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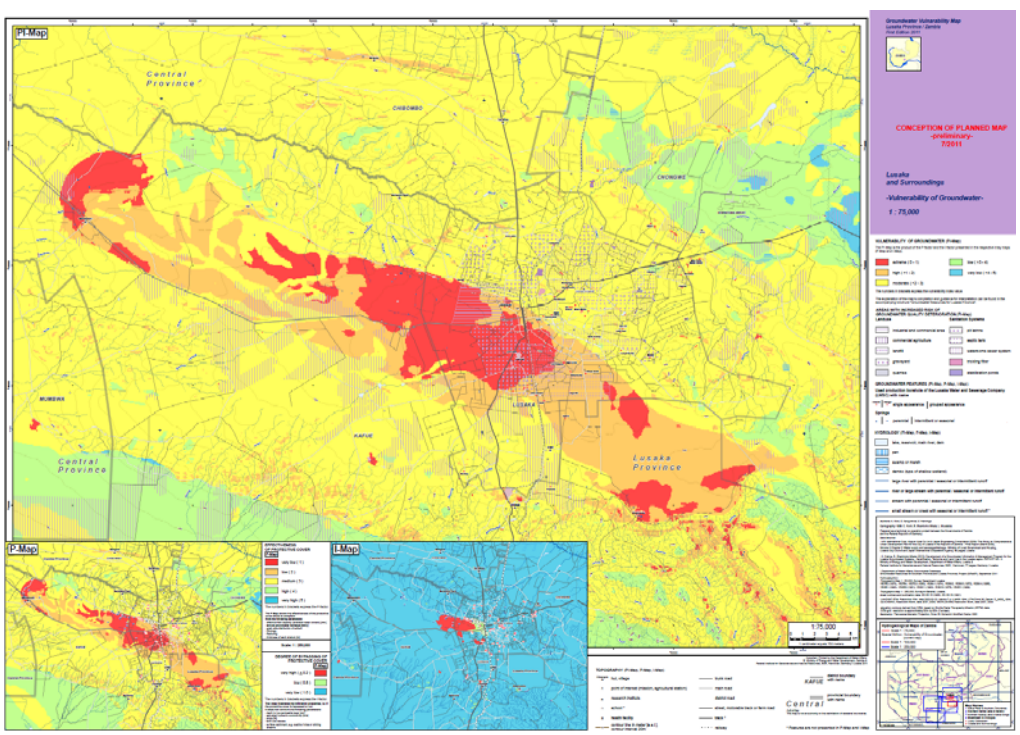
Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

TECHNICAL NOTE NO. 6

METHODOLOGY AND RESULTS OF THE VULNERABILITY MAP FOR LUSAKA AND SURROUNDINGS USING THE PI-METHOD –

A DOCUMENTATION AND MANUAL

Andrea Nick



Lusaka, August 2011

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

Methodology and Results of the Vulnerability Map for Lusaka and Surroundings using the PI-Method – A Documentation and Manual

Authors:	Andrea Nick (BGR)
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Table of Contents

List of Figures

List of Tables

Abbreviations

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
DEM	Digital Elevation Model
DWA	Department of Water Affairs
COST	Programme of the European Commission on vulnerability and risk mapping for the protection of carbonate (karstic) aquifers
eFC	effective Field Capacity (i.e. available water capacity)
Fm	Formation
GIS	Geographic Information System
GReSP	Groundwater Resources for Southern Province (project title)
K_{sat}	Saturated hydraulic conductivity
LCC	Lusaka City Council
LWSC	Lusaka Water and Sewerage Company
MEWD	Ministry of Energy and Water Development
NWASCO	National Water and Sanitation Council
PI (method)	Protective Cover and Infiltration Conditions (method)
PTF	Pedo-Transfer-Function
SRTM	Shuttle Radar Topography Mission
UTM	Universal Transversal Mercator (Projection)
WGS84	World Geodetic System 1984
ZARI	Zambian Agricultural Research Institute

List of reports compiled by the project in Phase II

Date	Authors	*Title*	Type	Target group
Apr 2009	Museteka L. & R. Bäumle	*Groundwater Chemistry of Springs and Water Supply Wells in Lusaka - Results of the sampling campaigns conducted in 2008*	Technical Report No. 1	DWA, Counterparts, Stakeholder
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*	Technical Report No. 2	DWA, Counterparts, Stakeholder
March 2010	Hahne K. & Shamboko-Mbale B.	*Karstification, Tectonics and Land Use in the Lusaka region*	Technical Report No. 3	DWA, Counterparts, Stakeholder
Oct 2010	Mayerhofer C., Shamboko-Mbale B. & R.C. Mweene	*Survey on Commercial Farming and Major Industries: Land Use, Groundwater Abstraction & Potential Pollution Sources-*	Technical Report No. 4	DWA, Counterparts, Stakeholder
Oct 2010	Tena T., Mweene R.C., & R. Bäumle	*GeODin Manual*	Manual	DWA, Counterparts to be trained (in pilot provinces and districts)
Nov 2010	Tena, T., Nick. A.	*Capacity Building and Awareness Raising Strategy for Phase II (2010-2012)*	Technical Note No. 2	DWA, Counterparts
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	DWA, Counterparts, Stakeholder
Feb. 2011	Bäumle R.	*Results of pumping test evaluation and statistical analysis of aquifer hydraulic properties*	Technical Note No. 4	DWA, Stakeholders
April 2011	Kringel, R., Fronius, A., Museteka, L., Nick. A	*Assessment of CVOCs and BTEX in Lusaka groundwater in 2010 (working title)*	Technical Note No. 5	DWA, Stakeholder

Summary

Author: Andrea Nick

Title: *Methodology and Results of the Vulnerability Map for Lusaka and Surroundings using the PI-Method – A Documentation and Manual*

Key words: groundwater, Lusaka, PI-method, vulnerability

This report deals with the methodology applied for and results of the vulnerability map for Lusaka and surrounding areas. The vulnerability map gives assistance in identifying areas which need protective measures. It gives an overview of the Lusaka area, in the scale 1:75.000, showing different classes of groundwater vulnerability, i.e. its sensitivity to pollution. This report outlines the PI-method and describes the parameters that were used for establishing the vulnerability map. The PI-method applies the concept of pollutant transport from an origin on the surface (i.e. above the soil) through the pathway of the unsaturated zone to the groundwater surface. The following chapters are meant to give guidance on how to set up, use and change the vulnerability map in a Geographical Information System (GIS), and explain how the map can be interpreted.

Extended Summary

Lusaka Province, with an estimated population of about 2.2 million in 2010 is experiencing a rapid population growth of 4.7 % per year. Lacking or unsafe sanitation facilities constitute a major pollution source to groundwater, both in terms of microbiological and inorganic contamination. The vulnerability map established by the GReSP project gives assistance in identifying areas which need protective measures. It gives an overview of the Lusaka area, in the scale 1:75.000, showing different classes of groundwater vulnerability, i.e. its sensitivity to pollution. This report outlines the PI-method and describes the parameters that were used for establishing the vulnerability map. It is meant to give guidance on how to set up, use and change the map in a Geographical Information System (GIS), and explains how the map can be interpreted.

The PI-Method was chosen as most suitable for mapping the vulnerability of the Lusaka groundwater system due to its level of accuracy and the fact that it takes into account both karstic and non-karstic aquifers. The acronym PI stands for the two factors protective cover (P factor) and infiltration conditions (I factor). The P-factor describes the effectiveness of the protective cover resulting mainly from the thickness and hydraulic properties of all the strata between the surface and the groundwater table (Goldscheider 2002). The I-factor describes the infiltration conditions, particularly the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow. The protection factor π is calculated as the product of P and I. It is divided into five classes. A protective factor of $\pi \leq 1$ indicates a very low degree of protection and an extreme vulnerability to contamination; $\pi = 5$ indicates a high degree of protection and very low vulnerability.

For the calculation of this vulnerability map a GIS working environment was used, namely an ESRI ArcGIS® licence with the Spatial Analyst extension. The sources of the parameters used for the PI-method and the calculation steps are described in chapter 3.

The PI-method applies the concept of pollutant transport from an origin on the surface (i.e. above the soil) through the pathway of the unsaturated zone to the groundwater surface. However, some pollution sources are located in the soil or even in direct contact with groundwater. Leaking sewer lines, pit latrines and leaking underground storage tanks of fuel stations (among others) present shortcuts for contaminants which are not taken into account by the method.

The mapped area which is most vulnerable to pollution is on the Lusaka Dolomite Aquifer (classes 1, red, and 2, orange). In these areas the probability of water quality deterioration is high to very high in the event of pollution. This is mainly due to the very thin soil cover which is removed in many places, the high groundwater table, and the fast transport channels that exist in this highly karstified groundwater body. In the yellow areas (class 3), the vulnerability is moderate, while in green and blue areas it is low or very low, respectively. Here, fracturing and karstification is less, soil cover more extensive and groundwater tables are lower. The vulnerability map presents an alarming picture of the risk that is taken if groundwater in the Lusaka area remains unprotected. Restrictions are needed for potential pollution sources such as industrial activities, storage facilities of potentially harmful substances, wastewater treatment plants and unsafe onsite sanitation, etc. Thus, a following step should be the establishment of recommendations for protection measures based on this vulnerability map.

1. INTRODUCTION

Lusaka Province, with an estimated population of about 2.2 million in 2010 (population census, URL 1), is experiencing a rapid population growth of 4.7 percent per annum (URL 1) and an increase in population density of over 400 % over the last 40 years (LCC 2008). According to the National Water and Sanitation Council (NWASCO), the water supply coverage by the Commercial Utility, the Lusaka Water and Sewerage Company (LWSC) is 68 %, while the sanitation coverage is only 17 % (NWASCO 2009).

Lacking sanitation facilities constitute a major pollution source to groundwater, both in terms of microbiological and inorganic contamination, i.e. mainly nitrates. If water supply boreholes are located in direct neighbourhood to malfunctioning pit latrines or septic tanks, microbiological pollution of the borehole will trigger a vicious faecal-oral infection cycle threatening public health. In Lusaka this threat becomes real especially during the rainy season when cholera outbreaks occur in the informal settlements almost annually (since 2003). Full sanitation coverage in combination with sustainable sanitation solutions reduces microbiological pollution, as well as unwanted dissolved organic and inorganic substances in the groundwater body.

Unaffected groundwater is an inexpensive and safe drinking water source, which makes long-distance water supply or expensive surface water treatment unnecessary. Thus, every precaution in form of sustainable sanitation and appropriate groundwater protection is more cost-effective than any subsequent and costly treatment of unsafe water resources or distance water supply.

The concept of groundwater vulnerability is based on the assumption that the physical environment provides some natural protection to groundwater against human impacts, especially with regard to contaminants entering the subsurface environment (Vrba & Zaporozec 1994). The fundamental concept of groundwater vulnerability is that some areas are more vulnerable to contamination than others. The ultimate goal of a vulnerability map is the subdivision of an area into several units showing the different degrees of vulnerability.

The first vulnerability map for Zambian aquifers was produced by GReSP in its first phase targeting Southern Province. With a scale of 1:2,800,000 it has to be regarded as an approximation in terms of regional vulnerability. It has therefore not been published as a map in the Hydrogeological Map Series, but can be referred to in the accompanying brochure.

