REPUBLIC OF ZAMBIA
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**FEDERAL REPUBLIC
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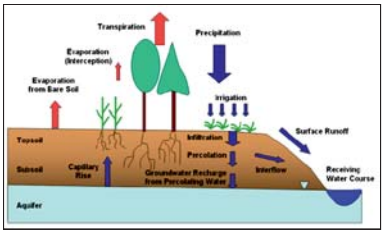
Federal Institute for Geosciences
and Natural Resources

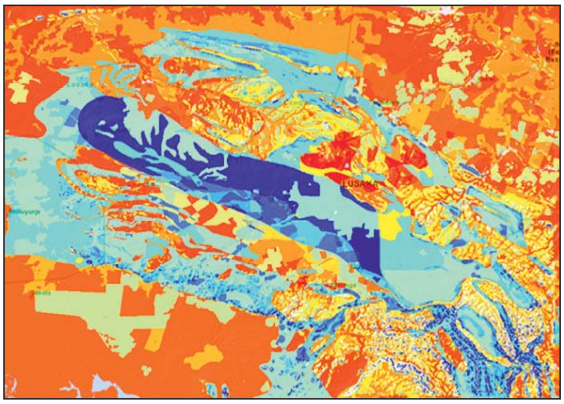
Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

REPORT NO. 5

Assessment of annual percolation rates in the Lusaka region

Volker Hennings





Hanover, August 2012

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

ASSESSMENT OF ANNUAL PERCOLATION RATES IN THE LUSAKA REGION

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Commissioned by:	Federal Ministry for Economic Cooperation and Development (BMZ: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung), Germany
Project Numbers:	BMZ PN 2008.2125.6 (Phase II) BGR 05-2344-01
Implementing Agencies:	Ministry of Mines, Energy and Water Development, Department of Water Affairs, Lusaka, Zambia Federal Institute for Geosciences and Natural Resources (BGR: Bundesanstalt für Geowissenschaften und Rohstoffe), Hanover, Germany
Pages:	43
Place and date of issuance:	Hanover, August 2012

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Abbreviations

awc	(soil) available water capacity
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
CROPWAT	specific name of a simulation model of the soil water balance
DWA	Department of Water Affairs
ETact	actual evapotranspiration
ETo	reference evapotranspiration
ETpot	potential evapotranspiration
FAO	Food and Agriculture Organization (of the United Nations)
GWR	groundwater recharge
Kc	crop coefficient
Kcb	transpiration component of the crop coefficient
Ke	evaporation component of the crop coefficient
MABIA	specific name of a simulation model of the soil water balance
PTF	pedotransfer function
RAW	readily available water
Ro	surface runoff
SWAP	specific name of a simulation model of the soil water balance
TDR	time domain reflectometry
WEAP	Water Evaluation and Planning (software)
ZARI	Zambian Agricultural Research Institute

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, in prep.	Bäumle R., Krekeler T., Shamboko-Mbale B. & C. Siwale	*Water Balance Estimates for Sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka region*	Report No. 6
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 (working title).- Ministry of Energy and Water Development*	Technical Note No. 7

List of reports compiled by the project in Phase II (continued)

Date	**Authors**	***Title***	**Type**
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: Volker Hennings

Title: Assessment of annual percolation rates in the Lusaka region

Key words: groundwater recharge, soil water balance, simulation model, Lusaka

Mean annual percolation rates in the Lusaka region were determined by a functional simulation model of the soil water balance. Climatic data from the hydrological year 1989/90 with 780 mm annual precipitation, a soil available water capacity of 100 mm/m and small-scale rainfed agriculture with cultivation of non-irrigated maize during the rainy season describe the reference scenario. Under these conditions 482 mm actual evapotranspiration and 258 mm groundwater recharge are calculated. A mechanistic simulation model (SWAP) provides similar results. Results are compared to existing estimates from the literature and sources of uncertainties are discussed.

Extended Summary

Within the framework of the technical cooperation project “Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems” quantification of the mean annual percolation rate from the soil as part of the groundwater recharge rate in the Lusaka region is one of the main objectives. For this purpose a functional simulation model of the soil water balance, named WEAP/MABIA, was applied; WEAP/MABIA is based on FAO Irrigation and Drainage Paper No. 56 and the dual crop coefficient approach. The hydrological year 1989/90 with 780 mm annual precipitation acts as a reference year, 1983/84 with 571 mm annual precipitation was chosen as a typical dry year. Simulations were carried out for five types of land use including small-scale agriculture (rainfed agriculture with maize as the dominant crop) and large-scale agriculture (irrigation agriculture with non-irrigated maize in summer and irrigated soybeans in winter). Cultivation of maize under rainfed conditions on deeply developed soils with an available water capacity of 100 mm/m represents the reference case for model comparisons. Under these conditions the WEAP/MABIA model calculates 482 mm actual evapotranspiration (ETact) and 258 mm groundwater recharge (GWR). Simulation results of SWAP, a mechanistic simulation model of the soil water balance, are very similar with 479 mm (ETact) and 261 mm (GWR) when "free drainage" or "free outflow at soil-air interface" was chosen as bottom boundary condition. Under conditions of large-scale agriculture with approximately 750 mm irrigation WEAP/MABIA provides the following results: 1184 mm ETact, 304 mm GWR. ETact and GWR are calculated for all combinations of land-use type and soil properties and are presented in form of thematic maps of the project area. These results are discussed in relation to available estimates from the literature. At some places with shallow groundwater tables probably the effects of capillary rise are neglected and groundwater recharge in total is overestimated. For conditions of 1983/84 and the reference scenario the WEAP/MABIA model indicates zero recharge; but because most local soils are shallower and are characterized by a smaller available water capacity, according to WEAP/MABIA deep percolation and therefore groundwater recharge take place in most parts of the project area even in a dry year like 1983/84. Due to the lack of existing lysimeters cited estimates cannot be validated against existing measurement results. The only chance to evaluate WEAP/MABIA results offer data from a local farm survey report. When simulated and reported irrigation water demand are compared results for some farms show close correspondence; on the average water demand as simulated by WEAP/MABIA is overestimated by approximately 20 %.

1. Project objectives

Within the framework of the technical cooperation project “Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems” between the Department of Water Affairs (DWA), Ministry of Mines, Energy and Water Development, Zambia and the Federal Institute for Geosciences and Natural Resources (BGR, Hanover/Germany) the main objectives are to facilitate an effective groundwater resource planning and management and to strengthen the capacities of the Zambian water sector. At the end of the project, among others two outputs are expected for the Lusaka area: the amount of groundwater that can be sustainably abstracted is quantified, i.e. the mean annual percolation rate from the soil is estimated, and groundwater quality and its vulnerability to pollution are known. To reach these two goals a simulation model of the soil water balance as well as a classification scheme to assess the protective effectiveness or filtering effect of the rock and soil cover are required. Soil available water capacity acts as an input variable to both types of models. The regionalization of soil physical parameters in the study area around Lusaka was described in a separate Technical Note (HENNINGS et al. 2012). Results of this study were used to compile a groundwater vulnerability map of the Lusaka region (NICK 2011). The following report focuses on the methodology to assess annual percolation rates in the study area and presents results for selected time intervals.

2. Existing estimates of local groundwater recharge rates

In the past, annual groundwater recharge rates within the project area were estimated by several authors (Table 1). Cited results are based on different approaches.

Table 1: Estimates of groundwater recharge rates in the Lusaka area (selected results)

Authors	Area	Time interval	Method	Groundwater recharge rate
VON HOYER et al. (1978)	Lusaka dolomite	1976/77	Daily actual evapotranspiration is calculated from an empirical relationship between ETact/ETpot and soil water content, expressed in % awc, given by RENGER et al. (1974)	
		1938-77	Long-term estimate on the basis of simulation results for single years	160 mm (forest) 180 mm (scrubland) 200 mm (arable land)
YEC (1995)	Lusaka province	1994/95	Calculation of ETact in dependance of precipitation and temperature, using an empirical relationship given by TURC (1954, 1955)	123 mm
			Baseflow separation	68 mm
NKHUWA (1996)	Lusaka dolomite	1971-90	Calculation of ETact according to RENGER et al. (1974), ETpot assessment based on PENMAN	109 mm
			Calculation of ETact according to RENGER et al. (1974), ETpot based on THORNTHWAITE	355 mm
			Calculation of ETact according to TURC (1954, 1955)	141 mm
			Mean of three approaches	202 mm (Ø)

In the international context the THORNTHWAITE method is considered as an out-dated approach to calculate potential evapotranspiration and is replaced by FAO's Grass Reference Evapotranspiration. In comparison to PENMAN the FAO method tends to underestimate the target variable und its results lead towards higher estimates for groundwater recharge rates. The method applied by RENGER et al. (1974) is based on empirical knowledge of the soil water balance and uses a parabolic function to express the ETact/ETpot ratio in dependence of the actual soil water content; it assumes different available water capacities for different land use types and therefore allows to quantify evapotranspiration and groundwater recharge in the Lusaka area in three different cases. The underlying empirical relationship was developed under climatic and vegetative conditions of Central Europe. Thus, its validity under semi-humid or semi-arid conditions of the outer tropics has at least to be confirmed (see BRUNNER in KINZELBACH et al. (2002)). The range of all values derived from soil water balance methods is marked between 100 and 200 mm annual recharge. All these estimates have in common that they neglect soil and plant effects. Against this background a re-evaluation of the local water balance seems to be useful. It should be based on updated climatic information and site-specific plant coefficients and soil properties.

3. Applied methodology

Under field conditions deep percolation can be measured directly by lysimeters or water fluxes can be calculated from neutron and TDR probe results. An extensive overview of all available methods for determining groundwater recharge is available from ARBEITSKREIS GRUNDWASSERNEUBILDUNG DER FACHSEKTION HYDROGEOLOGIE DER DEUTSCHEN GEOLOGISCHEN GESELLSCHAFT (1977) or particularly for semi-arid climates from KINZELBACH et al. (2002). Information on deep percolation can also be obtained by applying simulation models of the soil water balance. A classification scheme of adequate models is given by WAGENET et al. (1991). Models are generally categorized by the manner in which they represent basic processes of water flow. At one extreme are mechanistic models, which have been developed on the recognition that potential energy gradients are the driving force for water flow. This kind of model is termed mechanistic as it is presumed to be representative of the best possible understanding of basic mechanisms of water flow (WAGENET et al. 1991). At the opposite extreme are functional models, which greatly simplify physical process in order to reduce data demands and computational time (WAGENET et al. 1991). Both are different in terms of input data requirements and representation of soil physical processes (Fig. 1). To avoid high costs of field measurements and limitations in the availability of model input parameters, even more simplifying, robust methods such as empirical equations and nomograms were developed. They are called *(hydro-) pedotransfer functions* and are based on input variables that can be easily determined or are available from existing databases (Fig. 1).

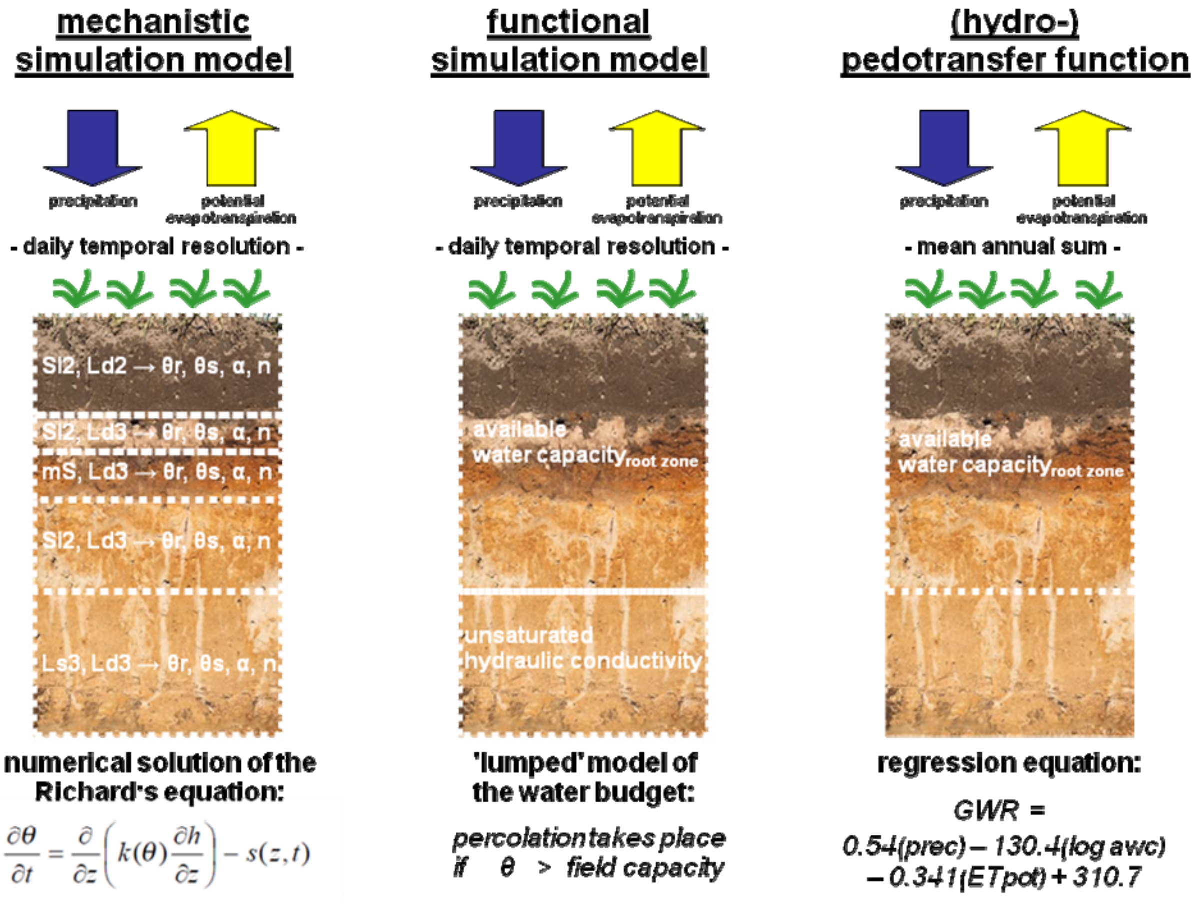

Figure 1: Principles of models applied to quantify the soil water balance

As Fig. 1 shows, *mechanistic simulation models* need climatic input data of high temporal resolution. The soil profile is usually discretized vertically into soil horizons and every horizon is characterized by certain parameter sets. The central element of the model is represented by a numerical solution of the Richard‘s equation.

