Groundwater Resources for Lusaka and selected Catchment Areas

TECHNICAL REPORT NO. 4

HYDROGEOLOGY OF THE TOWN AREA OF SOLWEZI - BASELINE STUDY ON HYDROGEOLOGY AND HYDROCHEMISTRY

by

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Lusaka, December 2015

REPUBLIC OF ZAMBIA

Ministry of Water Development, Sanitation and Environmental Protection
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<td><em>Hydrogeology of the Town Area of Solwezi. Baseline Study on Hydrogeology and Hydrochemistry</em></td>
<td>Technical Report No. 4</td>
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<td>November 2013</td>
<td>Tewodros Tena &amp; Dr. Tobias El-Fahem</td>
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Summary

Authors: Max Karen, Dr. Tobias El-Fahem, Levy Museteka

Title: Hydrogeology of the Town Area of Solwezi. Baseline Study on Hydrogeology and Hydrochemistry.

Keywords: protection, groundwater, Solwezi, Zambia, hydrochemistry

The town of Solwezi is a rapidly expanding mining town in the North Western Province of Zambia. The scale of the influx of workers to the town has outpaced the ability of the water utility and planning authorities to adapt the infrastructural development which has resulted in on site sanitation being prevalent. In order to improve the planning for the development of Solwezi a hydrogeological baseline study was conducted. This study included a sampling programme that looked at the water quality by analysing the inorganic and microbiological water quality.

The analysis of the available data indicates that there are two main aquifers in the area; a metamorphic basement type aquifer with shallow groundwater; this was termed the Solwezi Schist and is very important to domestic and commercial water supply as it underlies most of the main populated area. The other main aquifer is a karstic marble aquifer called the Chafugoma Marbles. It is present near the surface to the south of the town where several wellfields are located and also north of Solwezi town where an important mining area is situated.

A number of contamination sources and land use changes were identified during the study which pose a significant threat to the quality of the groundwater extracted from the major wellfields for public water supply. A conceptual model of the groundwater flow system for the town area of Solwezi was developed.

Recommendation is given on the delineation of protection zones for the major public supply wellfields. The implementation of the protection zones will require the integration of the plans into the district development plans which are under development by the Solwezi District Council. Furthermore it requires the cooperation between the local authorities with the local communities and mining companies for the sustainable development of Solwezi.

The Groundwater Resources management programme (GReSP) provided during the hydrogeological work in Solwezi Town training for the staff of the Provincial Water Office in different aspects of groundwater data collection. Based on the resulting data GReSP could provide important suggestions for the future development of protection zones around the wellfields for public water supply and to suggest future wellfield areas that are less vulnerable to contamination and can be protected both physically and through legislation.
Executive Summary

The town of Solwezi is a rapidly expanding mining town in North Western Province of Zambia, the scale of the influx of workers to the town has outpaced the ability of the water utility and planning authorities which has resulted in on site sanitation being prevalent.

Solwezi town represents many of the important issues that affect the present and future groundwater resources of Zambia. However, there is still little knowledge about the availability and quality of local groundwater resources around Solwezi. The Federal Institute for Geosciences and Natural Resources (BGR) through the Groundwater Resource Management and Support Programme (GReSP) implemented this hydrogeological baseline study in close cooperation with the Water Resource Management Authority (WARMA), and the Provincial and District Department of Water Affairs (DWA) staff.

The baseline study included the review of the hydrogeology of Solwezi Town and a sampling programme that looked at the groundwater hydrochemistry by analysing the inorganic and microbiological water quality. This data was backed up by stable isotope sampling and analysis to better understand the origins of groundwater in this area.

The analysis of the available data indicates that there are two main aquifers in the area; a metamorphic basement type aquifer with shallow groundwater; this was termed the Solwezi Schist; this aquifer is very important for the domestic and commercial water supply as it underlies most of the main populated area. The other main aquifer is a karstic marble aquifer, the Chafugoma Marbles that is present near the surface to the south of the town where several wellfields are located.

The Chafugoma marble is structurally controlled and interpreted to be present below the town. The marble aquifer south of Solwezi forms a continuous structural unit with the aquifer in the Kansanshi mine where it needs to be dewatered on a large scale. The marble aquifer is also linked to the wetland area that lies to the west of Solwezi – Lake Kimasala. The presumed lower water levels in the wetland area have therefore been attributed to the mine dewatering. This has been a controversial subject in Solwezi between people who used to use the lake for fishing and the mine. The structural setting combined with the Karstic nature of the aquifer mean that the link cannot be disproved.

The water levels were measured at over 300 locations around Solwezi in December 2014. The water level data was complimented by additional water level sampling in August 2015. The water level data indicated the presence of a low permeability shallow aquifer in the weathered zone of the Solwezi schist. This source is used extensively for as domestic water supplies, especially in the unplanned settlements of Solwezi. The shallow nature of the aquifer and the prevalence of pit latrines and unsafe faecal disposal methods pose a contamination threat which was confirmed by the organic sampling which found high levels of E.coli in the shallow wells. Boreholes in the area were also sampled and although lower levels of contamination were found compared to the shallow wells, over 56 % of the sampled boreholes were found to contain E.coli; this data indicates a major health risk to the population.
Water samples from the town were sampled in order to look at the general hydrochemistry but specifically also to create a baseline and to assess if there is heavy metal contamination due to mining activities. According to the results of the hydrochemical analysis no heavy metals were detected in the 32 water samples. The structure of the aquifer and the population distribution however means that the water samples were mainly taken from the shallow aquifer, it is therefore hypothesised that the non-presence of heavy metal contamination could be related to the fact that the samples are mainly from the shallow aquifer. The hydrochemical and stable isotope data also confirms that the groundwater sampled is relatively young and was possibly recharged only within a few kilometres of the sampling point.

The water samples taken from the water supply wellfields also indicate the presence of E.coli in the production wells and nearby hand dug wells. The wellfields are all located in the river valleys which are located to the South and Southeast of the town. The valleys are structurally controlled and underlain by the marble aquifer, the water level data within the karstic aquifer indicate that groundwater flow could transport pollutants from pit latrines and septic tanks to the water supply production boreholes. It is also possible that other sources such as surface runoff or harmful land use could contribute however pollution from septic tanks is the most probable source.

A detailed hydrogeological numerical model would be required to look not just at the dewatering in the mine area but to look at the sub regional groundwater flow. This will provide more data on the link with the wetland and can also be used to predict the possible direction of contaminant flow in the underlying Chafugoma marble aquifer. The model should also include a detailed analysis of the threat posed by the tailings and hazardous waste facilities in relation to the Kansanshi stream.

Protection zones around the existing wellfields are needed to prevent further deterioration in water quality and steps should be made to reduce the contamination threat from sanitation. Protection zone boundaries are recommended based on the three zone international standards. In the medium term it is recommended that the wellfields are relocated to areas that do not have high population density and where protection zones can be implemented upon construction, it will be essential that close cooperation between the water utility and the city council ensures that planning restrictions protect the areas. Several areas are presented in the report as possible exploration areas due to the low population and the presence of the highly permeable karstic marble aquifer.
1. Introduction

With the introduction of the Water Act from 2011 Zambia is turning towards water resource management on catchment level.

The Upper Kafue Catchment is an important catchment where many of the commercial water users are located, and in particular the major mining activities in Zambia take place. The mining towns in the Upper Kafue Catchment are “hot spots”, due to environmental concerns, population growth and rising sanitation issues. The regulation and permitting of water use in this area is therefore of high priority for the new Water Resource Management Agency (WARMA). The Upper Kafue Catchment comprises the eastern parts of the North-Western Province, all of the Copperbelt Province and parts of the west of Central Province (Fig. 1).

Solwezi is the Provincial centre of the North Western Province and one of the fastest developing settlements in Zambia due to its position in the so-called “New Copperbelt”. Mining activities are moving along the mineral rich geological formations from the Copperbelt area towards the North West of Zambia. Major mining companies such as First Quantum and Barrick, are exploiting the copper mineralisation in the area. In addition other minerals are mined such as cobalt, gold and uranium in the area around Solwezi. The scale of the mining activities has led to a huge influx of workers and their families to Solwezi. The population pressure has led to a major expansion in unplanned settlements and planned construction projects which are increasing in the town area rapidly. The municipal management has not been able to keep pace with the rapid development which has been exacerbated by a lack of investment (DAGDEVIREN, 2008) in infrastructure and land management.

The Solwezi District area is administratively part of the North-Western Province while the watershed between the Zambezi and the Upper Kafue Catchment is more or less dividing it in two halves.
Due to the positive dialogue between GReSP, WARMA and the Provincial Water Office (PWO) in Solwezi it was decided to have a baseline hydrogeological assessment for the town of Solwezi during 2014 and 2015 as an example of how a baseline hydrogeological study could facilitate planning and protection of groundwater resources.

2. Project Objective

The objective of this project is to provide a baseline hydrogeological assessment that integrates the available data on the groundwater of the area with new data collected during the fieldwork carried out in 2015 by the GReSP project. The groundwater resources have always been of secondary importance to the mineral exploration in the area and all the reports made available are related more to the mining geology or how mining activities could affect groundwater quality, no reports referring specifically to groundwater resources were found. This represented a major knowledge gap due to the vital importance of groundwater as a water supply source to the population of Solwezi.

The area has complex geological structures which have been the focus of many exploration and mining developments. Although the groundwater of the area has not been a focus of any major studies the formations that occur within and around the town have been targeted for water supply in other areas of Zambia and therefore information can be used and applied to the hydrogeology of the area. The area has many geological similarities to the Copperbelt and includes the economically important Mine Series and Kundelungu Formation.

The Kansanshi mine management was a significant source of information. The main geological mapping was carried out due to the presence of mineralised zones such at Kansanshi mine in the Solwezi area. The mine site was first pegged in 1899 and systematic production of Copper started in 1908 and carried on intermittently through to the 1950’s. Underground mining ceased in 1957 when a major groundwater inflow occurred after a high yield fault was intersected. The groundwater flow through the fault overwhelmed the available pumping capacity. Major mining operation have resumed since 2003 after privatisation. Due to the Kansanshi mine intersecting several aquifers major dewatering has been necessary, which has an effect on the groundwater of the area around the mine.

The rapid growth of Solwezi has led to expansion of housing without the water utility being able to keep pace with the demand for water supply or sewerage disposal. This has led to the people of Solwezi having to solve water supply and sanitation at local level by digging wells and pit latrines. This has created a situation where the water supply utility had reported incidences of pollution which needed to be quantified as a key objective of the baseline study.

