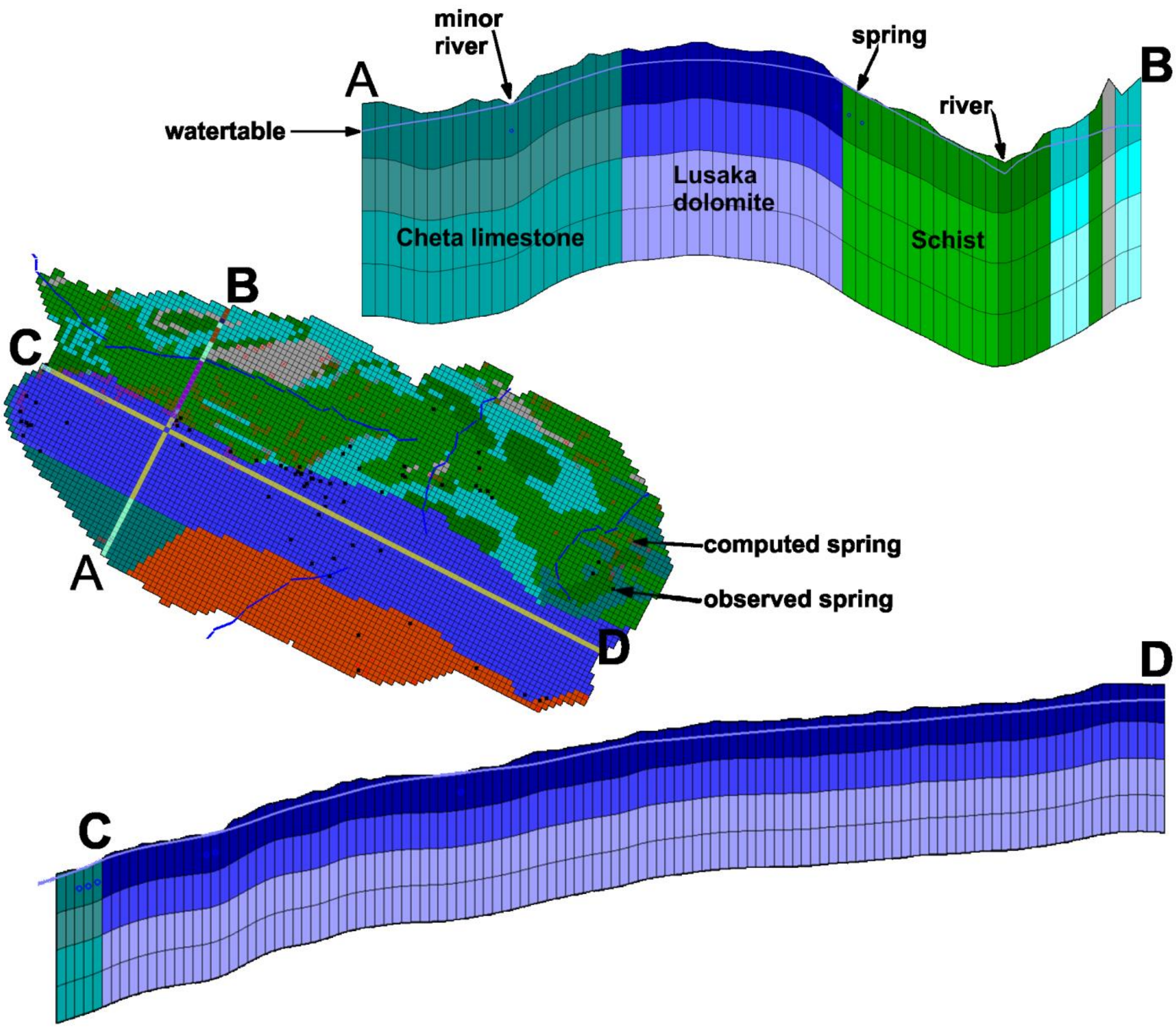


Figure 20: Cross sections, observed (black dots) and computed (marked in red) springs as well as computed water tables in October 2009.

4.4 Water balance

In Figure 21 and Table 5, the computed water budget for the calibration area is depicted. The recharge values are relatively high because they are based on the reasonable assumption of no surface runoff in the Lusaka dolomite and Cheta limestone. Thus, they include deep percolation and direct recharge. A portion of this water will directly flow out through drain cells.

