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Groundwater Resources of the Mwembeshi and Chongwe Catchments, including the Lusaka Region

A Manual of the Hydrogeological Maps
and the Vulnerability Map

Lusaka - Hannover 2012

Prepared as a technical co-operation project
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1. Groundwater Information System

The hydrogeological maps at hand are based on data which is stored and managed in a groundwater information system. The groundwater information system as described in reports [2] and [3] consists of:

1. The groundwater database
2. The Geographic Information System (GIS)

Groundwater Database

The groundwater database was established using the commercial software package GeODin®. The software is based on a MSAccess database but provides user-friendly data input masks as shown for instance in the Figure 1.

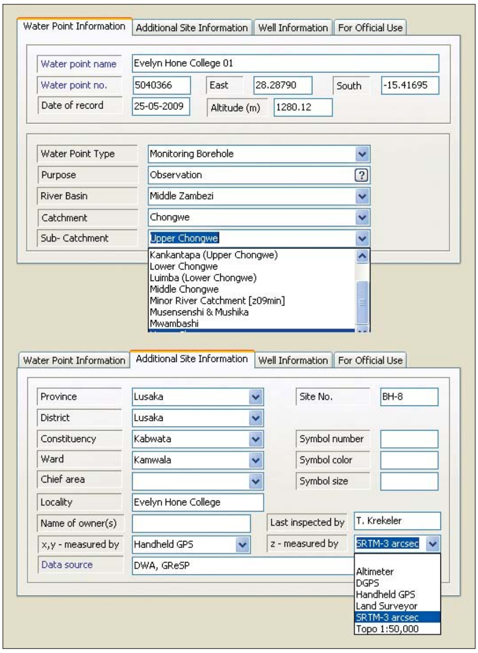
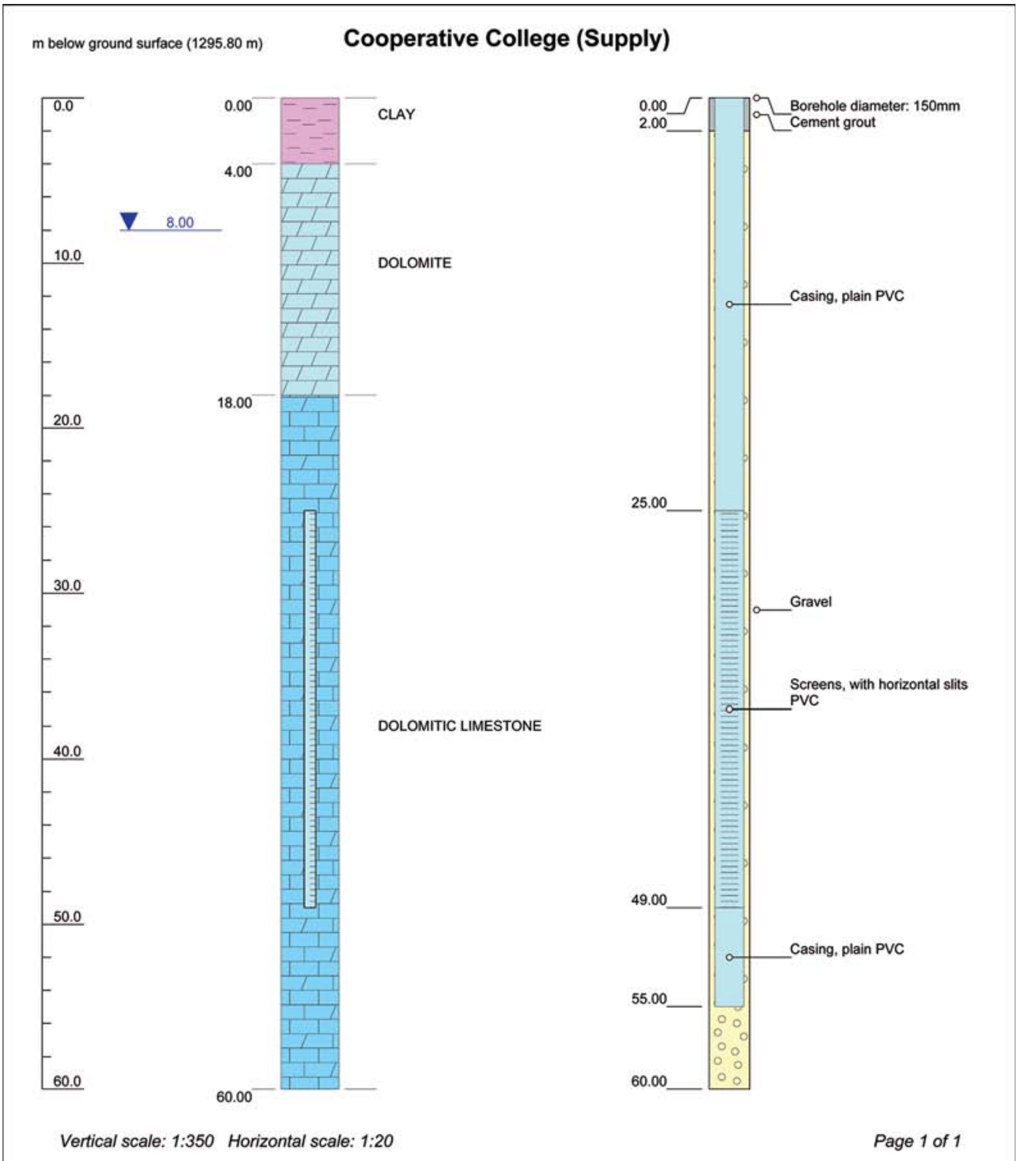


Figure 1: Data input mask for entering a new water point into the GeODin groundwater database. Detail shows, as an example, how available sub-catchments within Middle Zambezi River Basin can be selected from a dropdown list.

