Evaluation of the Groundwater potential of the Malala alluvial aquifer, Lower Mzingwane river, Zimbabwe.

Taurai Henryback Masvopo [a1], David Love [b,c] and Hodson Makurira [a]

[a] *Department of Civil Engineering, University of Zimbabwe, P.O. Box MP 167 Mount Pleasant, Harare, Zimbabwe*

[b] *WaterNet, PO Box MP600, Mount Pleasant, Harare, Zimbabwe*

[c] *ICRISAT Bulawayo, Matopos Research Station, PO Box 776 Bulawayo, Zimbabwe*

Abstract

The largest river in the semi-arid southwest of Zimbabwe, the Mzingwane River, is ephemeral and thus can only supply water for a limited period of time during the year. This limited temporal availability of surface water can be mitigated through accessing water stored in the river bed: the alluvial aquifer. 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 sulphate water with no dominant metals. 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 and field tests gave an average porosity of 39 %, hydraulic conductivity of 37 m day^{-1}, specific yield value of 5.4 % and the slope of the aquifer was measured as 0.38 %. Resistivity surveys showed that the alluvial aquifer has an average depth of 13.4 m. The bedrock is metamorphic rock mainly tonalitic and granodioritic gneisses which have been intruded by a dolerite dyke. Water level observations from the installed piezometers indicated that the water levels dropped on average by 0.75 m within 100 days after the observed dam release. After any flow event in the Mzingwane River, approximately 135 ML of water per km stretch of the river is available for use by the communal farmers at Malala, with the potential of irrigating at least 13.5 ha a^{-1}. The frequency of such flows suggests the abstraction would be possible throughout the year. The alluvial aquifer can thus store a significant amount of water and has the potential to sustain both irrigation water supply throughout the year.

Keywords: alluvial aquifer, piezometers, resistivity, water balance

1. Introduction

[1] Corresponding author. Tel.: +26311437826 / +26323310614; Email.: masvopo@yahoo.co.uk / masvopo@cooltoad.com

The erratic rainfall pattern in the south-west of Zimbabwe limits the possibilities for rainfed agriculture. However, the largest river in the area, the Mzingwane River, is ephemeral and thus can only supply water for a limited period of time during the year. This limited temporal availability of surface water can be mitigated through accessing groundwater stored in the river bed: the alluvial aquifer. This stored water can therefore be considered an extension of surface flow (Mansell and Hussey, 2005). The alluvial aquifer of the lower Mzingwane River is recharged by the ephemeral surface flows. Commercial farmers in the valley below Zhovhe Dam access this water for irrigation of citrus, wheat, maize, cotton and vegetables (Love *et al.*, 2007). However, the smallholder farmers of Mtetengwe Communal Land, through which the Mzingwane River flows, have little access to such productive water resources – which is typical in Zimbabwe and is considered a significant constraint on rural development (Magadzire, 1995).

In this study, two coupled techniques were applied to locate and evaluate a potential site for alluvial groundwater development for smallholder farmers: (i) identification of hydrogeologically favourable conditions such as geological boundaries (Owen and Dahlin, 2005) and (ii) resistivity profiling (Israil *et al.*, 2006; Owen *et al.,* 2006). Monitoring groundwater levels and determining aquifer hydrogeological properties allowed for the groundwater potential of the aquifer to be developed. Given the constraint that water chemistry may impose on agriculture, especially water from alluvial aquifers (Love *et al.*, 2006) it is also necessary to establish the major ion chemistry of the water in the alluvial aquifer. The objectives of this study were therefore (i) to determine the groundwater yield of the alluvial aquifer after a managed dam release, (ii) to classify the groundwater hydrogeochemically and (iii) to determine the irrigation potential from the alluvial aquifer storage after a dam release or a natural flood event.

2. Methods

2.1 Study Area

The study area lies in the Mzingwane river catchment which is in the south-western part of Zimbabwe and is part of the Limpopo River Basin (figure 1). The study area lies in the agro-ecological region V which experiences considerable low average annual rainfall of approximately 350 mm/a compared with the national average figure of 675 mm/a for Zimbabwe (Meteorological Services Department, 1981). The selected study site at Malala (see figure 1) lies approximately 35 km downstream of Zhovhe dam. The alluvial aquifer system between Zhovhe dam and the Limpopo River is recharged artificially by water which is released from Zhovhe dam for Beitbridge town and commercial farmers, as well as by spillage from the dam and natural flow from tributary rivers.

