UNIVERSITY OF ZIMBABWE

EVALUATION OF THE GROUNDWATER POTENTIAL OF THE MALALA ALLUVIAL AQUIFER, LOWER MZINGWANE RIVER, ZIMBABWE

By

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Integrated Water Resources Management

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DECLARATION

I declare that this thesis is my own work. It has not been submitted before, for any degree or examination of any University.

Name: **Taurai Henryback Masvopo**

Signed………………………………day of……………………………………………2008

DEDICATION

This work is dedicated to my late brother Wilbert and my late father Laiven Masvopo.

Life is but a small journey.

ABSTRACT

The study site lies in a semi arid climatic zone in the south eastern part of Zimbabwe. The overall climate, with a mean annual rainfall of 350 mm/annum is not generally suitable for farming, but groundwater from alluvial aquifers is a possible resource for supplementary irrigation. The main source of water for most purposes is surface water, but its scarcity causes problems for general livelihoods. The Mzingwane river is ephemeral and thus only flows for a limited period of time during the year. The local community as such has to rely on groundwater from alluvial aquifers for domestic purposes and food production. Alluvial aquifers have the advantage that when they are deeper than 1m, less water is lost to evaporation. However, the main challenge with such aquifers is that abstraction for large scale use is expensive and usually requires investment in motorized pumps which can be expensive for the local communities

This study evaluated groundwater resources at a local scale by characterizing the Malala alluvial aquifer, which covers a stretch of 1000 m of the Mzingwane river and is on average 200 m wide. The aquifer is recharged, naturally, by flood events during the rainy season and, artificially, by managed dam releases from Zhovhe dam during the dry season. The Malala site was selected from geological mapping and resistivity studies.

The site shows indications of deeper sand layers and hence would be expected to have a higher potential of storing more groundwater. Piezometers were installed in the river channel to monitor the water level fluctuations in the alluvial aquifer. Water samples were collected from Zhovhe dam, Mazunga area and Malala alluvial aquifer in order to analyse the major ion chemistry of the water at the aquifer and at the source of recharge. A piper diagram analysis showed that the water in the alluvial aquifer can be classified as sodium sulphate. The water is also of a low sodium hazard and can therefore be used for irrigation without posing much risk to the compaction of soils.

Laboratory tests were carried out to characterize the Malala alluvial aquifer material for the porosity, hydraulic conductivity and specific yield of the aquifer. The porosity of the alluvial aquifer was calculated to be 39% with a hydraulic conductivity of 59.76 md^{-1} and a specific yield value of 5.4 %. The slope of the alluvial aquifer was measured as 0.38 %.

Resistivity surveys showed that the alluvial aquifer has an average depth of 13.4 m. The alluvial aquifer is more enhanced on the upstream part of the dolerite dyke. The bedrock is metamorphic rock mainly tonalitic and granodioritic gneisses. A sieve analysis experiment showed that the alluvial aquifer is sand. Water level observations from the installed piezometers indicated that the water levels dropped on average by 0.75 m within 97 days after the observed dam release.

The alluvial aquifer system can store approximately 1 035 000 m^3 of water per km length of the river. 116 000 m^3 of this water is readily available for abstraction and has a potential of irrigating at least 11.6 ha/annum. An increase in the number of timed releases can lead to an increase in the groundwater potential. 46.4 ha of land can be irrigated from the alluvial aquifer from at least four releases per annum which saturate the aquifer. The alluvial aquifer can thus store a significant amount of water and has a high groundwater potential to sustain both domestic and irrigation water supply through out the year.

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To all those who assisted me and those whom I have not mentioned by name, may the lord shower you with blessings.

Taurai H. Masvopo, June 2008

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1. INTRODUCTION

1.1 Background

Zimbabwe is a Southern African country, 390,000 km^2 in extent and shares its borders with Botswana, South Africa, Zambia, Mozambique and Namibia. The country lies between latitudes 15^oS and 23^oS and longitudes 25^oE and 33^oE. The overall climate is not very favourable for rainfed farming, and substantial areas are classified as semi- arid (Owen, 2000). The country has a single rainfall season during the summer months from November to March, characterised by high inter-annual variability and the prevalence of mid-season dry spells (Mupawose, 1984). The country has an average rainfall of 675mm/annum (Meteorological services department, 1981).

Data analysis on rainfall and evaporation collected over eighty years shows that potential rainfall deficits are much greater than potential surpluses (Meteorological services dept, 1981). Indications show that the more humid north east of the country receives more rainfall during the rainy season as compared to the other parts of the country (Meteorological services dept, 1981).

In Zimbabwe potential evapotranspiration always exceeds precipitation on an annual time step (Owen, 2000). It can thus be anticipated that perennial water is generally only available where the storage of temporary water surpluses has occurred, either by man made reservoirs and dams, or naturally as lakes or groundwater storage in hydrogeologically favourable areas (Owen, 2000) .

The erratic rainfall pattern in the west of Beitbridge town has led commercial farmers to look for other sources of irrigation water such as groundwater from alluvial aquifers. Artificial recharge of alluvial aquifers as such has to be considered for water supply in commercial as well as communal areas. Alluvial aquifers for a long time have not been considered as possible sources for water supply in both rural and urban settings. People relying on groundwater from alluvial aquifers do not know how much groundwater resources are available in the channel sands since the resource is hidden. As such this study seeks to quantify the amount of groundwater which can be stored and abstracted from these sand aquifers. The thesis considers alluvial aquifers in hydrogeologically favourable conditions since such sites have the possibility of storing more groundwater.

The rural communities in Zimbabwe are mostly agrarian in nature (Tabex, 1994). In order to improve the living standards of the rural people there is a need to develop a water supply that has the potential to provide both food and additional income for the rural farmer. Communal farmers have little access to productive water resources at low cost and this factor is considered a significant constraint on rural development (Magadzire, 1995).

Alluvial aquifers are an important resource especially if they are found close to centres of demand. Owen (1989) considers shallow aquifers as being of particular interest to communities in Zimbabwe since they are easily accessible, have comparatively a rapid rate of recharge and can store and supply water through the long dry season and in some cases alluvial aquifers have abundant water to sustain large communities. The studied aquifer is an example of an aquifer which is located close to the community. The Malala alluvial aquifer is on average 1 km away from the individual homesteads.

Recharge of alluvial aquifers in the Mzingwane river catchment is generally excellent and is derived principally from river flow and dam releases. No river flow occurs until the channel aquifer is saturated and such full recharge normally occurs early in the rainy season. For lateral plains aquifers, recharge depends on the permeability of the aquifer, the distance from the channel and the duration of river flow. Artificial recharge comes from seepage from small dams and from releases from large dams such as Zhovhe (Mzingwane River) and Silalabuhwa (Insiza River), (Owen and Dahlin, 2005).

The channel sand aquifer i.e. sand deposited by a flowing river, is considered in the research. Resistivity surveys were carried out to locate a potential alluvial aquifer. The most suitable site chosen lied on a low resistivity trough and has a deeper sediment layer. The deeper the channel sand layer the higher the groundwater potential since the alluvial aquifer will be able to store more groundwater. The studied Malala alluvial aquifer is part of an extensive alluvial "ribbon" aquifer system stretching from the confluence of the Mzingwane and Limpopo rivers to Zhovhe dam which lies upstream of Beitbridge town along the Mzingwane river.

1.2 Problem Statement

The Mzingwane river is ephemeral and either flows immediately after a rainfall event or after a release of water from the upstream Zhovhe dam. The river is dry outside these events. The major problem in this area is thus the lack of surface water resources for domestic as well as for food production.

The Mzingwane river though dry for most times of the year has water stored in the sand bed (alluvial aquifer). The amount of water stored in the sand is not known due to variations in the thickness of the sand from place to place along the river length. Therefore the groundwater potential of the alluvial aquifer system is generally not known unless if such aquifers are studied in detail.

The water chemistry in alluvial aquifer systems varies considerably depending on the interactions of the water and the host media. In areas where water is scarce, communities tend to use available water even when the quality of such water is not acceptable. It would be of interest to establish the major ion chemistry of the water in the alluvial aquifers.

This study therefore seeks to address the problems highlighted above with the Malala alluvial aquifer being a case study.

1.3 Justification of the study

The main reason for the study on the groundwater potential of the Malala alluvial aquifer is to quantify the water stored and the water which can be abstracted from the river channel aquifer. The community relies on the alluvial aquifer for both domestic and agricultural water supply. However it is not known how much water is available in the aquifer. The community has no other source of water since the Mzingwane river is usually dry through out the year and when releases are made, the water is meant for downstream commercial farmers in the Mazunga area.

Previous work in groundwater resource estimation from alluvial aquifers in Zimbabwe has been carried out at a large scale covering major rivers in the Mzingwane river catchment and Save River catchment in the Manicaland province. Large scale analysis leads to generalisations which might not be true for specific conditions. Moyce et. al., al (2006) studied the Lower and Upper Mzingwane river channel aquifer and plain aquifers. This was a catchment wide study with a number of estimations of aquifer parameters. This study thus undertakes to quantify groundwater resources at a local scale by adequately characterizing a single aquifer. This study concentrates on alluvial aquifer recharge from managed dam releases and / or natural flood events. Previous work in alluvial aquifer resource estimation has not concentrated on groundwater availability after a managed dam release or a natural flood event.

The Zimbabwe National Water Authority is faced with a problem of quantifying groundwater that is stored in the river channel sands yet knowledge on groundwater storage is required when managing dam releases since a flow event in the river only occurs after the aquifer storage has been satisfied. Groundwater resource quantification is necessary since it will allow for the equitable sharing of the scarce water resources in the Lower Mzingwane river system. Therefore the study undertakes to provide data on typical sand aquifer potential storage and the potential groundwater yield from the aquifer which is expected to assist ZINWA and other stakeholders in managing dam releases and water permits for communal and commercial farming systems downstream of Zhovhe dam.

1.4 Objectives

1.4.1 Main Objective

The main objective is to determine the groundwater yield and the major ion chemistry of the Malala alluvial aquifer.

1.4.2 Specific objectives

a. To determine the aquifer saturated volume changes with respect to a given proposed abstraction level.

b. To determine the bedrock formation underlying the alluvial aquifer in order to determine seepage losses from the aquifer and also to establish the number of geological layers at the study site.
c. To determine the groundwater yield of the alluvial aquifer after a managed dam release or a natural flood event.
d. To classify the groundwater hydrogeochemically.
e. To determine the irrigation potential from the alluvial aquifer storage after a dam release or a natural flood event.

1.5 Research Questions

a. What is the effect of current and proposed abstraction levels on groundwater levels after a dam release or a natural flood event?
b. What is the geological setting of the alluvial aquifer?
c. How much groundwater can be abstracted after a dam release or natural flood event?
d. What is the water type according to the major ion chemistry of the alluvial aquifer?
e. What area of land can be potentially irrigated from the alluvial aquifer?

1.6 Scope and structure of the Thesis

The thesis evaluates the groundwater potential of the Malala alluvial aquifer which is located in a semi arid area. The results are expected to give an insight into the amount of water resources available for especially the communal farmers. The second chapter presents the theoretical background information about alluvial aquifers. The third chapter gives a brief account of the study area. The fourth chapter indicates the materials and methods which were used in the study. The fifth chapter presents the results and discussion of the results. The thesis ends with chapter six which presents the conclusion and recommendations.

2. LITERATURE REVIEW

2.1 Definition and introduction - alluvial aquifers

A rock formation or sedimentary deposit which yields appreciable quantities of groundwater is called an aquifer. An aquifer has the property of easily allowing water to move through to wells (Karanth, 1987).

An alluvial aquifer can be described as a groundwater unit, generally unconfined above, that is hosted in horizontally discontinuous layers of sand, silt and clay, deposited by a river in a river channel, banks or flood plain. Alluvial aquifers are usually recharged when a river is flowing (Barker and Molle, 2004) and also because of their shallow depth and close vicinity to the streambed, alluvial aquifers as such have an intimate relationship with stream flow. It can be argued that groundwater flow in alluvial aquifers is an extension of surface flow (Mansell and Hussey, 2005).

Alluvial aquifers are generally some form of natural rainwater harvesting formations. Alluvial aquifers in the Mzingwane catchment are generally unconfined and are recharged annually by precipitation as well as discharge by groundwater recession (Owen, 2000).

Alluvial aquifers are formed either due to a reduction in the transport capacity of a stream due to a loss of stream power or alluvial deposition can occur due to an increase in the sediment supply (Richards,1982). The loss of stream power occurs mainly due to a decrease in the river channel gradient, an increase in the channel width or due to a loss of stream flow caused by evaporation and infiltration. The sediments deposited usually form a gentle and planar surface on top of the pre- existing river bed topography.

Alluvial deposition can occur due to an increase in the sediment supply caused either by the introduction of fresh sediment source by glacial outwash or stream capture or secondly may be due to accelerated erosion due to climatic change, deforestation or overgrazing.

Owen (1989) in classifying the alluvial provinces in Zimbabwe considers the Lower Mzingwane river alluvial aquifer types to be those he termed “mature river alluvium”, these are developed due to the shallow gradients and broad channels in the downstream reaches of large rivers. He further suggests that alluvial sediment accumulation in Zimbabwe generally occurs at gradients of 1:500 or less.

Alluvial aquifers are significantly vulnerable to evaporation, especially in the top 1m zone of the alluvial aquifer. Wipplinger, (1958) suggests that at the end of the rainy season when inflows into the aquifer cease the top meter of the groundwater is usually lost within 90 days to direct evaporation. When water levels in the aquifer decline considerably, 20% of the saturated volume of the aquifer cannot be extracted due to practical constraints such as the intake positions of a borehole (Nord, 1985).

Surface water bodies can be classified as discharge water bodies if they receive a groundwater contribution from base flow, or as recharge water bodies if they recharge a shallow aquifer below the streambed (Townley, 1998). In semi-arid regions, streams with alluvial aquifers tend to vary from discharge water bodies in the dry season, to recharge water bodies during the rainy season or under a managed release regime (Owen, 1991).

Although there is a considerable body of research on the interaction between surface water bodies and shallow aquifers, most of this focuses on systems with low temporal variability. In contrast, intermittent rainfall patterns in semi-arid regions have the potential to impose high temporal variability on alluvial aquifers, especially small ones (Love *et al.,* 2007). For example, single high magnitude flows have been shown to have a greater influence on recharge than the more frequent, small to medium flows in the Kuiseb River in Namibia (Lange, 2005).

In semi arid climates, alluvial aquifers are totally recharged annually due to indirect recharge through river bed infiltration and may therefore be fully exploited on an annual basis (Owen and Dahlin, 2005). It has been shown that river flow only occurs after the aquifer channel sands have become fully saturated (Nord, 1985; Halcrow, 1982).

The hydraulic conductivity and hydraulic gradient determine the downstream movement of alluvial water within the channel sands. Since the alluvial sediment accumulation only begins at slopes of 1: 350 and greater (Sithole, 1987; Owen, 1989), then the hydraulic gradient is constrained by the channel slope in a natural system. Calculations that have been done for channel sands with typical hydraulic conductivity and gradient values show that the water front tends to move less than 1km per year, and is replaced by water moving in from the upstream part of the river channel. As such downstream discharge is not considered a significant component of discharge (Owen, 2000).

Owen and Dahlin (2005) suggest that the alluvial fill is augmented in width and thickness at geological boundaries/ contacts. They further suggest that if at a geological contact the resistant rock lies downstream a shallow meandering river channel occurs upstream of the geological boundary. A subsequent phase of river flow will result in a river which is wide and shallow on the upstream part of the contact.

For the case where the more resistant formation lies upstream of the geological contact the less resistant formation downstream will be eroded and scoured resulting in a plunge pool developing on the downstream part of the river system. In the case of a subsequent phase of alluvial aggradation, the waterfall and associated downstream plunge pool are buried and thus become the focal points were the alluvial sediment thickness can be enhanced (Owen and Dahlin, 2005).

2.2 Distribution of Alluvial Aquifers

Alluvial aquifers are wide spread in the Limpopo Basin. Alluvial aquifers in this basin are more extensive in the Mzingwane river catchment in Zimbabwe (Görgens and Boroto, 1997). Alluvial deposits are present in the lower reaches of most of the larger rivers of the Mzingwane Catchment (Bubye, Mwenezi, Mzingwane, Shashe, Thuli and their tributaries. The aquifers exhibit themselves as narrow bands, typically less than 1 km in width on the largest rivers (Love *et. al*., 2007).

In Zimbabwe the majority of alluvial aquifers occur away from the central watershed in the mature most downstream reaches of the river systems once the channel slopes decline to a gradient of 1: 350 or less (Owen, 1989; Sithole, 1987). As such alluvial areas are expected in the low-lying peripheral areas around the edges of Zimbabwe. Owen and Dahlin (2005), further suggest that aquifers generally occur in the active channels of ephemeral rivers in Southern Africa.

The slope of the river channel affects the distribution of alluvial aquifers. Were there are steep slopes alluvial aquifer formation is discouraged since these sites favour erosion rather than deposition of sediments. Hence alluvial aquifers would be expected were the slopes are gentle. In areas were evaporation and infiltration losses are high, sediment is expected to accumulate since the streams energy to transport material will be reduced. Were a tributary joins another stream, alluvial aquifers are expected to be developed since more sediment will be introduced into the main river channel. If the carrying capacity of the river is exceeded the sediment load will be deposited thus resulting in alluvial aquifer formation (Owen, 1991).

Owen (2000) has noted that productive alluvial aquifers can be found in Zimbabwe in the Southern lowveld, the western Kalahari sand region and at the base of the Mafungabusi and Zambezi escarpment in the north. He suggests that these alluvial occurrences are locally enhanced at geological boundaries. Owen (2000) further suggests that alluvial aquifers coincidentally occur in areas with a low average annual rainfall.

2.3 Geometry and Physical properties of Alluvial Aquifers

Ekstrom *et.al*., (1996) conducted electrical resistivity surveys of alluvial aquifers at localities where an alluvial channel crossed a geological boundary. This was done in order to ascertain the effect of such a boundary on the channel geometry. The resistivity work was also done and supported in a follow up study by Beckmann and Liberg (1997) who used radar imaging to determine the depth of the alluvial fill. These studies showed that the alluvial sediments are better enhanced in depth at geological boundaries as compared to shallower depths of the alluvial sediments on river sections which are further away from the geological boundaries.

An enhancement of the thickness and area of alluvial aquifers is commonly observed associated with geological boundaries, and this enhancement occurs both upstream and downstream of the geological contact (Ekstrom *et al*., 1997; Beckman and Liberg, 1997). After a rainfall event, the groundwater table declines away from the stream, and thus groundwater flow leaks away from the alluvial aquifer into the underlying host rocks (Sandstrom, 1997).

Moyce *et. al*., (2006) recognized that the Lower Mzingwane river has thicker and more extensive aquifers since the slopes are gentle (1:500 or even 1:1000), which is good for sediment accumulation. He further concludes that Landsat False Colour Composites can be used to map out alluvium deposits and panchromatic images are best used for the river channel deposits.

The alluvial aquifers form ribbon shapes covering over 20 km in length and aerial extents ranging from 100 hectares to 255 hectares in the channels and 85 hectares to 430 hectares on the flood plains (Moyce *et. al*., 2006). They also analysed the alluvial sediments in the Mzingwane catchment and estimated the hydraulic conductivity (K) values of between 40 and 200 m/day based on the Hazen's (1911) method.

Owen and Dahlin (2005) in their study of the Mzingwane river alluvial aquifer determined aquifer parameter values for the hydraulic conductivity, specific yield and porosity using a constant head permeameter and by laboratory gravimetric measurements respectively. Using measured values and values obtained from other alluvial channels in the region (Nord, 1985; Owen, 1994), average hydraulic conductivity for the Mzingwane river were estimated at 200m/day; specific yield estimated at 20% and porosity was estimated to be 35 %. The alluvial aquifer channel sediments are generally clean washed sands that have excellent hydraulic and storage characteristics, allowing for high well pumping rates (Owen and Dahlin, 2005)

Further to this (Owen and Dahlin, 2005) propose that in the case where the river is flowing it can be assumed that the aquifer is fully saturated for that period, provided that abstraction rates from the aquifer are less than the measured river flow.

Aquifer dimensions are determined by the extent and thickness of the alluvial fill in the river channel and under the lateral alluvial plains, where these are developed. In general, alluvial aquifer dimensions are of the order of a few tens to a few hundreds of meters in width and a few meters to a few tens of meters in thickness, developed along the length of the alluvial channel, resulting in a thin ribbon like aquifer. The geometrical extent of the saturated alluvial fill is a key limiting factor (Owen and Dahlin, 2005).

The three dimensional extent of the aquifer acts to provide for the quantification of available groundwater resources. Locations where alluvial sediment dimensions have been naturally enhanced represent potentially good sites for groundwater development. From the geological map of Zimbabwe it can be seen that alluvial aquifers generally form at geological boundaries.

2.4 Water losses from alluvial aquifers

Alluvial aquifers usually are significantly recharged by direct rainfall and mainly through river bed infiltration as a result of indirect runoff from rainfall or from managed dam releases. This does not imply that alluvial aquifers only get recharged. Alluvial aquifers are subjected to significant losses of water through especially four main processes.

1. Direct evaporation from the alluvial aquifer top surface.

   Wipplinger (1958) measured the losses of water due to direct evaporation from a sand body and showed that for "typical" river channel sand with no recharge, the top 90 cm of water would be lost to evaporation within a period of 120 days under the temperature and humidity conditions in Namibia at the time of the experiment. He suggests that water losses are greatest when the water table is close to or just below the river bed, and the rate of evaporation loss decreases as the groundwater levels decline. This therefore suggests that shallow and wide alluvial aquifers are prone to more evaporation losses as compared to deep and narrower alluvial aquifers of the same volume of aquifer.

It should however be noted that water losses in the top zone of alluvial aquifers does not occur at the same rate from place to place and from time to time. Water loss rates are higher in warmer climates as compared to colder climates. The number of sunshine days also determines the rate of water loss from the aquifer.

2. Evapotranspiration from the riparian vegetation

   If the riparian vegetation has access to the alluvial water, evapotranspiration will take place. Significant quantities of water can be lost through this process especially if the rooting system is several meters deep. It should be realized that rarely do trees grow in the river channel, transpiration losses are only significant if there exists an alluvial plain from which tress have direct hydraulic contact with the saturated channel sediments (Owen, 2000).

3. Seepage losses through the bedrock

   Seepage losses through the bottom of the aquifer occur and rely on the permeability of the bedrock and the downstream discharge mechanism for the seepage flow. Crystalline bedrock usually has limited seepage losses whilst Karst limestone and coarse grained, permeable sedimentary facies support very high seepage losses. Seepage losses are usually more evident when the water levels drop below 90cm, the level which can be attributed to evaporation loss (Owen, 2000).

4. Down stream movement of water through the channel sand

   The hydraulic conductivity and hydraulic gradient determine the downstream movement of alluvial water within the channel sands. Owen (2000) considers movement of water downstream in an alluvial aquifer to be insignificant. He suggests that on average the water front moves less than 1km per year through the alluvial sands and is replaced by water flowing from the upstream section of the river channel.

Love *et al.,* 2007 considers major losses from small alluvial aquifers as losses due to evaporation and seepage to underlying bedrock. He suggests that the depth of the alluvial material is an important factor contributing to water losses from alluvial aquifers. Shallow aquifers less than a meter in depth can dry up due to evaporation losses within 24 hours of a river flow (Love *et al*., 2007). The type of bedrock is also an important factor in aquifer loss considerations. Weathered bedrock results in more losses to seepage whilst younger less weathered intrusive bedrock inhibits the down ward movement of water from the aquifer.