The individual input masks were modified to meet the specific needs and requirements of the Department of Water Affairs. The individual fields often work with dropdown lists to facilitate a quick data entry and to prevent spelling mistakes.

Table 1: Type of information held in the GeODin database.

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



Water point number:	**5040939**		
Water point funded by	**Owner**	**Data Source:**	**DWA, GReSP**
Locality:	Leopard Hill	East:	28.37207
Ward:	Kabulonga	South:	-15.44860
District:	Lusaka	Altitude:	1295.80 m
Province:	Lusaka	Total depth of borehole:	60.0 m

Figure 2: Example of a borehole description exported from the GeODin database for the borehole in Lusaka's Cooperative College, Water-Point No. 5040939 in Lusaka District.

The software also offers various possibilities to query, export, display and visualize groundwater related data entered (e.g. selected data tables, borehole completion reports, lithological borehole logs, etc). An example for a borehole design with geological description is given in Figure 2.

The database contains information on more than 2,500 water points found in Lusaka and its surroundings including boreholes, hand-dug wells, unsuccessful drillings and springs. The data compilation combines general information (e.g. location, type and purpose of water point) with comprehensive and detailed technical information on groundwater hydraulics, borehole design, as well as geology and groundwater quality (Table 1).

GIS

The GIS includes individual digital map layers containing topographic, geological, hydrological and groundwater related information. The map layers are seamless, i.e. not bounded by the margins of the original map sheets. The GIS layers can be combined for the compilation of various thematic maps or applied to further geo-related applications and analysis.

Water Point Number

For reasons of structuring the database a water point numbering system had to be introduced. Each water point number is unique, i.e. can only be allocated to one point. The number is composed of seven digits with the first digit representing the Province (e.g. "5" for the Lusaka Province), the second and third given out according to the District and the remaining four digits specifying the individual water points.

Table 2 Composition of water point number.

Digit No.	Value
1	"**5**" for Lusaka Province "**1**" for Central Province
2 and **3**	"**01**" for Chongwe/Chibombo District "**02**" for Kafue/Kabwe District "**03**" for Luangwa/Kapiri-Mposhi District "**04**" for Lusaka/Mkushi District "**05**" for Mumbwa District "**06**" for Serenje District
4 to **7**	Indexed numbers ranging from **1** to **9999**

To water points located in Chongwe District, for example, numbers ranging from 5010001 to 5019999 can be given out. Accordingly, numbers ranging from 1010001 to 1019999 and from 5040001 to 5049999 represent water points in Chibombo District in Central Province and Lusaka District in Lusaka Province, respectively.

2. The Hydrogeological Maps

2.1. Coverage

The hydrogeological map series developed for the Mwembeshi and Chongwe catchments include one sheet at scale 1:250,000 and one sheet at scale 1:75,000 (Figure 3, incl. Southern Province maps). Additionally, a groundwater vulnerability map at scale 1:75,000 was produced. The maps are designed to display groundwater features at catchment and sub-catchment scale. The contents of the maps comprise:

- Topography including roads, villages, towns, health centres and schools,
- Hydrography including rivers and wetlands,
- Surface elevation,
- Surface catchment and sub-catchment boundaries,
- Water points such as boreholes and wells, including unsuccessful drilling sites, and thermal springs,
- Lithology and geological structures (faults, etc),
- Boundaries and potential of groundwater systems, so-called aquifers,
- Groundwater elevation contours and direction of groundwater flow,
- Rainfall distribution (Inset map).

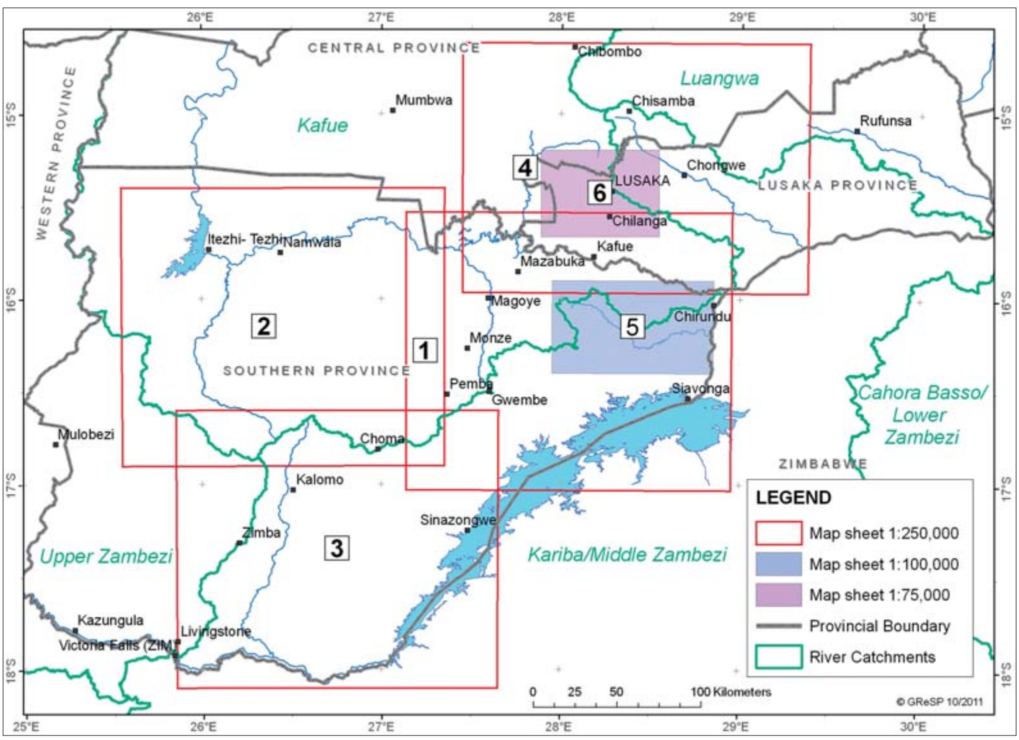


Figure 3: Available hydrogeological map sheets:
1. Northern Kariba Lake and Kafue Gorge
2. Kafue Flats and Southern Tributaries
3. Southern Kariba Lake and Kalomo
4. Mwembeshi and Chongwe Catchments
5. Lusitu River
6. Lusaka and surroundings.