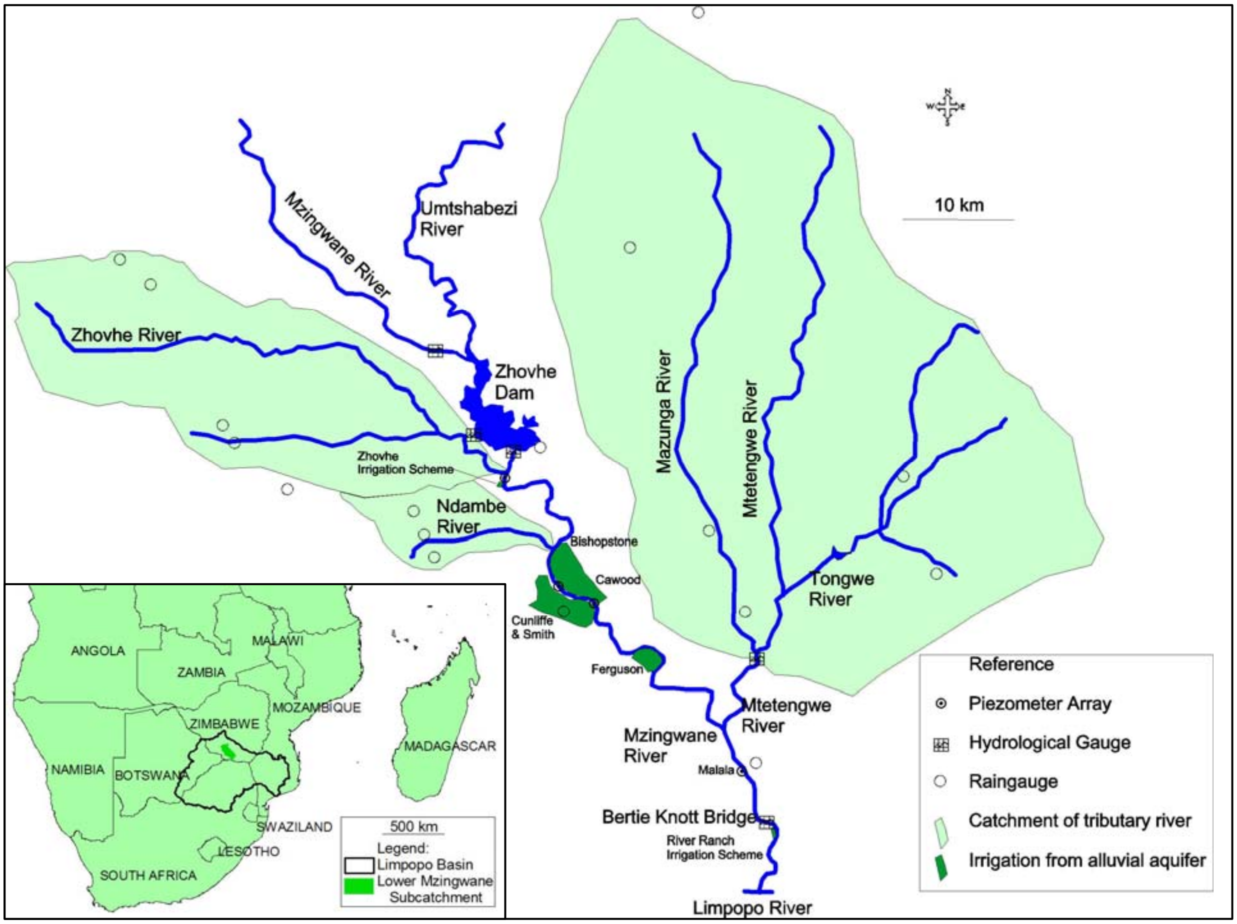

Figure 1. The Lower Mzingwane river system, showing the location of Malala and existing irrigation sites. Inset: location in Southern Africa

2.2 Reconnaissance

Owen and Dahlin (2005) have shown that alluvial aquifer development is pronounced at geological boundaries where there is a significant difference in the resistance to erosion of the lithologies in contact. The Mzingwane river valley was investigated in the Communal Lands between the downstream commercial farm (Ferguson, see figure 1) and Bertie Knott Bridge. Regional mapping showed the Mzingwane River being crossed by dolerite dykes, intrusive into the older gneisses at two sites (Watkeys, 1979). At each of the sites, resistivity measurements were made to determine the most favourable site (see section 2.3) and the Malala site was selected (section 3.1).