De Hammer (2007) calculated losses from an alluvial aquifer system after a single river flow event. The study was carried out in the upper Mnyabezi subcatchment of the Mzingwane river catchment, in Southern Zimbabwe. He estimated that 14 % of the water stored in the aquifer after a river flow event is lost to evapotranspiration. 86 % of the water is lost to the underlying granite bedrock. Therefore the type and nature of the bedrock are important factors in the storage of water in an alluvial aquifer system.

Studies of the water losses through evapotranspiration are important to this study since the Malala alluvial aquifer has riparian vegetation which is significant enough to cause considerable evapotranspiration.

2.5 Groundwater Resource Quantification

Groundwater resources in an alluvial aquifer can be estimated by multiplying the aquifer volume by a specific yield value of the aquifer material. To calculate the volume of the aquifer the aquifer surface area is multiplied by the depth of the sand. Water losses from the aquifer have to be incorporated and these include through flow, evaporation and seepage. Nord (1985) identified natural losses for Botswana sand rivers and measured the depletion of water levels in three river channels. The study was done in river channels which are similar to Zimbabwe river channel aquifers and therefore these depletion curves can be useful in this study.

Sieve analysis, pumping tests and the use of a permeameter in the laboratory can be used to estimate the specific yield and transmissivity values. Pump testing is the most accurate method as it measures the actual field values while the other methods only measure samples, which are unlikely to reflect the full heterogeneity of the alluvium (Owen. 1992).

However pumping tests are very costly. Well drilling and construction is an expensive venture which requires specialized drilling equipment (Karanth, 1987). Drilling in sand is even more expensive. Mud rotary type of drilling is required which has the additional cost of mud which is also very expensive. Pumping tests can be easily carried out especially where there exist already drilled boreholes. At the study site there are no existing boreholes as such the tests could not be done since both test wells and observation wells had to be drilled.

Another disadvantage of pump testing is that water has to be pumped from the aquifer in such a way that the water does not return to the aquifer. This therefore requires water to be pumped considerable distances away from the aquifer (Karanth, 1987). More pumping results in the need for more energy requirements such as diesel or electricity to power the pumping process. In alluvial aquifers pump testing has the disadvantage that considerable pumping might not result in sufficient drawdown in the observation wells. Hence the aquifer properties will be difficult to calculate if there is not much or any drawdown in the observation wells.

Nord (1985) proposed that an alluvial aquifer water resource could be divided into two main zones. The first zone being an upper "natural losses" zone; this refers to the groundwater which is lost especially during the dry season by evaporation, transpiration and seepage. The second refers to lower "water in storage "zone which contains water which is retained in the alluvial aquifer at the end of the dry season. A pumping regime of a controlled pumping rate and time period is required in order to utilize the amount of water in storage every year thus allowing space for the aquifer to be recharged by annual river flows.

In general alluvial aquifers are shallow in depth, usually as little as 3m in thickness of the alluvial fill. The basal 40cm is considered impossible to abstract for practical considerations (Nord, 1985). The top most 90cm is considered to be an evaporation zone and will thus lose water to evaporation. This implies that a limited thickness of saturated alluvium remains from which water can be abstracted. Owen (2000) suggests that the identification of lithological boundaries, which may indicate an increased aquifer thickness, is of considerable importance in terms of the available water resource.

Nord (1985) in studying an alluvial channel in Botswana considers that direct evaporation can deplete the top meter of the alluvial sediment and that evaporation losses may account for 25 % of the available water in the aquifer once annual recharge has ceased. Owen (2000) considers that, since evaporation losses are high any structures, man made or natural that increases the thickness and width of the coarse channel sediments can make a significant difference towards the total annual water availability from alluvial aquifers.

In order to adequately quantify groundwater resources from alluvial aquifers it is important to identify the bedrock geology and to also have an understanding of the processes of alluvial aquifer dimensions. By determining such conditions localities can be found that host groundwater resources capable of supporting large – scale water development such as is required for commercial irrigation.

2.6 Groundwater Development

Interconsult (1987) considers alluvial aquifers as having excellent groundwater development potential and suggests that they are one of the major under utilised groundwater resources in Zimbabwe, both in terms of the available water resources and their distribution which is in harmony with rural settlement patterns.

Owen (1992) suggests that significant quantities of irrigation water supplies are available in the alluvial aquifer deposits of Zimbabwe, both within existing river channels and beneath alluvial plains which may occur adjacent to these channels. He suggests further that the development of alluvial aquifers will have a very considerable impact on the economically deprived people in drought prone areas. Owen (1992) realised that the depth to the water table is shallow and this allows for exploitation by manual technologies. Dug wells and shallow lift manual pumps are effective systems for utilising these resources.

Mansell *et. al*., (2005) concludes that the availability of alluvial flows in rivers depends obviously on the presence of a significant depth of suitable alluvial material. If the alluvium consists of fine silt or clay, it would be difficult to extract much water. Mansell *et al.,* (2005) further suggest that in steeper channels with gravel-sized sediment, the water levels may fall too rapidly for any practical abstraction.

Recharge of the alluvial aquifers is generally excellent and is derived principally from river flow. No river flow occurs until the channel aquifer is saturated and such full recharge normally occurs early in the rainy season. For lateral plains aquifers, recharge depends on the permeability of the aquifer, the distance from the channel and the duration of river flow. Artificial recharge comes from seepage from small dams and from releases from large dams such as Zhove (Mzingwane River) and Silalabuhwa (Insiza River). The aquifers can sustain small-scale irrigation and infiltration galleries, and well point systems can be constructed to exploit the resource (Owen and Dahlin, 2005).

Significant commercial irrigation development has taken place from the alluvial sediments of the Mzingwane, Runde and Limpopo rivers in Southern Zimbabwe. This irrigated production coexists side by side and in contrast with low productivity dry land farming as practiced by the local communal farmers. At Mazunga Ranch on the river Mzingwane, an 800ha block of commercial irrigation is developed by means of suction lift well point system driven into alluvial channel sands upstream from a geological contact between resistant silicified sandstone downstream and less competent basalt upstream (Owen and Dahlin, 2005).

Abstraction of groundwater from the alluvial channels can be interrupted by summer river flows. The abstraction intake wells and well points may be destroyed or damaged by flooding. Conveyance structures are thus required to divert water from the river channel to the arable lands (Owen, 1989).

The productivity of the well field depends on the general flow of water through the channel sediments from the upstream to the downstream part of the aquifer. The higher the flow, the greater the groundwater availability in the aquifer. Annual recharge also ensures generally good fresh water quality in an alluvial aquifer (Owen and Dahlin, 2005).

Water resources are generally developed from alluvial aquifers by the user communities themselves usually on an ad hoc basis. This random approach to water resource utilization often leads to either under or non development or to unsustainable overuse of such a resource. Increased pressure on alluvial aquifers has arisen due to an increase in water demand brought about by rising populations and due to the extended drought periods that have occurred in Zimbabwe since 1981 (Kundhlande *et al.*, 1995). Mharapara (1995) considers alluvial aquifers as being substantially under utilized as compared to other aquifers such as dambo type wetland aquifers.

Alluvial aquifers can be of the 'buried waterfall' type or shallow aquifer types, The "buried waterfall type" are considered more favourable for groundwater extraction and development than the more extensive and shallow type aquifers. The former is preferred since it has a greater saturated thickness of the alluvial fill, increased available drawdown for wells and also due to less evaporation losses.

Shallow aquifers however can supply both primary water and productive water, as such they become important resources in the overall development of the under developed rural areas. Socio economic studies show that communities with access to shallow aquifer water supplies are much better off than communities without such access (Bell *et al*., 1987; Kundhlande *et al*., 1995).

Generally, alluvial aquifers are widely used in the semi arid regions of southern Africa, both for primary water supply and for irrigation development (Thomas & Hyde, 1972; Wikner, 1980; Nord, 1985; Owen & Rydzewski, 1991).

2.7 Water balance of an alluvial aquifer system

Hydrological processes affecting the flow of water in an alluvial aquifer are important in enhancing an understanding of sustainable water resources management (Uhlenbrook *et.al*., 2004), as such it is important to quantify the water balance of an alluvial aquifer system. The water balance is the equilibrium between the volume of water inputs, outputs and storage changes over a given fixed time span in the alluvial aquifer system (Shaw, 1994).

The water balance equation for an alluvial aquifer is presented below (Schicht & Walton, 1961). The variables in the equation are in terms of volume or depth per unit of time e.g mm/day. Lateral groundwater flows are included in the equation in the net groundwater flow computation.

$$\Delta S_G = P + Q_{IN} - Q_{OUT} + Q_L - Q_S \pm Q_P - E \quad \text{……………………equation 2.7.1}$$

Where

ΔS_G = Change in groundwater storage

P = Precipitation which percolates through the unsaturated zone

Q_{IN} = Flow from upstream of the aquifer through the sand formation

Q_{OUT} = Flow in the downstream direction through the sand formation

Q_L = Leakage or recharge from the river bed to the aquifer

Q_S = Seepage from the alluvial aquifer to the underlying geological formation

Q_P = The amount of pumping out of the aquifer.

E = Evapotranspiration from the unsaturated zone.

Net groundwater flows ($Q_{IN} - Q_{OUT}$) refer to the balance between inflows into the aquifer and outflows from the aquifer. A positive value implies that inflows are greater than outflows from the aquifer; as such a positive value implies that the aquifer gains more water than it losses to the downstream movement. Whilst a negative value indicates that the aquifer losses are greater than the inflows. Therefore net groundwater flows refer to changes in storage in the alluvial aquifer.

3. STUDY AREA

3.1 Geographical location, Topography and Climate

The study area lies in the Mzingwane river catchment which is in the South Eastern part of Zimbabwe. The Mzingwane Catchment is part of the Limpopo River Basin. The study area lies in the agro-ecological region V which experiences considerable low average annual rainfall of approximately 350mm/annum compared with the average figure of 675mm/annum for Zimbabwe (Meteorological services department, 1981). The topography is generally low lying and has a gentle landscape which is intersected at some localities by Mountains which rise abruptly from the gentle low lying areas.

The climate is that of semi desert to Savanna, having warm dry winters and hot summers with an unreliable sparse summer rainfall (Watkeys, 1979). Failure of this precipitation which falls on an average of 39 days each year results in frequent droughts. In the summer months from October to March the mean maximum temperature is usually over 30°C. During the winter the mean maximum temperature is a comparatively pleasant 26.5°C (Watkeys, 1979).

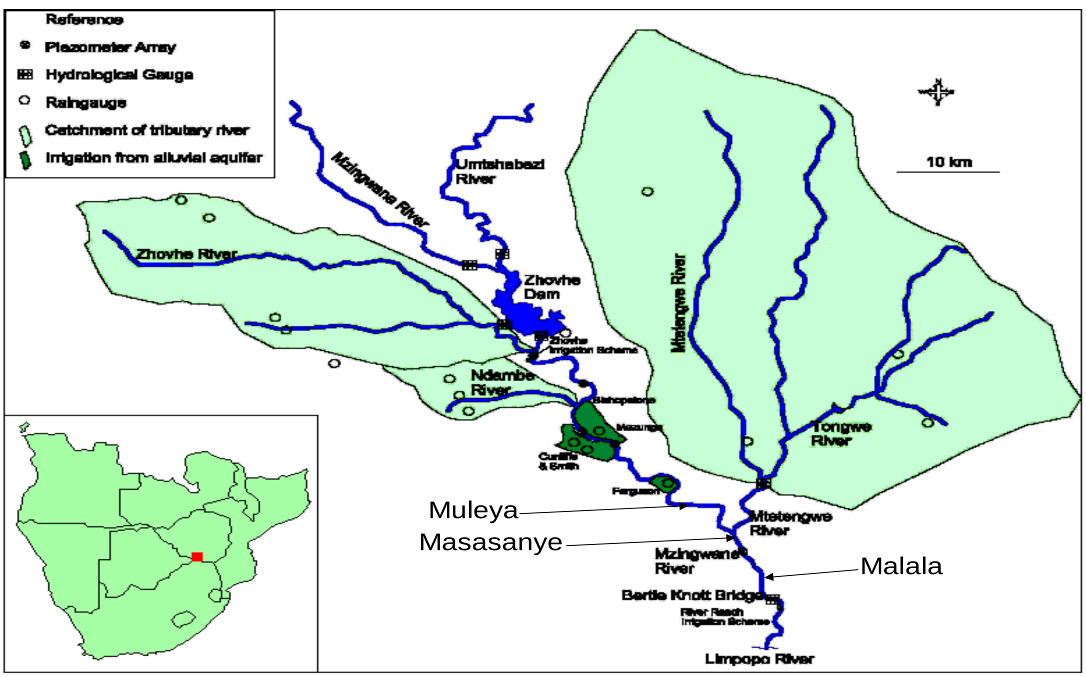


Fig 3.1.1 The Lower Mzingwane river system. Inset: location in southern Africa (Love, 2007)

The study site lies along the Mzingwane river in the Mzingwane river catchment between Zhovhe dam and Beitbridge town. The alluvial aquifer system between Zhovhe dam and Beitbridge is recharged artificially by water which is frequently released from Zhovhe dam for Beitbridge town and commercial farmers.

Downstream of the large commercial farmers, the Mzingwane River flows through the Mtetengwe Communal Lands, where smallholder farmers have less access to water for irrigation (Love, 2007).

3.2 Geology

The geological mapping carried out at the study area indicated that the area is underlain by Tonalitic and granodioritic gneisses of the beitbridge group. The gneisses are of Precambrian times. The tonalitic and granodioritic gneisses are in some places intruded by dolerite dykes which are probably of post karoo times (Watkeys, 1979).

Of notable significance is the dolerite dyke which crosses the river channel and strikes approximately east – west. The resistivity survey carried out in the river channel where the dolerite dyke under lies the section of the river, showed that the dyke is at an approximate depth of six meters. However physical probing in the river channel showed indications of the dolerite dyke at a shallow depth of three meters at some sections along the dyke crest. To a lesser extent the mapped area is underlain by mafic granulites and magnetite quartzites which are also of the beitbridge group (fig 5.3.1).

The geological mapping lumped together the tonalitic gneisses and the granodioritic gneisses since the two rock types have the same hydrogeological characteristics. The tonalitic and granodioritic gneisses are the host rock formations of the alluvial aquifer and occur as the basement rocks in this section of the river which was considered.

The river channel is flanked on both sides by alluvial terraces. The terraces were mapped as one lower terrace which lays closest to the river channel and an upper terrace which lies further away from the river channel and is at a higher elevation compared to the former. The lower terrace is on average eighty meters in width and runs as a linear segment along the river bank on both sides of the river channel. The lower terrace occurs on the entire length (approximately 2000m) of the mapped area.

The upper terrace is wider on the eastern bank as compared to the upper terrace on the western side of the river. The upper terrace lying on the eastern bank is on average 170 m in width and 2000 m in length on the stretch of the mapped area. The upper terrace is narrower on the western section of the river channel, having an average width of 50 m. The upper terrace on this section disappears at the dolerite dyke intersection located at approximately the central section of the mapped area. The upper terrace on this section therefore has an approximate length of 1 800 m.

3.3 Description of the river system

The Mzingwane catchment lies in the south eastern part of Zimbabwe on the eastern side of the central watershed. The Mzingwane river starts its flow in a southerly direction from close to the city of Bulawayo and ends at the confluence with the Limpopo river which lies on the border of Zimbabwe and South Africa. The upper Mzingwane catchment has the Ncema, Inyankuni and Insiza rivers as tributaries into the Mzingwane river.

In the lower Mzingwane catchment the Zhovhe, Umtshabezi and Mtetengwe rivers flow into the Mzingwane river. The major tributaries into the Mzingwane river upstream of the Malala alluvial aquifer are the Zhovhe and Ndambe river tributaries. The Mzingwane river and the Mtetengwe river confluence is a few kilometers downstream of the Malala alluvial aquifer. The Mzingwane river system is shown in figure 3.1.1 above.

The Mzingwane river is an ephemeral river which normally flows only after a dam release or immediately after a heavy rainfall event. The river as such is dry for most times of the year and is usually seen on the surface as a continuous mass of dry sand.

3.4 Water uses and water users

In the lower Mzingwane river, downstream of Zhovhe dam, water is abstracted from boreholes and well-points in the river and on the banks. Five commercial agro-businesses use alluvial groundwater for citrus, wheat, maize, cotton and vegetable production (love *et al.*, 2007). Some areas are reserved for game. Downstream of the large commercial farmers the Mzingwane river flows into the Mtetengwe communal areas were small scale farmers use both surface and groundwater resources for domestic and gardening purposes (Love *et al.*, 2007). The communal farmers, who live alongside the Mzingwane river, mainly practice dry land farming to provide for their basic food requirements. The major source of recharge for the alluvial aquifer is a series of releases of water from Zhovhe dam for Beitbridge town. Away from the watercourses groundwater is also abstracted from the boreholes drilled into the Karoo rocks, these boreholes are reasonably successful.

The ephemeral rivers in the lower Mzingwane river catchment usually exhibit a dry river bed; this however does not imply that the alluvial sediment is dry. There is usually a significant volume of water stored in the alluvial aquifers of these rivers (Jacobson *et al*., 1995; Seely *et. al*., 2003; Moyce *et. al*., 2006). Boreholes and pumps along intermittent rivers already make water available for communities of Southern Africa throughout the year, for example groundwater abstractions along the Mzingwane, Shashe and Save river in Zimbabwe (Hussey, 2003; Love, 2006b).

The local community close to the Malala alluvial aquifer relies on the alluvial aquifer for their domestic and gardening water requirements. The community abstracts water from the aquifer mainly through hand dug wells in the river bed. These wells are fairly shallow, usually dug to a maximum of two meters. Water is abstracted from these wells with bucket and rope water extraction techniques. The water is then used for domestic purposes and is also used to irrigate small gardens which lie adjacent and on both sides of the Mzingwane river banks.

3.5 Geometry and Physical Characteristics of the Malala Alluvial Aquifer

The Malala alluvial aquifer which was studied is 1 000 m long and is approximately 200 m wide. The aquifer can be divided into two sections depending on the location of the area relative to the dolerite dyke which cuts across the mid section of the aquifer. As such for reference the aquifer can be split into an upstream and downstream part of the dolerite dyke.

The alluvial aquifer is more enhanced in terms of depth on the upstream part of the dolerite dyke than on the downstream part of the aquifer. Electrical soundings in the river bed indicate that the alluvial aquifer has an average depth of approximately 13.4 m. The dolerite dyke is a natural embankment and thus the upstream part of the dolerite dyke can be considered as a natural sand dam.

4. METHODS

4.1 Selection of specific site and estimation of the aquifer depth

4.1.1 Desk study

An analysis of the available data, maps and aerial photographs was done. The Rhodesia Geological Survey; short report No. 45, an explanation of the geological Map of the country west of Beitbridge was consulted to give a background on the existing geological formations in the study area. Areal photographs of the lower Mzingwane catchment were also considered in choosing the sites to be considered for resistivity surveys. This was done by visualizing and estimating areas of the Mzingwane river sections were the width of the channel was longer. This approach resulted in some areas being selected for further geophysical investigations to determine the depth of the channel sand formation.

4.1.2 Resistivity Surveys

A reconnaissance visit was made to the Mtetengwe Area. A Terrametter SAS 300C geophysical equipment was used to determine the approximate depth of the sand and/ or the depth to the bed rock. The Schlumberger (AB/2) electrode configuration (figure 4.1.1) was used for the resistivity observations at the three selected sites i.e. Malala, Masasanye and Muleya site (fig 3.1.1).

At the three sites vertical electrical resistivity soundings (VES) were observed and the apparent resistivity measurements were plotted against depth. Resistivity measurements were taken from a depth of 1m to a maximum depth of 50m. The line transects were drawn along the river bed. This was done in order to make sure that the electric current induced at each electrode would penetrate relatively uniform ground formations.

Fig 4.1.1 Resistivity electrode arrangement

The electrical resistivity of a material is the resistance offered by a unit cube of it when a unit current passes normal to the surface of cross – sectional area (A), (Karanth, 1987). It is given by ohm's law:

$p = R * \frac{A}{L}$ Ω m^2/m = Ω.m ………………………..equation 4.1.1

Where p = Apparent resistivity
R = resistance offered by the medium of Length (L) and cross – sectional area (A).

From fig 4.1.1, A and B are the current electrodes. Current cables are connected to A and B, electrical current is then injected into the ground from the geophysical equipment through these two electrodes. M and N are the potential electrodes, these are also connected to the geophysical equipment and the potential difference (ΔV) is measured between these two electrodes. The resistance (V/I) is measured directly from the geophysical equipment.

The Apparent resistivity (p) of the ground at an approximate depth was calculated by multiplying the resistance (V/I) at that depth by a factor K. The factor derived depends on the spacing of both the potential and current electrodes. Breusse (1963) derived the factor (K) for use in the calculation of the apparent resistivity (equation 4.1.3).

p = K* ΔV/I ………………………equation 4.1.2 (from ohms Law i.e. V = I * R)

p = Apparent resistivity (Ω.m)
K = Factor [-]

ΔV = Potential difference (volts)
I = Current (A)

$$K = \frac{\Pi}{4} \times W\left[\left(\frac{L}{W}\right)^2 - 1\right] \text{………………equation 4.1.3}$$

That is

$$p = \frac{\pi}{4} \times W\left[\left(\frac{L}{W}\right)^2 - 1\right] \times \frac{V}{I} \text{ ………………..equation 4.1.4}$$

Where p = Apparent resistivity (Ω.m)
W = Potential electrode spacing (m) i.e. distance between M and N (fig 4.1.1)
L = Current electrode spacing (m) i.e. distance between A and B (fig 4.1.1)
V = Voltage (Volts)
I = Current (A)

After the selection of the study site at Malala, resistivity profiles were computed at the sites where the piezometers were installed. Resistivity plots were also done for other points outside these sites. The resistivity surveys were also done on the upstream and downstream side of the dolerite dyke which crosses the entire width of the Mzingwane river at the study site.

Resistivity measurements were taken along selected cross sections upstream and downstream of the dolerite dyke (Appendix V). The approximate depth of the sand or the sand /bedrock interface was then plotted against distance from the western river bank to the eastern river bank. On the upstream part, the cross section was plotted from the western side of the river channel, Point i.e. (X= 0800218, Y= 7553635) to the eastern side of the river channel, Point 7 i.e (X= 0800312, 7553722) and on the downstream part of the dolerite dyke the cross section was plotted from the western river bank, point 1 i.e. (X= 0800546, Y= 7553266) to the eastern side of the river channel, point 4 i.e. (X= 0800690, Y= 7553281). Resistivity measurements where also plotted along the river section where the dolerite dyke undercuts the alluvial aquifer.

4.1.3 Modelling using Rinvert software

The Rinvert software was used for interpreting resistivity sounding data collected from the schlumberger (AB/2) method. The method involves initially assuming an earth model of the acquired resistivity data by defining multiple horizontal layers and assigning resistivity values to each layer of a given initial thickness. The method is illustrated in appendix X.

Rinvert has a forward modelling procedure were a sounding curve is produced for the initial earth model. The curve is displayed as an overlay on the field sounding chart and the goodness of fit between the modelled curve and the field data curve is given as % RMS (Root-mean-square) error. Model parameters are adjusted until a good fit is attained.

The model proposed above is used as an initial model for inverse modelling. This procedure finds automatically the optimal model which gives the best least squares fit to the field data set. The resistivity and thickness of the layer can be fixed so that these do not change during the iterative inversion process. The stages from the initial model to the final model are shown in sequence by the display of the model sounding curve and the corresponding % RMS error at each iteration.

Equivalence analysis is done in order to show the uncertainty in the interpreted model. This is done by the determination of the range of models which fit the field data just as well within a user defined value of % RMS. Each acceptable model is displayed in order to give a visual impression of the uncertainty in each layer. Statistical analysis is carried out during this analysis and is given in descriptive terms.