2.2. Map elements

Each map sheet consists of the following elements (Figure 4):

- a cover page with the map title and institutional logos, etc.,
- the body of the main map,
- a map legend,
- a frame consisting of neatline(s) and grid,
- a scale and scale bar,
- inset map(s) and
- marginal text.

Main map (body)

The "map body" shows the main theme of the map for the selected map area. The main theme of the hydrogeological map is, of course, groundwater. Other examples of thematic maps are maps showing climate, vegetation, natural resources, population density, economic activity, etc.

Legend

The "map legend" or "map key" explains the map symbols used on the map and what objects or features (e.g. town, river, district, etc.) they represent. Map symbols are made of cartographic elements like points, lines and polygons.

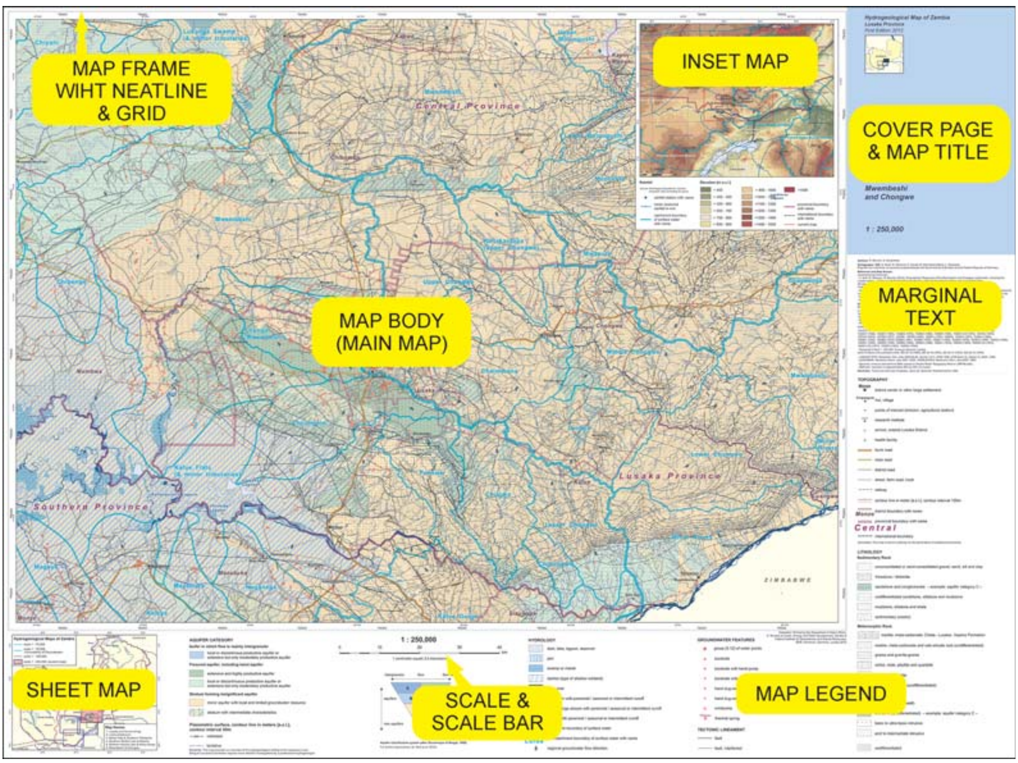


Figure 4: Main components of the hydrogeological maps.

Scale and scale bar

The “map scale” indicates the relationship between a certain distance on the map and the actual distance on the ground. A “large” scale map refers to one which shows greater detail. A graphic scale such as a scale bar can be used to determine distances on the ground along with a ruler. A word statement gives a written description of the map distance. For the maps at scale 1:250,000 and 1:75,000 this statement is “1 centimetre equals 2.5 kilometres” and ”1 centimetre equals 750 metres”, respectively. An example of the scale, scale bar and the corresponding word statement is given below:

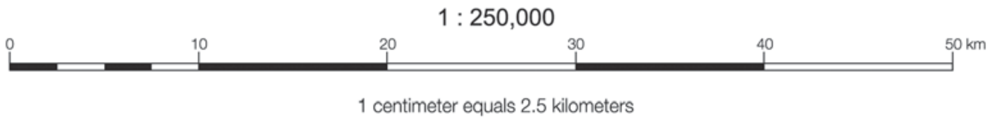


Figure 5: Scale and scale bar.

Neatlines and grid

Neatlines are used to frame the map and to indicate exactly where the area of a map begins and ends. The numbers next to the neatlines represent “world” coordinates of the geographic coordinate system and “metric” coordinates (easting and southing) corresponding to the projected coordinate system. The system of latitudes and longitudes form the “geographical graticule” whereas the network of lines connecting the metric coordinates is referred to as the map “grid”.

For the examples indicated in Figure 6 the geographic coordinates indicate an area 28 degrees east of the prime meridian (0 degree) which, by definition, passes through Greenwich (near London) and 16 degrees 30 minutes south of the Equator.