Functional simulation models are based on the same climatic input data. Concerning the soil the user only needs two specific values: the topsoils available water capacity of the root zone and the subsoils hydraulic conductivity. A "lumped" model of the water budget usually allows percolation to take place if soil moisture exceeds field capacity.

In contrast to the former type of models *(hydro-) pedotransfer functions* need only annual sums of precipitation and potential evapotranspiration additionally to one parameter describing the soil. The prediction model consists of just one equation.

Table 2: Properties of selected simulation models

Criteria	SWAP	MABIA/WEAP	CROPWAT
Type of model	mechanistic model	functional model	very simple functional model
Meteorological input data	precipitation and ET_{pot} data in daily temporal resolution	precipitation and ET_{pot} data in daily temporal resolution	precipitation and ET_{pot} data in monthly temporal resolution, transformation into daily values by disaggregation techniques
Realization of soil hydrological processes	calculation of water fluxes driven by matrix potential gradients; numerical solution of the Richard's equation	calculation of ET_{act} by empirical crop coefficients, occurrence of percolation if soil water exceeds field capacity	calculation of ET_{act} by empirical crop coefficients
Vertical Discretization of the soil profile	unlimited number of soil horizons of any depth	one soil compartment ("one bucket approach")	one soil compartment ("one bucket approach")
Soil physical input parameters	van Genuchten parameters for every soil horizon	available water capacity of the root zone, alternatively ascertainable from soil texture by pedotransfer functions	available water capacity of the root zone
Groundwater information	depth of the water table at specific dates	no groundwater information, no capillary rise	no groundwater information, no capillary rise
Spectrum of crops	standard settings of plant parameters exemplary delivered for three crops	internal library with plant coefficients for 181 crops	internal library with plant coefficients for 36 crops
Number of required plant coefficients	10	4	4
Simulation of crop growth	yes	no	no

Within this study three different models (Table 2) will be applied on a common reference data set ("small-scale agriculture") and results will be compared. For routine applications in the Lusaka area the dual crop coefficient concept as realized by several functional simulation models will be used.

The concept applied here is based on some simple fundamentals:

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

The FAO56 approach uses crop coefficients to modify the reference evapotranspiration to crop-specific conditions. The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass crop with specific characteristics. The concept of reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. Soil factors do not affect ETo. The most simplified version represents the single crop coefficient concept, where differences in the crop canopy and aerodynamic resistance relative to the reference crop of the FAO Penman Montheith method are accounted for within the crop coefficient Kc. The Kc coefficient serves as lumped parameter for the physical and physiological differences between crops. Kc integrates the relationships between evapotranspiration of the crop and the reference surface and summarizes all factors influencing evaporation and transpiration. This approach is realized in the CROPWAT model (CLARKE et al. 1998). CROPWAT's use is restricted to the period of growth.

In a second, more sophisticated approach Kc is split into two factors that separately describe the evaporation (Ke) and transpiration (Kcb) components. The soil evaporation coefficient Ke is maximal when the topsoil is wet, following rain or irrigation. Some days later when the uppermost topsoil layer is dried out Ke decreases and can even become zero. The largest dif-

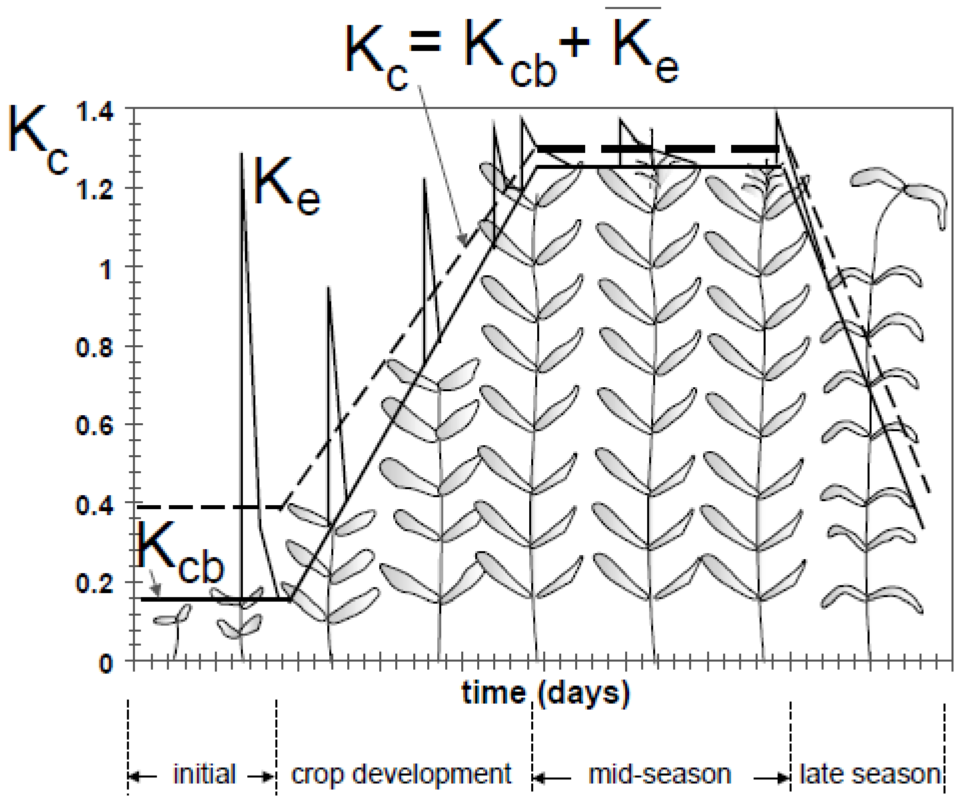

Figure 2: Crop coefficient curves showing the basal Kcb (thick line), soil evaporation Ke (thin line) and the corresponding Kc curve (dashed line) (taken from Allen et al. 1998)

ference between Kc and Kcb is found in the initial growth stage where evapotranspiration is predominantly in the form of soil evaporation and crop transpiration is still small. Because crop canopies are near or at full ground cover during the mid-season stage, soil evaporation beneath the canopy has less effect on crop evapotranspiration and the value for Kcb in the mid-season stage will be nearly the same as Kc. Depending on the frequency with which the crop is irrigated during the late season stage, Kcb will be similar to (if infrequently irrigated) or less than the Kc value. Fig. 2 presents typical shapes for the Kcb, Ke and single Kc curves. The Kcb curve in the figure represents the minimum Kc for conditions of adequate soil water and dry soil surface. The Ke spikes in the figure represent increased evaporation when precipitation or irrigation has wetted the soil surface and has temporarily increased total ETc. These wet soil evaporation spikes decrease as the soil surface layer dries. The spikes generally reach a maximum value of 1.0-1.2, depending on the climate, the magnitude of the wetting event and the portion of soil surface wetted. All relevant algorithms were published as part of the FAO Irrigation and Drainage Paper No. 56 "Crop Evapotranspiration" (Allen et al. 1998). Within the framework of this study the dual crop coefficient concept was applied to assess evapotranspiration and percolation rates as a function of climatic conditions and soil and plant properties in the Lusaka area.

The validity of the FAO56 or dual crop coefficient approach respectively has been tested and evaluated by several authors (BODNER et al. 2007, LÓPEZ-URREA et al. 2009, LIU & LUO 2010, ROSA et al. 2012b). Most of the examples given, do illustrate the robustness of the approach, describe a variety of application options and classify it as a reliable modelling tool to provide accurate results. ROSA et al. (2012b) report that the calibrated model does not tend to over- or underestimate available soil water over the course of a season, and that the model, prior to calibration, and using standard values for many parameters, also performed relatively well. The FAO56 dual crop coefficient approach was programmed in form of the MABIA software and since 2011, is available as part of the WEAP system. WEAP ("Water Evaluation and Planning") is a decision support system for quantitative water resources management (STOCKHOLM ENVIRONMENT INSTITUTE 2005). Since 2012, the FAO56 dual crop coefficient approach is also available as a software tool called SIMDualKc, developed by the Institute of Agronomy from the Technical University of Lisbon (ROSA et al. 2012a).

4. Input data

4.1 Climate

Within the study area the Meteorological Survey of Zambia maintains three meteorological stations (Lusaka City-Airport, Lusaka International Airport and Mt. Makulu) which are all located approximately at the same longitude. The lack of information about west-east-oriented gradients of climatic variables makes the compilation of isoline maps difficult. Against this background, at least for reference evapotranspiration, homogeneous conditions within the entire study area have to be postulated. This assumption is confirmed by the study on the National Water Resources Master Plan (YEC 1995) as well as by personal communications from staff members of the Meteorological Survey. In terms of hygric conditions increasing amounts of rainfall from NNW to SSE are reported by several authors (see YEC 1995). Because detailed information is missing and supposed regional differences in precipitation are not significant, all following calculations within the framework of this study are based on data from only one meteorological station All result have been calculated based on data from the meteorological station of Lusaka International Airport.

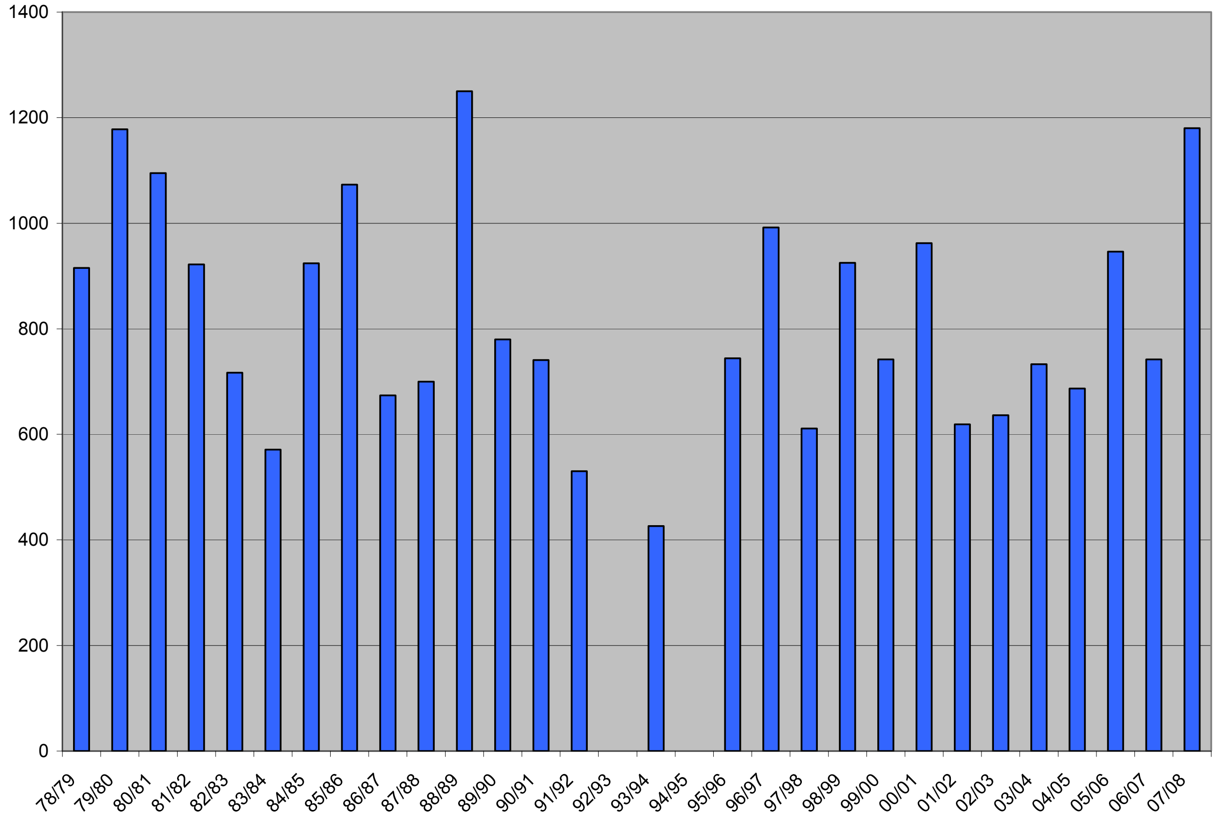

Figure 3: Long-term annual rainfall [mm] registered at Lusaka International Airport

Annual sums of precipitation at Lusaka International Airport were calculated from daily values as provided by the Meteorological Survey of Zambia. All values are related to hydrological years from 1st July to 30th June. For some years in the early nineties of the former century annual sums cannot be calculated due to missing periods of daily records. The long-term average of annual rainfall from 1978/79 to 2007/08 (30 years minus 2 years) equals 822 mm. Annual water balances are requested for one representative year close to long-term means as well as for one very dry year affected by drought. The hydrological year 1989/90 (annual precipitation = 780 mm) was selected as a "reference year" and 1983/84 represents a "typical dry year" (annual precipitation = 571 mm). Dryer years during the nineties could not be used because of gaps in daily records of several climatic parameters. Fig. 4 shows daily precipitation during the reference year. The temporal patterns during both selected years (Fig. 4 / Fig. 8) do not differ considerably; 1983/84 did not include longer periods of zero rainfall.