The vulnerability map of Lusaka and surroundings in the scale 1:75,000 is a special edition of the Hydrogeological Map Series of Zambia. It shows different classes of groundwater vulnerability, i.e. its sensitivity to pollution. It gives assistance in identifying areas which need protection measures. For orientation purpose, infrastructure and groundwater relevant features have been incorporated in the map. It also shows some potential pollution sources which present a risk to the groundwater quality downstream. The following report outlines the method and parameters that were used for establishing the vulnerability map, and explains how the map can be interpreted. It also incorporates some guidance on how to implement the PI-method in ArcGIS®.

2. THE PI-METHOD

2.1. Concept Note on the Choice of the Method

Methods for mapping the vulnerability of aquifers as a tool for their management have been developed mainly in the United States of America and Europe. Among the most widespread are the following methods:

- the DRASTIC method, developed by the U.S. Environmental Protection Agency (Aller et al. 1985), considering depth to groundwater table (*D*), net recharge (*R*), aquifer media (*A*), soil media (*S*), topography (*T*), impact of the vadose zone media (*I*), and hydraulic conductivity of the aquifer (*C*);
- the GLA method (Hölting et al. 1995), developed by the German States Geological Surveys and BGR. It is applied by the German States and Federal Government authorities, considering the protective cover with parameters such as available water capacity, thickness of vadose zone and type of lithology;
- the recent modification of the GLA method, called PI method (Goldscheider 2002) developed within the framework of the COST 620 program. It takes into account the protective cover (same with GLA) and furthermore the bypassing of the protective cover in epikarstic environments;
- the EPIK method (Saefl 2000), developed and used by Swiss authorities, considering epikarst (E), protective cover (P), infiltration conditions (I) and karst development (K);
- and the COP method (Vias et al. 2002), also developed in the COST 620 program, taking the concentration of flow (C), overlying layers (O) and the precipitation (P) into account.

The PI-Method was chosen as most suitable for mapping the vulnerability of the Lusaka groundwater system due to the following reasons:

- Most of the aquifers in the study area are karstic. Other than many vulnerability approaches, the PI-method considers karst environments and their characteristics. So does the EPIK method, which was developed purely for karst regions, but according to Margane (2003) the GLA- or PI-method is more suitable for areas in which karstic and non-karstic aquifers occur.
- According to the comparison by Neukum et al. (2008) the PI-method (together with the GLA method on which it is based) has a higher level of accuracy compared to the methods EPIC and DRASTIC, in terms of incorporating highly variable distributions and thickness of cover sediments and their protective properties. Such variability is found in the study area.
- From the vulnerability mapping methods presented in the COST Action 620 study (Zwahlen 2003), the COP method developed by the Hydrogeology Group of the University of Malaga was found suitable at first, as it incorporates the protective function of the overlying layers (O), the concentration of flow (C) and the precipitation (P). The factors O and C are quantified in a similar but slightly simplified way as in the PI method. The P factor (precipitation) is assessed on the basis of

annual precipitation amount and rainfall intensity. Due to the rather uniform distribution of the annual amount and intensity of rain within the study area (Lusaka City and adjacent areas), the precipitation factor was considered to be less significant for the vulnerability distribution in this area.

2.2. DESCRIPTION OF THE PI-METHOD

The acronym PI stands for the two factors protective cover (P-factor) and infiltration conditions (I-factor). The P-factor describes the effectiveness of the protective cover resulting mainly from the thickness and hydraulic properties of all the strata between the ground surface and the groundwater table – the soil, the subsoil, the non-karstic bedrock and the unsaturated zone of the karstic bedrock (Goldscheider 2002). The I-factor describes the infiltration conditions, particularly the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow. Therefore the factor distinguishes between the dominant flow processes (infiltration, subsurface flow or surface flow). The I-factor is 1 if infiltration occurs diffusely, e.g. on a flat, highly permeable and free draining surface, where no surface flow is produced. In contrast, the protective cover is completely bypassed by a swallow hole, through which surface water may pass directly into the karst aquifer. In such a case, the I-factor is 0 (Goldscheider 2002). After establishing maps for the I- and the P-factor, the protection factor π is calculated as the product of P and I. It is divided into five classes. A protective factor of $\pi \leq 1$ indicates a very low degree of protection and an extreme vulnerability to contamination; $\pi = 5$ indicates a high degree of protection and a very low vulnerability. The spatial distribution of the π-factor is shown on the vulnerability map.

The details of calculation of each factor are comprehensively described in the following chapters of this report as well as in Goldscheider (2002) and Goldscheider et al. (2000). In Figure 1 and 2 the determination of the P- and I-factors are shown as an overview.

Topsoil - T

eFC [mm] up to 1 m depth	T
> 250	750
> 200-250	500
> 140-200	250
> 90-140	125
> 50-90	50
< 50	0

Recharge - R

Recharge [mm/y]	R
0-100	1.75
>100-200	1.50
>200-300	1.25
>300-400	1.00
>400	0.75

Subsoil - S

Type of subsoil (grain size distribution)	S
clay	500
loamy clay, slightly silty clay	400
slightly sandy clay	350
silty clay, clayey silty loam	320
clayey loam	300
very silty clay, sandy clay	270
very loamy silt	250
slightly clayey loam, clayey silty loam	240
very clayey silt, silty loam	220
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200
sandy loam, slightly loamy silt	180
slightly clayey silt, sandy loamy silt, silt, very sandy loam	160

Type of subsoil (grain size distribution)	S
very clayey sand, clayey sand, loamy silty sand	140
sandy silt, very loamy sand	120
loamy sand, very silty sand	90
slightly clayey sand, silty sand, sandy clayey gravel	75
slightly loamy sand, sandy silty gravel	60
slightly silty sand, slightly silty sand with gravel	50
sand	25
sand with gravel, sandy gravel	10
gravel, gravel with breccia	5
non-lithified volcanic material (pyroklastica)	200
peat	400
sapropel	300

Lithology - L

Lithology	L
claystone, slate, marl, siltstone	20
sandstone, quarzite, volcanic rock plutonite, metamorphite	15
porous sandstone, porous volcanic rock (e.g. tuff)	10
conglomerate, breccia, limestone, dolomitic rock, gypsum rock	5

Fracturing - F

Fracturing	F
non-jointed	25.0
slightly jointed	4.0
moderately jointed, slightly karstified or karst features completely sealed	1.0
moderately karstic or karst features mostly sealed	0.5
strongly fractured or strongly karstified and not sealed	0.3
Epikarst strongly developed, not sealed	0.0
not known	1.0

Thickness of each stratum in [m] - M

Bedrock - B
$B = L \cdot F$

Artesian pressure A
1500 points

Total protective function P_{TS}

$$P_{TS} = \left[T + \left(\sum_{i=1}^{m} S_i \cdot M_i + \sum_{j=1}^{n} B_j \cdot M_j \right) \right] \cdot R + A$$

score P_{TS}	effectiveness of protective cover	**P-factor**	example
0-10	very low	**1**	0-2 m gravel
>10-100	low	**2**	1-10 m sand with gravel
>100-1000	medium	**3**	2-20 m slightly silty sand
>1000-10000	high	**4**	2-20 m clay
>10000	very high	**5**	> 20 m clay

P-map

Figure 1: Determination of the P-factor (Goldscheider 2002). (eFC [mm] stands for effective field capacity which is a translation from German for available water content.)

1st Step: Determination of the dominant flow process

		Depth to low permeability layer		
		< 30 cm	30-100 cm	> 100 cm
Saturated hydraulic conductivity [m/s]	> 10^{-4}	Type D	Type C	Type A
	> 10^{-5}-10^{-4}		Type B	
	> 10^{-6}-10^{-5}	Type E		
	< 10^{-6}	Type F		

2nd Step: Determination of the I'-factor

Forest				
dominant flow process		Slope		
		< 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**1.0**
subsurface flow	Type B	1.0	0.8	0.6
	Type C	**1.0**	**0.6**	**0.6**
surface flow	Type D	0.8	0.6	0.4
	Type E	1.0	0.6	0.4
	Type F	**0.8**	**0.4**	**0.2**

Field/Meadow/Pature				
dominant flow process		Slope		
		< 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**0.8**
subsurface flow	Type B	1.0	0.6	0.4
	Type C	**1.0**	**0.4**	**0.2**
surface flow	Type D	0.6	0.4	0.2
	Type E	0.8	0.4	0.2
	Type F	**0.6**	**0.2**	**0.0**

3^{d} Step: Determination of the I-factor

Surface Catchment Map		I' factor					
		0.0	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
a	swallow hole, sinking stream and 10 m buffer	0.0	0.0	0.0	0.0	0.0	0.0
b	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
c	catchment of sinking stream	0.2	0.4	0.6	0.8	1.0	1.0
d	area discharging inside karst area	0.4	0.6	0.8	1.0	1.0	1.0
e	area discharging out of the karst area	1.0	1.0	1.0	1.0	1.0	1.0

I-map

Figure 2: Determination of the I-factor (Goldscheider 2002).

3. PARAMETERS AND MAP CALCULATION

In the following the sources of data and the preparation of the parameter maps are explained in detail. If more or better data for some parameters will be available in future, the vulnerability map can be updated by incorporating the new maps. After initial considerations for setting up the GIS project, the parameters are discussed in the order in which they appear in Figure 1 and 2, for the preparation of the P- and I-Maps.

3.1. PREPARATION FOR MAP CALCULATION IN GIS

For the calculation of this vulnerability map an ESRI ArcGIS® license with the extension Spatial Analyst were used.

To start the mapping project, a new mxd-file was created in the geographical datum WGS84, with UTM projection. For the Lusaka area, UTM Zone 35 South was chosen. The units of the project were set to metric.

In order to bring all layers congruently onto each other, an extent was agreed upon in the beginning which was determined by the map-frame but slightly larger than the printed map. This was done by creating a polygon file in this extent and clipping all input layers with it. Thus, the numbers of rows and columns were the same for all files. It reaches from approximately UTM 8323 – 8265 (north-south) and UTM 5878 – 6704 (west-east).

The size of the raster cells was already specified by the soil input rasters which in turn were determined by the DEM in which for instance the slope calculation was based. The cell size is 91.1 x 91.1 m. All raster files used for the calculation must have the same extent and raster cell size.

3.2. USEFUL FUNCTIONS IN GIS

Establishing the vulnerability map requires many calculations using raster files. In order to simplify the first steps for those working with the map, the often used commands in ArcGIS® are listed below.

Table 1: Useful commands in Arc GIS®

Command	Data type	Where to find	What it does
Clip	Features	Analysis / Extract	Clips feature by another feature
Clip	Raster	Data Management / Raster / Raster Processing	Clips raster by a feature
Divide	Raster	Spatial Analyst / Math	Divides each cell value by fixed value or other raster cells
Majority Filter	Raster	Spatial Analyst / Generalization	Generalizes / simplifies a raster
Float	Raster	Spatial Analyst / Math	Turns raster values from integer (3) to float (3.00)

Table 1 continued: Useful commands in Arc GIS®

Command	Data type	Where to find	What it does
Polygon to Raster	Feature	Conversion / To Raster	Converts feature to a raster
Reclassify	Raster	Spatial Analyst / Reclass	Replaces old values with new values
Resample	Raster	Data Management / Raster / Raster Processing	Changes cell size of a raster
Smooth	Feature	Editor / Advanced Editing	Smoothes hand-drawn polygons (e.g. contours)
Topo To Raster	Feature	3D Analyst / Raster Interpolation	Interpolates from contours (Feature), returns raster

3.3. P-MAP

Topsoil – T

The parameter Topsoil is represented by the "effective Field Capacity" (eFC). This term is translated from German and stands for available water capacity (AWC). The available water capacity can be defined as the portion of the field capacity which is available to plants in a certain soil type (AWC = FC – permanent wilting point). The determination of the soil types will be discussed under "Subsoil – S".