The map projection applied is based on the Transverse Mercator system using the 27 degrees East line as the central meridian. By definition, a value of 500,000 meters (“false easting”) and of 10,000,000 meters (“false nothing”) is given to the central meridian and the Equator, respectively, in order to avoid negative values. Easting and southing indicate the position of a location in relation

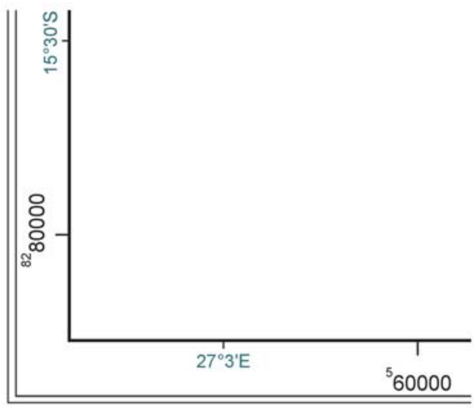


Figure 6: Neatline, graticule and grid.

to the central meridian and the Equator. In the examples given, the coordinates define an area approximately 100,000 m (600,000 minus 500,000 metres) east of the central meridian and 1,720,000 metres (10,000,000 minus 8,280,000 metres) south of the Equator.

Marginal Text

The additional text section includes the author’s and cartographer’s names, map projection details, disclaimers, source of data, etc.

2.3. Content of Main Map

2.3.1 Hydrology

The hydrology displays surface water bodies and boundaries. Surface water features include lakes, dams, wetlands as well as rivers and river catchments.

Rivers

The map symbology distinguishes perennial rivers from intermittent or seasonal rivers (Figure 7).

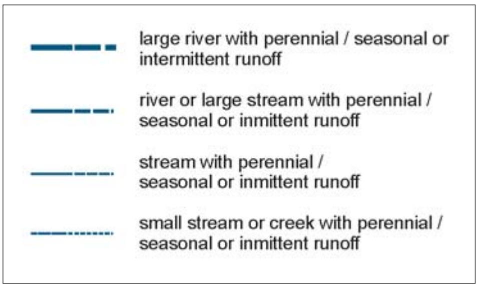


Figure 7: Map symbols for water courses.

A river or stream that flows all year round is called *perennial*.

A *seasonal* river or stream flows only during the rainy season and dries out during the dry season.

A river or stream is called *intermittent* if run-off is subject to interruption depending on the amount and duration of rainfall. The flow of intermittent rivers lasts over longer periods compared to ephemeral rivers, which are mostly dry and subject to water flow for only short periods (hours to a few days) after heavy rainfalls.

Wetlands

Wetlands cover more than 20% of Zambia's total area [1]. Five different symbol classes for wetlands are used in the hydrogeological maps. The symbols represent dams, lakes, lagoons, reservoirs; swamps or marshes; pans; dambos; and main river areas (Figure 8).

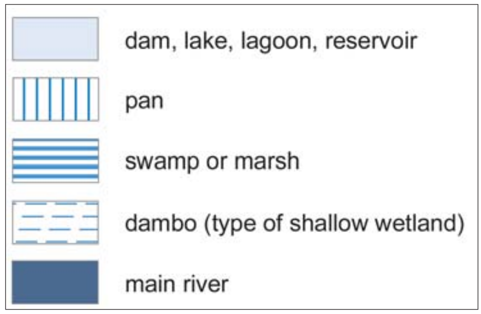


Figure 8: Map symbols for various types of wetlands (scale 1:250,000).

Additional hydrology features included in the hydrogeological map scale 1:75,000 comprise sewer stabilization ponds and open groundwater surfaces as frequently encountered in quarries (Figure 9):

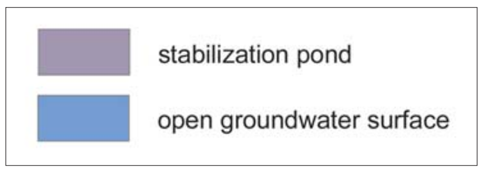


Figure 9: Additional map symbols for "wetlands" (scale 1:75,000).

In geography, a marsh is a type of wetland which is subject to frequent or continuous inundation. A marsh is different from a swamp, in that it has a smaller proportion of open water surface, and is generally shallower than a swamp.

A pan is a depression without drainage outlet where water pools seasonally.

Dambos have been defined as "seasonally waterlogged, predominantly grass covered, depressions bordering headwater drainage lines" [7]. The term for this complex type of shallow wetland is used in central, southern and eastern Africa, particularly in Zambia and Zimbabwe.

Figure 10: Dambo surrounded by woodland.

The treeless grass covered depression is seasonally waterlogged by seepage from surrounding high ground assisted by rainfall and has shallow water tables (<1 m) for most part of the year [1]. The vegetation of dambos is characterised by grasses, rushes, sedges and the lack of trees, contrasting with surrounding woodland such as miombo woodland (Figure 10).

Catchments

A catchment or drainage basin is the land area that is drained by a river or river system.

The catchment boundaries in the map refer to the main river systems and basins (Figure 11).

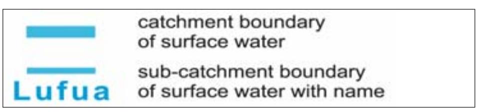


Figure 11: Map symbols for catchment boundaries.

According to the National Water Resources Master Plan [9], six such basins and river systems can be distinguished in Zambia, namely the Zambezi Main, Kafue, Luangwa, Chambeshi and Luapula rivers and the Lake Tanganyika basin. The Zambezi Main river was further divided in the Upper Zambezi defined as the drainage area upstream the Victoria Falls, and the Middle Zambezi drainage area.

Catchment boundary lines displayed on the maps separate the Kafue and Luangwa catchments from the Upper and Middle Zambezi Main catchments. Sub-Catchment boundaries delineate the river drainage areas of smaller tributaries to the Kafue, Luangwa and Zambezi Main rivers.

2.3.2. Geology

Lithology

The lithology describes the rock type and its composition. The maps distinguish between about a dozen different types of lithology. Sedimentary, igneous and metamorphic rocks together form the three major groups of rock.

Sedimentary rock is formed by the deposition and compaction of mineral grains or materials from living organisms, or by chemical precipitation. Sedimentary rocks include among others limestone, dolomite, conglomerate, sandstone and shale.

