Development of a regional groundwater monitoring network

Theoretical considerations and case study for a project area in the Upper Kafue Sub-catchment

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SUMMARY

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Abstract
Groundwater monitoring is the key prerequisite for groundwater management as sound decisions can only be made if sufficient and adequate data is available. Various aspects have to be taken into account when setting up a groundwater monitoring network for the first time. The objectives of the monitoring and the responsibilities have to be defined before the network can be designed. The design then has to specify which parameters are going to be monitored, where what kind of monitoring is needed and at which frequency observations have to be made.

The first part of this report outlines the theoretical considerations of designing groundwater monitoring networks based on a comprehensive review of existing manuals, reports and articles, published either by international organisations or in scientific journals.

The second part of the report applies these considerations to a study area of the Groundwater Resources Management Support Programme (GReSP) project in the Upper Kafue Sub-catchment, Zambia. After giving a background on groundwater monitoring responsibilities according to the Water Resources Management Act of 2011 and on the history of hydrometric monitoring in Zambia, the general hydrological and hydrogeological characteristics of the study area are outlined. The theoretical framework is then applied to design an initial network, intended to give a reference data set to enable a detailed description of the area’s hydrogeological conditions. Finally, first observations of the installed network are used to evaluate the decisions taken in the design process and conclusions on further steps ahead in the monitoring of the respective area are given.
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<tr>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)</td>
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<td>ACWI</td>
<td>Advisory Committee on Water Information</td>
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<td>EC</td>
<td>European Commission</td>
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<tr>
<td>eC</td>
<td>Electrical conductivity</td>
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<td>EEA</td>
<td>European Environmental Agency</td>
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<td>GGMN</td>
<td>Global Groundwater Monitoring Network</td>
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<td>GOS</td>
<td>Global Observing System</td>
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<td>GTN-H</td>
<td>Global Terrestrial Network Hydrology</td>
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<td>IGRAC</td>
<td>International Groundwater Resources Assessment Centre</td>
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<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>LAWA</td>
<td>Länderarbeitsgemeinschaft Wasser (German Federal States' Working Group on Water)</td>
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<td>LHPC</td>
<td>Lunsemfwa Hydro Power Company</td>
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<td>NGWMN</td>
<td>National ground-water monitoring network</td>
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<tr>
<td>SADC</td>
<td>South African Development Community</td>
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<tr>
<td>SASSCAL</td>
<td>Southern African Science Service Centre for Climate Change and Adaptive Land Management</td>
</tr>
<tr>
<td>UBA</td>
<td>Umwelbundesamt (Germany’s Environmental Protection Agency)</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UN/ECE</td>
<td>United Nations Economic Commission for Europe</td>
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<tr>
<td>URL</td>
<td>Uniform Resource Locator</td>
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<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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<td>WRMA</td>
<td>Water Resources Management Act</td>
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<td>ZABS</td>
<td>Zambian Bureau of Standards</td>
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<tr>
<td>ZESCO</td>
<td>Zambia Electricity Supply Company</td>
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<tr>
<td>ZMD</td>
<td>Zambian Meteorological Department</td>
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<td>ZRA</td>
<td>Zambezi River Authority</td>
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EXECUTIVE SUMMARY

Availability of accurate data on groundwater quantity and quality is the basis for sound management of groundwater resources. In order to gather these data, groundwater monitoring networks have to be set-up. First efforts in this respect, date back to the mid of the 19th century in England and Wales, yet systematic nationwide groundwater monitoring was not introduced until the period between 1950 and 1980. Only after 1980 systematic groundwater quality monitoring came into place. Yet in many developing countries such coordinated efforts are still absent.

The process of developing groundwater monitoring networks involves a variability of steps from gathering available information and developing a conceptual groundwater model of the area under investigation, defining objectives and type of the network, designing the network, implementing the design, set-up a monitoring plan, gathering and storing the recorded data. Once a suitable amount of measurements has been recorded, e.g. data of several hydrological years, these records can be analysed to evaluate and optimize the existing monitoring network. Hence, the process of developing a monitoring network is iterative. The entire process is presented in a scheme in Appendix A.6.

This report is separated into two parts. The first part gives theoretical considerations about the development of groundwater monitoring networks. The focus lies on the design of the network, the definition of monitoring objectives and network type as well as determining the responsibilities for the monitoring. The remaining of the aforementioned points like the development of a conceptual model or the set-up of a monitoring plan are not discussed in detail. Still, they are also discussed in the second part, which describes the development of a groundwater monitoring network for a study area in the Upper Kafue Sub-catchment, Zambia. This part also includes a preliminary evaluation based on already gathered data, leading to recommendations for the optimization of that network.

The theoretical part of the report first reviews definitions of monitoring. Then, the possible monitoring objectives are summarised. While, to Kresic (2009) the general objective is “to describe groundwater characteristics in space and time”, objectives can be grouped into three categories: Objectives related to the general status of groundwater and trends, objectives related to improved management and support for hydrogeological science and objectives related to protection of groundwater systems and the environment. Every group encompasses several sub-objectives. Also based on the objectives to be served, the monitoring network type has to be chosen. Differentiations can be made according to the size, development stage, parameters observed and the functions served by the network. The network type is one factor determining how is responsible for the monitoring, among the aquifer type, administrative scale and the water legislation in force.

The monitoring network has to not only consider objectives and arising information needs, network type and responsibilities, but also the logistical and financial constraints as well as the hydrogeological framework. The latter summarizes all information about aquifers, groundwater flow, location of recharge and discharge areas as well as water users, hydrochemistry and places of contamination or potential threats. Furthermore, the design has to be coordinated with surface water monitoring efforts, as, for instance, streamflow data allow to set up water balances or to derive baseflows, which serve as indicator for groundwater status and recharge.

The design of the network involves a variety of components. The network scale has to be defined, i.e. which area should be encompassed by the network. Parameters to be monitored have to be specified, both parameters describing quantitative (e.g. water levels, discharge) or qualitative aspects (e.g. chemical and biological parameters). One of the most crucial parts of the design is to determine the type (e.g. boreholes, handpumps, springs, lakes) and distribution of the observation points. Different strategies for the distribution exist. In general, the different factors
like hydrological and hydrogeological setting, land use and (potential) contamination sites have to be taken into account to achieve a suitable representation of the conditions monitored. The number of observations points needed is often determined by financial constraints, yet various recommendations for minimum densities in the literature exist. The same applies for the required observation frequency, which is different for quantitative and qualitative aspects and depends on aquifer type, hydraulic conductivity, recharge amount and groundwater withdrawal, among others.

All aspects of groundwater monitoring network development are exemplified for a study area of the GReSP project in the Upper Kafue Sub-Catchment in Zambia. The Groundwater Resources Management Support Programme (GReSP) is a technical cooperation project between the Zambian and the German government. The current task of the implementing authorities, the Water Resources Management Authority (WARMA) and the German Federal Institute for Geosciences and Natural Resources (BGR), is to develop components of groundwater management plans, which are prescribed by the Zambian Water Resources Management Act of 2011. These components are derived for a study area encompassing the Kafulafuta Catchment and the Mpongwe Karst area in Zambia’s Copperbelt Province and include the installation of a monitoring network.

Coordinated groundwater monitoring is basically absent in Zambia, as only a network of river gauges exists. According to the water legislation, monitoring responsibilities lie with WARMA and especially its sub-ordinate structures like catchment and sub-catchment councils (Appendix A.2). The study area encompasses about 6,880 km², has a temperate-dry winter/hot summer climate with a clear separation of a dry and a rainy season. A geological map is presented in Appendix A.4. The area’s geology is dominated by three granite, quartzite and dolomites/limestones – aquifers typical for large portions of Zambia. The area includes major cities (Ndola, Luanshya) and rural parts (in the districts of Masaiti and Mpongwe). Land use is fragmented and comprises small-scale and commercial farmers, which use groundwater for irrigation, urban, mining and industrial areas (the latter four represent the main water users) while natural vegetation remains occupies only a minor share of the area. The latter is threatened due to rising need for arable land and charcoal due to a growing population and industry.

The main objective of the monitoring network was to obtain basic hydro(geo)logical information of the study area, hence to create an initial regional quantitative reference network. Focus was on quantitative aspects while qualitative aspects were covered by measurement campaigns. The network design included both groundwater and river monitoring. The network scale was determined by the surface water catchments and the main aquifers. Observations points were distributed using a “stratified random sampling” approach, yet only abandoned boreholes or handpumps were used to save installation costs, posing a restriction on the locations available. In total, 9 river monitoring stations and 14 groundwater monitoring stations were chosen. Density of the groundwater network was therefore 1.9 stations per 1,000 km², which corresponded to a “well-developed” observation network. Water levels were measured at hourly interval by data loggers, complemented by occasional discharge and manual measurements (every 2 to 3 months). Gauge readers were employed for the river gauges, measuring three times a day. The network was installed between September and November 2016.

Preliminary evaluation of the gathered data showed that the rivers (Kafulafuta and Kafubu) react very fast to rainfalls in their upper reaches of the catchment and might require higher measurement frequencies during the rainy seasons. Problems were encountered at some very low yielding handpumps, but in general it was found that the use of loggers in handpumps is a suitable and cost-effective way to gather groundwater level data.
In general, the installed network provides basic hydrogeological data. Yet for groundwater management in the two cities of Ndola and Luanshya, special compliance networks with high density observations and a focus on hydrochemistry would be needed. Also specific issues like the continuing impact of deforestation would require additional monitoring efforts. A list of potential locations to be added, both for rivers and groundwater, is given in this report.

To provide suitable data for management, the maintenance of the monitoring network is key. Already in the only two years of operation, several repairs had to be conducted (e.g. replacement of cables or mal-functioning loggers). Since the value of data is strongly impaired by discontinuities in the records, it has to be assured that sufficient resources are made available to facilitate the ongoing operation of the monitoring efforts.
Introduction

Monitoring of groundwater levels and quality provides essential data needed to develop groundwater resources, identify changes in quantity or quality over time and to develop and assess the effectiveness of groundwater management and protection measures, among others. According to Koreimann et al. (1996) and Jousma & Roelofsen (2004) the first networks of water table monitoring were established in England and Wales during the mid-19th century, while the first groundwater quality monitoring network was set up in France in the early 1900s. The U.S. Geological Survey has been collecting water table data for about 120 years (Taylor & Alley 2001). Despite these first efforts, in most European countries and the U.S.A. systematic nationwide monitoring of water levels was not established before the period between 1950 and 1980; systematic groundwater quality monitoring did not start earlier than 1980, and special networks for observing trends in the water quality that may be caused by diffuse pollution sources as a consequence of land use changes were only installed after 1990 (Jousma & Roelofsen 2004). In many developing countries, including several countries in the Southern African Development Community (SADC) region, systematic groundwater monitoring is minimal and still in its early stages. Monitoring in these countries is often limited to development and observation of groundwater resources for the supply to urban areas (IGRAC 2013; Jousma & Roelofsen 2004). Unfortunately, many monitoring initiatives that were initiated by projects or created for the purpose of temporary investigations were not sustained after completion of the respective projects.

During the last 10 to 20 years, several national and international working groups were established to develop guidelines for groundwater observation at regional or national scale with the goal to encourage and establish a systematic and consistent long-term groundwater quantity and quality monitoring. In Europe, guidelines were developed as part of supporting the implementation of the new Water Framework Directive (EC 2003; 2007); in the U.S.A. a sub-committee under the “National Framework for Ground-water Monitoring” published a similar guiding document (ACWI 2011; 2013); in Australia, the Environment Protection Authority produced a guideline to provide for a consistent approach to sample groundwater (Johnston 2007). In South Africa, a toolkit for water service providers and catchment authorities specifying groundwater monitoring procedures was developed under the Department of Water Affairs and Forestry (Ravenscroft & Murray 2004). Previously, a UN task force under the 1992 Convention on the Protection of Transboundary Watercourses and International Lakes established the then state of the art on groundwater monitoring and assessment, and proposed guidelines for monitoring transboundary aquifers (Uil et al. 1999; UN/ECE 2000). Furthermore, the International Groundwater Resources Assessment Centre (IGRAC) carried out a world-wide inventory of groundwater monitoring (Jousma & Roelofsen 2004) and established a working group, which compiled a report on groundwater monitoring for general reference purposes (IGRAC 2008).

The UN Convention on the Protection and Use of Transboundary Watercourses and International Lakes, signed in Helsinki in 1992 (UN 1992) recognizes the need for measurements to foster the ecologically sound management and protection of water bodies, including groundwater, which crosses international borders. The Convention requires, among others, the establishment of programs for monitoring the conditions of transboundary waters (UN 1992).

In recent years groundwater monitoring has gained additional importance in the context of assessing the impacts of climate variability. Just like other hydrological elements such as ice, rivers, lakes and soil moisture, groundwater forms an integral part of the hydrologic cycle and
plays an important role in the variability of climate (WMO 2011). Groundwater resources are related to climate change through recharge processes, governed by the unsaturated zone, or interaction with surface water bodies and hence, cannot be considered in isolation of the regional hydrological cycle. Recognizing that there is a lack of groundwater data around the world, IGRAC initiated the Global Groundwater Monitoring Network (GGMN) in 2007. The network aims to improve in situ monitoring of groundwater resources and is a partner of the Global Terrestrial Network Hydrology (GTN-H).

In total, the literature body about groundwater monitoring is large and the purpose of this report is to summarize the main aspects that have to be considered when developing a groundwater monitoring network. In addition to this theoretical first part, the second part of the report presents the application of these considerations for a case study in Zambia.

**Part A** of this report reviews the state of the art of developing quantitative and qualitative groundwater monitoring networks. The objectives of Part A are (i) to summarize all relevant knowledge and information in the literature and (ii) to provide guidance for developing national and regional groundwater monitoring networks in less developed countries where no comprehensive network exists or where monitoring is scattered or discontinuous. The focus is on the development of national, regional and transboundary monitoring networks, which are designed for the observation of the general status of an aquifer, the identification of general trends or to provide reference values from unaffected areas for comparison. Networks on a local scale which are usually designed for areas that are influenced by interventions (e.g. dropping water levels, pollution) will also be discussed in a general.

**Part B** of this report describes how the theoretical considerations outlined in Part A and visualised in a scheme in Appendix A.6 were applied to a project area in the Upper Kafue Catchment, Zambia. A monitoring network comprising both surface water and groundwater monitoring sites was drafted and installed. Furthermore, preliminary conclusions about the future monitoring in the area are drawn based on a first evaluation of the observations made up to now. An overview of the considerations that were taken into account is given in Appendix A.5.

A summary of standards or technical regulations of measuring and sampling, construction of monitoring points, quality assurance, data processing, analysing and reporting is beyond the scope of this report. A practical overview on these topics was however published by the German Federal Institute for Geosciences and Natural Resources (BGR) in the framework of its technical cooperation in the Arab Region (Margane 2004).
1. DEFINITIONS

Monitoring in general is defined by UN/ECE (2000) as “the process of repetitive observing, for defined purposes of one or more elements of the environment according to pre-arranged schedules in space and time and using comparable methodologies for environmental sensing and data collection. It provides information concerning the present state and past trends in environmental behavior.”

In a similar way the International Organization for Standardization (ISO) (in Bartram & Helmer (1996)) describes monitoring as “the programmed process of sampling, measurement and subsequent recording or signalling, or both, of various water characteristics, often with the aim of assessing conformity to specified objectives”.

IGRAC (2008) defines groundwater monitoring as “the scientifically-designed, continuing measurement and observation of the groundwater situation (including evaluation and reporting procedures)”. According to Uil et al. (1999) groundwater monitoring is “the collection of data, generally at set locations and depths and at regular time intervals in order to provide information which may be used (i) to determine the state of groundwater both in quantitative and qualitative sense, (ii) to provide the basis for detecting trends in space and time and (iii) to enable the establishment of cause-effect relationships”.

2. MONITORING OBJECTIVES

The “underlying” general objective of groundwater monitoring according to Kresic (2009) is “to describe groundwater characteristics in space and time”.

The primary objective of an individual monitoring well is “to provide an access point for measuring ground-water levels and to permit the procurement of representative groundwater samples” (Jousma & Roelofsen 2004).

The following sections provide a summary of objectives of operating groundwater monitoring networks and for what purposes the data collected may be needed. The summary is based on information that can be found in various international publications including but not limited to Koreimann et al. (1996), LAWA (1999a), LAWA (1999b), Uil et al. (1999), UN/ECE (2000), EC (2003), Jousma & Roelofsen (2004), Chorus et al. (2006), EC (2007), IGRAC (2008) and ACWI (2011).

The objectives can be grouped under the following categories, which are, however, interconnected:

− Objectives related to the general status of groundwater and trends,
− Objectives related to improved management and support for hydrogeological science,
− Objectives related to protection of groundwater systems and the environment.

2.1. OBJECTIVES RELATED TO THE GENERAL STATUS OF GROUNDWATER AND TRENDS

Individual objectives under this category include:
i. To provide a general characterization of a groundwater system, i.e. its chemical and quantity status as well as spatial and temporal patterns and variability;

ii. To determine the potentiometric surface and establish the position of groundwater divides and areas of infiltration and seepage, to estimate the direction and rate of flow (including transboundary flow) and detect changes in flow directions and interactions between groundwater and surface water;

iii. To provide background information for classifying the chemical status of groundwater, to assess the state of contamination of a groundwater body, to identify associated contamination risks (large-scale/diffuse or point source) and to determine its suitability for different types of use (i.e. drinking water, irrigation, etc.);

iv. To identify general trends in time in groundwater discharge and storage as well as quality and to assess to which extent they are related (and may respond) to human activities (i.e. groundwater abstraction and land use change) or changes in natural conditions such as climate variability;

v. To gather periodical information on the actual status of groundwater for management or publication (e.g. yearbooks).

2.2. Objectives related to improved management and support for hydrogeological science

Individual objectives under this category include:

i. To provide groundwater data for a sustainable development of the groundwater resources, the assessment of the potential for water supply and the optimization of groundwater withdrawal;

ii. To support an integrated pro-active management of groundwater resources that avoids depletion or contamination of aquifers and helps to control the balance between matters of common interest;

iii. To determine and assess the impact of management and remedial measures and to assist in the design of additional measures;

iv. To provide reference values for detailed investigations, e.g. related to sustainable groundwater usage, protection zoning or construction;

v. To provide data to estimate groundwater recharge;

vi. To meet specific research goals, i.e. to provide inputs for numerical modeling of groundwater flow or contaminant transport;

vii. To allow early-warning, e.g. of the impact of diffuse sources of pollution in recharge areas.

2.3. Objectives related to protection of groundwater systems and the environment

Individual objectives under this category include:

i. To establish the effects on groundwater quality from contamination by diffuse, line or point sources of pollution (e.g. by application of agrichemicals, nutrient impacts, landfills, geological sequestration of carbon dioxide, etc.), and to provide data to avoid contamination during drilling and construction;

ii. To provide data for prevention of unacceptable impacts on surface waters and wetlands and for protection of nature conservation areas from unacceptably declining water tables;

iii. To provide data for control of saline water intrusion or up-coning in aquifers resulting from alteration of flow;

iv. To provide data for control of land subsidence caused by groundwater abstraction.
3. NETWORK TYPES

Unfortunately, the terms developed in the literature to describe monitoring network types such as “regional”, “local”, “primary”, “secondary”, “baseline” and “surveillance” monitoring are not used in a consistent manner. Instead, they are used with sometimes similar but not identical meanings.