2.3 Resistivity measurements

In the resistivity surveys, a Terrametter SAS 300C geophysical equipment was used to determine the approximate depth of the sand (the depth to the bed rock). The Schlumberger (AB/2) electrode configuration was used. 24 resistivity soundings were observed at the study site. The apparent resistivity of the ground surface was computed and its variation was modeled with an increase in the depth of the ground formations. The apparent resistivity was computed using equation (1) (Breusse, 1963).

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

Where *p* = apparent resistivity (Ωm), *W* = potential electrode spacing (m), *L* = current electrode spacing (m) , *V* = voltage (V), *I* = current (A).

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. A forward modelling procedure is done were a sounding curve is produced for the initial earth model. The model proposed 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. 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. The final model gives a reasonable guide into the earth layering at the studied site. The various depths of the layers are therefore estimated and the depth to the bedrock can be estimated with reasonable accuracy.

2.4 Field mapping

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. Approximately 2 km^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.

A topographical survey was carried out using standard surveying procedures. The theodolite was 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. The measured difference in elevation was then divided by the horizontal distance between the two points to calculate the slope of the river bed.

2.5 Water level monitoring

Eight piezometers were installed into the Malala alluvial aquifer. The piezometers were driven into the sand to 3 m. Water level monitoring was carried out daily using an electric dip measure. A point on the river channel was set at an elevation of 100 m during the topological survey. Water levels were then calculated by subtracting the depth to the water level from the surveyed elevation at any one point.

2.6 Hydrogeological properties of aquifer material

The grain size distribution of a sample of aquifer material was determined by the sieve shaker model. The used sieves are US standard sieves with sizes 4000, 2800, 2000, 1000, 500, 250, 180, 125 and 32 µm. The samples were electronically weighed at an accuracy of 0.001 g. The hydraulic conductivity was then calculated using the Hazen (1892) method and the Alyamani and Sen (1998) method.

Porosity (*n*) was derived indirectly from an empirical relationship using the coefficient of grain uniformity (Vukovic and Soro, 1992).

For the calculation of the specific yield the saturated sand method was used: 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. The value of 2.65 was used for the specific gravity of sand. The specific yield was then determined using equation (2)

$$S_Y = \frac{M_W}{M_s / S_G} \qquad (2)$$

Where S_Y = Specific yield (g), M_W = Mass of water (g), M_S = Mass of sand (g), S_G = Specific gravity of sand (%).

Permeability was determined using the permeameter test, which is based on Darcy's law. The test works with a vertical slope i = 1. Sand was collected from the aquifer and placed into a bucket with a volume of 0.045 m^3. 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 was stuffed with gravel in order to prevent the sand from flowing out of the bucket.

$$K = \frac{Q}{Ai} = \frac{V/t}{\pi(0.5d)^2} \qquad (3)$$

Where, K = Hydraulic conductivity (ms^{-1}), Q = Flow rate or discharge (m^3s^{-1}), 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).

2.7 Hydrogeochemistry

Seven water samples were collected from the Mzingwane river system: four at the study site, two at Zhovhe dam and one from a well point at Mazunga which lies approximately 20 km upstream of the study site but downstream of Zhovhe dam along the Mzingwane river (see figure 1 for locations). Water samples were filtered to less than 0.2 microns and were analysed for sulphate (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 the National Water Quality Laboratory, Harare, Zimbabwe.

The sodium hazard in irrigation water is expressed by determining the sodium adsorption ratio (SAR) by the following relation (equation 4).

$$SAR = \frac{c(Na)}{\sqrt{\frac{c(Ca)+c(Mg)}{2}}} \qquad (4)$$

Where c(M) is the concentration expressed in milliequivalents per litre of cation M.

2.8 Groundwater potential of the Malala alluvial aquifer

The Malala alluvial aquifer was subdivided into 125 cells, each cell representing a 40 m by 40 m square. 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 (5).

$$GP = A \times d \times S_Y \times 10^{-3} \qquad (5)$$

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

Area *A* for each cell was 1,600 m^2. Depth *d* was determined from the resistivity surveys (section 2.3). Depth measurements were observed for 24 cells. The remaining depth estimations for the other 101 cells were estimated using the nearest neighbour analysis method. The specific yield S_y was determined in the laboratory (section 2.6). The groundwater potential of the Malala alluvial aquifer was then calculated by summing up the quantities from each of the 125 cells.