The final model will give a reasonable guide into the earth layering at the studied site. The various depths of the layers will thus be estimated and the depth to the bedrock can be estimated with reasonable accuracy.

4.2 Geological Mapping

An area of approximately 4km^2 was considered during the mapping exercise. Approximately 2km^2 on either side of the river channel was mapped. Rock outcrops were recorded on a 1: 16 000 topographical map of the study area. Straight line transects were followed during the mapping exercise. Six major line transects running parallel to the river channel were followed, these lines were further away from the river bank and started along the terraces. River terraces were mapped separately and the transect lines ran perpendicular from the river channel bank to the first major transect line closest to the river bank on both sides of the river channel. Two terraces were mapped, a lower terrace and an upper terrace. The two terraces combined make up the alluvial plains aquifer.

4.3 Installation of piezometers and water level monitoring

A piezometer is a metal or PVC tube which is driven into the ground in order to monitor water level fluctuations in the subsurface. A piezometer has intake points which are perforated in order to allow water to flow from the geological formation into the tube. A piezometer which is driven into an unconfined aquifer will have the water level inside the tube at the same level with water in the formation into which the piezometer is drilled.

Eight piezometers were installed into the Malala alluvial aquifer. Manual techniques such as auguring were used to drive the piezometers into the alluvial aquifer. The piezometer was placed inside a metal rod which was then driven into the ground by twisting and turning the arms of the rod. At an approximate depth of 3m the metal rod would be detached from the piezometer. The piezometer would be left behind in the sand whilst the metal rod is removed (see fig 4.3.1 below).

Fig 4.3.1 Manual technique for the Installation of piezometers

Water level monitoring was carried out using an electric dip measure. Water levels from each piezometer were measured at 9.00 am everyday from the 31st of January 2008 to the 8th of May 2008, (Appendix VI). Piezometer B4 was blocked by sand on the 26th day of February 2008. Therefore there are no water level measurements from this date. Piezometers B3, B7 and B8 were installed on the 13th day of March 2008.

4.4 Surveying for Topographical analysis of the alluvial aquifer

The topographical survey was carried out using standard surveying procedures. A theodolite was used to measure ground surface elevations on the river channel bed and on the river banks. The theodolite was also used to calculate horizontal distances between one point and another. A dumpy level was used to calculate differences in elevation between two or more points.

A dumpy level was used to calculate differences in elevations since it is more accurate than the theodolite. When leveling the ground surface using a dumpy level the telescope remains horizontal and only rotates in the horizontal plane. Therefore errors are less as compared to a theodolite where the telescope rotates both in the vertical and horizontal planes.

A point was selected on the aquifer and was arbitrary set at 100 meters elevation. The other sections of the aquifer were then measured relative to this elevation. For example points downstream of this point would have elevations less than 100 meters.

The measured difference in elevation was then divided by the horizontal distance between the two points to calculate the slope of the river bed.

4.5 Laboratory analysis of aquifer material

Five sand samples were collected from the alluvial aquifer for further analysis of the hydraulic conductivity (m/day) and the porosity (%). Samples were obtained from a depth of approximately 1.5 m from the aquifer.

4.5.1 Grain size distribution and soil classification

The sieving was done by a sieve shaker model. The used sieves are US standard sieves with sizes 4000, 2800, 2000, 1000, 500, 250, 180, 125 and 32 µm. The 64 µm sieve was not available; this therefore gave slightly higher values for the 32 µm. It should however be noted that the 64µm sieve is an important sieve since it separates the sand from the silt grains. The samples were electronically weighed at an accuracy of 0.001 g.

The grain size distribution of the samples was plotted as a graph of the percentage of grains passing the sieve against the particle size (mm).

The hydraulic conductivity was calculated using two methods. Two methods were used in order to compare the results.

Method 1 : The Hazen (1892) method

$$K = \frac{g}{v} \times 6 \times 10^{-4} \times \left[1 + (n - 0.26)\right] \times d_{10}^{\ 2} \quad \text{.....................equation 4.5.1}$$

Where

K = hydraulic conductivity (m/day)
g = acceleration due to gravity (m/s^2)
v = kinematic coefficient of viscosity (m^2/day)
n = porosity (%)
d_{10} = effective grain diameter (mm)

The Hazen (1892) method is applicable since the sand has a uniformity coefficient less than 5 and the effective grain size lies between 0.1 and 3mm. Since the kinematic coefficient of viscosity is also necessary for the estimation of hydraulic conductivity, a value of 0.0874m^2/day derived for a water temperature of 20^{o}C was used in this study.

If water temperatures exceed 20^{o}C, the coefficient of viscosity becomes lower. This implies that the calculated K value will become higher. As such, the hydraulic conductivity calculated using this method can be considered to be the minimum value for the river section.

Method 2 : Alyamani and Sen (1998) method

$K = 1300[I_O + 0.025(d_{50} - d_{10})]^2$ …………………………equation 4.5.2

Where

K = hydraulic conductivity (m/day)
I_o = Intercept in mm of the straight line formed by d_{50} and d_{10} with the grain size axes
d_{50} = median grain diameter (mm)
d_{10} = effective grain diameter (mm)

The Alyamani and Sen (1998) method is one of the well known equations that also depends on grain-size analysis. The method considers both sediment grain sizes d_{10} and d_{50} as well as the sorting characteristics

4.5.2 *Porosity test*

According to Vukovic and Soro (1992), porosity (n) may be derived indirectly from the empirical relationship with the coefficient of grain uniformity (U) as follows:

$n = 0.255(1 + 0.83^U)$ ……………………………equation 4.5.3

where U is the coefficient of grain uniformity and is given by:

$U = \left(\frac{d_{60}}{d_{10}}\right)$ ……………………………………equation 4.5.4

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm) for which, 60% and 10% of the sample respectively, are finer than. The coefficient of grain uniformity is determined from the grain size distribution curve derived from the sieve analysis.

Two laboratory experiments were carried out using standard procedures to determine the porosity of the alluvial aquifer material.

4.5.3 *Specific yield test*

Specific yield is the term used to refer to the capacity of a saturated rock to drain water under the force of gravity (Karanth, 1987). Johnson (1967) derived a formula for calculating the specific yield as shown below.

$$\text{Specific yield} = \frac{\text{Volume of water drained } (V_{Wd})}{\text{Total rock or material volume}}$$

$$= \frac{\text{Mass of water}}{(\text{Mass of sand / specific gravity of sand})}$$ ……equation 4.5.5

The sand sample was placed in a beaker of a known mass. The sand sample was saturated with water and the mass of the saturated sample measured. The sample was then placed in a sieve and was closed. This was done in order to minimize evaporation losses. After water was allowed to flow out of the sample under gravity the sand was then weighed to determine the mass/ volume of water drained. The specific yield was then determined using equation 4.5.5.

4.5.4 Permeability test

Sand was collected from the aquifer and placed into a bucket with a volume of 0.045 m^3. The Darcy law is the basis of the permeameter test. The test works with a vertical slope i = 1. Water is poured into the bucket through a tube connected to a continuously flowing source of water. The continuous flow of water thus holds the hydraulic head constant A stop watch was used to measure the time required to fill 1; 1.5; 2; 2.5; 3; 3.5; 4 and 4.5 litre containers. The outlet pipe which had a radius of 0.04 m was stuffed with gravel in order to prevent the sand from flowing out of the bucket.

$$K = \frac{Q}{Ai} = \frac{V/t}{\pi(0.5d)^2} \text{ ……………………………………equation 4.5.6}$$

Where
K = Hydraulic conductivity (m/s)
Q = Flow rate / or discharge (m^3/s)
A = Cross sectional area (m^2)
V = Volume of percolated water (m^3)
t = Time taken to fill a container of known volume (seconds)
d = Diameter of container (m)

4.6 Slug test

This is a field based method which was employed to derive the hydraulic conductivity of the alluvial aquifer. The Darcy law (equation 4.6.1) is the basis for this method A PVC tube was driven into the aquifer until the slotted part of tube was at the same level with the water level in the aquifer. The used PVC tube was 1.00 m in length and of a 0.07 m diameter. The tube was driven 17.1 cm under the groundwater level and the remaining section was 82.9 cm above the ground surface. Water was then poured into the pvc tube until it reached the top of the tube. A stop watch was used to measure the time needed to attain the initial water level.

$$Q = K * A * i \text{ …………………………………………………equation 4.6.1}$$

$$K = \frac{Q}{Ai} = \frac{Q}{A} = \frac{[\pi \times (0.5d)^2 \times h]}{T[\pi \times d \times H + \pi(0.5d)^2]} \quad \text{i.e. } K_z : i = 1 \text{ ………… equation 4.6.2}$$

Where K = hydraulic conductivity (m/day)
Q= Discharge/ flow rate (m^3/day)
A = Cross sectional area of the sample (m^2)

i = Slope [-]
h = Head difference (m)
d = diameter of the PVC tube (m)
H = Length of PVC tube under the water level (m)
T = Time taken for water column to reduce to the water level in aquifer (day)
K_z = hydraulic conductivity in the vertical direction (m/day)

Note: for the first field experiment h = 82.9 cm; H= 17.1 cm; d= 7cm; T= 3mins & 12 secs
For the second experiment h = 82.9 cm; H= 17.1 cm; d= 7cm; T= 3mins & 30 secs

4.7 Groundwater sampling for hydrogeochemical analysis

Four water samples were collected from four piezometers at the Malala alluvial aquifer using standard sampling procedures. Two litres of water were sampled from each piezometer and were immediately placed in a cooler box with ice. Two samples were also collected from Zhovhe dam which lies approx 35 km from the alluvial aquifer. One sample was collected from a well point system at Mazunga. Mazunga lies approximately 20 km upstream of the Malala alluvial aquifer but downstream of Zhovhe dam along the Mzingwane river. The samples were collected spatially from the source of recharge (Zhovhe dam) to the Malala alluvial aquifer in order to analyse whether any water chemistry changes occur from the source of the water to the alluvial aquifer.

4.8 Hydrogeochemical Analysis

General chemistry samples were filtered to less than 0.2 microns and were analysed for sulfate (SO_4^{2-}) and Chloride (Cl^-). The samples were also analysed for bicarbonate (HCO_3^-) using a standard acid titration. Samples were analysed for Ca^{2+}, Mg^{2+}, K^+, and Na^+ using a perkin – Elmer 5100 Atomic Absorption Spectrophotometer (AA). The water samples were analysed at an accredited laboratory.

The Piper diagram was used in the analysis. A plot of the major ions as percentages of milli-equivalents in two base triangles was done. The total cations and the total anions were set equal to 100% and the data points in the two triangles were projected onto an adjacent grid. The main purpose of the Piper diagram was to show clustering of data points to indicate samples that have similar chemical compositions.

Conversion of ionic concentrations to units of equivalent weight i.e concentrations in mg/L were converted to meq/L using the relation below:

$$\text{Concentration in meq/L} = \frac{(\text{concentration in mg/L}) \times (\text{Valence})}{\text{Formula Weight}} \quad \text{……….equation 4.8.1}$$

The conversions represented by equation 4.8.1 are shown in appendix III.*1* to appendix III.*14*

4.9 Groundwater potential of the Malala alluvial aquifer

The Malala alluvial aquifer was subdivided into 125 cells. Each cell representing a 40m by 40m square of the studied aquifer. The length of the aquifer (1000 m) was divided into 25 cells and the width of the aquifer (200 m) was divided into 5 cells. The groundwater potential of each cell was calculated using equation 4.9.1 below.

$GP = A \times D \times S_y \times 10^{-3}$ ………equation 4.9.1

Where
GP = Groundwater potential (ML)
A = Area represented by the cell (m^2)
D = Depth represented by the cell (m)
S_y = Specific yield (-)

The groundwater potential of the Malala alluvial aquifer was then calculated by summing up the quantities from each of the 125 cells. The depth measurement for each cell was calculated from the resistivity method and the specific yield value was calculated using a laboratory approach (section 4.5.3). Twenty four resistivity measurements were done at the study site. Depth measurements were observed for these cells. The remaining depth estimations for the other 101 cells were estimated using the nearest neighbour analysis method.

5. RESULTS AND DISCUSSION

5.1 Selection of specific site and estimation of the aquifer depth

Resistivity measurements were taken in the river bed from the upstream to the downstream direction, firstly at the Muleya site, Masasanye and finally at Malala site (fig 3.2.1). The resistivity plots are presented graphically as shown below. WP 295 and WP 296 are different stations were the resistivity measurements were made at the Muleya site. Resistivity data for the three sites is given in appendix I.

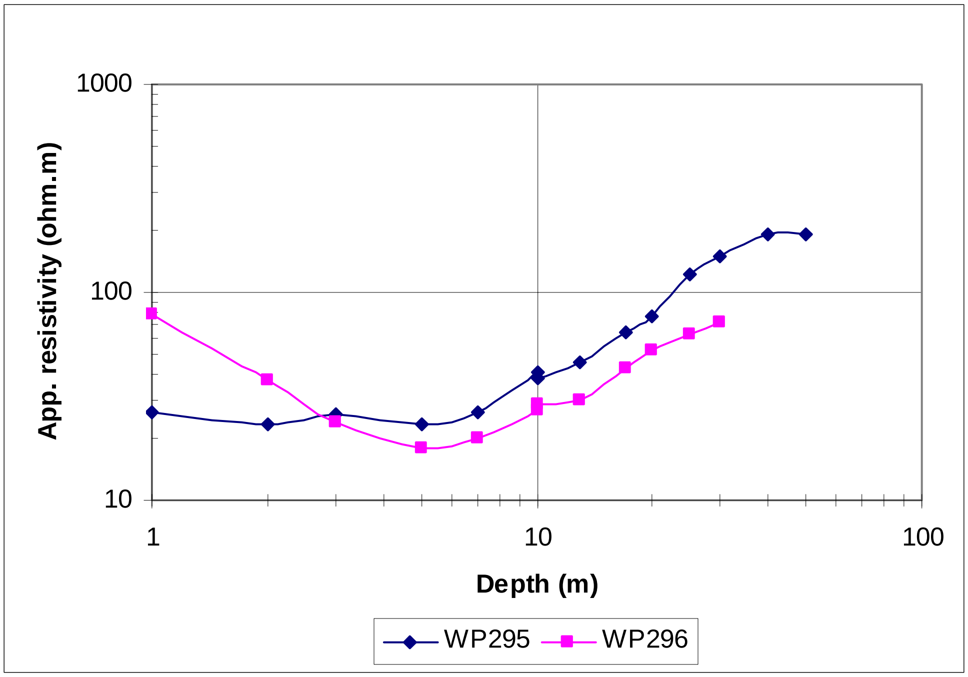


Fig 5.1.1 Resistivity profile at the Muleya site

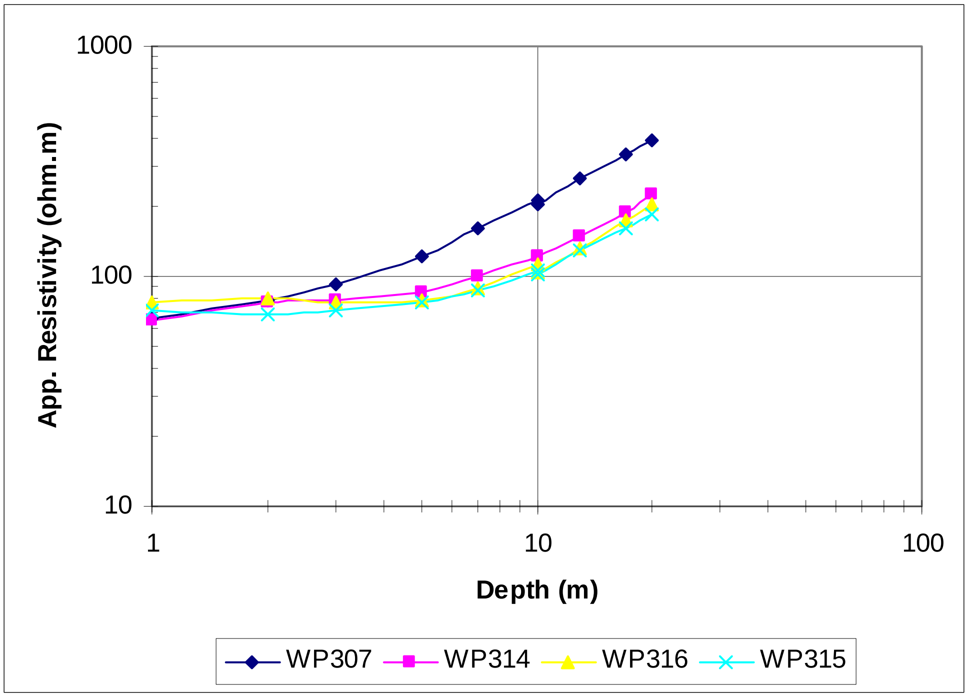


Fig 5.1.2 Resistivity profile at the Masasanye site

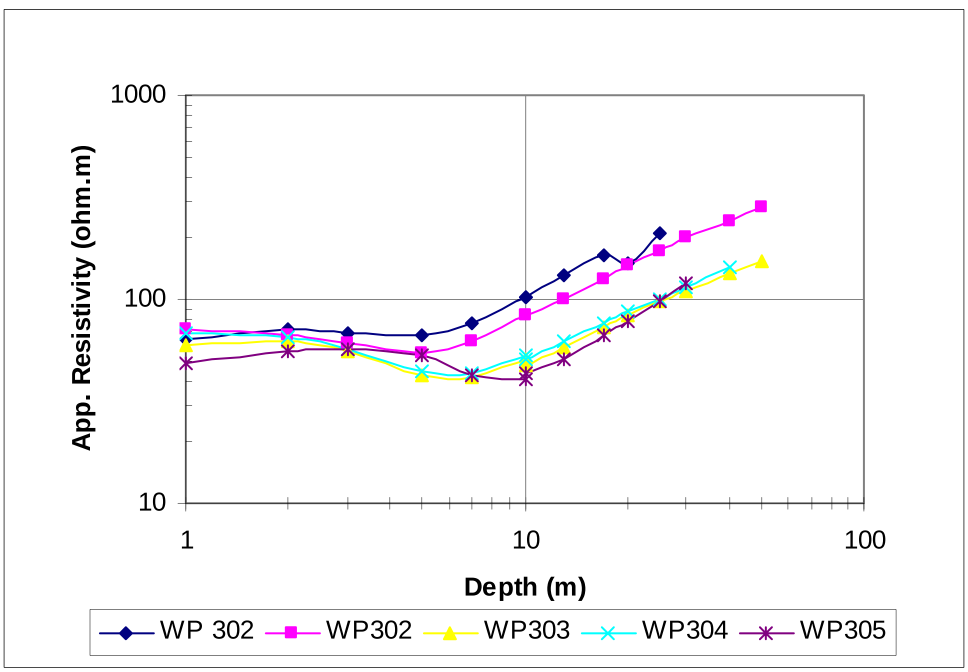


Fig 5.1.3 Resistivity profile at the Malala site

The apparent resistivity values recorded at Muleya site ranged from a minimum of 17.9 Ω.m to a maximum value of 189.2 Ω.m. Resistivity values recorded at Masasanye site range from a minimum of 64.7 Ω.m to a maximum value of 388.3 Ω.m. The resistivity values recorded at Malala site ranged from a minimum value of 40.4 Ω.m to a maximum value of 282.1 Ω.m. The maximum apparent resistivity value at this site shows that at approximately 50 meters depth most of the electric current will be penetrating the metamorphic bedrock formation. Summary results of the reconnaissance work is presented in Table 5.1.1

Table 5.1.1 Summary results of reconnaissance resistivity work

Site	Minimum observed Resistivity (Ω.m)	Maximum observed Resistivity (Ω.m)	Modelled Max depth To bedrock (m)
Muleya	17.9	189.2	20
Masasanye	64.7	388.3	10
Malala	40.4	282.1	20

The Masasanye site was discarded since the resistivity measurements indicated a shallow depth of the sand of an approximate maximum of 10 meters. Malala was the chosen site since it showed indications of the sand to a maximum depth of 20 meters. An increase in the depth of the sand layer is expected to increase the volume of water stored by the alluvial aquifer and hence an increase in the groundwater potential. At the Muleya site only two measurements were taken and the results did not give a convincing pattern. The resulting curve was rather irregular and could thus infer a heterogeneous subsurface. The Malala site was also chosen due to the influence of the dolerite dyke which is expected to provide conditions for a natural sand dam. The dolerite dyke acting as a "dam wall".

5.2 Resistivity observations at the Malala alluvial aquifer

Rinvert modeling results for the upstream and down stream part of the dyke indicated a minimum depth of the sand to be approximately 5 meters and the maximum depth of the sand to be 25 meters.

Summary results of the resistivity measurements which were taken along selected crossections upstream and down stream of the dolerite dyke are also presented graphically below. Data for plotting figure 5.2.1 and figure 5.2.2 are presented in Appendix V.
[Note: plotted curves are numbered in ascending order from the western river bank (point 1) to the eastern river bank (point 4)].

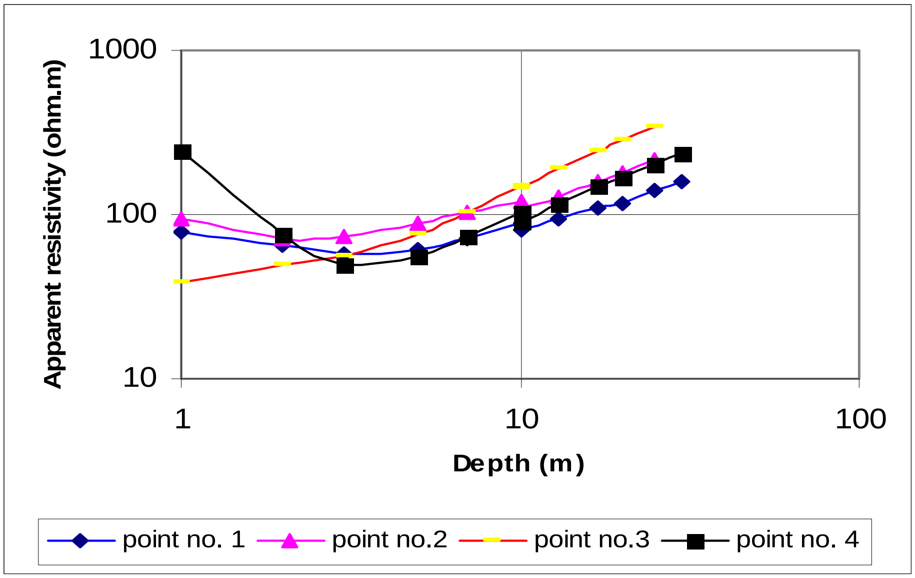


Fig 5.2.1 Resistivity profile Downstream of the dyke at the Malala site

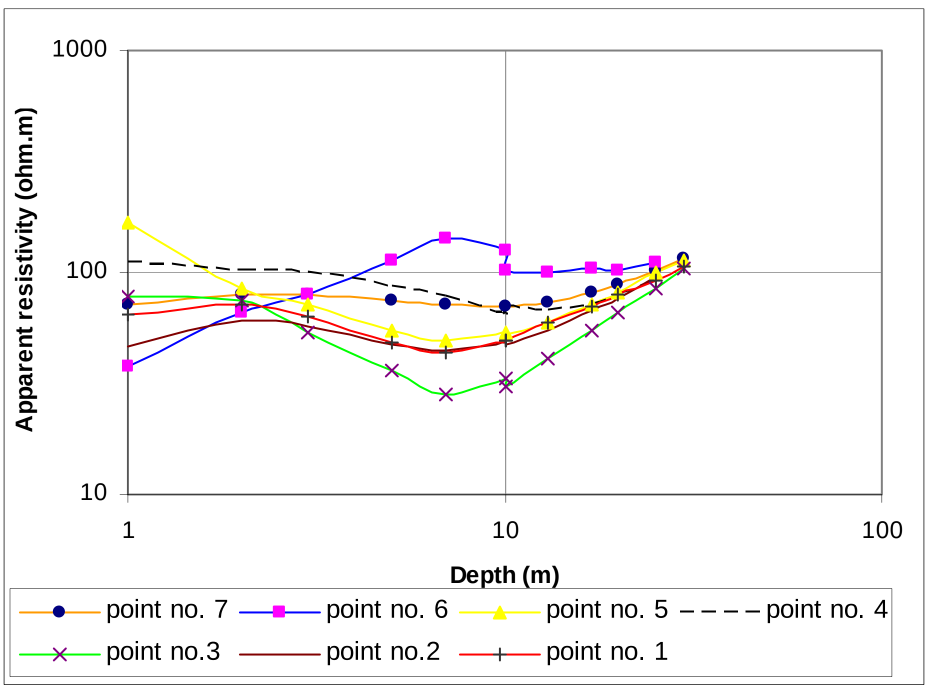


Fig 5.2.2 Resistivity profile upstream of the dyke at the Malala site

Modelling in Rinvert suggested that there is a top layer in the alluvial aquifer which is dry and is of an average depth of 3 meters. However modelling results for point no. 6 suggest that the top dry layer is approximately 8 meters thick.