The criteria used to distinguish network types include the size of a monitoring network, its development stage, the parameters observed or the various functions a network must fulfil.

3.1. NETWORK TYPES WITH RESPECT TO ITS SIZE

With respect to the size of a network large “regional” networks covering aquifers of large regional size (including “sub-national”, “national” and “transboundary” aquifers) can be distinguished from “local” networks designed for specific requirements at local scale (including networks around well fields and pollution sites) (IGRAC 2008). Local and regional networks are often combined to a wide-spaced regional network with denser-spaced parts in areas of particular interest (Jousma & Roelofsen 2004).

3.2. NETWORK TYPES WITH RESPECT TO ITS DEVELOPMENT STAGE

With respect to the development stage of a monitoring network Van Bracht (2001, in Margane (2004)) distinguishes between “pilot/extended pilot” networks, “final” networks and “optimized final” networks. In a comparable way the reports by Jousma & Roelofsen (2004), IGRAC (2008) and ACWI (2013) emphasize the need of “initial” or “baseline” monitoring for up to 5 years during which information regarding groundwater characteristics is scarce. Pilot networks aim at an initial description of water levels and quality and their natural variability and at a preliminary assessment of the regional characteristics and potential of aquifers. Once baseline data are gathered, the monitoring network can be evaluated and optimized. A broad range of optimization approaches can be used for this purpose (Mishra & Coulibaly 2009).

3.3. NETWORK TYPES WITH RESPECT TO PARAMETERS OBSERVED

With respect to the observed parameters quantitative networks focusing on variations of water level and discharge in space and time are distinguished from networks for monitoring groundwater quality (e.g. EC (2007)).

3.4. NETWORK TYPES WITH RESPECT TO ITS FUNCTIONS

It is essential that a network is “tailor-made” to the information needs, and observation points are linked to the objectives and requirements defined by groundwater management (Mäkelä & Meybeck (1996), Timmerman & Mulder (1999), Jousma & Roelofsen (2004)). It therefore makes sense to define network types with respect to the functions the network needs to fulfil. The terminology used below to distinguish networks with respect to their functions mainly follows the proposals by Uil et al. (1999) and Kresic (2009).

i. “Basic/reference” monitoring refers to networks, which are designed to establish background or enhance existing water quality and quantity data such as water levels and discharge of regional water resources, and to collect continuous data to enable determination of long-term natural trends or the effect of slowly changing anthropogenic activities. Other terms used for such a network or a network with similar functions include “ambient” (Bloomfield 2000; Kresic 2009), “background” (Van Lanen 2004), “strategic” (Uil et al. (1999), UK Environmental Agency (2006))
“primary” (IGRAC 2008), and “surveillance” (ACWI 2013; EC 2007) network. The report by ACWI (2013) further distinguishes between networks in aquifers under “unstressed (background)” conditions, for monitoring points located in undisturbed portions of aquifers, and “targeted” areas, for monitoring points located in areas that are undergoing slow changes in groundwater or land use.

ii. “Compliance” monitoring is needed to assess whether groundwater use complies with existing regulation and standards. It is usually linked to a specific purpose and aquifers considered at risk, e.g. to measure concentrations of pollutants near facilities where groundwater contamination has occurred, to assess the risk of suspected sources of contamination or the effectiveness of remedial measures. For similar network types the terms “regulatory” (Ravenscroft & Murray 2004), “operational” (EC 2007), and “special studies” (ACWI 2013) or “specific” (Van Lanen 2004) network were used.

iii. “Early warning” or also termed “sentinel” monitoring networks are built upstream of a water production well or spring capture and are used to provide early warning against pollution of drinking water where accidental spills or hazardous waste could harm drinking water quality. Some consider early warning a special type of compliance monitoring.

iv. “Performance” monitoring refers to measuring quantity and quality associated with water supply pumping and remediation on a regular basis.

It should be added that basic/reference monitoring networks usually correspond to regional networks whereas compliance, early warning and performance monitoring can be considered special studies with monitoring at local scale around well fields or contamination sites.

4. RESPONSIBILITIES

The principal obligations to monitor groundwater use are usually laid down in the national water legislation. Detailed requirements of a monitoring network that should also include coordination of data gathering, interpretation and storage are often contained in subsidiary legislation or technical standards and guidelines (Mechlem 2012).

The type and spatial scale of the aquifers influence the relative administrative scale of groundwater management – from private to international level - as illustrated in Figure 1. However, administrative scale might also differ with the size of a country.

The overall responsibility for monitoring activities supporting groundwater management and the supervision of delegated tasks lies in the hands of the competent central (national or regional) governmental institution. With respect to water quality protection, this is often the Ministry of Health, Ministry of Environment and Natural Resources or a national environmental protection agency. The Ministry of Water or a national water resources management authority is usually responsible for water resources management, which includes surveillance of sustainable use of groundwater and monitoring of groundwater development.
Irrespective of which specific state institution has been granted the legal authority for overseeing groundwater monitoring, it is crucial that the function of supervision and regulatory compliance is strictly separated from the function of controlling the safety and quality of water supplied, and that both are performed by separate independent entities because of conflict of interests that may arise when they are combined (WHO 2008; 2014). The surveillance agency is responsible for monitoring of compliance with supply service standards regarding quality and quantity, and should be given necessary powers to enforce laws and regulations. Water utility companies are responsible at all times for the quality of the water they supply and liable for failure in quality. State institutions are usually in charge of basic/reference and compliance monitoring while water utilities and developers are responsible for performance monitoring. However, performance monitoring has to be supervised by state institutions by providing guidelines, certifying laboratory standards and, if necessary, check measurements. Monitoring by the water administration and large water utilities should be complemented by information provided by well owners on their abstractions (Mechlem 2012). Table 1 provides a typical division of responsibilities of state institutions and private entities for common tasks related to groundwater monitoring.
Table 1: Division of responsibilities for groundwater monitoring (modified after IGRAC (2008) and Kresic (2009))

<table>
<thead>
<tr>
<th>Requirement, Task</th>
<th>Function (Network Type)</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline or reference groundwater monitoring or monitoring of trends at national and regional (basin) levels</td>
<td>Basic/reference monitoring</td>
<td>Central Government or National Water Authority Regional Government or Basin Authority</td>
</tr>
<tr>
<td>Collection of data to meet specific research goals</td>
<td>Research monitoring</td>
<td>Project teams commissioned by research institutions</td>
</tr>
<tr>
<td>Monitoring of effluents</td>
<td>Compliance or early-warning monitoring</td>
<td>Central Government (but paid for by operator) or operator under supervision/surveillance of regulatory or local authority</td>
</tr>
<tr>
<td>Monitoring of spills at site level</td>
<td>Compliance or early-warning monitoring</td>
<td>Central Government (or ordered by Government and paid by polluter); in case of diffuse pollution paid and conducted by Central Government</td>
</tr>
<tr>
<td>Monitoring of saltwater intrusion near abstraction areas</td>
<td>Compliance or early-warning monitoring</td>
<td>Central Government, the company over-abstracting could be made accountable</td>
</tr>
<tr>
<td>Monitoring of compliance with drinking water standards at sentinel wells near large water supply wells</td>
<td>Early-warning monitoring</td>
<td>Water utility company or respective large groundwater developer*</td>
</tr>
<tr>
<td>Monitoring of metered groundwater abstraction and drawdown of well fields</td>
<td>Performance monitoring</td>
<td>Water utility company or respective large groundwater developer*</td>
</tr>
<tr>
<td>General feedback on abstraction from small developments</td>
<td>Performance monitoring</td>
<td>Small groundwater developer (utility) or commercial farm*</td>
</tr>
</tbody>
</table>

* Monitoring has to be supervised by respective state institution(s).

5. **NETWORK DESIGN**

5.1. **GENERAL CONSIDERATIONS IN DEVELOPING A GROUNDWATER MONITORING PROGRAM**

Designing a monitoring program is a complex process and usually involves an iterative procedure (IGRAC 2008). According to the European Environmental Agency (EEA 2008) and Johnston (2007) considerations to be included in the development of a groundwater monitoring program comprise the monitoring objective, the hydrogeological setup (type and complexity of main aquifers), the spatial extent of existing or expected impacts of withdrawals or pollution, existing monitoring systems, the precision and accuracy required to reach the objectives as well as logistical and cost aspects (Figure 2).
Figure 2: Development of a monitoring plan according to Johnston (2007).

Essentially all existing guidelines emphasize that the monitoring objectives and resulting information needs must be carefully analysed and identified. It is furthermore recommended to clearly link functions of individual observation points to the various objectives and data requirements defined by the groundwater monitoring program (Jousma & Roelofsen 2004).

For the continuity of a monitoring program, it is considered critical that the collected data is useful and tailored to management requirements. To quote just one example of this, there would be no particular merit in frequent groundwater sampling for analysis of major ions once the baseline aquifer quality has been established (Morris et al. 2003).

Regarding available resources and costs it may be necessary to prioritize monitoring activities. The prioritizing requires the identification and assessment of threats such as potential pollution sources, areas of over-exploitation or land subsidence. The prioritizing of quality networks could be achieved by making use of risks assessments which may be in parts derived from aquifer vulnerability maps (IGRAC 2008). For quantitative networks, the various uses and functions of groundwater (e.g. drinking water supply, agricultural use, industrial use, conservation of wetlands and minimum baseflow, etc.) should be identified and subsequently, the risks and possible damage regarding the preservation of these functions evaluated.

Estimated abstraction volumes, expected three-dimensional extent of drawdown and population density are among the factors that should be considered in a risk assessment. The final prioritization could be achieved by establishing functions and risk tables to define whether the issues are in conflict with the functions of the groundwater systems (Chave et al. 2006; UN/ECE 2000).

The preliminary characterization of the hydrogeological framework and the conditions of groundwater flow is regarded an essential major precondition for the development of a monitoring program according to the relevant literature (e.g. Bloomfield (2000), UN/ECE (2000), Jousma & Roelofsen (2004), EC (2007), Kresic (2009)).

Regarding hydro-geochemistry knowledge about the dominant geochemical processes, the natural or background situation, aquifer vulnerability as well as threats from actual or potential pollution sources should be gained in the course of developing a monitoring program. Furthermore, it is useful to evaluate - to the extent that existing data permit - water-level trends or seasonal fluctuations, local hydrological influences such as abstractions, the variability in natural geochemical conditions and the behavior of pollutant(s).
In addition, criteria related to logistics and the specific local conditions such as accessibility, ownership, required protective measures, and the availability of an observation point over a long enough period need to be considered.

5.2. COMPARISON OF GROUNDWATER WITH CLIMATE/METEOROLOGICAL MONITORING

As groundwater takes part in the hydrological cycle and plays an important role in the variability of climate, general concepts of climate monitoring may - to some extent - also be applicable to regional monitoring of groundwater volumes. Compared to the fields of hydrology/hydrogeology global cooperation is much more advanced in meteorology as meteorological processes are mostly on a global scale and require standardized international coordination whereas most hydrological tasks arise on a catchment scale. The World Meteorological Organization’s (WMO) guidance on climate observations, networks and stations is among others based on the ten climate monitoring principles (WMO/TD-No.847, in WMO (2011)). The ten principles are included in Appendix A.1 of this document. Principles no. 2 and 5 to 7 are unrestrictedly valid for groundwater monitoring as well:

- “A suitable period of overlap for new and old observation systems is required” (Principle no. 2).
- “Consideration of the needs for environmental and climate monitoring products and assessments should be integrated into national, regional and global observing priorities” (Principle no. 5).
- “Operation of historically uninterrupted stations and observing systems should be maintained” (Principle no. 6).
- “High priority for additional stations should be focused on data poor areas, poorly observed parameters, areas sensitive to change and key measurements with inadequate temporal resolution” (Principle no. 7).

It has been stated that at least ten years of daily observations are necessary to produce the relevant statistical parameters for most meteorological elements, and at least thirty years for precipitation (WMO 2011). Due to the slow movement in groundwater with relatively large residence times, the storage behavior of groundwater reservoirs, and the considerable degree of chemical interaction between water and aquifer material (EEA 2008), groundwater levels and quality, however, behave overall less erratically and hence have statistical properties that are quite different to, for instance, rainfall. Nevertheless, time series over a duration of not less than 10 years and sometimes up to several decades are required to compile hydrological records of groundwater level fluctuations which enable a reliable estimation of the potential range of water-level fluctuations in an observation well and to track long-term trends with time Taylor & Alley (2001).

Finally, it is worthwhile to take a look at minimum requirements of meteorological networks regarding the network density and spacing of observation points. According to the WMO Guide to Climatological Practices (WMO 2011), the density of a “Regional Basic Synoptic Network” (for the provision of average monthly climatological data) should not be less than 1 to 10 stations per 250,000 km², and stations of such a network should have a maximum average separation of not less than 500 km. Compared to existing groundwater networks in western states, however, this represents a very low network density (Chapter 5.4.4). In connection with requirements towards the implementation of the meteorological Global Observing System (GOS) it was acknowledged that the interval between surface synoptic stations should not exceed 250 km, or 300 km in sparsely populated areas (Bojinski 2010; WMO 2010-2017). WMO technical regulations (WMO 1988) require that the minimal horizontal resolution of surface stations should be between 100 km (e.g. for temperature and
5.3. RELEVANCE OF SURFACE WATER MONITORING FOR GROUNDWATER MONITORING (AND VICE VERSA)

Surface water and groundwater bodies are mutually interlinked and their monitoring has to be considered in an integrated way. Groundwater can sustain large portions of streamflows, especially in rain-free periods, and is often connected to standing surface waters like lakes and reservoirs. Monitoring of surface waters can therefore allow drawing conclusions on the groundwater status. Deep and fossil aquifers might present an exception as they operate on a time scale that strongly differs from those of other water cycle components.

Both surface water and groundwater are typically assessed on catchment basis, for which a water budget can be formulated as (cf. Healy (2010))

\[
P + Q_{i,sw} + Q_{i,gw} = ET + \Delta S + Q_{o,sw} + Q_{o,gw}
\]

(1)

where \(P\) is precipitation (including irrigation), \(ET\) is actual evapotranspiration, \(\Delta S\) is water storage change, and \(Q_{i,sw}\) and \(Q_{i,gw}\) are surface and groundwater flow into the catchment, respectively. Likewise \(Q_{o,sw}\) and \(Q_{o,gw}\) are surface and groundwater flow out of the catchment, respectively. All components refer to rates, typically given as mm per time unit, where mm equals liter per m². Over longer time periods (i.e., several years) \(\Delta S\) is commonly assumed to vanish. For periods in which it has to be considered, it can be divided into sub-components like storage change in surface water bodies (\(\Delta S_{sw}\)), groundwater (\(\Delta S_{gw}\)) and the unsaturated zone (\(\Delta S_{uz}\)) (Healy & Cook 2002). As water budgets are mostly set up based on surface water catchments, \(Q_{i,sw}\) should, by definition, be zero except for artificial (piped) inter-basin water transfers. \(Q_{o,sw}\) is the catchment runoff, being the sum of runoff generated by rainfall and baseflow (\(Q_{bf}\)), which is defined as the groundwater component of stream flow drained from adjacent aquifers. Baseflow can be an important or even the only contribution to streamflow, especially during droughts or seasons without rainfalls. The baseflow is also of importance for estimating groundwater recharge of a catchment based on the water budget

\[
R = Q_{o,gw} - Q_{i,gw} + Q_{bf} + ET_{gw} + \Delta S_{gw}
\]

(2)

where \(ET_{gw}\) is the evapotranspiration sustained by groundwater and \(Q_{o,gw} - Q_{i,gw}\) is the net subsurface flow from or to the study area, which includes abstractions by pumping (Healy & Cook 2002). In case the remaining terms on the right-hand side of Equation 2 are very small, baseflow allows drawing conclusions on the groundwater recharge.

Considerations of the design of river monitoring networks differs from those of groundwater monitoring networks. For instance, river gauges should be positioned close to the outlets of catchments or sub-catchments in order to be representative for most parts of the area. In selecting a proper site, different criteria have to be taken into account (e.g. no flow obstacles, straight stream reach) (Rantz & others 1982a; b; WMO 2010). In comparison to groundwater levels, accessibility of the site might be of higher importance as regular discharge measurements have to be done to generate a rating curve (i.e. a relationship between water level and discharge). In addition, river water levels require higher measurement frequencies as they react much faster to meteorological boundary conditions than groundwater levels.

Groundwater monitoring points should be located close to surface water gauges, as comparing both water level measurements can serve as indicator for the interaction between groundwater and surface water. Flow can be either directed towards the river (i.e.
exfiltration of groundwater) or towards the groundwater (i.e. infiltration of surface water). The flow direction might change during the seasons or as consequence of massive groundwater abstraction in the vicinity of the river. Quantifying this flow by one of available approaches (Kalbus et al. 2006) might be important to estimate the water budget.

5.4. GROUNDWATER MONITORING DESIGN COMPONENTS

The design of monitoring networks that are representative for a groundwater body includes the following components (ACWI 2013; UN/ECE 2000):

- The identification of aquifers to be monitored, which determines the scale of the network;
- the determination of the location (distribution), in three dimensions, of observation points within aquifers;
- the selection of types of observation and sampling points included in the network;
- the specification of the network’s spatial density;
- the specification of monitoring time frames and observation/sampling frequency;
- the choice of measured parameters and water-quality analytes.

All design components of a monitoring network depend on the objectives pursued, the hydrogeological situation and, as a matter of fact, on the available resources. All nationally important aquifers should be observed, including aquifers not being used at the time (EEA 2008). As pointed out by Chilton & Foster (1996) the location and density of observation points will largely depend on the complexity of the hydrogeological situation, the lithology, aquifer distribution and land use patterns whereas the sampling frequency will be mainly determined from flow velocities, residence times and seasonal influences (i.e. hydrology). The choice of the parameters to be observed will be largely dependent on dominant geochemical processes, water quality issues and statutory requirements (Table 2).