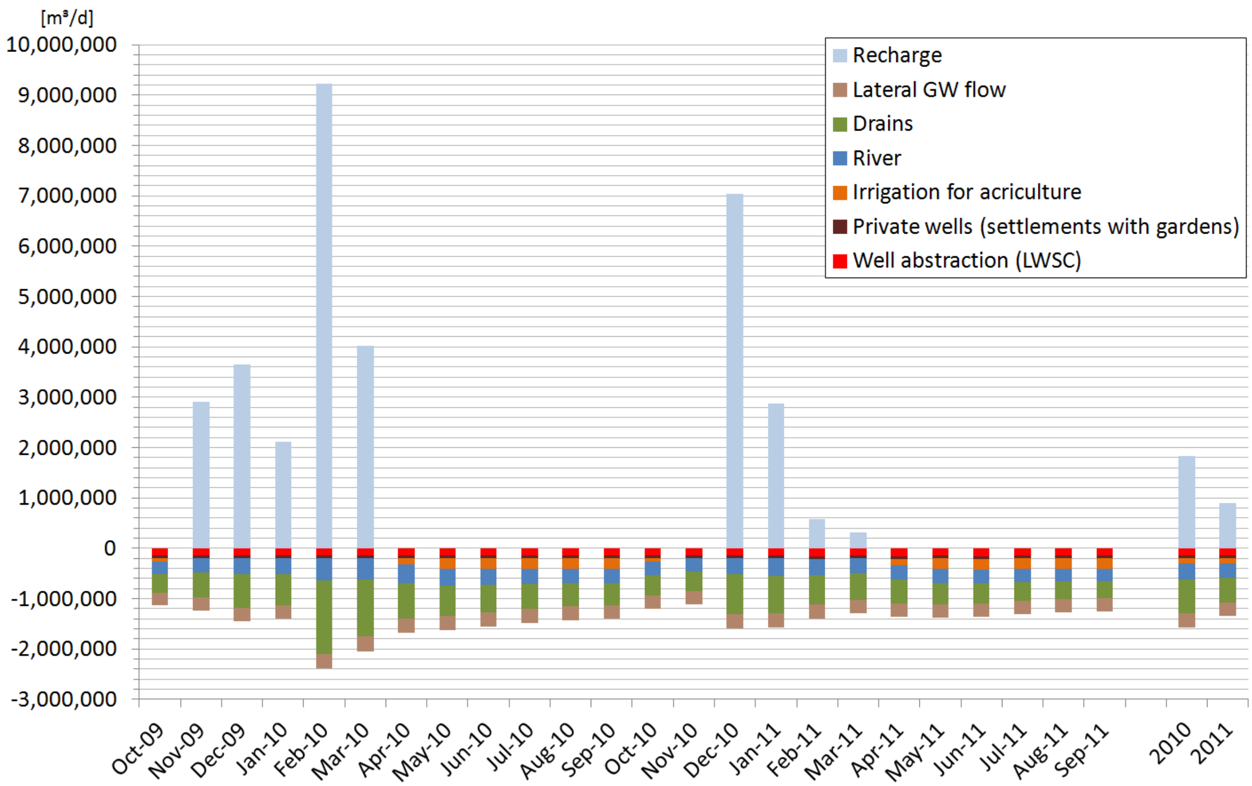


Figure 21: Water budget in the calibration area in m³/d for the water years 2010 and 2011.

Table 5: Yearly water budget of the calibration area (water years 2010 and 2011).

		Wells	Private wells (settlements with gardens)	Irrigation for acriculture	River	Drain	Lateral GW flow	Recharge	Change in GW storage
2010	MCM	-53	-19	-38	-119	-243	-101	683	110
	mm	-33	-12	-24	-75	-152	-63	429	69
2011	MCM	-54	-19	-38	-102	-178	-98	341	-149
	mm	-34	-12	-24	-64	-112	-61	214	-93

The only considerable input is recharge, which varies strongly with season and year. Within the numerical model, the recharge cannot be further subdivided into direct recharge (karst and preferential flow paths) and percolation (infiltration through the soil). The man-made abstractions sum up to 110 MCM/year in 2010. Because the calibration area constitutes a plateau, there is noticeable lateral groundwater outflow (97 MCM), mainly to the Kafue flats. Even if the groundwater table varies only slightly, the groundwater storage shows high variations. The aquifer is drained by rivers and drains. As already mentioned in chapter 3.8, the drains represent draining conditions at minor rivers and springs, as well as evapotranspiration in wetlands and areas with shallow groundwater tables.

Detailed water budgets have been determined for the sub-catchment shown in Figure 22 (Table 6 to Table 9).

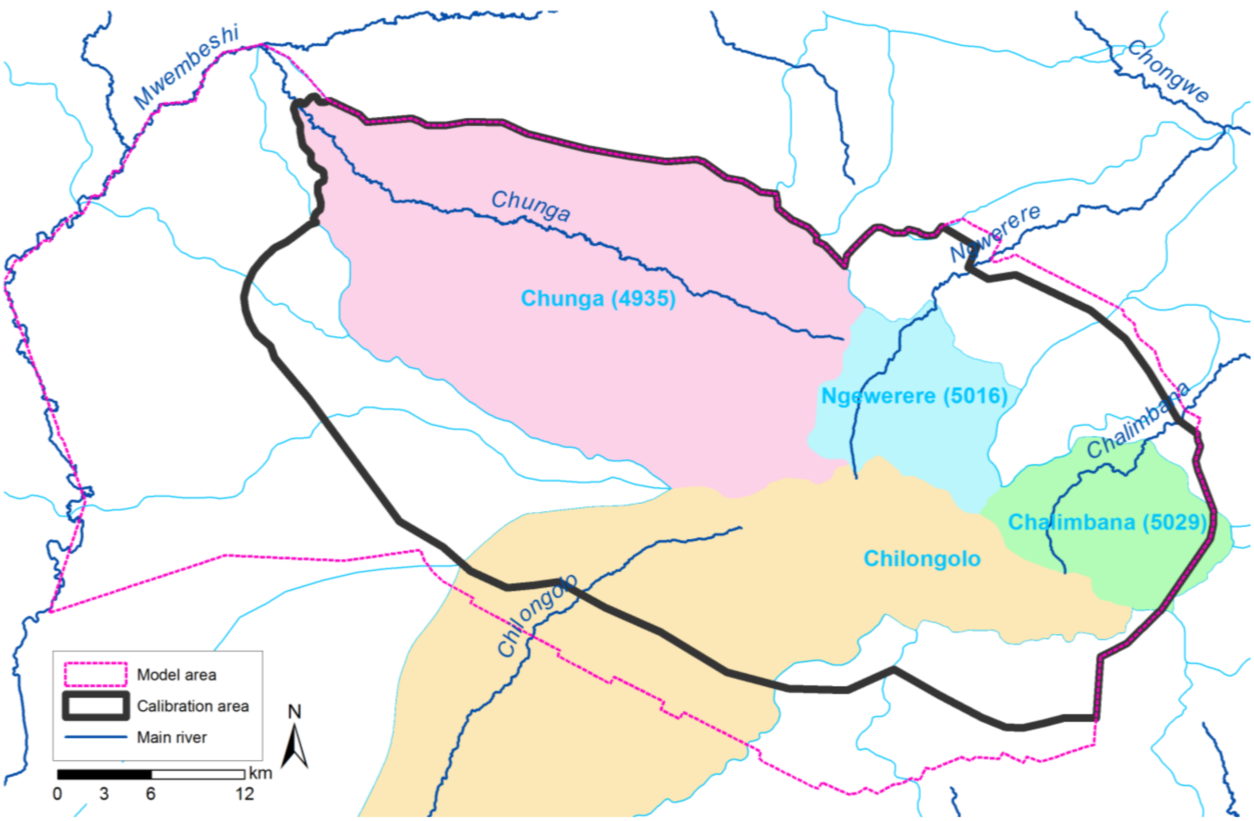


Figure 22: Sub-catchment areas.

Table 6: Yearly water budget of the catchment "Chunga" (594 km²) for the water years 2010 and 2011.

		Wells	Private wells (settlements with gardens)	Irrigation for agriculture	River	Drain	Lateral GW flow	Recharge	Change in GW storage
2010	MCM	-9	-1	-4	-80	-157	22	258	29
	mm	-15	-1	-7	-135	-265	38	434	48
2011	MCM	-9	-1	-4	-69	-118	23	127	-51
	mm	-15	-1	-7	-117	-199	39	214	-86

Table 7: Yearly water budget of the catchment "Chalimbana" (115 km²) for the water years 2010 and 2011. The area within the model domain equals 107 km².