The presence of the mine is also perceived by some to be a contamination threat. Therefore an additional objective was to assess how comprehensive the monitoring network for the mine was in terms of spatial coverage and objectivity and to carry out independent water sampling of water supply wells in the vicinity of the mine to test for heavy metal contamination and organic pollution.

3. Physiography

3.1 Topography and Drainage

Solwezi is just 24 kilometres south from the border with the Democratic Republic of Congo (DRC) in the North Western Province of Zambia. The border marks the main water shed between the rivers that flow south to the Zambezi and the northern drainage basin which flows to the Congo drainage basin. Water from the main rivers in the area are tributaries of the Kafue River; the area between
Solwezi and Ndola along the border form the headwaters of the Upper Kafue catchment. A second watershed lies to the west of Solwezi where the rivers form the headwaters of the Zambezi catchment.

![Drainage map of the Upper Kafue Catchment](image)

**Fig. 2: Drainage map of the Upper Kafue Catchment**

The main drainage feature in the Solwezi area is the Chifubwa River (Fig. 2) which flows from the north east then meets with the Solwezi River within Solwezi town. The Solwezi and Chifubwa rivers are tributaries of the Kafue River. In general the drainage patterns can be attributed to the underlying geology and an increased density of drainage channels is directly related to the underlying geology and geological structures.

The topography in the area is typical of the area with broad rolling hills with interfluves characterised by grassland and dambos. The topography and the drainage are closely linked, with the high ground to the north and south of Solwezi being related to changes in geology. The topography falls from 1,440 masl to less than 1,320 masl close to the confluence of the river within a distance of 10 kilometres. To the North West of Solwezi is Lake Kimasala, a wetland area that has seen a decline in water levels in recent years.

### 3.2 Climate

The climate of the area has three distinct seasons, with over 95 % of annual rainfall occurring from November to March during the hot wet season. The other seasons are a mild to cool dry season
from May to August, then a hot dry spell from September until the annual rain arrive in October/November.

The monthly maximum mean temperature is about 30.5 °C and monthly minimum mean temperature is 5.6 °C and the mean annual temperature is 19.8 °C at an altitude of about 1350 m. The average pan evaporation is 2080 mm per year and the average potential evapotranspiration is 1485 mm per year in Solwezi (JICA, 1995). The average annual rainfall is close to 1300 mm with a maximum recorded of 1575 mm and a minimum of 985 mm.

The rainfall in the area is linked to the southward shift of the Inter-Tropical Convergence Zone (ITCZ). The southward shift of the ITCZ creates a convergence of the trade winds into a low pressure zone and pronounced convective activity which is associated with heavy tropical rainfall. The intensity of the rainfall is an important factor for the hydrogeology for two main reasons:

1. The recharge to the aquifers is from rainfall. Extreme intensity rainfall events lead to increased surface runoff and less infiltration to groundwater relative to rainfall totals in the higher recharge areas.
2. Extreme intensity rainfall events can erode the surface if the protective vegetation cover is removed due to changes in land use.

### 3.3 Vegetation

The vegetation of the area around Solwezi has been fundamentally altered by the rapid expansion of the town due to the demand for charcoal. Within the town very little of the original vegetation remains. Around the town the woodland is seen to be typical Miombo woodland which is classified as the Northern type *Brachystegia Julbernardia* woodland (ARTHURS, 1974); this type of woodland is a fire climax forest in which the undergrowth is burnt off by people in most years.

The ecological associations are closely related to the soils and drainage and also intimately to the climate and geomorphology which is controlled to a large extent by the geology. The vegetation has been used and interpreted during previous geological mapping exercises. The secondary woodland is mostly associated with the Solwezi Schists and the Mwashia Group while the carbonate formations are less cultivated and feature more dambos and grassland.

### 4. Geology and Hydrogeology

#### 4.1 Overview and Structure

The North Western Province of Zambia has a long history of geological investigation which involved detailed mapping and structural interpretation (ARTHURS, 1974). The geology of the Solwezi area (Fig. 3) is dominated by the Solwezi granitic dome to the south of the city and the high ground to the north where the Kansanshi mine is located. The area has been affected by multiple phases of deformation related to the Lufilian Arc.
Fig. 3: Geology and topography

The Geology of the area is dominated by the Katanga System (Tab. 1) which is well documented in Zambia and the Democratic Republic of Congo (DRC) due to the present mineralisation (mostly sulphides of copper, but also of others) associated with the Mine Series. This is the reason for the presence and rapid expansion of Solwezi and of many other mining towns in the Copperbelt. The lithological structural succession is complex in the area but for the purposes of creating a baseline for groundwater three formations are important: the basement complex to the south of Solwezi, the Chafugoma Marbles and the Solwezi Biotite Schists which underlie almost the entire urban area.
Fig. 4: Schematic Geological Cross Section

Mine Series

The Lower part of the Katanga System in the Solwezi area consists of the Mine Series which unconformably overlies the basement complex. The Mine Series is divided into three groups, the Lower Roan, the Upper Roan and the Mwashia Groups. In the Solwezi area it is the Chafugoma Marble series that is of major importance to the water resources of the area.

Tab. 1: Solwezi simplified Stratigraphy

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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Metaconglomerate</td>
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<td></td>
<td></td>
<td>Pelitic</td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Chafugoma Schist</td>
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<td></td>
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<td>Lower Ironstone</td>
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<td></td>
<td></td>
<td>Lower Roan</td>
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<tr>
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The Chafugoma Marble formation is generally not well exposed and is linked with the low lying river valleys and plains. The formation is karstic which results in solution lowered plains with overlying red brown clay rich soil which are synonymous with savannah and marshy vegetation. The formation is associated with high groundwater yields due to solution features. Other formations of the mine series are present in the area around Solwezi but the major water resources are linked to the Chafugoma Marble formation.

Kundelungu

The Kundelungu Series is represented in Solwezi by two formations, Solwezi Biotite Quartzite formation and the Pelitic Formation (referred to collectively hereon in as Solwezi Schists). These
formations are a series of sediments that have undergone metamorphic recrystallization. These metasediments occur in a series of folded belts on the edge of the granite dome with the main folding occurring in the Kansanshi mine area.

In the lithological succession the units appear to be separated from the Chafugoma Marbles by several other formations but evidence from the geological reports (ARTHURS, 1974) places the Solwezi Schist in direct lithological succession with the marbles.

The main urban area of Solwezi is underlain by the Solwezi Schists which occurs in a synclinal structure. The geology map (Fig. 3) illustrates the areas underlain by the different units but the Chafugoma marbles are believed to form a continuous layer (Fig. 4) under the Solwezi Schists, this structure is vital to understanding the hydrogeology of the area since the water bearing properties of the rocks is very different due to the very high permeability of the marbles and the low permeability in general of the schists.

**Basement and Undifferentiated Metamorphic Rocks**

Beneath the Chafugoma Marble formation lies a sequence of metamorphic rock and crystalline basement rocks which are exposed to the south of Solwezi. The metamorphic rocks and the basement rocks have for the purpose of the hydrogeological baseline been grouped under undifferentiated metamorphic and basement rocks as they have similar geological structures to the Solwezi schists.

The basement complex is divided into a gneiss group and granite group. The gneiss group is made up of quartz biotite gneisses which occupy the greater part of the outcrop area of the basement complex in the area to the south of Solwezi. The rapid urbanisation of Solwezi has so far not spread as far south as the outcrop areas of the basement complex, the urban area mostly end near the confluence of the Kifubwa and Solwezi rivers.

The undifferentiated metamorphic rocks are formed from the Upper Roan and Lower Roan. The Lower Roan consists of quartz mica schists, the Chafugoma schists and the Lower Ironstone formation. Beneath these formations and lying unconformably on the basement complex is the Lower Roan quartz mica schist.

4.2 Main Aquifers

The main aquifers in the area correspond to the main lithologies in the area, the Chafugoma Marbles and the Solwezi Schists. The granite dome occurs to the south of Solwezi, composed of granite and gneissic rocks, these rocks underlie the metasediments of the Kundelungu and Mine Series. As Solwezi expands southward this unit will become part of the larger Solwezi urban area. The granite and gneissic rocks are collectively termed and usually described as “basement rocks”.

**The Solwezi Schists**

The Solwezi schists and the basement rocks have different lithological origins but in fact are similar hydrogeologically. Both types of rock possess very little primary porosity and permeability, the water bearing properties of both rocks is due to secondary features that are due to two processes:

1. The rocks are over 500 million years old and have been subjected to repeated folding and metamorphism due to the Lufilian Orogeny. These processes have led to the rocks becoming
more brittle and the movement has resulted in fracturing and faulting which has increased the permeability and porosity of the rock significantly.

2. The age of the rock and the fracturing lead to the upper layers of the rock becoming weathered, this process is due to chemical and physical weathering due the flow of water and the vegetation growth which act to transform the rock into secondary weathering products such as sand and clay.

The weathered zone (Fig. 5) that has developed over the Solwezi schists is a very important feature that in fact supplies more people with water in Solwezi than all the other water points combined. This is due to the fact that over most of the Solwezi area most dwellings have developed “family wells” which are hand dug water supplies wells usually less than 10 m in depth. These water points are supplied by water that is present within the weathered zone that is derived from local infiltration of rainwater.

The aquifer within the weathered zone behaves as a primary porosity and permeability aquifer (FREEZE AND CHERRY, 1979), this permeability will vary based on the clay content of the weathered zone developed over the biotite schist and reduce the specific yield. The number of wells indicates that the aquifer occurs over most of the populated areas and demonstrates the continuity of the aquifer.

Understanding the weathered aquifer is also vital in understanding why shallow wells (Fig. 5-B) are so vulnerable to contamination. The features that make these water supplies cheap to develop such as a shallow water table and rapid infiltration create the conditions for transport of contaminants.

The weathered zone that is typical of schist in Zambia develops three zones:

1. The soil layer which contain significant organic content, a layer of ferricrete may develop at 1 - 2 m
2. An upper weather zone which usually has a high clay content, termed the saprolite
3. A lower weather zone with less clay, termed the saprock

![Fig. 5: Weathered Zone – Schematic Description](image)

At the base of the saprock at the interface between the weathered rock and the fresh schist bedrock there usually exists a zone where there is sufficient water to supply a hand pump, usually less than 1
l/s, the evidence for this comes from DWA Solwezi records which records over 500 drilling records, most of which record drilling depth to less than 21 m, the water level in these boreholes range from 3 m to 19 m.