Igneous rock is a rock solidified from cooled magma. It is called extrusive if formed at the earth's surface or intrusive if the magma cools and solidifies underneath the surface. Typical examples for extrusive and intrusive igneous rocks are basalt and granite.

Metamorphic rock is a rock derived from pre-existing rock, of either sedimentary or igneous origin that was transformed in response to marked changes in temperature and pressure usually at considerable depth under the Earth's surface. Metamorphic rocks include among others marble, gneiss and schist.

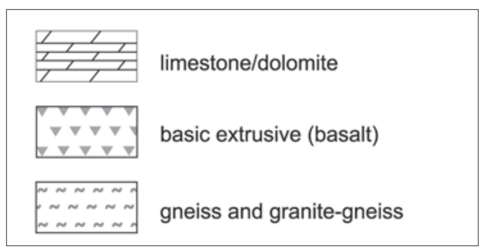


Figure 12: Map symbols for various types of lithology.

Three examples for map symbols used to display lithological characteristics in the maps are shown in Figure 12.

Tectonic lineaments

A fault is a fracture or a zone of fractures along which there has been displacement of the sides relative to each other. In rocks with little primary porosity (voids) faults may constitute major pathways for underground water flow.

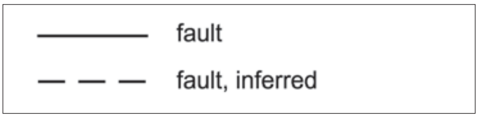


Figure 13: Map symbols for faults.

Inferred faults are faults that cannot be detected on the surface. Instead, their position was derived from geological interpretation.

2.3.3. Groundwater Features

Water Point Information

Individual map symbols are used to differentiate between the various water point types (Figure 14). Boreholes are thus distinguished from shallow hand dug wells. The symbols also denote the type of installation such as handpump, submersible pump, bucket and windlass or windmill. Finally, the maps show natural occurrences of hot (thermal) springs.

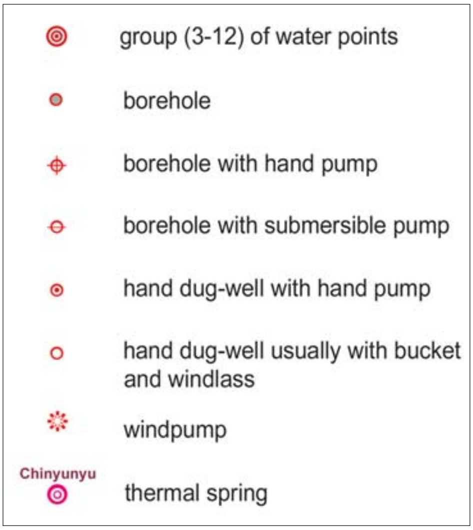


Figure 14: Map symbols allocated to the various water point types.

On the 1:75,000 scale map the water points are labelled with the water point number (see Chapter 1). There are some features in the 1:75,000 scale map which do not appear on the 1:250,000 scale map. These are listed in the following. All mapped springs are distinguished by their flows being perennial (constantly flowing) or seasonal/intermittent (flows only during the rainy season or from time to time) as presented in Figure 15.

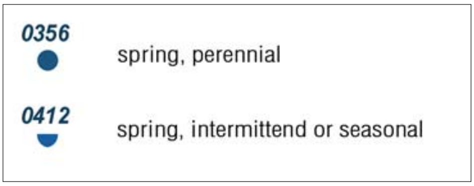


Figure 15: Map symbol for springs.

Furthermore, water points serving as monitoring boreholes carry the symbol depicted in Figure 16.

Figure 16: Map symbol for monitoring boreholes.

Production wells of the water supply utility are shown on the 1:75,000 scale map using the symbols given in Figure 17.

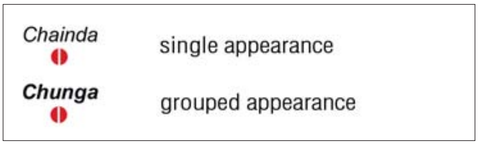


Figure 17: Map symbol for production boreholes.

Examples for wells in rural areas and production boreholes used for municipal water supply are presented in Figure 18 and Figure 19, respectively.

Figure 18: The two most common water point types: Handpump of type India Mark II (left) and hand dug well with bucket and windlass (right).

Figure 19: Municipal water supply wells in Lusaka.

Groundwater Potential

In the hydrogeological maps, the groundwater systems were grouped in six classes (or "categories") according to their potential. Rocks that are water saturated and sufficiently permeable to store and transmit groundwater are called "aquifers".

The applied distinction of aquifer classes was adopted from the method proposed by Struckmeyer and Margat [8]. The classification combines information on aquifer potential (productivity and lateral extent) and the type of groundwater flow regime (intergranular or fissured).

A scheme of areal colours was developed to represent hydrogeological characteristics in the maps. The colouring scheme is illustrated in Figure 20 as a triangle in which the potential is decreasing from top to bottom. Dark blue and dark green colours represent aquifers with high potential. Light blue and light green colours represent aquifers with moderate potential. Formations with limited potential are coloured in light brown while strata with essentially no groundwater are in dark brown.

For groundwater systems with high or moderate potential the colouring scheme also considers the dominant type of groundwater flow within the rock. Blue colours are used for systems in which flow is mainly intergranular while green colours represent systems formed by hard rock, including karst rock, in which flow occurs in fissures, fractures or dissolution cavities (see box "Groundwater Flow Regimes" for more details).

An attempt was made to give practical examples for the possible use of the groundwater resources for each category (Table 3, last column). Aquifers with a high potential (categories A and C) for example may permit withdrawals of regional importance such as supply to major towns or large-scale irrigation. Aquifers with limited potential (category E) should suffice for the supply of water to rural villages with a handpump.