		Wells	Private wells (settlements with gardens)	Irrigation for agriculture	River	Drain	Lateral GW flow	Recharge	Change in GW storage
2010	MCM	-0.3	0.0	-1	-15	-16	0.2	38	6
	mm	-3	0.0	-10	-138	-154	2	357	54
2011	MCM	-0.3	0.0	-1	-13	-12	0.2	18	-8
	mm	-3	0.0	-11	-123	-113	2	169	-78

Table 8: Yearly water budget of the catchment "Ngwerere" (109 km²) for the water years 2010 and 2011.

		Wells	Private wells (settlements with gardens)	Irrigation for agriculture	River	Drain	Lateral GW flow	Recharge	Change in GW storage
2010	MCM	-16	-9	0	-6	-5	3	42	8
	mm	-152	-86	0	-59	-47	30	387	73
2011	MCM	-17	-9	0	-5	-3	4	19	-11
	mm	-156	-86	0	-46	-26	34	178	-101

Table 9: Yearly water budget in the catchment "Chilongolo" (676 km²) for the water years 2010 and 2011. The area within the model domain equals 406 km².

		Wells	Private wells (settlements with gardens)	Irrigation for agriculture	River	Drain	Lateral GW flow	Recharge	Change in GW storage
2010	MCM	-21	-4	-16	-11	-17	-71	177	37
	mm	-51	-11	-38	-28	-42	-174	435	90
2011	MCM	-20	-4	-16	-9	-14	-68	90	-41
	mm	-49	-11	-39	-22	-33	-166	221	-100

In Table 6, the water budget for the Chunga catchment is depicted, which is dominated by natural processes and only low abstraction rates.

The Chalimbana sub-catchment above gauging station no. 5-029 is covered to 93-percent by the numerical model. Obviously, the water budget, as shown in Table 7, can only be related to this major portion of the sub-catchment.

The same applies to the Chilongolo sub-catchment (Table 9). Here, the huge amount of lateral groundwater flow can be explained by the intersection of the sub-catchment by the model boundary perpendicular to the direction of flow. About half of the lateral flow is associated with this boundary.

4.5 Future scenarios

An increase of domestic water demand is predicted in the Lusaka region due to socio economic development (mainly population growth). The LWSC expects nearly a doubling of the water demand from 2010 to 2035 (JICA, 2009). Today, about 35 MCM is transferred by pipelines from the Kafue. In the following, three future scenarios are investigated, considering different assumptions on the development of the water abstractions by LWSC. The water abstractions for irrigation, private wells and industrial wells are the same for all scenarios.

It is assumed that new well fields (WF) or pipeline capacities are not available before the water year 2014. The increase until 2014 is evenly divided between the existing wells. Since the pipeline and well capacities are reached, additional demand has to be satisfied by new pipelines and well fields, respectively.

In Figure 23, the five proposed new well fields are depicted. The selection of the location of new well fields is based on geology and the flow regime as well as simulation results. Where possible, information on the yield of existing exploration wells drilled during the late 1970s (von Hoyer et al. 1978) is used. Attempts were made to restrict the drawdown around the wells. Wells to the west of Lusaka will not significantly worsen the drawdown at the existing wells in Lusaka. However, the water quality could be affected by waste water from Lusaka, because the regional direction of groundwater flow is north-west.

The well fields are described in the following in detail:

- WF1: located in the far west. This well field is used as "last option", because of the costs for a pipeline and for pumping the water up to Lusaka. The well field is modelled by 3 groups, each consisting of 4 well cells. The wells are in the area of the exploration boreholes U-11b, U-14 and U-13, which offer a high yield (von Hoyer et al. 1978).
- WF2: located in the western area beneath the City. The wells are distributed over the entire width of the Lusaka Dolomite perpendicular to the groundwater flow (10 well cells). The boreholes U-5, U-7, U-20f are located in this area.
- WF3: located near the City in the west. Only minor costs for pipelines can be expected, because they are in close proximity to Lusaka. Thus, this well field is "first choice". The two well cells coincide with the boreholes U-8d and U-4, which offer high yields.
- WF4 and WF5: located in the Southeast of Lusaka. They are located at the edge of the Lusaka dolomite in order to restrict the influence on the existing wells in Lusaka. WF4 is represented by one well cell, which coincides with the borehole U-22 (140 m^3/h yield); WF5 is represented by two wells cells, near to U-10b (180 m^3/h yield).

It has to be understood, that this study cannot be used to define the exact location of the new wells. In the numerical model, wells are modelled using an abstraction rate at one cell (MODFLOW well cell), representing an area of 250,000 m^2 (500 m x 500 m). This abstraction could correspond to the abstraction by several wells in reality. Furthermore, the aquifer's inhomogeneities are not considered. Thus, in-situ investigations would be needed for further planning. Nevertheless, this study can give a first impression of possible regions for new well fields and their impact on the regional flow regime.

In Table 10 a summary of the applied scenarios is given.