Below the weathered zone the age of the rock and the structural history mean that there are many fractures (Fig. 5 - A and C), in fact it has been proven (ARTHURS, 1974) that in many cases the deep weathering is in fact linked to fracture zones where water flows and increases the chemical weathering process. Fractures in the schists below the weathered zone have been intersected in numerous boreholes developed for commercial enterprises such as the golf course and other institution such as the hospital (ANSCOMBE, 2008). Detailed borehole record (COBBING AND DAVIES, 2008) show water strikes from 38 m to 156 m with yields in the range of 2–4 l/s. What is also of note from these records is that very deep weathering of over 50 m is recorded at locations with high yielding fractures; this follows the documented link between fracturing, weathering and higher yields.

The population distribution in the town is situated mainly in the areas underlain by the Solwezi schists; this can be linked to the availability of shallow groundwater. The shallow wells that are so common around Solwezi have two major issues that make them unreliable and unsafe, this is due to limitations of construction which in Solwezi restrict the depth of construction to just a metre or two below the water table; the effect of this is that wells not constructed during the lowest water levels at the end of the dry season become unreliable or dry out completely.

The Chafugoma Marbles

The Chafugoma Marble formation is an even older formation that is part of the upper section of the Mine Series. The Chafugoma Marble is composed of metamorphosed carbonate rocks that have been altered into marbles due to tectonic movement related to the Lufilian Orogeny i.e. marbles are metamorphosed limestones. The chemical composition of the formation is fundamentally different to the schist

Marbles and other carbonate rocks have very little primary permeability and porosity in the matrix of the rock, which makes them similar to the schists.

![Fig. 6: Karst Hydrogeology (after GOLDSCHEIDER AND DREWS, 2007)](image)

The age of the rocks and the metamorphic transformation in the Solwezi area has created secondary (Fig. 6) fracturing; this has allowed pathways for the slightly acid water to flow. The slight acidity is
caused by Carbonic Acid which forms when water combines with Carbon Dioxide in the atmosphere and in the soils. Due to the acidity the rock is dissolved in minute quantities. This process has occurred over hundreds of millions of years to form highly permeable conduits and cavities that massively increase the permeability and porosity.

Flow through the schist and overland flow over the schist will form a hydraulic connection with the Karst aquifer, this is termed the allogenic (Fig. 6) recharge area and will recharge the marble aquifer through flow within the fractures and weathered layer and through overland flow; this is an important flow path for recharge which can also transport contaminants.

In Zambia karstic limestones, dolomites and marbles form very important aquifers that supply water to major centres such as Lusaka, Ndola and Mazabuka and underlie many of the important agricultural areas. In Southern Africa the dissolution process has been increased by the climate variations that have occurred over the Quaternary period (ARTHURS, 1974) of recent geological history. The quaternary period has been characterised in Southern Africa by repeated changes in climate. The changes in climate have led to large fluctuations in the water table. Most solution of carbonate rocks occurs in the zones immediately above and below the water table. In wet phases the zone would be nearer to the surface, then in dry periods the zone would be lower, thus a zone at least 30 m thick of highly permeable karst develops. The occurrence of sinkholes which are well documented in the Kansanshi area is further local evidence of this process.

In the Solwezi area the marbles occur to the south of Solwezi, they are synonymous with the low lying areas (Fig. 3). In the south east of Solwezi, the Kifubwa River runs along the area underlain by the marbles. The link between the river and the location of the marbles illustrates the link between the geomorphology and the geology as the rivers will preferentially flow along the less resistant rocks and form the valleys. The course of the river is also important as a major recharge zone for the marbles.

The marbles also occur to the north and northwest of Solwezi. In the north the nature of the marbles is well documented due to the presence of the mine and the detailed geological investigation. The
mineral exploration and mining drilling has allowed a highly detailed picture of the geology to be created in the mining area.

Fig. 8 is a cross section provided by First Quantum mining that illustrates the geology. The detailed geological information from the area has been also due to the need to dewater the mine; this has created detailed information on the hydraulic properties of the aquifer.

The information from the mine management also illustrates and proves a very important hydrogeological concept that occurs in the area that is that the marbles and the schist aquifer can occur in the same location with the schists forming a shallow low permeability unconfined aquifer (Fig. 4) above the more prolific karstic marble aquifer below. In the cross section the Solwezi schist and the Chafugoma marbles, which are represented by the Upper Clastics and Upper Marble respectively. The cross section also shows the two distinct shallow and deep water levels, with the shallow water level in the weathered saprolite layer effectively forming a perched aquifer and the deep water level in the marbles being a confined aquifer (Fig. 4) overlain by the schist and an unconfined aquifer in the river valleys and to the north where the schist aquifer is not present.

The information from the mine is also very important for the baselines survey as the objective of the project is to understand the status of the area in terms of contamination, in order to do this the hydrogeology of the area must be understood. This is illustrated by a recent drilling project at the mine for monitoring boreholes, most of the boreholes were meant to penetrate the upper and lower aquifer but failed due to collapse and other reasons and shallow (>20 m) piezometers were installed (SHEQ, 2013). Although information from the shallow perched aquifer is important the flow in the deep aquifer must be monitored in order to have a representative picture of the groundwater chemistry and flow directions.

Boreholes have been developed in the marbles that supply water to the water utilities in Solwezi in north western Province – North Western Water and Sewerage Company (NWWSC). NWWSC has developed two wellfields in Solwezi in the river valleys to the south of the Solwezi town (Fig. 9), both areas are the same geomorphologically in that they are located at the base of the low rolling hills in the flatter river valleys.
NOTES

Cross section provided by First Quantum mining. Minor modifications to the cross section image have been carried out for clarity such as changes to the location of the labelling of each geological unit.

The cross section orientation is inferred based on the location of the main pit and the north-west pit. The location of the cross section is marked A – A’ with the line of section illustrated on the Google Earth image. The approximate distance between A and A’ is five kilometres.

The cross section illustrates the presence of two distinct water levels, a upper shallow water level within the upper unconfined aquifer and a deep groundwater level associated with the deeper formations.

Fig. 8: Kansanshi cross section (First Quantum Mining Limited)
The Kifubwa and College wellfields (Fig. 9) intersect the marbles based on the digitised geological map although no drilling or lithological information was available from the production boreholes. Another wellfield was developed in 2014 to supply the new Kabitaka housing development; the exploration targeted the marbles to the south of Solwezi where the marble formation is coincident with the course of the Solwezi and Kifubwa rivers in the river valley. The exploration drilling hit water at 24 m and 54 m with an estimated yield of 51 l/s from the karstic marbles.

To the north west of Solwezi is a wetland area (Fig. 3), this is the area where Lake Kimasala is located, this area is underlain by the marbles and based on the geological structures is a continuous unit with the marbles to the south of Solwezi and in the Kansanshi mine area. A number of anecdotal reports state that the hydraulic connection with the Lake Kimasala area and the dewatering at the mine is related to the wetland having less open water in the past ten years.

One of the objectives of a baseline survey is to address issues such as the reports about the lower water levels at Lake Kimasala or mining contamination and make qualified reports on the validity of such theories or to outline where there is a lack of information to quantify the allegations and suggest monitoring and investigation methods.

**The Basement and Undifferentiated Metamorphic Rocks**

The basement and metamorphic rocks are hydrogeologically very similar to the schists in that they have very little primary permeability and porosity. The aquifer potential is developed due to fracturing and the development of a weathered profile. The basement rocks are however very important sources of water for many people in Zambia; over 38% of Zambia (JICA 1995) is underlain
by basement rocks. There are many boreholes that have been drilled in Zambia over the last twenty years that intersect the water zones at the base of the weathered zone however it is still the shallow hand dug wells that are numerically more important due to the sheer number that are developed in areas with a shallow water table. The intersection of water capable of sustaining a hand pump yield of 0.2 l/s is usually possible at the base of the weathered zone and improved yields (>1 l/s) can be located in fractured basement rocks.

4.3 Groundwater Levels and Recharge

Water levels are a function of the rainfall, the soil and weathered zone and the aquifer. Water levels enable the behaviour of the aquifer to be understood, this includes estimates of recharge which can provide information on whether the aquifer is being overexploited. Water levels are however dynamic and a common perception that water levels rise and fall is misleading; water levels do appear to rise and fall but in fact the groundwater is flowing, in the case of the Solwezi schist aquifer the groundwater flows from the high ground towards the river valleys where it contributes to recharge and to baseflow for the rivers – this is the reason most rivers flow months after the rains end in March/April.

Water levels in a shallow aquifer need to be understood to enable construction guidelines. The fluctuation in water levels can thus be used to provide guidelines on construction depth. The behaviour of the water table is illustrated in Fig. 10, this illustrate the dynamic nature of the water table. For shallow wells (Fig. 10 – Well C) the fluctuation in water levels in most years can create problems at the end of the dry season, this can be exacerbated in years with low rainfall where the water table drops below the construction depth of the well.

![Fig. 10: Groundwater flow in different seasons](image)

For boreholes a similar situation occurs where boreholes are drilled and completed once shallow water is intersected (Fig. 10 – Borehole B), this is especially a problem where boreholes are drilled just after the rains when water levels are high. In the case of the shallow wells and the borehole drilled to an insufficient depth this creates the situation where the water point fails during drought, exactly when it is most needed. This underlines the need for data to provide specifications for drilling so that water points are constructed to sufficient depth (Fig. 10 – Borehole A). In order to understand the groundwater system data is needed so that predictions can be made based on the local aquifer conditions. Water levels and rainfall data was obtained from field surveys during the project; this dataset was augmented by the long term monitoring of water levels at the Provincial Water Office (PWO) in Solwezi and rainfall data from the Kansanshi mine.
In order to assess the water resource in the shallow aquifer long term water level data is needed; one dataset was obtained from PWO Solwezi monitoring borehole, which was drilled in the PWO yard in Solwezi. This dataset has a mostly complete daily record for 10 years from 2005 to 2014; this data was complimented by rainfall data from Kansanshi mine (Appendix I). The results (Fig. 11) indicate average groundwater level fluctuations of about 3 meters which show a response to changes in rainfall pattern with approximately a one month lag between rainfall and water level rise.

The data also shows some anomalous results where rainfall spikes are not followed by larger rises in water levels, this can be explained in two ways:

1. The rainfall data and the water level data are not from the same point and tropical rainfall events can vary significantly over several kilometres.

2. That the second measure of rainfall is very important and will increase in importance based on the climate change models – that is the intensity of rainfall. The larger rainfall represented by B (Fig. 11) is not followed by a large rise in water levels when compared to the next year, this can be explained by the intensity of rainfall exceeding the infiltration capacity of the soil, the duty point, when this happens the excess rainfall will flow overland to the local drainage system and be lost to the groundwater system in the local catchment.