Resistivity measurements upstream of the dyke indicate that the channel sands increase in depth from the western river bank (0m on fig 5.2.3) to the eastern river bank (200m on fig

5.2.3 below). On the western side of the alluvial aquifer the approximate depth of the sand ranges from 10 meters to 12 meters (Appendix VII.1). On the eastern side of the aquifer the alluvial aquifer deepens to a maximum approximate depth of 25 meters (Appendix VII.1). An enhanced thickness of the alluvial aquifer thus increases the groundwater storage of the alluvial aquifer. The enhanced thickness also suggests that less water will be lost to evaporation losses. Figure 5.2.3 below shows the plot of the expected sand and bedrock interface surface. This is an imaginary surface and a smooth curve was thus chosen for the representation of the surface.

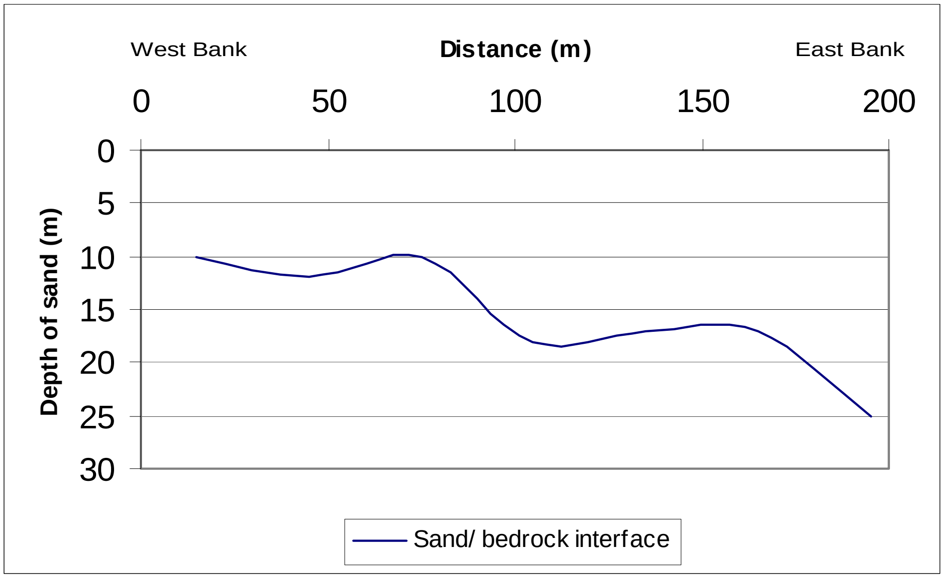


Fig 5.2.3 Cross section indicating the variation in the depth of the sand across the aquifer on the upstream part of the dolerite dyke

On the downstream part of the alluvial aquifer, downstream of the dolerite dyke, the sand layer varies from a shallow depth of 5 meters to a maximum depth of 11meters (Appendix VII.2).

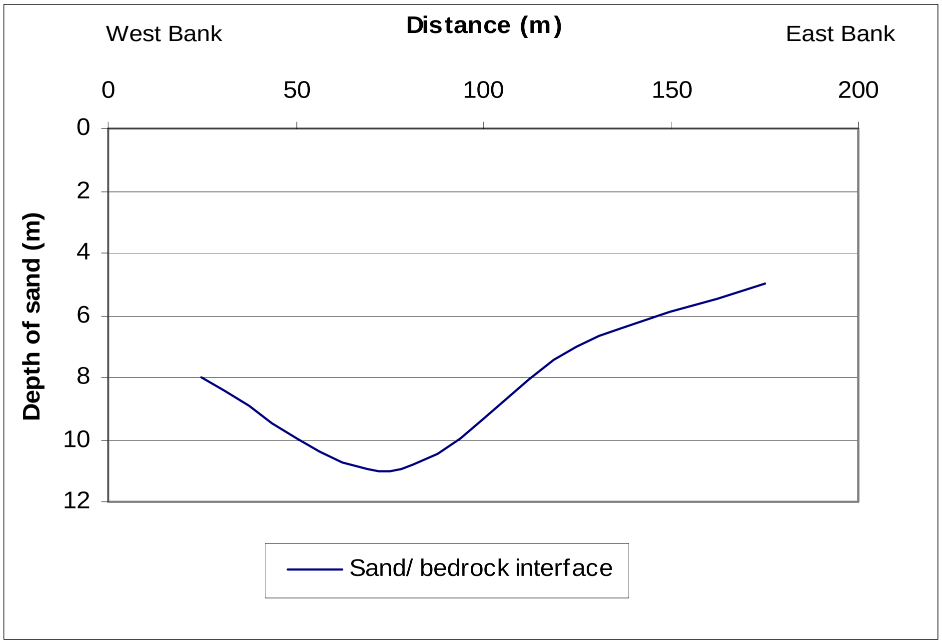


Fig 5.2.4 Cross section indicating the variation in the depth of the sand across the aquifer on the downstream part of the dolerite dyke.

It can thus be concluded that on the upstream part, the alluvial fill is deeper than the downstream part of the alluvial aquifer. As such the groundwater potential is better enhanced on the upstream side of the dolerite dyke. The dolerite dyke therefore favours the formation of a natural sand dam on the upstream part of the alluvial aquifer. The upstream part is thus favoured for the installation of a sand abstraction unit. More water can be abstracted from this section of the river since the catchment area of the borehole will be increased with increased surface area and depth. Water particles are also expected to flow to deeper sediment zones upstream of the dyke.

Modelling results for the river section where the dolerite dyke crosses the alluvial aquifer showed an average depth of the sand along this section to be 6 meters. Resistivity measurements can also be further utilized for specific sites to be considered for borehole drilling in the alluvial aquifer. The specific sites can be chosen based on those sites which have the deepest alluvial fill.

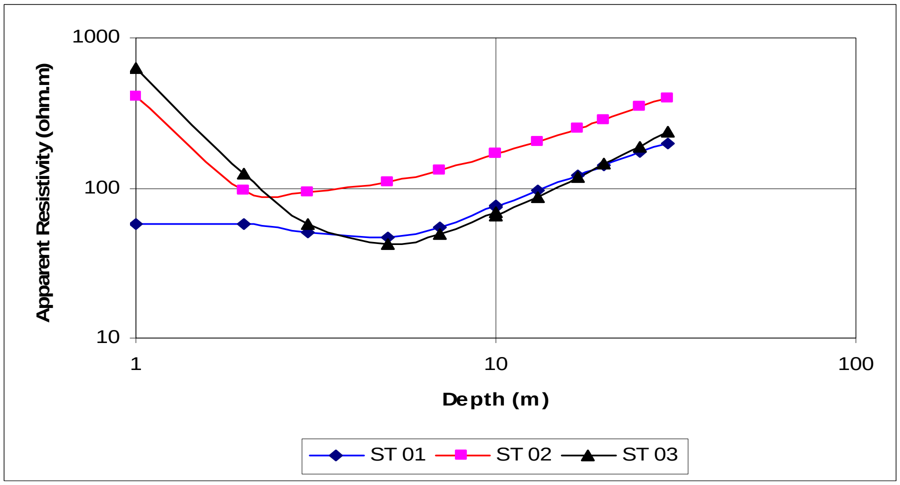


Fig 5.2.5 Resistivity profile on the dolerite dyke

It can also be seen from fig 5.2.5 that the resistivity increases steeply from a depth of approximately 6 meters. This indicates that the current at this depth and deeper begins to penetrate a different layer (dolerite dyke) with a higher resistance to the flow of electrical current.

5.3 Geological mapping

The geological mapping showed the geological setting of the alluvial aquifer. The river bed which consists of an alluvial fill is underlain by tonalitic and granodioritic gneisses on the entire length of the Mzingwane river. The alluvial fill is intersected mid way along the studied length of the river channel by a dolerite dyke at an approximate depth of six meters. The dolerite dyke is assumed to have intruded into the older gneisses and into the existing river channel. The dolerite dyke is of an approximate width of eighty meters on the stretch where it crosses the river channel. As such the alluvial aquifer is separated at approximately six meters depth into two segments an upstream alluvial fill and a downstream alluvial fill. Seepage is also expected from the alluvial aquifer into the underlying gneiss bedrock.

Figure 5.3.1 below shows the geological map produced for the study area.

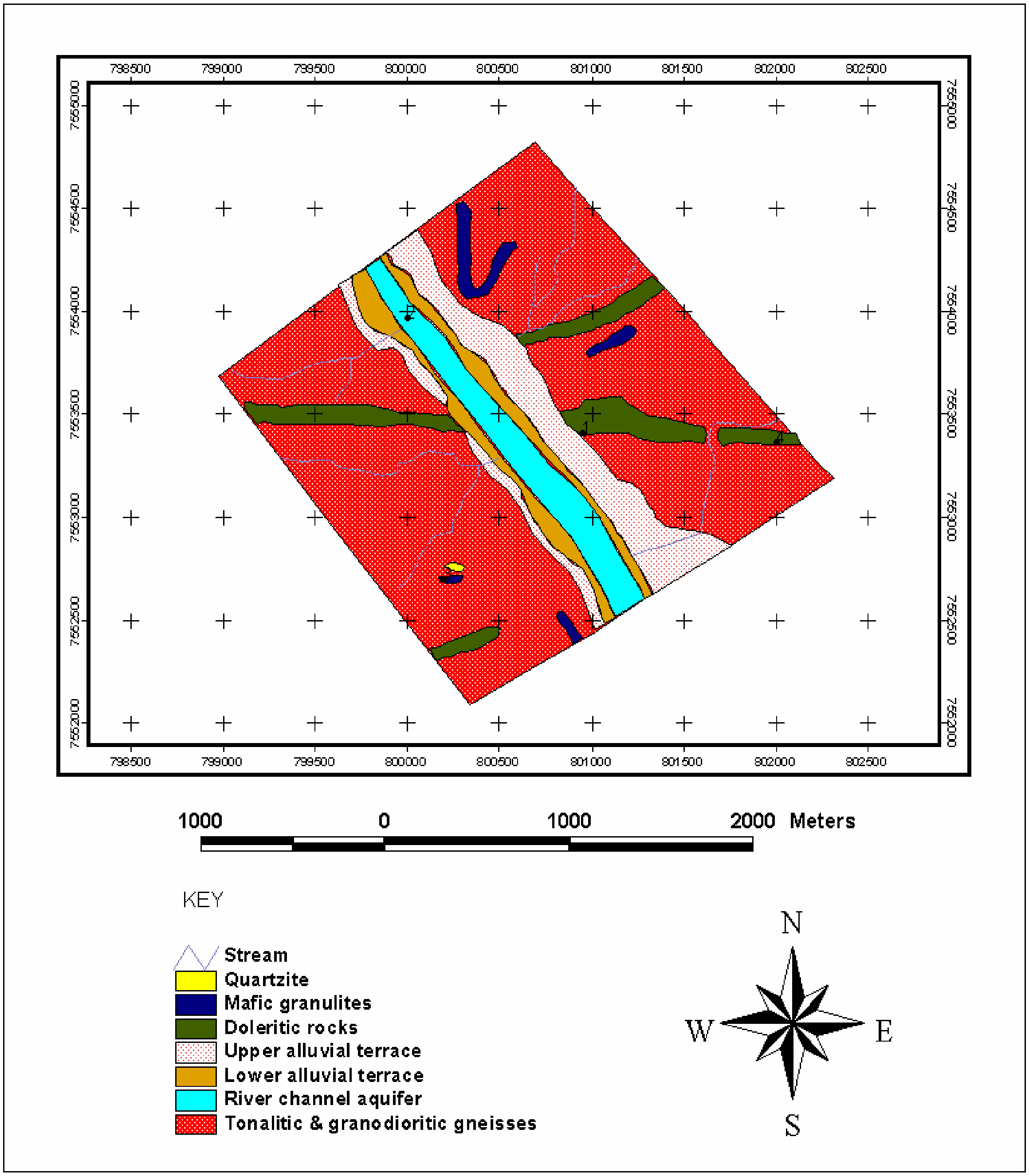


Fig 5.3.1 Geological map of the Malala area

5.4 Fluctuation of water levels after a dam release

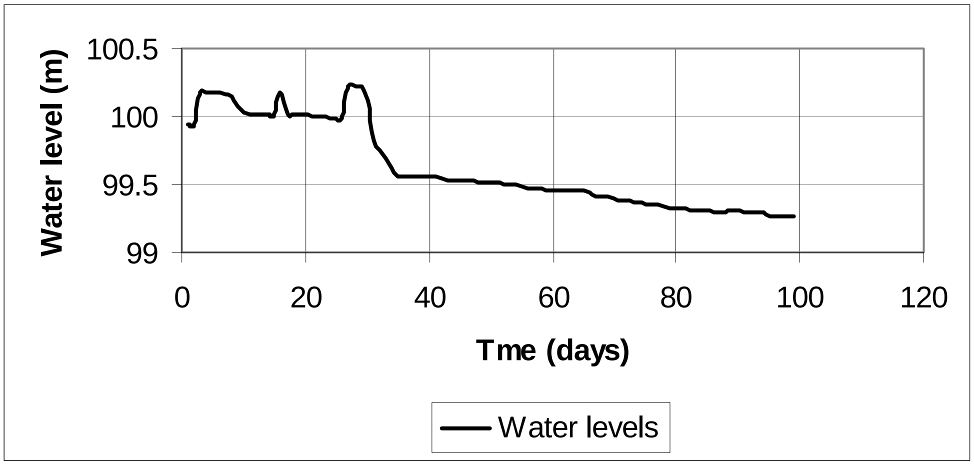


Fig 5.4.1 Observed water levels after a dam release

The river flowed for 4 days during the water level monitoring exercise. It flowed from the 2nd day of February 2008 to the 5th day of February 2008. This can be seen in the graph by the initial water levels which rise to over 100 meters. The water levels were greater than or equal to 100 meters for almost 30 days. This implies that for the 30 days the alluvial aquifer was fully saturated. After this water levels dropped below the full saturation level by approximately 0.75 meters.

The drop in water levels after 30 days could be as a result of seepage losses to the metamorphic bedrock. The drop of water levels by an average of 0.5 meters after 30 days suggests seepage losses of 5.4 ML which translates to 3.7% water losses to bedrock from the total volume of the alluvial aquifer when fully saturated. Water managers can thus be able to estimate how much water will be lost to the bedrock after water has been released into the river system. It should however be noted that the calculated seepage loss of 3.7 % is only applicable to the granodioritic and tonalitic bedrock or rocks of similar hydrogeological character.

It can thus be summarized from fig 5.4.1 above that after a release of water the water levels in the aquifer drop by approximately 0.75 meters within the observed 97 days after the aquifer is saturated. Therefore the average aquifer saturated thickness drops by approximately 0.75 meters at the current abstraction levels from the aquifer and also due to evaporation and downstream losses. However it should be noted that current abstractions are very low from the aquifer since the local community is abstracting water for mainly domestic purposes and for small vegetable gardens.

In summary, water levels in the Malala alluvial aquifer drop by 0.75 meters from full saturation after a managed dam release within a period of approximately 100 days.

5.5 Topographical survey results

The topographical survey which was carried out along the channel river bed gave a slope of 0.38 % for the section of the river channel. This is a rather steep section of the river as compared to the between 1: 500 and 1: 1000 average derived by Moyce *et. al.,* (2006) in their overall study of the Mzingwane river system. The result of 0.38 % is justified since river sections are not uniform in nature but localized disparities do occur.

5.6 Grain size distribution and soil classification

The sieve analysis results are given as a plot of the percentage of grains passing a sieve of a given diameter against the particle size.

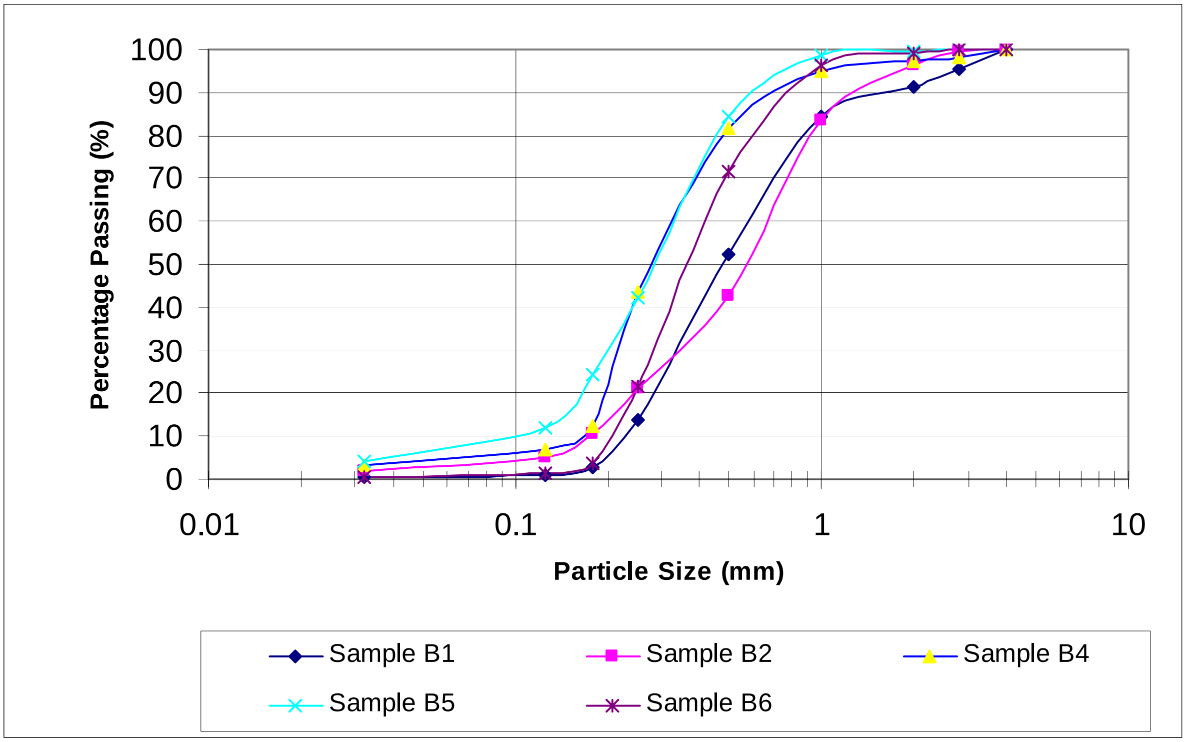


Fig 5.6.1 Grain size distribution curves for sand samples

It can be derived from the fig 5.6.1 above that the particle size distribution of the soil samples ranges from 0.03 mm to 3mm in diameter. The median grain diameter (d_{50}) = 0.4 mm, the effective grain diameter (d_{10}) = 0.17 mm and the effective grain size (d_{20}) = 0.25mm.

Generally more than 85% of the grains pass through the 1mm sized sieve. This implies that 85% of the grains are less than 1mm in diameter. Analysis of appendix II gives the grain size ranges which are given in table 5.6.1 below.

Table 5.6.1: Grain size ranges for material classification

Sample	Percentage of material Greater than 0.125mm Sieve size	Percentage of material Greater than 2mm Sieve size	Percentage of material Between 2mm and 0.125mm sieve size
B1	99.06	8.90	90.16
B2	94.82	3.70	91.12
B4	93.01	2.90	90.11
B5	88.05	0.50	87.55
B6	98.46	0.70	97.76
AVERAGE			91.34

The sand size range is between 0.0625mm and 2mm (Johnson, 1967). Table 5.6.1 shows that at least 91.34% of the alluvial aquifer material lies in the sand size region. The result could be higher since values of the 0.0625 mm sized sieve are not available because the sieve could not be obtained. However the result in Table 5.6.1 is adequate to classify the alluvial material. Therefore according to the British standard classification system the overall classification of the material at the Malala alluvial aquifer is sand.

According to Johnson (1967) soil classification system (figure 5.6.2 below) the Malala alluvial aquifer material can also be classified as sand. This is obtained by plotting a specific yield value of 27% (from literature) and plotting a sand size percentage of 91.34% (derived in Table 5.6.1). Johnson (1967) considers that sand has a range of specific yield between 21% and 27%.

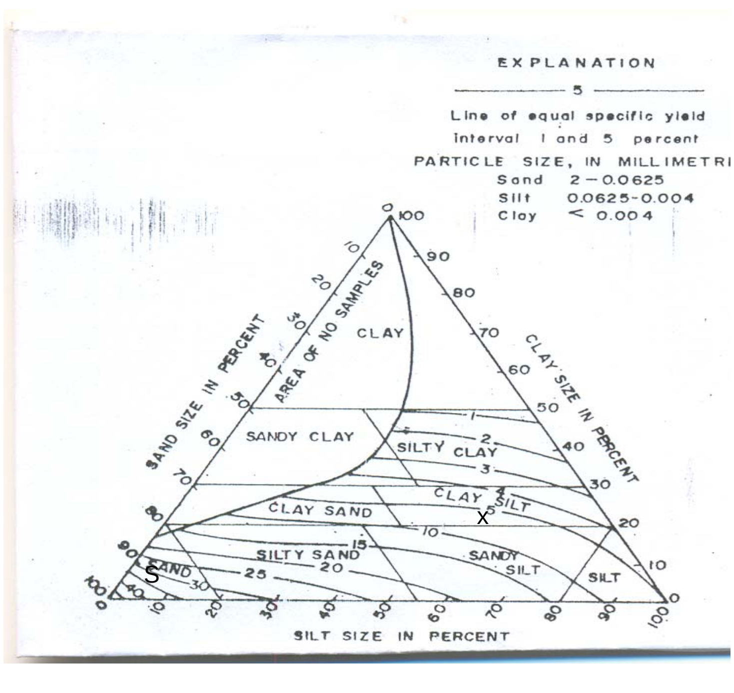


Fig 5.6.2 Sand classification system, Johnson (1967). i.e. (S) in the sand region represents the position of the plotted point.

5.7 Porosity tests

Table 5.7.1: Laboratory test 1 for porosity.