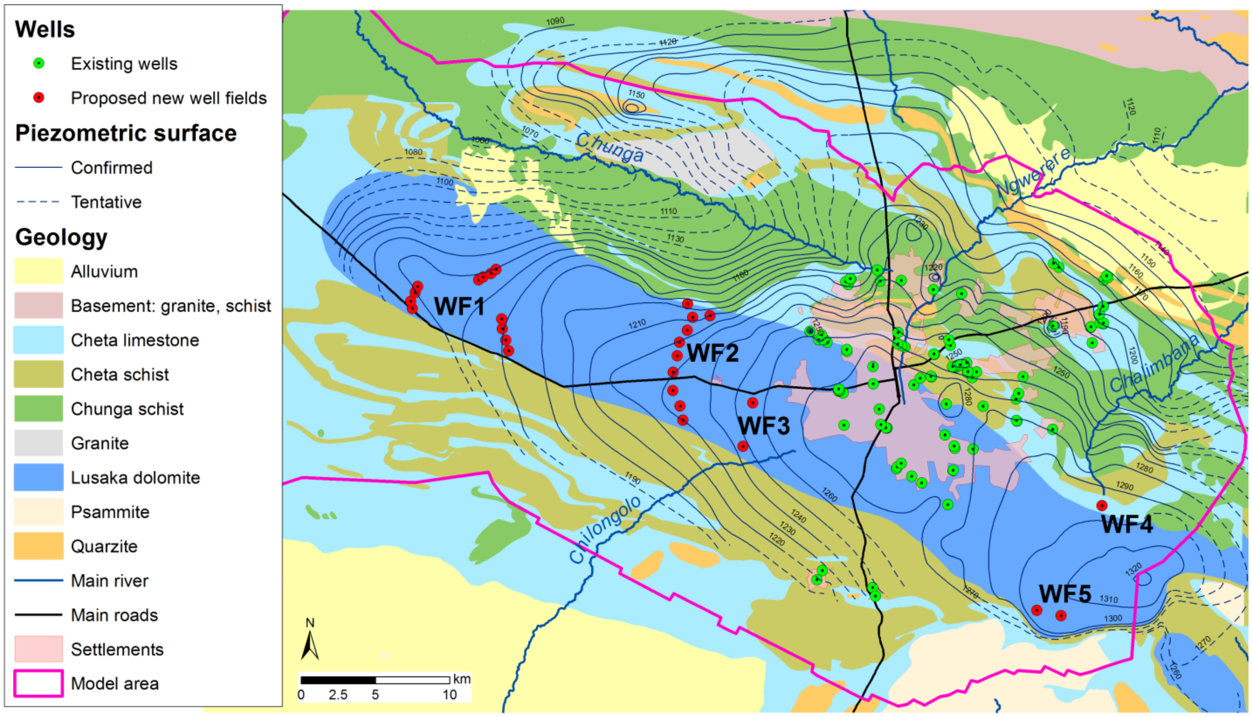


Figure 23: Location of the proposed new well fields.

Table 10: **Summary of applied scenarios.**

	Scenario 0	Scenario 1	Scenario 2
New transfer from Kafue			
starting year	2014	-	2026
MCM in 2035	67.	-	32.
WF 3-5			
starting year	-	2014	2014
MCM in 2035	-	18.	13.
WF 2			
starting year	-	2020	2020
MCM in 2035	-	33.	22.
WF1			
starting year	-	2032	-
MCM in 2035	-	16.	-

4.5.1 Scenario 0: no new wells

In the reference scenario 0 it is assumed, that the abstraction rates will not be increased after 2013. Consequently, a transfer capacity of about 102 MCM is needed in 2035 (Figure 24).

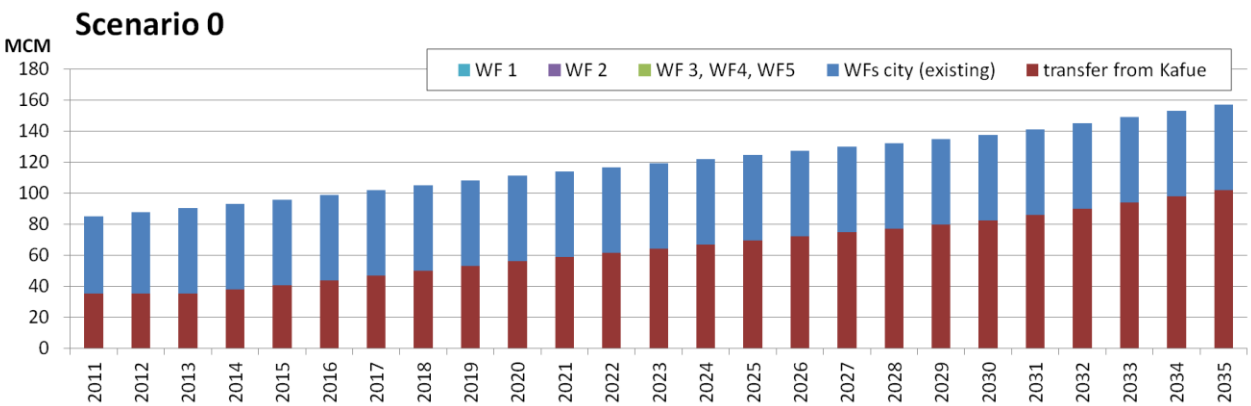


Figure 24: Abstraction rates and water sources in the reference scenario 0. No new well fields will be developed; additional water demand is supplied by transfer from Kafue.

The long term temporal development of the groundwater table is shown in Figure 25. Since the abstraction rate at wells will not further increase in scenario 0, most graphs reflect the long term average at the end of the simulation. Only at monitoring borehole BH-4, a reasonable decrease can be observed. This indicates that the groundwater table in this area is not in balance to the abstractions in 2010. The high abstractions in “International School” and “Mass Media” will lead to groundwater drawdown up to 7 m, even if the abstraction rate will not be increased in future.