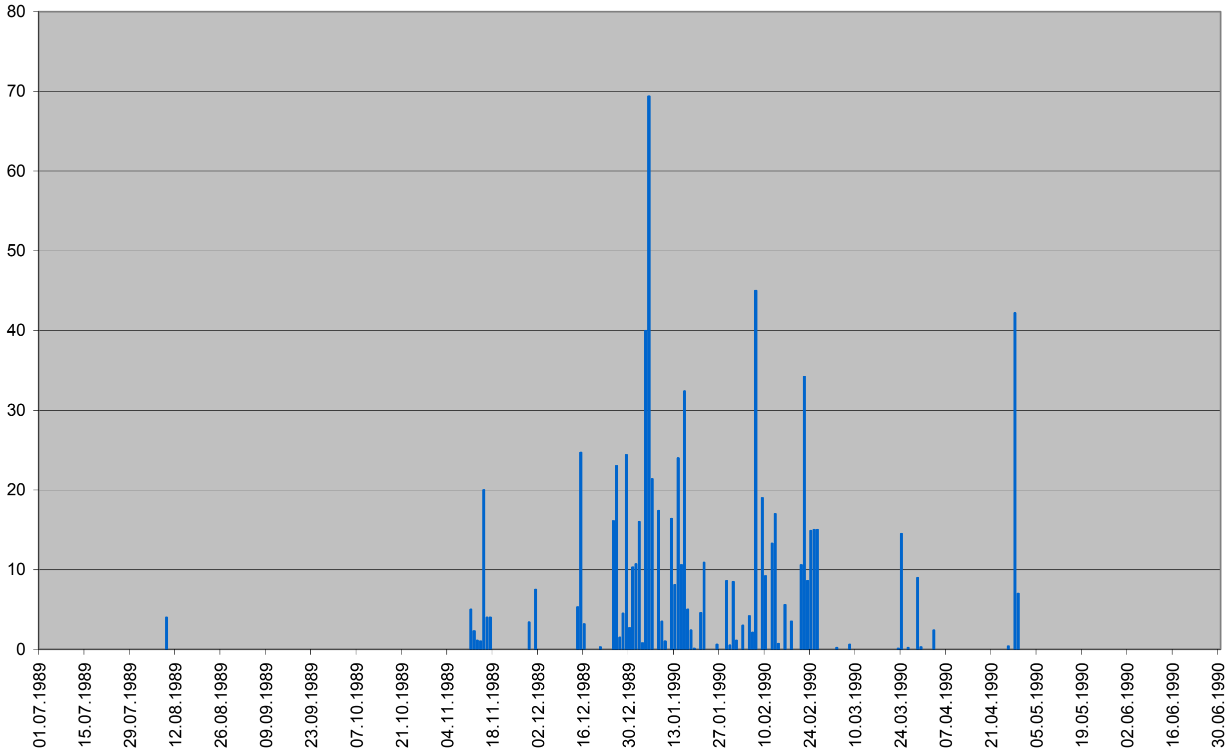

Figure 4: Daily precipitation in mm during 1989/90 at Lusaka International Airport

Simulation models of the soil water balance need additional information on potential evapotranspiration (ETpot). FAO's Grass Reference Evapotranspiration can be calculated from five daily meteorological input parameters: minimum temperature, maximum temperature, mean humidity, mean wind speed, solar radiation or duration of sunshine. For Lusaka International Airport ETo was calculated by applying WEAP functionalities. Annual sums of ETpot are 1908 mm in 1989/90 and 1815 mm in 1983/84. Fig. 5 shows daily potential evapotranspiration over the course of the reference year 1989/90. 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 registered.

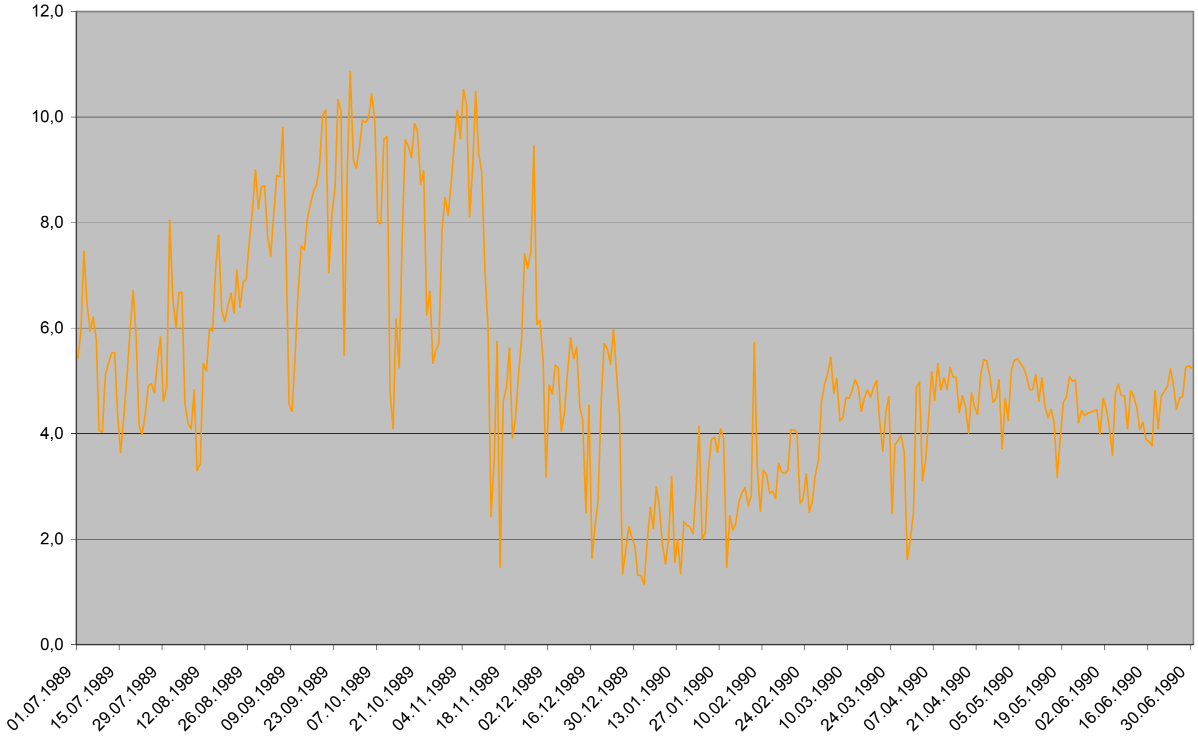

Figure 5: Daily potential evapotranspiration in mm during 1989/90 at Lusaka International Airport

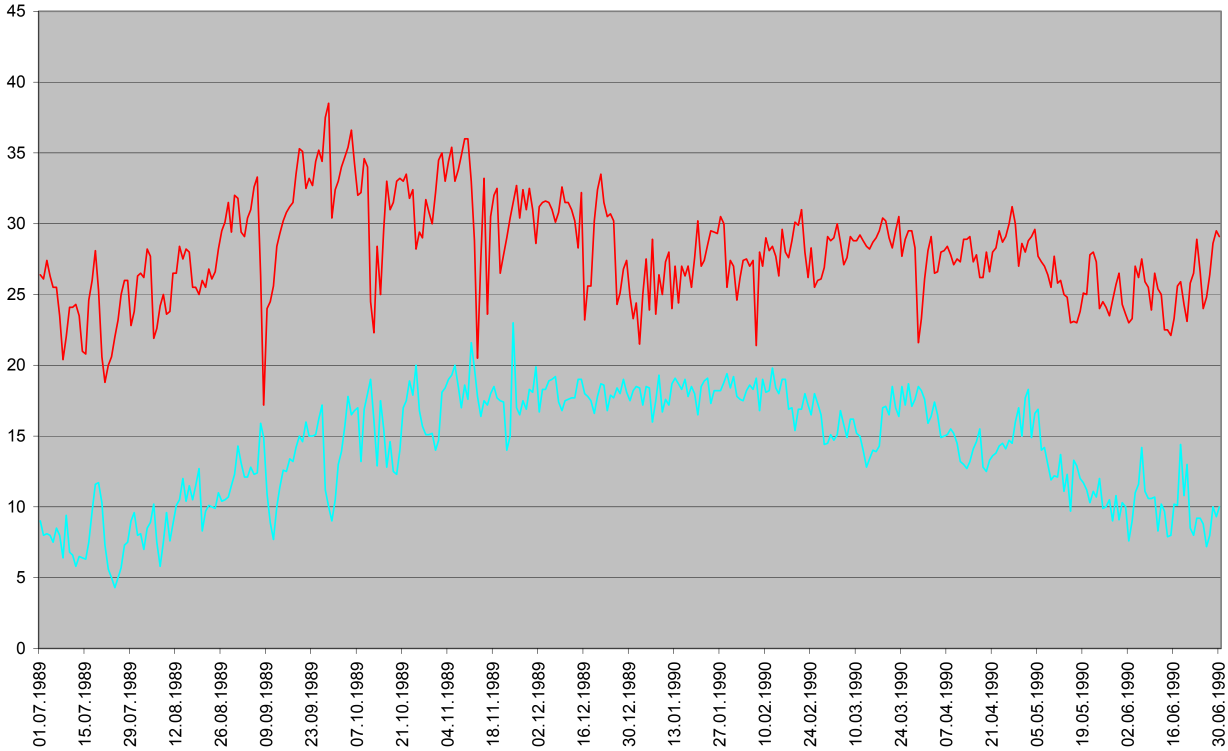

Figure 6: Daily minimum / maximum temperatures during 1989/90 at Lusaka International Airport

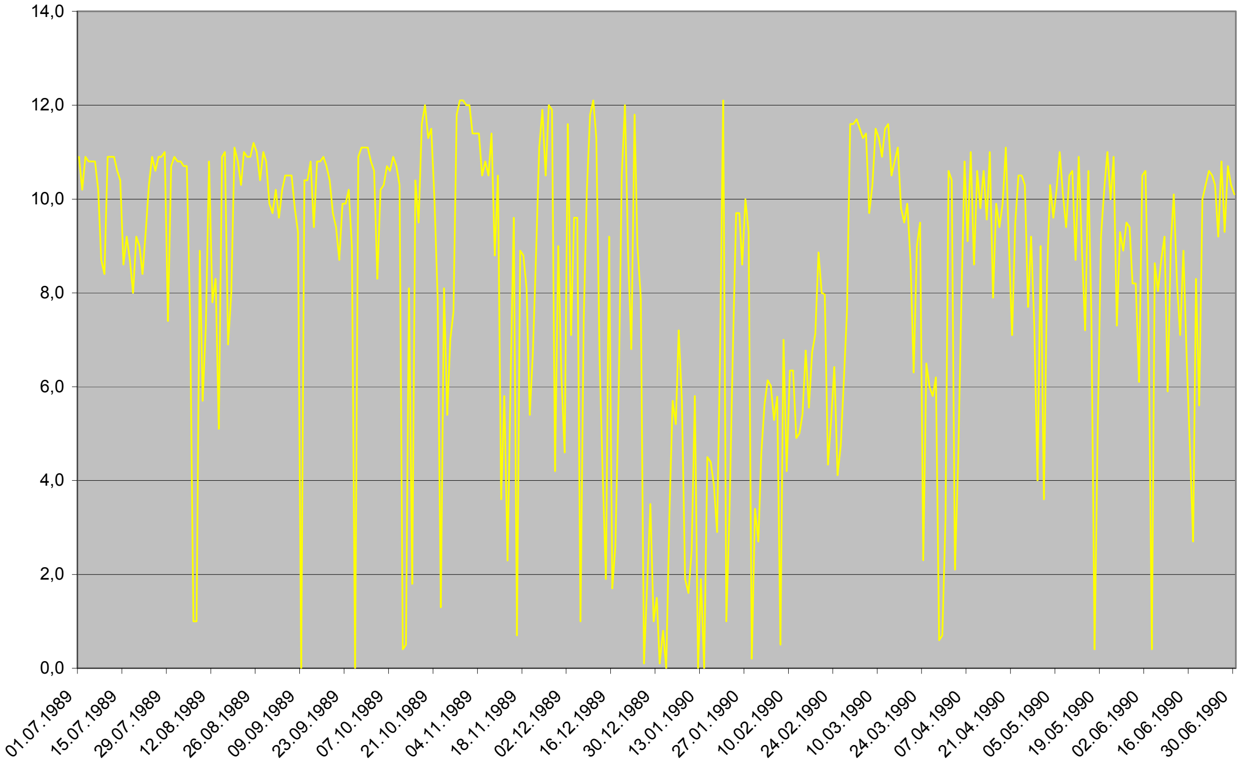

Figure 7: Daily hours of sunshine during 1989/90 at Lusaka International Airport

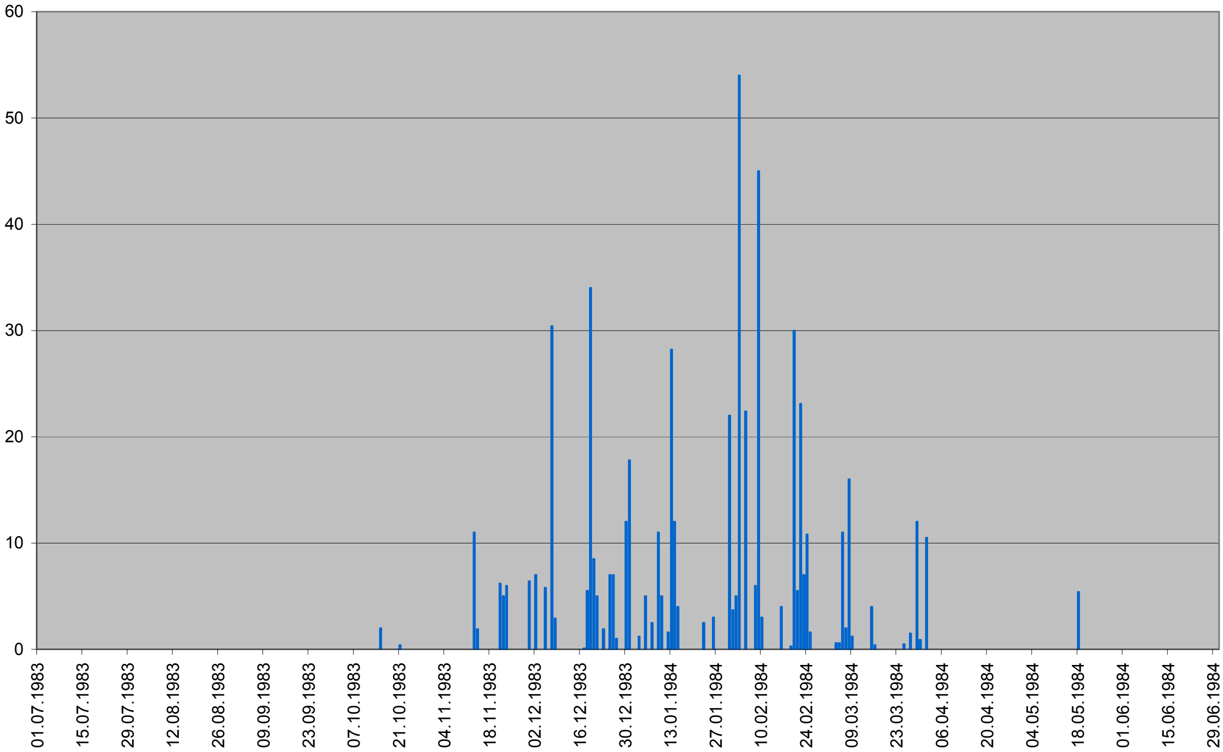

Figure 8: Daily precipitation in mm during 1983/84 at Lusaka International Airport

4.2 Soil

Physical and hydrological properties of local soils such as depth of soil development, water retention characteristics, saturated hydraulic conductivity and available water capacity of the root zone were estimated and regionalized as described within a separate project-internal Technical Note (HENNINGS et al. 2012). The resulting land quality map (Fig. 9) is required for applications of simulation models such as WEAP/MABIA.