The available water capacities for the four different soil types in the study area were calculated by pedo-transfer-functions (PTF) according to Table 1. Final estimates were calculated as means of the PTF results and local measurements and are presented in Table 2.

Table 2: Available water capacities of selected pedo-transfer functions for texture classes in the study area (Hennings et al. 2011).

Available Water Capacity [mm/dm]					
Texture class	FAO	Vereecken et al. (1989)	Woesten et al. (1998)	German soil mapping guidelines, 4th edition	Means from local measure-ments
sandy loam	16	10	9.2	10.5	7.7 (n = 36)
sandy clay loam	13	10.5	9.5	10.5	8.6 (n = 26)
sandy clay	9	8.3	11.8	8.0	7.5 (n = 10)
clay	12	6.4	9.1	7.0	7.2 (n = 14)

Table 3: Available water capacity estimates used for the Vulnerability Map (Hennings et al. 2011).

Texture class	Available Water Capacity [mm/dm]
sandy loam	10
sandy clay loam	10.5
sandy clay	8.5
clay	7.5

For the final calculation of the parameter eFC [mm] the available water capacity estimates [mm/dm] were multiplied by the estimated depth of soil [dm] (based on a relief model and the development depth of soils according to the lithological units, Hennings et al. 2011), resulting in values between 3 and 165 mm (see Fig. 3).

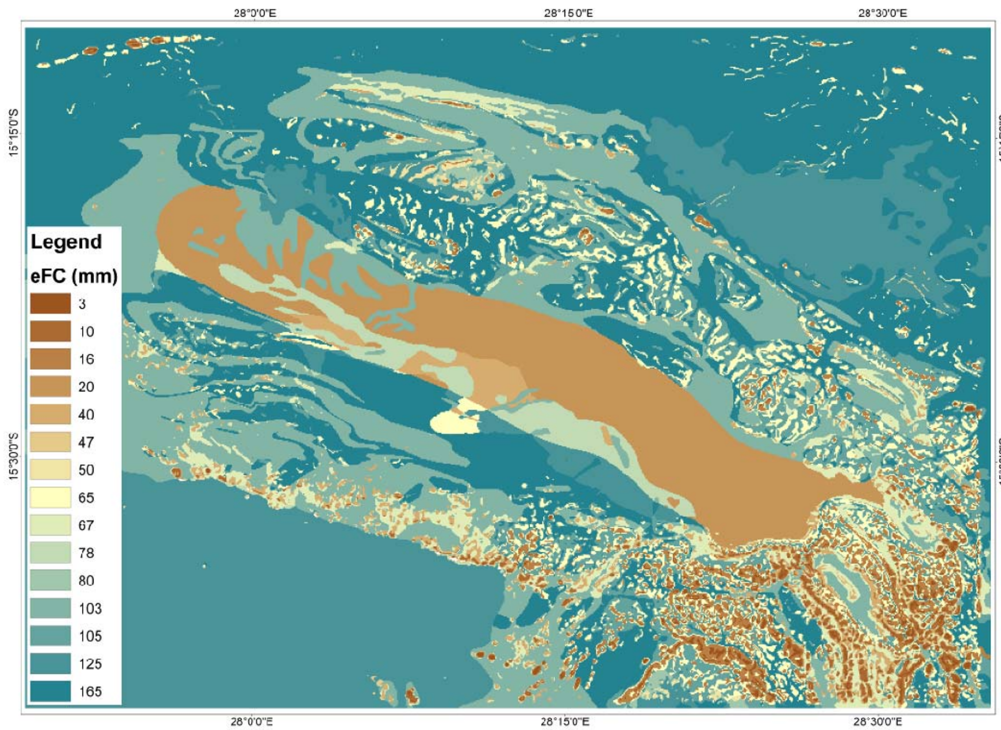

Figure 3: Grid of the calculated available water capacity (eFC [mm]).

The eFC-values were then reclassified according to the table given in Figure 1, and the T-factor was assigned according to the respective class, resulting in the raster shown in Figure 4.

Figure 4: Grid of the T-factor according to the classified values of eFC [mm].

Recharge – R

Annual groundwater recharge was estimated in a separate study by BGR and the Zambian Agricultural Research Institute (ZARI) using a model based on pedo-transfer functions, FAO values for evapo-transpiration and the land-use map by Hahne & Shamboko-Mbale (2010) (see Figure 5). A detailed description of the methodology and assumptions of the soil study will be given in a report by Hennings et al. (2011). The recharge values of up to 380 mm/year on the Lusaka Dolomite appear to be unusually high and not in line with earlier recharge estimations of the area (see Table 3). The values were used for this calculation nevertheless for the following reasons:

- there is no other spatially distributed recharge assessment for the area under consideration
- for vulnerability assessment overestimation is better than underestimation
- the difference of higher or lower recharge values to the final P-factor values is marginal. A P-map which was calculated with a value of 0-100 mm/year recharge on all non-irrigated areas and 100-200 mm/year on irrigated land turned out almost alike, except for few small areas.

Table 4: Estimates of recharge in the Lusaka area (Bäumle & Kang'omba 2009).

Source	Area	Period	*R* [mm]	*R%*
Tague 1965	Lusaka main well field	1962/63	210	25
		1963/64	75	10
Chenov 1978	Kafue Basin	1977/78	180	14.3

Source	Area	Period	*R* [mm]	*R%*
YEC 1995b	Lusaka Province	1994/95	68	7.9
	Lusaka Urban		66	7.7
	Central Province		82	8.7
Nyambe & Maseka 2000	Lusaka main well field	not spec.	186	27
Mpamba 2008	Forest Reserve 26	2007/08	707	80
	Lusaka Aquifers	10/07-01/08	226	26
Von Hoyer et al. 1978	Lusaka Dolomite Fm	1975/76	202	21
		1976/77	37	5
Nkhuwa 1996	Lusaka Dolomite Fm	1971-1990	202	23
Maseka 1994	Schist aquifers	1986/87	40	6
		1987/88	89-310	13-45
	Carbonate aquifers	1986/87	591	47
		1987/88	731-771	57-60

R = recharge, *R%* = recharge rate in per cent of *MAR*, not spec. = not specified.

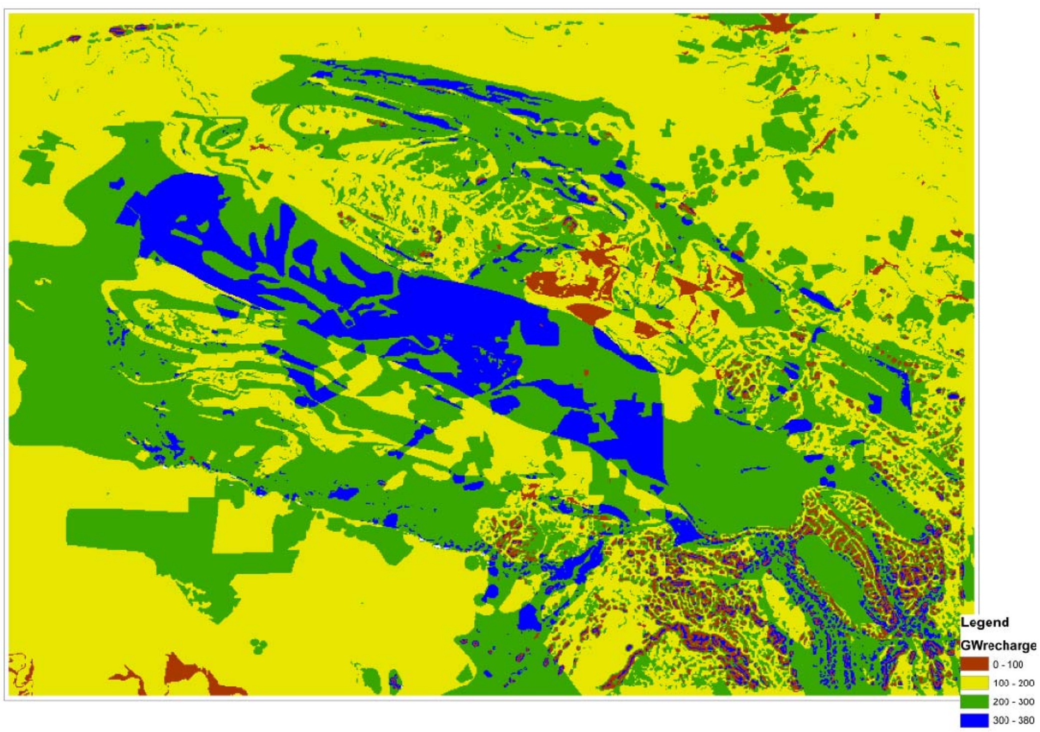

Figure 5: Grid of the assumed groundwater recharge rate [mm/year] (Hennings et al. 2011).

The groundwater recharge values were reclassified according to the table in Figure 1. Areas with assumed recharge of more than 300 mm/year were assigned a value of 1.00, areas with 200-300 mm/year of recharge got an R-value of 1.25, 100-200 mm/year 1.50 and areas with less than 100 mm/year recharge were classified as 1.75.

Subsoil – S and Thickness of subsoil – M_S

The PI-method defines subsoil as the interval of soil beyond 1 m from the surface (the top one meter is defined as topsoil). In the study area soil profiles of more than 1 m are scarce. They are only found in the south-western area (Kafue Flats) and the north-eastern area of the map. The type and thickness of soils in the study area were estimated by Hennings et al (2011), but were hardly used for the P-factor calculation.

The **type of soil** is referred to as texture class, because the classification of the PI-method only takes into account the grain size distribution. Information on soil texture is derived from different scales. A regional overview is given in the 1:1,000,000 Exploratory Soil Map of Zambia, while site-specific information is available from soil profiles evaluated by the Soil Survey Unit at Mount Makulu Research Station in various soil survey reports. Because of their sparse distribution these profile descriptions don't allow any spatial interpolation of soil properties. Therefore a medium-scale map of the study area (Figure 6) was compiled from the lithological units of the 1:100,000 geological maps covering the area (degree sheets: 1528 NW (Lusaka) by Simpson et al. (1963), 1527 NE (Mwembeshi) by Simpson (1962), 1528 NE (Chainama Hills) by Garrard (1968), 1528 SW (Kafue) by Smith (1963) and 1528 SE (Leopard Hill) by Cairney (1967)). A detailed description of the methodology of the soil-related parameters is found in Hennings et al. (2011).

