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Estimating Hydraulic Properties of Alluvial Sand Aquifer in Motloutse River course, Eastern Botswana

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Abstract

A single layered alluvial aquifer in Botswana along the Motloutse River catchment was studied to estimate its hydraulic properties. Ground Penetrating Radar Survey (GPR) was used to determine the thickness and porosity of the aquifer. Specific yield of the aquifer was determined in the laboratory. The hydraulic conductivity of the riverbed sediments were estimated using the Alyamani-Sen empirical formula and the hydraulic conductivity of the river bank sediment was measured using the slug test. Geologically, the area is consists of alluvial deposits overlying granite, which is the bed rock of the area. The geophysical survey, GPR, provided information on the range of the thickness of the alluvium (9 – 12m) and also the porosity of the sediments (40%). The laboratory test resulted in an average specific yield of 13.68% for the riverbed sediments and 8.84% for the river bank sediments. A slug test performed in the riverbank yielded estimates of hydraulic conductivity of 26.43m/day. An average hydraulic conductivity value of 160m/day for the riverbed sediments was determined using the Alyamani-Sen formula. This difference in the hydraulic properties of the riverbed and the riverbank sediments is likely to be a result of sediment heterogeneity as more fine grained sediments is found together with sand in the riverbank sediments. These combined hydraulic properties estimation using empirical formulas, geophysical survey, laboratory tests, and the slug test highly improved the understanding of the hydrologic properties of the single layered alluvial aquifer system in the Motloutse River catchment. In the same area, groundwater resource modelling can be done using these aquifer parameters to determine the groundwater potential of the aquifer.

Keywords: Alluvial aquifer, Botswana, Groundwater, Hydraulic properties, Motloutse River.

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Contents

1. Introduction

1.1. General

Botswana is a semi-arid country with subdued topography, low surface runoff, and low groundwater recharge [1]. Rural communities in Botswana rely on agriculture for income, food and employment. The farming activity is sustained with rain-fed agriculture, which is affected by harsh climatic conditions. However, in eastern Botswana, ephemeral sand rivers constitute a large source of groundwater [1, 2] which may be useful for irrigation. Rainfall over the Motloutse catchment area occurs in summer, and mean monthly evaporation exceeds mean monthly rainfall. Communities within the river catchment depend on the river to sustain their agricultural needs.

The geology of the area is consists of alluvial deposits overlying the granite, which is the bed rock of the area. The alluvial deposits or the Motloutse sand river consists mainly of sand and gravel at variable depth, with coarse sand along the middle of the river and silt and clay occurring adjacent to river banks. The alluvial sediments in the flood plain are a source of water for the different needs of the community during the dry months. The aquifer is unconfined and receives recharge from the river flow and direct percolation.

The hydrogeological characteristics of the Motloutse alluvial aquifers are not documented [3] and effective water management, water storage planning and management are hampered by the lack of knowledge of their storage properties. This complicated by the varying thickness of the river sand, river morphology, and the increasing demand from the community. Groundwater potential of the Motloutse alluvial aquifer was investigated to support irrigation development and to improve the livelihoods of the communal farmers. The main objective of this work was to determine the different hydraulic properties of the Motloutse alluvial aquifer on a one kilometre stretch of the Motloutse River that can be used to quantify the groundwater resource potential in the area.

1.2. Location

The study area is located in eastern Botswana near the Mmadinare, Tobane and Bobonong villages (Figure 1). It lays along the Motloutse River, downstream of the Letsibogo dam in the Motloutse catchment, a sub-catchment of the Limpopo basin. Four countries in south-eastern Africa share the Limpopo basin: Botswana, Mozambique, South Africa and Zimbabwe.

The majority of the Motloutse catchment is characterised by flat savannah and, although devoid of major mountains, few hills are present in the catchment. It is ~20, 000 km^2 in area and the Motloutse river has a stream length of ~250 km in an east-west trend with the tributaries trending north-south (Figure 1). The main land use is subsistence farming with vast areas of land used as grazing growing crops.