3. Results and Discussion

3.1 Reconnaissance

Two sites with suitable geological boundaries were selected: Malala and Massasanye. At both sites, a dolerite dyke crosses the Mzingwane River (Watkeys, 1979), thus giving the potential for a significant difference in the resistance to erosion at the contact, and thus greater depths upstream or downstream of the contact. Resistivity profiles carried out at the two sites showed a significantly greater depth to bedrock at Malala than at Massasanye (figure 2); on this basis Malala was selected for further study.

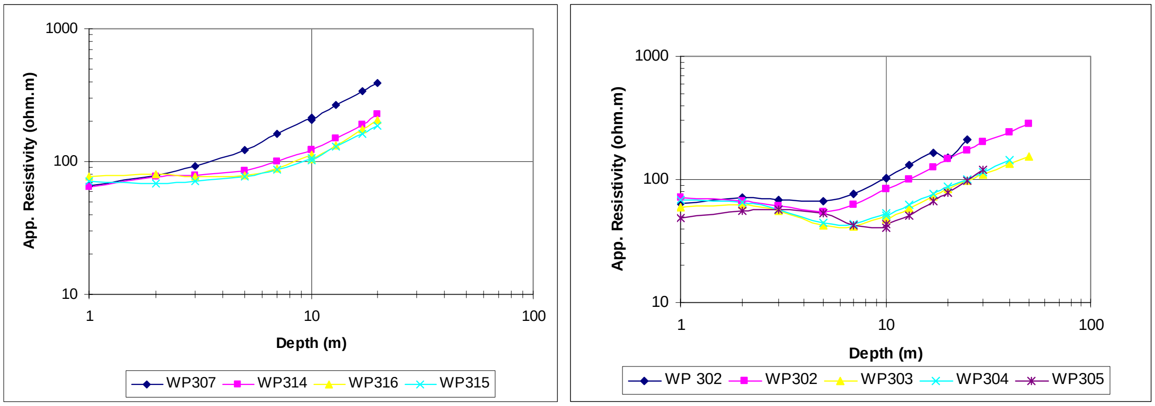

Figure 2. Resistivity results from the reconnaissance exercise, lower Mzingwane valley. The resistivity profile at Malala (right) indicates a much greater depth (20 m) than the 10 m at Massasanye (left), and on this basis Malala was selected for further study.

3.2 Resistivity

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 (figure 3). The results suggest that the aquifer on the upstream side of the dolerite dyke has a thicker sand layer as compared to the downstream section of the dolerite dyke, which is functioning as a natural sand dam on the upstream part of the alluvial aquifer. The upstream part is thus preferred for the installation of an abstraction unit.

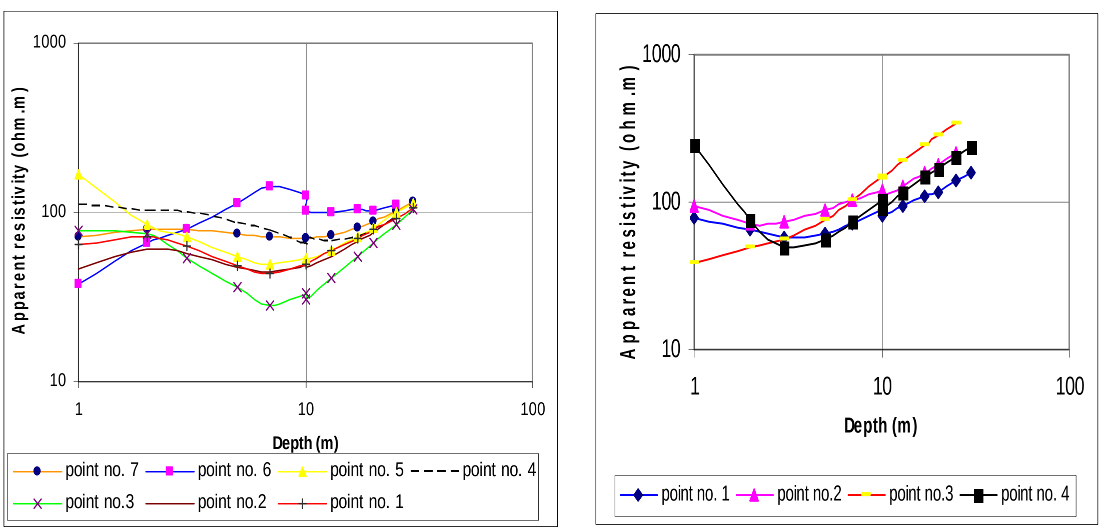

Figure 3. Resistivity profiles, Malala. (Left) upstream of the dolerite dyke; (right) downstream. Several measurements were made at each site. The upstream profile appears deeper.