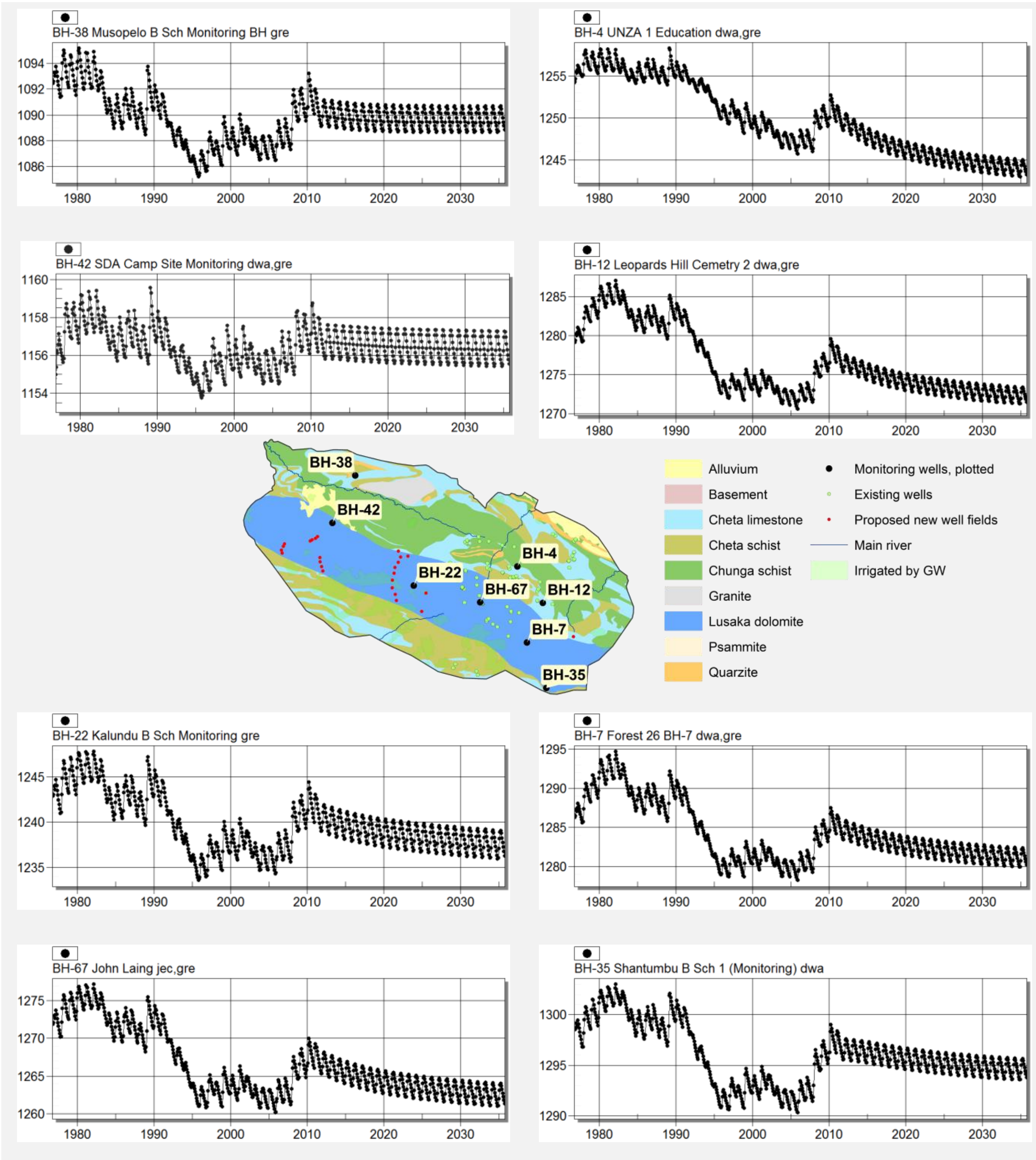


Figure 25: Scenario 0 (reference): temporal development of the groundwater table.

The same trend is reflected in Figure 26, which shows the differences in groundwater table between 2009 and 2035. The groundwater table will distinctly decrease in two zones, namely in the area of the well fields mentioned above and in areas used for commercial agriculture, where increasing abstraction for irrigation is considered (from 42 MCM in 2009 to 63 MCM in 2035). In the other areas only minor changes occur.

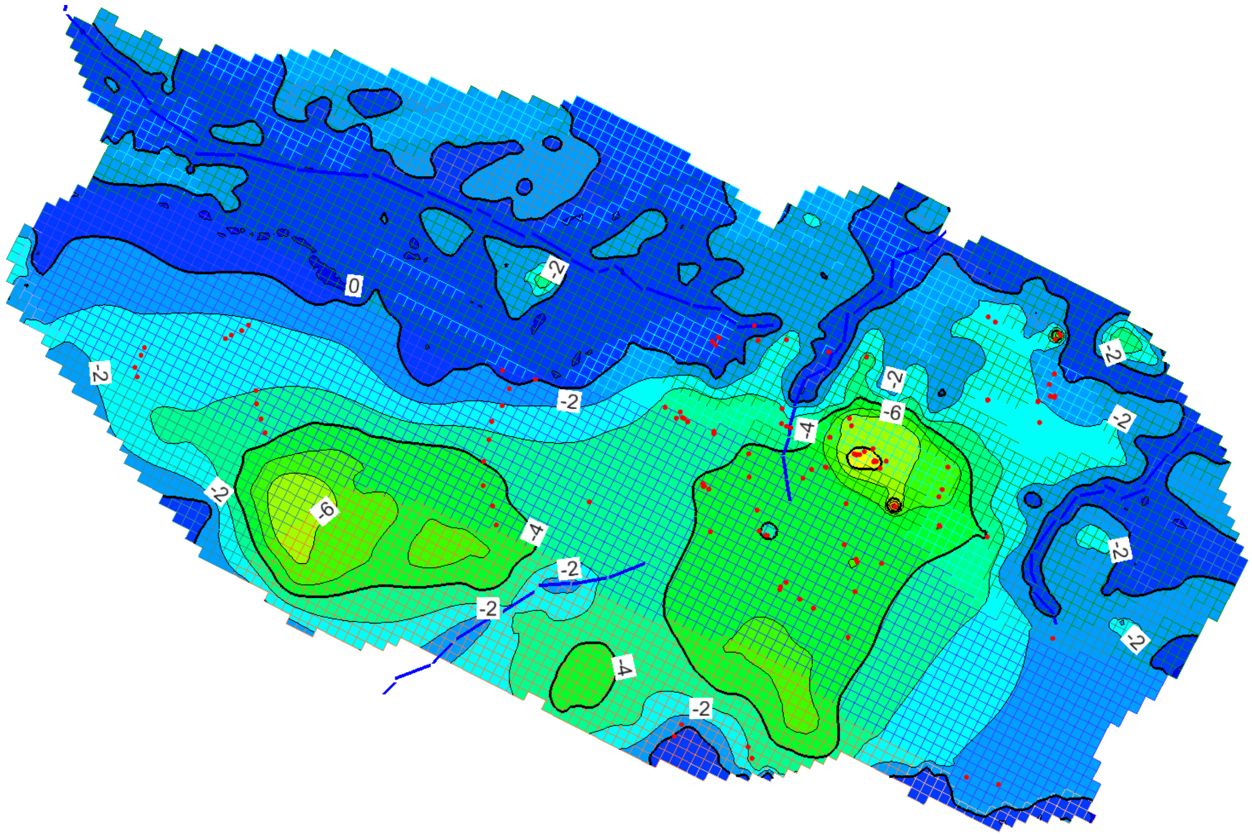


Figure 26: Scenario 0: Differences in the groundwater tables between 2009 and 2035.

4.5.1 Scenario 1: no new pipeline

In the scenario 1 the water transfer from Kafue is fixed to the current value (35 MCM/year). Consequently, the well abstraction has to be increased from 50 (2011) to 122 MCM (2035). All proposed well fields are used to satisfy the water demand until 2035. In order to restrict the drawdown to reasonable values, the first new wells are needed in 2014. The WF2 is used in 2020 additionally and WF1 in 2032 (Figure 27).

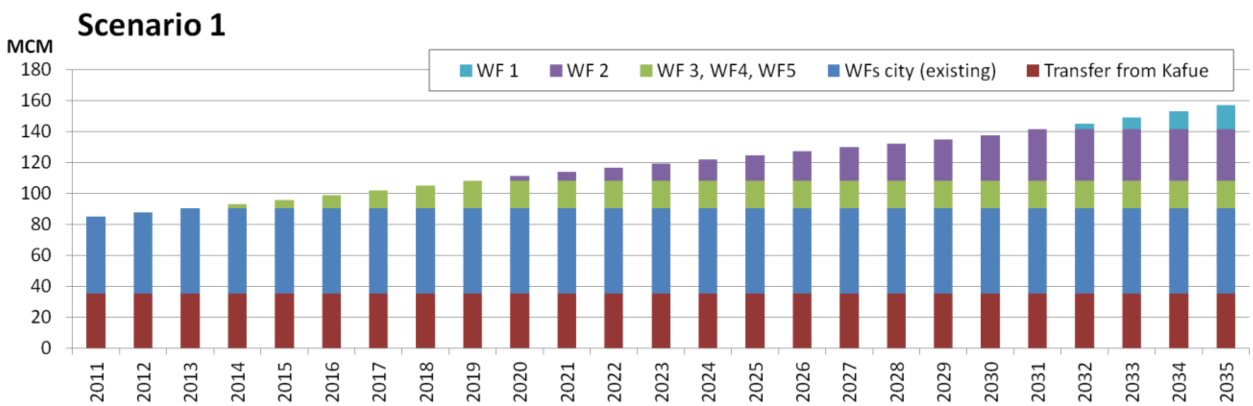


Figure 27: Abstraction rates and water sources applied in the scenario 1. The water transfer from Kafue is fixed since 2011 and all proposed well fields are used.