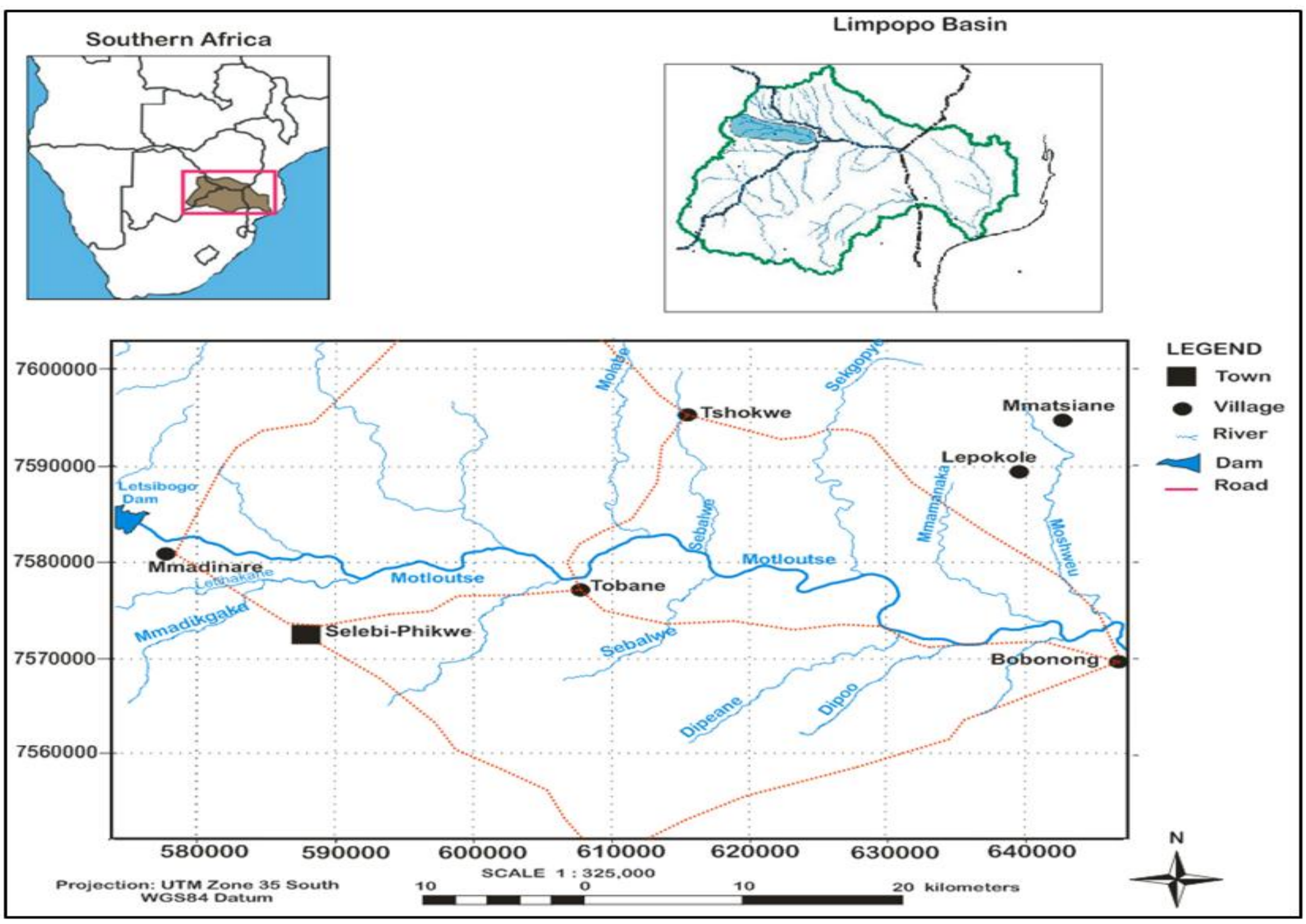

Figure-1. Location map of study area within Southern Africa and Limpopo basin.

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

2. Methodology

Ground Penetrating Radar (GPR) was used to map the depth to bedrock across the Motloutse River, and indirectly the thickness of the sand within the channel.

Ground Penetrating Radar (GPR) is a geophysical method used to detect and map shallow subsurface features with high precision. It is similar in many respects to seismic reflection and refraction methods but it utilizes electromagnetic waves to reflect, refract, and diffract from subsurface targets instead of acoustic waves.