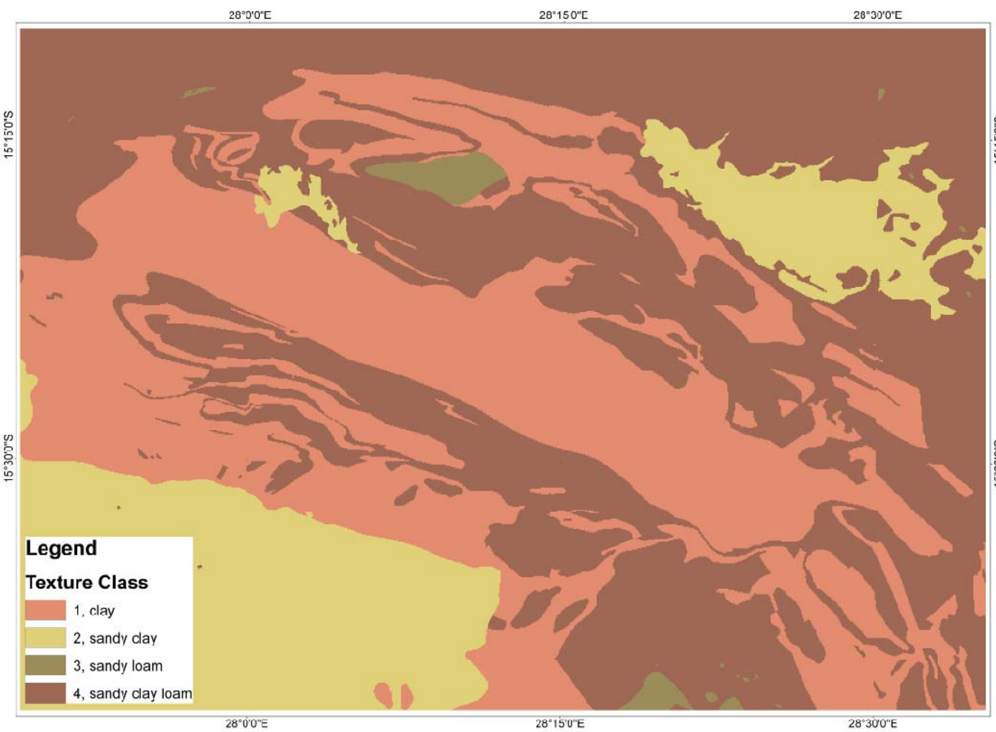

Figure 6: Texture classes according to lithological units (Hennings et al. 2011)

The **thickness of subsoil** is zero in most of the area as hardly any soils reach beyond 1 m of depth (and therefore count as topsoil). Figure 7 shows the estimated total thickness of soil in the study area, based on a relief model and the development depth of soils according to the lithological units. Texture class 2 (sandy clay) has been reported to develop depths of up to 6 m (Clayton 1974). However, there are not enough point values for a spatial interpolation of soil thickness in this class. In chapter 4.1 the estimation of thickness is described in detail.

Estimation of subsoil thickness by evaluation of borehole completion reports was looked into, but eventually not used for the vulnerability calculation. The values given in the reports for the soil strata appeared unlikely as the scientific description of soils was apparently given little emphasis. In total 57 completion reports were evaluated but the results were not considered for the method and are thus not published in this report.

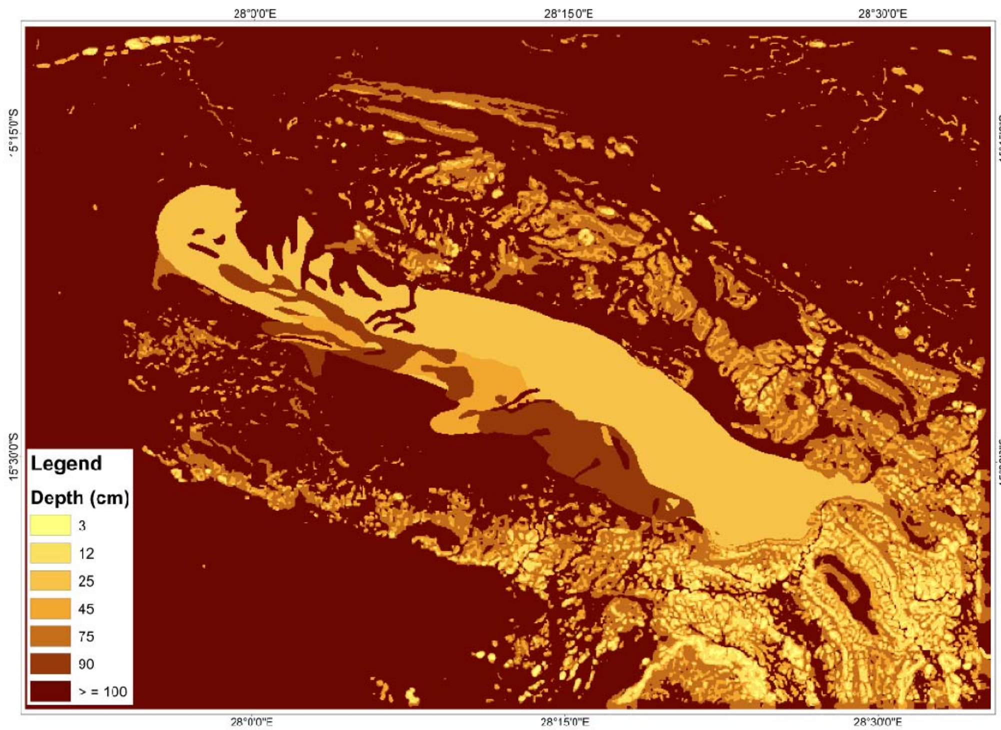

Figure 7: Total thickness of soils in the study area (Hennings et al. 2011).

The texture class grid (Figure 6) was reclassified assigning the following values: 500 to clay, 270 to sandy clay, 180 to sandy loam and 200 to sandy clay loam.

In most of the study area the total soil thickness is less than 1 m while subsoil in the PI-method is defined as the soil below 1 m depth. Therefore the term S•M in the total protective function (see Fig. 1) becomes null in these areas. For the areas where soil thickness potentially is more than 1 m it was assumed that the total unsaturated zone (i.e. the thickness of all strata up to the water table) is composed of "subsoil". These areas are underlaid by unconsolidated sediments (mainly alluvial deposits) and were therefore not divided into subsoil and lithology but summarized in the subsoil estimation. This assumption was supported by the fact that the lithology parameter in the PI-method does not cater for unconsolidated material. Figure 8 shows the distribution of the term $S{\bullet}M_S$ as it has been incorporated in the total protective function.

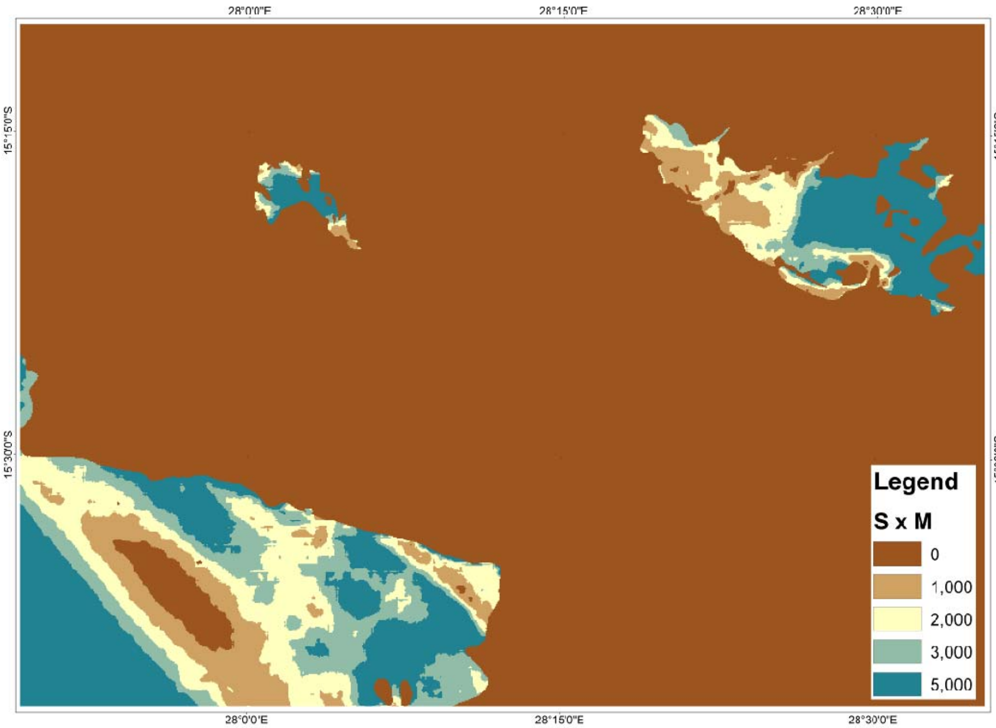

Figure 8: Grid of the product of the S-factor and its thickness M_S.

Lithology – L and Thickness of unsaturated bedrock – M_B

The **lithology** was determined by the 1:100,000 geological map sheets and their lithological units (Simpson et al. (1963), Simpson (1962), Garrard (1968), Smith (1963), Cairney (1967)).

The **thickness** of the unsaturated bedrock depends on the height of the groundwater table and the surface elevation. The difference between these two layers – minus the 1 m topsoil and where present the thickness of subsoil – is assumed to be the thickness of the vadose zone. In the study area, estimates of the groundwater table exist for both, dry season and wet season conditions. For the vulnerability calculation the groundwater contours of April 2009 (end of wet season conditions) were used, as they represent the "worse case" scenario. The contours were interpolated from water level point data measured by the project, DWA and LWSC. It was assumed that there are no lithological strata overlaying the aquifer stratum, meaning that the vadose zone incorporates only one layer (Günther 2011). This results in a simplification of the protective cover term of the vulnerability function, as the bedrock-term $\sum^{n}_{j=1} B_j{*}M_{Bj}$ hence refers to n = 1.

The digital elevation model (DEM) that was used for the calculation is a 90m-resolution piece of the worldwide Shuttle Radar Topography Mission (SRTM).

The **lithological units** of the geological map were converted from feature to raster. They were assigned the following values (according to the table given in Figure 1): 15 to schist, gneiss, granite and pellites/psammites, 5 to all limestone units, 0 to unconsolidated sediments as they were fully incorporated in the subsoil parameter. Figure 9 shows their distribution.

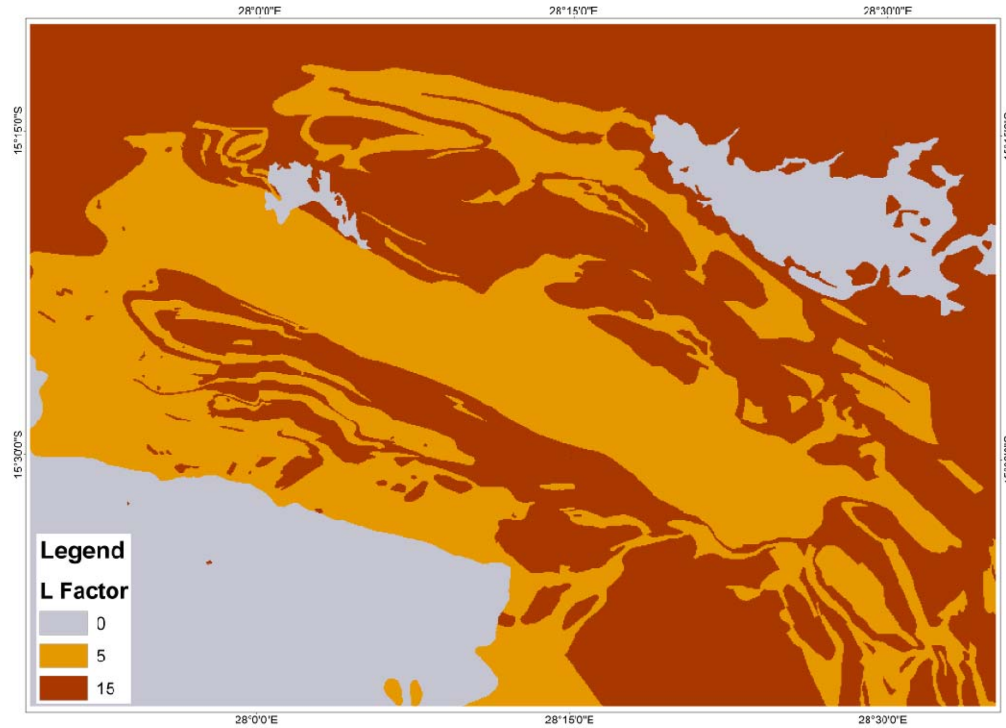

Figure 9: Grid of the L-factor.