Table 2: Main factors determining the network design (after Chilton & Foster (1996))

<table>
<thead>
<tr>
<th>Design component</th>
<th>Type, location and density of observation points</th>
<th>Observation frequency</th>
<th>Choice of determinants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major controlling factors</td>
<td>Objective pursued (network type)</td>
<td>Objective pursued (network type)</td>
<td>Objective pursued (network type)</td>
</tr>
<tr>
<td></td>
<td>Hydrogeology (complexity)</td>
<td>Hydrogeology (residence time)</td>
<td>Hydrogeology (geochemical processes)</td>
</tr>
<tr>
<td></td>
<td>Lithology (aquifer distribution)</td>
<td>Climate/hydrology (seasonal variations)</td>
<td>Water quality issues</td>
</tr>
<tr>
<td></td>
<td>Land use</td>
<td>Costs</td>
<td>Statutory requirements</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td></td>
<td>Costs</td>
</tr>
</tbody>
</table>

It should be mentioned that in the literature (e.g. Uil et al. (1999), UN/ECE (2000)) the design of a groundwater monitoring program is sometimes defined in a broader sense and may include e.g. well construction requirements, comparable field methods and protocols (SOPs), laboratory standards, definition of agreements between data providers, and a data and geo-information management systems that allow access to data.
5.4.1. **NETWORK SCALE**

It is generally accepted that monitoring programs for surface water and groundwater monitoring networks should be designed and operated in an integrated way, based on river basin boundaries and tailored to the specific needs of each aquifer (ACWI 2011; EC 2007; UN/ECE 2000). Monitoring network boundaries should therefore be oriented along surface water or (if known) groundwater catchment boundaries rather than administrative boundaries. The total scale of a regional or transboundary network is therefore usually determined by the size of the river basin, the groundwater flow system or aquifers of interest. Local networks should as far as possible be delineated along other suitable hydraulic boundaries. Their dimension is site-specific and depends on the zone of impact of an identified threat (e.g. over-abstraction, pollution, saline intrusion).

5.4.2. **PARAMETERS**

Monitoring of **groundwater quantity** may incorporate the observation of:

- Groundwater levels
- Lake levels (stage)
- Stage/discharge of springs
- Baseflow (stage/stream flow)
- Discharge of pumping wells

Groundwater levels are “the principal source of information about the hydrological stresses acting on aquifers and how these stresses affect groundwater recharge, storage and discharge” (Taylor & Alley 2001). Lake levels, baseflow and spring discharge are parameters that describe the discharge from a groundwater body. Baseflow can be indirectly determined from stream flow records using baseflow recession analysis (for a collection of such approaches, refer to Healy (2010)). If pumping rates are not observed it can be often estimated by recording the time of pumping and by multiplying it with the estimated net capacity of the pump. For agricultural areas, the area under cultivation and specific crop water requirements may be used to get reasonable estimates of abstraction.

Monitoring of **groundwater quality** is achieved by collecting water samples and measuring field parameters at wells or springs. The list of possible parameters to be observed is extensive. The determinants may be divided into the following groups:

- Field (physic-chemical) parameters such as temperature (T), electric conductivity (eC), pH, oxygen reduction potential, dissolved oxygen (DO)
- Major ion chemistry
- Minor ions (e.g. fluoride, iron, boron)
- Nutrients
- Microorganisms (total coliforms (TC), faecal coliforms (FC))
- Heavy metals and trace metals
- Radioisotopes
- Organics (hydrocarbons, detergents, organic solvents, explosives, herbicides/insecticides)

During a general reconnaissance of water quality (including water types and first indications of contamination) physico-chemical parameters, major ions and a few selected minor ions (e.g. iron, manganese, phosphate) are investigated. Physico-chemical parameters, major ions and nutrients (nitrate, ammonium) are the most commonly measured parameters followed by specific minor ions, microbial indicators (coliforms), common heavy metals (e.g. lead, zinc, caesium, nickel, mercury, chromium), and organic substances including chlorinated solvents.
and pesticides (Uil et al. 1999). For water quality monitoring the European Water Framework Directive requires the measurement of a core set of parameters including DO, pH, eC, nitrate and ammonium, but obviously additional parameters need to be considered based on the purpose of monitoring and the identified pressures and pollution risks (EC 2003). Table 3 contains a non-exhaustive list of common pollution sources together with typical contaminants of concern that should be observed under a monitoring program.
<table>
<thead>
<tr>
<th>Type of site</th>
<th>Problem(s) identified:</th>
<th>Contaminants of concern and/or parameters to be observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acidification</td>
<td>Salinisation</td>
</tr>
<tr>
<td>Mines</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Carbon capture and storage</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Coastal aquifers, aquifers near saline/brackish layers/zones</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Urban areas, traffic lines</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Commercial farms</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Orchards</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Livestock/dairy farm</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Municipal waste water plant</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Leach fields and septic systems</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Industrial waste water plants</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Landfills</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Gas stations, gas storage tanks</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Heating oil tank</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Petroleum refineries</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Metal refineries</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Dry cleaners</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Airport</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Common groundwater pollution sources and the associated indicators or contaminants of concern (after Chilton & Foster (1996), UN/ECE (2000), EC (2003) & Kresic (2009))
<table>
<thead>
<tr>
<th>Type of site</th>
<th>Problem(s) identified:</th>
<th>Contaminants of concern and/or parameters to be observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail switching yard; rail tracks</td>
<td>✓ ✓ ✓</td>
<td>TPH, PAH, VOC, pesticides</td>
</tr>
<tr>
<td>Quarry</td>
<td>✓</td>
<td>VOC, HMX, RDX, TNT, perchlorate</td>
</tr>
<tr>
<td>Nuclear power plant</td>
<td>✓</td>
<td>Tritium, strontium, caesium</td>
</tr>
<tr>
<td>Thermal power plant</td>
<td>✓ ✓ ✓</td>
<td>PAH, TPH, metals, dioxin</td>
</tr>
<tr>
<td>Military ranges</td>
<td>✓ ✓ ✓</td>
<td>HMX, RDX, TNT, metals (lead), perchlorate</td>
</tr>
<tr>
<td>Machinery shops</td>
<td>✓ ✓ ✓</td>
<td>VOC, SVOC, metals</td>
</tr>
<tr>
<td>Wood treatment/preserving plants</td>
<td>✓ ✓ ✓</td>
<td>PAH, VOC, SVOC</td>
</tr>
<tr>
<td>Paper mill</td>
<td>✓ ✓ ✓</td>
<td>PAH, metals, dioxin</td>
</tr>
<tr>
<td>Automated car washes</td>
<td>✓ ✓ ✓</td>
<td>TPH, PAH, VOC</td>
</tr>
<tr>
<td>Chemical manufacturing plant</td>
<td>✓ ✓ ✓</td>
<td>Chemical specific, e.g. cyanide, VOC, SVOC (solvents)</td>
</tr>
<tr>
<td>Waste incineration, combustion</td>
<td>✓ ✓ ✓</td>
<td>Dioxin</td>
</tr>
<tr>
<td>Manufacturing gas plant</td>
<td>✓ ✓ ✓</td>
<td>PAH, metals, TPH</td>
</tr>
</tbody>
</table>

Abbreviations: BTEX = benzene, toluene, ethylbenzene, and xylenes, DBP = Disinfection byproducts, DO = Dissolved oxygen, eC = Electrical conductivity, FC = Faecal coliforms, HMX = hexahydro-1,3,5-trinitro-1,3,5-triazine, PAH = polynuclear aromatic hydrocarbons, PCB = polychlorinated biphenyls, RDX = octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine, SVOC = Semi-volatile organic carbons, T = temperature, TC = Total coliforms, TDS = Total dissolved solids, TNT = 2,4,6-trinitrotoluene, TOC = Total organic carbon, TPH = total petroleum hydrocarbons, VOC = Volatile organic carbons

In order to reduce the number of determinants in a routine monitoring program it is often essential to identify chemical indicators of rapid environment change that are typical for a type of pollution (Chilton & Foster 1996; EC 2003; IGRAC 2008). Such indicators, however, are sometimes not easy to choose. Electrical conductivity (eC) and chloride could be an early indicator for industrial and urban emissions or saline intrusions, nitrate, phosphate and dissolved organic carbon for agricultural impacts, total and faecal coliforms for pathogens, pH for acidification and oxygen and oxygen reduction potential for general changes of the geochemical milieu. Certain ion ratios or isotopes may also be useful as indicators for the detection of changes in geochemical processes or pollution depending on the problem being addressed.
5.4.3. TYPES, LOCATION AND DISTRIBUTION OF OBSERVATION POINTS

General considerations regarding the location and types of observation points

Due to the strong correlation of water tables in shallow aquifers and rainfall, it is generally advisable to build groundwater observation points (boreholes, piezometer) near rainfall gauges. Obviously, groundwater observation points should be close to existing stream gauges if surface water – groundwater interaction is to be studied. From a cost-effectiveness point of view, it may also make sense to combine water level and water quality monitoring at one site. However, as pointed out by Uil et al. (1999), groundwater levels have a relatively strong spatial coherence, but relatively large fluctuations whereas groundwater quality may vary strongly over relatively short distances and are less variable in time. It therefore appears advisable to carry out groundwater quality investigations by less frequent sampling of a higher density network (Chilton & Foster 1996). Furthermore, groundwater sampling points have to fulfil higher technical requirements, especially because of vertical variations in contaminant contents.

Springs and active production wells may be used in order to obtain groundwater samples. Springs in particular can provide representative data for catchments. Sampling points should yet not exclusively comprise drinking water abstraction points, as this would usually not yield results representative for the whole catchment (EEA 2008). In the absence of alternatives, water level measurements in active production wells can be taken under the condition that pumping can be stopped for the period of recovery of the groundwater level. For well performance monitoring or for the purpose of developing groundwater models, water level measurements during pumping operations are indispensable provided that abstraction rates (including pumped wells in the vicinity) are monitored at the same time.

Distribution of observation points

ACWI (2013) recommends applying a “stratified random sampling within blocks” as the general design for distributing monitoring sites. This approach is represented by a combination of picture (b) and (d) in Figure 3. According to the report stratified random sampling generates more precise estimates of population statistics (e.g. of a pollutant such as nitrate) than (non-stratified) random sampling. The sub-division of each identified stratum into grids (blocks) can help preventing clustered distribution of monitoring wells. The strata could represent aquifers or different zones (e.g. specific land uses) within an aquifer. If layered (deeper) aquifers systems exist they need to be treated separately.

![Figure 3: Probability design for spatial monitoring (from ACWI (2013), p 27).](image-url)
Apart from this generally applicable probability approach, specific factors have been identified that need to be considered in the process of distributing monitoring points in a target area, including:

i. The network type and associated monitoring objectives;

ii. The hydrological and hydrogeological characteristics such as different climate zones, altitude and topography (mountainous, hilly, plain) and associated surface water drainage, position within groundwater catchment (recharge with predominant downward directed flows, through-flow or discharge zones with upward directed flow), type of confinement (confined/unconfined), presence of stratified (3-D) aquifer systems, changes in aquifer lithology (unconsolidated, consolidated sedimentary, volcanic, basement & intrusive, karst), aquifer zones or hydrogeological units (based on hydrogeological map) and their respective relevance for water development, aquifer vulnerability combined with identified potential high threats for health and environment; In general, areas with a high rate of recharge should be monitored more intensively;

iii. Current or predicted land use and groundwater exploitation, e.g. areas for which total abstraction exceeds estimated groundwater recharge and estimated stored volume, and hence conflict situations (trends) with respect to water supply, groundwater-fed springs or ecosystems are predicted, areas that are or could be negatively affected by salinisation or land subsidence due to pumping, or areas that are experiencing deterioration of water quality due to diffuse pollution sources from intensive agriculture or urban waste and sanitation.

iv. Contamination sites (point or line sources)

Due to the complexity of monitoring objectives and site specifications, it is difficult to develop precise guidelines for the selection of observation point locations within a monitoring network. Table 4 contains some typical criteria for the positioning of groundwater observation points for different network types and monitoring objectives. Chilton & Foster (1996) and Jousma & Roelofsen (2004) propose to develop some kind of classification or ranking system that incorporates aspects such as the hydrogeological, land use and other characteristics of an area together with identified challenges regarding groundwater utilization. The ranking system defines the need and suitability of monitoring sites. Part of the planning process hence is to make all relevant information available, enabling a zoning of the target areas, and a ranking of monitoring needs and costing of available options. This would allow identifying the monitoring needs systematically. No substantial monitoring for instance may be required in areas with local patches of shallow aquifers, such as in weathered zones of basement terrains (IGRAC 2008).

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Monitoring objective</th>
<th>Proposed positioning of observation point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic/reference monitoring</td>
<td>Determination of general/natural status of groundwater reservoir (Quantity and quality)</td>
<td>Locations with negligible anthropogenic influences (forests, natural parks, non-fertilized grassland and fallow land) Relatively even distribution of observation points; usually in areas of near-horizontal groundwater flow or near zones of groundwater discharge into streams or springs; Stream gauging for determination of baseflow</td>
</tr>
</tbody>
</table>

Table 4: Criteria for the positioning of groundwater observation points for different network types and monitoring objectives (after LAWA (1999a), supplemented)
<table>
<thead>
<tr>
<th>Network Type</th>
<th>Monitoring objective</th>
<th>Proposed positioning of observation point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Identification of long-term trends in water levels or deterioration of water quality due to climate change or diffuse pollution sources</td>
<td>Preferably located near the downstream end of the catchment area; Springs that are unaffected by direct anthropogenic influences are suitable points for water quality monitoring of respective catchment.</td>
</tr>
<tr>
<td>Compliance monitoring</td>
<td>Determination of groundwater pollution from agriculture</td>
<td>Predominantly in groundwater recharge areas; in addition, specific land use differences should be taken into account</td>
</tr>
<tr>
<td></td>
<td>Determination of groundwater pollution from industrial areas</td>
<td>Mainly surface-near observation points in unconfined aquifers</td>
</tr>
<tr>
<td></td>
<td>Determination of groundwater pollution from urban (built-up) areas</td>
<td>Mainly surface-near observation points in downstream direction from the industrial sites and additionally in the direction of predominant wind direction if airborne pollution dispersion occurs</td>
</tr>
<tr>
<td></td>
<td>Determination of groundwater pollution from roads, railway tracks or surface streams</td>
<td>Mainly surface-near observation points both within and in downstream direction of built-up areas; quality monitoring at different depths is essential in case of density driven flow</td>
</tr>
<tr>
<td></td>
<td>Determination of groundwater pollution from point sources (e.g. landfills)</td>
<td>Surface-near wells located in the immediate vicinity and downstream of presumed infiltration areas</td>
</tr>
<tr>
<td>Early warning</td>
<td>Early recognition of risks (sentinel well)</td>
<td>In areas vulnerable to pollution or areas where potential pollution sources have been identified; Upstream but at sufficient distance to production well or spring capture; along a line perpendicular to the general groundwater flow direction</td>
</tr>
<tr>
<td>Performance monitoring</td>
<td>Surveillance of water quality and drawdown around groundwater supply wells</td>
<td>Selection from mainly existing wells, springs, galleries used for public water supply</td>
</tr>
</tbody>
</table>

### 5.4.4. NUMBER AND DENSITY OF OBSERVATION SITES

Owing to the different monitoring purposes and the complexity of hydrogeological conditions, there is no general answer to the question how many observation sites are needed. Uil et al. (1999) state that “the density of a network has to fulfil the monitoring objectives as far as possible”, and that a sufficient number of observation sites need to be installed at appropriate locations and depth to make sure that “the characteristics of the identified zone, e.g. geohydraulic unit, (is) represented”. The EU Water Framework Directive (EC 2000) stipulates under paragraph 2.2 that “the network shall include sufficient representative monitoring points [and monitoring frequency] to estimate the groundwater level in each groundwater body or group of bodies taking into account short and long-term variations in recharge” and
“to assess the impact of abstractions and discharges on the groundwater level”. Furthermore, “the monitoring network shall be designed so as to provide a coherent and comprehensive overview of groundwater chemical status within each river basin and to detect the presence of long-term anthropogenically induced upward trends in pollutants”.

In general, the required density mainly depends on the following three factors:

i. The network type and associated monitoring objectives;
ii. The degree of spatial variability of the parameter(s) of concern (i.e. water level, pollutant), which is often related to
iii. The hydrogeological and hydrochemical complexity of the groundwater system.

The following examples can illustrate this:

Widely spaced networks are usually sufficient for regional basic/reference networks whereas closely spaced networks are specially designed for compliance or performance networks; Pollutant concentrations (e.g. microbial contamination, nitrate contents) may vary considerably with space and depth; Groundwater levels in confined aquifers are often representative for large areas whereas the spatial variability of the groundwater table in shallow karstic environment is usually much higher.

The literature provides relatively few concrete recommendations regarding network density. The IGRAC expert team (IGRAC 2008) reckons that in deep, large confined aquifers monitoring of groundwater levels with a density of 1 well per 25 km² to 100 km² may be appropriate. Locations in the upper part of catchments (recharge areas) are considered often more useful. Denser networks are typically in the range 1 well per 10 km³ to 25 km³. For shallow aquifer systems, an even higher density may be required. Typically, the required density in unconfined aquifers may be 3 to 4 times higher compared to the underlying confined or semi-confined deeper aquifer to give the same spatial accuracy. The team furthermore suggests combining monitoring at an acceptable number of representative monitoring wells, preferably located in the upper recharge zones of a catchment, with monitoring of spring flow and baseflow. The EEA states that at least 1 site per 20 to 25 km³ should be established for all main aquifers and only in special cases a lesser density is acceptable (EEA 2008). LAWA (1999b) gives an example for an optimized water-level monitoring network for the state of Brandenburg in Germany. Accordingly, 4 and 1.7 observation sites per 100 km² of aquifer are considered adequate for Pleistocene water table aquifers and older quaternary confined aquifers, respectively. According to EC (2007) there should be, as a general rule, a minimum of three points in a groundwater body or group of bodies that are considered “not at risk” if the confidence in the risk assessment is considered “low”. A (unspecified) higher number of sites is required for bodies considered “at risk”, a lower number may be sufficient for bodies that are “not at risk” and for which the confidence in the risk assessment is “high” (e.g. monitoring of natural background and trends). ACWI (2013) presents two different principal approaches for determining the number of water quality monitoring sites: (a) a set minimum number of monitoring sites, ideally a sample size of 30, or (b) a prescribed spatial density of one well per 100 km² of aquifer. The first demands a relatively great amount of effort for small areas while the latter would lead to an unrealistic number of wells for large aquifers. Therefore, the final network design would in most cases be a combination of the two approaches. Finally, if the parameter to be studied is spatially variable but the investigation area is large, a pilot study area that could be “indicative” (IGRAC 2008) for the overall behavior of the system with respect to stress or diffuse pollution sources should be selected, and specially designed local networks of adequate density could be designed (typical for shallow flow systems).
Geostatistical methods provide a tool to optimize network densities. This usually involves an assessment of the accuracy of spatial interpolation using a variogram analysis. Van Lanen (2004) provided a valuable summary on this topic.

Table 5 contains examples of the largely differing densities of networks operated in the U.S., Australia, Europe and SADC countries. In general, network densities in countries that cover a large geographical area are commonly lower than in (small) city states.