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.

3.3 Field mapping

The geological mapping showed the geological setting of the alluvial aquifer. The river bed, which consists of an alluvial fill (the aquifer), is underlain by tonalitic and granodioritic gneisses. 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 gneisses due to their relatively old age of 2,690 ± 60 Ma (Watkeys, 1979) are expected to be weathered and fractured at depth. Therefore seepage losses are expected from the aquifer to the underlying rocks.

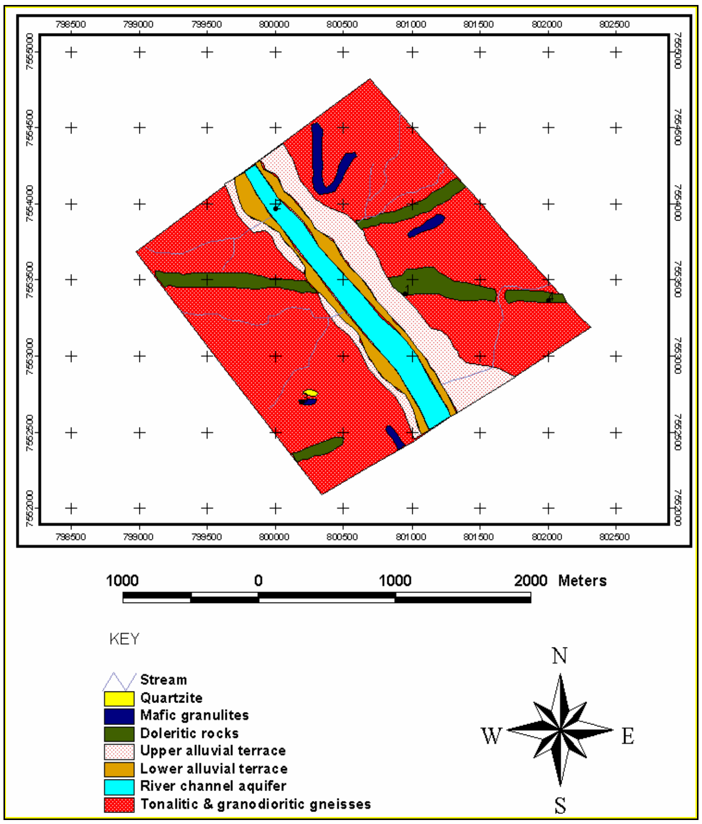

Figure 4. Geological map of the field study site, Malala, based on field mapping.

3.4 Water level monitoring

The alluvial aquifer was fully saturated for approximately 30 days (figure 5). After this water levels dropped below the full saturation level by an average of 0.5 meters, suggesting seepage losses of 5,400 m^3 or 3.7 % water losses from the total volume of the alluvial aquifer when fully saturated. This loss represents seepage to bedrock and evaporation, and the loss of 3.7 % is likely to be specific to the granodioritic and tonalitic bedrock or rocks of similar hydrogeological character.