For the calculation of the **thickness of unsaturated bedrock** the SRTM DEM (90 m resolution) and the groundwater table contours for April 2009 were used. As a first step water level contours for the Lusaka area which were produced by the GReSP project based on water level point measurements for April 2009 were extended to cover the complete map area by extrapolation. Piezometer contours were added in 10 m steps according to surface contours (based on the DEM) and the regional piezometer contours of 50 m steps (produced for the Mwembeshi catchment map by the GReSP project). The 10-m-piezometer-contours were then used (as a feature file) in the "Topo to Raster interpolation" tool available in ArcGIS, resulting in raster file showing the surface of the groundwater table (see Fig. 10).

The DEM was projected to the UTM coordinate system and its cell-size resampled to fit the cell-size of all other rasters. After clipping both grids to the correct extent the piezometer "topography" was subtracted from the DEM, resulting in the total thickness of unsaturated zone.

From this total thickness the thickness of soil (depth in cm converted into m) and subsoil (for unconsolidated areas) was then subtracted. In some areas the groundwater table in April was above the surface (inundation zones), consequently these areas return a negative value for thickness of unsaturated zone. Negative values were set to zero (see Figure 11).

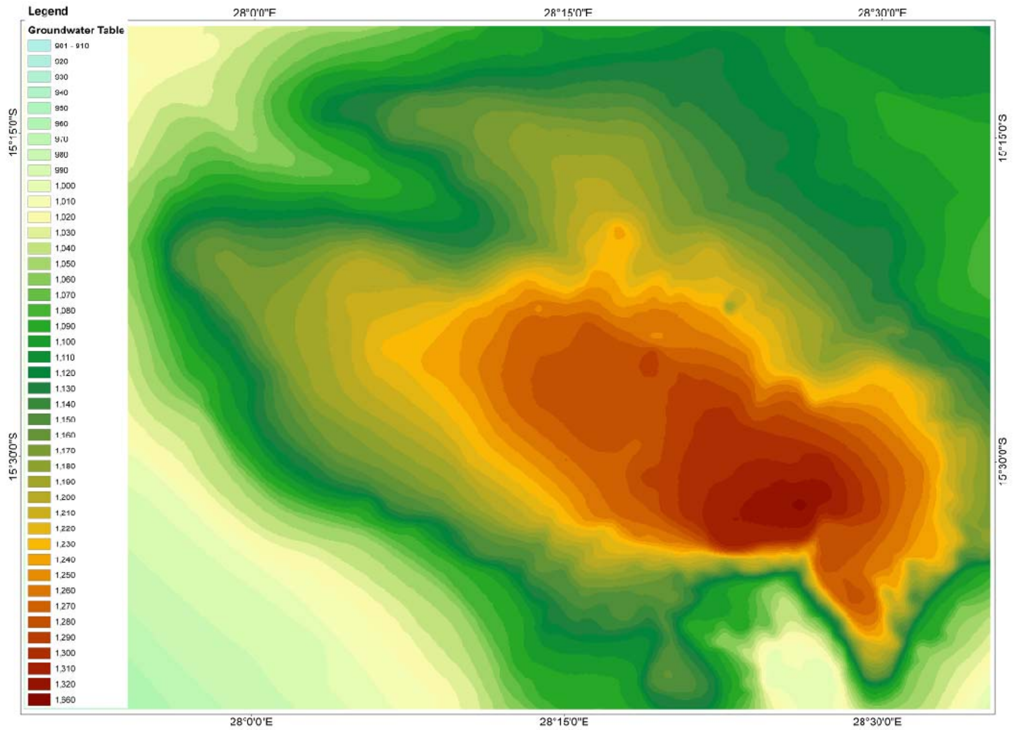

Figure 10: Result of the “Topo to Raster” tool for groundwater table interpolation.

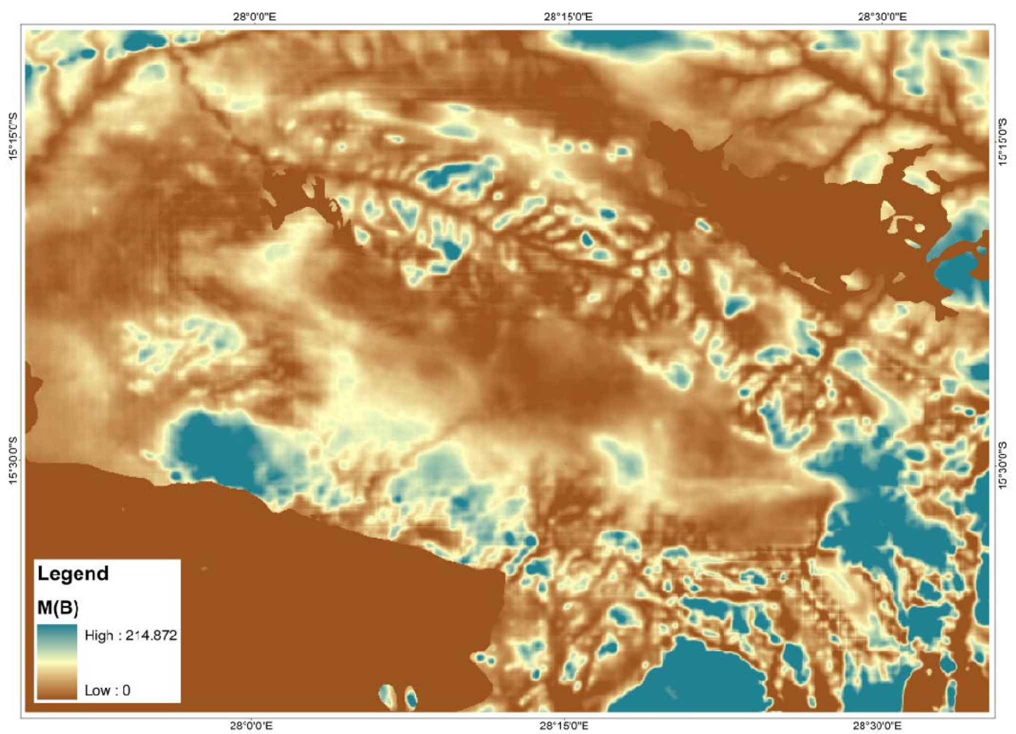

Figure 11: Grid of the thickness of unsaturated bedrock M(B).

Fracturing – F

Fracturing was estimated according to the lithological unit due to the lack of more elaborate data sources for the degree of fracturing. The following fracturing values were given to the lithological units (Figure 12) and compared to the hydraulic characteristics found in the pumping test evaluation (Bäumle 2011), finding that they correspond quite well:

Lithological unit	Fracturing index PI	Aquifer category
Unconsolidated sediments	4.0	E
Schists	1.0	E
Basement rocks	1.0	E
Cheta limestones	0.5	D
Lusaka Dolomite	0.3	C

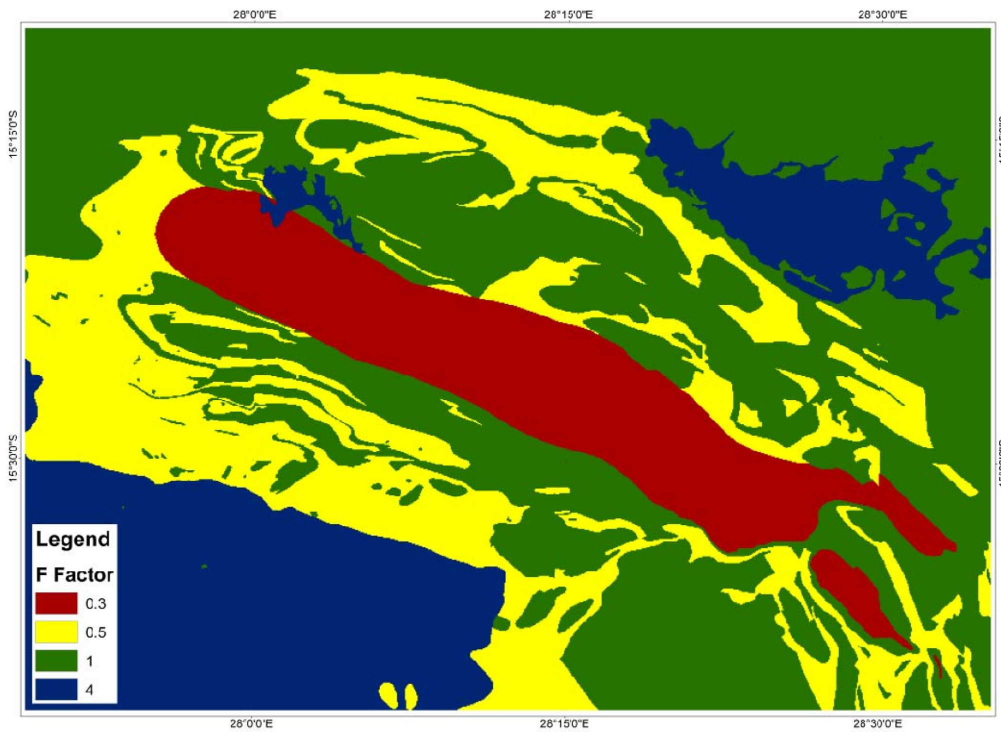

Figure 12: Grid of the F-factor.

Artesian Pressure – A

There is no artesian pressure in the study area. Thus, the factor was not considered.

3.4. I-MAP

Saturated hydraulic conductivity

The saturated hydraulic conductivity (K_{sat}) was estimated by applying pedo-transfer functions on typical soil texture classes and associated bulk density and humus content. Measured K_{sat} values for soils in the Lusaka area were not available. All calculations are based on bulk densities of 1.6 g/cm^3 and organic matter contents of 0.1 %. Table 3 gives the different estimates for every texture class according to the different pedo-transfer functions as well as the final value that was assumed to be a realistic value for the local conditions. Macropores and other preferential flow phenomena have not been taken into account as vertisols only occur on the Kafue flats outside the study area.

Table 5: K_{sat} estimates of selected pedo-transfer functions for typical soil texture classes of the study area (Hennings et al. 2011).

Texture class	Most appropriate PTF as given by:	K_{sat} estimate of selected PTF [cm/d]	K_{sat} estimate according to German soil mapping guidelines, 4th edition [cm/d]	K_{sat} estimate according to German soil mapping guidelines, 5th edition [cm/d]	Applied K_{sat} estimate [cm/d] (in brackets [m/s])
sandy loam	Brakensiek et al. (1984)	136	34	67	42 ($5 \cdot 10^{-6}$)
sandy loam	Vereecken et al. (1990)	14			
sandy clay loam	Brakensiek et al. (1984)	70	16	42	28 ($3 \cdot 10^{-6}$)
sandy clay loam	Vereecken et al. (1990)	11.5			
sandy clay	Brakensiek et al. (1984)	1.8	---	11	6 ($7 \cdot 10^{-7}$)
sandy clay	Vereecken et al. (1990)	7.9			
clay	Saxton et al. (1986)	3	1	6	2 ($2 \cdot 10^{-7}$)
clay	Cosby et al. (1984)	20			

As can be seen from the table, K_{sat} values were in the two lowest classes offered in Step 1 of the I-Map determination. The depth to a low permeability layer is estimated to be more than 100 cm, resulting in the groups Type E and F (see Figure 2).