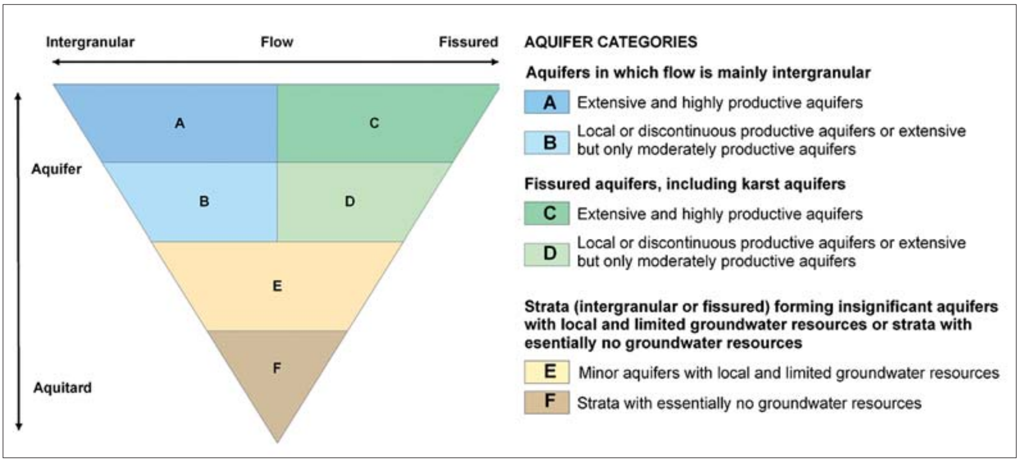


Figure 20: Aquifer classification system (after [8]).

Table 3: Hydraulic characterisation of the aquifer categories (modified after [6], [8]). See box "Hydraulic Characteristics of Aquifers" for an explanation of the listed parameters.

Aquifer Category	Specific Capacity [L/s/m]	Transmissivity [m^2/d]	Hydraulic conductivity [m/d]	Very approx. expected yield [L/s]	Groundwater Potential
A ,C	> 1	> 75	> 3	> 10	High: Withdrawals of regional importance (supply to towns, irrigation)
B, D	0.1 – 1	5 – 75	0.2 – 3	1 – 10	Moderate: Withdrawals for local water supply (smaller communities, small-scale irrigation etc.)
E	0.001 – 0.1	0.05 – 5	0.002 – 0.2	0.01 – 1	Limited: Smaller withdrawals for local water supply (supply through handpump, private consumption)
F	< 0.001	< 0.05	< 0.002	< 0.01	Essentially none: Sources for local water supply are difficult to ensure

Hydraulic Characteristics of Aquifers

Groundwater systems are usually characterised according to their hydraulic properties, including:

The *specific capacity q*, given in units L/s/m, which is obtained by dividing the discharge of a pumped well by the stabilised drawdown at the specific pumping rate that was observed during the pumping test.

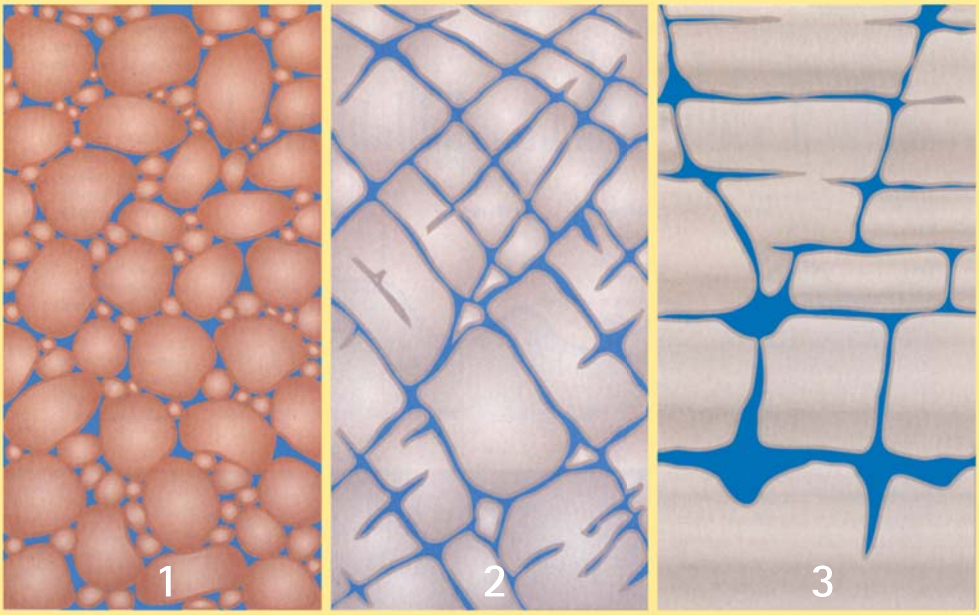
The *transmissivity* T, given in units of m^2/d, which can be considered a measure of the amount of water that can be transmitted through a rock formation.

The *hydraulic conductivity* k, given in units m/d, is defined by Darcy's Law and can be considered a measure (or a "coefficient") of the permeability of rock with regard to water.

The *yield* Q, given in L/s, which refers to the likely or characteristic yield that a well can produce from a rock formation.

Suggested further reading: Fetter C W (2001): Applied Hydrogeology.- 4^{th} ed. 598 pp; Prentice Hall; Upper Saddle River, New Jersey.

Groundwater Flow Regimes



There are three major types of groundwater flow regimes:

(1) Intergranular flow occurs through the voids (pore space) between individual mineral grains (left picture). This type of flow is typical for rock consisting of unconsolidated deposits (e.g. loose gravel, sand or sandstore or silt).

(2) In hard rock, groundwater can be transmitted through fissures or fractures. The void space created by fissures is called "secondary" porosity in contrast to the "primary" porosity referring to the original (unfractured) pore space when the rock was formed. If the primary porosity is small groundwater flow is virtually restricted to fissures.