<table>
<thead>
<tr>
<th>State/Country</th>
<th>Network scale</th>
<th>Network type</th>
<th>Network density (stations/100km²)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected states of the U.S.</td>
<td>Pilot aquifers, size between 23 km² and 1333 km²</td>
<td>National surveillance, proposed optimized water-level network</td>
<td>0.08 – 4.3</td>
<td>ACWI (2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>National surveillance, proposed optimized quality network</td>
<td>0.12 – 0.68</td>
<td></td>
</tr>
<tr>
<td>U.S.</td>
<td>Figures based on total State land area</td>
<td>USGS¹ water level network</td>
<td>0.001 – 17.5 median of 0.2</td>
<td>ACWI (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>USGS water quality network (incl. springs)</td>
<td>0 – 0.4 median of 0.043</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>Groundwater Management Units (GMU) of largely varying size and relative importance of groundwater resources</td>
<td>Not specified</td>
<td>0 – 116</td>
<td>(Merz 2012)</td>
</tr>
<tr>
<td>Selected European states</td>
<td>Aquifers of widely varying size</td>
<td>Water-level networks of varying types</td>
<td>0.4 – 730</td>
<td>Koreimann et al. (1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water quality networks of varying types</td>
<td>0.3 – 57</td>
<td></td>
</tr>
<tr>
<td>Selected European states</td>
<td>Figures based on total national land area</td>
<td>All water-level networks</td>
<td>0.02 – 10.7</td>
<td>UN/ECE (2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All quality networks</td>
<td>0.02 – 1.61</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Figures based on total national land area</td>
<td>Quantitative network</td>
<td>2.5</td>
<td>Umweltbundesamt (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water quality network</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>State/Country</td>
<td>Network scale</td>
<td>Network type</td>
<td>Network density (stations/100km²)</td>
<td>Source</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------</td>
<td>--------------</td>
<td>-----------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Germany</td>
<td>German provinces (&quot;Bundesländer&quot;), figures based on total provincial land area</td>
<td>Water-level networks</td>
<td>1 – 186 median of 6.5</td>
<td>LAWA (1999b)</td>
</tr>
<tr>
<td>Germany</td>
<td>Aquifers of widely varying size</td>
<td>In Karst aquifers In porous aquifers</td>
<td>1.65 0.19</td>
<td>(EEA 2008)</td>
</tr>
<tr>
<td>SADC countries</td>
<td>Figures based on total national land area</td>
<td>Networks combined (incl. springs)</td>
<td>0.08 in Namibia 0.23 in South Africa 0.69 in Lesotho</td>
<td>IGRAC (2013)</td>
</tr>
</tbody>
</table>

Abbreviations/notes:
1) United States Geological Survey
2) Includes basic/reference ("surveillance") and “operational” monitoring for aquifers considered “at risk” as defined by the EU Water Framework Directive
3) For regular reporting to the European Environment Agency (EEA)

Calculated network densities could be a rough indicator of the status of a regional network. Based on the recommendations and figures presented above the following coarse differentiation may be reasonable:

- Densities below 0.1 stations/100 km² → poorly- or underdeveloped networks
- Densities between 0.1 and 1 stations/100 km² → medium-developed networks, or well-developed networks for very large areas or deep aquifers
- Densities above 1 stations/100 km² → well-developed networks

5.4.5. OBSERVATION FREQUENCY

The frequency of observation decides whether the range of natural fluctuations can be accurately assessed and whether they can be distinguished from variations caused by anthropogenic impacts (Uil et al. 1999).

The technically required frequency of observations depends on the following factors:

i. The type of network (water level or water quality);
ii. The objective of monitoring (general trend or impact assessment);
iii. The nature of temporal variations of the parameter observed;
iv. The hydrogeological setup (in particular the type of confinement, flow velocities, amount of withdrawals).

The following types of temporal variations may be distinguished (e.g. IGRAC (2008)):

- Long-term fluctuations or trends corresponding for instance to periods of several successive dry or wet years, a gradual depletion by over-abstraction, a gradual increase by induced recharge, gradual changes in water quality;
– **Seasonal** or **periodical** fluctuations, corresponding to wet and dry seasons, recharge processes during snowmelt or return flow from irrigation;
– **Short-term** fluctuations, corresponding to diurnal or short events (e.g. severe precipitation, human influences, withdrawal due to groundwater evapotranspiration etc.).

In general, long-term trends require a relatively low frequency of observation, whereas accurate identification of seasonal and short-term fluctuations demands a higher frequency. If only long-term variations are of interest (e.g. for basic/reference networks), short-term and seasonal variations would be perceived as “noise”. Therefore the best strategy would be to start during an initial stage with a frequency high enough to observe variations of shorter duration, and to adjust observation frequencies once seasonal and short-term influences are understood (Jousma & Roelofsen 2004). The impact of long-term (or seasonal) trends, in turn, may have to be eliminated from time series using statistical analysis methods if short-term fluctuations are investigated (e.g. Van Lanen (2004)).

Temporal variations are highest in unconfined aquifers with shallow water table as these aquifers are more dynamic with respect to recharge and more vulnerable to pollution. The other factor to consider is groundwater flow velocity. Temporal fluctuations are higher in aquifers with high groundwater velocities, such as karst, fractured rock and gravel.

**Quantitative networks**

According to the European Commission’s expert group (EC 2007) monthly measurements may be sufficient for quantitative monitoring in areas where temporal variability is low. Generally, however, the group advocates daily readings, in particular when measuring flows. IGRAC (2008) recommends about four readings per year in humid and semi-arid regions that show seasonal variability and about 12 to 24 readings per year for studies of recharge in these zones. In arid areas where seasonal fluctuations are absent and which are remote and difficult to access a very low frequency, for instance 1 to 2 times a year may be sufficient. According to the ACWI (2013) guideline, the recommended minimum sampling frequency for quantitative monitoring varies between daily and annual depending on the following factors: aquifer type (confined/unconfined), withdrawals (very few/moderate/many), permeability (high/low), recharge (high/low) and network type (initial baseline networks/ optimized basic-reference networks) (Table 6).

Transducer-converter devices provide the opportunity to record successive measurements at very short intervals. They might be preferable for karstic aquifers subject to rapid responses to rainfall, areas of difficult access, water supply and irrigation wells integrated in operation and control systems (Uil *et al.* 1999) and early warning systems. For such systems, it would also be worthwhile to assess whether they should be operated remotely.

**Water quality networks**

For a reconnaissance survey of water quality, a single round of sampling is usually conducted making use of existing wells and springs found in the area.

Compared to water-level observations the frequency of water quality monitoring is comparably low. In regional deep aquifers that are only influenced by natural geochemical processes, sampling every five to ten years may be sufficient. Higher frequencies (at least once per year) are required to observe water quality variations in aquifers where larger changes are to be expected including specifically vulnerable phreatic aquifers or aquifers that show higher flow velocities because they are affected by abstraction (IGRAC 2008). EEA (2008) recommends a sampling frequency of twice a year. It must be emphasized that compliance, early warning and performance monitoring require higher frequencies than basic/reference
networks. Especially in aquifers with high flow velocities and known pollution risks it is necessary to observe “indicative” parameters continuously, maybe weekly or even daily. In the literature, proposed sampling frequencies for general surveillance of water quality vary between monthly and every five to six years. The ACWI (2013) distinction of measurement frequencies is based on the following parameters: aquifer type (unconfined/confined), hydraulic conductivity (high/low), recharge (high/low), type of aquifer lithology (porous/fractured/karst), depth of wells (shallow/deep) and the quantity of nearby long-term aquifer withdrawals (very few/moderate/many) (Table 6). The British Geological Survey (BGS) uses the following criteria: flow velocities (slow/fast), aquifer type (outcrop/confines), relative responsiveness of a determinant to human impacts, and network type (basic-reference/compliance) (Table 7). In Germany, a similar sampling matrix based on aquifer characteristics and monitoring scenarios was developed (Table 8).

Table 6: Matrix of sampling frequencies for water quality and quantitative networks, proposed by ACWI (2013)

<table>
<thead>
<tr>
<th>Measurement type</th>
<th>Aquifer type</th>
<th>K 1)</th>
<th>Recharge 2)</th>
<th>Flow characteristics:</th>
<th>Minimum frequency of water quality measurements</th>
<th>Minimum frequency of water level measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Baseline 1)</td>
<td>Unconfined</td>
<td>-</td>
<td>-</td>
<td>Porous</td>
<td>Quarterly to twice per year</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>-</td>
<td>-</td>
<td>Fractured</td>
<td>Twice per year</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>-</td>
<td>-</td>
<td>Karst</td>
<td>Quarterly to twice per year</td>
<td>Hourly</td>
</tr>
<tr>
<td>Basic/reference (optimized after initial monitoring)</td>
<td>Unconfined</td>
<td>Low</td>
<td>Low</td>
<td>Annual</td>
<td>Annual</td>
<td>Quarterly</td>
</tr>
<tr>
<td></td>
<td>Unconfined</td>
<td>High</td>
<td>High</td>
<td>Deep wells: annual</td>
<td>Twice per year</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>Low</td>
<td>Low</td>
<td>Shallow wells: twice per year</td>
<td>Every five years</td>
<td>Hourly</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>High</td>
<td>High</td>
<td>Shallow wells: twice per year</td>
<td>Every two years</td>
<td>Hourly</td>
</tr>
</tbody>
</table>

Notes:
1) “Low” conductivity: K<60 m/d, “high” conductivity K>60 m/d
2) “Low” groundwater recharge: GWR<127 mm/a, “high” groundwater recharge: GWR>127 mm/a
3) Initial national network (first five years)

Table 7: Matrix of sampling frequencies for water quality networks, proposed by BGS (as quoted in IGRAC (2008) and EC (2003))

<table>
<thead>
<tr>
<th>Aquifer Type</th>
<th>Hydrochemical determinant</th>
<th>Unresponsive</th>
<th>Responsive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow flow</td>
<td>Outcrop</td>
<td>Every 3 years</td>
<td>Twice per year</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>Every 6 years</td>
<td>Annual</td>
</tr>
<tr>
<td>Fast flow</td>
<td>Outcrop</td>
<td>Annual</td>
<td>Quarterly</td>
</tr>
<tr>
<td></td>
<td>Confined</td>
<td>Every 3 years</td>
<td>Twice per year</td>
</tr>
<tr>
<td></td>
<td>Basic/reference (“surveillance”)</td>
<td>Compliance</td>
<td>(“operational”)</td>
</tr>
</tbody>
</table>
Table 8: Matrix of sampling frequencies for water quality networks in relation to aquifer properties (top) and different scenarios (bottom), recommended in Germany (as quoted in EC (2003))

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Groundwater table</th>
<th>Frequency range 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined porous aquifer</td>
<td>Shallow (&lt;3m)</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Deep (&gt;10m)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Unconfined fractured aquifer</td>
<td>Shallow (&lt;3m)</td>
<td>% yearly</td>
</tr>
<tr>
<td></td>
<td>Deep (&gt;10m)</td>
<td>Annual</td>
</tr>
<tr>
<td>Karst aquifer (uncovered)</td>
<td>Not considered</td>
<td>Every 2 years</td>
</tr>
<tr>
<td>Karst aquifer (protected)</td>
<td>Not considered</td>
<td>Every 5 years</td>
</tr>
<tr>
<td>Confined aquifer,</td>
<td>Not considered</td>
<td></td>
</tr>
<tr>
<td>impervious layer with thickness &lt; 2m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined aquifer,</td>
<td>Not considered</td>
<td></td>
</tr>
<tr>
<td>impervious layer with thickness &gt; 2m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Frequency range 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High rate of recharge</td>
<td>Monthly</td>
</tr>
<tr>
<td>Trend assessment</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Season-dependent human activities</td>
<td>% yearly</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
</tr>
<tr>
<td></td>
<td>Every 2 years</td>
</tr>
<tr>
<td></td>
<td>Every 5 years</td>
</tr>
</tbody>
</table>

Note:

1) Light grey represents the range of frequencies, dark grey the most likely frequency
6. CONCLUSIONS

In conclusion, the development of regional and national networks should incorporate the following seven basic steps:

1. Identification of the different monitoring objectives and assessment of the possibilities of combining regional/national and local networks (parallel networks);
2. Assessment of existing networks and data;
3. Development of a conceptual hydrogeological model that includes the delineation of (main) aquifers (horizontal distribution, multi-layered aquifers) and the determination of the various functions of the groundwater bodies (water use);
4. Review of statutory requirements and evaluation of risks and threats by overexploitation, salinisation or diffuse or point/line sources of pollution, etc.;
5. Zoning which is based on hydrogeological and risk analysis (functions and risks table) and defines the scale and areas for regional (i.e. basic/reference) networks and local (i.e. compliance, performance) networks;
6. Planning and establishing of a pilot network (over 3-5 years) by taking into consideration the existing information, and specifying the network design components such as observation point distribution, density, parameters and analytes, and frequency of sampling;
7. Optimization of network based on analysis of preliminary data from network (e.g. statistical analysis) by adding or omitting observation points and reducing or increasing sampling frequency.

A scheme that summarizes the main steps in the process of developing such a groundwater monitoring network can be found in Appendix A.6.
PART B: Proposed monitoring network for the GReSP study area in the Upper Kafue Sub-catchment, Zambia

The main aspects of Part B, i.e. the process of designing a groundwater monitoring network for a study area in the Upper Kafue Sub-catchment, are summarized in Appendix A.5

7. BACKGROUND

7.1. LEGAL REGULATIONS DEFINING RESPONSIBILITIES OF HYDRO(GEO)LOGICAL MONITORING IN ZAMBIA

The monitoring of water resources in Zambia was for decades the task of the Department for Water Affairs (DWA). In the course of the water sector reform, the DWA was split into two new governmental bodies, the Department for Water Resources Development (DWRD) and the Water Resources Management Authority (WARMA), both under the Ministry of Water Development, Sanitation and Environmental Protection (MWDSEP). A new water legislation was put into force and this Water Resources Management Act (WRMA) of 2011 defines that the responsibility for monitoring of quantity and quality of water resources in Zambia rests with WARMA (see Appendix A.2).

The act prescribes that it is WARMA’s task, upon prescription by the Minister for Water Development, Sanitation and Environmental Protection, to put in place and maintain a national monitoring and information system on water resources (WRMA2011 §38 (1), see also §8 (2)(h)). The respective procedures for data collection and analysis have to be provided by the same minister (§38 (2)). WARMA has to publish information on water resources (§8 (2)(i)) and make all information contained in the monitoring and information systems accessible to any person upon payment of a fee (§38 (6)(a)).

Furthermore, WARMA has to monitor the quality of the water resources (§8 (2)(o)) – in collaboration with the Environmental Agency (§47 (2)) and measure the impacts of climate change (§8 (2)(b)(i) and (iii)). WARMA can oblige “persons, whose activities may lead or give rise to the pollution of a water resource” to conduct monitoring measures for a specified period (§49(1)), request water permit holders to install a meter in order to monitor the permit holder’s water use (§67(1)) or to let WARMA install their own meter (§67(2)).

The general monitoring tasks shall be conducted by WARMA’s subordinate structures. Monitoring of water quantity and quality should be done by catchment councils (§18 (1)(i), quality monitoring is also mentioned under §18 (1)(n)), sub-catchment councils (§20 (1)(d), with monitoring of water quality especially mentioned under §20 (1)(k)) and water users associations, having the task to collect hydrological, hydro-geological data (§25 (c)) and to monitor water quality (§25 (b)). Finally, monitoring tasks are also assigned to institutions that manage shared watercourses (like the Zambezi River Authority, ZRA) (§58(a)). In addition, companies running hydropower plants like ZESCO (Zambia Electricity Supply Company) and LHPC (Lunsemfwa Hydro Power Company) run their own river discharge stations. WARMA has concluded or is about to conclude agreements with ZRA and ZESCO on data exchange (Ministry of Energy and Water Development (Zambia) 2016). The later cited report also summarizes in various tables the responsibilities of WARMA as assigned by the WRMA of 2011 (WRMA 2011).

WARMA shall set and recommend water quality standards, for each water resource, to the Zambia Bureau of Standards, in consultation with the Environmental Agency (§8 (2)(n) and §47 (1)). Setting those standards indirectly defines the water quality parameters that have to
be monitored for the different water resources, in case these are not already set by the monitoring procedures (§38 (2)).

7.2. CURRENT STATE OF WATER RESOURCES MONITORING IN ZAMBIA

A short historical overview about water resources monitoring in Zambia is given in the report by the Ministry of Energy and Water Development (Zambia) (2016), to which the next paragraphs refer if not indicated otherwise. The report was written by the AURECON consulting group in their task of designing an optimal national hydro-meteorological monitoring network.

Monitoring of river discharge began as early as 1926, and in total 334 stations were installed. Still, 66 of those stations have no data records at all and the maximum number of stations being operational at the same time was 210 (in 1980). After 65 stations had been rehabilitated and equipped with telemetric data loggers by a project funded by the German Kreditanstalt für Wiederaufbau (KfW), 104 stations, in total, were operational by 2016. A number of stations were operated by ZESCO (14), ZRA (10 in Zambia) and LHPC (8). Reports of consulting companies suggested an optimal number of 168 (CES-AHT 2013) to 172 (Ministry of Energy and Water Development (Zambia) 2016) river gauging stations required in Zambia. The numbers are primarily based on expert judgement and assumptions about WARMA’s upcoming technical staff, as the availability of technicians determines how many stations can be properly operated.

In contrast to the long lasting efforts in monitoring river streamflows, only limited groundwater data are available. The GReSP project (see next sub-chapter) installed a groundwater level monitoring network in Lusaka that covered more than 40 sites, 10 of those being regularly tested for water quality (Bäumle et al. 2012). The monitoring network was partially established for the purpose of providing input data for the groundwater model of the Lusaka karst plateau. Within another project, which was funded by the KfW, 12 boreholes (out of which two were dry) were quite recently drilled for monitoring purposes in the Copperbelt and around Kabwe (AGW Ltd. 2016) for operation by WARMA.

Still, at the moment there is no coordinated national groundwater monitoring program and especially the absence or missing accessibility of long-term data must be regarded as a major shortcoming for sustainable management of Zambia’s groundwater resources.

The Zambian Meteorological Department (ZMD) is in charge of monitoring weather related data and runs a network of 38 manual stations of which 29 provide synoptic information. Out of these stations, seven were automated and integrated in a network comprising 19 automated weather stations. The later network was established under the SASSCAL (Southern African Science Service Centre for Climate Change and Adaptive Land Management) project. Additionally, rainfall is also recorded automatically (and manually) at the 65 rehabilitated river gauging stations. Hence, possible extension of the automatic river network in the future will also improve the information about spatial rainfall distribution.

7.3. GReSP PROJECT

The Groundwater Resources Management Support Programme (GReSP) is a bilateral cooperation project between the Zambian Government and the German Government. The task of the German implementing agency, the Federal Institute for Geosciences and Natural Resources (BGR), is to support WARMA with their task of developing groundwater management plans for Zambian catchments. These plans are one part of the catchment management plans that WARMA is obliged to develop and publish as prescribed by the WRMA (2011).
The GReSP project started in 2005 and is currently in its 4th phase. After previously focusing on groundwater resources in the Southern Province, Lusaka and its surroundings as well as preparing case studies for Solwezi and the Itawa Springs in Ndola, the investigations of the current phase target the Upper Kafue Sub-catchment. A study site was selected that encompasses groundwater users from mines, commercial farming and urban centres (e.g. water utility companies). The area also comprises aquifer types typical for Zambian geology, including granitic basement, quartzite aquifers and dolomitic karst systems. Hence, the study area is representative for a wide range of groundwater related aspects and issues found in Zambia and can have an exemplary function for groundwater management. Details about the area are given in Chapter 8.