Sample	Volume in measuring cylinder	Volume remaining in cylinder after saturation	Volume of voids (V v)	Volume of Beaker (V)	Porosity (V v / V)
	[ml]	[ml]	[ml]	[ml]	%
B1	100	20.5	79.5	200	39.75
B2	100	28.0	72.0	200	36.00
B4	100	24.0	76.0	200	38.00
B5	100	26.0	74.0	200	37.00
B6	100	19.5	80.5	200	40.25
AVERAGE					38.20

Table 5.7.2: Laboratory test 2 for porosity

Sample no.	Weight of dried sample + Beaker	Weight of saturated sample + Beaker	Volume of Voids (V v)	Volume of Beaker (V)	Porosity (V v / V)
	[g]	[g]	[ml]	[ml]	%
B1	405.50	484.60	79.10	200	39.55
B2	427.60	498.80	71.20	200	35.60
B4	375.18	451.20	76.02	200	38.01
B5	419.72	493.50	73.78	200	36.89
B6	422.92	503.90	80.98	200	40.49
AVERAGE					38.11

Using the Vukovic and Soro (1992) approach the average porosity for the five samples was 40.8%. The porosity was also derived using two standard laboratory approaches (Table 5.7.1 and 5.7.2). The methods gave porosities of 38.2 % and 38.1% respectively. Thus an average porosity for the alluvial aquifer is estimated at 39%. This is a high porosity and is expected for sand. Moyce *et al* (2006) used a value of 30% as an average for the Mzingwane river catchment. Nord (1985) and Owen (1994) derived an average value of 35 % for the Mzingwane river sands. The porosity result at Malala is thus comparable with other results from the Mzingwane river.

5.8 Specific yield

The laboratory experiment (table 5.8.1) gave a specific yield value of 5.4 %. The value of 2.65 was used for the specific gravity of sand in equation 4.5.5. The specific yield derived for this river section is low. This shows that at least 5.4 % of the aquifer saturated volume can actually be abstracted. As such a larger volume of the saturated aquifer is required so that more water can be abstracted.

The derived specific yield value is rather low for a sand formation. Johnson (1967) considers a sand formation to have a specific yield value between 21% and 27%. Moyce *et al.,* 2006, used a specific yield value of 15% for some sections of the Mzingwane river. This therefore would give rise to higher groundwater estimates. Nord (1985) and Owen (1994) calculated an average value of specific yield for the Mzingwane river sands to be 20 %. The disparities as such will give gross differences in groundwater estimations.

The study at Malala only carried out one experiment for the specific yield. As such it would have been more conclusive if more tests for the specific yield were made. The result cannot however be discredited since the samples for the specific yield test could have been collected from an aquifer section which has a higher clay content. The clay would thus give rise to the lower results for the specific yield.

Table 5.8.1: Calculation of the specific yield of the aquifer

Mass of Beaker + Saturated Sand	Mass of Empty Beaker	Mass of Saturated Sand	Mass of Beaker + Drained Sand	Mass of Drained Sand	Mass of Water	Specific Yield
[g]	[g]	[g]	[g]	[g]	[g]	[%]
2570.0	258.0	2312.0	2523.5	2265.5	46.5	5.4

5.9 Hydraulic conductivity

The hydraulic conductivity was determined using three approaches. Calculations based on grain size analysis of the samples, slug tests performed in the field and permeameter tests which are done in the laboratory were performed in order to get a representative hydraulic conductivity value. Pumping tests were not done because of the lack of capital and also due to the fact that considerable pumping is required to obtain sufficient drawdown in the observation wells when pumping alluvial aquifers of such a magnitude.

Table 5.9.1: Hydraulic conductivities calculated from grain size analysis using empirical formulae

Sample	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	U	I_o (mm)	n	Hazen (m/day)	A/S (m/day)
B1	0.22	0.50	0.57	2.59	0.18	0.41	61.40	45.46
B2	0.16	0.52	0.64	4.00	0.12	0.38	27.80	21.63
B4	0.15	0.30	0.35	2.33	0.13	0.42	29.42	23.26
B5	0.12	0.30	0.34	2.83	0.11	0.41	17.77	17.04
B6	0.20	0.38	0.42	2.10	0.18	0.43	53.78	44.25

Note A/Z represents the Alyamani and Sen (1998) method.

It can be seen from Table 5.9.1 that the Hazen (1892) method gave an average hydraulic conductivity of 38 m/day and the Alyamani and Sen (1998) method gave an average hydraulic conductivity of 30.3m/day.

Table 5.9.2: Slug test results

Experiment	Radius (m)	h (m)	T (secs)	H (m)	K (m/day)
1	0.035	0.829	192	0.171	34.63
2	0.035	0.829	210	0.171	34.91
				Average	34.77

Table 5.9.3: Permeameter test results

Experiment	V (m^3)	T (secs)	Radius (m)	K (m/day)
1	0.0010	135	0.04	139.3120
2	0.0015	193	0.04	139.1240
3	0.0020	255	0.04	138.5630
4	0.0025	313	0.04	137.8221
5	0.0030	374	0.04	137.2350
6	0.0035	434	0.04	134.7594
7	0.0040	494	0.04	133.5374
8	0.0045	555	0.04	127.2727
			Average	135.95

The slug test gave an average value of the hydraulic conductivity of 34.77 m/day. This compares quite well with the results from the Hazen (1892) and Alyamani and Sen (1998) methods. The results of the permeameter test gave an average value of 135.95 m/day. This is a higher permeability as compared to the other methods discussed. This result is higher probably because the crossectional area of the outlet in the experiment was smaller as compared to the inlet section of the experiment.

Therefore the overall hydraulic conductivity of the aquifer is estimated at 59.76 m/day. This result is derived as an average of the results from the four methods used to calculate the hydraulic conductivity.

This is a realistic result considering that the alluvial material is sand which at some sections shows indications of some clay content. The clay would therefore reduce the rate of water movement in the alluvial material. This result shows that water can freely move and be transmitted from one point of the aquifer to the other. The derived hydraulic conductivity suggests that the aquifer can be recharged by water flowing through the sand from the upstream direction.

The hydraulic conductivity derived shows that the aquifer can be vulnerable to pollution. If a pollution event occurs, a contaminant/ or harmful substance can be expected to spread the entire 1km stretch of the aquifer in about 17 days. This rate therefore provides water managers with an idea of how pollution events occurring in the Mzingwane catchment can impact on the quantity of available groundwater resources. For example toxic effluent from mining activities can thus render water resources unfit for human use within a certain time period from the time of the effluent discharge.

Nord, (1985) and Owen, (1994) derived a hydraulic conductivity value for the Mzingwane river of 200m/day. The difference in hydraulic conductivities can be attributed to the fact that the Malala alluvial aquifer sediment is composed in some sections of clay which does not allow water to flow easily through the formation. The higher value derived by Nord (1985) and Owen (1994) could be expected in clean sand which is free from clay.

5.10 Hydrogeochemical results

Chemical results for cation and anion concentrations for the water samples collected from the piezometers at the alluvial aquifer (B1, B2, B5 & B6), as well as from the Mazunga area (MAZ) and Zhovhe dam (ZH1 & ZH2) are presented in the table 5.10.1 below.

Table 5.10.1: Chemical analysis results

Sample Number	Sample Date	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	K^{+} (mg/l)	Na^{+} (mg/l)	SO_4^{2-} (mg/l)	Cl^{-} (mg/l)	HCO_3^{-} (mg/l)	CO_3^{2-} (mg/l)
B1	03/03/2008	20.44	16.78	5.00	43.67	176.00	73.00	213.50	<0.01
B2	03/03/2008	23.55	13.33	4.33	25.56	169.00	53.00	213.50	<0.01
B5	03/03/2008	35.44	17.67	9.00	31.11	167.00	68.00	237.90	<0.01
B6	03/03/2008	25.09	20.33	5.67	45.44	162.00	38.00	213.50	<0.01
MAZ	04/03/2008	22.55	13.00	2.56	19.20	143.00	8.00	149.45	<0.01
ZH1	04/03/2008	13.55	5.22	4.44	8.91	159.00	3.00	100.65	<0.01
ZH2	04/03/2008	19.44	5.83	4.44	9.08	157.00	3.00	122.00	<0.01

Miliequivalents per litre values were calculated for anions and cations (Appendix III) and a standard anion/cation balance was performed for each sample. A composite Piper diagram was created representing the chemistry of the studied aquifer and is presented in fig 5.10.1 below. Examination of this figure reveals that the Malala alluvial aquifer is dominated by sodium sulphate water. The piper plots of Zhove dam water samples (fig 5.10.2) and Mazunga water sample (fig 5.10.3) shows that the water can be classified as calcium sulphate water type. These results show that the water types vary only in the cation concentrations, however all the water samples show the same classification of the anions i.e higher sulphate concentrations.

Fig 5.10.1 – Fig 5.10.3 show the major ion chemistry of water samples from the Malala alluvial aquifer, Mazunga and Zhovhe areas as piper diagram plots.

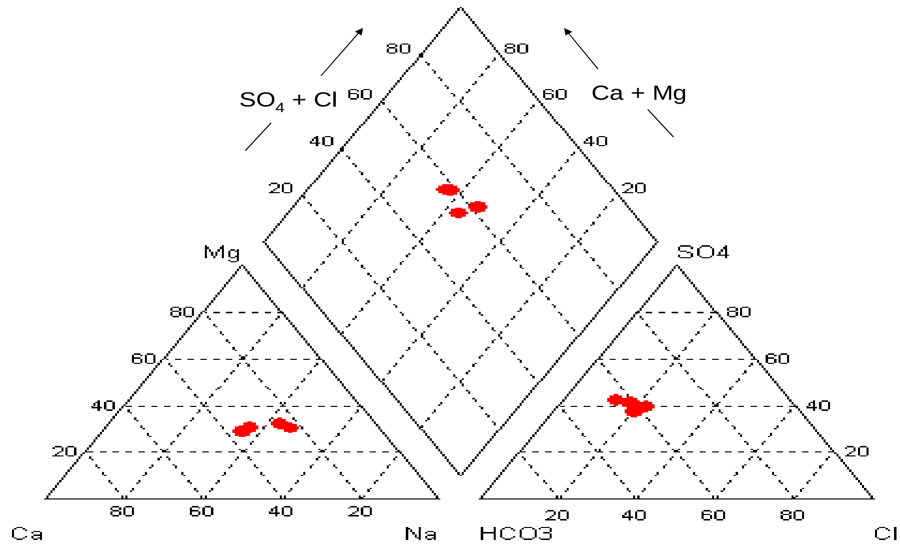


Fig 5.10.1 Piper plot of Malala water samples

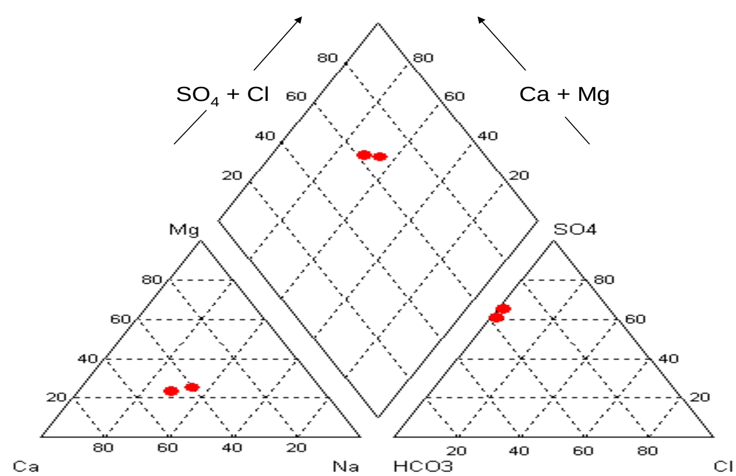


Fig 5.10.2 Piper plot of Zhovhe dam water samples

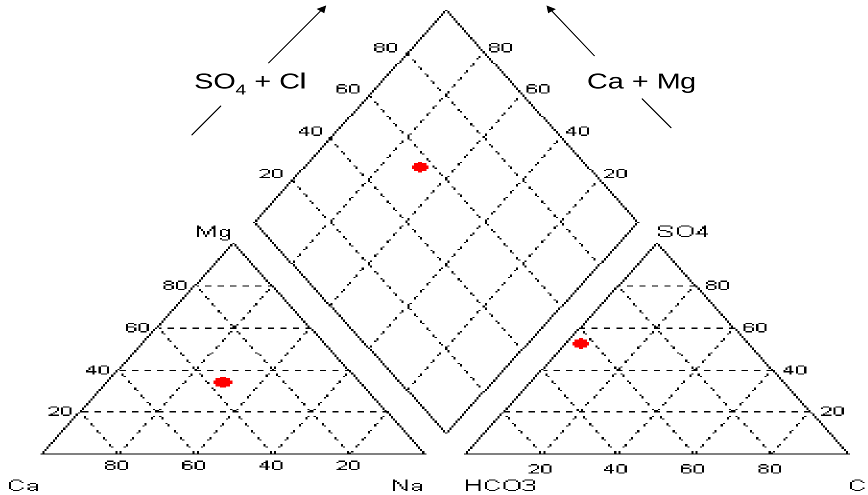
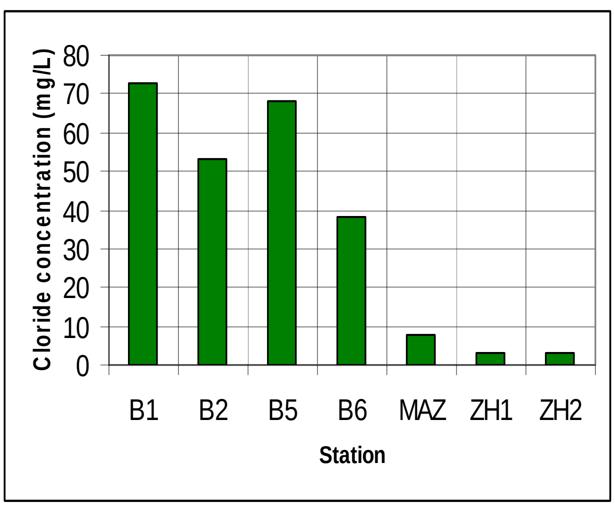


Fig 5.10.3 Piper plot of Mazunga water sample

However there are differences in the concentration of other major ions from the source water to the aquifer. Of immediate interest also is the low concentration of chloride at Zhovhe dam and Mazunga water samples and comparatively higher concentrations of chloride at the Malala aquifer.

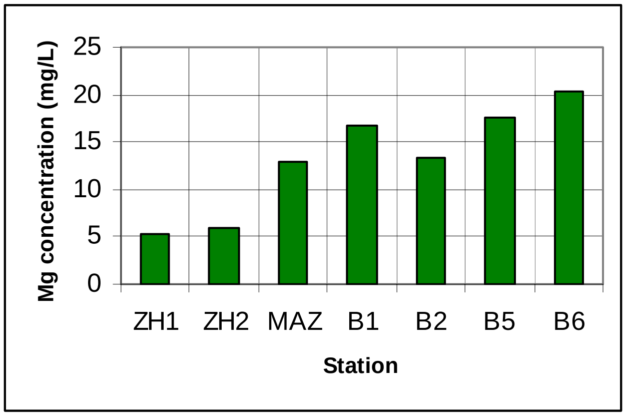


Key	
B1	Malala aquifer water sample
B2	Malala aquifer water sample
B5	Malala aquifer water sample
B6	Malala aquifer water sample
MAZ	Mazunga water sample
ZH1	Zhove dam water sample
ZH2	Zhove dam water sample

Fig 5.10.4 Chloride concentrations of the Zhovhe dam, Mazunga and Malala water samples

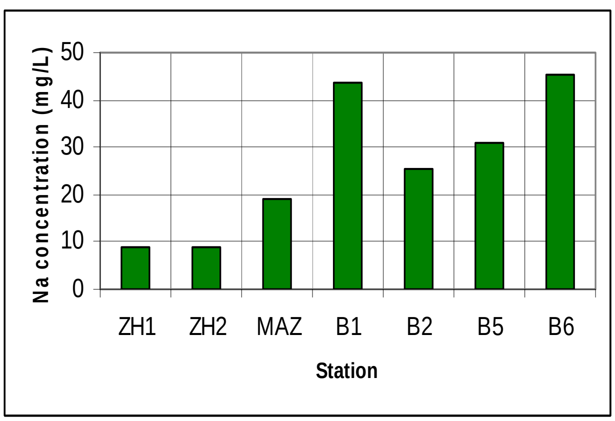
The increase in the chloride concentration between the source of water and the Malala alluvial aquifer possibly indicates that the water reacts with the host rocks along the river channel which have a higher chloride composition. The increase in chloride could also arise due to agricultural activities upstream were the farmers might be using chemicals which are high in chloride.

It is also evident that the water becomes enriched in Sodium and Magnesium (fig 5.10.5 & fig 5.10.6) as it flows from the source to the Malala alluvial aquifer. The increase in magnesium could result from the weathering of dolerite. The mineralogy of dolerite is mainly ferromagnesian minerals i.e. magnesium and iron enriched rock. Dolerite weathers to form chlorite which contains magnesium. Chlorite is a hydrous aluminium silicate of iron and magnesium. Therefore the higher levels of magnesium could be due to the influence of the dolerite dyke. The higher magnesium concentrations could also result from the gneisses which are composed also of ferromagnesian minerals. The source of sodium enrichment could be from the weathering of plagioclase feldspar especially albite ($Na\ Al\ Si_3\ O_8$).



Key	
B1	Malala aquifer water sample
B2	Malala aquifer water sample
B5	Malala aquifer water sample
B6	Malala aquifer water sample
MAZ	Mazunga water sample
ZH1	Zhove dam water sample
ZH2	Zhove dam water sample

Fig 5.10.5 Magnesium concentration of Zhovhe dam, Mazunga and Malala aquifer water samples



Key	
B1	Malala aquifer water sample
B2	Malala aquifer water sample
B5	Malala aquifer water sample
B6	Malala aquifer water sample
MAZ	Mazunga water sample
ZH1	Zhove dam water sample
ZH2	Zhove dam water sample

Fig 5.10.6 Sodium concentration of the Zhovhe dam, Mazunga and Malala aquifer water samples

The water chemistry does not change considerably but does change from Zhove Dam (the source of release) through the Mazunga area and finally to the Malala alluvial aquifer. However sulphate concentrations (Table 5.10.1) are comparatively higher at the Malala alluvial aquifer as compared to the Zhovhe dam and Mazunga area water samples. The broader classification of all the samples from the alluvial aquifer, Mazunga area and Zhovhe dam show clustering on the pier diagram (fig 5.10.7) below and as such the water samples can all be broadly classified as sodium- calcium – sulphate water type.

Sulphates could result from the weathering of rocks upstream such as Iron sulphide (FeS_2, FeAsS), calcium sulphate as gypsum ($CaSO_4.H_2O$) and anhydrite ($CaSO_4$). Sulphates may generate toxic acids such as sulphuric acid when exposed to pH conditions below 5 and this may pose a possible health hazard for people drinking the water from the aquifer.

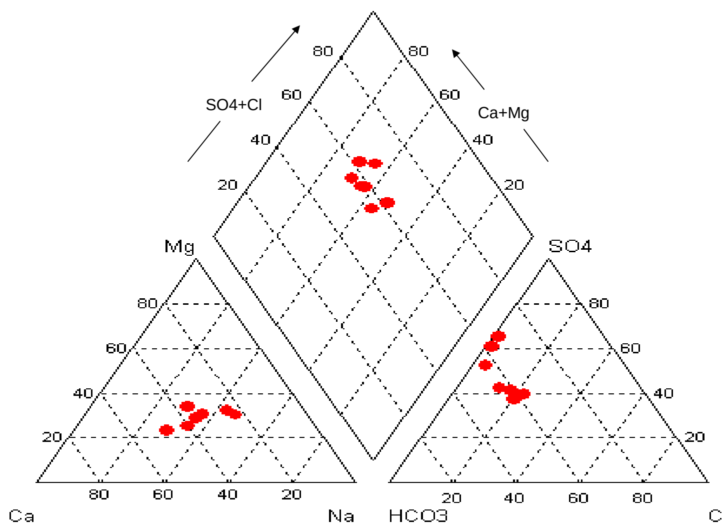


Fig 5.10.7 Piper diagram of the Malala, Zhove and Mazunga area water samples

Several chemical constituents affect the suitability of water for irrigation. Excessive sodium content in water renders it unsuitable for soils containing exchangeable Ca++ and Mg ++ ions. Soils containing exchangeable calcium and magnesium take up sodium in exchange for calcium and magnesium causing deflocculation and impairment of tilth and permeability of soils. The sodium hazard in irrigation water is expressed by determining the sodium adsorption ratio (SAR) by the following relation (equation 5.10.1), concentrations expressed in milliequivalents per litre.

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$ ……………………………equation 5.10.1

Table 5.10.2: Summary results for the calculation of the SAR

Sample	Na (meq/L)	Ca (meq/L)	Mg (meq/L)	Source of Values
B1	1.90	1.02	1.38	Appendix III.7
B2	1.11	1.18	1.10	Appendix III.9
B5	1.35	1.77	1.45	Appendix III.11
B6	1.98	1.25	1.67	Appendix III.13
Total	6.34	5.22	5.6	
Average	1.59	1.31	1.4	

Average values derived in Table 5.10.2 for sodium, calcium and magnesium were used in the calculation of the SAR. SAR = 1.37 was thus derived for the water at the Malala alluvial aquifer. According to Richards (1954) classification, the water in the aquifer is of a low sodium hazard and can thus be used for irrigation without posing much risk to the permeability of the soils. A low sodium Hazard according to Richards (1954) lies between 0 and 10; a very high sodium hazard is greater than 26. This therefore suggests that the water at the Malala alluvial aquifer is of a very low sodium hazard.

5.11 Groundwater potential of the Malala alluvial aquifer

Based on the observed water levels after a dam release, it is clear that the water level only drops to a maximum of 0.75 m in almost 100 days. When water levels drop to this point the groundwater available for abstraction in the alluvial aquifer is approximately 135 ML. This amount of water has the potential of irrigating an area of 13.5 ha per annum. The figure is derived by dividing groundwater available by 10 ML/Ha/ annum (Ministry of local government rural and urban development, 1996). 10 – 15 ML/Ha/ annum is the average value which is used by the ministry of agriculture for planning irrigation developments. This amount of water is used essentially for planning for irrigation water use for most crops in Zimbabwe.

The groundwater available in the alluvial aquifer when it is fully saturated is approximately 145 ML (Appendix IX). This amount of water has the potential of irrigating 14.5 Ha per annum. This implies that for each km stretch of saturated aquifer along the Mzingwane river, 14.5 Ha of land can be irrigated per annum given one dam release.

Based on the observed water levels the current abstraction plus the natural water losses lead to an average drop in the water level of 0.75 m. This implies that approximately 10 ML of water is lost per km stretch of the river channel in the Malala area. This translates to an average loss of water of 6.9 % from the volume of water extractable when the aquifer is saturated. The 6.9 % loss can be attributed more to evaporation losses since there is not much direct abstraction by the local community.

The loss of 10 ML of water per km stretch of the river can be attributed more to evaporation losses. It can thus be advised that instead of losing this amount to evaporation losses, this amount of water should be abstracted quickly for gainful agriculture immediately after a release. This activity will lower the water levels to a depth were evaporation water losses are less expected.

The aquifer stores more water than is readily available for abstraction. This occurs since some of the water is held between pores which are not hydraulically connected. This means that some of the water remains attached to the grains by surface tension and cannot be extracted easily. The total storage when the aquifer is saturated is calculated using equation 4.9.1. The specific yield value is replaced by the calculated porosity (39%) value. This formula is applied to all the 125 cells. The groundwater storage was calculated to be 1 035 ML. Porosity is used in this calculation since it indicates the percentage of the aquifer which can store water but does not necessarily transmit it to other parts of the aquifer.