(3) Secondary porosity can also be created by dissolution of minerals. As rock dissolves along fractures or bedding planes large cavities and even caves can develop (right picture). This leads to the development of "Karst" formations in which groundwater can drain quickly. Karst is usually developed in carbonate rocks such as limestone and dolomite. Groundwater is often abundant in these formations, but can almost as easily be polluted as surface streams.

Groundwater Flow

The direction of groundwater movement of groundwater in the rock is displayed on the maps by means of arrows and groundwater contour lines (Figure 21). The arrows indicate the regional direction of groundwater flow. The groundwater contours give the elevation of the groundwater table in meters above sea level.

The groundwater table is the surface that separates the zone that is saturated with water from the unsaturated zone above. The depth of groundwater at a specific point can be estimated by subtracting the altitude of the ground surface from the elevation of the groundwater table.

Figure 21: Excerpt of the hydrogeological map showing groundwater contours (thin blue lines) and regional flow direction (blue arrows).

Figure 22 explains the occurrence, movement and circulation of water in the hydrosphere with emphasis on groundwater. When rain falls onto the ground surface, a portion infiltrates into the ground by gravity where it moves both vertically and laterally depending on the slope. Infiltrating water first passes through the unsaturated zone before it reaches the groundwater table. Groundwater fills the interconnected open spaces (pores) between mineral grains and fractures. Groundwater generally flows from high (in terms of elevation) areas to low areas. Along topographic sinks it recharges rivers as base flow as well as lakes and oceans. Springs and seeps occur where the ground surface intersects the groundwater table or where groundwater is under pressure and can reach the surface through fracture zones.

Within the mapped area, the Lusaka plateau forms a 70 km long and 10 km wide ESE-WNW stretching low ridge that acts as a local topographic high dividing the Kafue from the Chongwe drainage area. The groundwater flow generally follows the topography with springs commonly emerging at the plateau's margins.

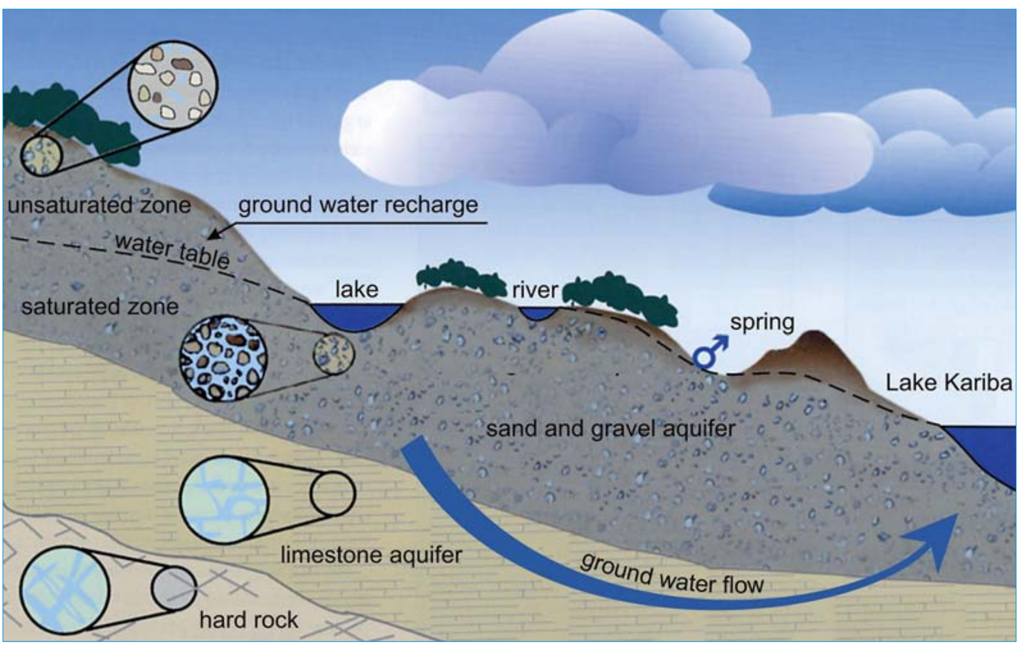


Figure 22: Schematic illustration of groundwater flow.

2.4. Inset maps

There are two inset maps included in the 1:250,000 map sheet, a sheet map located in the lower left corner and a second map inside the body of the main map.

The inset sheet map shows the position and rectangular extent of the six hydrogeological maps available for Southern and Lusaka Province in relation with the entire Zambia and neighbouring countries. A similar inset map is included in the 1:75,000 map sheets of the hydrogeological map and vulnerability map of Lusaka Province.

The second inset map (Figure 23) shows a separate thematic map of the topography, dominant topographic features such as the Kafue Flats and the Escarpment as well as meteorological stations and the general rainfall pattern. The altitude given in metres above sea level is displayed as classified colour bands at 100 metre intervals. The rainfall isolines known as "isohyets" show the distribution of mean seasonal rainfall in millimetres for the southern and central parts of Zambia. Seasonal rainfall refers to rainfall totals from September to April. The extent of the hydrogeological map sheet (body of main map) within the frame of the inset map is shown as a rectangle bordered in red colour.