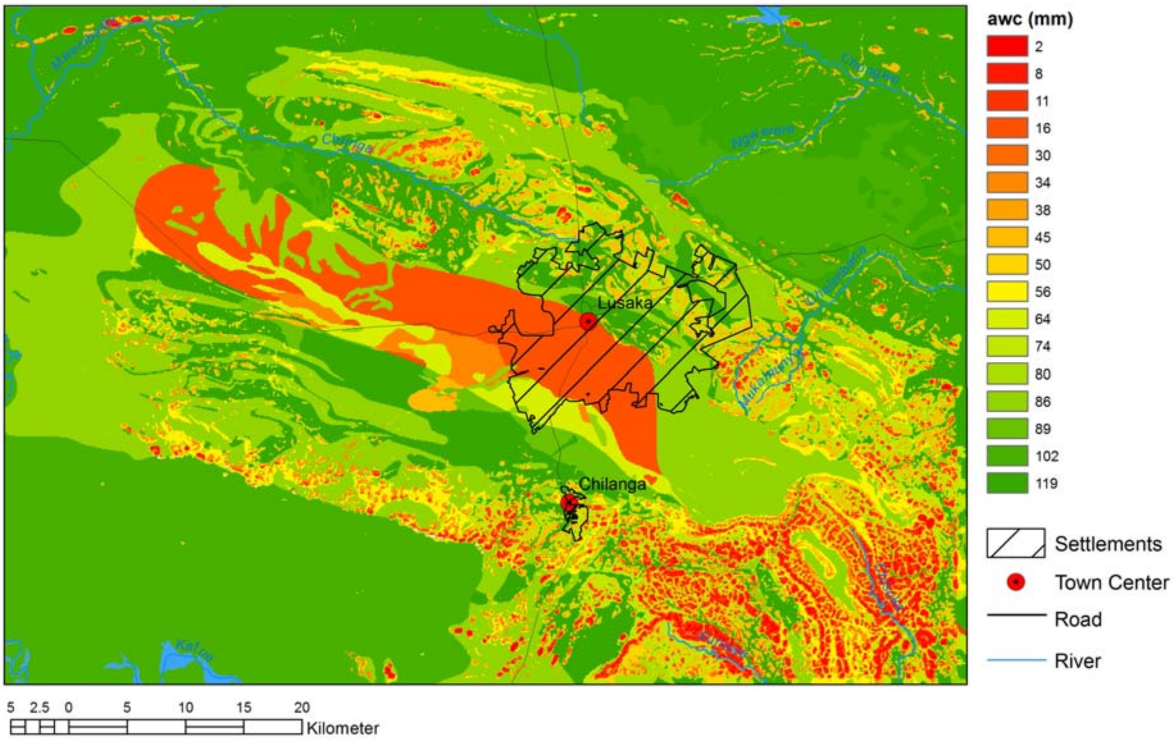

Figure 9: Available water capacities of the root zone in the study area (HENNINGS et al. 2012)

4.3 Land use

Spatial patterns of land use classes in the Lusaka area were mapped by remote sensing, i.e. interpretations of satellite images (HAHNE & SHAMBOKO-MBALE 2010). Additional information on local crops, crop rotation patterns, cultivation practices, irrigation techniques and water abstraction rates are available from results of a project-internal survey on commercial farmers (MAYERHOFER et al. 2010). A local plant calendar is available from the above mentioned study on the National Water Resources Master Plan (YEC 1995).

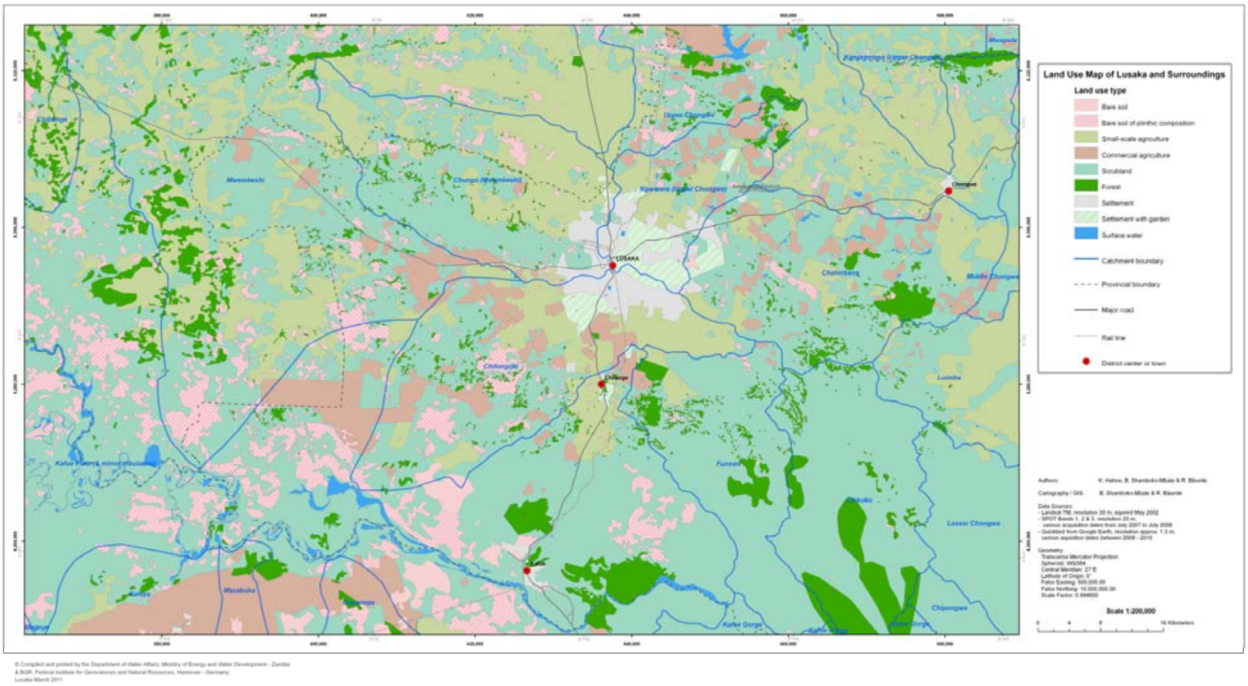

Figure 10: Land use types in the Lusaka area (HAHNE & SHAMBOKO-MBALE 2010)

HAHNE & SHAMBOKO-MBALE differentiate eight land use classes. For modelling soil water balances this degree of detail is not required: several land use classes (scrubland, forest, "bare soil", "bare soil of plinthic composition") are spatially aggregated into one common unit of natural vegetation without any agricultural use. Within urban areas two types of settlement structures, differing in the degree of sealing, are distinguished. This classification leads towards five land use classes as used for further considerations:

--- (Miombo) woodland including scrubland, forest,
--- small-scale agriculture, managed by peasants on the basis of subsistence economy,
--- large-scale agriculture, managed by commercial farmers on the basis of market economy,
--- settlements (of poorer social ranks, "compounds"),
--- settlements with garden, i.e. upper-class settlements with very few sealed surfaces.

Small-scale agriculture characterized by rainfed agriculture and maize as the dominant crop, acts as the reference case for the following model comparisons and scenarios.

Table 3: Plant physiological parameters and cultivation dates for land use type "small-scale agriculture", i.e. maize under conditions of outer tropics and altitudes of 1200 m

crop season	stage length [days] initial	development	mid-season	late	total
11 Nov - 5 Apr	28	40	48	30	146

Kcb initial	Kcb mid-season	Kcb late	depletion factor initial	depletion factor mid-season	depletion factor late	maximum height [m]	root depth min. [m]	root depth max. [m]
0.15	1.15	0.30	0.55	0.55	0.55	2.00	0.15	1.20

The farm survey report from MAYERHOFER et al. (2010) provides detailed agricultural statistics about 43 commercial farms within the Lusaka region. Their agriculturally used area sums up to approximately 12,830 ha. This area covers less than 50% of all farmland that is cultivated by commercial farmers in the project area. In total MAYERHOFER et al. list 34 agricultural crops. Not all of them can be taken into account; fields smaller than 30 ha are excluded from this study. Secondly the WEAP-internal library must offer the required information on plant coefficients. When these two criteria are applied 19 crops remain for further considerations on regional water balances (maize, sorghum, beans, soybeans, groundnuts, sunflower, wheat, cotton, potatoes, barley, tomatoes, citrus, peppers, tobacco, cabbage, sweet corn, peas, onion and squash). Some of them are exclusively cultivated during the rainy season, e.g. sorghum, sunflower and groundnuts, some of them are exclusively cultivated under irrigated conditions in the dry season, e.g. wheat and barley. Other crops such as peppers and cabbage are cultivated during both seasons of the year. The averaged cropping intensity – although not precisely calculable – at least has to be assumed as > 1.15. From all detailed information as given by local farmers 45 possible crop rotation patterns were generated, and all crop rotation patterns were assigned to farms where they occur. 19 of these 45 crop rotations consist of 2 crops per year. Simulations in WEAP were carried out for 18 crop rotations; six of them consist of only one crop in the rainy season (Table 10), seven of them consist of only one crop in the dry season (Table 11), and five of them are composed of two crops, one in the rainy and one in the dry season (Table 12). The land use type "large-scale agriculture" is represented by a sequence of two crops, non-irrigated maize in summer and irrigated soybeans in winter. All relevant dates and coefficients for this land use type are presented in Table 4.

Table 4: Plant physiological parameters and cultivation dates for land use type "large-scale agriculture", i.e. sequence of maize (rainy season) and soybeans (dry season)

– for maize (11 Nov – 5 Apr) see Table 3 –

	stage length [days]				
crop season	initial	development	mid-season	late	total
1 Jun - 13 Sep	20	20	45	20	105

Kcb			depletion factor			maximum height	root depth	
initial	mid-season	late	initial	mid-season	late	[m]	min. [m]	max. [m]
0.15	1.10	0.30	0.50	0.50	0.50	0.75	0.15	0.95

The cultivated land MAYERHOFER's farm survey report refers to covers 12.8 km^2; the proportion of irrigated land comes up to almost 48 % (6.15 km^2). The most frequently applied methods are sprinkler irrigation or centre pivot and lateral move systems (Fig. 11, 12). For all these irrigation methods the "wetted fraction" as required for running the WEAP software can be set to 1.0. Inside WEAP the irrigation schedule is controlled by two internal, user-dependent criteria: irrigation timing and irrigation depth. Within this study the following methods and thresholds were chosen: irrigation starts when soil moisture depletion is greater than or equal to a specified percentage of "Readily Available Water (RAW)", and 100% are defined as the relevant threshold ("irrigation trigger"). In case of irrigation a specified percentage of the RAW level is applied, and again 100% are defined as the relevant threshold ("irrigation amount"). In this study following conditions were applied on land use type "large-scale agriculture": during the dry season irrigation is restricted to soybeans, and supplemental irrigation during the rainy season is neglected. For general calculations of the regional water balance the "Deficit Irrigation" scenario was applied, i.e. the availability of irrigation water is unlimited, no yield reduction caused by water stress is tolerated, and optimal water supply is the overall goal.

Figure 11: Mobile sprinkler irrigation systems in the project area

Figure 12: Fixed sprinkler irrigation systems in the project area

Coefficients to estimate actual evapotranspiration in accordance to the FAO56 approach are available only for agricultural crops. The dominant land use type of the project area is Miombo woodland, a savannah like grassland vegetation that includes single Brachystegia trees. Under semi-humid conditions of central and southern Zambia the spatial proportion of trees can be estimated by 10%. Actual evapotranspiration (ETact) of this land use type is assumed to equal ETact of grassland plus 10 %. For unsealed areas within settlements ETact is also equalized to that of grassland; the spatial proportion of sealed surfaces is assessed by 35 % in compounds and 10 % in residential estates in park-like surroundings.

4.4 Assumptions concerning surface runoff

Before the rate of percolation for the soil can be calculated, the proportion of precipitation accountable for surface runoff has to be subtracted from the (gross) precipitation rate, i.e. for model simulations of the soil water balance, net or effective precipitation has to be known. Surface runoff is recorded at several gauging stations, but local measurement results refer to larger subcatchments that are heterogeneous in soils and parent materials. During 1989/90 the surface runoff rate as registered in the Mwembeshi and Chongwe catchment averages 80 mm, i.e. surface runoff accounts for a 10% share of gross precipitation. In order to differentiate into groups of parent material that differ in their hydrological behaviour surface runoff in 1989/90 was set to 40 mm on limestone and dolomite and 120 mm on schist, gneiss and quartzite. In 1983/84 comparable numbers are 0 and 40 mm.

For 1989/90 the annual rate of surface runoff was additionally calculated by an empirical rainfall runoff model. The curve number method (USDA-SCS 1972) was used for this purpose. This is an often tested method that takes land use, soil, precipitation, and slope into consideration. The method needs the soil to be classified as one of four "hydrological soil types", reflecting a semi-quantitative assessment of the infiltration capacity. With the additional consideration of the slope and 1989/90 rainfall data of high temporal resolution the annual surface runoff was then calculated for typical cropland of the Lusaka region ("large-scale agriculture", CN = 76). For this purpose the SIMDualKc software as developed by ROSA et al. (2012a) was applied. The model result of approximately 120 mm shows acceptable correspondence to measurement results as mentioned above.

5. Results

5.1 Groundwater recharge and water balance

All following results refer to climate data from the hydrological year 1989/90. Deeply developed soils with an available water capacity of 100 mm/m and cultivation of maize under rainfed conditions (Table 3) represent the reference case for model comparisons.