Water can be abstracted from the alluvial aquifer but this reduces the saturated thickness of the alluvial aquifer. The average thickness as determined from the resistivity surveys is 13.4 m. This was obtained by averaging the modeled depth values from 24 electrical soundings in the aquifer. The alluvial aquifer is currently under utilized and can thus be further utilized for more gainful agricultural activities. The area of land which can be potentially irrigated using the water in the aquifer after one dam release or natural flood event is given in the table 5.11.1 below. The effect of a proposed abstraction on the saturated thickness of the alluvial aquifer is also given in Table 5.11.1 below.

Table 5.11.1: The effect of a proposed abstraction on the saturated thickness of the alluvial aquifer after a single release.

Proposed abstraction (ML)	Volume Remaining (ML)	Saturated thickness (m)	Potential area irrigated per annum (Ha)
10	135	12.47	1
30	115	10.62	3
50	95	8.77	5
100	45	4.14	9
140	5	0.44	11.8

It can thus be seen from the table 5.11.1 above that the aquifer saturated thickness reduces with an increase in the amount of abstraction from the aquifer. The aquifer becomes depleted when the proposed abstraction increases beyond 145 ML after a single dam release.

An increase in the number of releases or natural flood events will increase the groundwater potential of the alluvial aquifer. If abstraction from the aquifer is maximized within 100 days after a release or natural flood event the aquifer can be effectively utilised. Subsequent to the abstraction if the aquifer receives another release the volume of water available after two releases thus increases almost double the initial groundwater potential. Figure 5.11.1 below shows the groundwater potential of the aquifer after a number of releases per annum which are able to saturate the aquifer. (i.e. provided the available water resources from the previous release are utilized to the maximum). 20 % of the available groundwater resources have been subtracted from the computation of the groundwater potential. This is done since some of the water cannot be abstracted due to practical constraints. For example the pump in the borehole should be set a few meters above the base of the borehole. This will imply that the water column below the water pump will not be extractable from the aquifer.

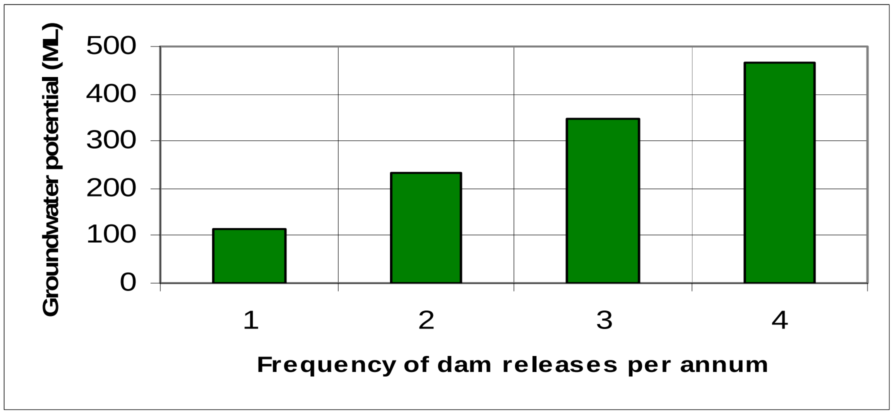


Fig 5.11.1 Groundwater potential of the alluvial aquifer in relation to dam releases per annum.

If the water in the alluvial aquifer is used to the maximum within 100 days from a dam release the potential area which can be irrigated per annum thus increases. As such an increase in the number of releases or flood events after each 100 days will translate to a higher potentially irrigated area. The figure 5.11.2 below illustrates the effect of dam releases on the area which can be potentially irrigated.

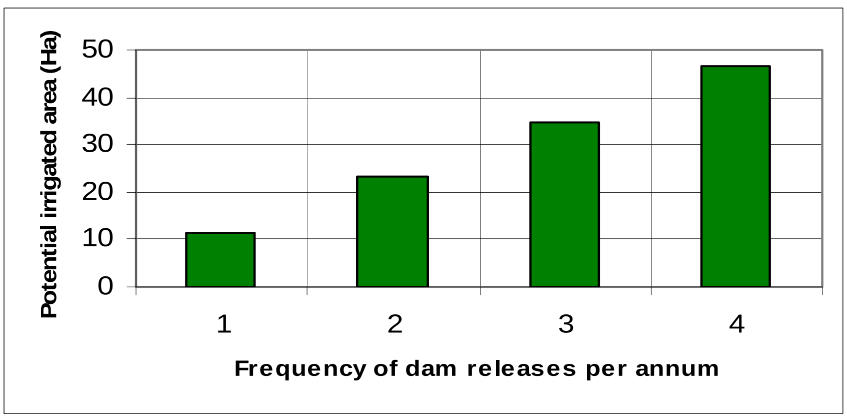


Fig 5.11.2 Potential irrigated area in relation to the number of dam releases per annum

The volume of water which is available after a number of releases per annum is given in table 5.11.2 below.

Table 5.11.2 Summary of groundwater availability (ML)

	Number of dam releases per annum			
	1	2	3	4
Minimum volume of water available (ML)	145	290	435	580
Volume of water available (ML) i.e. less 20%	116	232	348	464
Potential irrigated area per annum (Ha)	11.6	23.2	34.8	46.4

The fourth dam release might be replaced by a flood event. This is the case since the fourth release is expected in the rainy season. Therefore it is expected that the river may flood naturally due to a rainfall event. The relationship between dam releases and water availability is linear since it is assumed that the water from the previous storage is utilised fully before the commencement of a subsequent release. Therefore the cumulative total of water available increases with an increase in the number of dam releases which are able to saturate the aquifer.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Malala alluvial aquifer can be utilized for the benefit of the communal farmers at Malala. Small scale irrigation schemes can be implemented using water resources from the alluvial aquifer. The number and frequency of dam releases is an important factor in the recharge of the alluvial aquifer at Malala. With a single release or a natural flood event approximately 145 ML of water per km stretch of the river can be available for use by the communal farmers at Malala.

If water is utilized fully between managed dam releases the water levels in the aquifer will decline and thus the aquifer would be ready to store more water which can be utilized in subsequent drier months. The observed water levels during a 99 day period showed that with the current abstraction and also due to natural water losses the aquifer water levels decline on average by only 0.75m. This implies that of the estimated average depth of 13.4 m of the aquifer, 12.65 m of saturated thickness remains.

When the water levels drop by 0.75 m the aquifer would have lost to evapotranspiration approximately 6.9 % of water from the saturated volume after a release of water. Therefore approximately 93.1 % of the saturated volume of aquifer remains after 97 days of a release. Thus 93.1 % of the aquifer potential remains under utilized at the end of the observed 97 days after a release of water. The Malala alluvial aquifer is thus under utilized and there is greater potential for irrigation development.

Geological mapping indicated that the Malala area has an overall area of approximately 40 ha per km stretch of the river channel which can be utilized for farming. This is shown in the geological map (fig 5.3.1) as a lower terrace and an upper terrace. The terraces are composed of river deposited alluvium which is expected to provide fertile soils for farming.

It can also be concluded that the water chemistry changes as it flows from Zhovhe dam to the Malala alluvial aquifer. The water becomes more enriched in chloride, sodium and magnesium as it flows from the source of recharge (Zhovhe dam) to the alluvial aquifer. This enrichment could be as a result of agricultural activities upstream in the Mazunga area. However a broad classification of the water using a piper diagram illustrates that the water in the alluvial aquifer and at Zhovhe dam can be broadly classified as sodium - calcium - sulphate water type. This water can pose a possible health impact since the water becomes acidic with an increase in sulphates and at pH conditions below 5.

Resistivity work which was done at the Malala alluvial aquifer indicated that the alluvial aquifer is not a uniform homogenous geological unit, but rather it is heterogenous in nature and the depth of alluvial fill in the aquifer varies from a minimum depth of approximately 5m to a maximum depth of 25m. The depth of the alluvial aquifer seems more enhanced on the upstream part of the dolerite dyke as compared to the downstream part of the aquifer. This suggests that the intrusion of the dolerite dyke (fig 5.3.1) had an influence on the geometry of the alluvial aquifer.

The dolerite dyke which cuts across the mapped area (fig 5.3.1) could be an important natural sand dam. The dolerite dyke which is intrusive into the older gneisses seems to create a natural sand dam upstream of the dyke. Therefore water is expected to accumulate upstream of the dyke and its downstream movement is inhibited by the dolerite structure. Less water is thus expected to be lost due to downstream movement of water under the influence of gravity.

Water level monitoring indicated that the water level in the aquifer is relatively shallow, within 0.75 m below the river bed. This therefore allows water abstraction by manual technologies. Hand dug wells and shallow lift manual pumps can be used to abstract water from the aquifer.

The water level monitoring exercise also showed that less water would be lost to downstream movements. However when a borehole is installed in the aquifer and water begins to be abstracted, the water movement in the aquifer becomes rather complicated and can probably be modeled using Visual Modflow. Therefore downstream impacts can possibly be modeled using Visual Modflow or any other groundwater software which can model particle movement in an alluvial aquifer.

The studied site is representative of the other sites along the Mzingwane river since the depths of the alluvial fill at the site are comparable to other parts of the Mzingwane river. Upstream of the studied area at Mazunga, a well point system has been installed at depths of 15 m. These well points pump water continuously throughout the year. The major disparity is expected on the quantification of the groundwater resources. At the studied site a very low value was used for the specific yield as such this lowered the estimated amount of available groundwater resources. In the other sections of the river other authors have used higher values of specific yield thus realizing higher groundwater potentials. The results at the studied site are thus expected to give the minimum groundwater potential per km stretch of the Mzingwane river.

It should however be borne in mind that river sections are heterogeneous in nature and local disparities are thus expected. It is thus not easy to give general convincing estimates for the whole river stretch unless otherwise reasonably work has been carried out on the entire stretch of the Mzingwane river.

There is great water potential also in the plains aquifer which is adjacent to the river channel aquifer. The plains also exhibit adequate porosity and specific yield and therefore a similar analysis is recommended to evaluate the groundwater potential of the plains aquifer. As such the groundwater potential estimated in this study is the minimum water available per km stretch of the river at Malala, more water is also expected in the plains aquifer.

The major significance of alluvial aquifers is thus their ability to act as natural water harvesting formations. They can store water which can be utilized in future drier periods. They have the advantage that evaporation water losses are less as compared to surface evaporation water losses. However abstraction of water from alluvial aquifers can require specialized drilling equipment and can thus be costly to the ordinary local community.

6.2 Recommendations

- Boreholes should be drilled at river sections where the depth of the sand is largest.

- The upstream part of the dolerite dyke is recommended for drilling wells and boreholes. Resistivity work has provided sites which can be considered for drilling were the aquifer has an enhanced thickness.

- It is recommended that geological boundaries be considered as higher potential groundwater zones when exploring for groundwater

- Motorized pumps powered by diesel or electricity are recommended for abstraction of water from the aquifer. However pumps should be installed which draw water from the aquifer at rates which do not deplete the water levels rapidly.

- It is recommended that a similar study be carried out in order to monitor the drop in the water levels between two managed releases. The study only managed to monitor water levels in the alluvial aquifer after a single release of water.

- This study did not evaluate the characteristics of the soil and their suitability for agriculture. As such further study is recommended in this area.

- The very significant increase in salinity between the inflow water from Zhovhe dam and the Malala alluvial aquifer water needs further study.

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APPENDICES

Appendix I Field resistivity measurements : 1.1 Muleya resistivity data - Waypoint 295

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	11.23	26.50
2	0.5	11.79	1	1.98	23.30
3	0.5	27.48	1	0.94	25.80
5	0.5	77.72	1	0.30	23.24
7	0.5	153.08	1	0.17	26.64
10	0.5	313.22	1	0.13	41.03
10	2	75.36	1	0.51	38.66
13	2	129.53	1	0.35	45.59
17	2	223.73	1	0.29	63.76
20	2	310.86	1	0.25	76.78
25	2	487.49	1	0.25	122.85
30	2	703.36	1	0.21	147.71
40	2	1252.86	1	0.15	189.18
50	2	1959.36	1	0.10	190.06

Appendix 1.2: Muleya resistivity data - waypoint 296

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	33.50	79.06
2	0.5	11.79	1	3.23	38.08
3	0.5	27.48	1	0.86	23.63
5	0.5	77.72	1	0.23	17.88
7	0.5	153.08	1	0.13	19.75
10	0.5	313.22	1	0.09	27.25
10	2	75.36	1	0.39	29.01
13	2	129.53	1	0.24	30.57
17	2	223.73	1	0.19	42.73
20	2	310.86	1	0.17	52.22
25	2	487.49	1	0.13	62.40
30	2	703.36	1	0.10	72.45

Appendix 1.3: Masasanye resistivity data - waypoint 307

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	27.70	65.37
2	0.5	11.79	1	6.68	78.76
3	0.5	27.48	1	3.33	91.51
5	0.5	77.72	1	1.58	122.88
7	0.5	153.08	1	1.05	160.27
10	0.5	313.22	1	0.69	215.50
10	2	75.36	1	2.75	207.24
13	2	129.53	1	2.04	264.24
17	2	223.73	1	1.50	336.04
20	2	310.86	1	1.25	388.26

Appendix 1.4: Masasanye resistivity data - waypoint 314

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	27.40	64.66
2	0.5	11.79	1	6.56	77.34
3	0.5	27.48	1	2.85	78.32
5	0.5	77.72	1	1.09	85.03
7	0.5	153.08	1	0.65	99.35
10	0.5	313.22	1	0.39	121.53
10	2	75.36	1	1.62	122.31
13	2	129.53	1	1.15	148.57
17	2	223.73	1	0.85	190.62
20	2	310.86	1	0.72	225.06

Appendix 1.5: Masasanye resistivity data - waypoint 315

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	30.00	70.80
2	0.5	11.79	1	5.85	68.97
3	0.5	27.48	1	2.57	70.62
5	0.5	77.72	1	0.99	76.55
7	0.5	153.08	1	0.57	86.64
10	0.5	313.22	1	0.34	105.87
10	2	75.36	1	1.37	102.87
13	2	129.53	1	0.99	128.75
17	2	223.73	1	0.72	160.41
20	2	310.86	1	0.60	185.27

Appendix 1.6: Masasanye resistivity data - waypoint 316

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	32.70	77.17
2	0.5	11.79	1	6.86	80.88
3	0.5	27.48	1	2.83	77.77
5	0.5	77.72	1	1.02	78.89
7	0.5	153.08	1	0.58	89.09
10	0.5	313.22	1	0.36	113.07
10	2	75.36	1	1.38	103.62
13	2	129.53	1	1.02	131.86
17	2	223.73	1	0.78	174.29
20	2	310.86	1	0.67	207.65

Appendix 1.7: Malala resistivity data - waypoint 301

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	26.70	63.01
2	0.5	11.79	1	6.00	70.74
3	0.5	27.48	1	2.49	68.43
5	0.5	77.72	1	0.86	66.99
7	0.5	153.08	1	0.50	76.23
10	0.5	313.22	1	0.33	102.11
10	2	75.36	1	1.36	102.79
13	2	129.53	1	1.01	130.83
17	2	223.73	1	0.74	164.67
20	2	310.86	1	0.49	150.77
25	2	487.49	1	0.43	209.62

Appendix 1.8: Malala resistivity data - waypoint 302

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	30.00	70.80
2	0.5	11.79	1	5.67	66.85
3	0.5	27.48	1	2.19	60.18
5	0.5	77.72	1	0.71	54.87
7	0.5	153.08	1	0.41	62.76
10	0.5	313.22	1	0.26	82.69
10	2	75.36	1	1.10	83.20
13	2	129.53	1	0.78	100.52
17	2	223.73	1	0.56	125.96
20	2	310.86	1	0.47	145.48
25	2	487.49	1	0.36	173.55
30	2	703.36	1	0.29	200.46
40	2	1252.86	1	0.19	241.80
50	2	1959.36	1	0.14	282.15

Appendix 1.9: Malala resistivity data - waypoint 303

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	25.30	59.71
2	0.5	11.79	1	5.24	61.78
3	0.5	27.48	1	2.01	55.23
5	0.5	77.72	1	0.55	42.82
7	0.5	153.08	1	0.27	41.18
10	0.5	313.22	1	0.16	50.43
10	2	75.36	1	0.62	46.95
13	2	129.53	1	0.45	57.77
17	2	223.73	1	0.32	72.49
20	2	310.86	1	0.27	83.00
25	2	487.49	1	0.20	97.01
30	2	703.36	1	0.16	109.72
40	2	1252.86	1	0.11	132.80
50	2	1959.36	1	0.08	152.83

Appendix 1.10: Malala resistivity data - waypoint 304

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	29.00	68.44
2	0.5	11.79	1	5.48	64.61
3	0.5	27.48	1	2.05	56.33
5	0.5	77.72	1	0.57	44.07
7	0.5	153.08	1	0.29	43.63
10	0.5	313.22	1	0.17	52.93
10	2	75.36	1	0.67	50.57
13	2	129.53	1	0.48	61.66
17	2	223.73	1	0.34	76.74
20	2	310.86	1	0.28	87.04
25	2	487.49	1	0.21	100.91
30	2	703.36	1	0.16	115.35
40	2	1252.86	1	0.12	144.08

Appendix 1.11: Malala resistivity data - waypoint 305

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	1	20.50	48.38
2	0.5	11.79	1	4.73	55.77
3	0.5	27.48	1	2.05	56.33
5	0.5	77.72	1	0.69	53.32
7	0.5	153.08	1	0.28	42.56
10	0.5	313.22	1	0.13	40.41
10	2	75.36	1	0.57	43.26
13	2	129.53	1	0.39	51.03
17	2	223.73	1	0.30	66.22
20	2	310.86	1	0.25	77.40
25	2	487.49	1	0.20	98.47
30	2	703.36	1	0.17	120.98

Appendix 1.12: Resistivity data at piezometer B1- Upstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	24.50	57.82
2	0.5	11.79	5	7.89	93.02
3	0.5	27.48	5	3.51	96.45
5	0.5	77.72	5	1.58	122.64
7	0.5	153.08	5	1.04	158.44
10	0.5	313.22	5	0.69	214.56
10	2	75.36	5	2.54	191.41
13	2	129.53	5	1.88	243.52
17	2	223.73	5	1.37	305.62
20	2	310.86	5	1.11	345.37
25	2	487.49	5	0.83	402.67

Appendix 1.13: Resistivity data at piezometer B3 - Upstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	19.64	46.35
2	0.5	11.79	5	5.13	60.48
3	0.5	27.48	5	2.10	57.71
5	0.5	77.72	5	0.61	47.56
7	0.5	153.08	5	0.29	44.55
10	0.5	313.22	5	0.15	48.24
10	2	75.36	5	0.63	47.40
13	2	129.53	5	0.42	54.53
17	2	223.73	5	0.30	66.90
20	2	310.86	5	0.25	76.78
25	2	487.49	5	0.20	95.06

Appendix 1.14: Resistivity data at piezometer B7 - Upstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	47.40	111.86
2	0.5	11.79	5	8.71	102.69
3	0.5	27.48	5	3.64	100.03
5	0.5	77.72	5	1.11	86.58
7	0.5	153.08	5	0.51	77.61
10	0.5	313.22	5	0.21	64.52
10	2	75.36	5	0.93	70.39
13	2	129.53	5	0.52	67.10
17	2	223.73	5	0.32	72.49
20	2	310.86	5	0.26	79.58
25	2	487.49	5	0.19	92.72

Appendix 1.15: Resistivity data at point B1 - Upstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	36.60	86.38
2	0.5	11.79	5	6.05	71.33
3	0.5	27.48	5	2.68	73.65
5	0.5	77.72	5	1.14	88.60
7	0.5	153.08	5	0.67	101.95
10	0.5	313.22	5	0.38	119.02
10	2	75.36	5	1.47	111.08
13	2	129.53	5	1.00	129.14
17	2	223.73	5	0.70	156.83
20	2	310.86	5	0.57	178.12
25	2	487.49	5	0.45	217.42

Appendix 1.16: Resistivity data at piezometer B2 -Upstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	2	36.60	86.38
2	0.5	11.79	2	6.05	71.33
3	0.5	27.48	2	2.68	73.65
5	0.5	77.72	2	1.14	88.60
7	0.5	153.08	2	0.67	101.95
10	0.5	313.22	2	0.38	119.02
10	2	75.36	2	1.47	111.08
13	2	129.53	2	1.00	129.14
17	2	223.73	2	0.70	156.83
20	2	310.86	2	0.57	178.12
25	2	487.49	2	0.45	217.42

Appendix 1.17: Resistivity data at piezometer B5 - Downstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	36.60	86.38
2	0.5	11.79	5	6.05	71.33
3	0.5	27.48	5	2.68	73.65
5	0.5	77.72	5	1.14	88.60
7	0.5	153.08	5	0.67	101.95
10	0.5	313.22	5	0.38	119.02
10	2	75.36	5	1.47	111.08
13	2	129.53	5	1.00	129.14
17	2	223.73	5	0.70	156.83
20	2	310.86	5	0.57	178.12
25	2	487.49	5	0.45	217.42

Appendix 1.18: Resistivity data at piezometer B8 - Downstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	16.31	38.49
2	0.5	11.79	5	4.21	49.64
3	0.5	27.48	5	2.01	55.23
5	0.5	77.72	5	0.97	75.62
7	0.5	153.08	5	0.67	102.72
10	0.5	313.22	5	0.47	147.21
10	2	75.36	5	1.89	142.66
13	2	129.53	5	1.45	187.95
17	2	223.73	5	1.09	244.54
20	2	310.86	5	0.90	280.40
25	2	487.49	5	0.70	340.76

Appendix 1.19: Resistivity data at piezometer B6 - Downstream of the dolerite dyke

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	55.30	130.51
2	0.5	11.79	5	12.19	143.72
3	0.5	27.48	5	4.60	126.41
5	0.5	77.72	5	1.09	84.87
7	0.5	153.08	5	0.38	58.78
10	0.5	313.22	5	0.15	45.98
10	2	75.36	5	0.62	46.95
13	2	129.53	5	0.38	48.83
17	2	223.73	5	0.28	61.97
20	2	310.86	5	0.24	74.30

Appendix II Soil particle size distribution

Sample B1

Particle size (mm)	4	2.8	2	1	0.5	0.25	0.18	0.125	0.032
Percentage passing (%)	100	95.43	91.1	84.40	52.14	13.87	2.85	0.94	0.24

Appendix II.1: Sample B2

Particle size (mm)	4	2.8	2	1	0.5	0.25	0.18	0.125	0.032
Percentage passing (%)	100	99.65	96.3	83.59	42.69	20.90	10.48	5.18	1.98

Appendix II.2: Sample B4

Particle size (mm)	4	2.8	2	1	0.5	0.25	0.18	0.125	0.032
Percentage passing (%)	100	98.13	97.1	95.08	81.50	43.47	12.41	6.99	3.39

Appendix II.3: Sample B5

Particle size (mm)	4	2.8	2	1	0.5	0.25	0.18	0.125	0.032
Percentage passing (%)	100	99.88	99.5	98.59	84.32	42.24	24.12	11.95	4.07

Appendix II.4: Sample B6

Particle size (mm)	4	2.8	2	1	0.5	0.25	0.18	0.125	0.032
Percentage passing (%)	100	100	99.3	96.54	71.55	21.56	3.84	1.54	0.39

Appendix III Hydrogeochemical data for plotting piper diagrams

Sample ZH 1 (Zhove Dam) - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	13.55	2.00	40.08	0.68	Ca^{2+}	42.08
Mg^{2+}	5.22	2.00	24.31	0.43	Mg^{2+}	26.73
K^{1+}	4.44	1.00	39.10	0.11	$Na^{+1} + K^{+1}$	31.19
Na^{+1}	8.91	1.00	22.99	0.39		
			Total Cations	1.61	Total	100.00