![Fig. 11: Water levels and rainfall (Data source: PWO records)](image)

The data was initially analysed by looking at the section represented by the line A (Fig. 11), when this section of the data is looked at in isolation a clear trend indicating falling water levels is visible; this however is not a valid trend when the entire dataset is looked at. This illustrates the danger of interpreting short term trends and interpreting them as a sign of climate change for example; what is needed is longer term data.

Long term water level data can also be used to estimate the groundwater resources of an area; the long term average maximum and minimum represents important information on the aquifer. The
variation in the water levels when calculated with the estimate recharge rate and the rainfall record can be used as an initial estimate of the sustainable groundwater resource.

Water level monitoring was carried out at the end of the rainy season in December 2014 (Appendix II) at over 300 sites; specific water points were then measured again during August 2015. The water levels data indicate a shallow water table with an average depth of 5.6 mbgl, this varies as expected based on topography with the shallowest water levels nearer to the river valleys. The water level data from August 2015 (Appendix II) indicate an average depth of 6.95 m with an average water column of only 66 cm above the base of the shallow wells; of the 58 shallow wells measured 23 had water levels of less than 50 cm above the base. The average depth of the hand dug shallow wells was 6.95 m. The water level measurements confirm that the water supply for a large number of residents is from the shallow aquifer which confirms the importance of this low yielding weathered aquifer and a vital water resource.

One of the key questions is how sustainable the water resources are. The water level data from the shallow wells reveal another aspect of the water level fluctuations that affect tens of thousands of people in Solwezi and in many urban and peri-urban areas of Zambia. As the water utilities have been unable to keep pace with the rapid expansion of the town, especially the informal settlements, thousands of households have constructed their own wells that abstract water from the upper weathered zone in the shallow aquifer.

Most of the wells measured were found to have very little water left in August 2014 and the users reported that many become unreliable and/or completely dry at the end of the dry season. The unreliability of wells must be partly due to the difficulty of excavating hand dug wells beyond the water table. This is however a capacity restraint and previous projects in North West Province have constructed (GITEC, 2008) many metres beyond the water table by the use of dewatering pumps, however for the majority of private wells in Solwezi these were excavated by private contractors at a low cost without access to dewatering pumps.

Water level data must however be analysed in terms of what other influences control water levels. In particular water levels from and close to boreholes equipped with pumps can be influenced by the water level being drawn down by the pumping, this can even reverse the natural water flow direction. In the Solwezi area this will occur locally around production boreholes for the water utility and on a much larger scale the dewatering operation at Kansanshi will affect water levels in a much larger area.

In the Solwezi area the dewatering operation and the production boreholes will not have an influence of the shallow aquifer, there are conceptually two aquifer units with the exception of area close to the river valleys where the aquifers coalesce. For the purpose of this report the water levels are related to the shallow aquifer in the Schist aquifer.

The water resource were also analysed by looking at the stable isotopes (Chapter 6), the data indicates that the groundwater resources at the 32 sample points have a composition close to rainfall with a minor component of evaporation. The isotope and inorganic sampling do not show any significant indication that the groundwater has been in residence for a long period. This indicates that the infiltration of rainfall is likely to occur recently and close (several km) to the where
the rainfall occurred. The infiltration from surface water bodies also seems to be of lesser importance.

4.4 Groundwater Flow

The flow of groundwater within aquifers is controlled by the hydraulic properties of the rocks. In general the pathways from recharge area to discharge area need to understood. In the areas underlain by the Solwezi schist aquifer the groundwater levels were expected to represent a subdued reflection of the topography. In order to compare water levels the topographic maps and Shuttle Radar Topography Mission (SRTM) data generated topographic contours where analysed and found to be too general to enable accurate comparison of water levels due to uncertainty in ground elevation of +/- 2 metres. This was especially important in areas around the wellfield and the mine where flow directions are key to understanding groundwater flow and possible contaminant pathways.

In order to make accurate comparison of water levels the ground elevations at (Appendix IV) locations were measured accurately by using Differential GPS (DGPS). DGPS allows the surface elevation to be measured to up to +/- 2 cm of accuracy while a standard GPS only gives an accuracy of +/- 4 m. The water levels were then subtracted from the surface elevation, the datum used was Arc1950 and the units used were masl. The water level data confirms the prediction that the water levels in the schist forms a subdued reflection of the topography. In practical terms this information can thus be used to predict groundwater flow directions based on the topographic contours.

To the north of Solwezi adjacent to the mine there is now a large and expanding community being built adjacent to the Kansanshi mine which is also down gradient from the mines and located in the Solwezi Schist. It therefore follows that groundwater flow would flow downhill towards the community water points. This is important as groundwater can transport contaminants and thus pose a potential health risk.

When the two aquifers are looked at together it can be conceptualised (Fig. 4) that the schist forms a low permeability upper aquifer above the more prolific marble aquifer that is confined. The schist can be described as an unconfined aquifer with groundwater flow in the shallow subsurface. In comparison the marble aquifer will be unconfined in some areas, such as the area to the south of Solwezi where the river valleys are underlain by the marble aquifer and a confined aquifer where the aquifer is structurally controlled. In the Solwezi town area the formation will follow the synclinal structure and be present at depth below the town; to date the deepest borehole record obtained in the Solwezi area was 182 m at the Kansanshi Golf Club (ANSCOMBE, 2013); this borehole intercepted only the schists.

4.5 Groundwater flow around the wellfield areas

In the wellfield areas the water table of the shallow and deep aquifer converge where the hills meet the valleys which are underlain by the marbles. At the edge of the valleys the weathering profile is developed over the carbonate aquifer. In the College wellfield area (Fig. 12) the shallow aquifer has been located and measured in close proximity to the boreholes in the marbles.
Fig. 12: Groundwater flow around the college wellfield
The water level data (Fig. 12) illustrates the change in permeability between the two aquifers. In the Schist aquifer the water level change by over 27 m between SW54 and SW4 within 600 m with a clear flow direction of the hill; this confirms the theory that the groundwater levels will form a subdued reflection of the topography. The change in the shape of the water levels is clear once the marble aquifer is reached, between SW4 and SW1, a similar distance to SW54 there is only a 3 m difference in water levels.

When the geological map and the google image are compared it is apparent the marshland/dambo area also corresponds with the change in geology and topography. What is also clearly apparent is that the wetland area has now been developed for private housing; it was confirmed that this area is not serviced by a sewer system, thus pit latrines are the method of faecal waste disposal in an area with a shallow water table.

The water levels at the College production borehole were not measured due to lack of access and the dynamic nature of the production borehole water levels. Based on the water level data the flow direction is towards the river and locally the wellfield will focus groundwater flow; this creates the condition where contaminated groundwater could flow towards the wellfield. It must also be included in the equation that the river could also be acting as a recharge and potential contamination source. The water level data in the vicinity of the Kifubwa and Kabitaka wellfields further confirm this hypothesis by demonstrating steep water table elevation in the schist aquifer which flattens once the marble aquifer area is intercepted in the river valleys.

### 4.6 Groundwater flow link between Lake Kimasala and mine dewatering

The groundwater flow within the marble aquifer in the Kansanshi area is affected by the dewatering of the mine. Large scale dewatering operations not only influence the groundwater flow direction but can change the local and sub regional flow directions due to the groundwater being focussed and flowing towards the dewatering points; groundwater flow directions also need to be understood in detail because once the mine closes and the pumps are turned off the original flow direction will resume, however groundwater flow could be contaminated and the possible contaminant flow direction will follow the pre-mining groundwater flow directions. The fact that the hazardous waste dump at the mine is located over the pre-existing tributary of the Kansanshi stream underlines the importance of this issue.

To the north west of the town is Lake Kimasala, a wetland area (Fig. 8), that is reported to have less water in recent years; this wetland area is also underlain by the marble aquifer. The reason for this wetland having less water has been attributed to the mine, however this is not based on any water level or other data but an empirical observation. Based on the available information the mine if situated 4 km to the East, however the open cast pits are located over 8 km away. The groundwater dewatering reports and models made available (GOLDER ASSOCIATES AFRICA LTD., 2011) indicate that the cone of depression around the mine is localised due to the highly permeable marble aquifer; however the degree of dewatering over an extended period of time could be affecting the sub regional groundwater flow patterns in the extended area.
The anticline structure (Fig. 13) that runs through the high ground above Solwezi town and the wetland area is topographically above the wetland area. The wetland area is aligned along a syncline structure, the effect of these geological structures when combined with the fracturing that is present in the marble aquifer present more evidence that the open cast mine dewatering could be linked to the lowered water levels in the wetland area; if the depth of the open cast mine is included in the equation the water level flow directions may influence groundwater flow to the wetland area.

Fig. 13: Sub regional groundwater flow around the mine
The direction of regional groundwater flow will be based on the flow of groundwater from the higher elevation recharge areas. To the North of Solwezi close to the border with the DRC the Chafugoma marbles will have their main recharge area; the groundwater flow will be structurally controlled, based on the anticline structure and syncline structure (Fig. 13) the regional groundwater flow will also be to the south east.

It must also be included in the equation other causes such as the simplest explanation that the decline in water levels could also simply be the result of reduced rainfall over a long period. The lack of baseline water level data from the wetland will however make it difficult to prove as there is no baseline water level data.

If the monitoring data were to include monitoring boreholes drilled in a transect between the mine and also in an extended area around the mine then combined with the detail data from within the mine the groundwater flow directions can be understood and a factual basis for claims that the dewatering is affecting the mine can be established; Fig. 13 includes example locations for monitoring points within the Chafugoma Marbles.

5. Groundwater Hydrochemistry and Water Quality

The hydrochemistry and in particular the water quality of the schist aquifer and the large number of shallow wells is a hydrogeological and major social issue. The reason that the aquifer is exploited by so many people creates a situation where shallow wells could also be creating major health problems for large numbers of people but especially the vulnerable such as young children, the elderly and people afflicted with low immunity to infection.

Groundwater quality also affects the marble aquifer as the expansion of the population has led to people building in the floodplain area in the river valleys adjacent to the Solwezi and Kifubwa rivers, this has occurred in the wellfield areas and due to the shallow water table it is a potential sanitation hazard to both private and public water points. Water levels and both inorganic and microbiological water quality were sampled at three wellfields around Solwezi town.