The temporal development of the groundwater table near to the proposed new well fields is characterized by drawdowns of up to 10 m (Figure 28). Directly at the well fields, the drawdowns reach up to 20 m, as depicted in Figure 29. Concerning the temporal development, only the water table in the Local Forest Reserve area and North of the Chunga River seems to be stabilized, while all others are still showing declining water tables. Consequently, it is not clear, how deep the drawdown in a steady state will be at these points.

It has to be mentioned that high drawdowns, as predicted in this scenario, comes along with additional uncertainties, because it is not known, how the hydraulic properties change with depth. As a general rule it can be stated that the higher the difference between computed values and the values in calibration period, the higher the uncertainties of the prediction.

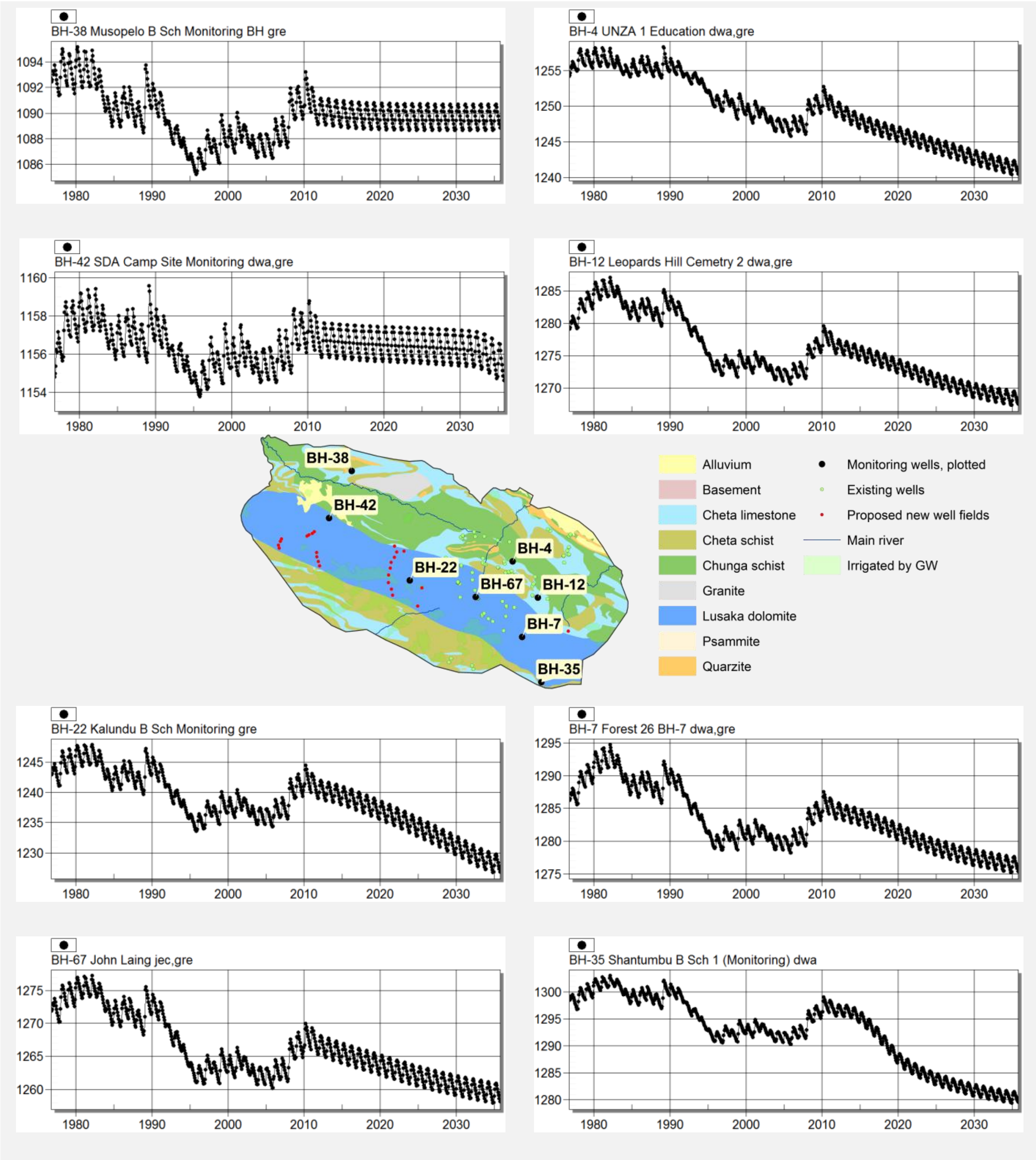


Figure 28: Scenario 1: temporal development of the groundwater table.