The CROPWAT model (CLARKE et al. 1998) realizes the single crop coefficient version of the FAO56 approach (see chapter 3 and Table 2). Daily climatic data from 1989/90 had to be transformed into monthly data, i.e. monthly precipitation sums and monthly means of daily temperature, humidity, wind speed and duration of sunshine. Monthly means of FAO's reference evapotranspiration per day were then calculated by the model. Monthly sums of precipitation had to be disaggregated again to obtain daily values; in our study an internal algorithm was chosen that distributes rainfall evenly over many single days per month and rain occurs every five days. Effective precipitation was set to a fixed percentage, resulting in a fixed amount of surface runoff (Ro) of 40 mm. Preset soil available water capacity could be entered directly. Plant physiological parameters and cultivation dates from Table 3 were used to calculate crop transpiration, but evaporation from bare soil during this time interval is not specified by the model. Outside the period of growth evaporation is calculated by using empirical crop coefficients for fallow. Under these general conditions the CROPWAT model leads to 576.5 mm actual evapotranspiration (ETact), leaving 163.5 mm percolation for annual groundwater recharge (GWR).

Table 5: Water balance of the reference scenario by application of the CROPWAT model

Precipitation	Ro	ETact	GWR
780.0	40.0	576.5	163.5

The dual crop coefficient version of the FAO56 approach (see chapter 3 and Table 2) is realized in form of the MABIA software as part of the WEAP system (JABLOUN & SAHLI 2011). In contrast to CROPWAT, its application is no longer restricted to the period of growth. The model can be run on a daily basis, so original climatic data can be directly read in. Again daily values of FAO's reference evapotranspiration are then calculated by the model. Surface runoff is calculated by the model itself; in this case the model was calibrated to provide the same amount of surface runoff as shown in Table 5. The required soil physical properties were not derived from information on texture class or individual sand, silt and clay contents and were neither taken from FAO guidelines nor estimated by pedotransfer functions. Instead water retention parameters were directly entered: total pore volume was assumed as 35 % volume, field capacity volume was assumed as 32 % volume, and permanent wilting point was assumed as 22 % volume, resulting in an available field capacity of 10% volume. These comparably low estimates of pore volume and field capacity are a result of the high bulk densities of local soils (see HENNINGS et al. 2012). Required plant physiological parameters and cultivation dates were directly taken from Table 3. Outside the period of growth the Kcb coefficient is set to that of fallow. Under these general conditions the WEAP/MABIA model leads to 482 mm actual evapotranspiration (ETact), leaving 258 mm percolating water for annual groundwater recharge (GWR).

Table 6: Water balance of the reference scenario by application of the WEAP/MABIA model

Precipitation	Ro	ETact	GWR
780.0	40.0	482.0	258.0

As mentioned in chapter 3, the Portuguese SIMDualKc model as published by ROSA et al. (2012a) offers another possibility to apply the FAO56 concept with a dual crop coefficient. But SIMDualKc does only calculate evaporation, transpiration and deep percolation within the period of growth from 11th November to 5th April. Because there is some rainfall and probably also some surface runoff outside this time interval model results as shown in Table 7 are not comparable to those of Table 5 and 7. But contents of Table 7 may demonstrate that also the SIMDualKc model calculates groundwater recharge rates of more than 250 mm in case of the reference scenario with 40 mm surface runoff.

Table 7: Water balance of the reference scenario (truncated time interval) by application of the SIMDualKc model

Precipitation	Ro	ETact	GWR
705.0	120.0	404.0	181.0

The third model that is taken into account for comparisons is the SWAP model. SWAP is a mechanistic, process-based simulation model of the soil water balance (KROES & VAN DAM 2003; for more details see Table 2). Again, original climatic data from 1989/90 can directly be used and daily values of FAO's reference evapotranspiration are then calculated by the model. SWAP does not contain any process-based rainfall runoff module so that gross precipitation equals net precipitation. Cultivation dates can be taken from Table 3, but FAO's crop coefficients are useless because SWAP is based on a total different methodology to calculate evapotranspiration. All together, SWAP requires empirical knowledge of ten plant parameters such as leaf area index and root density distribution. For the reference scenario standard parameter settings for maize as available from Wageningen Agricultural University or Appendix 9 from the SWAP Manual (KROES & VAN DAM 2003) were used. The length of the crop cycle was set to 146 days.

Typical soils of the Lusaka region consist of loose soil over weathered, karstic dolomite. Such a soil profile can be studied close to the Zambian Agricultural Research Institute (ZARI) in Mt. Makulu. In order to reflect these conditions in SWAP a two layer profile was generated: the top layer represents the soil, the bottom layer represents physically weathered parent material. The depth of soil development was assessed by 1.20 m because this value corresponds to the maximum rooting depth of maize. Soil physical properties were assumed to be homogeneous over depth. The reference soil was vertically discretized into soil horizons and for every soil horizon identical hydrological parameters were allocated. Van Genuchten parameters were estimated by applying pedotransfer functions from WOESTEN et al. (1998). For this purpose various parameter sets for a typical sandy loam, sandy clay loam, sandy clay and clay soil were compared and evaluated. The reference soil is targeted by an available water capacity of approximately 10.0 % volume. To reach this goal van Genuchten parameters were set to $\theta_r = 0.01$, $\theta_s = 0.378$, $\alpha = 0.069$, $n = 1.3$ and ksat = 24 cm/d. The thickness of the second or “rock” layer was 0.80 m. In this case the lower boundary of the second layer is located 2.00 m below the soil surface. In SWAP this "rock" layer also needs to be characterized by van Genuchten parameters. For this purpose van Genuchten parameters of a coarse sand were allocated and a saturated hydraulic conductivity of 500 cm/d was assumed. As shown later, model results are nearly insensitive to hydraulic properties of this second or "rock" layer. For model simulations with SWAP this "rock" layer can even be omitted.

The last determining adjustment of the model was the choice of the bottom boundary condition. SWAP offers eight options for this purpose. Because most soils of the project area are underlaid by consolidated rocks and are not affected by groundwater or capillary rise from the water table, the "free drainage" option was chosen. The "free outflow at soil-air interface" option provides identical results. To reach the default amount of surface runoff the evapotranspiration rate was left unchanged and 40 mm were subtracted from the calculated percolation rate. Under these general conditions the SWAP model leads to results as shown in Table 8.

Table 8: Water balance of the reference scenario by application of the SWAP model

Precipitation	Ro	ETact	GWR
780.0	40.0	479.0	261.0

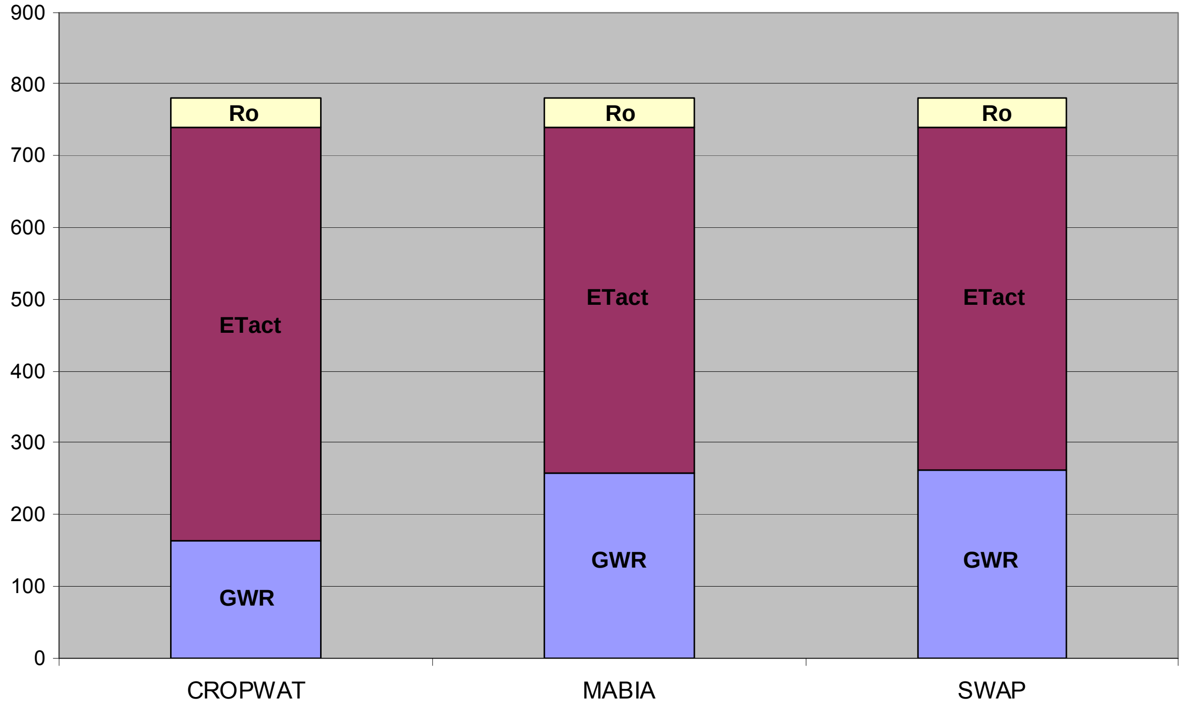

Figure 13: Water balances of the reference scenario as provided by three simulation models

In addition to contents of Tables No. 5, 6 and 8 Figure 13 illustrates that MABIA and SWAP separate into almost identical proportions of evapotranspiration and recharge while the CROPWAT and MABIA results – although both models are based on the FAO56 approach – differ considerably. Figures No. 14 and 15 show daily ETact and GWR estimates for the reference scenario. Both diagrams are not comparable in every detail; both water balances are based on 780 mm gross input but SWAP provides no result for surface runoff. Despite these restrictions Figures No. 14 and 15 may visualize some conceptual differences. Daily maximum rates of evapotranspiration are close to 6 mm/d in both cases, but daily rates of deep percolation differ considerably. This is due to the underlying abstraction of soil physical processes: a mechanistic simulation model such as SWAP calculates water fluxes as driven by matric potential gradients while MABIA is based on a simple bucket approach.

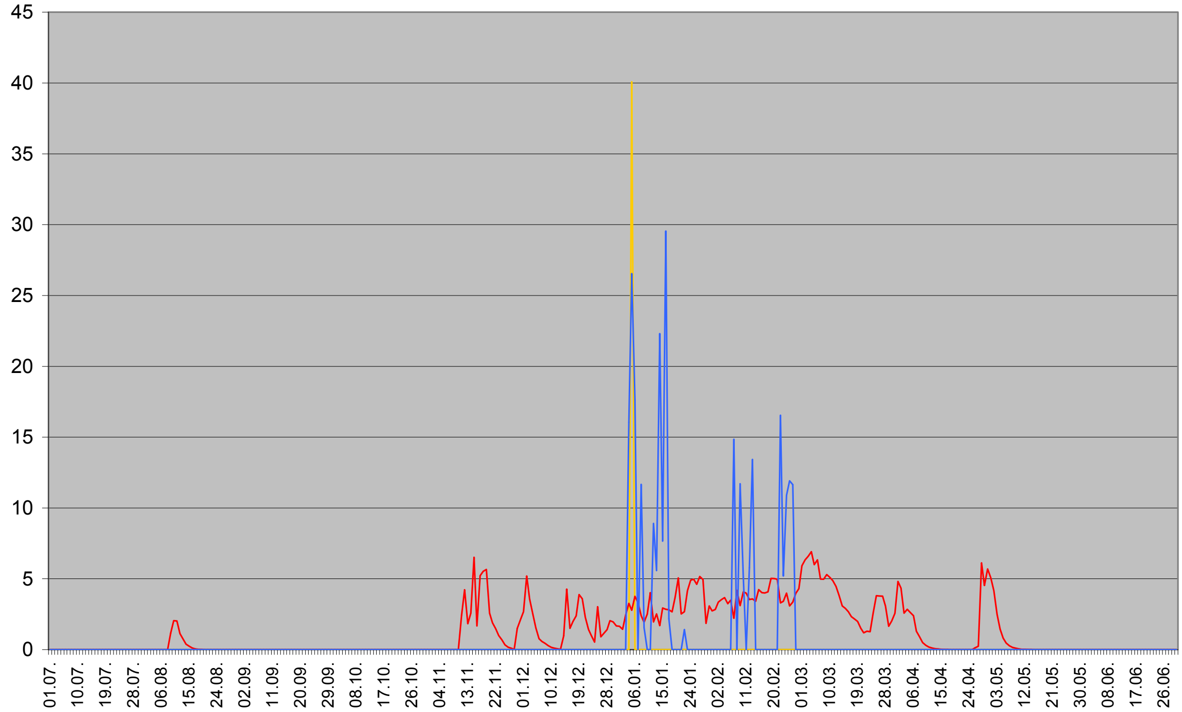

Figure 14: Results of the MABIA model for the reference scenario in daily temporal resolution (yellow = Ro, red = ETact, blue = GWR; all results in mm/d)

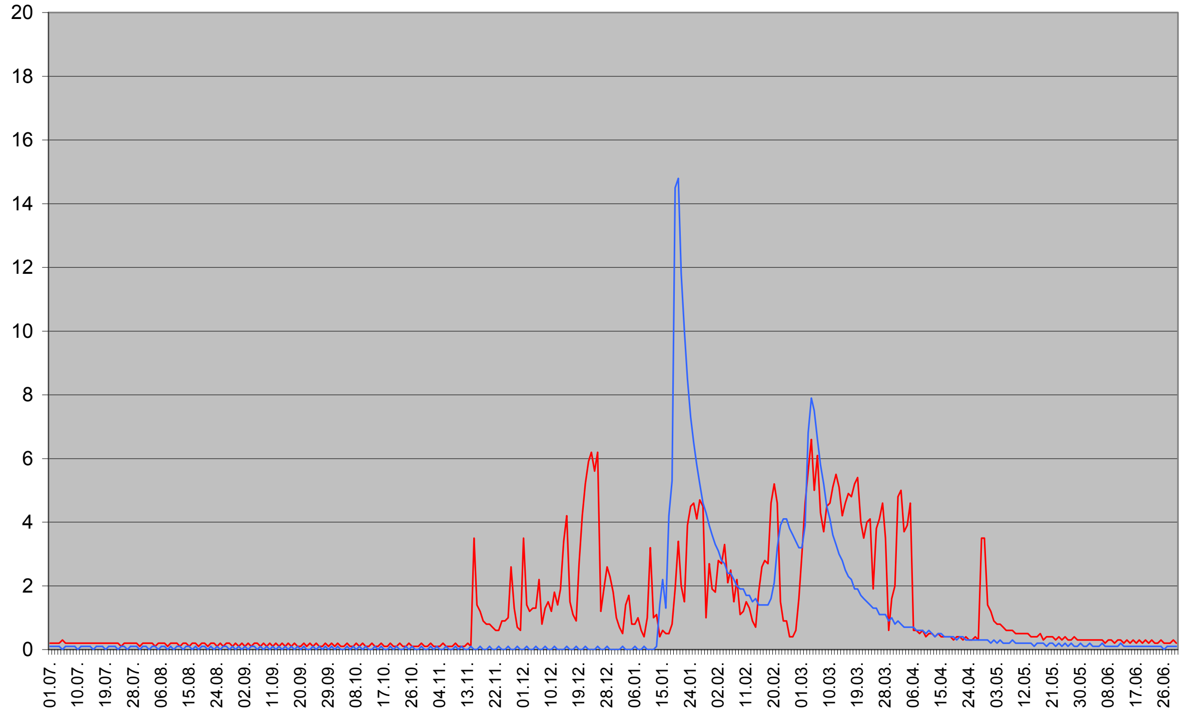

Figure 15: Results of the SWAP model for the reference scenario in daily temporal resolution (red = ETact, blue = GWR; all results in mm/d)