The choice of location for the GPR profiles was based on the width, access, and slope of the riverbed. Five (5) radar transects across the Motloutse river were recorded near Tobane village (Figure 2). These profiles were trending north-south and their length was determined by the river width ranging between100 and 135m. These transacts were spaced at 250m as illustrated in Figure 2. Along each of these profiles, elevations and coordinates were captured with Trimble Differential Global Positioning System (DGPS) from the two (2) banks and along the middle section of the river for topographic corrections. The radar grid was confined to the channel width and not extended to the alluvial plains due to riverine vegetation that impedes access. Optimum offset GPR reflection profiles were recorded along the profiles using a 50 MHz Ramac™-Mala Geoscience™GPR system with unshielded antennae. The antennae's were kept at a constant separation of 2 m with a wooden raft. The antennas were orientated parallel to each other and perpendicular to the profile. To improve the signal to noise ratio every trace was vertically stacked sixteen (16) times. A hip chain with a bio-degradable thread was used to measure the profile length. The velocity of the profiles was recorded directly from the display device at 59m/µs. This value was be used to calibrate the processing software packages so that correct depths are determined.

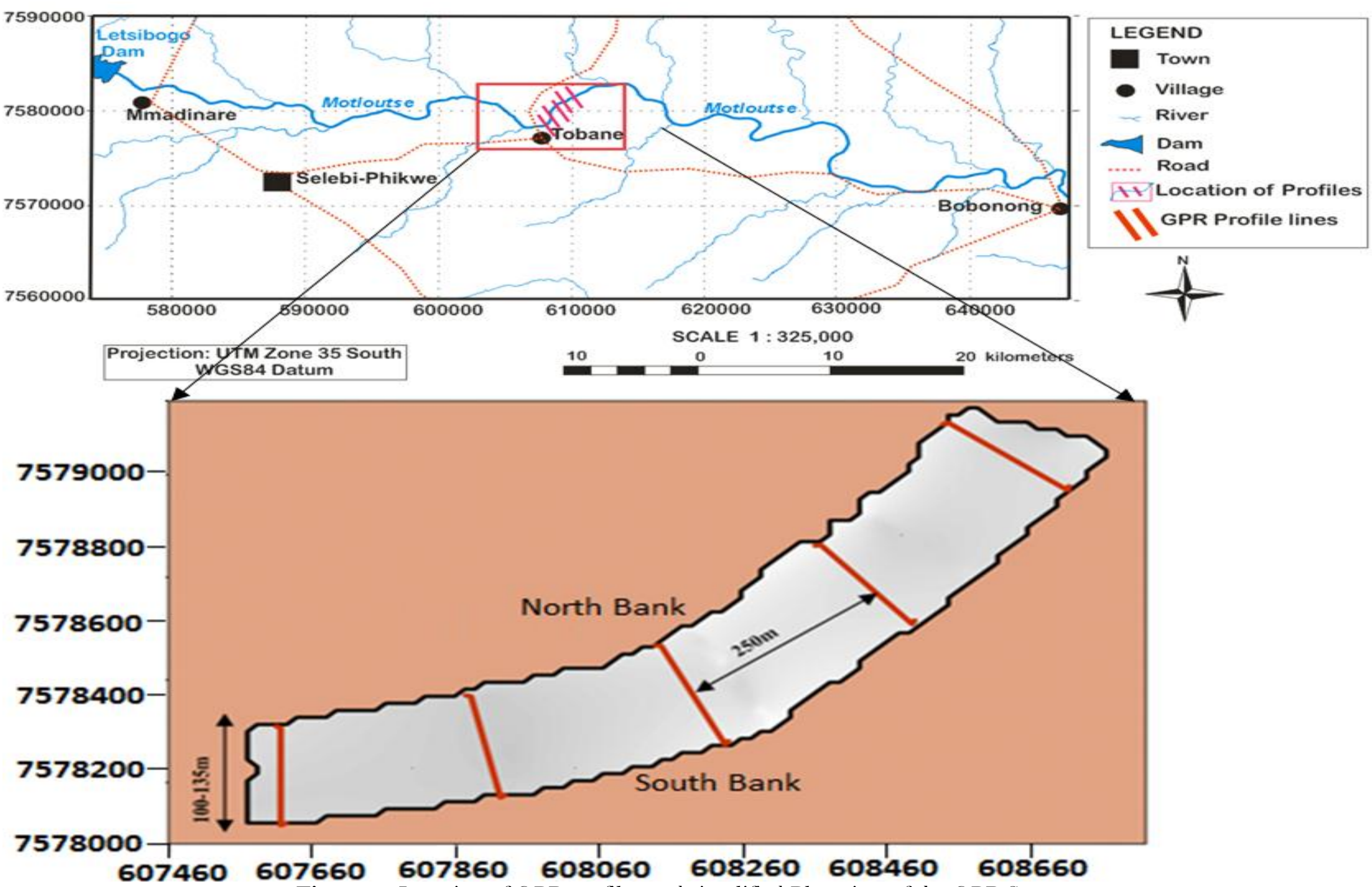

Figure-2. Location of GPR profiles and simplified Plan view of the GPR Survey.

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

Apart from the basic detection and mapping of subsurface geological features, GPR measurements can also be used to determine hydraulic properties of porous materials such as porosity, hydraulic conductivity, water saturation, etc. as has been shown in numerous previous investigations [4-9]. This is because related parameters such as dielectric constant and radar wave velocity are highly dependent on moisture content. In low loss medium (soils with low salinity and clay content) which is expected of river sand, the velocity (V) of the soil can be related to the dielectric constant by Eq. 1 [10].

$$V = \frac{c}{\sqrt{K'}} \qquad (1)$$

Where c is the electromagnetic wave velocity in free space, and K' is the real part of the dielectric constant of the medium.