As most other areas of Zambia, the site lacks suitable data about water resources, especially related to groundwater. However, such data are the basic precondition for management. Extensive knowledge about the aquifers, their characteristics and the on-going hydrogeological processes is required. The initial step of the current project phase was therefore to develop and install a monitoring network to obtain data about the hydrogeology and hydrology of the area, serving as basis for groundwater management (plans).

While this report elaborates the underlying thoughts of the design of the monitoring network, the technical specifications of the installation and the installed monitoring stations are given in a technical note by Fahle et al. (2017).

8. SITE DESCRIPTION AND PRIMARY HYDROGEOLOGICAL FRAMEWORK

8.1. GEOGRAPHICAL AND GEOLOGICAL OVERVIEW

The study area for the GReSP project was selected together by WARMA and BGR and is located in Zambia’s Copperbelt Province. The area encompasses about 6,880 km² and comprises the catchment of the Kafulafuta River, with the Kafubu River as its biggest tributary, as well as the Mpongwe Karst area (Figure 4). The Mpongwe Karst area is a calcareous-dolomitic plateau that is drained by several smaller rivers such as the Mpongwe, Chisanga and Bundi. The entire study area discharges to the Kafue River. However, in the Mpongwe Karst area it is assumed that a considerable amount of water is discharging into the Kafue River underground. The contribution of this groundwater discharge has not yet been quantified.

The study area is located on the Central African Plateau with 95% of the area ranging between altitudes of 1,140m a.s.l. and 1,350m a.s.l. (according to Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data set (SRTM 2000)). Natural vegetation in the area consists of Miombo woodland, characterized by tall trees complemented by shrubs and grasslands underneath, and reed grass in the wet areas of surface depressions, the so-called dambos. Nowadays land use is highly fragmented and natural vegetation remains only in limited parts of the area. Trees are cut for charcoal production and areas were and are still cleared to gain agricultural land, which also includes huge commercial farms in the Mpongwe area.

The geology of the area is dominated by three major rock types, namely granite, quartzite and dolomites/limestones (Appendix A.4). These also form the major hydrogeological units. Main groundwater potential is found in the Mpongwe Karst area and in the limestone and dolomite aquifers northeast of Ndola. The remaining areas can be locally productive (quartzite) or low-yielding (granitic aquifers).
8.2. CLIMATE

The climate of the study area can be described as temperate-dry winter/hot summer climate (Cwa) according to the Köppen climate classification (Köppen (1936), updated by Peel et al. (2007)) as the temperature of the coldest month does not fall beneath 0°C while reaching more than 22°C in the hottest (summer) month. The year is divided into a rainy and a dry season. During the latter rainfall is basically absent. The rainy season lasts from November to April, followed by a cold (May to July) and then a hot dry season (August to October, see Figure 5).

At the weather station in Ndola the average temperature measured in the period from 1961 to 1988 was 20.3 °C and the annual precipitation amounted to 1,233 mm in the period from 1961 to 1991 (NOAA 2018). According to data provided by the Zambian Meteorological Department annual precipitation reduced to 1,151mm during the period from 1985 to 2013. Further, a report of consulting group (AHT 1975) states that during an unspecified time period of 57 years before 1975, on average 1,171 mm of rainfall were observed at a station in Ndola.

Figure 5: Climatic data of the weather station in Ndola (WMO Station Number: 67561). Reference period 1961 to 1988 for temperature and 1961 to 1991 for precipitation. Data were extracted from National Oceanic and Atmospheric Administration’s ftp server(NOAA 2018).
8.3. Socio-economic situation

The Copperbelt Province, to which the study area belongs, is an important economic hub of Zambia and contributes the biggest share to the Zambian gross domestic products in the fields of agriculture, forestry and fishing, mining and quarrying, manufacturing, water supply as well as transportation and storage (Central Statistical Office 2015). According to the 2010 census, population of the Copperbelt amounted to about 1,970,000 inhabitants, of which nearly 81% lived in urban areas, by far exceeding the Zambian average urbanization at that time (39.5%) (Central Statistical Office 2014).

Table 9: Area and population figures of the districts that are partly covered by the study area (Central Statistical Office 2014).

<table>
<thead>
<tr>
<th>District</th>
<th>Area in km²</th>
<th>Population by 2010</th>
<th>Population growth from 2000 to 2010</th>
<th>Degree of urbanization</th>
<th>Population Density by 2010 in capita per km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luanshya</td>
<td>811</td>
<td>156,059</td>
<td>5.5%</td>
<td>85.5%</td>
<td>192.4</td>
</tr>
<tr>
<td>Masaiti</td>
<td>5,383</td>
<td>103,857</td>
<td>8.7%</td>
<td>2.0%</td>
<td>19.3</td>
</tr>
<tr>
<td>Mpongwe</td>
<td>8,339</td>
<td>93,380</td>
<td>45.1%</td>
<td>16.0%</td>
<td>11.2</td>
</tr>
<tr>
<td>Ndola</td>
<td>1,103</td>
<td>451,246</td>
<td>20.4%</td>
<td>100.0%</td>
<td>409.1</td>
</tr>
</tbody>
</table>

The study area includes parts of the districts Ndola, Luanshya, Masaiti and Mpongwe. The districts formerly served as water management units in Zambia before the WRMA of 2011 (WRMA 2011) prescribed that management has to be based on catchment and sub-catchment level. District characteristics differ strongly in terms of area, urbanization, population growth and density (Table 9). The area investigated contains two major towns, Ndola and Luanshya, while the remaining part of the study area is rural having low rates of urbanization. Ndola is an important economical centre within Zambia, having an international airport, notable industries including the country’s only refinery and cement mining companies. In contrast, economy in Luanshya is mainly connected to copper mining. Agricultural activities dominate in the two remaining districts. In Masaiti, subsistence and small-scale farming prevails, while Mpongwe is also home of large-scale commercial farmers that use irrigation to grow crops during the dry season. As the population of the area keeps on increasing, induced land-use change from natural vegetation to farmlands is likely to continue. Furthermore, rising need
for charcoal especially in the two major cities puts the remaining forested areas under pressure.

8.4. HYDROLOGY AND WATER RESOURCES MANAGEMENT

Water management and hydrology in the Copperbelt Province are determined by the abundance of water during the rainy season and the scarcity of water at the end of the dry season, when smaller streams eventually fall dry. During the latter time span, water supply relies on the limited number of perennial rivers, water stored in reservoirs and, especially where none of the former is accessible, on groundwater.

The study area is part of the Upper Kafue Sub-Catchment, the Kafue being the biggest tributary to the Zambezi River. The Kafue catchment is divided into different basin blocks and the study area corresponds to the eastern part (i.e. on the left riverbank) of the basin block BK-04 (see Figure 7). Appendix A.3 shows a hydrological map of the study area.

The Kafubu River is the most important river of the study area with regard to domestic water supply. Shortly after its emergence in the Itawa dambo northeast of Ndola city center, the river is ponded by two small dams. The Kafubu dam, located about 15 km downstream of Ndola and being built in 1963, is the largest dam of the area investigated. The water stored in its reservoir is used by the water facility company Kafubu Water and Sewage Company (KWSC) to supply water to the city by the water treatment plant located next to the dam. Since part of the water stems from effluents of the sewage water treatment plants in Ndola or even untreated sewage, water quality is poor. Other sources of water supply in Ndola are the water treatment plant in Itawa, which also draws water from the Kafubu River, and a series of production boreholes in Misundu, which pump water from the limestone/dolomite aquifer north-east of Ndola. Formerly, water was also supplied from Lake Ishiku, a sinkhole located south-east of Ndola. Yet pumping was stopped in 1988 due to low water levels, indicating an over-abstraction of groundwater, either due to water abstraction from the lake or groundwater lowering by neighboring limestone mines.

Some 20 kilometres before reaching the Kafue, the Kafubu flows into the Kafulafuta River, which is the main means of discharge of the area investigated. The Kafulafuta emerges in the study area’s eastern part, where the catchment border coincides with the border to the Democratic Republic of Congo. In contrast to the Kafubu, the river is nearly unregulated, except for small dams located in its tributaries, like the Muyenge and the Lwankuni.

However, the Kafulafuta’s flow regime is expected to change drastically in the future as the construction of a dam just upstream of the gauging station in Ibenga just began. The proposed reservoir is designed for a total volume of 125 million m³, with its lake spanning over an area of 19.5 km² (Kafubu Water Sewage Company 2017). The dam’s purpose is to supplement water supply in currently unserviced areas of Ndola, as well as in the districts of Masaiti, Luanshya and Mpongwe. Given the dimension of the dam, strong impacts on local hydrology and hydrogeology of the area can be expected, both during filling of the reservoir and once the reservoir has filled up.

Surface hydrology in the area around the towns of Mpongwe and Munkumpu deviate from those of the remaining study area. Topography is relatively flat and catchments are relatively small, leading to a number of smaller rivers and streams discharging into the Kafue. Parts of the area have no surface drainage at all. Also the gradient of Kafue River is low, as expressed by its meandering (AHT 1975). Commercial farmers in this area use, depending on their location, either water abstracted from the Kafue, water from reservoirs or groundwater from the Karst aquifer.
Up-to-date hydrological data for the area is largely absent, yet historical records of river water levels and streamflows are available for multiple (former) stream gauging stations throughout the area. Yet the quality of the data can be questioned and a retrospective evaluation is hardly possible.

8.5. HYDROGEOLOGICAL SETTING

In terms of hydrogeology, no official monitoring efforts are known and, if any, only measurements by campaigns (e.g. Krampe (1975)) exist. Private monitoring, for example by farmers, might have been conducted. Yet the only monitoring effort known are recurrent measurements of Lake Nampamba water levels by the Zambeef farm, as irrigation water for the farm is mainly drawn from this sinkhole.

Due to massive groundwater abstractions for water supply in Ndola and commercial farms in Mpongwe as well as dewatering by mines, long-term monitoring is a key to ensure sustainable water management and for WARMA to decide upon applications for the issuing of new water permits.

The study area is dominated by three geological entities (see attached geological map). Gneiss and foliated granite, i.e., hard crystalline rocks belonging to the so-called Basement complex, is found in the centre of the area, covering a big share of the entire study area and prevailing in the districts of Luanshya and Masaiti. Quartzites of the Lower Roan Series occur at the eastern and southern, including the south-western, parts of the study area (Moore 1965; Smith 1966). Finally, the Mpongwe Karst, formed by Upper Roan Dolomites of the Mine series Group, is the most prominent hydrogeological feature of the part of the Mpongwe District that belongs to the study area (Hickman 1973). In the surroundings of the Kafue River, where surface slopes are rather flat and surface drainage poorly developed, a band of shales, silt- and sandstones of the Kundelungu Group spans over both sides of the river.

These main aquifers differ in their potential for water abstractions (Figure 7). Using the classification scheme introduced by BGR (Struckmayer and Margat, 1995), the aquifers with the highest expected yields are the Upper Roan dolomites and the Lower Kundelungu limestone (Class C), i.e., the Karst areas in Mpongwe and north-east of Ndola. The quartzite aquifers found in Masaiti as well as the silt-/sandstone aquifer along the Kafue River belong to class E and can only be regarded as locally productive, depending on location and tectonic history. Finally, the aquifers of the basement complex and the quartzites found in the southwestern most corner of the study area are classified as E-F, as stratum with intermediate characteristics, and cannot be considered as important aquifers. Still, these aquifers might contribute a significant amount of baseflow to the streams of their area.

Of course, geological complexity is much higher on a local scale. Especially the geology of Ndola and surroundings is spatially highly variable, including schists, quartzite, granite and carbonate rocks of different ages (Upper Roan and Lower Kundelungu). The combination of these rock types and their layering leads to the formation of several springs within the city limits, mostly stemming from areas of Lower Roan Quartzite. The Lower Kundelungu limestones and dolomites are found along the Itawa dambo and include prominent Karst features like sinkholes southeast of Ndola (Lake Chilengwa and Lake Ishiku). Further, limestone is mined in various quarries south-east of Ndola, serving as basis for cement production. A detailed discussion of the geology of the Ndola area is given by Hadwen (1972) and Karen et al. (2015).
The Mpongwe Karst provides the highest potential for water abstractions of the entire study area. Water tables in the area are generally relatively shallow, mostly ranging between 4 and 7 meters below ground level, rarely exceeding 15 meters (Krampe 1975). As commercial farms are already extracting considerable amounts of groundwater, up to date information about the hydrogeological situation is needed to avoid over-abstractions in the future. The prevailing Upper Roan Dolomite is a marine deposit of calcareous and dolomitic marble (alternating with phyllite and containing intercalations of alkaline and acid volcanic rocks), forming the Ipumpu formation between Munkumpu, St. Anthony’s Mission and Mpongwe Boma (Krampe 1975). These carbonate rocks can be dissolved by acidic water, creating pathways along faults or fractures. These connected voids then allow for high flow velocities and enable high abstraction rates. Main Karst features present are a shallow, superficial cave system close to the Bilima River (Kaiser et al. 1998) and the two sinkholes Lake Kashiba and Lake Nampamba. Both sinkholes are deeper than the regional drainage basis (i.e., the Kafue River), yet no geological indications of existence of valleys in former periods are found and it is assumed that solution stems from groundwater flow below the base level (Krampe 1975). In general, permeable zones are expected especially in karstified parts where joint and fault zones
enlarged to cavities, but as karst weathering is relatively young, the size of the cavities is expected to be small but occurring at high frequency (Krampe 1975).

Knowledge of areas where groundwater is recharged and discharged is of importance for management, as recharge areas should be protected with respect to land use and because changes in land use might lead to lower recharge rates or contamination of the groundwater. As measurements are missing, it has to be assumed that recharge areas are predominately located in the headwaters and more elevated parts of the catchments. The amount of water recharged depends on a variety of factors like soil cover, land use, underlying rock type and its weathering. For the areas belonging to the basement complex relatively low recharge rates are expected while for the carbonate aquifers in Mpongwe and north-east of Ndola recharge is expected to be high, as recharge rates of more than 20% of the annual rainfall were estimated by Bäumle et al. (2012) for similar conditions in Lusaka. Hence, it can be assumed that these carbonate aquifers, which are located in the headwaters of their respective catchments, are the most important in terms of groundwater recharge in the investigated area.

Discharge areas are generally expected to be located close to streams, rivers and wetlands (i.e., dambos). Topographical maps providing the drainage network and the wetland distribution therefore can provide an initial idea about discharge zones. For the Mpongwe area with its poorly developed surface drainage system, it is assumed that the aquifers are recharged in the higher elevated southern areas, while groundwater is flowing northwards along the topographical gradient, where it is being discharged to the Kafue River.

River catchments are derived from topography and indicate the area from which all rainfall discharges to the respective river. Yet geology can substantially differ from topographical features, leading to a mismatch between subsurface and surface water catchments. In this case, groundwater abstraction in one river catchment might (negatively) affect the water balance of the other river catchment (i.e., lead to inter-basin water transfer). In the study area, parts of the Mpongwe Karst might drain towards the Lukanga swamps, south of Mpongwe district, and transfer water from the basin complex BK4 to BK6. Furthermore, there are indications that a transboundary aquifer (i.e., an aquifer spanning over at least two States) between the Democratic Republic of Congo and Zambia exist north-east of Ndola (see Karen et al. (2015)).

9. TYPE AND OBJECTIVES OF MONITORING NETWORK

As the aim of the GReSP project is to establish a basis for groundwater management, the monitoring should deliver a general characterisation of groundwater availability (i.e., groundwater recharge and amounts stored) and abstraction, chemistry and groundwater flow patterns in the area investigated. At this initial stage (i.e., the setup of a new monitoring network), monitoring focusses on quantitative aspects to determine how much groundwater is available and how much groundwater is used (i.e., abstracted) while hydrochemical investigations are restricted to reconnaissance surveys. Hence, the network type is best described as initial regional quantitative reference network. The size of the area is, by Zambian standards, small and it is set to be a baseline network for up to 5 years, enabling a first description of water levels and quality including their natural variability as well as an estimation of groundwater recharge.

In order to gather basic data describing the general status of the groundwater, both in terms of quantity and quality, the objective of the monitoring task is to establish a basic (or
reference) network. Of the objectives mentioned under Sub-section 2.1 the following apply: Provide a general characterisation, determine groundwater contours and chemistry, identify trends and provide periodical information. Yet there is no particular focus on identifying groundwater contamination and areas at risk of contamination. Some of the monitoring objectives described in Sub-section 2.2 apply as well: Providing groundwater data for a sustainable development of the groundwater resources, assessing the potential for water supply and providing estimates of groundwater recharge.

Some of these objectives, like the identification of trends related to anthropogenic activities or changes of the climate, require long term observations. These cannot be achieved by a project of limited duration. Therefore, it will be important that WARMA integrates at least part of the established monitoring stations in their own monitoring network at the end of the project as the value of monitoring data increases with the length of the record available.

The monitoring efforts should generate different data sets. First of all, as information on groundwater levels is nearly absent, temporal changes in groundwater levels have to be recorded and analysed. Second, data suitable to derive a groundwater contour map, thus visualising the large-scale groundwater flow patterns, is required. Third, to enable a spatial differentiation of the different aquifers and an evaluation of potential pollution sites as well as reference data about the groundwater quality, hydrochemical data representative for the entire study area is needed. Finally yet importantly, monitoring should also comprise streamflows in major rivers to set up large-scale water balances and to gain information on baseflows, which is indicative for the quantitative state of the groundwater and its recharge.

The major focus will be obtaining highly resolved water table variations. The resulting data will allow evaluating how quickly water tables of the different aquifers react to the on-set of the rainy season and when the highest and lowest values are encountered. By interpreting these variations, also qualitative insights about groundwater recharge or discharge (i.e., abstractions) can be gained. Long time observations will enable to draw conclusions on effects of climatic and land use changes on the aquifers. For instance, the conversion of natural forest into farmland can have multiple effects including a change of the evapotranspiration patterns and direct abstraction of groundwater in case of irrigated agriculture. Water table time series will enable to evaluate whether irrigation is done in a sustainable way, i.e., irrigation needs do not exceed average groundwater recharge. Otherwise, groundwater over-abstraction will manifest in a long-term declining trend. According evaluation can be backed by analyzing streamflows, as strong groundwater use might have a negative impact on the baseflows.

10. NETWORK DESIGN

The design of the groundwater monitoring network and program is based on the objectives (Chapter 9) and the hydrogeological information about the study area (Sub-Chapter 8). The order of presenting the design components is adopted from the theoretical considerations in Sub-Chapter 5.4 (see also Appendix A.5).

10.1. NETWORK SCALE

The monitoring network, due to the hydrological and hydrogeological composition of the study area, can be split into two parts. The first part monitors the Kafualafuta Catchment, while the second covers the Mpongwe Karst area.