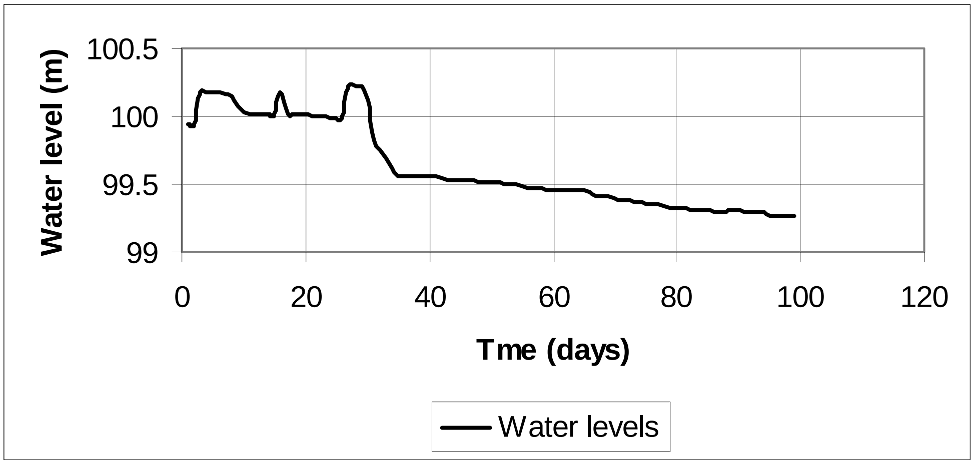

Figure 5. Observed groundwater levels at Malala, after flow in the Mzingwane River (spill of water from Zhovhe Dam).

3.5 Hydrogeological properties of aquifer material

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 (figure 6). At least 91 % of the alluvial aquifer material lies in the sand size region (between 0.0625 and 2 mm; Johnson, 1967).

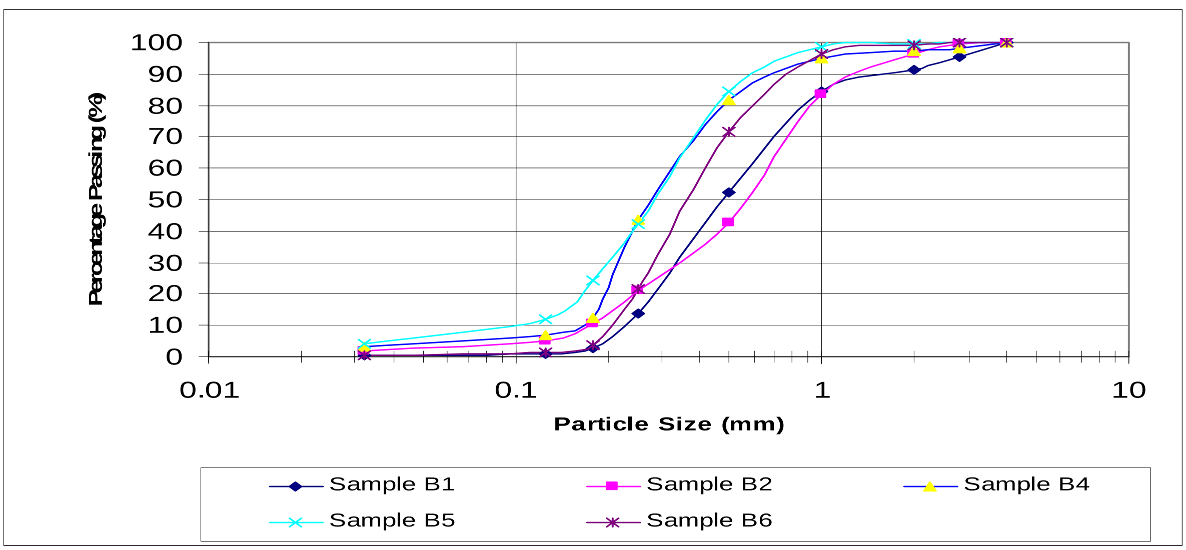

Figure 6. Grain size distribution curves for sand samples taken from the alluvial aquifer at Malala.

Using the Vukovic and Soro (1992) approach the average porosity, based on the grain size distribution of the five samples, was 40.8%. Standard laboratory methods gave porosities of 38.2 % and 38.1%. Thus an average porosity for the alluvial aquifer using the three methods is estimated at 39%, comparable to previous values determined for sands in this river system: 30 % by Moyce *et al.* (2006) and 35 % by Nord (1985) and Owen (1992).

The saturated sand method (table 1) gave a specific yield value of 5.4 % using equation (2) The specific yield derived for this river section is low: 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. This is quite a low value, compared to 20 % from Nord (1985) and Owen (1992), and indicates high clay content. It is comparable to that of Johnson (1967) for sandy clay.

Table 1: Calculation of the specific yield of the aquifer

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

Hydraulic conductivity estimated from grain size distribution, gave a range from 17 to 61 m day^{-1} (table 2), and with average values of 38 m day^{-1} from the Hazen (1892) method and 30 m day^{-1} from the Alyamani and Sen (1998) method. The permeameter test (table 3) gave a range of 43 to 45 m day^{-1} and an average of 44 m day^{-1}. The overall average hydraulic conductivity is thus 37 m day^{-1} or 0.043 cm s^{-1}, which is at the lower end of the range proposed by Bear (1972) for good aquifer material and well sorted sand.