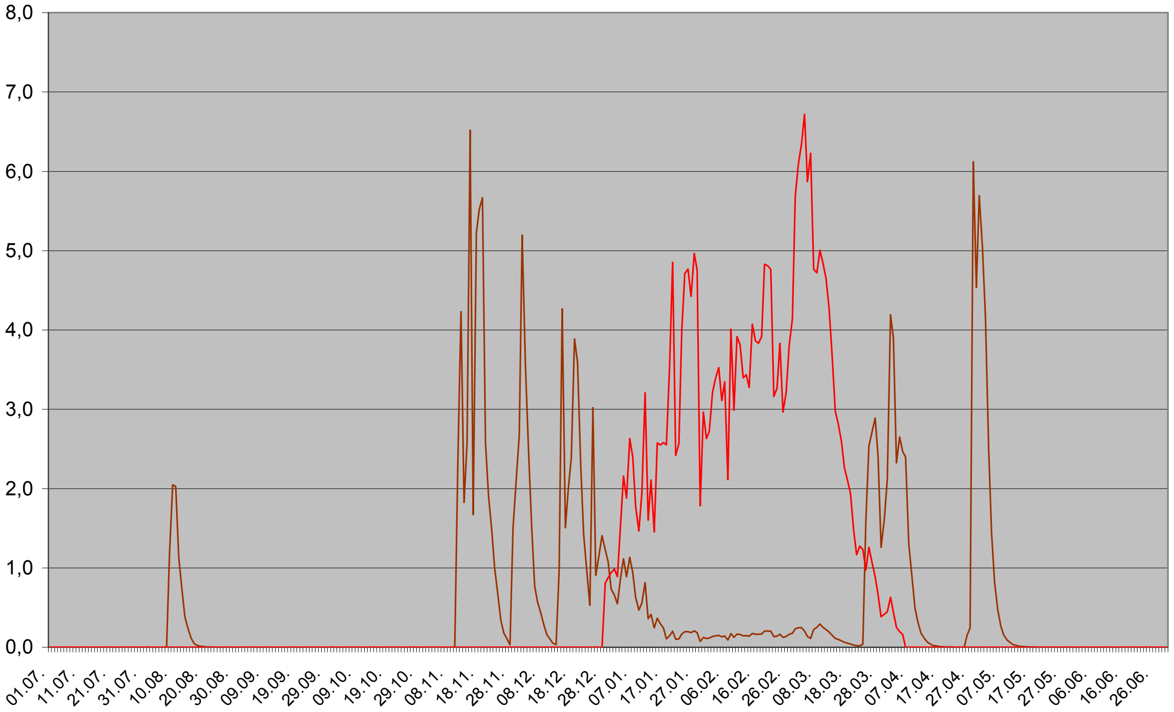

Figure 16: Results of the MABIA model for the reference scenario in daily temporal resolution (brown = evaporation, red = transpiration; all results in mm/d)

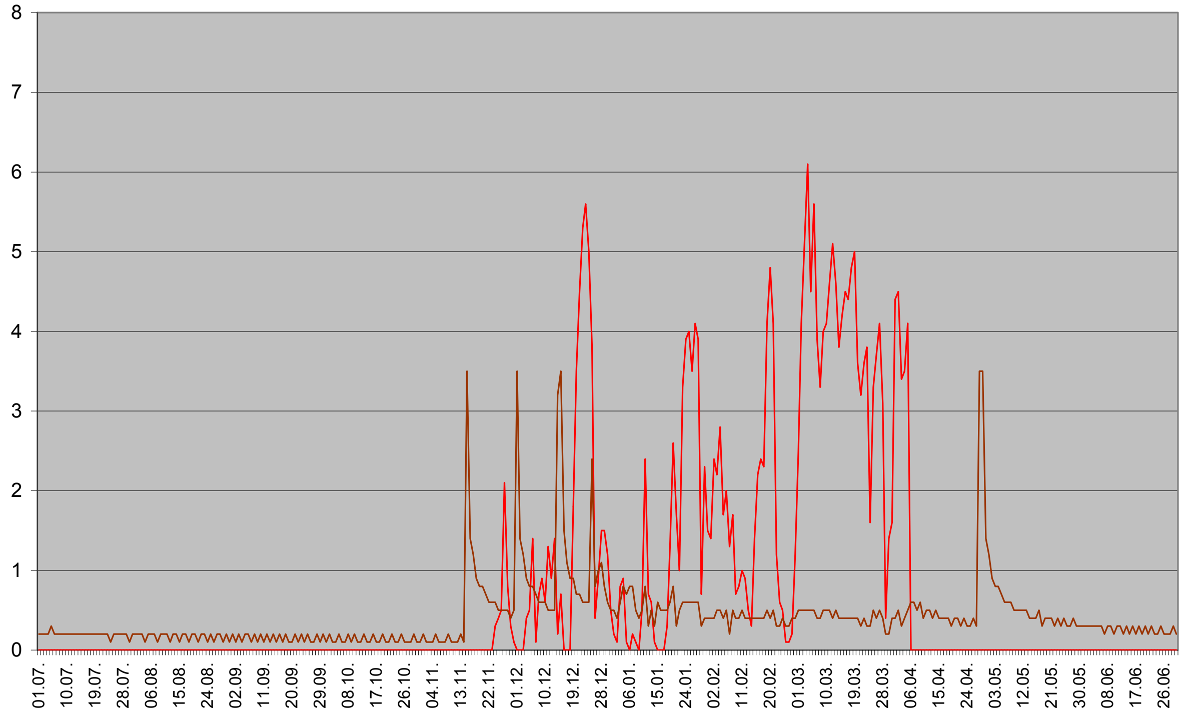

Figure 17: Results of the SWAP model for the reference scenario in daily temporal resolution (brown = evaporation, red = transpiration; all results in mm/d)

In comparison to Figures No. 14 and 15, in Figures No. 16 and 17 the ETact graph is split up into two separate graphs for evaporation and transpiration. Maximum rates of transpiration are similar, but MABIA estimates higher evaporation rates. In general the relative proportion of evaporation as a component of ETact as determined by the MABIA model is higher and the underlying algorithms to simulate evaporation differ from model to model. MABIA reacts more sensitively to short-term rainfall events (Fig. 16).

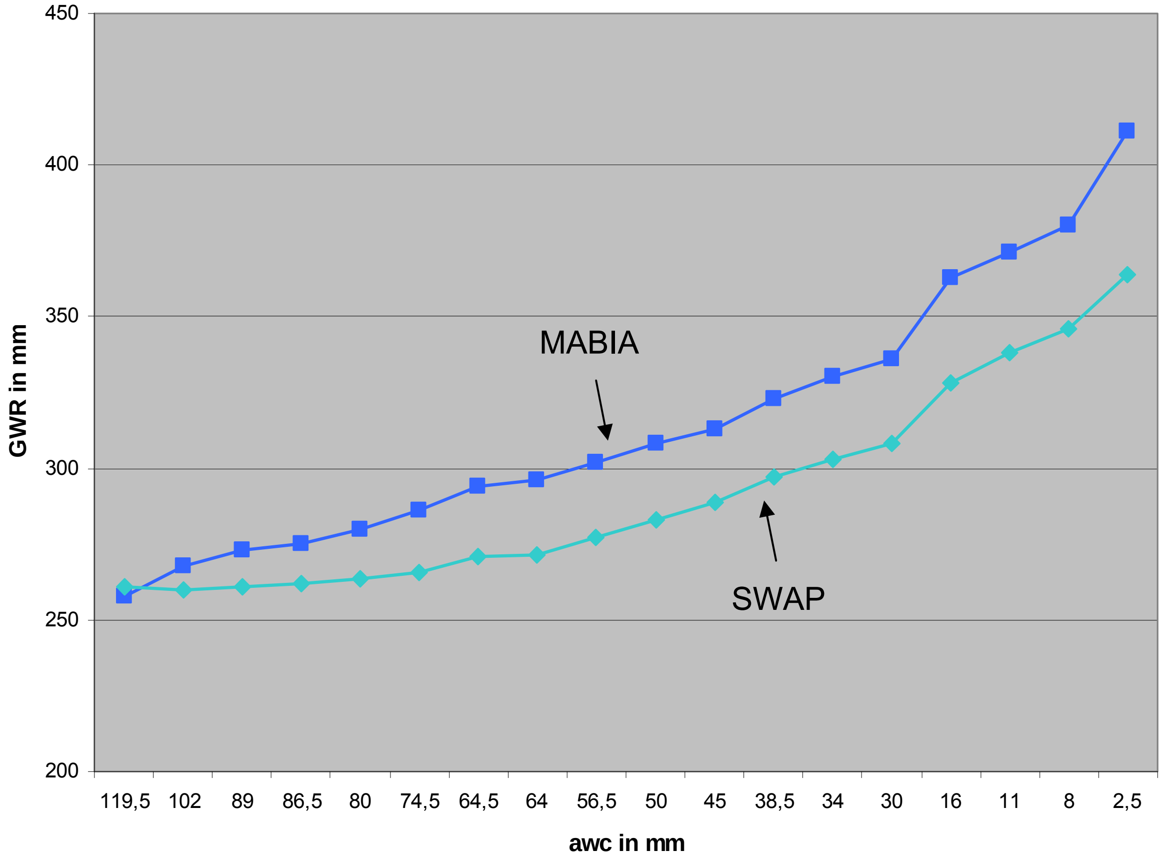

Figure 18: Groundwater recharge (GWR) as a function of available water capacity (awc) for the reference scenario according to the MABIA and SWAP model

Both, MABIA as well as SWAP, agree in groundwater recharge results for the reference scenario, based on an available water capacity of 120 mm (Tables 6 and 8). Both models provide increasing recharge rates with decreasing soil water storage capacities, but for MABIA the increase is larger and the discrepancy between both models reaches its maximum for very shallow soils (Fig. 18). A deviation between results of both models can also be observed when different crops or plants are compared. WEAP/MABIA assumes similar recharge rates for maize and grass, and the difference in recharge between deep soils (awc = 120 mm) and shallow soils (awc = 30 mm) is constantly 90 mm. SWAP assumes higher transpiration rates and smaller percolation rates for grass vegetation, and the soil-related difference in recharge is 50 mm for maize (Fig. 18) and 90 mm for grass.

WEAP/MABIA and SWAP show close correspondence in their water balances for certain crops and certain soils. This exceptionally good agreement is limited to conditions of the reference scenario (maize and 120 mm available water capacity). Any deviation in soil properties or plant physiology may lead towards differing model results. Additionally is has to be emphasized that SWAP's above cited results refer to one specific bottom boundary condition ("free drainage"). Any other choice like "calculate bottom flux as function of groundwater level" reduces deep percolation and therefore reduces groundwater recharge. It can only be postulated that the free drainage option is the most appropriate one and fits best to soils of the project area.

In case of land use type "large-scale agriculture" the soil water balance for a crop sequence of maize (rainy season) and soybeans (dry season) was simulated (for details see Tables 3 and 4) and results of the WEAP/MABIA model were used for the regional water balance. Results for a deeply developed soil with an available water capacity of the root zone of 120 mm are presented in Table 9 and Fig. 19. In comparison to conditions of the reference scenario "small-scale agriculture" an additional water input by irrigation during the dry season increases ETact by 702 mm and deep percolation by 46 mm. Although there is no supplemental irrigation during the rainy season and no groundwater recharge during the irrigated season, there is a general increase in recharge. This is because soils do not run completely dry over the dry season and start the rainy season with higher water contents. As a consequence, groundwater recharge in summer starts earlier and reaches a plus of approximately 50 mm (Fig. 19).

Table 9: Water balance for land use type "large-scale agriculture" by application of the WEAP/MABIA model

Precipitation	Irrigation	Ro	ETact	GWR
780.0	748.0	40.0	1184.0	304.0

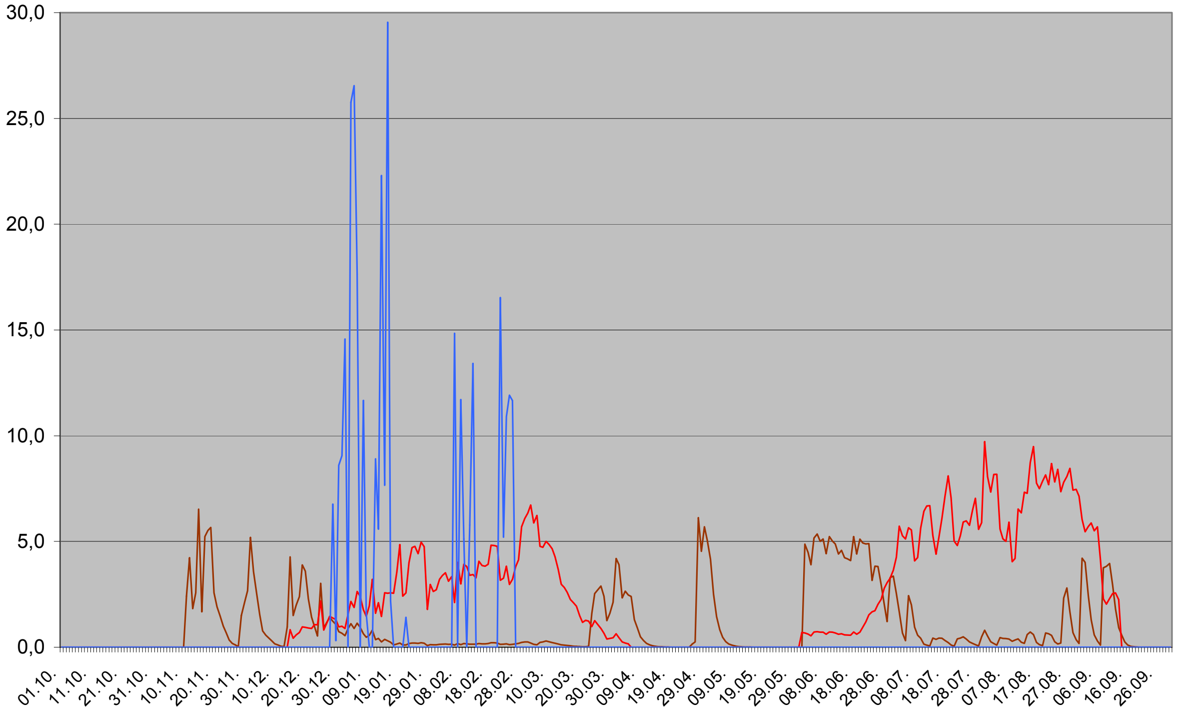

Figure 19: Results of the MABIA model for the reference year 1989/90 and large-scale agriculture (brown = evaporation, red = transpiration, blue = GWR; all results in mm/d)

The scenario of large-scale agriculture is based on two selected crops only, maize and soybeans. On commercial farms often other crops are cultivated (see chapter 4.3). For some typical crops and crop rotation patterns WEAP/MABIA results are presented in Tables 10 - 12.