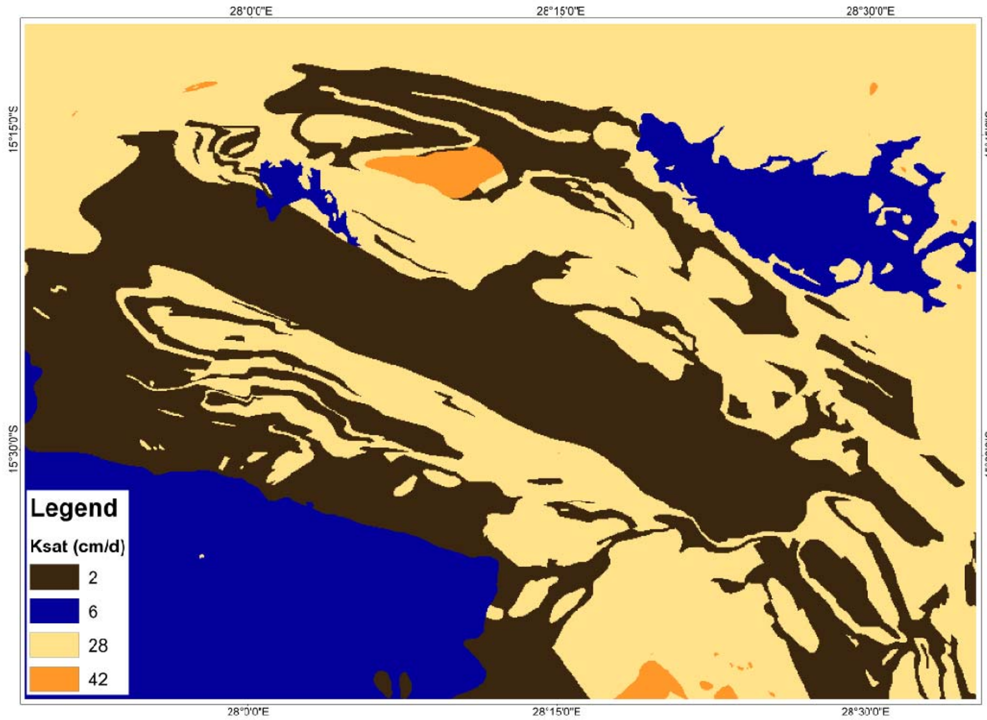

Figure 13: Grid of the K_{sat} values in cm/d (Hennings et al. 2011).

Slope

The slopes (Figure 14) were modelled with a relief model based on the SRTM elevation model (for details see Hennings et al. 2011).

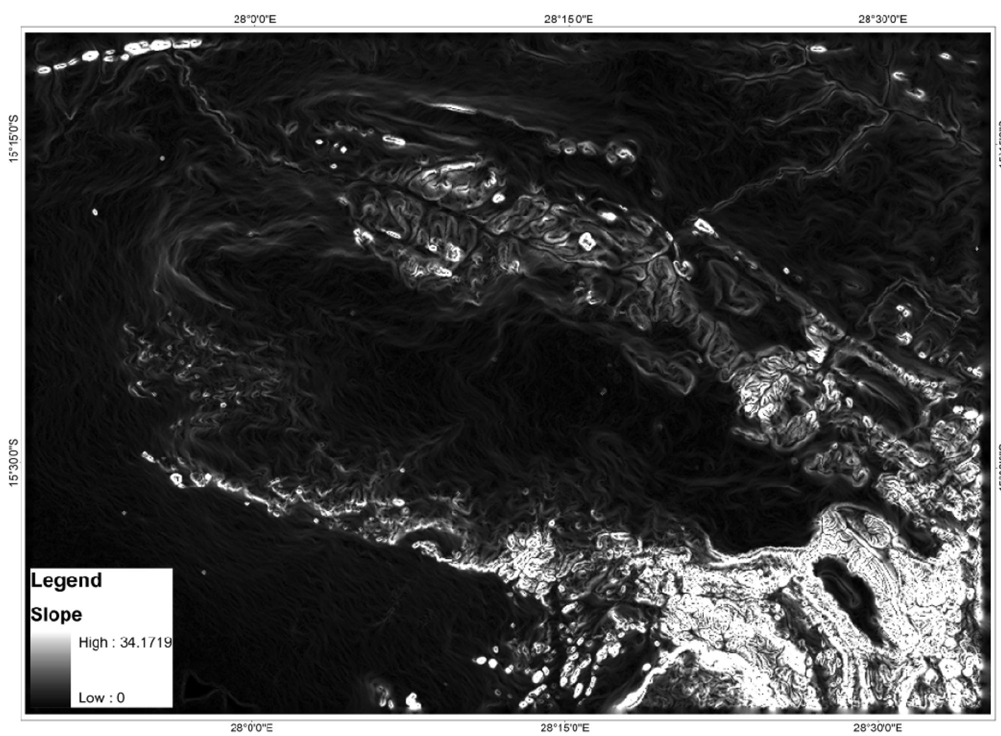

Figure 14: Slopes (in %) in the study area (Hennings et al. 2011).

Landuse

Landuse classification is based on the landuse map by Hahne & Shamboko-Mbale (2010) and was altered and amended to meet the requirements of the method (Figure 15). The two landuse classes mentioned in the PI-method are “forest” and “field/meadow/pasture”. The largest part of the map area falls under either of these two categories as “scrubland” is considered to show characteristics similar to “forest” and “smallscale agriculture” being similar to “field/meadow/pasture”.

The landuse class “settlement” was divided into three groups, characterizing their dominant flow process. It is assumed that in urban areas with surface sealing reaching up to 40% (inner town area) the main flow process is surface runoff, while in residential areas with a large portion of gardens infiltration prevails. The major part of Lusaka City is classified as a third category (“settlement”) and was estimated by satellite images to range in between the other two settlement classes in terms of flow process conditions.

Furthermore the main water and wetland features were incorporated into the I-Map calculation. It was assumed that open water surfaces and areas like dambos where the groundwater table is very shallow are especially vulnerable to pollution as they can form shortcuts to the groundwater for contaminants.

Quarries and other karstic features were also added as a new group to the landuse classification. In order to identify relevant karstic features, the reports of von Hoyer et al. (1978) and Hahne & Shamboko-Mbale (2010) were looked at. Outlines and further features (mainly the quarries) were identified from satellite images.

The landuse classes were grouped into the following categories:

Landuse-Map classification	I-Map category (extended)
forest scrubland	Forest
(smallscale) agriculture baresoil (plinthic)	Field/Meadow/Pasture
settlement	Settlement (highly sealed)
	Settlement
settlement (with garden)	Settlement with garden
(none)	Quarry & karstic area
	Water & wetlands (e.g. dambo)

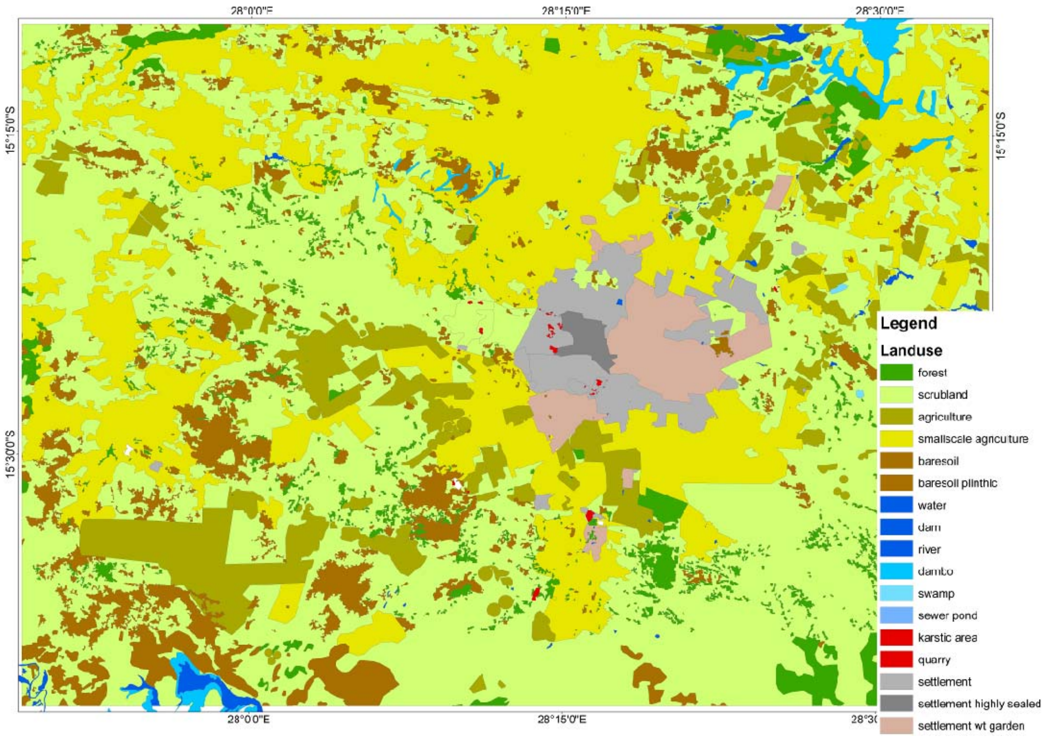

Figure 15: Landuse distribution in the study area (after Hahne & Shamboko-Mbale 2010).

Determination of the I'-Map

The determination of the I'-Map was done in two major steps, firstly for the landuse classes Forest and Field and secondly for the remaining landuse classes (the three settlement classes, quarries & karstic areas and water & wetland areas).

For the first step, the K_{sat}-Grid was reclassified according to the Type E and F categories, the Slope-Grid was reclassified according to the classes (< 3%, 3 – 27%) and the landuse map was reclassified to show only the I-Map categories Forest and Field (landuse-map classes as outlined above). Then all three grids were multiplied and the result reclassified to meet the values given by the method (see Figure 16).

For the second step, the urban area was subdivided into the three identified classes all of which were directly assigned their estimated I'-value. Areas classified as "settlement with garden" were given a value of 0.6, 0.2 was assigned to highly sealed urban areas, and 0.4 to all other settlement areas; quarrying and open water received a value of 0.15 in order to distinguish them from the areas which were handled in the first step (and thus received the value 0 in the second step). The resulting map can be seen in Figure 17.