For the Kafualafuta, the monitoring network is based on the surface water catchment. (Sub-) Catchments delineate water management zones according to WRMA (2011). The groundwater catchment, as a first estimate, is assumed to coincide with the surface water...
catchment. Yet there are indications that the Kakontwe limestone aquifer in Ndola is a transboundary aquifer extending to the DRC (cf. Karen et al. (2015)). Still, as the network is oriented on a regional scale, these smaller deviations can be considered tolerable. In case of future water resources issues arising in this area (e.g. related to transboundary water management), a specific local monitoring network has to be set up. This would require bilateral efforts of the two states involved. Additionally, as a water users association was formed for the Kafubu River, there might be a future need for an enhanced monitoring of this area based on the stations that are contained in the herein described monitoring network.

In the Mpongwe area, the hydro(geo)logical conditions differ from those observed in the Kafulafuta Catchment. While the entire area is also supposedly discharging into the Kafue, the surface drainage is not well developed and scattered. There is a variety of mostly smaller streams, but it is likely that a greater amount of the water is discharged to the Kafue underground. Hence, the design of this part of the monitoring network cannot be based on surface water catchments as this would require an unrealistically high number of monitoring stations, covering small catchments with limited importance. The choice of monitoring points in this area is therefore focusing on the areal distribution of the aquifers as underground flow is predominant.

10.2. PARAMETERS

The main aim of the monitoring was to retrieve data that can be used to estimate groundwater potential, recharge and abstractions, i.e., the key figures required for quantitative groundwater management. The network therefore concentrated on quantitative parameters, while investigations on qualitative parameters were restricted to field campaigns (reconnaissance surveys).

Monitoring involved both groundwater and surface water levels. Groundwater levels at different aquifers were recorded to assess the annual range of fluctuation and get insights on recharge during the rainy season. Additionally, the water level at Lake Kashiba was observed to analyse whether its fluctuations are correlated with those of the aquifers in the Mpongwe area or if there are additional influences on the lake water level (e.g. evaporation).

A network of river gauging stations completed the groundwater level observations. Discharge was measured repeatedly to set up or update the rating curves at these stations. Combining both, time series of discharge over the year can be calculated. Hence, low flows during the dry season were determined, which are an important criteria for issuing water permits and water management in general. In addition, analysis of the discharge can be used to estimate baseflows during the year and the surface runoff, both important water budget variables (Equations 1 and 2).

No spring discharges were measured, as suitable locations were missing and/or would have been highly prone to vandalism (e.g. the Itawa Spring in Ndola is surrounded by a compound with high population density). Discharge of pumping wells was not recorded directly, as it was intended to retrieve these data from the water facilities and other users. To estimate and verify water used for irrigation by large-scale farmers, a tool based on remote sensing data was developed.

For the water quality reconnaissance study, the default physical-chemical parameters (temperature, EC, pH, oxygen reduction potential, dissolved oxygen) were measured at site while for analysis of the water sample the laboratory facilities of the BGR Headquarter in Germany were used. The analysis included major, minor ion chemistry, nutrients as well as heavy, and trace metals. Additionally, stable isotopes of hydrogen and oxygen (i.e., Deuterium ($^2$H) and Oxygen-18 ($^{18}$O)) were determined to get insights in the interaction between surface and groundwater.
Due to the nature of the sampling and logistical challenges, indicators for microorganisms (i.e., biological contamination of the water) like faecal coliforms could only be measured for a limited number of points. Organic parameters to detect residues of pesticides were not measured since the measurement procedure is more demanding and cost of analysis is high.

10.3. LOCATIONS OF OBSERVATION POINTS

10.3.1. GENERAL CONSIDERATIONS

As the main design criteria was to allow for a general characterisation of the study area, the core principal was to distribute the observations points in a way to cover the entire area and all different strata, especially with respect to the major aquifers present. Further, groundwater monitoring locations had to avoid strong anthropogenic influences and be preferably located close to streams, while monitoring included streamflows for baseflow determination (cf. Table 4: Criteria for the positioning of groundwater observation points for different network types and monitoring objectives (after LAWA (1999a), supplemented). The selected approach was to first decide on selecting a network of river gauges, which was intended to provide information on baseflow and runoff (Section 5.3). Secondly, a cost-minimising approach was followed, considering only abandoned boreholes and those equipped with handpumps for monitoring. A team was sent out to find such potential boreholes for monitoring. Finally, out of these potential boreholes 13 sites were selected according to the criteria described below. All stations were equipped with data loggers, i.e., automatic water level recording devices.

10.3.2. POSITIONING OF RIVER GAUGING STATIONS

Concerning river gauging stations, priority was given to existing and historic stations but also new installations were considered where necessary. In order to develop rating curves, recurring streamflow measurements were necessary. Hence, accessibility also during the rainy season was a requirement. Furthermore, gauging close to the downstream end of the catchment (cf. Table 4) was preferred and conditions about gauging sites given in Section 5.3 had to be fulfilled.

The study area is part of the Upper Kafue catchment and, hence, discharging towards the Kafue River. Two out of the 65 monitoring stations of WARMA’s national hydrological monitoring network are located in the study area, monitoring the Kafue River at the beginning (Mpatamatu) and close to the end (Machiya Ferry) of the basin block BK-4. Both stations, which have historical data including rating curves, were recently rehabilitated with data transmission devices and had gauge readers assigned to them. So, data could be obtained from WARMA, but additional streamflow measurements were done to verify whether historical rating curves were still valid. Data of these two stations serve as indicator of the discharge of the basin block to the Kafue or the water loss by exfiltration from the Kafue in case loosing stream conditions should prevail.

In addition to these stations, it was decided to rehabilitate a historic Kafue River station approximately halfway between the existing stations, in Ndubeni. A small ferryboat exists at the site, enabling streamflow measurements. Comparison of these measurements with those of Mpatamatu and Machiya stations enable to estimate the contribution of groundwater flow into the Kafue from the eastern Mpongwe area, when subtracting inflows from surface water sources like the Kafulafuta River. A gauge reader under WARMA was still assigned to the station.

Other gauging stations were selected in a way to describe the runoff of three catchments:
The Kafulafuta River was represented by a newly built station at Kasamba. The historic station, which was located a couple of kilometres downstream and therefore closer to the confluence with the Kafue River, was not rehabilitated as streamflow measurements at this site would have required a boat and accessibility during the rainy season was questionable. Instead, the road from Ibenga to Kasamba is passable throughout the year and streamflow can be easily measured from a bridge, where the river has a defined cross-section and flows straight up- and downstream of the bridge.

The Kafubu River was characterised by the historic gauging station in Masaiti, located directly at the tar road. As the station is situated just upstream of the confluence with the Luanshya River, it is not representative for the whole Kafubu catchment, but for the part that is draining Ndola and northern Masaiti. The streamflow is thereby governed by the influence of the Kafubu Dam. A gauge reader was still assigned to the station by WARMA.

A suitable monitoring station of the Mpongwe River was identified at Nsensenta, about 5 km before the river’s confluence with the Kafue River. Distance to the Kafue River should be big enough to omit any backwater effects during times of high water levels in the Kafue. The location represented the biggest part of the water discharged from the Mpongwe River catchment, being the biggest surface drainage basin in the Mpongwe Karst area. Generally, gauging conditions along the Mpongwe River were not ideal but the selected site has at least a suitable river profile during low and mid-flows.

In order to allow water budget and baseflow investigations for sub-catchments, three additional gauging stations were built/rehabilitated:

- The station at the Kafulafuta in Ibenga was a historic station that needed to be rehabilitated. It represents large portions of the Kafulafuta catchment before its confluence with the Kafubu River and hence allows for direct comparison regarding flows and dynamics with the measurements at the Kafubu River in Masaiti. The station still had a gauge reader assigned to it, who, however, was not able to read the values properly most of the year due to damaged gauge plates.

- Another station of the Kafulafuta River was rehabilitated. Being located directly at the Great North Road, access was assured at all times. The streamflow represents the contribution of the Upper Kafulafuta catchment, which is largely unaffected by anthropogenic influences except for some smaller dams and fishponds. However, the cross section was far from ideal, as the stream splits into two branches during mid to high flows.

- To assess the contribution of the Ndolian limestone/dolomite aquifer to the flow of the Kafubu, a location for river gauging in Ndola was needed. No proper historic site could be identified. Measuring the flow just downstream of the Itawa Spring was envisaged, but no proper stretch with a defined stream profile was found. Instead, a suitable location was detected at a pedestrian bridge in the quarter Twapia, where the river was flowing straight in a defined profile. In contrast to the Kafulafuta station at the Great North Road, this station was strongly anthropogenically affected by the outflow of the sewage treatment plant located just upstream and other sources of discharge from the city. Hence, the streamflow allowed to estimate water use and abstractions of the city of Ndola during the dry season, although it was less suited to determine baseflow. Furthermore, the flow in Twapia is assumed to represent the major share of the flow entering the Kafubu Dam Lake.

In sum, monitoring comprised nine river gauging stations. Two of them (the stations in the Kafue at Mpatamatu and Machiya) were operated within WARMA’s national hydrological
monitoring network. The remaining seven stations were operated by the GReSP project. The stations were rehabilitated or newly build by equipping them with new gauge plates and a logger for automatic data gathering. As for these stations no or only outdated rating curves existed, recurring discharge measurements at different water levels were undertaken. Gauge readers, where not already employed, were hired between July and September 2017.

For the technical aspects of the installations, refer to Fahle et al. (2017).

### 10.3.3. POSITIONING OF GROUNDWATER MONITORING STATIONS

When referring to the ACWI (2013) classification (Figure 3), the spatial design approach used for the presented network can best be described as stratified random sampling. Considered strata were mainly the geological units (i.e., the different aquifers). Additionally, hydrological aspects and land use patterns were also taken into account. While no strict gridding approach was followed, the aim was to spread the monitoring locations over the entire area.

Combining these considerations, 14 locations of potential interest were identified (Figure 8). These locations encompassed areas close to the already installed river gauging stations (C, F, G, H, K, N, P), as comparison of groundwater and river water levels allows for an evaluation of hydraulic conditions, i.e., whether groundwater flows to the river or gets recharged by the river. All major aquifers should be represented by different monitoring boreholes, hence several points in the Mpongwe Karst (J, K, L, M), quartzite (D, B, E) and basement complex (C, E, F, G, H) were targeted.

Defining the final monitoring locations was driven by an approach to set up a cost-effective network. Hence, the installations were done at existing handpumps or abandoned boreholes, while no new boreholes were drilled. The task was then to identify available boreholes in or close to the 14 targeted areas. A field campaign was launched to find existing boreholes, which was facilitated by using coordinates of known boreholes, and identify those suitable for monitoring. Only publically accessible boreholes, which belonged to governmental institutions (e.g. schools), were considered. For private boreholes, access or change of ownership might cause serious troubles for long term investigations. No special safety measures were applied, since the loggers were installed in already existing boreholes, so it was hardly visible for strangers that the borehole served monitoring purposes and that equipment had been inserted.
Figure 8: Geology of the study area (modified, after Thieme et al. (1981)) and target areas for groundwater monitoring.
Besides ownership and access, the following criteria were assessed to select suitable boreholes:

- Locality
  (Coordinates; District; River catchment; Next gauging station)
- Distance to nearest (production) borehole,
  (i.e., the nearest borehole where water is pumped electrically)
- Borehole information
  (Depth; Casing type and diameter; Organization or company that drilled the borehole)
- Static water table
- Accessibility during rainy season
  (Compared to river gauging stations of lower importance since only water level measurements are conducted and automatic records had just to be verified with manual measurements)
- Functionality of handpump
  (Currently in use; Frequency of use; Time since break down; Type as not all types were suited for installation of loggers)
- Existence of problems due to low water table at the end of the dry season
  (i.e., borehole or handpump falling occasionally dry)
- Further aspects (e.g. safety issues, need for rehabilitation) were discussed in a comment section

Based on the assessment, the final stations were selected. No suitable boreholes were identified for target areas F (close to the Kafubu gauging station in Masaiti) and P (close to the Kafue gauging station in Machiya). For target area M it was decided to monitor the water level at Lake Kashiba, as it is very likely to be connected to the surrounding aquifers.

Target area A was the only one, where proper monitoring boreholes were used. Yet they were already existing and belonging to a network of 11 stations installed by a project funded by the Kreditanstalt für Wiederaufbau (KfW, German Development Bank). The boreholes were located at the airport of Ndola and at the Misundu Forest. The latter had been vandalized and was equipped with a new logger and cover by GReSP. The remaining KfW boreholes were not located within the study area.

Table 10 gives a summary of the selected boreholes, their positions, their type, their supposed lithology and the main characteristics of the area they are installed in. The network is displayed in Figure 9 and details concerning the technical installation can be found in Fahle et al. (2017).
Figure 9: Installed monitoring network of the study area.

Table 10: Selected groundwater monitoring stations. Coordinates refer to WGS84.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude Longitude</th>
<th>Type</th>
<th>Lithology</th>
<th>Characteristics of location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiwale</td>
<td>13.20835° S 28.71532° E</td>
<td>Handpump</td>
<td>Basement Complex (Border to quartzite)</td>
<td>Recharge area, Headwater of tributary to Kafualufuta River, Rural area with small scale farms</td>
</tr>
<tr>
<td>Titibuke</td>
<td>13.50511° S 28.68981° E</td>
<td>Handpump</td>
<td>Quartzite</td>
<td>Recharge area, Headwater of Nyayishi (i.e., tributary of Kafualufuta River), Rural area with relatively high percentage of forest cover</td>
</tr>
<tr>
<td>Shingwa PS</td>
<td>13.40915° S 28.12411° E</td>
<td>Handpump</td>
<td>Dolomites</td>
<td>Discharge area, Interaction with Mpongwe River, Possible effects of groundwater abstraction for irrigation in upstream part of the aquifer</td>
</tr>
<tr>
<td>Kafubu Block B PS</td>
<td>13.15289° S 28.53093° E</td>
<td>Rehabilitated historical borehole</td>
<td>Basement Complex (Border to quartzite)</td>
<td>Center of catchment, Small scale farmer dominated area</td>
</tr>
<tr>
<td>Ibenga Water Treatment Plant</td>
<td>13.34546° S 28.41888° E</td>
<td>Old production borehole</td>
<td>Basement Complex</td>
<td>Discharge area, Interaction with Kafualufuta River, Possible effects of urban expansion of Ibenga, Very shallow water table (&lt;2m bgl)</td>
</tr>
<tr>
<td>Ibenga Forest</td>
<td>13.34397° S 28.41817° E</td>
<td>Old production borehole</td>
<td>Basement Complex</td>
<td>Discharge area, Interaction with Kafualufuta River, Possible effects of urban expansion of Ibenga</td>
</tr>
<tr>
<td>Location</td>
<td>Latitude Longitude</td>
<td>Type</td>
<td>Lithology</td>
<td>Characteristics of location</td>
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<td>---------------------</td>
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<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Kambowa</td>
<td>13.1064° S 28.8029° E</td>
<td>Rehabilitated historical borehole</td>
<td>Quartzites</td>
<td>Recharge area, High altitude as close to catchment boundary, Headwater of Mukulingwe (i.e., tributary of Kafubu River), Small scale farm dominated area</td>
</tr>
<tr>
<td>Ndubeni Mayeba Community</td>
<td>13.4087° S 27.8275° E</td>
<td>Handpump Shales</td>
<td>Basement Complex</td>
<td>Discharge area, Interaction with Kafue River, Area dominated by natural vegetation (Miombo woodland)</td>
</tr>
<tr>
<td>Kabya PS</td>
<td>13.5179° S 28.1962° E</td>
<td>Handpump Dolomites</td>
<td>Recharge area, Possible effects of groundwater abstraction for irrigation downstream</td>
<td></td>
</tr>
<tr>
<td>Kasamba Community</td>
<td>13.2634° S 28.2605° E</td>
<td>Handpump Basement Complex</td>
<td>Discharge area, Interaction with Kafulafuta River, Small scale farm dominated area</td>
<td></td>
</tr>
<tr>
<td>Lake Kashiba</td>
<td>13.4430° S 27.9405° E</td>
<td>Sinkhole Dolomites</td>
<td>Discharge area, Interaction with Kafubu River’s baseflow, Aquifer tapped by pumping gallery by KWSC</td>
<td></td>
</tr>
<tr>
<td>Mpongwe Farm</td>
<td>13.5917° S 28.0935° E</td>
<td>Abandoned borehole Dolomites</td>
<td>Recharge area, Area of groundwater abstraction for irrigation, Commercial farming plot</td>
<td></td>
</tr>
<tr>
<td>Misundu Forest</td>
<td>12.9066° S 28.6320° E</td>
<td>KfW monitoring borehole, stolen logger was replaced</td>
<td>Recharge area for Itawa Springs, One of the main sources of Kafubu River’s baseflow, Aquifer tapped by pumping gallery by KWSC</td>
<td></td>
</tr>
<tr>
<td>Ndola Airport</td>
<td>12.9937° S 28.6610° E</td>
<td>KfW monitoring borehole</td>
<td>Interactions with water table measured in Misundu Forest possible (same aquifer), Area of urban impacts like domestic and industrial groundwater abstractions, Close to industrial area of Ndola</td>
<td></td>
</tr>
</tbody>
</table>

**Lithological information:**
Basement complex refers to “Undifferentiated Basement Complex; mainly granitic gneisses & migmatites with some granite”, Quartzites refer to “Shales, mudstones, sandstones & quartzites”, Dolomites refer to “Upper Roan: Dolomites, argillites”, Shales refer to “Kundelungu undifferentiated; may include some Mine Series in the north-west; predominantly shales, siltstones, sandstones & mixtites”

a) Logger was first installed at handpump (13.1524° S, 28.5302° E) but yield was so low that no meaningful measurements were retrieved.

**10.3.4. DENSITY OF OBSERVATION POINTS**

With the 13 groundwater monitoring stations (i.e., including Lake Kashiba) installed and a study area of about 6,879 km², the density of the network is about 1.9 stations per 1,000 km². According to the classification given in section 5.4.4, the network falls within the well-developed networks. As discussed in the same section, for basic/reference networks a widely spaced network is generally sufficient. Still, according to the recommendations of the IGRAC
expert team (IGRAC 2008) a much higher density of up to 1.5 stations per 100 km² or higher would have been necessary for the area as unconfined aquifers are investigated. In our case, groundwater management within the cities of Ndola and Luanshya would require local monitoring networks with much higher densities, but was beyond the scope of the current project.

It also has to be taken into account that all stations are equipped with loggers, hence water table fluctuations are recorded constantly. More information is provided, e.g. the exact times of peaks and troughs, which are very likely to be missed by manual measurements. The value of such automatic stations is therefore much higher than those of manual stations.

Relatively low density of groundwater observations is also compensated by the streamflow measurements made. The baseflows determined at these stations enable to derive statements about groundwater recharge in an integrative manner for large areas.

Finally, the measurements of the pilot monitoring network will be indicative of the necessary density of a future optimized network. In case the measurements have nothing in common, additional observations will be needed. In contrast, a high redundancy of the measurements would indicate that even fewer stations are necessary or that some of the stations can be downgraded from automatic to manual stations. However, one must consider that manual measurements at handpumps might be disturbed by pumping, especially when the specific yield of the borehole is low or medium.

10.4. MEASUREMENT FREQUENCY

Extent of water level fluctuations, especially of short-time fluctuations, was not known beforehand and a high frequency of measurements was therefore chosen. Gathered data might be used in a later stage to adjust the frequency of the measurements when optimizing the monitoring network.