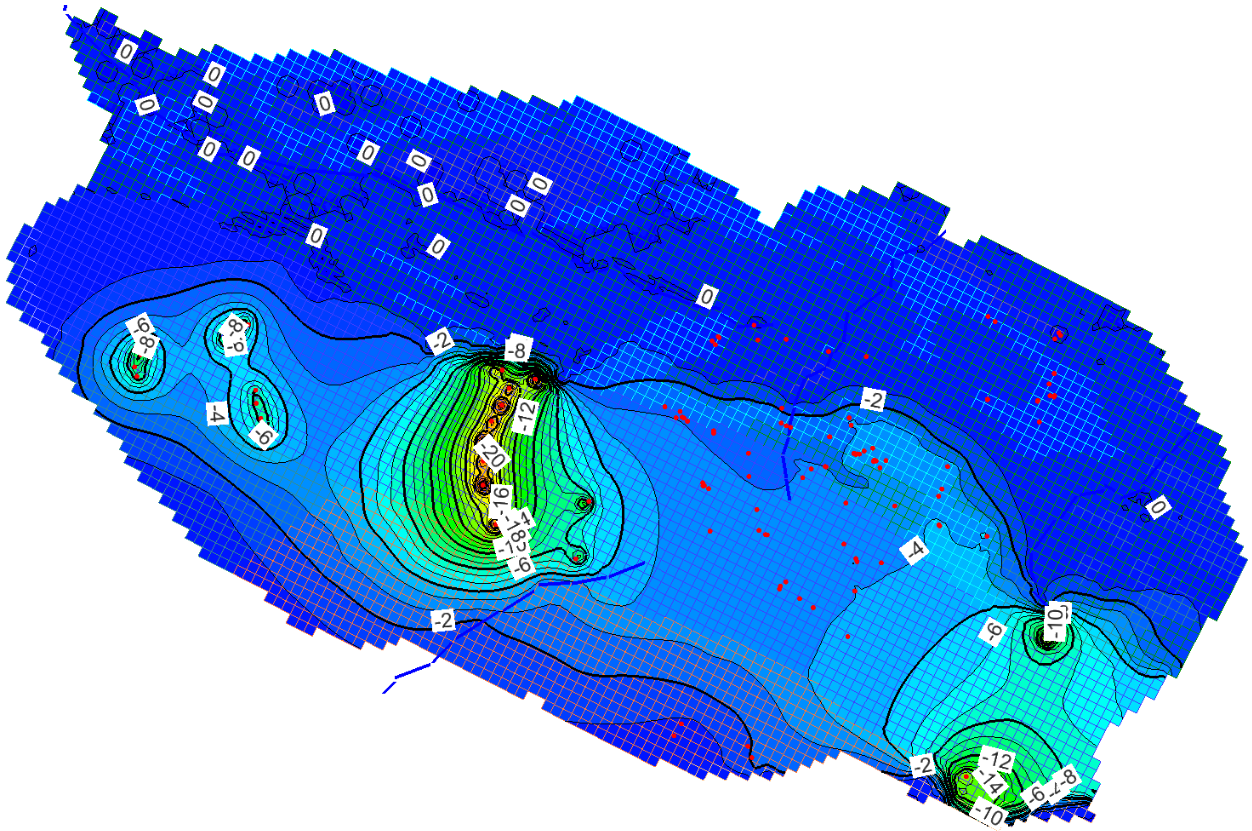


Figure 29: Scenario 1: additional drawdown due to new wells (differences in the groundwater tables between scenario 0 and scenario 1, October 2035).

4.5.2 Scenario 2: new pipeline capacities after 2025

The scenario 2 constitutes a compromise between the both foregoing scenarios. New pipeline capacities are proposed in 2026 and the development of new well fields is moderate. The needed capacity of all pipelines increases from 35 MCM (2011 to 2025) to 67 MCM (2035). New well fields are needed in 2014 and 2020, respectively (Figure 30). In comparison with scenario 1, the WF1, which is located far from the City, is not needed until 2035.

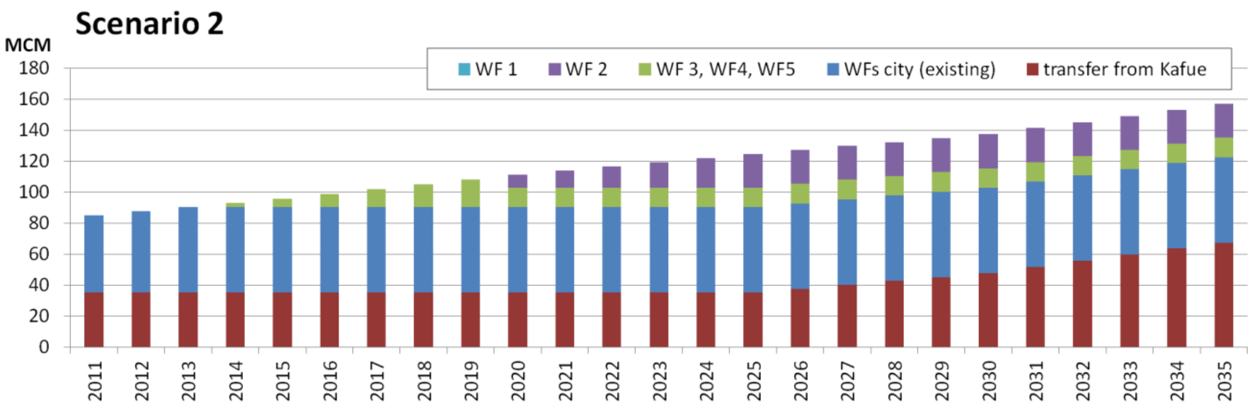


Figure 30: Abstraction rates and water sources in the scenario 2. New pipeline capacities are developed in 2026 and two well fields are used additionally.

The resulting groundwater tables are presented in Figure 31 and the comparison with the reference scenario in Figure 32. The temporal development of the groundwater table emphasizes that a steady state is gradually reached by 2035. The drawdowns at the new proposed well fields are lower than in scenario 1, because the abstraction rates are lower and the abstraction rates are not increasing after 2025.