Table 2. Hydraulic conductivities estimated from grain size distribution using empirical formulae of Hazen (1892) and Alyamani and Sen (1998).

Sample	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	U	I_o (mm)	n	Hazen (m day^{-1})	Alyamani and Sen (m day^{-1})
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

Table 3: Hydraulic conductivities determined using the permeameter test. V = volume, t = time, Q = discharge, A = area, K = hydraulic conductivity.

V(m^3)	t (s)	Q (m^{3}day^{-1})	A (m^2)	K (m day$^{-1)}$
0.01	134	6.45	0.16	41.5
0.015	194	6.68	0.16	43.0
0.02	253	6.83	0.16	43.9
0.025	313	6.91	0.16	44.4
0.03	374	6.93	0.16	44.6
0.035	434	6.97	0.16	44.8
0.04	494	7.00	0.16	45.0
0.045	555	7.01	0.16	45.0

3.6 Hydrogeochemistry

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 4 below and on a piper diagram in figure 7, showing a composition dominated by sulphate, but with no dominant metal. Sodium levels are higher at Malala than elsewhere.

Table 4. Chemical composition of groundwater in the alluvial aquifer at Malala (B1, B2, B5 and B6), at Mazunga (MAZ, for location see figure 1) and surface water at Zhovhe dam (ZH1, ZH2).

Sample Number	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	20.44	16.78	5.00	43.67	176.00	73.00	213.50	<0.01
B2	23.55	13.33	4.33	25.56	169.00	53.00	213.50	<0.01
B5	35.44	17.67	9.00	31.11	167.00	68.00	237.90	<0.01
B6	25.09	20.33	5.67	45.44	162.00	38.00	213.50	<0.01
MAZ	22.55	13.00	2.56	19.20	143.00	8.00	149.45	<0.01
ZH1	13.55	5.22	4.44	8.91	159.00	3.00	100.65	<0.01
ZH2	19.44	5.83	4.44	9.08	157.00	3.00	122.00	<0.01