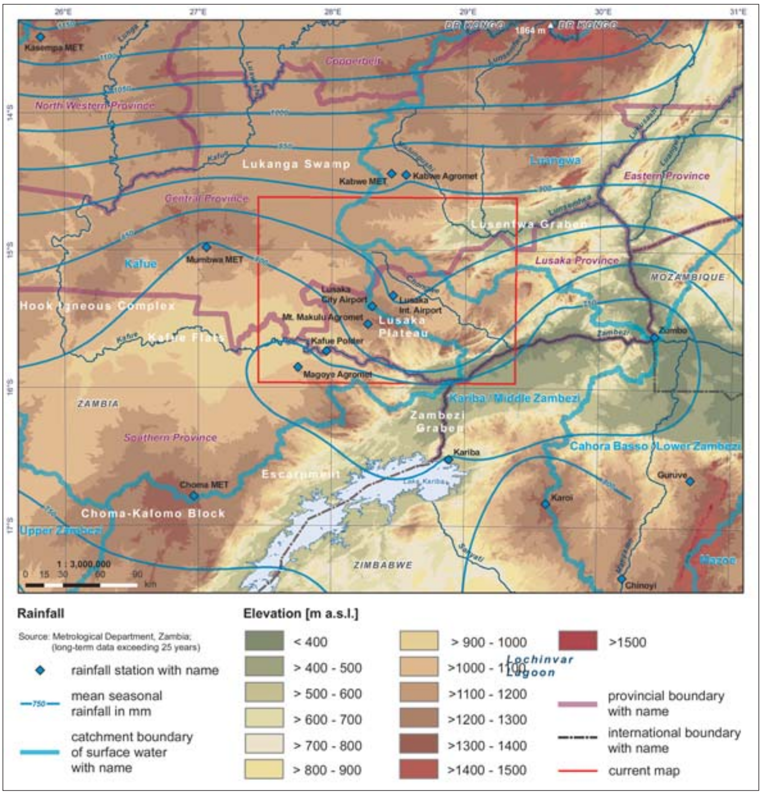


Figure 23: Inset map included in the hydrogeological map 1:250,000 showing topography and overall rainfall pattern.

3. The Vulnerability Map

3.1. Coverage

The coverage of the vulnerability map corresponds to the map extent of the hydrogeological map at scale 1:75,000. The content of the vulnerability map comprises:

- topography including roads, villages, towns, health centres and schools,
- hydrography including rivers and wetlands,
- surface elevation,
- production boreholes of the water supply utility, and springs,
- groundwater elevation contours and direction of groundwater flow,
- groundwater vulnerability,
- risk areas of potential water quality deterioration, and
- effectiveness of the protective cover and degree of bypassing (inset maps).

3.2. Content of Main Map

Apart from the topographic features, hydrology and groundwater features, described in Chapter 2.3, the following thematic information is displayed in the vulnerability map.

3.2.1. Risk Areas

The areas with increased risk of groundwater contamination comprise the categories as shown in Figure 24.

It should be noted that these areas with an increased risk of being the source of pollution do not necessarily represent areas with a high vulnerability. While vulnerability depends on the characteristics of the natural system, risk areas are anthropogenic features imposed on the natural system.

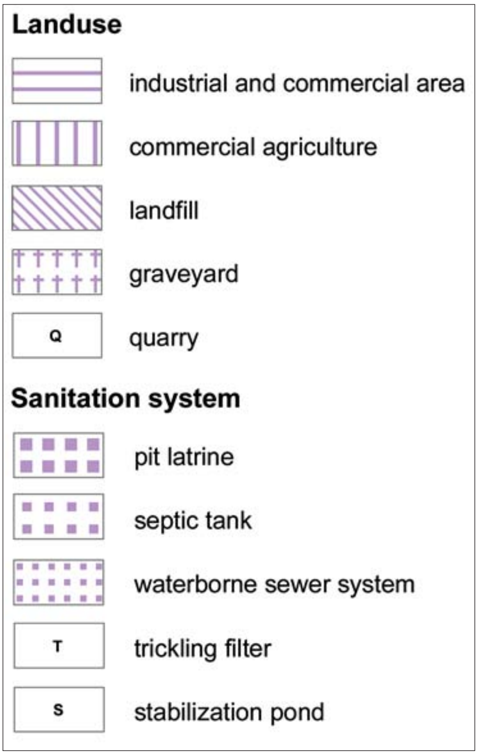


Figure 24: Map symbols for different features with increased risk of groundwater pollution.

3.2.2. Vulnerability

Groundwater vulnerability describes the sensitivity of groundwater to pollution, or, in other words, how likely it is that a pollutant originating from the surface reaches the groundwater table. Vulnerability maps are tools to assess the ability of the system to protect the groundwater from contamination. They assist in identifying areas which need additional protection measures, such as restrictions of human activities. In areas where vulnerability is high or extreme, it is not advisable to build infrastructure which potentially harms groundwater quality (e.g. sewerage plants, heavy industry, landfills). The degree of vulnerability is shown in the classes in Figure 25.

Figure 25: Map symbols for vulnerability of groundwater (numbers in brackets show the vulnerability index).

An excerpt of the distribution of the various vulnerability classes in Lusaka is shown in Figure 26.

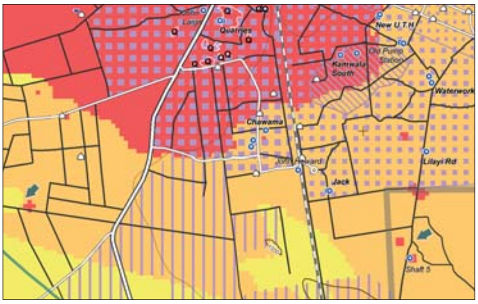


Figure 26: Excerpt of the vulnerability map showing areas with extreme (red), high (orange) and moderate (yellow) degree of vulnerability.

3.3. Inset Maps

There are two inset maps in the scale 1:250,000 included in the vulnerability map sheet, located in the lower left corner and overlapping into the body of the main map.

The inset maps show the two factors determining the vulnerability of groundwater: the P- and I-factor [5]. The acronym "P" stands for protective cover and the "I" stands for infiltration conditions. The P-factor distribution (given in the left inset map) specifies the effectiveness of the protective cover resulting mainly from the thickness and hydraulic properties of the layers between the surface and the groundwater table. The I-factor (right inset map) characterizes the infiltration conditions, particularly the degree to which the protective cover can be bypassed as a result of lateral surface and subsurface flow.

Both inset maps have a separate legend while the main legend includes features that appear in all three maps.

4. References

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