Table 10: Groundwater recharge rates (GWR) for the reference year 1989/90, a moderate available water capacity of 120 mm, surface runoff of 40 mm and selected crops under rainfed conditions according to the WEAP/MABIA model

Crop	Period of growth		GWR in mm
Sorghum	26 Dec – 29 Apr	125 days	160.0
Soybeans	1 Dec – 15 Mar	105 days	273.5
Groundnuts	1 Dec – 25 Mar	115 days	236.0
Sunflower	1 Dec – 5 May	156 days	216.5
Potatoes	21 Oct – 19 Feb	122 days	235.0
Cabbage	1 Jan – 5 May	125 days	143.0

Results of Table 10 are based on the scenario that arable land is not used during the dry season ("fallow"). Recharge rates under typical rainfed crops cover a range between 143 and 273.5 mm. Recharge rates for the reference crop (maize) are close to the maximum result. When the length of the period of growth is similar, kcb coefficients and rooting depths are the differentiating factors. Recharge under sorghum is limited because sorghum is characterized by a large rooting depth and accordingly high transpiration rates.

Table 11: Groundwater recharge rates (GWR) for the reference year 1989/90, a moderate available water capacity of 120 mm, surface runoff of 40 mm and selected crops under irrigated conditions according to the WEAP/MABIA model

Crop	Period of growth		GWR in mm
Wheat / Barley	21 Apr – 2 Sep	135 days	122.0
Cotton	10 Apr – 26 Sep	170 days	107.0
Potatoes	21 Apr – 23 Aug	125 days	122.0
Beans	16 Jul – 28 Sep	75 days	121.5
Peppers	1 Mar – 15 Jul	137 days	124.0
Maize	8 May – 30 Sep	146 days	111.0
Soybeans	1 Jun – 13 Sep	105 days	121.5

Results of Table 11 are based on the scenario that arable land is not agriculturally used during the rainy season and that it is covered by grass vegetation during this time of the year. All winter crops are exactly irrigated according to their water demand and no irrigation water is wasted, i.e. no deep percolation occurs outside the rainy season. Groundwater recharge usually takes place in January and February (see Figures No. 14 and 19), and at this time the conditions are identical for all scenarios of Table 11. Against this background it is not surprising that groundwater recharge rates differ very little, and there is no dependency on the agricultural crop. Even between cotton and vegetables there is almost no difference in recharge. The only remarkable difference can be observed in the amount of irrigation water, and this water is totally consumed by transpiration. Because all scenarios of Table 11 are based on grass coverage in summer and grass is characterized by a small rooting depth, groundwater recharge rates are also not dependent on soil properties such as the available water capacity of the root zone.

Table 12: Groundwater recharge rates (GWR) for the reference year 1989/90, a moderate available water capacity of 120 mm, surface runoff of 40 mm and selected crop sequences (one non-irrigated crop in summer, one irrigated crop in winter) according to the WEAP/MABIA model

Crop of the rainy season	Crop of the dry season	GWR in mm
Maize	Soybeans	304.0
Maize	Beans	311.0
Maize	Maize	268.0
Soybeans	Wheat	305.0
Beans	Tomatoes	203.5

The sequence of maize and soybeans represents the reference scenario for large-scale agriculture (Table 9). A sequence of double maize is only theoretically considered and is not practiced. All results are close to 300 mm GWR instead of those of the beans/tomatoes scenario. That underlines that detailed results of the farm survey report may be neglected for a regional water balance of the Lusaka region.

Table 13: Estimated groundwater recharge rates [mm] in the Lusaka region as a function of soil properties (available water capacity, awc) and land use classes for the reference year 1989/90

Land use class	awc in mm																	
	2.5	8	11	16	30	34	38.5	45	50	56.5	64	64.5	74.5	80	86.5	89	102	119.5
Woodland	331	367	277	340	225	300	215	209	204	277	189	269	179	173	246	164	150	132
Large-scale agriculture	260	340	260	340	260	338	257	254	252	329	246	326	242	240	317	236	231	224
Small-scale agriculture	331	380	291	363	256	330	243	233	228	302	216	294	206	200	275	193	188	178
Settlements	218	271	185	255	154	232	149	145	142	218	133	213	127	123	199	118	110	98
Settlements with garden	317	360	272	338	229	305	221	215	211	286	199	279	190	186	260	178	167	152

blue = based on 120 mm surface runoff
red = based on 40 mm surface runoff

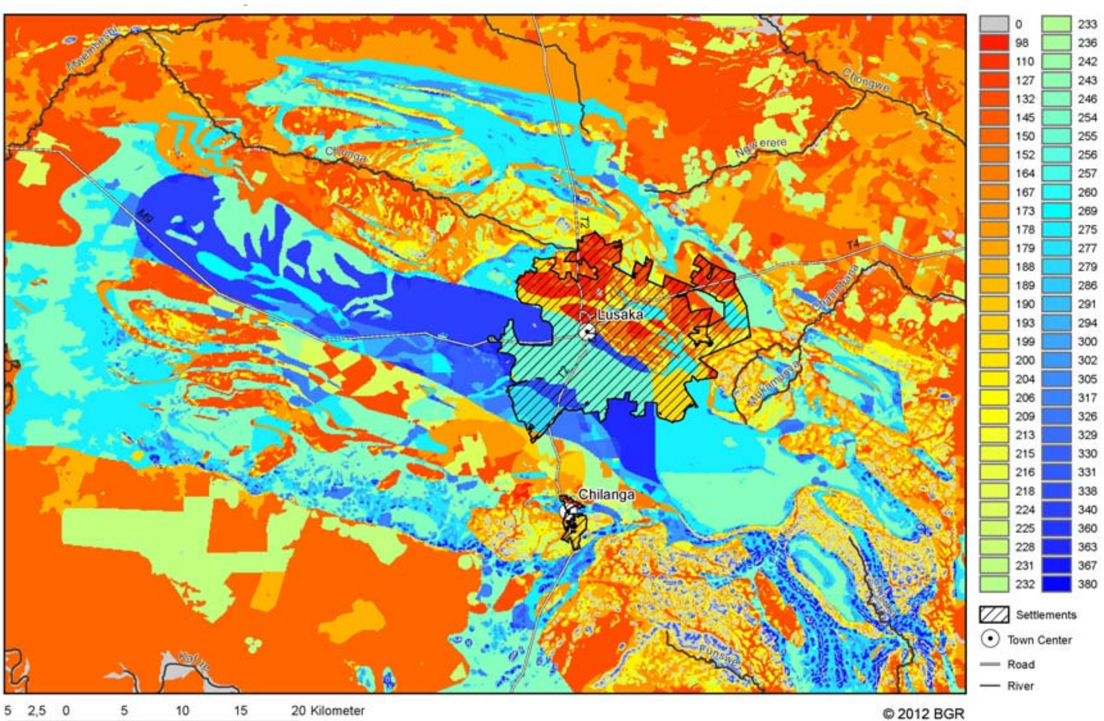

Figure 20: Estimated groundwater recharge rates [mm] in the Lusaka region in the reference year 1989/90

Annual groundwater recharge rates as determined by the WEAP/MABIA model cover a spectrum between 98 and 380 mm. The lowest values belong to urban areas where larger proportions of sealed surfaces prevent infiltration and therefore reduce groundwater recharge. Outside urban areas, the minimum value of 132 mm corresponds to non-karstic parent material such as schist or gneiss, higher surface runoff, deeply developed soils with a higher available water capacity and natural woodland vegetation. The maximum values of 380 or 363 mm correspond to karstic parent material such as limestone or dolomite, limited surface runoff, shallow soils with a very small available water capacity and small-scale agriculture, managed by peasants on the basis of subsistence economy and characterized by rainfed agriculture and monocropping of maize. The overall average value, weighted according to spatial proportions of soil and land use classes, accounts for 208.5 mm. This is slightly higher than estimates from other authors in the past (see Table 1).

One possible reason for this deviation could be an underestimation of surface runoff. The reference year of 1989/90 includes five single days where daily precipitation exceeded 30 mm (5 Jan: 69.4 mm, 16 Jan: 32.4 mm, 7 Feb: 45 mm, 22 Feb: 34.2 mm, 28 Apr: 42.2 mm). The total amount of surface runoff was empirically assessed by 40 mm on limestone and dolomite. The calibrated WEAP/MABIA model pools the entire amount of surface runoff on the 5th of January (Fig. 14). As a consequence, daily infiltration rates of > 30 mm are required on four single days during the rainy season. It is questionable if these infiltration rates correspond to hydrological properties of typical clay soils as they can be observed on limestones in the study area.

Unrealistic results may also be caused be neglecting groundwater effect. All values of Fig. 20 refer to "free drainage" or "free outflow" conditions at the bottom of the root zone. All recharge results are only valid for site conditions not affected by capillary rise from the groundwater table. Existing soil maps of the study area such as the "Exploratory Soil Map of Zambia", scale 1:1,000,000 (MINISTRY OF AGRICULTURE 1991) classify local soils as not affected by groundwater. During their soil survey campaign in May 2010 the authors of this study found gleyic soils only in one specific area west of Lusaka International Airport. More detailed information on site-specific water tables is available from isoline maps showing the depth of the water table at the end of the rainy season, e.g. in April 2009. These maps are based on observations at wells and were compiled by spatial interpolation techniques (BÄUMLE, pers. comm.). In general, typical groundwater amplitudes of the study area are characterized by considerable fluctuations and large differences between lowest and highest water tables. At the end of the growing season the difference from the water table to the surface at some places is < 2 m and capillary rise towards the root zone is possible. As a consequence, groundwater recharge rates as shown in Table 13 and Fig. 20 have to be evaluated as slighty overestimated for some places.

On the other hand, comparably high groundwater recharge rates of more than 200 mm under conditions of dryland savannas of Central Namibia with approximately 600 mm annual precipitation during single years are reported by GRÖNGRÖFT et al. (2012). These calculations are based on field measurements of soil water contents in deeply developed sandy soils.

The same methodology and scenarios as applied on data from the reference year and described above were applied on data from 1983/84 which acts as a typical dry year. Surface runoff was assessed by 40 mm on schist, gneiss and quartzite and 0 mm on limestone and dolomite. Results are presented in Table 14 and Fig. 21.

Table 14: Estimated groundwater recharge rates [mm] in the Lusaka region as a function of soil properties (available water capacity, awc) and land use classes for the dry year 1983/84

	awc in mm																	
Land use class	2.5	8	11	16	30	34	38.5	45	50	56.5	64	64.5	74.5	80	86.5	89	102	119.5
Woodland	231	233	181	197	112.5	142.5	90	74	65.5	96	46.5	85.5	38	34	70	28.5	20.5	9.5
Large-scale agriculture	236	241	190.5	210.5	128	161.5	112	100	92	121	80.5	118	67.5	70.5	96	61.5	49	52
Small-scale agriculture	216	212	157.5	168.5	83	113	59.5	39	28	55	3	41.5	0	0	21.5	0	0	0
Settlements	145	159	110.5	133.5	66.5	100.5	52.5	40.5	34	66.5	19	58	12.5	9.5	46.5	5	0	0
Settlements with garden	216	220	168.5	184.5	107	139	88.5	71	62	92	42	80.5	32.5	28.5	64.5	22.5	14	2.5

blue = based on 40 mm surface runoff
red = based on 0 mm surface runoff

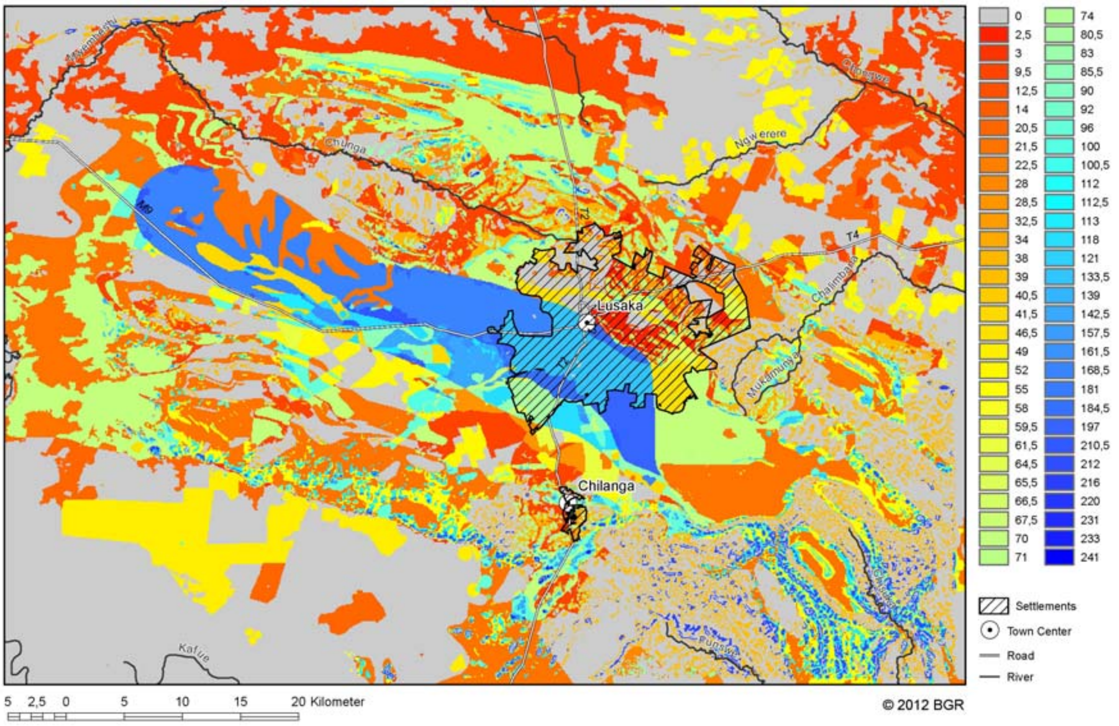

Figure 21: Estimated groundwater recharge rates [mm] in the Lusaka region in the dry year 1983/84

In 1983/84 annual (gross) precipitation is reduced by 209 mm in comparison to the reference year 1989/90. Net precipitation however is only marginally reduced because less water is lost for surface runoff. Even in a dry year like 1983/84 deep percolation and therefore groundwater recharge takes place in most parts of the project area (Table 14). In Fig. 21, the dolomite plateau around Lusaka stands out as the most important recharge area. Areas of commercial farms, especially in the Kafue flats southwest of the dolomite plateau, contribute almost no recharge to local aquifers (Fig. 21). The overall average, weighted according to spatial proportions of soil and land use classes, accounts for 48 mm. However, under conditions of the reference scenario (soils with an available water capacity of 100 mm/m, rainfed agriculture and cultivation of maize) the WEAP/MABIA model indicates zero recharge. Differences in estimated recharge to 1989/90 do mostly occur on deeply developed soils with higher available water capacities, e.g. 0 mm against 178 mm in case of small-scale agriculture and 52 against 224 mm in case of large-scale agriculture. On very shallow soils with limited available water capacities where less water is provided for water consumption by plant transpiration differences between a normal and a dry year do carry less weight, e.g. 231 against 331 mm in case of woodland.