Velocity of 0.06m/ns that was read from the Ramac Mala Geoscience display device which is also in conjunction with velocity for unsaturated sands was used and dielectric constants read from tables of dielectric constants for different materials [10, 11]. Topp, et al. [7] using various soil samples found out that the real part of the dielectric constant was increasingly sensitive to volumetric water content, while also weakly sensitive to soil type and density and derived an empirical relationship (Eq. 2) between apparent dielectric constant and volumetric water content:

$$\theta_v = -5.3\,X\,10^{-2} + 2.92\,X\,10^{-2}K_a - 5.5\,x\,10^{-4}K_a^2 + 4.3\,X\,10^{-6}K_a^3 \qquad (2)$$

Where θ_v is the volumetric water content (the ratio of water volume to total sample volume). For low-loss materials Ka ≈ K' where Ka is the apparent dielectric constant and K'is the real part of the dielectric constant of the medium as it was defined in Eq. 1.

The water content (θ_v) equals the product of porosity ($\emptyset$) and water saturation (S_w) as in Eq. 3 [5].

$$\theta_v = \emptyset S_w \qquad (3)$$

Where w**ater** saturation $(\boldsymbol{S_w})$ is the ratio of water volume to pore volume.

However in water saturated soils the water content (θ_v) is a measure of porosity ($\emptyset$), that is, $\theta_v \approx \emptyset$.

After ground penetrating radar survey, as a ground-truth control the Motloutse River was augered at the sites where GPR data was collected. The riverbed was augered to a depth of 3.5m and the water was striked at a depth of 0.6m. Augering to a further depth was not possible because the auger tool itself nearly got damaged, any further twist it would have broken. It was initially a pit was dug to a depth of about 2m using shovels and from there the auger was installed but the water that was collected in the pit was too much and hindered the augering process.3.5 m is not the exact thickness; the sand is much thicker than this amount. However, the thickness of sand is not uniform throughout the area where this measurement was conducted; the riverbed in some areas had deeper sand thicknesses and the augering was done in areas were the sand is thinner.

The specific yield of the sandy aquifer was determined in the Engineering Geology laboratory of the Department of Geology in the University of Botswana. Specific yield is the ratio of water that can be drained by gravity from a saturated sample to the total volume of sediment in laboratory terms. Freeze and Cherry [12] defined it as the amount of water released from storage of an unconfined aquifer per unit surface area of the aquifer per unit decline of the water table. Specific yield is given by Eq. 4 after Meinzer [13].

$$S_y = \frac{V_d}{V_t} \quad (4)$$

Where Sy is specific yield, V_d is volume drained from aquifer by gravity; and, V_t is total volume.