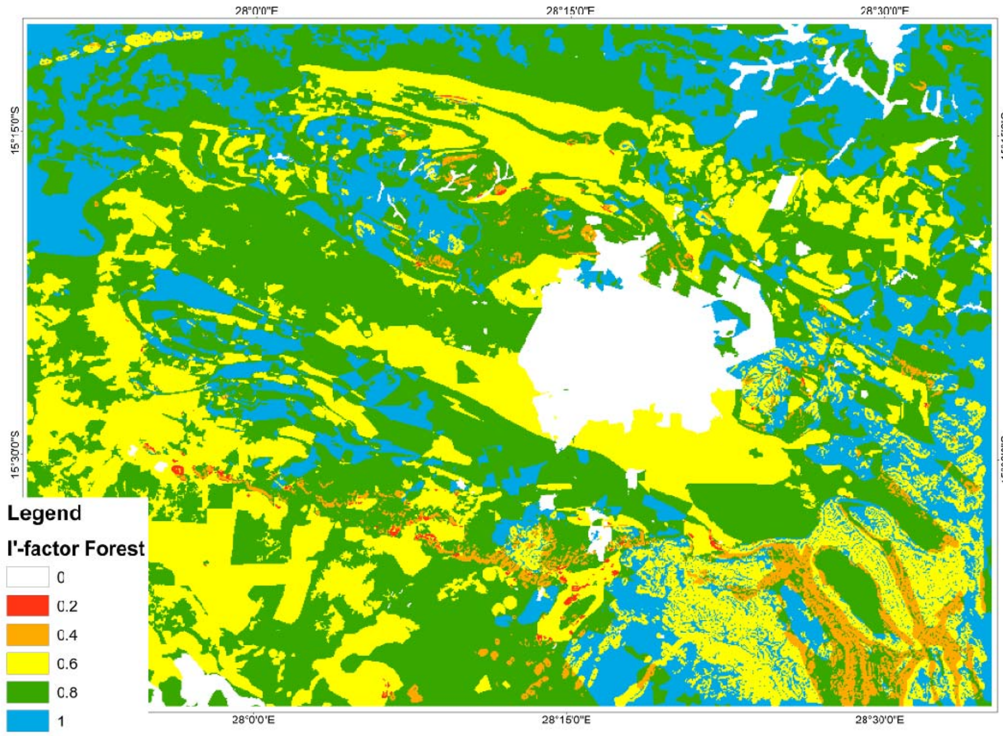

Figure 16: I'-Map of the forest, scrubland and agricultural area.

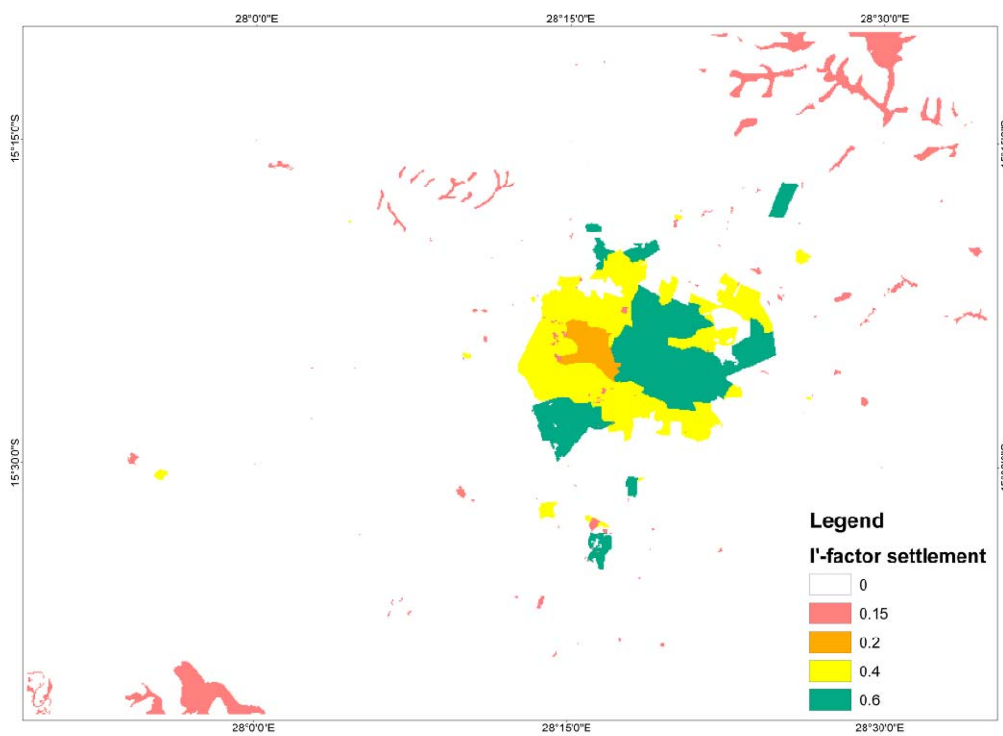

Figure 17: I'-Map of the urban area.

Afterwards the two maps resulting from the first and second step were added by using the "Plus"-function (see Figure 18).

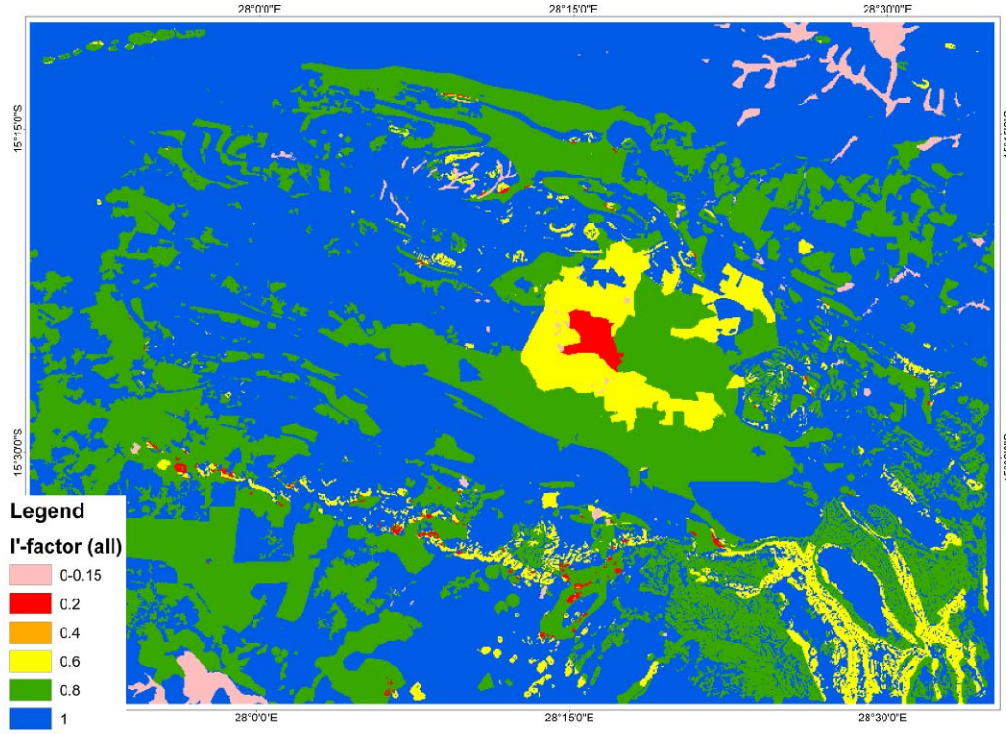

Figure 18: I'-Map of the study area.

Determination of the I-Map

As the PI-method distinguishes between karst and non-karst areas, the study area was divided into surface catchment areas considering

a. karstic sinkholes
b. 100 m buffer zones around the sinkholes
c. areas outside buffer zones which discharge inside the karst
d. areas which discharge outside the karst area.

In category a sinkholes were regarded although the method outlines sinking streams as the features to be mapped under this category. However, there are no sinking streams in the study area but von Hoyer et al. (1978) extensively mapped sinkholes. Furthermore, in areas where rock mining (quarrying) is done on a large scale, the features which are suggested to act as sinkholes were determined and mapped from satellite pictures. Despite these efforts, the mapped sinkholes cannot be considered to be exhaustive. All known sinkholes were considered for the mapping and a 100 m buffer zone was produced around them with the "Buffer" tool in ArcGIS® (category b). Category c was estimated to be the area where dolomites or limestones prevail and no rivers or other surface waters are mapped. The rest of the study area was categorized as d.

In the area discharging outside the karst, the I-factor becomes 1.0 in general, as there is no bypass of the protective cover (P-factor) in these non-karstic areas. For the area in category c, the respective I'-factors were altered according to the table given in Figure 2. This meant an increase of all I'-factors by 0.4 (e.g. an area with an I'-factor of 0.2 and a position inside the karst was assigned an I-factor of 0.6). The karst sinkholes, quarries and water/wetland areas received the I-factor 0, as they are potential bypass areas for infiltrating pollutants. Buffer zones (category b) got an I-factor equal to their I’-factor. This reclassification resulted in the I-Map picture seen in Figure 19.

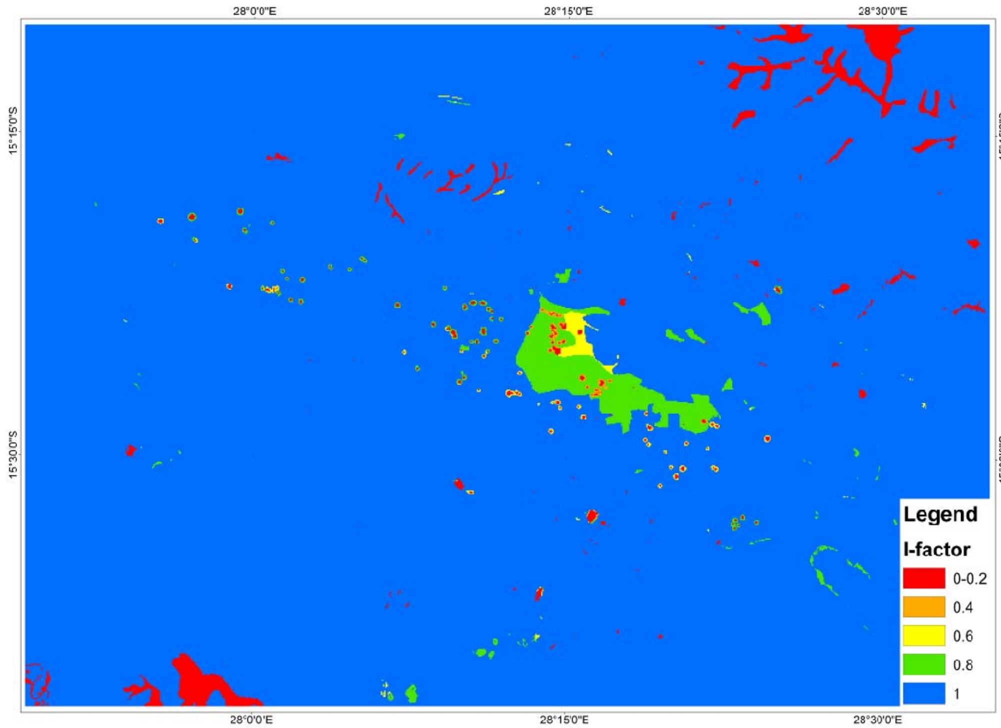

Figure 19: I-Map of the study area.

The final vulnerability map is the product of the P-Map and the I-Map (P-factor times I-factor) and is presented in Figure 20.