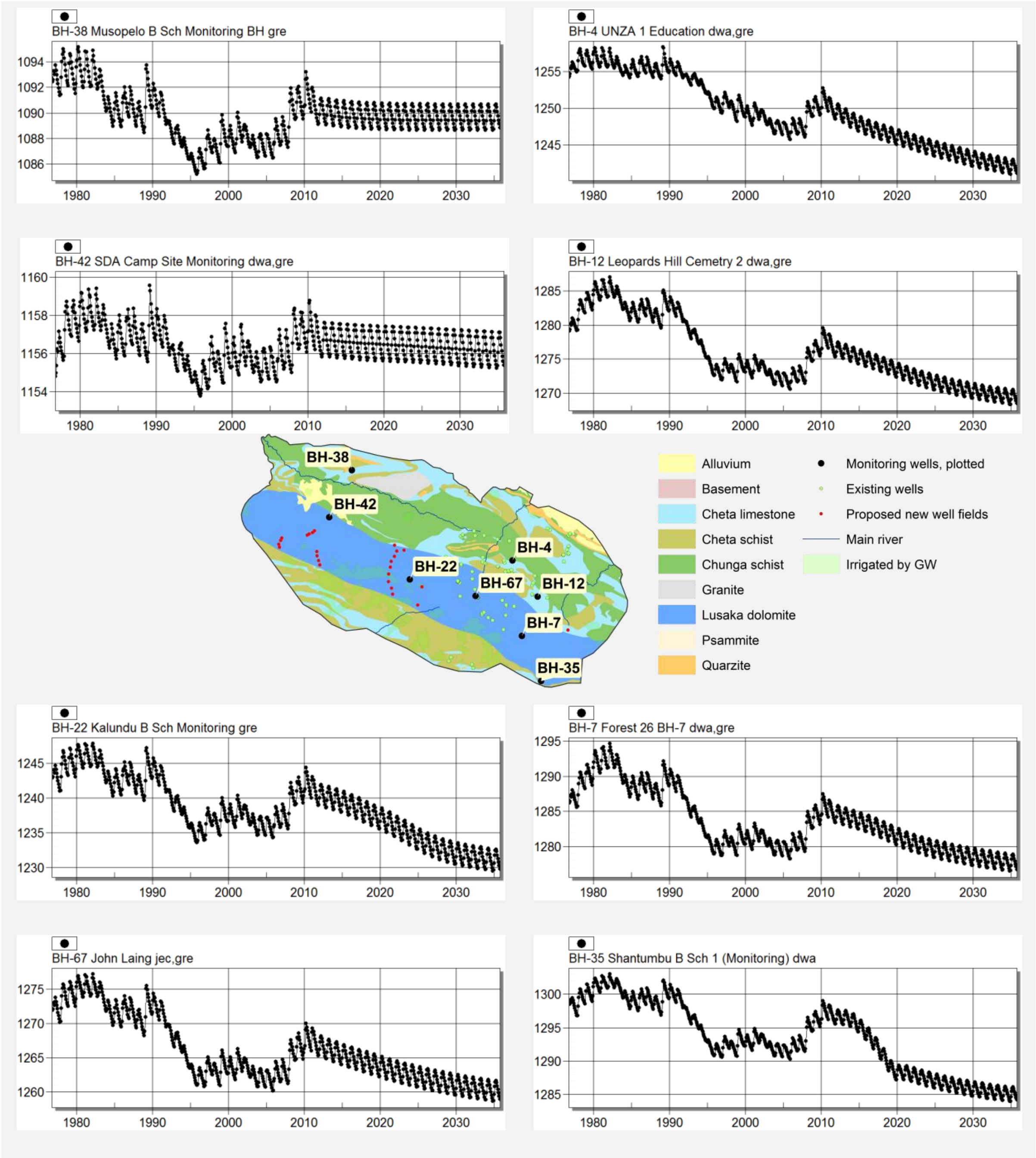


Figure 31: Scenario 2: temporal development of the groundwater table.

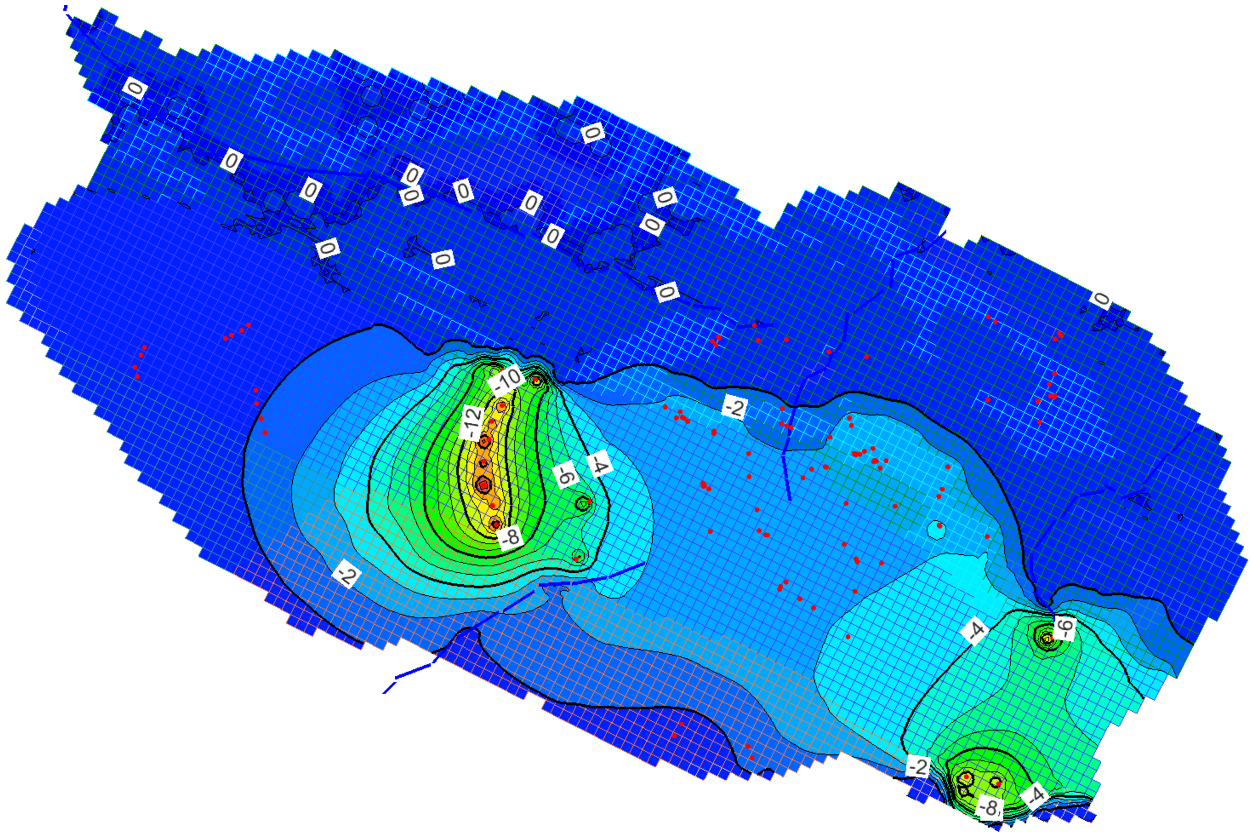


Figure 32: Scenario 2: additional drawdown due to new wells (differences in the groundwater tables between scenario 0 and scenario 2, October 2035).

5 Conclusions and Recommendations

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

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

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

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

Despite the mentioned shortcomings, the numerical model is a good tool to investigate the current and future water budget considering different water management options. Analysis has brought out that the current abstraction rates are sustainable, even if additional drawdowns up to 7 m can be expected at the well fields “International School” and “Mass Media” in future.

The calculated significant drawdowns at the well fields from 1976 to 2000 are in accordance to the findings from Schmidt (2002). However, an increase of the water table is calculated between 2000 and 2010 and a stable state is predicted for the future, assuming average rainfall patterns and constant abstraction.

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

In order to allow further sustainable abstractions, new well fields outside the City are essential. In a first expansion phase, well fields in the Local Forest Reserve area and in the vicinity of the City should be developed. In a later phase well fields in the West of Lusaka would be needed.

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

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