Nine sand samples representative of the aquifer material were collected both from the riverbed and at the riverbanks for this purpose. Out of these samples 5 of them were from the riverbed and the remaining four were from the riverbank (Figure 3). Samples were obtained from a depth of 2 and 3 m on the aquifer to avoid surface sampling, this is due to some physical and biological processes such as surface shrinkage, silty layers or lenses referred to as "planosols" that result in varying aquifer properties [14].

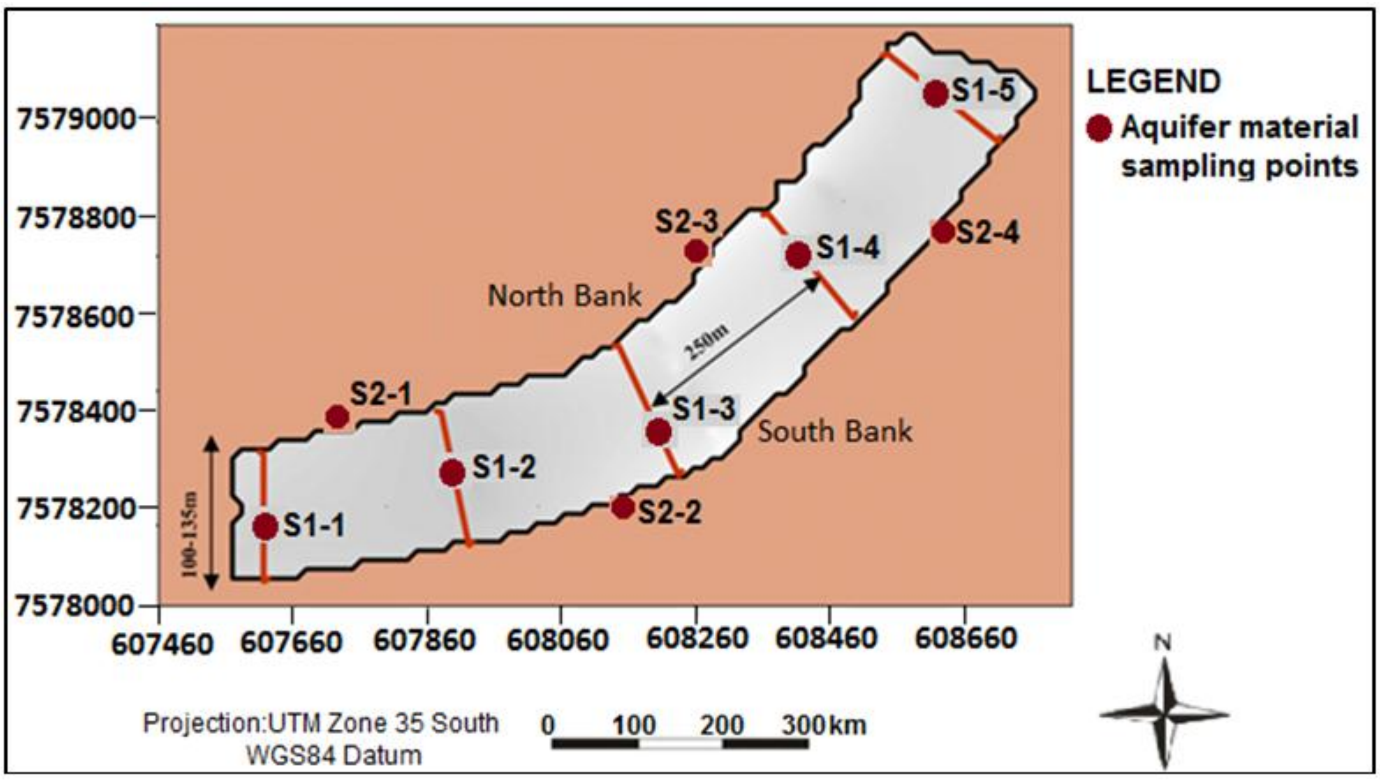

Figure-3. Location of aquifer material sampling sites in relation to GPR profiles.
Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

The hydraulic conductivity of the sediments was determined using an empirical formula and the slug-test method.