As data loggers were used at all the monitoring stations, higher measurement frequencies were not associated with higher costs. The main negative effects are that high-frequent logger measurements might lead to faster exhaustion of the logger’s battery and that due to the limited storage capacity it is necessary to read out the logger more often. For example, the HOBO® loggers used can store around 2 years of data when measuring at hourly intervals. For 15 minute intervals the storage is reduced accordingly to half a year, which might already pose problems as loggers installed at rivers might be submerged for a long time during and after the rainy season.

Hourly intervals were therefore chosen for the groundwater levels. This is justified as the aquifers investigated are considered unconfined and mostly shallow, partly subject to probably high flow velocities, especially in the Mpongwe Karst area. Also recharge during the rainy season is assumed to be a relatively fast process in the latter area. Areas with very shallow groundwater tables might also show diurnal fluctuations caused by evapotranspiration (Gribovszki et al. 2010), which in turn can be used to estimate evapotranspiration when high-resolution data is available.

Furthermore, having chosen handpumps for installation of some of the loggers, a high measurement frequency is necessary as the water table during the day might be affected by the pumping and the (nearly) static water table can be only measured in the early hours of the days after pumping had ceased during the night. High-frequent measurements at the handpumps also give an indication of the specific yield of the borehole.

In addition to the logger measurements, reference values are measured manually every 2 to 3 months (as trafficability of the roads allows). First, this is to detect any malfunctioning of the loggers, which are read out at these instances. Second, manual measurements ensure that
sufficient data is gathered in case of logger failure. Ideally, measurements would be conducted during the annual extremes. The lowest and the highest values are expected to occur at the end of the dry season and after the rainy season, respectively. Still, one has to consider that these dates vary according to the infiltration conditions encountered (e.g. rainfall distribution, groundwater level, soil permeability). Measurements from the loggers can be used to define these dates for the different monitoring stations and optimize the manual measurements.

Hourly observation intervals were also used for river water levels. In general, these have to take into account the size of the river, its location in the catchment and the catchment size. For instance, the stations in the Kafue with its large corresponding catchments do not show an instant reaction to rainfalls. An hourly interval is likely to create redundant information. Yet in headwaters of rivers, like at the Great North Road station of the Kafulafuta, the reaction to rainfall is very fast, so the high frequency was justified.

Gauge readers were employed to conduct manual water level readings at the rivers. According to Zambian standards, they are supposed to read at 06:00, 12:00 and 18:00 hours. Hence, manual readings are sufficient at the stations with big catchments (Kafue and Kafulafuta in Kasamba) while they are likely to miss peaks during the rainy season at upstream monitoring stations or smaller rivers.

As described above, quality measurements were only done in form of campaigns. To cover a wide range of conditions, two campaigns were conducted: One during the rainy season and one at the end of the dry season including the start of the rainy season. Still, the results will not allow to evaluate the frequency needed for future quality monitoring stations, hence reference should be made to the recommendations given in chapter 5.4.5 and Table 6 to Table 8.

11. PRELIMINARY EVALUATION OF INSTALLED MONITORING NETWORK

11.1. STATUS OF THE INSTALLED NETWORK AND MEASUREMENTS CONDUCTED

The designed monitoring network was installed between end of September to mid of November 2016. Details about the installation and all stations are given in the technical note by Fahle et al. (2017). A field guide describing how to measure streamflow and groundwater levels was also compiled (Krekeler 2017). Since the initial installation, various maintenance measures have been conducted. For instance, malfunctioning loggers and worn-out gauge plates had to be replaced. The station at Kafubu Block B was shifted from a handpump to a now rehabilitated abandoned borehole. Also cases of vandalism occurred (at Lake Kashiba and at the Kafue gauging station in Ndubeni). Furthermore, some of the cables used to hold the loggers were perforated by rust and broke. Most loggers affected were rescued by using a magnet, but some were damaged and had to be replaced. All cables were replaced as well. Unfortunately, gaps in the time series resulted from the cable failure.

In the following a preliminary evaluation of the monitoring network and efforts based on the data gathered up to now is given. A more detailed evaluation of the measurements will be provided in an upcoming technical report, covering the measurements conducted during the three hydrological years (lasting from October to September) 2016/2017 to 2018/2019. Separate reports will be issued concerning the water quality and water level sampling campaigns, providing an overview of the hydrochemical characteristics and a groundwater contour map, respectively.
11.2. Evaluation of the River Gauging Stations

Figure 10: Water level of the Kafulafuta River in Ibenga. Note that in November 2016 water level fell below logger installation depth and, hence, could not be recorded.

First hydrological characteristics can be derived from the water level data collected up to this point. For instance, the Kafubu in Masaiti is likely to be influenced by the Kafubu Dam, although it is located more than 30 km downstream of its outlet. Still, high flows and flood peaks were not as pronounced as those of the Kafulafuta in Ibenga, having a similar catchment size. On the other hand, baseflow was much higher at the Kafubu, stemming either from the compensating effects of the dam or the higher discharge of Ndola’s karst aquifers and effluents from the city’s water supply. In contrast, the Kafulafuta in Ibenga nearly dried out in 2016 (Figure 10). The water level time series of the dry season in 2017 also showed unnatural drawdowns and fast recoveries, clearly indicating a (not permitted) water abstraction from the river upstream. The Mpongwe River completely dried out during the dry season 2016. As water was still observed upstream in Mpongwe Boma, the cause for the vanishing discharge might be either water abstraction or, more likely, the evapotranspiration of the riparian vegetation along the course of the river. Long time records will show whether drying out was exceptional or common and whether land use or climatic changes will cause a more frequent occurrence of the dry spells.

Figure 11: Example of a preliminary rating curve established for the study area. Graph shows results for the Kafubu monitoring station in Ndola/Twapia.

Discharge was measured at most gauging stations for a wide range of water levels and preliminary rating curves were developed (e.g. Figure 11). At some stations, discharge
measurement was difficult during extreme conditions. For instance, at the Mpongwe River water ponded during low flows, so flow velocities were too low to ensure reliable measurements and the cross-section at places with discernible flow was too shallow to be measured. During very high flows, water was flowing over a width of 100m on the floodplain. At other stations, the river diverges into two branches during high flows (Kafubu/Masaiti, Kafulafuta/Great North Road), which then have to be measured separately.

At the two stations in the Kafue River rehabilitated by KfW, only occasional discharge measurements were conducted to verify the existing (historical) rating curve. At the station Mpatamatu, streamflow measurements were impeded, as no boat was available. The station in Ndubeni proved to be inaccessible by road during and even after the end of the rainy season. Gauge plates were vandalized and the logger pipe broke loose during an attempt to access the logger. Finally, it was decided to abandon the station, yet two discharge measurements were conducted up to then.

Concerning the measurement frequency, the points discussed in Sub-Section 5.4.5 apply. Yet the reaction in headwaters were so fast that a higher frequency than hourly intervals is suggested during the rainy season. Especially the Kafubu River in Ndola/Twapia reacted very quickly, probably due to the high degree of sealing in its catchment. In addition, the sewage water treatment plant located just upstream might have an influence by discharging rainfall water channeled by the sewer network. Even during the dry season, high frequent daily variations were recorded, probably also stemming from the plant. Therefore, at Ndola/Twapia and at the Kafulafuta station at the Great North Road automatic recording devices are necessary and the measuring interval should be set at 15 minutes during the rainy season. Frequency can be switched to hourly after the cessation of the rains. The advantage of these stations is that the pipes hosting the loggers are only submerged for a limited time and logger access is granted during most parts of the year.

Gauge readers are currently assigned to all stations. Those who were already employed before the rehabilitation of the stations (Kafue/Ndubeni, Kafubu/Masaiti) showed a poor performance. Of the five remaining gauge readers employed by the GReSP project, performance was mixed. Some readings showed inexplicable deviations from manual measurements of the GReSP team and sometimes values were just made up in time of absence. Concerning the gauge readers at the KfW rehabilitated stations in the Kafue, no data for evaluation was available. In general, when doing their work properly, the employment of gauge readers was helpful for backing up logger data or in case of logger failure (like at the Kafulafuta station in Kasamba). Still, for fast reacting rivers like the Kafubu in Twapia, three measurements a day will miss most short-lived flood peaks at night and will underrepresent the runoff generated during the rainy season. Figure 12 shows an example of divergence of the water level time series derived from automatic and gauge reader data, resulting from a nocturnal flood peak. The difference will even magnify when converting the water level into a discharge time series due to the exponential shape of the rating curve (Figure 11).
Figure 12: Comparison of hydrographs from logger data and gauge reader data (assuming perfect readings) at the Kafubu monitoring station in Ndola/Twapia.

The installed river gauging network delivers the basic discharge data to describe the study area. Except for the problematic Kafue gauging station in Ndubeni, it is recommended to continue monitoring at the remaining eight gauging stations. Since the initial installation was done with a rather low budget approach, installations should be upgraded with better gauge plates (as at some stations a thick layer of organic material deposited during high water levels and its removal also caused the plate inscription to disappear) and a logger installation featuring a buried pipe, allowing logger access throughout the year and avoiding problems faced with welding the logger pipe to angle irons (e.g. submergence, break off).

Of course, additional river gauging stations could be considered to improve the hydrological understanding of the area. Examples include (cf. Figure 4):

- **Kafulafuta upstream of new dam**
  The historic gauging station at Ibenga will soon only reflect outflows from the Kafulafuta Dam, which will be built just upstream. As an alternative, an additional gauge should be considered upstream of the dam to measure the inflow to the dam, an information needed to manage the dam properly.

- **Lufanyama River**
  While not part of the study area, the Lufanyama is the biggest tributary to the Kafue in the western side of the basin block. Hence, discharge at the Kafue River in Mpatamatu could be compared to the discharge observed at the Kafue River in Machiya, considering the inflows from the Kafulafuta, Mpongwe and Lufanyama rivers in between to better assess how much groundwater is exfiltrating into the Kafue.

- **Little Mukulungwe**
  Being a tributary to the Kafubu just downstream of the Kafubu dam, the catchment of the Little Mukulungwe comprises small scale farmers, mining areas and might be in the future, assuming a fast growth of Ndola, subject to urbanization.

- **Luanshya River**
  The Luanshya River enters into the Kafubu just downstream of the gauging station in Masaiti, hence is up to now only accounted for by the Kafulafuta station in Kasamba, where its contribution is supposed to be minimal. Still, the river might be of interest since it passes through Luanshya and its mining areas. The river is prone to contamination and should at least be considered for water quality monitoring.

- **Kafulafuta tributaries**
  While from a socio-economic point of view the upper catchment area of the
Kafulafuta might be of limited importance as it is dominated by small-scale farms and forest cover, investigating the discharge of these tributaries might be of interest to reflect the impacts of deforestation. Forest cover, especially in the southern part of the study area is diminishing strongly since the 1990s as will be shown in an upcoming technical note. Monitoring could, for instance, include the Lwankuni River, whose catchment covers a large share of the area threatened by deforestation. Also it comprises shares of all three major hydrogeological units.

- **Chisanga River**

  Emerging in the vicinity of Lake Kashiba, this stream flows through an area of low relief and a major floodplain of the Kafue River, making it particularly interesting concerning runoff generation. Also interactions with the water levels of Lake Kashiba could be analyzed. Yet the stream channel is probably not well defined, especially during high flows, and discharge might be difficult to measure. Accessibility might also be critical during the rainy season.

In general, WARMA is supposed to handle water permissions for water abstractions from all surface waters. It is therefore recommended to conduct annual campaigns at the end of the dry season measuring the discharges of all streams and rivers during the driest time of the year. This information is of crucial importance needed to decide upon approval or rejection of water permits.

### 11.3. Evaluation of the Groundwater Monitoring Stations

Groundwater monitoring worked well at most of the stations. Logger malfunctioning occurred at the KfW-funded monitoring borehole at Ndola airport and at Kambowa and Kafubu Block B. For the latter two, loggers recorded inexplicable fluctuations that did not match with manual measurements. Both loggers were installed in abandoned boreholes, which had been flushed. At Kafubu Block B, the logger had been initially installed at a handpump but the borehole yield was so low that no meaningful data could be retrieved. Hence, the logger was relocated to the mentioned nearby abandoned borehole. At some stations the logger also dropped due to cable failure, resulting in time series gaps. At times loggers installed at handpumps got stuck during removal or re-insertion due to the narrow casing.

![Figure 13: Examples of groundwater level measurements at handpumps: Low yielding borehole in Kasamba (left) vs. high yielding borehole in Titibuke (right). Note that water table fluctuations at Kasamba resulting from frequent pumping and a very low yielding borehole are so frequent that the lines showing these fluctuations appear as a filled area in the graph.](image-url)
Except for the station at Kafubu Block B, handpump installations proved to be a good and inexpensive option to monitor water tables. At several stations (Fiwale, Kabya, Titibuke – see Figure 13, right) yields were so high that water tables recovered quickly after pumping. At Kabya, a bounce back effect was observed, i.e., after pumping the water table shortly reached values slightly above the stationary level. In Shingwa and Kasamba (Figure 13, left), the yield was low and drawdown (especially in Kasamba) high. Since the loggers did not measure the water table directly but the combined pressure of the water and the atmosphere, calculation of water tables requires a barometric compensation (Krekeler 2017). This step needs a manual reference measurement, yet manual measurements at these two handpumps are always done at times of recovery and not at the exact same time when the logger was recording. If attempting to measure at the top of the hour (i.e., the time when the logger is recording), slight shifts in the internal logger clock will cause strong deviations between logger and manual measurements. Hence, no reference values were available and alternative ways have to found to reference the water tables. For Kasamba the minimum water table of a day (i.e., the water table measured when the water table dropped below the logger) was assigned to the depth of the logger. The water tables then may not reflect the absolute values (i.e., the distance of the groundwater from the surface), but their relative variations are still captured and allow for evaluation of year-to-year differences.

In general, water table dynamics caused by handpump activity allowed drawing conclusions on the hydrogeological characteristics. For instance, while the station at Shingwa is, according to the geological map, situated in a dolomitic area, the low yield rather suggests that it is already part of the schist formation that is located just north of the Mpongwe Karst. The data further contains some information on the water use patterns of the rural population. The deepest water tables were recorded in Misundu/Ndola (partly exceeding 40 m) and at the Zambeef Farm (up to 30 m). The latter showed the highest water table fluctuations during the year (more than 10 meters), suggesting either a low water storage potential or large rates of recharge and abstraction. The shallowest water table was measured at the water treatment plant in Ibenga, varying mostly between 2 m and 1 m below ground level. Recession during the dry season was limited and it is questionable whether the station is representative for the aquifer. The station installed at Lake Kashiba was vandalized within one week and only manual measurements were done. As the road to the Lake is hardly accessible during the rainy season, peak water levels were likely missed and re-installation of a logger is planned.

The data gathered up to now allows a first qualitative evaluation of the recharge patterns. Time when water tables increased considerably after the on-set of the rainy season 2016/2017 differed throughout the study area. At some stations, including those with the deepest water tables, recharge was observed already in mid-November (Misundu, Ibenga Forest & Water Treatment, Zambeef Farm) or mid-December (Shingwa). At other places, water tables just rose during January (Fiwale, Kabya, Ndubeni, Titibuke, Kasamba). These preliminary observations suggest that on-set of recharge cannot be derived from lithology of the area alone but has to incorporate other factors.

Furthermore, a comparison of water tables at the end of the dry season 2016 and 2017 showed that water tables of some aquifers were up to two meters higher than in 2016 (Fiwale, Shingwa, Titibuke, Zambeef). At other areas, water tables reached a similar level (Kabya, Kambowa) and in Kasamba the values observed in 2017 were even slightly lower.

Concerning the spatial density of the monitoring network, the variety of the water table and recharge dynamics strongly emphasize that at least the number of installed stations is necessary to cover the differences of the area. For permanent monitoring, it is recommended to complement automatic measurements with manual ones, especially for trend detection. Even an increased number of monitoring stations will however not suffice to determine
changes in flow direction, for which recurrent measurement campaigns are required. Handpumps are only an option for manual measurements when installed at high yielding boreholes or when measurements are taken at the early morning hours after the water table completely recovered during the night. However, in this case only one or two readings could be conducted per day as from around 6:00 hours on pumping activities will commence. Hence, permanent manual monitoring stations should be located at abandoned boreholes or, if finances allow, boreholes drilled for monitoring purposes. Accessibility is also a key requirement for manual monitoring stations, as measurements have to be taken during or at the end of the rainy season.

As funds allow, additional stations (either manual or automatic) could be considered for the following target areas:

- **Areas outside the project area**
  The initial network only considered monitoring points within the project area. The area was delineated based on surface water catchments, while is not sure whether these coincide with the groundwater catchments (cf. Sub-section 8.5). Hence, monitoring beyond the southern catchment border would help to clarify the boundaries between the Mpongwe and the Lukanga catchments.

- **Areas with deep water tables**
  Water tables at the installed monitoring sites are generally quite shallow, except for the stations at Ndola/Misundu and the Zambeef farm. Areas with deeper water tables are of interest as they lie within the recharge zone of the study area (i.e., the higher elevated areas) and since their processes might differ or be delayed compared to sites with shallower groundwater. Possible locations are in the surroundings of the headwaters of the Lwankuni River and the Nyayishi River in the south of the study area, where deep water tables were measured during a campaign.

- **Dambo areas**
  No water tables are currently monitored within or very close to wetland areas (i.e., dambos). Yet their hydrological regimes might be strongly affected by climatic or land use changes. Hence, monitoring would allow evaluating whether their high water tables are sustained in the long term. A suitable location would be at the edges of the Itawa dambo, which is probably already affected by urbanization and groundwater abstractions within Ndola. The huge lowland north of Lake Kashiba might be also of interest in that regard.

- **Urban areas**
  Groundwater should be also monitored in the two cities of Luanshya and Ndola. Yet since the water tables patterns are likely to be complex due to a multitude of production boreholes, a high number of monitoring stations are needed and it is advisable to design groundwater monitoring networks for the cities separately. Water quality issues will be of major importance.

- **Effects of mining**
  Impacts of mining activities should be monitored. Possible locations would be in the vicinity of the limestone quarries south-east of Ndola or close to mining operations in Luanshya. It is of interest whether water quality is impaired by the mining and whether mine dewatering has an impact on the surrounding groundwater (e.g. resulting in cones of depression).

- **Locations with natural vegetation**
  In the very southwestern part of the study area close the Kafue and in the
southeastern part in the surroundings of the Nsobe Camp, there are bigger areas of natural forest remaining, which could be monitored as a baseline/reference. Yet monitoring boreholes would be needed as the areas are unpopulated.