The area to the north of Solwezi, along the border with the mine is an area that is perceived to be vulnerable to contamination from the mine. The reports of numerous shallow wells having low pH levels is anomalous and has been linked to contamination, however there are other reasons for low pH in groundwater and the source needs to be located based in scientific analysis not conjecture.

The baseline project included the sampling of 32 water points around Solwezi and around the periphery of the Kansanshi mine, the water samples were analysed for inorganic content (Appendix V) such as major cation, anions and trace elements such as copper, lead etc. The inorganic sample results provide data that can be used to create an overview of the hydrochemistry of the project area.

Sampling was also done to look at microbial contamination by testing for E.coli to identify locations with faecal contamination (Appendix VI). The sample data provides clear indication of the variability in water quality related to shallow well and boreholes.
5.1 Hydrochemical Overview

The results of the sampling programme indicate a wide range of water types, in order to create a visual and easily interpretable method to distinguish the water types each of the samples have been plotted as stiff diagrams (Fig. 14). The results are in meq/l; this unit allows the elemental concentration to be compared without bias due to atomic weight.
Fig. 14: Hydrochemical water types
The results do not indicate clear distinction between the Chafugoma Marble and the Solwezi Schist aquifer, however there are four water types apparent, stiff diagrams from fous samples are presented for each water to illustrate the hydrochemical signature of each water type:

Type I Young Water – this is mostly shallow water from wells which demonstrate short residence time and therefore represent young water.

**Fig. 15: Type I young water**

Type II Carbonate Signature – The water which shows a spike to the right representing high levels of HCO₃+CO₃ and also high level of Ca indicate residence within a carbonate aquifer, many samples also exhibit elevated Magnesium levels which is consistent with the dolomitic nature of the aquifer. The higher dissolved load within the water represents longer residence time and therefore older water. The four samples illustrated below are from the aquifer in the mining area (SB22 and SB23) and below Solwezi town (SB04 and SB05), there similarity and the high dissolved concentration from the samples from the mining area, which is topographically elevated relative to the lower samples, indicates the low possibility of a direct flowpath between the mining area and the wellfield areas, this is significant as a direct flowpath would increase the possibility of contamination.

**Fig. 16: Type II carbonate signature water**

Type III Mixed Water- Many of the borehole that are located on the schist do not exhibit low level of Ca and HCO₃+CO₃, however due to a lack of depth data only a basic assumption can be made that this water represents a mixed water type with recharge from directly through the schist in the local area but also could represent mixing with water from lower levels due to the sub regional deeper flow from the lower carbonate aquifer.

**Fig. 17: Type III mixed water**

Type IV Solwezi Schist – Few of the samples exhibit a typical schist signature with the exception of boreholes in the centre of the project area, such as SB01 and SB32, both these boreholes demonstrate low levels of dissolved solids relative to most of the other sample and significantly lower level of Ca and HCO₃+CO₃. SB11 illustrates the hydrochemical signature for the schist formation below the Chafugoma Marble to the south east of the town.
The cross section A – A’ is based on the geological map indicating a synclinal structure, the hydrochemical data shows similar water types but does not show significantly elevate levels of Ca and HCO₃+CO₃ at the topographic lower area in the south of the project area where the main wellfield are located, this indicates that recharge is unlikely to come solely from the Kansanshi mine area. This interpretation is important as the lack of elevated levels related to mining may be related to the lower groundwater flow, this does not however indicate that there is no deeper flow, it indicates that flow and possible contamination is not measured; this could be due to the interpreted subregional flow to the south east.

Many of the boreholes located on the schist aquifer but close to the carbonate aquifer show a mixed signature, this indicates a more complex flow dynamic which could include longer residence time and flow with the deeper aquifer and more local groundwater which is acting to dilute the water, SB10, SB12 and SB30 exhibit this signature. To define this hypothesis however it would be necessary to have depth data and ideally to have at least one or two boreholes penetrate the schist aquifer in order to quantify the thickness of the upper unconfined schist aquifer.

The signature of the water from the spring SS07 shows low dissolved load but the location of the spring is close to the outcrop of the marble aquifer which is located to the north and topographically above the spring, this confirms the theory of the local shallow flow.

The other sample in the area, from the monitoring borehole SB24 also shows a similar very low dissolved load. This indicated that this borehole is also linked to shallow groundwater flow and this is also important as the value of a monitoring borehole that is only receiving local and young water may will not be representative for water from deeper flow zones which could be vulnerable to contamination.
5.2 Contamination of Shallow Wells

The rapid expansion of Solwezi, which in many areas has been largely unplanned, has meant that infrastructure development has not kept pace, this is especially true with water supply from the water utility, NWWSC. Over most of Solwezi people have constructed either primary water supplies or created backup water supplies due to the perceived unreliability of the water utility.

The sewer network in Solwezi has also not kept pace with developments and in many areas pit latrines are the method of faecal waste disposal. The issue with pit latrines is that the effluent movement is dynamic and will flow, where there is a shallow water table, this will lead to a high contamination risk.

The construction depth limitations of the shallow wells is due to the difficulty in dewatering the shallow wells during construction, in most cases the water is only dug to about a metre below the water table; mainly due to the cost and non-availability of dewatering pumps. The shallow water table coupled with the low cost construction also creates other major issues related to groundwater vulnerability to contamination, from both contaminated flow from pit latrine (Fig. 19), septic tanks and from contamination due the buckets used to bail the water becoming contaminated due to handling.

Fig. 19: Pit latrine located near to a water supply well

The sampling programme has revealed that numerous water points in the Solwezi area contain E.coli. A total of 32 water points were tested for microbiological contamination (Appendix VI), of these 5 samples were taken from hand dug wells; at all the wells contamination with E.coli was found. The vulnerability of the aquifer is also exacerbated by the depth. During the water level survey the average water level in shallow wells was of 5.6 m which is close to the average pit latrine depth of 2 – 3 mbgl.

Boreholes are regarded as a safer water source due to a number of reasons such as depth and a lifting method that reduces the contact between groundwater and potentially contaminated lifting devices such as buckets. Water from boreholes is also often perceived as being cleaner due to it being clear, however this does not preclude the possibility of contamination as construction and
distance to contaminated sources can also lead to borehole pollution, this is combined with many borehole being drilled to less than 25 m (PWO Solwezi Records).

The results of the microbial contamination in boreholes would be expected to be significantly lower than in shallow well. During the sampling 26 boreholes (Fig. 20) were analysed for faecal coliforms, of the 26 boreholes E.coli contamination was found at 14 borehole sites. The implication of 53 % of the boreholes samples being contaminated is that although they are safer than wells however there is still a significant amount of contamination.

The field programme also included a survey of water points (Appendix VII) around Solwezi to investigate how many were at risk from pit latrines in very close vicinity to the water source; of the 58 water points 20 were found to have pit latrines within 15 m. The recommended minimum

Fig. 20: Sampling and water level measurement points

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The field programme also included a survey of water points (Appendix VII) around Solwezi to investigate how many were at risk from pit latrines in very close vicinity to the water source; of the 58 water points 20 were found to have pit latrines within 15 m. The recommended minimum
distance for a pit latrine is 30 m from a water point (COBBING AND DAVIES, 2008), it is clear than planning and/or enforcement of standard practice are needed to prevent direct contamination threats.

The water level monitoring and DGPS levelling survey has confirmed that the groundwater can be visualised in the Solwezi schist aquifer as a subdued reflection of topography (see section 5.3), the implication of this is that for shallow wells and boreholes the groundwater flow direction can be predicted; it should therefore be possible to locate water points with the location of the contaminant source ideally located down gradient or at least not directly in the flow line i.e. not immediately downhill and if this is not possible at least 30 m away.

The implication for public health are severe as faecal coliforms have a zero E.coli per 100 ml requirement according to Zambian Bureau of Standards (ZABS) and WHO standard. The presence of E.coli is an indicator of risk to many debilitating water borne diseases; contaminated water represents a major financial cost to the population.

In order to assess the risk other components of construction need to be included such as depth of drilling, grouting, and whether the upper water strike was cased off must be quantified. These factors as well as surface works to prevent flow from the surface are all essential elements of a well-constructed borehole. This data is important for assessing the situation with regard to the presence of E.coli in boreholes and can be used to justify higher standards of construction.

The new Water Resource Management Act is now being legislated and standard practices for construction are being prepared. The level of contamination in boreholes and wells represents a real financial cost at the personal and national level. In terms of mitigating the risk there is also low cost methods to reduce risk that should be investigated such as conversion of hand dug wells to shallow boreholes with low cost handpumps and/or low yield solar systems.

5.3 Wellfield Contamination

There are three main wellfields that were located and sampled in Solwezi that supply drinking water. NWWSC have two wellfields to the south of Solwezi and the third more recent wellfield to the south east that supplies the new Kabitaka housing development. The wellfields are all similar in that they are located in river valleys. The wellfields are located on two different rivers, College on the Solwezi River and Kifubwa and Kabitaka close to the Kifubwa River; the wellfields are however similar in that both rivers run along areas underlain by the Chafugoma marble aquifer which has preferentially eroded the carbonates and created the valleys where the wellfield are located.
Fig. 21: Kifubwa Wellfield

The flat areas adjacent to the rivers in both wellfield areas have been developed as residential areas; the groundwater in both areas is very shallow. In the case of the Kifubwa wellfield (Fig. 21) the upstream areas have many residential properties that completely surround the wellfield. Adjacent to the wellfield the land has been developed for housing; these developments have even encroached into the area that should be protected by an inner protection zone, Fig. 21 shows the wellfield located adjacent to the river. The image shows that the encroachment of houses has major contamination risks; one house is located immediately adjacent to one of the production boreholes; the septic tank within the property was located only 15 m from a functioning production borehole. The house immediately to the east has a shallow well which is used for drinking water; this was sampled and found to be contaminated with E.coli, this represents a major contamination risk.

The water levels were measured at locations on the hill adjacent to the Kifubwa wellfield in the schist aquifer; the groundwater levels indicate a steep gradient towards the river. The significance of this is that recharge and possible contaminated water may flow off the hill into the marble aquifer.
The contamination levels at each of the production boreholes will vary with the borehole located closest to the septic tank having the highest levels of E.coli. The production borehole outside the fence is also located in close proximity to the pit latrine at the nearby houses (Fig. 21). The production borehole and proximity to the septic tank are also shown on the report cover picture. The production boreholes closest to the entrance is furthest from nearby contamination sources however pump number 5 was tested and found to contain E.coli, this is probably due to the fact that the wellfield is located at the base of a steep hill and water level data has proven there is shallow groundwater flow towards the valleys, this coupled with the cone of depression around the production borehole creates elevated contamination risk.