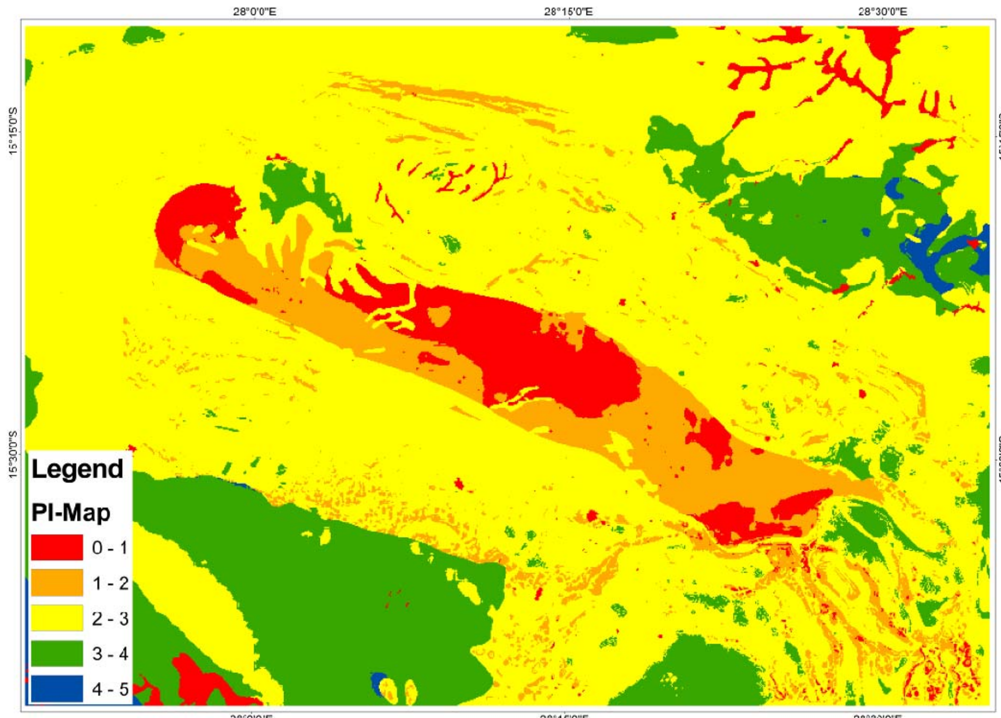

Figure 20: Vulnerability-Map (PI-Map) of the study area.

4. DISCUSSION OF THE MAP

4.1. SCALE OF THE MAP

With a scale of 1:75,000 the vulnerability map of Lusaka District and adjacent areas must be considered as an approximation when it comes to local vulnerabilities. Especially in the urban area of Lusaka and with the diversity of lithological units and soil developments in the mapped area, the prediction of vulnerability to pollution needs to be looked at more closely for specific localities.

4.2. POLLUTION PATHWAYS

The PI-method applies the concept of pollutant transport from an origin on the surface (i.e. above the soil layer) through the pathway of the unsaturated zone to the groundwater surface and further through the second pathway of intra-aquifer transport to the source (i.e. borehole or well). In many cases of contamination this concept can be applied, for example in agricultural fertilizer application, open defecation practices, oil spillage on roads or garages, etc. In other cases the pollution source is located under the surface, i.e. in the soil or even in direct contact with groundwater. Leaking sewer lines, unlined septic tanks, pit latrines and underground storage tanks of fuel stations or depots pose a much higher threat to groundwater quality as they shortcut the filter properties of the unsaturated zone. The method applied here does not take these shortcuts into account. The vulnerability map shows the sensitivity of groundwater to pollution from the surface only. The risk from pollution sources underground is higher, especially in areas with high groundwater tables.

4.3. QUARRIES

Another problem that increases groundwater vulnerability locally is the removal of soil cover in areas with calcareous lithology for the purpose of quarrying. Especially in the Lusaka Dolomites in and around the city small and larger businesses produce aggregate and cement from the limestone. These operations remove the soil cover from the underlying rocks and mine the rocks so that a ragged surface remains. In areas where mining is done on a large scale (e.g. Chilanga and Misisi area), these features were determined from satellite pictures and incorporated in the map (receiving the I-factor 0 as they present potential bypasses for pollutants). However, in areas where small-scale miners operate especially in the urban environment it is difficult to map the features from satellite images. Thus vulnerability can be higher in areas where it is not mapped as “extreme” in case of anthropogenic removal of the protective cover or parts of it.

5. INTERPRETATION OF THE MAP

5.1. VULNERABILITY CLASSES

As can be clearly seen from the vulnerability map the area most vulnerable to pollution is on the Lusaka Dolomite Aquifer. The ratings "very high" (red) and "high" (orange) in relation to vulnerability appear only on this aquifer. In these areas the probability of water quality deterioration is high to very high in the event of pollution. This is mainly due to the very thin soil cover which is removed in many places, the high groundwater table, and the fast transport channels that exist in this highly fractured groundwater body. In the yellow areas, the vulnerability – or risk of pollution – is moderate, while in green and blue areas it is low or very low, respectively. Here, fracturing is less, soil cover more extensive and groundwater tables lower. While the explanation for vulnerability classes given here is very summarized, the detailed parameter values for each areas in the map can be enquired from the Geographical Information System and the individual parameter maps.

5.2. RISKS OF POLLUTION

Looking at the areas with increased risks of groundwater quality deterioration in the orange and red areas, onsite sanitation options prevail. Most the onsite sanitation in Lusaka is made of pit latrines. The latrines are found in areas where soil cover – if present – extends over approximately a couple of decimetres. The effects of this constellation are experienced during almost every rainy season in Lusaka: cholera and other (waste)water-borne diseases. Even in the moderately vulnerable area of Lusaka City the impact of unsafe sanitation is visible from the results of a groundwater quality sampling campaign (Nick et al. 2010). The majority of boreholes sampled in the study were polluted with coliforms which originate from sanitation systems releasing them into the groundwater. In areas of lesser vulnerability pit latrines might not pose such a high risk to the quality of groundwater. However in the moderately and highly vulnerable areas a protection strategy has to take adequate sanitation options into account.

5.3. NEED FOR PROTECTION

The vulnerability map presents an alarming picture of the risk that is taken if groundwater in the Lusaka area remains unprotected. Next to the sanitation recommendations, restrictions are needed for other pollution sources such as industrial activities, storage facilities of potentially harmful substances, wastewater treatment plants and their outlets, intensive agriculture, etc. Thus, a following step should be the establishment of recommendations for restrictions of activities and protection measures based on this vulnerability map.

6. REFERENCES

[1] ALLER, L., BENNETT, T., LEHR, J. H. & PETTY, R. J. (1985): DRASTIC: A Standardized System for Evaluating Groundwater Pollution Using Hydrogeologic Settings. – US EPA / Robert S. Kerr Environmental Research Laboratory, EPA/600/2-85/018: 163 pages; Ada (Oklahoma).

[2] BÄUMLE, R. (2011): Results of Pumping Test Evaluation and Statistical Analysis of Aquifer Hydraulic Properties. Technical Note No. 4, Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany: 77 pages, Lusaka.

[3] CAIRNEY, T. (1967): The Geology of the Leopard Hill Area. – Explanation of Degree Sheet 1528, SE Quarter.- Republic of Zambia, Ministry of Lands and Mining, Report of the Geological Survey No. 21: 64 pages; Lusaka.

[4] CLAYTON, D.B. (1974): Detailed Soil Survey Zamic Chisamba Farms (Ntendere, Nsadzu & Penyaonse Blocks), Soil Survey Report No. 14, Ministry of Rural Development, Landuse Service Division, Soil Survey Unit, Mount Makulu Research Station.

[5] GARRARD, P. (1968): The Geology of the Chainama Hills Area. – Report of the Geological Survey No. 24, Explanation of Degree Sheet 1528, NE Quarter; Republic of Zambia, Ministry of Mines and Minerals Development, Geological Survey Department: 80 pages; Government Printer, Lusaka.

[6] GOLDSCHEIDER, N. (2002): Hydrogeology and Vulnerability of Karst Systems – Examples from the Northern Alps and Swabian Alp. – PhD thesis, University of Karlsruhe: 229 pages; Karlsruhe.

[7] GOLDSCHEIDER, N., KLUTE, M., STURM, S. & HÖTZL, H. (2000): The PI Method – a GIS-based Approach to Mapping Groundwater Vulnerability with Special Consideration of Karst Aquifers. – Z. angew. Geol., 46 (2000) 3: 157-166; Hannover.

[8] GÜNTHER, A. (2011): 3-D Structural Model of Lusaka and Surroundings. Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany; Lusaka (unpublished work in progress).

[9] HAHNE, K. & SHAMBOKO-MBALE, B. (2010): Karstification, Tectonics and Land-use in the Lusaka Region. Technical Report No. 3, Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany: 77 pages; Lusaka.

[10] HENNINGS, V. et al. (2011): Regionalization of Soil Physical Parameters and Estimation of Mean Annual Percolation Rates in the Lusaka Area. Technical Report No. 5, Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany; Lusaka (unpublished work in progress).

[11] HÖLTING, B., HAERTLE, TH., HOHBERGER, K.-H., NACHTIGALL, K. H., VILLINGER, E., WEINZIERL, W. & WROBEL, J.-P. (1995): Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. – Geol. Jb., C 63: 5-24; Hannover.

[12] LUSAKA CITY COUNCIL (2008): Lusaka City State of Environment Outlook Report: 91 pp; Lusaka.

[13] NATIONAL WATER AND SANITATION COUNCIL (2009): Urban and Peri-urban Water Supply and Sanitation Sector Report 2008/2009: 54 pages; Lusaka.

[14] NEUKUM, CH., HÖTZL, H. & HIMMELSBACH, TH. (2008): Validation of Vulnerability Mapping Methods by Field Investigations and Numerical Modelling. – Hydrogeology Journal, 16: 641-658.

[15] NICK, A., MUSETEKA, L. & KRINGEL, R. (2010): Hydrochemical Sampling of Groundwater in the Lusaka Urban Area (April/May 2010) and Preliminary Findings. Technical Note No. 3, Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany: 32 pages; Lusaka.

[16] SIMPSON, J. G. (1962): The Geology of the Mwembeshi River Area.- Report of the Geological Survey No. 11, Explanation of Degree Sheet 1527, NE Quarter, Northern Rhodesia Ministry of Labour and Mines: 29 pages; Government Printer, Lusaka.

[17] SIMPSON, J. G., DRYSDALL A. R. & LAMBERT, H. H. J. (1963): The Geology and Groundwater Resources of the Lusaka Area.– Report of the Geological Survey No. 16, Explanation of Degree Sheet 1528, NW Quarter; Northern Rhodesia Ministry of Labour and Mines: 59 pages; Government Printer, Lusaka.

[18] SMITH, A. G. (1963): The Geology of the Country Around Mazabuka and Kafue. – Explanation of Degree Sheet 1527 SE Quarter and 1528 SW Quarter; Northern Rhodesia Ministry of Labour and Mines: 32 pages; Government Printer, Lusaka.

[19] SWISS AGENCY FOR THE ENVIRONMENT, FORESTS AND LANDSCAPE (SAEFL) (2000): Practical Guide Groundwater Vulnerability Mapping in Karst Regions (EPIK). – Report: 57 pages; Bern.

[20] VIAS, J. M., ANDREO, B., PERLES, M. J., CARRASCO, F., VADILLO, I. & JIMENEZ, P. (2002): Preliminary Proposal of a Method for Contamination Vulnerability Mapping in Carbonate Aquifers. – In: CARRASCO, F., DURAN, J. J. & ANDREO, B. (Eds.): Karst and Environment: 75-83.

[21] VON HOYER, M., KÖHLER, G. & SCHMIDT, G. (1978): Groundwater and Management Studies for Lusaka Water supply, Part 1: Groundwater Studies, Vol. I, Text, Vol. III + IV: Annexes, Vol. V: Maps.- Federal Institute for Geosciences and Natural Resources (BGR) & Lusaka City Council: 152 pages; Lusaka.

[22] VRBA, J. & ZOPOROZEC, A. [eds.] (1994): Guidebook on Mapping Groundwater Vulnerability. – International Contributions to Hydrogeology (IAH), 16: 131 pages; Hannover.

[23] ZWAHLEN, F. (ed) (2004): Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers, Final Report (COST Action 620). Report EUR 20912, European Commission, Directorate XII Science, Research and Development: 297 pages; Brussels.

[24] URL 1: http://www.scribd.com/doc/47739810/Zambia-2010-Census-of-Population-and-Housing (downloaded June 21, 2011)