For the riverbed, the hydraulic conductivity of the sandy aquifer was determined by empirical formula using the collected riverbed samples. The method used in this study is the Alyamani-Senempirical formula, which is given by Alyamani and Sen [15] as

$$K = 1300[I_o + 0.025(d_{50} - d_{10})]^2 \quad (5)$$

Where K is hydraulic conductivity (m/day), I_0 is intercept (in mm) of the line formed by d_{50} and d_{10} with the grain-size axis, or simply the x-axis, d_{50} is median grain diameter (mm), and, d_{10} is effective grain diameter (mm).

The Alyamani and Sen [15] formula was chosen because the equation considers both sediment grain sizes as well as the sorting characteristics.

Grain size analysis of the sediment was done in accordance to the ASTM D-422 or D2487 standard (American Society for Testing and Materials) and Unified Soil Classification System (USCS) as both are the most widely used technical standards.

To determine the hydraulic conductivity of the riverbank sediments an in situ measurement was carried out using Slug test. The test was carried out as follows.

- A one metre PVC tube was pressed vertically into the aquifer until the slots in the tube were submerged under the water level;
- The tube was submerged up to 24cm under the water level with 76cm remaining over the water table;
- Sufficient water was then poured into the tube until it reached top of the tube and this is to ensure the saturation of a large area of the aquifer around and below place of measurement; and,
- Time taken for the head to fall or attain initial water level was recorded.

K from Slug test was estimated using Eq. 6 after Masvopo, et al. [16] as follows;

$$K = \frac{Q}{A_i} = \frac{[\pi R^2 h]}{T[2\pi RH + \pi R^2]} \quad (6)$$

Where K is hydraulic conductivity (m/day), Q is discharge (m^3/day), A is cross sectional area of soil sample (m^2), i is hydraulic gradient, R is radius of tube (m), T is time taken for water column to attain initial water level (day), and, H is length of PVC tube under the water level (m).

3. Results and Discussions

3.1. Geophysics

Even though five radar transacts were recorded and analyzed only two of them are presented here for the purpose of discussion. This radar transacts were the one that was recorded at the beginning (Figure 4) and in the end (Figure 5) of the measurements; recorded in the downstream and upstream side of the river, respectively, or at the site from where the soil samples S_{1-1} and S_{1-5} (Figure 3) were collected. These figures show both the raw radar images (Figure 4A and Figure 5A) and the migrated radar images (Figure 4B and Figure 5B) in these sites. In the Figure 4B the migration was accomplished using a DC permitivity value of 65 (dielectric constant) whereas in Figure 5B migration was done with a dielectric constant of 70.

The first reflections in all the figures are a characteristic airwave and groundwave, respectively. This is caused by the direct electromagnetic wave interaction with air, and is represented by black, continuous reflection amplitudes that form a very straight, horizontal solid bar as on in Figure 4A and 5A. Below the groundwave reflection is the unsaturated zone of the sediment, interpreted as the unsaturated sand.

The next two or three prominent (three in Figure 4A and 2 in Figure 5A), high amplitude reflections that are easily identified and traced across all the radar records are interpreted as the water table. This is because in sediments, the water content primarily causes the changes in dielectric properties [17]. A change from dry to wet sand results in a change from a three- phase system (air, water and sediment) to a two- phase system (water and sediment) in which other factors apart from porosity control the dielectric properties [18].

Further down the profile after the water table, the next reflections are generally weak in all the radargrams (Figure 4A and Figure 5A) but follow a similar trend to it. Since attenuation is strong below this point this could be indicative of groundwater. Conyers [19] affirms that the water content often increases with depth resulting in attenuation of radar waves with increasing depth. These stronger groundwater reflectors could be related to sediments that have a larger sand fraction at depths: suggesting to be bounding surfaces between two sand layers of different periods of deposition.

Below these reflections, no further reflections are observed in wiggle form in all radargrams; suggesting a marked change in reflective characteristics. This is interpreted as an interface between the sediments and the bedrock because at the resolution used, radar signals will not be able to penetrate the granite bedrock. However, this not at achieved at the same depth in all the profiles. As shown in Figure 4B on the migrated image that the sand thickness reaches up 12 m whereas in the upstream side the sand thickness is less and reaches up 9 m (Figure 5B).