At the College wellfield located 2 km to the west the area immediately around the wellfield is not developed, the only obvious contamination source is a nearby stream (Fig. 12), however the groundwater levels indicate flow towards the river.

The physical environments are however similar in that they are both areas which are located in river valleys where the floodplain has been seen housing development, the area is also not serviced by a central sewer system and thus the shallow water table coupled with on-site sanitation create contamination sources.

The analysis of the water from the College production borehole was found to have significantly high levels of E.coli contamination comparable to the Kifubwa production borehole. The results and the hydraulic gradient coupled with a shallow and permeable karstic aquifer indicate that the location of numerous pit latrines and septic tanks in the floodplain valley area upstream from the wellfield is the most likely contaminant source.

The new wellfield for the Kabitaka housing development is located in a similar hydrogeological environment to the NWWSC wellfields. The production borehole was sampled and found to contain no contamination. This could be due to a number of factors which include:

- The area around the wellfield has very little housing or other development.
- An important recharge source will be the Kifubwa River, as this borehole is situated to the north west of the town. The main catchment will include the floodplain area upstream which does not have dense housing; this differs from the two other wellfields where the river valley upstream from the wellfield is densely populated.
- The construction details of the borehole are known and this borehole was well constructed intersecting water strikes below 30 m (ANSCOMBE, 2014) and using a surface grout that prevent shallow water entering the borehole; as no construction details for the NWWSC borehole was available it can only be highlighted that good construction details and full time trained supervision are important factors.

Groundwater is a viable source of water for NWWSC but the hydrogeology of the areas and the catchment for the groundwater must be considered. In the case of the College and Kifubwa wellfield the housing development cannot be reversed and relocation and resettlement is unlikely, the main objective should be that the contamination source is mitigated as far as is possible and that future planning consider alternative sites where wellfield protection zones can be implemented. The location of potential wellfield areas has been proposed based on the controlling factors and data analysis, see wellfield development (Chapter 9).
The groundwater system cannot be viewed in isolation as the Kifubwa River system flows past two of the wellfields. The catchment for the Kifubwa also includes the Kansanshi River which rises within the mining area; it can be seen that in fact two tributaries of the Kansanshi stream are now covered by a mine waste dump. The issue is that no indication of contamination at this point in time does not preclude the possibility of future contamination of surface and groundwater, the long term implication of this is that wellfield developed downstream from abandoned mines are at risk from contamination as the pre-mining surface flows return to their natural drainage paths.

5.4 Mining Contamination

Contamination from Copper and other mines is a worldwide problem (e.g. SRACEK ET AL, 2012), in Zambia there are numerous cases of contamination; the city of Kabwe is judged to be the tenth most polluted city on earth. The perception of mines is that they pollute, however this is conjecture; a key objective of a hydrogeological baseline mapping exercise is to understand the hydrogeology in order to quantify the possible issues using a scientific approach.

First Quantum mining was visited on several occasions and the technical staff made numerous reports and data available to the project. The mine has a large number of monitoring wells which are located around the perimeter and within the mine, the water level and depth data was made available. The geological and mining reports (GOLDER ASSOCIATES AFRICA LTD., 2011) confirm that there is a shallow perched aquifer in the weathered zone and shallow fractures in the schist. Below the schist, as is demonstrated by the wellfield, there lies the high permeability karstic marble aquifer.

The mine also has to deal with a major groundwater issue; in fact the volume of groundwater flow caused the mine to close underground mining operations in 1957 when a major inflow of groundwater overwhelmed pumping capacity. The underground mine has been used as part of the dewatering operation which was recently upgraded by the construction of a decline, a sophisticated and expensive dewatering method.

A large dewatering operation is now running at Kansanshi, the volume of dewatering confirms that the marble aquifer is a highly productive aquifer with solution features typical of karst aquifers and major fault and fracture controlled flow zones. The consequence of this is that the schist aquifer which from the perspective of groundwater supply is the major aquifer to most of the population has limited hydraulic connection and can be visualised as a perched low permeability aquifer over the highly permeable marble aquifer.

Groundwater samples were taken from within and around the mine, a sample was also taken from the east close to the sulphide tailing storage facility (SB23). In total four samples were taken from the mining area; three of the samples which we taken from shallow levels show no indication of contamination, however the water samples from SB22, a deeper dewatering borehole shows elevated Sulphate levels of over 70 mg/l, however the same borehole sample did not show elevated levels of heavy metals so this could be due to the natural occurrence of minerals such a pyrite.

The mine also carries out regular sampling although the hydrochemical data was not made available. The sampling points were all similar in the samples were taken from shallow water points. A recent project was carried out to drill additional 15 additional monitoring boreholes (SHEQ, 2013). The report indicates that all the boreholes target the shallow aquifer (<20 m). The intention was to also
install at a deeper level (20 – 50 m) but due to collapse this was not done. The effect of this is that the samples taken in the mine and peripheral area are from the shallow schist aquifer.

The samples taken from the water points adjacent to the mine did not show elevated levels of metals in any of the samples, while this is important as it indicates that water quality with respect to trace metals is not a source for concern; however it must be underlined that finding no metal concentration above Zambian standards in the shallow wells is a reflection of the shallow water quality.

The inorganic samples are not believed to represent a comprehensive picture of the groundwater quality in the mine and surrounding area as contaminant flow will be taking place below the schist aquifer in the more preferential flow paths of the deeper more permeable aquifer. In order to understand, predict and protect the groundwater a hydrogeological model of the local and regional flow needs to be carried out to predict any possible pollution migration direction. This possible pollution migration routes should also be monitored by the installation of monitoring boreholes located along possible migration routes.

The mine is located on an anticline which has pushed the mineral rich core near to the surface. Based on the structural geology and topography the anticline structure dips to the south east. (Fig. 13). The sampling result that found no heavy metal contamination in the marble aquifer south of Solwezi only indicates the lack of contamination in this area which is believed to be due to the structural controls and a south easterly groundwater flow direction.

The mine intersects the marble aquifer which is could be hydraulically linked to the water supply aquifer and Lake Kimasala. The possible hydraulic link means that heavy metal mobility needs to be understood. In the case of the marble aquifer this is a carbonate aquifer therefore the dissolution and release of CaCO₃ into solution will increase the alkalinity which will provide a buffer against low pH level. Low pH levels are very important in relation to mining environment and groundwater since higher pH levels has a “buffering” effect which reduces metal mobility.

The inorganic chemical results found no presence of heavy metals; the existence of a major tailing dam and other chemical processing indicate the need for more data from the deeper aquifer. The lack of information on the groundwater flow was also noted in the report into the new tailing facility (GOLDER ASSOCIATES AFRICA LTD., 2011); this report stated that “there is insufficient data to determine the potential significance of groundwater and surface water contamination”.

The mine was built on an existing surface drainage system, the Kansanshi stream and its tributaries rise within the mine area. The main tailing storage area to the south of the mines was built over tributaries of the Kansanshi stream. The significance of this is that the Kansanshi stream is a tributary of the Kifubwa River which flows past two water supply wellfields in Solwezi town. Evidence from across the Copperbelt (KAMBOLE, 2003) demonstrated and proven the link between mine waste and contamination. The Kifubwa River and the water supply wellfields have a possible direct hydraulic link which must be understood and water quality monitored.

5.5 Shallow well contamination close to the mine

One project recently completed by the mine was an investigation into anomalous low pH levels in shallow well adjacent to the southern boundary of the mine. A hydrocensus (GOLDER ASSOCIATES
AFRICA LTD., 2011) was carried out at 129 water points along the southern border of the Kansanshi mine, the data indicates various pH values in shallow wells, with 68 % less than pH 6 and 9 % less than pH 5. Two water points were sampled during the existing baseline project. The results do not indicate elevated levels of heavy metals. The negative reading for heavy metals indicates that the shallow water is not contaminated.

The anomalous low pH values found (Appendix VIII) adjacent to the mine are not seen in the samples taken from the larger Solwezi area. Of the 32 samples taken in the Schist aquifer, 5 sample sites were below pH 6 and none were below 5, this includes the four samples that were taken within the mine. This indicates that the anomalous pH i.e. below pH <6 values are localised. The anomalous pH was explained (personal communication with mine hydrogeologist) by a “product of the weathering process”. The area is mineralised therefore there could be a geological explanation such as concentration of pyrite but this needs to be proved as low pH could also be linked to mine waste; the cause of the low pH needs further investigation.

The inorganic results indicate no contamination; however this is based mostly on samples of groundwater from the shallow aquifer. In this type of mining environment it would be probable to find a range of water types which show mixing of shallow groundwater with mining contamination. The report supplied by the mine (SHEQ, 2013) and the hydrocensus (GOLDER ASSOCIATES AFRICA LTD., 2011) both indicate that the hydrogeological and hydrochemical environment needs to be better understood through more data from the deeper aquifer(s) and numerical modelling of the groundwater flow in the larger area rather than a local numerical model that is only intended to assist in dewatering.
6. Environmental Isotopes

6.1 Occurrence of Deuterium and Oxygen-18

The concentration of the natural occurring stable isotopes deuterium ($^2$H) and oxygen-18 ($^{18}$O) in water has been used as a tool to examine the hydrological cycle. MAZOR (1997) considers them as ideal tracers for analysing the movement of water. Recharge and discharge processes of aquifers or between surface water and groundwater can be identified through the analysis of stable isotopes.