Appendix III.2: Sample ZH 1 (Zhove Dam) - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	159.00	2.00	96.06	3.31	SO_4^{2-}	65.62
Cl^-	3.00	1.00	35.45	0.08	Cl^-	1.68
HCO_3^-	100.65	1.00	61.02	1.65	HCO_3^-	32.70
			Total Anions	5.04	Total	100.00

Appendix III.3: Sample ZH 2 (Zhove dam) - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	19.44	2.00	40.08	0.97	Ca^{2+}	49.54
Mg^{2+}	5.83	2.00	24.31	0.48	Mg^{2+}	24.49
K^{1+}	4.44	1.00	39.10	0.11	$Na^{+1} + K^{+1}$	25.97
Na^{+1}	9.08	1.00	22.99	0.39		
			Total Cations	1.96	Total	100.00

Appendix III.4: Sample ZH 2 (Zhove Dam) - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	157.00	2.00	96.06	3.27	SO_4^{2-}	61.07
Cl^-	3.00	1.00	35.45	0.08	Cl^-	1.58
HCO_3^-	122.00	1.00	61.02	2.00	HCO_3^-	37.35
			Total Anions	5.35	Total	100.00

Appendix III.5: Sample MAZ (Mazunga Area) - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	22.55	2.00	40.08	1.13	Ca^{2+}	36.35
Mg^{2+}	13.00	2.00	24.31	1.07	Mg^{2+}	34.55
K^{1+}	2.56	1.00	39.10	0.07	$Na^{+1} + K^{+1}$	29.10
Na^{+1}	19.2	1.00	22.99	0.84		
			Total Cations	3.10	Total	100.00

Appendix III.6: Sample MAZ (Mazunga Area) - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	143.00	2.00	96.06	2.98	SO_4^{2-}	52.68
Cl^-	8.00	1.00	35.45	0.23	Cl^-	3.99
HCO_3^-	149.45	1.00	61.02	2.45	HCO_3^-	43.33
			Total Anions	**5.65**	**Total**	**100.00**

Appendix III.7: Sample B1 - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	20.44	2.00	40.08	1.02	Ca^{2+}	23.04
Mg^{2+}	16.78	2.00	24.31	1.38	Mg^{2+}	31.18
K^{1+}	5.00	1.00	39.10	0.13	$Na^{+1} + K^{+1}$	45.79
Na^{+1}	43.67	1.00	22.99	1.90		
			Total Cations	4.43	Total	100.00

Appendix III.8: Sample B1- Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	176.00	2.00	96.06	3.66	SO_4^{2-}	39.73
Cl^-	73.00	1.00	35.45	2.06	Cl^-	22.33
HCO_3^-	213.50	1.00	61.02	3.50	HCO_3^-	37.94
			Total Anions	9.22	Total	100.00

Appendix III.9: Sample B2 - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	23.55	2.00	40.08	1.18	Ca^{2+}	33.63
Mg^{2+}	13.33	2.00	24.31	1.10	Mg^{2+}	31.38
K^{1+}	4.33	1.00	39.10	0.11	$Na^{+1} + K^{+1}$	34.99
Na^{+1}	25.56	1.00	22.99	1.11		
			Total Cations	3.49	Total	100.00

Appendix III.10: Sample B2 - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	169.00	2.00	96.06	3.52	SO_4^{2-}	41.33
Cl^-	53.00	1.00	35.45	1.50	Cl^-	17.56
HCO_3^-	213.50	1.00	61.02	3.50	HCO_3^-	41.10
			Total Anions	8.51	Total	100.00

Appendix III.11: Sample B5 : Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	35.44	2.00	40.08	1.77	Ca^{2+}	36.80
Mg^{2+}	17.67	2.00	24.31	1.45	Mg^{2+}	30.25
K^{1+}	9.00	1.00	39.10	0.23	$Na^{+1} + K^{+1}$	32.95
Na^{+1}	31.11	1.00	22.99	1.35		
			Total Cations	4.81	Total	100.00

Appendix III.12: Sample B5 - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	167.00	2.00	96.06	3.48	SO_4^{2-}	37.41
Cl^-	68.00	1.00	35.45	1.92	Cl^-	20.64
HCO_3^-	237.90	1.00	61.02	3.90	HCO_3^-	41.95
			Total Anions	9.29	Total	100.00

Appendix III.13: Sample B6 - Cations

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
Ca^{2+}	25.09	2.00	40.08	1.25	Ca^{2+}	24.81
Mg^{2+}	20.33	2.00	24.31	1.67	Mg^{2+}	33.15
K^{1+}	5.67	1.00	39.10	0.15	$Na^{+1} + K^{+1}$	42.04
Na^{+1}	45.44	1.00	22.99	1.98		
			Total Cations	5.05	Total	100.00

Appendix III.14: Sample B6 - Anions

Parameter	Concentation (mg/l)	Valence	Formula Weight	Concentration (meq/l)	Parameter	Percentage of Total (%)
SO_4^{2-}	162.00	2.00	96.06	3.37	SO_4^{2-}	42.46
Cl^-	38.00	1.00	35.45	1.07	Cl^-	13.49
HCO_3^-	213.50	1.00	61.02	3.50	HCO_3^-	44.05
			Total Anions	7.94	Total	100.00

Appendix IV Topographical measurements at the studied site

HI	MR	Slope Distance	ANGLE	Reduced Level B	Remarks
1.5	1	88.00	1.54	103.18	top left bank
1.5	1	76.00	1.58	99.84	river bank
1.5	1	73.50	1.58	99.94	water edge
1.5	1	72.00	1.58	99.70	Spot shot
1.5	1	54.00	1.59	99.73	Spot shot
1.5	1	45.00	1.59	99.60	water edge
1.5	1	40.00	1.59	99.76	ss water edge
1.5	1	36.00	1.57	100.49	top of piz2
1.5	1	34.50	1.57	100.52	top of peg
1.5	1	31.00	1.59	99.76	Spot shot
1.5	1	16.00	1.60	100.10	Spot shot
1.5	1	24.90	1.59	99.95	Spot shot
1.5	1	30.90	1.59	99.76	Spot shot
1.5	1	48.00	1.59	99.57	Spot shot
1.5	1	64.00	1.58	99.79	Spot shot
1.5	1	88.00	1.57	100.17	river edge
1.5	1	110.00	1.54	103.66	top right bank
1.5	1	28.20	1.59	100.01	Spot shot
1.5	1	57.00	1.58	99.74	Spot shot
1.5	1	90.00	1.58	99.63	Spot shot
1.5	1	113.50	1.58	99.56	Spot shot

Appendix V Resistivity data for cross sectional analysis

(Downstream of the dyke)
Point no. 1 (Western river bank)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	33.50	79.06
2	0.5	11.79	5	5.46	64.37
3	0.5	27.48	5	2.10	57.71
5	0.5	77.72	5	0.78	60.47
7	0.5	153.08	5	0.47	71.49
10	0.5	313.22	5	0.28	88.01
10	2	75.36	5	1.07	80.33
13	2	129.53	5	0.73	94.56
17	2	223.73	5	0.49	110.52
20	2	310.86	5	0.38	116.88
25	2	487.49	5	0.29	140.40
30	2	703.36	5	0.23	159.66

Appendix V.2 - Point no.2 (mid section of the river)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	39.60	93.46
2	0.5	11.79	5	6.05	71.33
3	0.5	27.48	5	2.68	73.65
5	0.5	77.72	5	1.14	88.60
7	0.5	153.08	5	0.67	101.95
10	0.5	313.22	5	0.38	119.02
10	2	75.36	5	1.47	111.08
13	2	129.53	5	1.00	129.14
17	2	223.73	5	0.70	156.83
20	2	310.86	5	0.57	178.12
25	2	487.49	5	0.45	217.42

Appendix V.3 - Point no. 3 (mid section of the river)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	16.31	38.49
2	0.5	11.79	5	4.21	49.64
3	0.5	27.48	5	2.01	55.23
5	0.5	77.72	5	0.97	75.62
7	0.5	153.08	5	0.67	102.72
10	0.5	313.22	5	0.47	147.21
10	2	75.36	5	1.89	142.66
13	2	129.53	5	1.45	187.95
17	2	223.73	5	1.09	244.54
20	2	310.86	5	0.90	280.40
25	2	487.49	5	0.70	340.76

Appendix V.4 - Point no.4 (Eastern river bank)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	103.90	245.20
2	0.5	11.79	5	6.38	75.22
3	0.5	27.48	5	1.80	49.49
5	0.5	77.72	5	0.73	56.66
7	0.5	153.08	5	0.48	73.63
10	0.5	313.22	5	0.33	103.68
10	2	75.36	5	1.21	91.49
13	2	129.53	5	0.91	117.35
17	2	223.73	5	0.67	149.68
20	2	310.86	5	0.55	170.35
25	2	487.49	5	0.42	205.23
30	2	703.36	5	0.34	236.33

Appendix V.5 - Point no. 1 (Western river bank)
(upstream of the dyke)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	27.20	64.19
2	0.5	11.79	5	6.10	71.92
3	0.5	27.48	5	2.29	62.93
5	0.5	77.72	5	0.62	48.50
7	0.5	153.08	5	0.29	43.78
10	0.5	313.22	5	0.16	49.18
10	2	75.36	5	0.65	49.06
13	2	129.53	5	0.46	58.94
17	2	223.73	5	0.32	70.92
20	2	310.86	5	0.26	79.58
25	2	487.49	5	0.19	92.62
30	2	703.36	5	0.15	105.50

Appendix V.6 - Point 2 (mid section)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	19.64	46.35
2	0.5	11.79	5	5.13	60.48
3	0.5	27.48	5	2.10	57.71
5	0.5	77.72	5	0.61	47.56
7	0.5	153.08	5	0.29	44.55
10	0.5	313.22	5	0.15	48.24
10	2	75.36	5	0.63	47.40
13	2	129.53	5	0.42	54.53
17	2	223.73	5	0.30	66.90
20	2	310.86	5	0.25	76.78
25	2	487.49	5	0.20	95.06

Appendix V.7 - Point no. 3 (mid section)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	33.30	78.59
2	0.5	11.79	5	6.28	74.04
3	0.5	27.48	5	1.93	53.15
5	0.5	77.72	5	0.47	36.37
7	0.5	153.08	5	0.18	28.01
10	0.5	313.22	5	0.11	33.20
10	2	75.36	5	0.41	30.97
13	2	129.53	5	0.32	41.06
17	2	223.73	5	0.25	55.26
20	2	310.86	5	0.21	66.21
25	2	487.49	5	0.17	84.82
30	2	703.36	5	0.15	103.39

Appendix V.8 - Point no. 4 (mid section)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	47.40	111.86
2	0.5	11.79	5	8.71	102.69
3	0.5	27.48	5	3.64	100.03
5	0.5	77.72	5	1.11	86.58
7	0.5	153.08	5	0.51	77.61
10	0.5	313.22	5	0.21	64.52
10	2	75.36	5	0.93	70.39
13	2	129.53	5	0.52	67.10
17	2	223.73	5	0.32	72.49
20	2	310.86	5	0.26	79.58
25	2	487.49	5	0.19	92.72

Appendix V.9 - Point no.5 (mid section)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	71.90	169.68
2	0.5	11.79	5	7.21	85.01
3	0.5	27.48	5	2.61	71.72
5	0.5	77.72	5	0.71	55.26
7	0.5	153.08	5	0.32	48.99
10	0.5	313.22	5	0.17	53.25
10	2	75.36	5	0.70	52.38
13	2	129.53	5	0.46	59.71
17	2	223.73	5	0.32	72.04
20	2	310.86	5	0.26	81.76
25	2	487.49	5	0.21	99.94
30	2	703.36	5	0.16	113.94

Appendix V.10 - Point no. 6 (mid section)

AB/2	MN/2	Factor	Current	Resistance	App. Res
(m)	(m)		(mA)	(ohm)	(ohm.m)
1	0.5	2.36	5	16.06	37.90
2	0.5	11.79	5	5.61	66.14
3	0.5	27.48	5	2.88	79.14
5	0.5	77.72	5	1.46	113.63
7	0.5	153.08	5	0.94	143.44
10	0.5	313.22	5	0.40	125.91
10	2	75.36	5	1.37	102.87
13	2	129.53	5	0.77	99.87
17	2	223.73	5	0.47	104.93
20	2	310.86	5	0.33	102.58
25	2	487.49	5	0.23	111.15

Appendix V.11 - Point no. 7 (Eastern river bank)

AB/2	**MN/2**	**Factor**	**Current**	**Resistance**	**App. Res**
(m)	**(m)**		**(mA)**	**(ohm)**	**(ohm.m)**
1	0.5	2.36	5	30.60	72.22
2	0.5	11.79	5	6.75	79.58
3	0.5	27.48	5	2.88	79.14
5	0.5	77.72	5	0.97	75.39
7	0.5	153.08	5	0.47	71.64
10	0.5	313.22	5	0.23	70.79
10	2	75.36	5	0.94	70.91
13	2	129.53	5	0.57	73.18
17	2	223.73	5	0.36	81.21
20	2	310.86	5	0.29	89.22
25	2	487.49	5	0.21	102.37
30	2	703.36	5	0.17	116.76

Appendix VI Observed water level data ; water levels (cm) represent water column in the piezometer from the base of the piezometer.

	Piezometer							
	B1	B2	B3	B4	B5	B6	B7	B8
Piezometer depth (cm)	300	265	260	230	300	278	300	283
31/01/2008	288	263		102	202	260		
1/2/2008	286	263		100	200	259		
2/2/2008	290	265		104	300	280		
3/2/2008	290	265		104	300	280		
4/2/2008	290	265		104	300	280		
5/2/2008	290	265		104	300	280		
6/2/2008	289	270		104	289	279		
7/2/2008	277	269		104	289	279		
8/2/2008	250	265		103	288	278		
9/2/2008	230	265		103	288	278		
10/2/2008	225	265		103	288	278		
11/2/2008	221	264		103	290	277		
12/2/2008	221	264		103	290	276		
13/2/2008	222	264		103	290	275		
14/2/2008	207	264		104	295	277		
15/2/2008	290	265		104	300	280		
16/2/2008	250	265		108	290	244		
17/2/2008	248	264		108	290	244		
18/2/2008	247	264		108	290	244		
19/2/2008	247	264		108	289	244		
20/2/2008	247	263		107	289	243		

	B1	B2	B3	B4	B5	B6	B7	B8
21/2/2008	247	263		107	288	243		
22/2/2008	246	263		107	288	243		
23/2/2008	246	262		107	285	243		
24/2/2008	246	262		106	285	242		
25/2/2008	246	261		106	285	242		
26/2/2008	235	261			284	242		
27/2/2008	235	261			284	242		
28/2/2008	235	261			284	240		
29/2/2008	201	260			283	240		
1/3/2008	202	190			283	186		
2/3/2008	200	185			282	170		
3/3/2008	200	189			240	179		
4/3/2008	195	198			222	169		
5/3/2008	194	193			220	148		
6/3/2008	193	185			210	171		
7/3/2008	193	185			208	170		
8/3/2008	193	185			208	171		
9/3/2008	193	185			208	171		
10/3/2008	193	185			207	170		
11/3/2008	193	185			207	170		
12/3/2008	192	184			207	170		
13/3/2008	190	183	206		206	168	232	224
14/3/2008	190	183	206		206	168	232	224
15/3/2008	190	183	206		206	168	232	224
16/3/2008	190	183	206		206	168	232	224
17/3/2008	190	183	206		206	168	232	224
18/3/2008	189	182	205		205	167	232	224
19/3/2008	189	182	205		205	167	232	223
20/3/2008	189	182	204		204	166	232	223
21/3/2008	188	182	204		204	166	232	223
22/3/2008	188	182	204		204	163	232	223
23/3/2008	187	182	204		204	160	232	222
24/3/2008	187	182	204		204	165	232	222
25/3/2008	186	181	203		203	152	230	222
26/3/2008	185	181	203		203	150	230	222
27/3/2008	185	181	203		201	150	230	220
28/3/2008	184	181	203		201	151	230	220
29/3/2008	184	181	203		201	142	230	220
30/3/2008	185	179	201		201	141	229	220
31/3/2008	185	179	201		200	141	229	220

	B1	B2	B3	B4	B5	B6	B7	B8
1/4/2008	181	179	201		200	151	229	219
2/4/2008	181	179	201		200	151	229	219
3/4/2008	180	178	201		200	151	229	219
4/4/2008	180	178	201		200	151	229	219
5/4/2008	174	178	200		200	151	229	219
6/4/2008	174	178	200		200	139	227	211
7/4/2008	174	178	200		199	139	227	211
8/4/2008	173	177	199		199	139	227	211
9/4/2008	173	177	199		199	136	226	210
10/4/2008	173	177	198		199	127	226	210
11/4/2008	172	176	198		198	127	225	210
12/4/2008	172	176	198		198	124	225	209
13/4/2008	172	176	197		198	124	225	209
14/4/2008	171	175	197		198	120	224	208
15/4/2008	171	172	196		197	116	224	208
16/4/2008	171	171	196		197	116	224	208
17/4/2008	169	171	196		197	112	223	207
18/4/2008	169	171	195		196	110	223	207
19/4/2008	169	171	195		196	110	223	207
20/4/2008	169	169	195		196	109	223	207
21/4/2008	168	169	194		195	106	222	206
22/4/2008	168	169	194		195	105	222	206
23/4/2008	168	168	194		195	104	222	206
24/4/2008	168	168	194		194	102	221	206
25/4/2008	168	168	193		194	102	221	205
26/4/2008	167	168	193		194	101	221	205
27/4/2008	167	168	193		194	101	221	205
28/4/2008	166	182	194		183	112	222	198
29/4/2008	166	182	194		183	110	222	198
30/4/2008	166	182	193		182	109	222	197
1/5/2008	165	181	193		182	108	222	197
2/5/2008	165	181	192		182	108	222	197
3/5/2008	164	181	192		181	107	221	196
4/5/2008	164	170	192		181	107	221	196
5/5/2008	164	170	191		180	107	220	196
6/5/2008	164	170	191		180	107	220	196
7/5/2008	164	170	191		180	107	220	196
8/5/2008	164	170	191		180	106	220	196

Appendix VII Data for depth analysis

Data for the plotting of the cross section upstream of the dolerite dyke

Point No.	Distance from River bank (m)	X	Y	Approximate depth of sand/bedrock interface (m)
1	15	800218	7553635	10
2	45	800225	7553643	12
3	75	800241	7553652	10
4	105	800262	7553676	18
5	135	800270	7553686	17
6	165	800296	7553708	17
7	195	800312	7553722	25

Appendix VII.2 Data for the plotting of the crossection downstream of the dolerite dyke

Point No.	Distance from River bank (m)	X	Y	Approximate depth of sand/bedrock interface (m)
1	25	800546	7553266	8
2	75	800597	7553265	11
3	125	800646	7553272	7
4	175	800690	7553281	5

Appendix VIII Geological mapping data sheet

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
1	801155	7553265	Tonalitic gneiss	Sample no. 1
2	801022	7553437	Dolerite	Sample no. 2
3	800722	7553858	Tonalitic & Granodioritic gneiss	Weathered
4	801208	7553916	Mafic gneiss	Sample no. 3
5	801209	7553945		Sample no. 4
6	800425	7554039	Tonalitic & Granodioritic gneiss	
7	800438	7554064	Tonalitic & Granodioritic gneiss	
8	800451	7554085	Tonalitic & Granodioritic gneiss	
9	800485	7554041	Tonalitic & Granodioritic gneiss	
10	801603	7553801	Tonalitic & Granodioritic gneiss	Altitude 476m
11	801104	7554453	Tonalitic & Granodioritic gneiss	
12	801805	7553108	Tonalitic & Granodioritic gneiss	
13	801604	7553298	Tonalitic & Granodioritic gneiss	
14	802015	7553310	Tonalitic & Granodioritic gneiss	
15	800703	7554659	Tonalitic & Granodioritic gneiss	
16	800733	7553013	Dolerite	
17	801300	7554150	Dolerite	
18	801988	7553384	Dolerite	
19	800500	7554120	Tonalitic & Granodioritic gneiss	
20	800464	7554159	Tonalitic & Granodioritic gneiss	
21	800450	7554176	Mafic gneiss	Sample no.5
22	800458	7554190	Mafic gneiss	
23	800465	7554201	Mafic gneiss	
24	800438	7554225	Tonalitic & Granodioritic gneiss	
25	800425	7554212	Tonalitic & Granodioritic gneiss	
26	800406	7554172	Tonalitic & Granodioritic gneiss	
27	800354	7554195	Mafic granulite	Sample no.6

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
28	800326	7554223	Mafic gneiss	
29	800311	7554229	Mafic gneiss	
30	800322	7554243	Mafic gneiss	
31	800315	7554240	Mafic granulite	
32	800243	7554298	Tonalitic & Granodioritic gneiss	Edge of alluvium
33	800259	7554322	Tonalitic & Granodioritic gneiss	
34	800293	7554365	Tonalitic & Granodioritic gneiss	
35	800222	7554395	Tonalitic & Granodioritic gneiss	
36	800205	7554396	Tonalitic & Granodioritic gneiss	
37	800221	7554401	Quartz vein	
38	800321	7554549	Mafic granulites	
39	800424	7554555	Tonalitic & Granodioritic gneiss	
40	800437	7554565	Tonalitic & Granodioritic gneiss	
41	800472	7554429	Tonalitic & Granodioritic gneiss	
42	800528	7554413	Tonalitic & Granodioritic gneiss	
43	800546	7554378	Mafic gneiss	
44	800555	7554347	Mafic gneiss	
45	800648	7554219	Porphyritic gneiss	
46	800675	7554210	Porphyritic gneiss	
48	800749	7554138	Tonalitic & Granodioritic gneiss	
49	800939	7554083	Mafic granulite/ Quartz vein	Sample no.7
50	801006	7553986	Dolerite	
51	800990	7553978	Tonalitic & Granodioritic gneiss	
52	801034	7553805	Mafic gneiss	
53	801071	7553805	Tonalitic & Granodioritic gneiss	
54	801090	7553792	Tonalitic & Granodioritic gneiss	
55	801110	7553734	Tonalitic & Granodioritic gneiss	
56	801147	7553648	Quartz vein	
57	801187	7553559	Dolerite	
58	801193	7553522	Dolerite	

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
59	801197	7553486	Dolerite	
60	801193	7553453	Dolerite	Mt peak. Altitude 506m
61	801194	7553409	Dolerite	
62	801212	7553310	Tonalitic & Granodioritic gneiss	
63	801201	7553271	Tonalitic & Granodioritic gneiss	
64	801228	7553256	Tonalitic & Granodioritic gneiss	
65	801290	7553191	Tonalitic & Granodioritic gneiss	
66	801317	7553163	Tonalitic & Granodioritic gneiss	
67	801615	7553365	Dolerite	
68	801624	7553402	Dolerite	
69	801618	7553412	Dolerite	Adjuscent to gneisses
70	801616	7553414	Tonalitic & Granodioritic gneiss	
71	801617	7553424	Tonalitic & Granodioritic gneiss	
72	801613	7553456	Tonalitic & Granodioritic gneiss	
73	801573	7553460	Tonalitic & Granodioritic gneiss	
74	801532	7553487	Tonalitic & Granodioritic gneiss	
75	801509	7553448	Tonalitic & Granodioritic gneiss	
76	801498	7553435	Dolerite	
77	801478	7553407	Dolerite	
78	801436	7553418	Dolerite	
79	801416	7553452	Dolerite	
80	801357	7553469	Dolerite	
81	801308	7553473	Tonalitic & Granodioritic gneiss	
82	801300	7553457	Dolerite	
83	801279	801279	Dolerite	
84	801280	7553426	Tonalitic & Granodioritic gneiss	
85	801272	7553408	Tonalitic & Granodioritic gneiss	
86	801275	7553375	Tonalitic & Granodioritic gneiss	