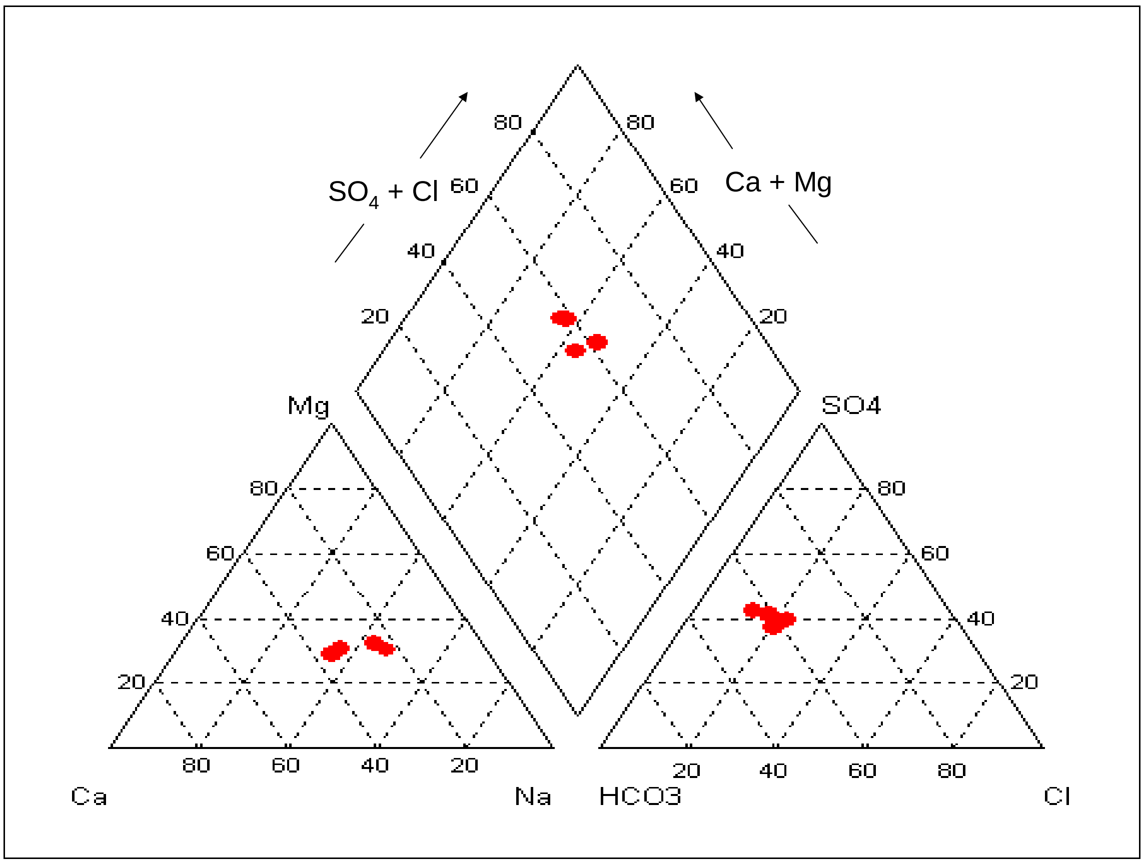

Figure 7. Piper plot of Malala alluvial aquifer water chemistry

Chloride concentration shows great variation (figure 8), with much higher levels being recorded at Malala than elsewhere. These high levels – together with the slightly higher sodium concentrations - are similar to those reported by Love *et al.* (2006) from alluvial plains upstream of Malala, suggesting interaction between the riverbed aquifer at Malala and older alluvial material. However, all levels are below the maximum recommended level for irrigation of 100 mg/l chloride (DWAF, 1996).

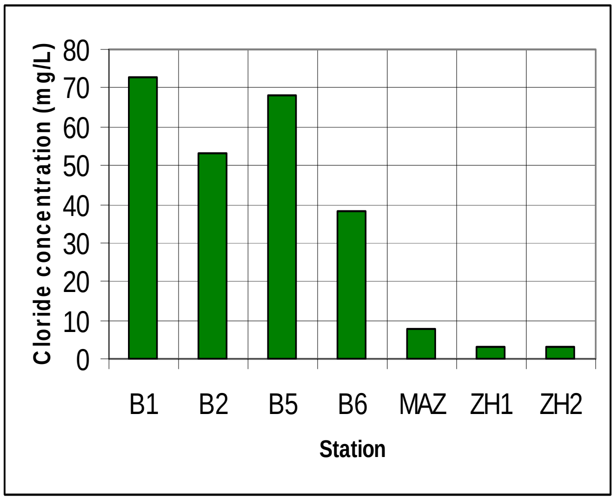

Figure 8. Chloride concentrations in the alluvial aquifer at Malala (B1, B2, B5 and B6), at Mazunga (MAZ, for location see figure 1) and surface water at Zhovhe dam (ZH1, ZH2). Note the substantially higher concentrations at Malala.

The sodium hazard in irrigation water is expressed by determining the sodium adsorption ratio (SAR). SAR = 1.37 was derived for the water at the Malala alluvial aquifer. According to Richards (1954) classification, the water in the aquifer is of a very low sodium hazard and can thus be used for irrigation without posing much risk to the permeability of the soils.

3.7 Groundwater potential of the Malala alluvial aquifer

The total yield of 1 km length of the aquifer when it is fully saturated is calculated, using equation (5) as 145 ML. Based on the observed water levels after a flow event, it is clear that the water level 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 13.5 ha per year – based on smallholder irrigation demand of 10 ML ha^{-1} a^{-1} (Ministry of Local Government Rural and Urban Development, 1996), provided that the water is available throughout the year.

To ensure sustainability of 135 ML of water supply, a flow event is needed approximately every 100 days. Examination of records from Zhovhe Dam reveal that, since the dam's construction in 1995, at least one spill event or managed release from the dam can be expected in a given three month periods. This is also confirmed from flow records at Bertie Knott Bridge, downstream of Malala (see figure 1). The frequency of such flows satisfies the need for a flow event at least every 100 days to recharge the aquifer at Malala.

4. 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 on the Mzingwane River, approximately 135 ML of water per km stretch of the river can be available for use by the communal farmers at Malala, and the frequency of such flows suggests the abstraction would be possible throughout the year. The major significance of alluvial aquifers, such as at Malala, is thus their ability to act as natural water harvesting formations. They can store water which can be utilized in future drier periods. Although greater salinity (sodium and chloride) was observed at Malala than at Zhovhe Dam, it is not high enough to be a problem for irrigated agriculture.

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.

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