The isotope relationship of a water sample is notated as deviation in ‰ from the international reference concentration, the Vienna Standard Mean Ocean Water (VSMOW). The deviation of deuterium and oxygen-18 is calculated by:

$$
\delta^{2}H[\%] = \frac{(^{2}H/^{2}H)_{\text{Sample}} - (^{2}H/^{2}H)_{\text{VSMOW}}}{(^{2}H/^{2}H)_{\text{VSMOW}}} \times 1000
$$

(Eq. 1)

$$
\delta^{18}O[\%] = \frac{(^{18}O/^{16}O)_{\text{Sample}} - (^{18}O/^{16}O)_{\text{VSMOW}}}{(^{18}O/^{16}O)_{\text{VSMOW}}} \times 1000
$$

(Eq. 2)

$\delta$ = relative deviation in ‰
Ratio$_{\text{Sample}}$ = isotope content of the sample
Ratio$_{\text{VSMOW}}$ = isotope content of the Standard Mean Ocean Water

The relationship between $^2$H and $^{18}$O in global precipitation can be expressed by the formula:

$$
\delta^{2}H = 8 \delta^{18}O + d
$$

(Eq. 3)

$d$ = deuterium excess

The comparison of worldwide precipitation data through CRAIG (1961) determined the global meteoric water line (GMWL) with a d-excess of 10:

$$
\delta^{2}H = 8 \delta^{18}O + 10
$$

(Eq. 4)

The meteoric line is normally plotted in a $\delta^2$H - $\delta^{18}$O diagram (Fig. 22), where it is used as a reference line. The figure shows also a selection of fractionation processes which may influence the isotope values in rain water and consequently the composition of groundwater. The isotope values of rainwater may be influenced by the temperature of rainwater, evaporation, the altitude or its intensity. Groundwater may also interact with its geological environment.
6.2 Stable Isotopes in Precipitation and Surface Water

The collection of rainwater samples in Solwezi could not be realized. However, the comparison of the stable isotope composition of rainfalls in Ndola, Lusaka and Chongwe showed a close plot along a local meteoric water line (Fig. 23) which is very close to the GMWL. It is suggested to use the calculated MWL as reference also for Solwezi. In addition the MWL is also very close to the standard Global meteoric water line which is by definition a global mean trend of the stable isotope composition of precipitation.

During the rainy season 2014/2015 rainwater has been collected in Ndola (10 samples), Lusaka (6 samples) and Chongwe (5 samples) through standard rain collectors (Tab. 2). Data, amount and duration of rainfall events were noted. If quantities of rainwater allowed for, it has been collected in 50 ml plastic bottles.
Tab. 2: Rainwater isotope composition from Chongwe, Lusaka and Ndola.

<table>
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<th>No.</th>
<th>Code</th>
<th>Location</th>
<th>$d^{18}$O [%]</th>
<th>$d^2$H [%]</th>
<th>DE*</th>
<th>Symbol</th>
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<td>□</td>
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<td>13</td>
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<td>12</td>
<td>□</td>
</tr>
<tr>
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<td>P-CHO-D-01</td>
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*DE = Deuterium Excess

6.3 Stable Isotopes in Groundwater

The stable isotope composition of groundwater represents generally the mean annual precipitation (Fig. 24). The 32 groundwater samples from Solwezi (Appendix IX and Fig. 25) are grouped close along the MWL. This would point at the infiltration of rainfall being the origin of shallow and also deep groundwater. However, as slight scatter of samples along the GMWL can be observed.

The determination of groundwater age is not possible with the measurements of stable isotopes. Other tests, e.g. tritium analyses, may reveal more information on the recharge age of groundwater in the Solwezi area. Isotope studies for the aquifers of Kabwe and Lusaka by TEMBO & NKHUWA (1997) calculated a mean age of 5 to 14 years derived from Tritium measurements. Water in comparable systems could therefore be equally recent.

The groundwater samples are also plotting very close to the MWL. Although a mathematical fit of the groundwater sample points shows a linear with a lower slope than the MWL it seems that evaporation plays a minor role for the recharge of the groundwater resources. Therefore it is possible to say infiltration of rainwater is likely to occur very close to where the rainfall occurred and also happened quite quickly. The infiltration from surface water bodies which were under a stronger evaporation influence seems to be of lesser importance.
The results of the isotope data at this stage of investigation are not revealing an eventual geogenic influence on the groundwater composition due to a long residence time in the aquifer. Therefore the recharge of the aquifers in Solwezi seems to take place only in close distance of maybe only a few km. Also the comparison of isotope data from the different groundwater boreholes in regard to their respective tapped geology is not very distinct from another. That may also show that groundwater in Solwezi is formed by recent recharge and that at least the major part of recharge takes place locally or nearby.

Further specialized chemical and isotope investigations may reveal more detail about the groundwater recharge processes in and around Solwezi.

**Fig. 24:** Stable isotope composition of groundwater equals the mean annual precipitation. (from CLARK & FRITZ, 1997).

**Fig. 25:** Stable isotope composition of the 32 groundwater samples in Solwezi in relation to the rainfall samples.
7. Groundwater Protection

Groundwater protection can only be possible if the hydrogeological system is understood. What can be stated with certainty is that groundwater protection is urgently needed in the Solwezi area to prevent contamination on the large and small scale.

The wellfield areas were found to be vulnerable to local contamination. The sources have been defined, however the solution to mitigating the risk is more complex. The fact is that people have taken possession of land and built their houses, the lesson from recent projects such as the IWaSP project at the Itawa Springs (KAREN ET AL, 2015) is that relocation is a very difficult, expensive and a long procedure. In Solwezi, relocation of large numbers of people is not a realistic goal. The method to protect the wellfield is first to understand the system so that protection zones can be designed then to locate and try to mitigate contamination sources with the protection zone.

In the case of the main wellfields in Solwezi as they are all located on karst areas, the vulnerability of the area needs to be analysed to look for karstic features which could provide direct pathways, such as sinkholes. In the medium term it is unlikely that people will be relocated. In consequence future wellfields should target areas that have not been developed (see below).

Groundwater protection zones are essential for sustainable groundwater use, they encompass a staged zoning around the drinking water source with increasing land use restrictions closer to the source. The establishment of protection zones is one of the legal instruments prescribed by the Zambian Water Resource Management Act of 2011. Further legislation is being created that will outline the methodology for delineating the protection zones.

The protection zones are defined by the hydrogeology and ground condition of the area around the water points. It should be emphasised that the protection zones illustrated below gives examples, however the accurate delineation of protection zones should be based on more data and field testing using techniques such as pumping tests, tracer tests.

According to international standards for groundwater protection zones (e.g. KANGOMBA & BÄMLE, 2013 and SCHOLL ET AL., 2006) a division into three zones is proposed:

7.1 Inner Zone (Zone 1)

This innermost zone is usually defined based on a 10 – 50m zone around the source itself. In the case of Solwezi it is recommended that a 50m zone in implemented due to the nature of the aquifer. It should be emphasised that this is 50m form the location of the production borehole, in a number of cases this falls outside the fenced areas, this is the reason why the innermost zones falls outside the fences in the figures below. For domestic supplies a minimum distance of 30 m is recommended.

Within Zone 1 the following land use restrictions should apply:

- No activities apart from necessary work related to water supply
- If sanitation systems are present and cannot be moved in the short term they should be lined and not below 2 m
- No wastewater facilities in the zone
- No handling of hazardous material
7.2 Outer Zone (Zone 2)

This is defined based on the hydrogeology and vulnerability of the area. Zone II encompasses areas of high vulnerability such as areas around sinkholes, streams that follow structural features and slopes with runoff into streams or sinkholes. In the Solwezi area all the wellfields will be vulnerable from surface and shallow groundwater flow off the hill underlain by the schist aquifer. More data is needed to define the zone. The figures below (Fig. 19, Fig. 20 and Fig. 21) illustrate the protection zones; the necessary data to define the zones is not available. Examples of the zone II for each wellfield area is illustrated based on a 50 day travel time and inferred hydraulic and boundary conditions.

Land use restrictions in the zone are recommended as:

- If sanitation systems are present and cannot be moved in the short term they should be lined and not below 2 m
- If sewers cross this zone they should be double walled or surrounded by an impermeable layer.
- No wastewater treatment plants
- No industrial use, landfills of dumping of wastes
- No quarries or mines
- Agricultural activities are allowed but the application of pesticides is prohibited
- No new developments or buildings should be allowed; all existing residential buildings have to be connected to a wastewater plant
- No new construction of roads

7.3 Total Catchment (Zone 3)

This is defined that the source area within which all groundwater recharge is interpreted to the discharged at the source. In confined aquifers the catchment in the Solwezi area can also be based on structural controls. In karst area ideally vulnerability mapping for the delineation of the protection zones and hydrogeological investigations such as tracer tests should be implemented to improve delineation of the zone boundary. The recommended land use restrictions with the catchment are:

- Most activities are permitted but general care should be taken not to contaminate the groundwater resource.
- Operation of industrial or commercial sites should follow environmentally sound practices
- No underground storage of hazardous substances, but if necessary only with an impermeable layer and double walled.
- No discharge of untreated wastewater
- No infiltration of strongly contaminated wastewater such as from petrol stations or industrial premises.
- Landfill should be constructed with liners and incorporate drainage systems to avoid percolation
- Sewage collectors should be surrounded by soils of low permeability
- Environmental Impact Assessments for industrial activities
- Erosion should be controlled through natural indigenous vegetation cover
For the main wellfields run by NWWSC the protections zones are detailed below, however they are based on distance and are estimated, to define the zones more accurately groundwater velocities need to be measured. In the case of family and local water supplied by hand dug wells or borehole even a 50 m protection zone is not practical, especially in areas where high density informal settlement. What should be implemented is the International guidelines for rural water supply where no pollution source should be located within 30 m of the source; this should however be qualified in the karstic marble aquifer and extended based on groundwater flow direction to at least 50 m upstream from the source.

Within Zone 1 and 2 the sanitation systems such as septic tanks and pit latrines are the main risk due to leakage to the shallow groundwater and direct flow to the production boreholes. The disposal of the waste cannot be left to an informal or uncontrolled systems and should be managed by NWWSC and Solwezi City Council. In places where centralized systems cannot be implemented other safe decentralized systems such as composting or urine diversion toilets should be considered rather than traditional pit latrines. Where necessary pit latrines in the groundwater protection zones should have cement or other forms of lining which should not reach beyond two metres in depth. In areas where groundwater is close to the ground surface during the rainy season, sanitation systems which store waste and allow for later removal out of the area need to be implemented.

8. Protection Zones for Water Supply Wellfields

8.1 Kifubwa Wellfield

Instituting protection zones at the Kifubwa wellfield (Fig. 26) will be difficult due to the density of the housing close to the wellfield. The production boreholes should all be tested for microbiological contamination. It is assumed that the borehole that is situated close to the septic tank outside the existing fences area will be most vulnerable to contamination.

It is recommended that in the medium term the well field is moved, however in the short term if the wellfield it is to remain then the production borehole outside the fence is decommissioned and a new production borehole is drilled as far as possible from the housing in proximity to the river - but within the fenced area. It is recommend that any pit latrine in the houses within zone II are identified by a field survey and steps taken to mitigate the contamination source through alternative waste disposal techniques.