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
87	801302	7553371	Tonalitic & Granodioritic gneiss	
88	801305	7553406	Tonalitic & Granodioritic gneiss	
89	801313	7553415	Dolerite	
90	801354	7553393	Dolerite	
91	800604	7553484	Dolerite	Outcrop under alluvium
92	801399	7553363	Dolerite	
93	801165	7553337	Tonalitic & Granodioritic gneiss	
94	801076	7553414	Dolerite	
95	801017	7553439	Dolerite	
96	800958	7553476	Dolerite	
97	801270	7552552	Lower terrace (T1)	1st terrace from the river bed
98	801286	7552576	Lower terrace	
99	801297	7552599	Upper terrace (T2)	2nd terrace from the river bed
100	801317	7552651	Upper terrace	
101	801245	7552651	Lower terrace	
102	801190	7552780	Lower terrace	
103	801217	7552832	Upper terrace	
104	801159	7552937	Upper terrace	
105	801063	7552945	Lower terrace	
106	801019	7553048	Upper terrace	
107	801019	7553185	Upper terrace	
108	800954	7553269	Upper terrace	
109	800854	7553237	Upper terrace	
110	800814	7553240	Lower terrace	
111	800742	7553294	Lower terrace	
112	800679	7553372	Lower terrace	
113	800626	7553435	Lower terrace	
114	800490	7553573	Lower terrace	
115	800395	7553705	Lower terrace	
116	800398	7553852	Upper terrace	
117	800352	7553944	Upper terrace	
118	800080	7554338	Upper terrace	
119	n/a	n/a	n/a	
120	799992	7554261	Upper terrace	

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
121	799963	7554245	Lower terrace	
122	799806	7554140	Lower terrace	
123	799908	7553966	Lower terrace	
124	799922	7553866	Upper terrace	
125	799962	7553833	Tonalitic & Granodioritic gneiss	
126	800063	7553744	Upper terrace	
127	800206	7553563	Upper terrace	
128	800262	7553530	Lower terrace	
129	800285	7553487	Lower terrace	
130	800261	7553463	Dolerite	
131	800358	7553399	Lower terrace	
132	800427	7553326	Lower terrace	
133	800467	7553252	Lower terrace	
134	800488	7553198	Upper terrace	
135	800542	7553153	Upper terrace	
136	800568	7553163	Lower terrace	
137	800668	7553016	Lower terrace	
138	800757	7552886	Lower terrace	
139	800810	7552825	Lower terrace	
140	800791	7552735	Tonalitic & Granodioritic gneiss	
141	800962	7552645	Lower terrace	
142	800997	7552651	Lower terrace	
143	801014	7552575	Lower terrace	
144	801055	7552365	Upper terrace	
145	801107	7552349	Lower terrace	
146	801131	7552333	Lower terrace	
147	800940	7552286	Magnetite quartzite	Sample no.8
148	800808	7552461	Magnetite quartzite	
149	800768	7552481	Tonalitic & Granodioritic gneiss	
150	800680	7552541	Tonalitic & Granodioritic gneiss	
151	800406	7552655	Tonalitic & Granodioritic gneiss	
152	800379	7552677	Tonalitic & Granodioritic gneiss	
153	800257	7552806	Tonalitic & Granodioritic gneiss	
154	800174	7552949	Tonalitic & Granodioritic gneiss	

Number	X - Coordinate	Y - Coordinate	Geological Outcrop	Comments
155	800129	7552988	Mafic gneiss	
156	800054	7553052	Tonalitic & Granodioritic gneiss	
157	800027	7553072	Mafic gneiss	
158	799955	7553188	Tonalitic & Granodioritic gneiss	
159	799848	7553333	Tonalitic & Granodioritic gneiss	
160	799831	7553377	Tonalitic & Granodioritic gneiss	
161	799801	7553454	Tonalitic & Granodioritic gneiss	
162	799788	7553498	Dolerite	Mt peak
163	799792	7553522	Dolerite	
164	799776	7553577	Tonalitic & Granodioritic gneiss	
165	799077	7553771	Tonalitic & Granodioritic gneiss	
166	799706	7553802	Tonalitic & Granodioritic gneiss	
167	799630	7554063	Tonalitic & Granodioritic gneiss	
168	799617	7554098	Tonalitic & Granodioritic gneiss	
169	799449	7553942	Tonalitic & Granodioritic gneiss	
170	799458	7553891	Tonalitic & Granodioritic gneiss	
171	799480	7553829	Tonalitic & Granodioritic gneiss	
172	799566	7553747	Tonalitic & Granodioritic gneiss	
173	799651	7553657	Tonalitic & Granodioritic gneiss	
174	799756	7553542	Tonalitic & Granodioritic gneiss	
175	799774	7553518	Dolerite	
176	799772	7553492	Dolerite	
177	799767	7553466	Dolerite	
178	799771	7553432	Tonalitic & Granodioritic gneiss	
179	799807	7553360	Tonalitic & Granodioritic gneiss	

Appendix IX Calculation of the groundwater potential

Row	Column	Length (m)	Width (m)	Depth (m)	Specific yield (-)	Groundwater Potential (ML)
1	1	40	40	11	0.054	0.9504
1	2	40	40	12	0.054	1.0368
1	3	40	40	18	0.054	1.5552
1	4	40	40	17	0.054	1.4688
1	5	40	40	25	0.054	2.16
2	1	40	40	11	0.054	0.9504
2	2	40	40	12	0.054	1.0368
2	3	40	40	18	0.054	1.5552
2	4	40	40	17	0.054	1.4688
2	5	40	40	25	0.054	2.16
3	1	40	40	11	0.054	0.9504
3	2	40	40	12	0.054	1.0368
3	3	40	40	18	0.054	1.5552
3	4	40	40	17	0.054	1.4688
3	5	40	40	25	0.054	2.16
4	1	40	40	11	0.054	0.9504
4	2	40	40	12	0.054	1.0368
4	3	40	40	18	0.054	1.5552
4	4	40	40	17	0.054	1.4688
4	5	40	40	25	0.054	2.16
5	1	40	40	11	0.054	0.9504
5	2	40	40	12	0.054	1.0368
5	3	40	40	18	0.054	1.5552
5	4	40	40	17	0.054	1.4688
5	5	40	40	25	0.054	2.16
6	1	40	40	11	0.054	0.9504
6	2	40	40	12	0.054	1.0368
6	3	40	40	18	0.054	1.5552
6	4	40	40	17	0.054	1.4688
6	5	40	40	25	0.054	2.16
7	1	40	40	11	0.054	0.9504
7	2	40	40	12	0.054	1.0368
7	3	40	40	18	0.054	1.5552
7	4	40	40	17	0.054	1.4688
7	5	40	40	25	0.054	2.16
8	1	40	40	11	0.054	0.9504
8	2	40	40	12	0.054	1.0368
8	3	40	40	18	0.054	1.5552
8	4	40	40	17	0.054	1.4688
8	5	40	40	25	0.054	2.16
9	1	40	40	11	0.054	0.9504
9	2	40	40	12	0.054	1.0368

Row	Column	Length (m)	Width (m)	Depth (m)	Specific yield (-)	Groundwater Potential (ML)
9	3	40	40	18	0.054	1.5552
9	4	40	40	17	0.054	1.4688
9	5	40	40	25	0.054	2.16
10	1	40	40	11	0.054	0.9504
10	2	40	40	12	0.054	1.0368
10	3	40	40	18	0.054	1.5552
10	4	40	40	17	0.054	1.4688
10	5	40	40	25	0.054	2.16
11	1	40	40	11	0.054	0.9504
11	2	40	40	12	0.054	1.0368
11	3	40	40	18	0.054	1.5552
11	4	40	40	17	0.054	1.4688
11	5	40	40	25	0.054	2.16
12	1	40	40	11	0.054	0.9504
12	2	40	40	12	0.054	1.0368
12	3	40	40	18	0.054	1.5552
12	4	40	40	17	0.054	1.4688
12	5	40	40	25	0.054	2.16
13	1	40	40	11	0.054	0.9504
13	2	40	40	12	0.054	1.0368
13	3	40	40	18	0.054	1.5552
13	4	40	40	17	0.054	1.4688
13	5	40	40	25	0.054	2.16
14	1	40	40	11	0.054	0.9504
14	2	40	40	12	0.054	1.0368
14	3	40	40	18	0.054	1.5552
14	4	40	40	17	0.054	1.4688
14	5	40	40	25	0.054	2.16
15	1	40	40	6	0.054	0.5184
15	2	40	40	6	0.054	0.5184
15	3	40	40	18	0.054	1.5552
15	4	40	40	17	0.054	1.4688
15	5	40	40	25	0.054	2.16
16	1	40	40	6	0.054	0.5184
16	2	40	40	6	0.054	0.5184
16	3	40	40	6	0.054	0.5184
16	4	40	40	6	0.054	0.5184
16	5	40	40	25	0.054	2.16
17	1	40	40	6	0.054	0.5184
17	2	40	40	6	0.054	0.5184
17	3	40	40	6	0.054	0.5184
17	4	40	40	6	0.054	0.5184
17	5	40	40	25	0.054	2.16
18	1	40	40	8	0.054	0.6912
18	2	40	40	6	0.054	0.5184

Row	Column	Length (m)	Width (m)	Depth (m)	Specific yield (-)	Groundwater Potential (ML)
18	3	40	40	6	0.054	0.5184
18	4	40	40	6	0.054	0.5184
18	5	40	40	6	0.054	0.5184
19	1	40	40	8	0.054	0.6912
19	2	40	40	11	0.054	0.9504
19	3	40	40	11	0.054	0.9504
19	4	40	40	6	0.054	0.5184
19	5	40	40	6	0.054	0.5184
20	1	40	40	8	0.054	0.6912
20	2	40	40	11	0.054	0.9504
20	3	40	40	11	0.054	0.9504
20	4	40	40	7	0.054	0.6048
20	5	40	40	6	0.054	0.5184
21	1	40	40	8	0.054	0.6912
21	2	40	40	11	0.054	0.9504
21	3	40	40	11	0.054	0.9504
21	4	40	40	7	0.054	0.6048
21	5	40	40	5	0.054	0.432
22	1	40	40	8	0.054	0.6912
22	2	40	40	11	0.054	0.9504
22	3	40	40	11	0.054	0.9504
22	4	40	40	7	0.054	0.6048
22	5	40	40	5	0.054	0.432
23	1	40	40	8	0.054	0.6912
23	2	40	40	11	0.054	0.9504
23	3	40	40	11	0.054	0.9504
23	4	40	40	7	0.054	0.6048
23	5	40	40	5	0.054	0.432
24	1	40	40	8	0.054	0.6912
24	2	40	40	11	0.054	0.9504
24	3	40	40	11	0.054	0.9504
24	4	40	40	7	0.054	0.6048
24	5	40	40	5	0.054	0.432
25	1	40	40	8	0.054	0.6912
25	2	40	40	11	0.054	0.9504
25	3	40	40	11	0.054	0.9504
25	4	40	40	7	0.054	0.6048
25	5	40	40	5	0.054	0.432
					TOTAL GROUNDWATER POTENTIAL (ML)	143.3376

Appendix X Modelling using Rinvert software

Example: Modelling for point No. 1 Upstream of the dolerite dyke

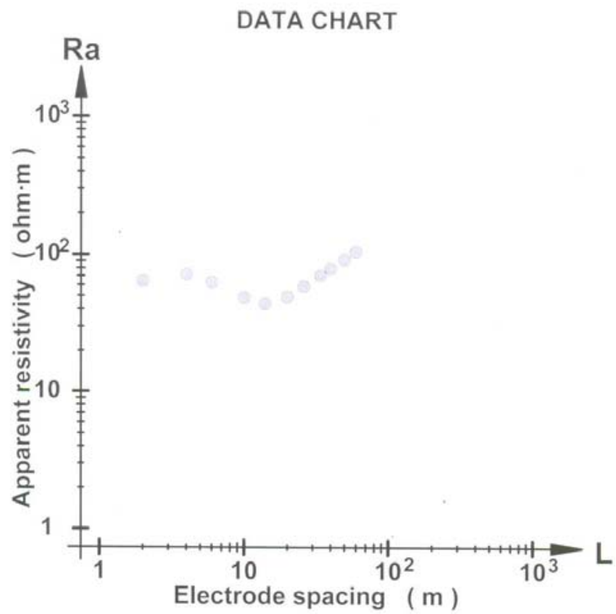

Figure 1. *Sounding curve for sounding <Field pt 1.dat> - Schlumberger array at "Malala 1".*

Point	Spacing (m)	App.Res. (ohm·m)
1	2.000	64.190
2	4.000	71.920
3	6.000	62.930
4	10.000	48.500
5	14.000	43.780
6	20.000	49.180
7	26.000	58.940
8	34.000	70.920
9	40.000	79.580
10	50.000	92.620
11	60.000	105.500

Table 1. *Sounding data for sounding <Field pt 1.dat> - Schlumberger array at "Malala 1".*

(a)

Layer	Depth (m)	Thickness (m)	Resistivity (ohm·m)
1	0.000	1.679	72.420
2	1.679	23.540	40.000
3	25.219	INFINITY	196.500

(b)

Point	Spacing (m)	App.Res. (model) (ohm·m)	App.Res. (field) (ohm·m)	Percent error
1	2.000	67.082	64.190	4.51
2	2.936	61.227	71.083	-13.87
3	4.309	53.669	70.992	-24.40
4	6.325	47.186	61.352	-23.09
5	9.283	43.542	50.308	-13.45
6	13.626	42.503	43.841	-3.05
7	20.000	43.818	49.180	-10.90
8	29.356	48.531	64.109	-24.30
9	43.089	58.413	83.747	-30.25

Table 2. *Forward modelling for model <Model1 pt 1.mdl> in comparison with data <Field pt 1.dat> - Schlumberger array at "Malala 1".*

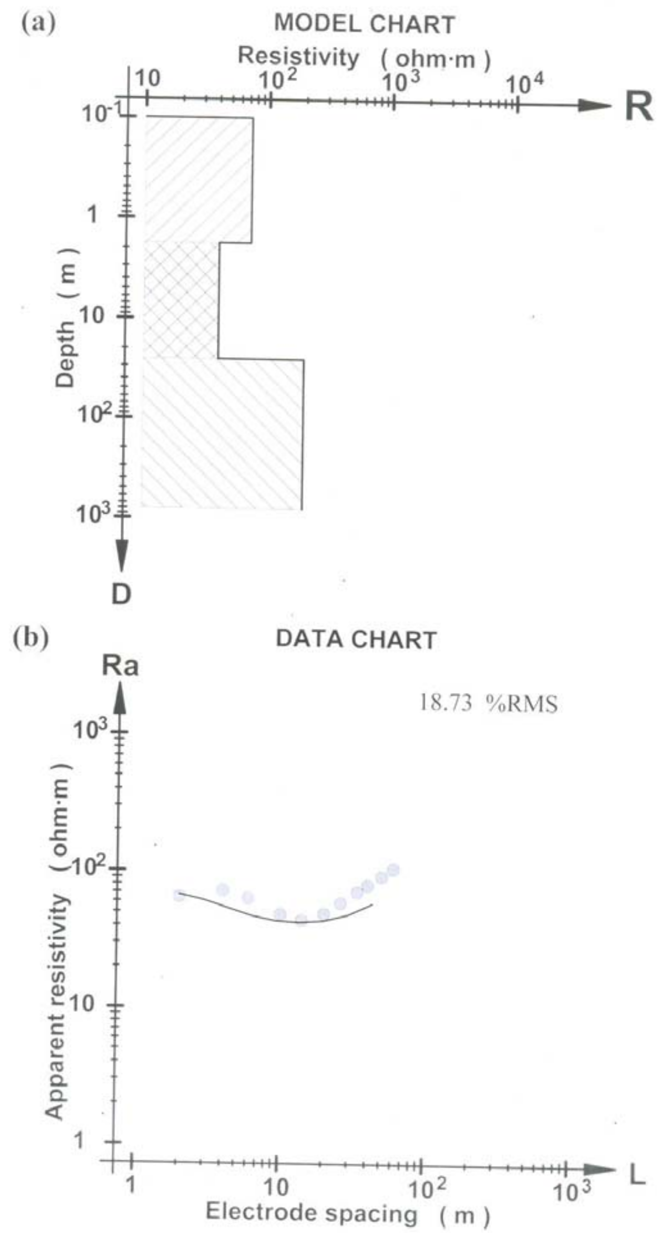

Figure 2. *Forward modelling for model <Model1 pt 1.mdl> in comparison with data <Field pt 1.dat> - Schlumberger array at "Malala 1".*

(a)

Point	Spacing (m)	App.Res. (model) (ohm·m)	App.Res. (field) (ohm·m)	Percent error
1	2.000	70.998	64.190	10.61
2	2.936	69.129	71.083	-2.75
3	4.309	65.107	70.992	-8.29
4	6.325	58.662	61.352	-4.38
5	9.283	51.856	50.308	3.08
6	13.626	48.185	43.841	9.91
7	20.000	50.356	49.180	2.39
8	29.356	60.990	64.109	-4.86
9	43.089	83.294	83.747	-0.54

(b)

Layer	Depth (m)	Thickness (m)	Resistivity (ohm·m)	Thick/Res (1/ohm)	Thick*Res (ohm·m²)
1	0.000	3.144	72.100	0.044	226.682
2	3.144	18.740	40.000F	0.468	749.600
3	21.884	INFINITY	3474.000	-	-
			TOTAL:	0.512	976.282

Table 3. *Inverse modelling for sounding <Field pt 1.dat> - Schlumberger array at "Malala 1".*

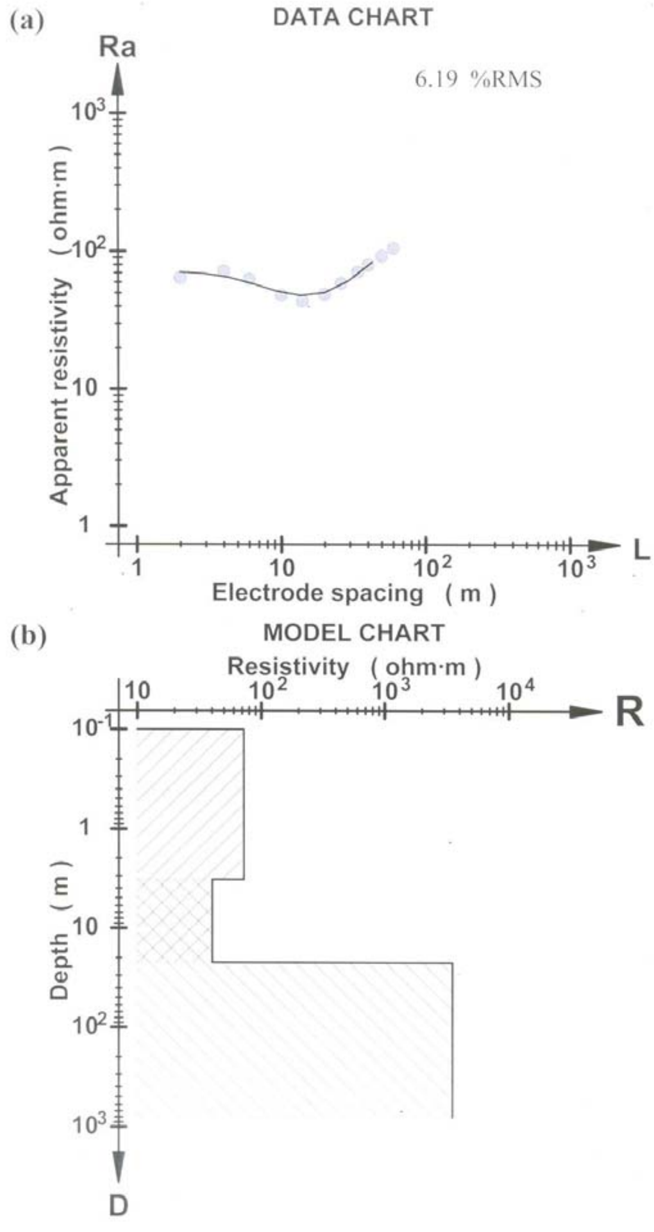

Figure 3. *Inverse modelling for sounding <Field pt 1.dat> - Schlumberger array at "Malala 1".*

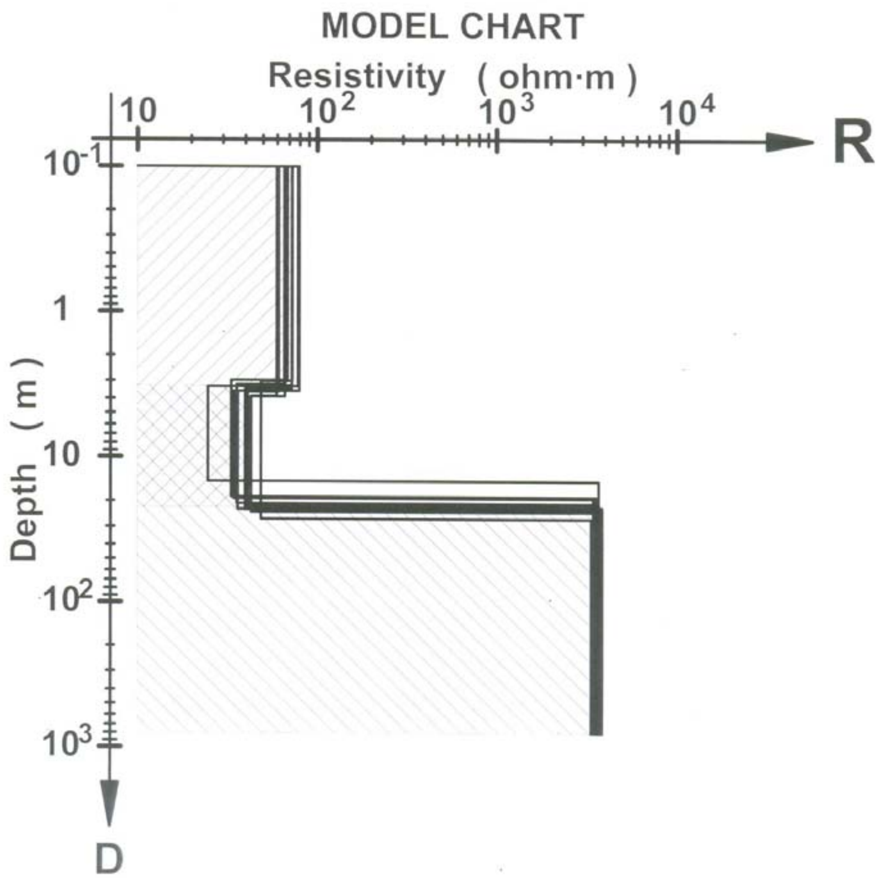

Figure 4. *Equivalence analysis for data <Field pt 1.dat> (cutoff 12.39%RMS).*

(a)

Layer	Thickness range (m)	Resistivity range (ohm·m)
1	2.86 - 3.76 (13.6%)	59.18 - 79.26 (14.5%)
2	11.29 - 23.43 (35.0%)	24.69 - 48.52 (32.6%)
3		3312.35 - 3818.45 (7.1%)

(b)

Layer	Transverse resistance (ohm·m²)	Longitudinal conductance (S)	Equivalence
1	194.73 - 271.01 (16.4%)	0.0402 - 0.0630 (22.0%)	UNIQUE
2	278.82 - 1136.77 (60.6%)	0.4256 - 0.5298 (10.9%)	SEVERE

Table 4. *Equivalence analysis for data <Field pt 1.dat> (cutoff 12.39%RMS).*