- **Additional locations downstream of farming blocks**
  
  To assess long term effects of irrigation, additional boreholes downstream of the big farming blocks (e.g. along the Mpongwe – Machiya Ferry road) could be monitored. A *measurement frequency* at manual stations of three times a year will suffice, when measurements are conducted on the same days every year. For the stations equipped with loggers, hourly intervals seem to be a good compromise but measurement frequency could be reduced. At handpumps, daily measurements at 4:00 or 5:00 hours would suffice, but information about pumping activity and yields would be missed. At the stations with deep water tables, hardly any dynamics are observed at hourly intervals. Still, data can be thinned out afterwards. In contrast, at stations with shallow water tables like those in Ibenga, water tables are much more dynamic and high frequency measurements are needed, i.e., to determine the influence of evapotranspiration.

12. OUTLOOK

Designing and installing an initial monitoring network is the first step in developing a monitoring program for an area (Figure 14). Evaluation of the *initial network* based on the measurements made (cf. Section 11) allows selecting future priority stations and excluding stations that deliver redundant information, leading to the design of the *basic (reference) network*. This network is intended to provide reference hydrogeological data and to characterise the hydrogeological units. In the process of optimizing the initial network, it has to be considered that seemingly redundant stations might provide more data that are independent in the future. Rather than completely discarding such stations, downgrading from automatic to manual measurements is recommended. For the short time span of the initial monitoring (about three years), manual measurements are of limited value, yet for the *basic network* they can provide valuable data about long-term changes, given time series are long enough and consist of two to four water table measurements per year. Of course, intra-annual patterns and shifts (e.g. temporal changes of the recharge patterns due to shifts in the on-set of the rainy season) cannot be assessed by such low-frequent measurements.

The network evaluation and optimization can be done by applying some of the widespread statistical methods available (see Mishra & Coulibaly (2009)), based on expert knowledge alone or a mixture of the two approaches. In any case, the evaluation has to take financial and human resources, problems that occurred during the initial phase as well as possible future developments (e.g. sites where land is converted into arable or urban areas or where commercial farming and irrigation is introduced) into account.

In order to achieve a comprehensive groundwater management, functionality of the network cannot be restricted to obtain a reference data set concentrating on quantitative aspects. Instead, qualitative aspects and additional monitoring functions as stated in Sub-Section 3.4 should be considered.

Hence, a water quality monitoring program has to be drafted. The results of the reconnaissance study conducted in the year 2017 can serve as a reference to detect priority areas, i.e. those with water quality problems. An elevated nitrate level was measured at a school in Ndola, indicating possible coliform contamination. In addition, indications of contamination (high concentrations of sulphate, elevated electrical conductivity) were found at a farm downstream of the tailings of a mine southeast of Ndola. Otherwise, the only
violations of standards defined by the Zambian Bureau of Standards (ZABS) were encountered concerning iron, manganese and pH (lower than 6.5), which do not pose any immediate health risk.

Figure 14: Way forward concerning monitoring in the project area.

Groundwater quality should therefore especially consider the large urban areas and surroundings of mines and tailings, both active and historical ones. Furthermore, impacts of large-scale farming have to be investigated. Especially in the big urban areas of Ndola and Luanshya monitoring should comprise regular measurements of potential biological contamination, analysing coliform and nitrate concentration as well as measuring electric conductivity. Measurements should comprise points in compounds, e.g. at handpumps or the artesian well at the Itawa springs. These measurements are important to map potential risk areas for water-borne diseases like cholera. Quality monitoring close to mines should concentrate on heavy metal concentrations as well as abnormal pH, electrical conductivity as well as sulphate concentrations (cf. Table 3). In the vicinity of farming blocks, nitrate can serve as an indicator of over-fertilization. Pesticides are another potential issue, as they are ubiquitous in Zambia and frequently used even by small scale farmers, including substances regarded as highly hazardous (cf. Jenkins et al. (2015)). Yet requirements regarding water sampling and cost of laboratory equipment far exceed those of the routine water sampling procedures, probably requiring the samples to be shipped abroad. Hence, measurements are very costly and may only be carried out whenever there is a concrete suspicion that a contamination exists, for example after a massive large-scale application of pesticides as during the Armyworm crisis in early 2017.

In general, quality monitoring needs a lower observation frequency than water table monitoring but a denser network, as spatial variations are typically higher. In accordance with Table 6 to Table 8, a measurement frequency of twice per year would be ideal under the given circumstances, covering quality changes between rainy and dry season. A network of 30 to 40 stations might be defined, which should include at least some of the stations used for water table monitoring as this would allow to relate water table dynamics with water quality. Repeating the reconnaissance survey, say every three years, might be considered as well to reveal temporal hydrochemical changes of the entire study area. Yet this would be
complementary as the survey focused on the general picture and not on areas of possible contamination or of importance for large-scale public water supply.

In addition to the basic network, compliance monitoring is needed, i.e., to control whether the quality of the abstracted groundwater complies with the standards defined by ZABS and to check whether groundwater abstractions are in line with the granted permits. Especially the latter is key to ensure sustainable management of the water resources. By law, WARMA can either install their own meters or let the permission holder install a meter (WRMA 2011 §67). Another option would be to request groundwater monitoring data from permit holders. These obligations should be primarily imposed to the biggest water users, like the water utilities in Ndola and Luanshya, farmers operating major irrigation schemes in Mpongwe and major industries (e.g. manufacturers of beverages, mines). Whenever a permission holder delivers data, it is crucial that the data are checked for plausibility and verified by WARMA’s own measurements. In sum, obtaining reliable abstraction rates is key to set up water balances and determining whether additional permits can be granted. Furthermore, part of the water fees are related to actual abstraction, so both users and WARMA should have a common interest in accurately measuring the usage.

Regarding water supply schemes (e.g. the well field in northern Ndola), performance monitoring in terms of quantity and quality is needed. Boreholes in the surrounding of the well field should be monitored to assess quantitative aspects of the groundwater abstraction. The quality of the water abstracted has to be frequently monitored. Additionally, groundwater upstream of the production boreholes should be monitored occasionally to provide early warning before actual contamination reaches the production sites, allowing to take suitable precautions. Suitable locations can be identified based on a groundwater contour map. In the current network, the borehole in the Misundu Forest in Ndola can serve for such purposes, as it is located upstream of the production wells. The performance monitoring network should be primarily operated by the corresponding water facility, yet WARMA could gather complementary data, e.g. to verify the quality analysis of the water facility.

Independent of the type of a monitoring network, maintenance is the key to sustainability. Without the corresponding effort, a network will sooner or later deteriorate, resulting in negative consequences for the water management. Sustainable management cannot be based on three years of reference data but needs reliable long-term measurements that allow assessing changes over time. Only data spanning over multiple years or decades enable, when combined with meteorological data and possibly interpreted by models, to distinguish natural (weather) variations from overexploitation of resources and impacts of climate change. The value of data is strongly impaired by discontinuous records. The longer the data gaps, the lower the value for hydrogeological evaluation. In order to ensure the continuation of the monitoring, a monitoring plan has to be developed (cf. Figure 2). This concept has to specify the frequencies of measurements to be done and to assign persons responsible for the monitoring. The latter not only includes technicians, who conduct the measurements and process the data, but also senior staff to check and evaluate the information. The data should be stored in the databases WARMA has set up for surface water and groundwater data. Optionally, annual reports resembling the hydrological yearbook could be issued and should include the data in form of a digital storage medium like a CD. In connection with the monitoring plan, it is inevitable to allocate a suitable budget for the field and laboratory work as well as to rehabilitate stations where necessary.
13. REFERENCES


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Appendices

A.1 CLIMATE MONITORING PRINCIPLES

The ten climate monitoring principles according to WMO (WMO/TD-No.847, in WMO 2011)

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems is required.

3. The details and history of local conditions, instruments, operating procedures, data processing algorithms, and other factors pertinent to interpreting data (metadata) should be documented and treated with the same care as the data themselves.

4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.

5. Consideration of the needs for environmental and climate monitoring products and assessments should be integrated into national, regional, and global observing priorities.

6. Operation of historically uninterrupted stations and observing systems should be maintained.

7. High priority for additional observations should be focused on data poor areas, poorly observed parameters, areas sensitive to change, and key measurements with inadequate temporal resolution.

8. Long term requirements should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation

9. The conversion of research observing systems to long term operations in a carefully planned manner should be promoted.

10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.
A.2 WATER MONITORING RESPONSIBILITIES IN ZAMBIA
AS PRESCRIBED BY THE WATER RESOURCES
MANAGEMENT ACT OF 2011
A.3 HYDROLOGICAL MAP OF THE STUDY AREA
A.4 GEOLOGICAL MAP OF THE STUDY AREA

Modified, after Thieme et al. 1981
## A.5 Monitoring Network Development Overview for the Case Study

<table>
<thead>
<tr>
<th>Target</th>
<th>Summary for case study</th>
</tr>
</thead>
</table>
| Legal Background, Responsibilities | Water Resources Management Act (WRMA) of 2011  
WARMA is responsible to  
- put in place and maintain a national monitoring and information system on water resources,  
- monitor the quality of the water resources, and set and recommend water quality standards in collaboration with the Environmental Agency,  
- measure the impacts of climate change.  
Persons, whose activities may lead or give rise to the pollution of a water resource, and permit holders can be asked to conduct monitoring measures for a specified period, or to install a meter.  
WARMA’s subordinate structures (i.e. (Sub-) Catchment Councils, WUAs) shall conduct the general monitoring tasks. |
| Assessment of Existing Monitoring and Available Data | Historical but partially dilapidated river gauging station network exists since the mid-1920s; data quality is often inconsistent or poor. The earliest records for the river gauges within the study area date back to the 1950s. Most records ended decades ago.  
Basically no groundwater monitoring data available. |
| Hydrogeological Setting/Main Aquifers, Land & water use | Total area of about 6,900 km² including the following main catchments and aquifers:  
Kafualafutu Catchment with Kafubu River as important tributary; aquifer is largely made of crystalline and metamorphic rocks of overall limited potential; dominated by rural water supply and small-scale farming.  
Urban areas of Ndola and Luanshya forming part of the Kafualafuta Catchment but with very complex geology and hydrogeology including a transboundary limestone aquifer with the DRC. Water is mainly supplied from dams, but also from springs and boreholes. High number of individual domestic boreholes. Various industries including |
limestone quarrying and copper smelting are present.

Mpongwe Karst plateau drained by a number of small rivers. Areas without surface drainage exist and significant amount of subsurface discharge into the Kafue River is presumed. Area is characterized by variable but partially high water potential suitable for commercial farming with dry-season irrigation.

Water tables are overall shallow in the entire area, except some areas close to the area’s boundaries.

Risks & Pressures

General uncertainty about exploitation potential of aquifers as well as recharge areas, processes, and amounts

Long-term changes/trends in water resources by changes in land use (deforestation, agricultural use) or climate change

Overexploitation leading to severe reduction in baseflow of rivers during droughts

Increase in water demand esp. in the urban center of Ndola due to population and economic growth

Groundwater pollution related to poor sanitation, industrial effluents, mining and use of fertilizer, pesticides and herbicides

Impact on river discharge and local hydrogeology by existing Kafubu dam and future dam along Kafulafuta River

<table>
<thead>
<tr>
<th>Component</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Type</td>
<td>Initial monitoring network (for up to 5 years) as basis for a basic (reference) network</td>
</tr>
</tbody>
</table>
| Overall Objectives | Initial description of status and potential of water resources, with strong focus on quantitative monitoring
Provide basis for an optimized design of network
Establish first monitoring stations for basic network |
| Constraints | Maximum of about 20 monitoring automatic stations and loggers
Costs-efficiency, use of existing infrastructure (handpumps, abandoned boreholes)
Existing historical gauging stations should be rehabilitated and included |
<table>
<thead>
<tr>
<th>Scale</th>
<th>Catchment scale, covering main aquifers</th>
</tr>
</thead>
</table>
| Distribution          | Fairly even distribution of groundwater monitoring sites (“stratified random sampling” considering geology, land use and recharge zones)  
Access during rainy season a crucial point in the area; monitoring boreholes to be placed in vicinity to gauging stations; locations prone to vandalism to be avoided |
| Types of Observation & Method | River gauging stations  
(2 from national network, 7 for catchment network)  
Boreholes with handpumps (6), rehabilitated abandoned (5) boreholes, existing (KfW) monitoring boreholes (2) and sinkhole (1)  
Springs proved not suitable  
All stations were monitored by data logger supplemented by manual readings  
Employment of gauge readers at river gauging stations |
| Parameters            | Mainly groundwater levels, stage of river/sinkhole and streamflows  
Stream flow for establishing water budgets for all relevant subcatchments and assessment of baseflow and groundwater/surface water interaction  
Water quality survey includes full analysis of inorganic water chemistry, stable isotopes and indicators for microorganism  
Abstraction for irrigation was estimated using a tool based on remote sensing imagery |
| Density               | 1.9 groundwater monitoring stations per 1,000 km² corresponding to a “well-developed” observation network |
| Time & Frequency of Water Level Measurements | Hourly for logger operated observation points  
Manual checks (every 2 – 3 months)  
Manual gauge readings three times per day (at 06:00, 12:00 and 18:00 hours)  
Reconnaissance surveys during dry and wet season |
### Implementation & Operation

<table>
<thead>
<tr>
<th>Component</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction/Implementation of Network</td>
<td>As described in the technical note by <em>Fohle et al.</em> (2017)</td>
</tr>
<tr>
<td>Monitoring Plan</td>
<td>Responsibility for measurements, data retrieval and maintenance with GReSP staff (except for stations at the Kafue river operated by WARMA)</td>
</tr>
<tr>
<td></td>
<td>Frequency of measurements as discussed above</td>
</tr>
<tr>
<td></td>
<td>Timing of discharge measurements adjustable to hydrological conditions as measurements had to be conducted at different water levels to establish rating curves</td>
</tr>
<tr>
<td></td>
<td>Measurement procedures as discussed in field guide (<em>Krekeler 2017</em>)</td>
</tr>
<tr>
<td></td>
<td>Reconnaissance survey of water tables to generate contour map and identify flow patterns</td>
</tr>
<tr>
<td></td>
<td>Reconnaissance surveys of water quality to establish the status of water quality representative for entire area and for dry/wet season</td>
</tr>
<tr>
<td>Data Storage &amp; Analysis</td>
<td>All data were stored in tailor-made spreadsheets</td>
</tr>
<tr>
<td></td>
<td>Data transfer to WARMA was envisioned</td>
</tr>
<tr>
<td></td>
<td>Quality checked data of the three hydrological years under consideration to be issued in a technical note</td>
</tr>
</tbody>
</table>

### Outlook on Future Development of Monitoring Network

<table>
<thead>
<tr>
<th>Recommendations based on preliminary evaluation of measurements</th>
<th>Initial network is overall suitable for long-term monitoring, but a few cost-efficient manual stations should be added with 2-4 measurements per year.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement frequency be set to 15 minutes at gauging stations in headwater locations with high observed fluctuations during rainy season</td>
</tr>
<tr>
<td></td>
<td>Compliance networks to be developed in Luanshya and Ndola comprising monitoring water quality incl. biological contamination, and in areas under commercial agriculture</td>
</tr>
<tr>
<td></td>
<td>In the Mpongwe Karst, the investigations and setup of the monitoring network should be extended into the adjacent catchments as groundwater divides are unknown.</td>
</tr>
<tr>
<td></td>
<td>Special network may be required to assess the impact of deforestation; e.g. in the Lwankuni River sub-catchment</td>
</tr>
</tbody>
</table>
A.6 SCHEME OF GROUNDWATER MONITORING NETWORK DEVELOPMENT
Guideline on Establishing a Groundwater Monitoring Network

Collect available background information of the monitoring framework

<table>
<thead>
<tr>
<th>Questions</th>
<th>Existing Monitoring and Data</th>
<th>Hydrogeological Setting</th>
<th>Land &amp; Water Use</th>
<th>Potential Risks &amp; Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>What kind of monitoring already exists?</td>
<td>Which catchments can be delineated?</td>
<td>What are the main land uses of the area? (E.g. industries, irrigation, farming, mining, urban)</td>
<td>Which groundwater-related issues exist or will arise in the future?</td>
<td></td>
</tr>
<tr>
<td>Are hydrogeological and hydrological monitoring data available &amp; does the quality of the data meet required standards?</td>
<td>Which aquifers and strata exist?</td>
<td>Where and how much water is used?</td>
<td>Where are points of possible groundwater contamination?</td>
<td></td>
</tr>
<tr>
<td>Data bases of water and local authorities</td>
<td>What are the hydraulic properties (e.g. permeability, depth to water table, confined/unconfined)?</td>
<td>Satellite imagery and remote sensing products</td>
<td>Satellite imagery and remote sensing products</td>
<td></td>
</tr>
<tr>
<td>Data published in reports (e.g. hydrological yearbooks &amp; reports)</td>
<td>(Hydro-)Geological &amp; topographic maps</td>
<td>Information from statistical offices</td>
<td>Spatial information on potential sources of contamination (industries, agriculture) or excessive water use</td>
<td></td>
</tr>
</tbody>
</table>

Develop Conceptual Groundwater Model

Delineate the (main) aquifers and develop a conceptual understanding of groundwater flow, areas of recharge and discharge, vulnerability, possible quality issues and pressures exerted by water uses

Define Monitoring Objectives

Possible objectives:
- Determine general status of groundwater & trends
- Provide data for management or hydrogeological science
- Protection of groundwater systems and the environment

Define Network Type

Network size: National / regional / local
Development stage: (Extended) pilot / final / final optimized
Parameters observed: Quantitative / qualitative
Functions: Basic / research / compliance / early warning / performance

Design the Monitoring Network

Network Scale: Define the areas that should be covered by the monitoring network based on:
- Surface & sub-surface catchments
- Extent of aquifers
- Surface water monitoring network (if already existing)
Distribution of Observation Points: Define the places (and for groundwater the depth) to be monitored based on:
- Lithology, hydrogeology, water use, land use, contamination, accessibility and monitoring objective.
- Proximity to rain and river gauges is preferable
Type of Observation: Define which water bodies should be monitored.
- Possible monitoring types comprise: Production wells, boreholes, springs, (groundwater-connected) lakes and rivers.

Density of Observation Points: Define the number of monitoring points. Higher numbers are needed if:
- Spatial variability of parameter is high (e.g. for quality parameters)
- Hydrogeological or hydrochemical setting is complex
Observation Time & Frequency: Define frequency of measurements.
- Higher frequencies are needed for (e.g.) highly variable parameters
- High hydraulic conductivity
- Fast flows & high recharge amounts
- High groundwater withdrawal
Parameters: Define the parameters to be monitored.
- Quality parameters comprise water levels, discharges and pump rates
- Quantity parameters are manifold – often statutory instruments define minimum parameter set.

Installation of Monitoring Gauges

Compile overview of installations made and equipment used.

Set-Up a Monitoring Plan

- Plan supplementary measurement campaigns (e.g. reconnaissance studies to derive groundwater flow patterns and assess groundwater quality)
- Specify procedures for data collection and storage
- Specify schedule for measurement and maintenance
- Define responsibilities for different tasks
- Allocation of staff and financial resources (also for repairs)

Collect, Store & Analyse Data

- Set up data base(s) to store measurements
- Define responsibilities for data entering, quality checks and data analysis
- Make data available on request and on fixed terms (e.g. in form of hydrological year books)
- Analyse data with respect to monitoring objectives and hydrogeological processes