The recommended Zone II protection area at the Kifubwa wellfield has been extended to cover the main Lusaka road; this road is used by hundreds of trucks including fuel and chemical tankers. The inclusion of the bridge is designed to highlight the fact any spill of a hazardous fluid could on or around the bridge could cause a major health risk if water is abstracted after a major spillage. In the event of a contamination event the wellfield should not supply water until the water quality in the river can be proved to contain no contaminants as the hydraulic link between the shallow groundwater and the river could include fast pathways and thus increase the contamination risk.
8.2 College Wellfield

The college wellfield (Fig. 27) is not surrounded by housing so an inner protection zone can be established by extending the fenced area, however the contamination could be coming from the stream nearby and/or the pit latrines constructed in the floodplain area which is well outside the usual prescribed distance of 50 m.

The density of the housing in the catchment for the wellfield means that a secondary Zone 2 protection zone will be impractical to implement unless the housing in the area can be connected to a sewer line. In the short term if the wellfield cannot be moved to another area the same recommendation as to land use restrictions as mentioned above and any future boreholes should be drilled to intersect preferable deeper water (>30 mbgl) and include surface grouting. This should be installed to reduce shallow groundwater flow to the borehole.
8.3 Kabitaka Wellfield

The Kabitaka wellfield (Fig. 28) is the only existing wellfield which can be comprehensively protected due to the low existing settlement pattern, this area should act as an example of how protection zones should be implemented based on the hydrogeology and international standards for groundwater protection zones and through cooperation between NWWSC and Solwezi District Council.

The protection zones for the Kabitaka wellfield also include an example of how the Zone III, the total catchment zone can be estimated; this area is based on the geology and structures in the area. In the case of this wellfield there is a large fault less that a kilometre to the west of the wellfield that has offset the geological formations, this is almost certainly also a groundwater conduit. The fault zone is also coincident with the alignment of the river, this illustrates a structural control on a river and the link between the river and the underlying karstic marbles is probable. The slopes around the structurally controlled river needs to be included in a catchment and also any possible major contaminant source such as a large housing development where the centralised sewer discharge needs to be monitored so that it conforms to ZEMA standards.
9. Future Groundwater Development

Protection zones are essential and in the short to medium term can represent major cost savings if the groundwater resource is protected; however once development has taken place they are difficult to implement.
In the current situation there can be measures implemented to protect the wellfields but only in the case of the Kabitaka wellfield can the resource be protected by implementing zones of protection timely before development takes place.

Future groundwater development should take place in areas that are not developed (Fig. 29) so that the implementation of protection zones can be guaranteed. The location of the suggested wellfield locations is based on the hydrogeology of the area and the land use. The main criteria is that the upstream recharge areas remain not developed.

10. Conclusions

Solwezi town has a complex hydrogeological setting where a shallow unconfined schist aquifer is underlain by a highly permeable karstic marble aquifer which is confined or semi confined below the town and unconfined in the river valleys to the south and to the west of the town where the Lake Kimasala wetland area is located. The marble aquifer also is located to the north in the Kansanshi mine where large volumes of water are abstracted for dewatering the open cast mine.

As part of the hydrogeological baseline study hydrochemical sampling was carried out at 32 sites, the samples were analysed for major, minor and trace elements; also analysed were the stable Isotope relations of the water samples and the microbiological contamination. The results indicated no contamination with heavy metals at any of the sample sites but major microbiological contamination. The hydrochemistry and isotope data indicates that the water is very young; this fits with the hypothesis that the aquifer is mainly an unconfined shallow aquifer in the schist and that the marble aquifer receives local recharge, probably through infiltration from the schist aquifer and the river systems that overlie the aquifer.

The unconfined schist aquifer is mostly very low yielding but forms a vital water supply aquifer for much of the population that is not serviced by a reticulated water supply from the water utility. This is mainly due to the shallow groundwater that can be found within metres of the surface all over the town. The shallow unconfined aquifer however is highly vulnerable to pollution from pit latrines which are the main method for faecal disposal, especially in the informal unplanned settlements which cover much of the town. The results of the sampling indicate 56 % of the sampled boreholes and all the wells were contaminated with E.coli, this represents a major health issue.

The marble aquifer in the river valleys to the south of Solwezi are the sites for the three water supply wellfields. The College and Kifubwa wellfields were sampled and found to be contaminated by E.coli. The source of their contamination was explained by the fact that the floodplain areas around the wellfields have now been built on for domestic houses with pit latrines located at many of the houses. This combined with a shallow water table and highly permeable karstic aquifer makes the production boreholes highly vulnerable to pollution.

The production boreholes should be protected by defined protection zones, this will be difficult to implement, especially for the Kifubwa wellfield, which is now surrounded by houses with septic tanks and pit latrines. The College wellfield is less encroached but the levels of E.coli indicate that contamination is coming from a larger distance. The results indicate that in the medium term it would be preferable to relocate the wellfields to areas in the river valleys underlain by the marbles
in areas further from the town that have not been settled; this relocation should be combined with the establishment of defined protection zones which is carried out in partnership with the local council so that the sites can be protected.

The wetland area to the North East of Solwezi town has experienced falls in water levels over several years that have been linked to the dewatering in the open cast mines at Kansanshi. The distance of 8 km between the open cast pits and the wetland creates doubt on the theory however the karstic nature and the structural setting of the aquifer mean it should be proved that dewatering is not affecting the wetland. This could be done by drilling and monitoring water levels and including this area as part of a detailed hydrogeological model.

The monitoring data from the area around the mine and the town indicate no evidence of heavy metal pollution, however the samples were mostly taken from well and boreholes in the upper schist aquifer which forms the main water supply aquifer. The lack of heavy metals and the uniform hydrochemical signature of the water does not however fully prove a total lack of pollution. It is recommended that more sampling is necessary from the Chafugoma marble aquifer in the vicinity of the mine so that the hydrochemistry around the mine can be better understood.

The anomalous pH levels close to the southern boundary of the mine have not been explained and the low pH levels were not found in other areas around the mine: The source of the low pH needs further investigation. The uncertainties due to the shallow monitoring data, the low pH and wetland issue indicate that there is a need to better understand the hydrogeology of the mine in the larger area in order to understand the hydrogeology and predict deep groundwater flow directions.

In the long term the surface drainage channels that are covered by mine waste dumps are a potential contamination hazard as they are located over tributaries of the Kifubwa River which is linked to the sites of present and possibly future water supply wellfield sites. The long term contamination risk should be quantified as part of a detailed numerical groundwater flow model.
11. Recommendations

The wellfield sites must be protected by setting up aquifer protection zones. The wellfields that abstract water from the Chafugoma marbles were found to be contaminated by E.coli, the reason for the contamination at Kifubwa wellfield is clearly the proximity of the septic tanks. At College Wellfield the contamination source needs to be identified. The proven contamination gives strong grounds for the setting up of an exclusion zone around existing and future wellfields for groundwater protection.

Protection zones around small scale water supplies. Implementing full protection zones around small scale water supplies is not a practical or realistic possibility. However increased public awareness and publicity should be funded so that the distance between water supplies and pit latrines is increase and the reason for doing this clearly explained in a non-technical manner.

The issue related to sanitation and health must be investigated further. All the hand dug wells that were sampled were contaminated with E.coli, the reason for the contamination is due to the shallow water table and the proximity of pit latrine and/or the use of buckets which are continuously in contact with human hand and the ground which could introduce faecal bacteria. The population needs to understand that pit latrines must be moved as far away as possible from water sources and the existing hand dug wells should be sterilised periodically in combination with the use of household filtration devices.

The hand dug wells that supply a large proportion of the population should be deepened and improved with respect to contamination risk. The hand dug wells visited during the water level and sampling survey are a major water supply source for much of the population in Solwezi; this will not change in the short or medium term. What is needed is a cost effective method to improve the well by deepening them and to find an improved method of abstraction that does not contaminate the water supply.

A monitoring network needs to be set up so that the groundwater resource of the main aquifers in Solwezi can be quantified. Monitoring water levels and rainfall volume and intensity will allow the groundwater resources of Solwezi to be quantified with greater accuracy, this should include the weathered aquifer that supplies water to much of the population. This should be done by using cost effective methods such as the use of jetting to install piezometers that cannot be used for water abstraction (due to small diameter).

Low cost methods for deepening shallow wells and safe technology for protection and abstraction is available and proven in many parts of the world. The hidden costs due to illness related to water borne diseases has been estimated to be 1.5 % of the GDP of Zambia. The cost due to illness is thus directly related to water level fluctuations and technology which may become a critical issue if climate change predictions affect the rainfall and technology does not adapt.

In the wellfield areas main sewer lines should be constructed to transport waste away from the area. The hydrochemical and hydrogeological data indicates that the settlement around the wellfield pose a major contaminant risk due to on site sanitation. To reduce the contamination threat the areas should be prioritised for installation of sewer lines to transport waste out of the wellfield protection zones.
**Future wellfield development.** The existing wellfield sites at Kifubwa and College are both vulnerable to pollution, this threat will be difficult to mitigate and the implementation of protection zones especially at Kifubwa will be difficult. It is recommended that future wellfield development should take place at locations on the marble aquifer in areas not yet settled and the construction should be coincident with the implementation of physical and legal implemented protection zones.

**The Kansanshi mine needs to install monitoring boreholes in the marble aquifer below the schist to monitor for contamination.** The existing monitoring network at Kansanshi should be expanded to include piezometers that penetrate the deep aquifer at depth, this should be done to the west, south and south west of the mine in order to monitor for contamination plumes from the mine.

**The low pH values around the edge of the mine should be further investigated.** The pH values around the edge of the southern boundary of the mine should be investigated further to identify the reason for the low pH. The source of the acidity needs to be quantified in order to protect the population that uses water from the shallow aquifer.

**The link between dewatering and the lower water levels is uncertain but should be proven through monitoring and a detailed sub regional hydrogeological model.** The community around Lake Kimasala have seen water levels decrease in this important wetland area that they believe are coincident with the dewatering at the mine. The geological structures and the karstic nature of the Chafugoma marbles indicate that the lowering of water levels cannot be dismissed as a cause of lower water levels and there is a need for monitoring boreholes to analyse flow direction which is coupled with a detailed hydrogeological model.

**There is a need for a detailed hydrogeological model to understand the present groundwater flow and hydrochemistry to predict the future threat of contamination.** The present data made available and the nature of the marble aquifer that is present at the mine area leaves major data gaps, especially with relevance to the existing hydrochemistry and the large scale groundwater flow around the mine. A detailed numerical groundwater flow model is needed to look not just at the dewatering in the mine area but to look at the subregional groundwater flow. This will provide more data on the link with the wetland and can also be used to predict the possible direction of contaminant flow in the underlying Chafugoma marble aquifer. The model should also include a detailed analysis of the threat posed by the tailings and hazardous waste facilities in relation to the Kansanshi stream.
12. References


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