5.2 Consumption of irrigation water

All contents of chapter 5.1 are based on model calculations and have not been evaluated against existing measurement results, e.g. data from lysimeters. Estimates of groundwater recharge rates originating from the WEAP/MABIA model have not been validated so far. Figures about the consumption of irrigation water as reported by local farmers and published as part of the farm survey report from MAYERHOFER et al. (2010) can be used to check model results on the basis of real world data.

MAYERHOFER et al. (2010) considered 43 commercial farms within the Lusaka region. Eighteen of these farms were taken into account for a detailed study about irrigation practices. They were extracted from the basic population according to their size of cultivated area and according to their number of crops per season or complexity of crop rotation patterns respectively. Sequences of crops per farm had to be identified and the cultivated area of individual crops had to be assessed. Soil physical properties of corresponding parcels of land could only be roughly estimated from maps as compiled for a project-internal report by HENNINGS et al. (2012) (see Fig. 9). All farmers apply sprinkler irrigation, center pivot and/or lateral move systems, i.e. there is no difference in the "wetted fraction" as required for running the WEAP system. Highly effective methods such as drip irrigation are not reported. On 6 of the 18 considered farms supplemental irrigation during the rainy season is practised. Detailed information about general conditions and results of the WEAP/MABIA model is listed in Table 15.

Table 15: Cultivated crops and irrigation water demand as modelled by WEAP/MABIA for 18 farms of the project area

Farm Name	crop of rainy season	irrigation yes/no	irrigation amount in mm	crop of dry season	irrigation yes/no	irrigation amount in mm	area in ha	irrigation amount in m^3 per crop	irrigation amount in m^3 per farm
Water Force Farm	soybeans	yes	212	wheat	yes	800	128	1295360	
	soybeans	yes	237	fallow	no	0	20	47400	
	sugar cane	yes	79	sugar cane	yes	944	20	204600	1547360
Airport Farm	maize	no	0	fallow	no	0	200	0	
	soybeans	no	0	fallow	no	0	50	0	
	fallow	no	0	wheat	yes	755	140	1057000	1057000
MRI Seed	maize	yes	306	wheat	yes	774	120	1296000	
	maize	yes	360	fallow	no	0	60	216000	
	soybeans	yes	211	fallow	no	0	60	126600	1638600
Zambian Extracts Oil	fallow	no	0	peppers	yes	776	40	310400	310400
Liempe Farm UNZA	maize	no	0	fallow	no	0	120	0	
	soybeans	no	0	fallow	no	0	60	0	
	fallow	no	0	maize	yes	972	30	291600	
	cabbage	yes	165	cabbage	yes	855	15	153000	444600
Palabana Training Institute	cabbage	no	0	fallow	no	0	20	0	
	maize	no	0	wheat	yes	858	20	171600	
	wheat	no	0	soybeans	yes	782	20	156400	328000
Pebblebrook Farm	soybeans	no	0	wheat	yes	787	40	314800	314800
Silverrivers Farm	soybeans	yes	220	fallow	no	0	20	44000	
	fallow	no	0	wheat	yes	751	40	300400	344400
Balmoral Farm	soybeans	no	0	wheat	yes	823	100	823000	
	soybeans	yes	209	fallow	no	0	150	313500	
	maize	no	0	fallow	no	0	80	0	
	cabbage	yes	182	cabbage	yes	829	10	101100	1237600
Musekese Farm	soybeans	yes	183	wheat	yes	789	30	291600	
	fallow	no	0	soybeans	yes	678	50	339000	
	banana	yes	298	banana	yes	1127	10	142500	773100

Table 15: Cultivated crops and irrigation water demand as modelled by WEAP/MABIA for 18 farms of the project area (continued)

KP Farm	maize	no	0	wheat	yes	858	40	343200	851400
	soybeans	no	0	wheat	yes	847	60	508200	
China Zambia Friendship Farm	maize	no	0	wheat	yes	832	50	416000	1229000
	soybeans	no	0	wheat	yes	813	100	813000	
Sunlight Farm	maize	no	0	wheat	yes	858	35	300300	514100
	soybeans	no	0	maize	yes	1069	20	213800	
Marydale Farm	maize	no	0	fallow	no	0	170	0	1010100
	soybeans	no	0	fallow	no	0	105	0	
	fallow	no	0	wheat	yes	777	130	1010100	
Azeeb Farm	fallow	no	0	wheat	yes	757	90	681300	681300
Bunde Farm	sorghum	no	0	fallow	no	0	100	0	1345600
	soybeans	no	0	wheat	yes	841	160	1345600	
Noorani Farm	maize	no	0	fallow	no	0	250	0	394500
	soybeans	no	0	wheat	yes	789	50	394500	
Christian Vision Farm	maize	no	0	fallow	no	0	100	0	394500
	soybeans	no	0	wheat	yes	789	50	394500	

Table 16: Simulated and reported irrigation water demand for 18 farms of the project area

Farm Name	Irrigation water amount in m^3 as simulated by WEAP/MABIA	Irrigation water amount in m^3 as reported by farmers
Water Force Farm	1,547,360	1,268,000
Airport Farm	1,057,000	1,100,075
MRI Seed	1,638,600	800,000
Zambian Extracts Oil	310,400	622,080
Liempe Farm UNZA	444,600	187,300
Palabana Institute	328,000	252,288
Pebblebrook Farm	314,800	336,000
Silverrivers Farm	344,400	198,720
Balmoral Farm	1,237,600	525,000
Musekese Farm	773,100	907,200
KP Farm	851,400	600,000
China Zambia Friendship Farm	1,229,000	900,000
Sunlight Farm	514,100	350,000
Marydale Farm	1,010,100	783,000
Azeeb Farm	681,300	540,000
Bunde Farm	1,345,600	1,280,000
Noorani Farm	394,500	393,984
Christian Vision Farm	394,500	978,000

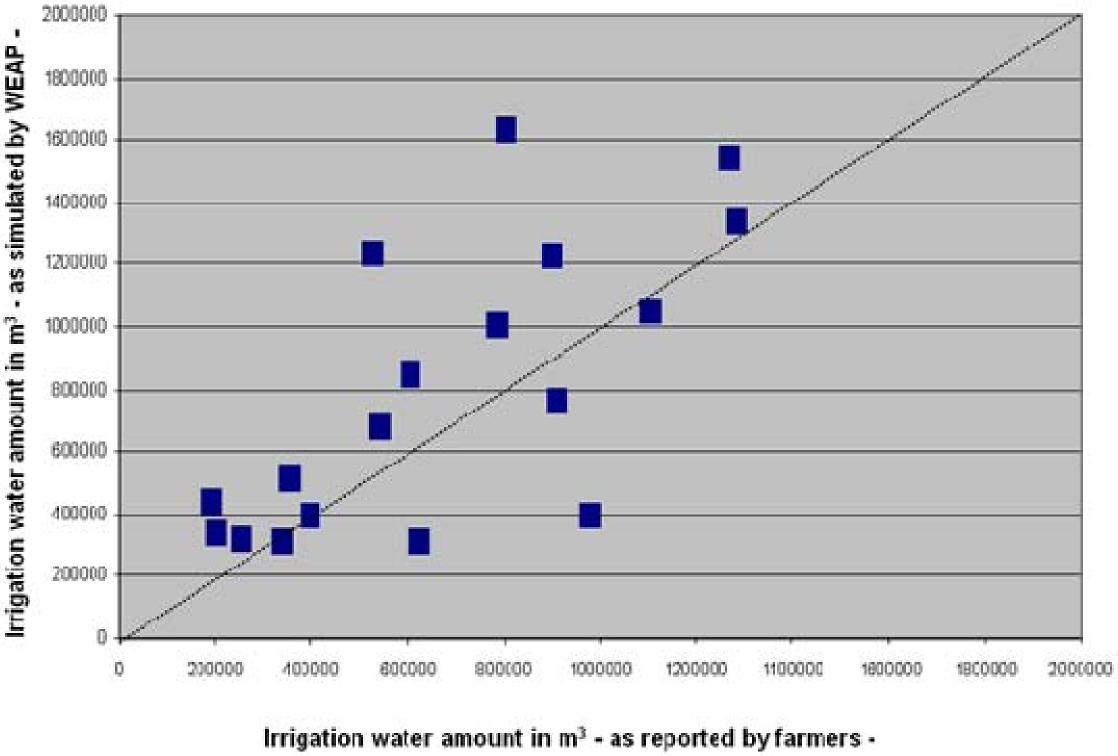

Figure 22: Simulated and reported irrigation water demand for 18 farms of the project area

In total WEAP predicts an amount of 14,416,360 m^3 while a total consumption of 12,021,647 m^3 can be summarized from data given by MAYERHOFER et al. (2010). 1,529,510 m^3 out of 14,416,360 m^3 or 10.6 % are used for supplemental irrigation over the rainy season. Against this background the error caused by using climatic data from the "typical", mean year 1989/90 instead of effective data from 2009/10 can be neglected when data from Table 16 are interpreted.

Water demand for irrigation as reported by local farmers and simulation results of the WEAP/MABIA model are compared in Table 16 and Figure 22. Seven farms such as Pebblebrook, Airport and Noorani Farm show close correspondence, another 7 farms such as Marydale, KP and Water Force Farm follow a general trend and spend approximately 250,000 m^3 less water than predicted by the model, and another 4 farms stand out because of larger deviations between model results and reality. For two of them (Balmoral Farm, MRI Seed) water demand is vastly overestimated. For two other farms (Christian Vision Farm, Zambian Extracts Oil) water demand is seriously underestimated. Last cited results can only be explained by internal errors in data extracted from the farm survey report (MAYERHOFER et al. 2010). When local farmers spend less water than predicted, this is probably due to high water costs and they tolerate some yield depression.

6. Conclusion

Within the framework of this study the FAO 56 method including the dual crop coefficient concept was applied in the Lusaka region in order to quantify mean annual percolation rates from the soil as part of the groundwater recharge rate. This approach is well-established and acknowledged internationally, its results are confirmed by data from experimental sites all over the world (see chapter 3). Under conditions of the reference scenario (climatic data from the hydrological year 1989/90, small-scale rainfed agriculture with cultivation of non-irrigated maize during the rainy season) there is close correspondence between results of an FAO 56-based, functional simulation model (WEAP/MABIA) and a high-sophisticated, process-based mechanistic simulation model such as SWAP. Although the high conformity in the model results, measured percolation rates are needed to validate the simulation results.

In comparison to existing estimates from the literature (Table 1) results of the FAO 56 approach, or WEAP/MABIA model respectively, look comparatively high. This evaluation is relativized when the whole range of available water capacities of local soils is taken into account; for land-use type “small-scale agriculture” groundwater recharge in a typical year according to WEAP/MABIA varies between minimum rates of approximately 180 mm on deep soils and maximum rates of approximately 330 mm on shallow soils. Both numbers refer to soils developed from schist or gneiss and are based on the same assumption concerning the amount of surface runoff. The long-term estimate of 200 mm for arable land given by VON HOYER et al. (1978) after applying the method of RENGER et al. (1974) lies within this range. That means that estimates following the FAO 56 approach fit well to estimates that were published as part of the BGR report from the seventies. In comparison to this report Figure 20 and Figure 21 are based on regionalized soil properties and contain site-specific information.

WEAP as a decision support system includes functionalities to simulate crop water requirements, actual evapotranspiration and water flow across the lower boundary of the root zone. Only simulated crop water requirement by WEAP/MABIA can be evaluated against existing data from a local farm survey report (MAYERHOFER et al. 2010). When simulated and reported irrigation water demand are compared simulated demand is overestimated by approximately 20 % on the average. But this evaluation is based on personal communication only and cannot be reviewed.

It has to be confessed that all estimates as presented within this study are fraught with uncertainties. Sources of errors are the accuracy of meteorological measurements, the availability of information about soil properties, the representativeness of crop coefficients and several others. Meteorological data have been checked, soil physical properties were analyzed in the laboratory and were not obtained by pedotransfer functions, and crop coefficients originate FAO publications or tables FAO offers via its website. One of the most serious deficiencies is the absence of a qualified, fine-scale isoline map of the groundwater table. At places with shallow groundwater tables knowledge of capillary rise is essential for modelling soil water fluxes. When the effects of capillary rise are neglected percolation rates and therefore groundwater recharge rates are overestimated. A final evaluation of all estimates as presented within this study will be possible not till soil-hydrological measurements from the field are available; this remains a future task.

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