The GPR results obtained match or corroborate with the augering findings. As earlier noted from augering observation the sand was much thicker than 3.5 m. Based on water strikes the water levels seem to be a bit shallower from those in GPR interpretations because at the time of augering it was already rainy season.

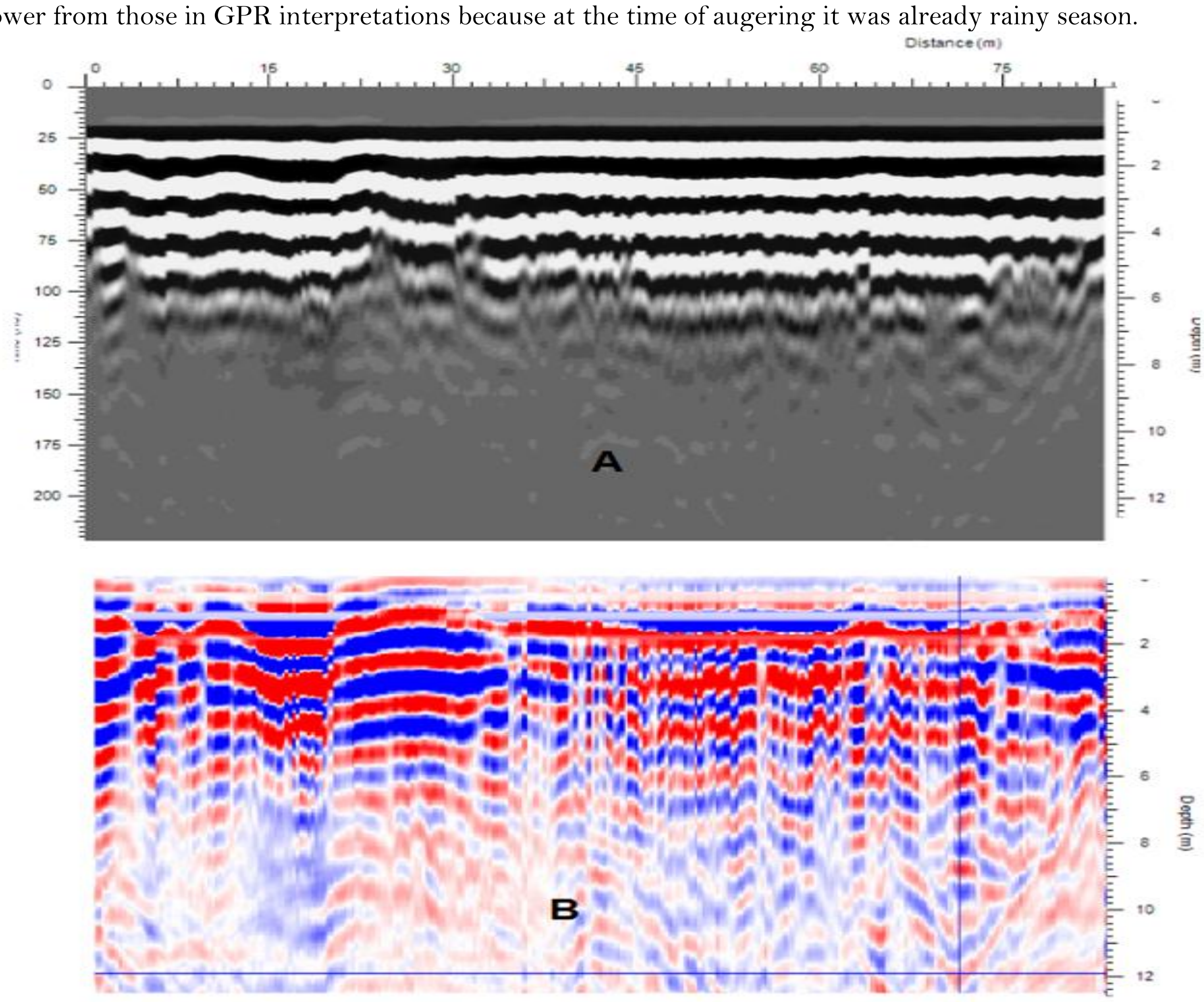

Figure-4. A) The raw radar image before migration; B) The migrated radar image.
Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

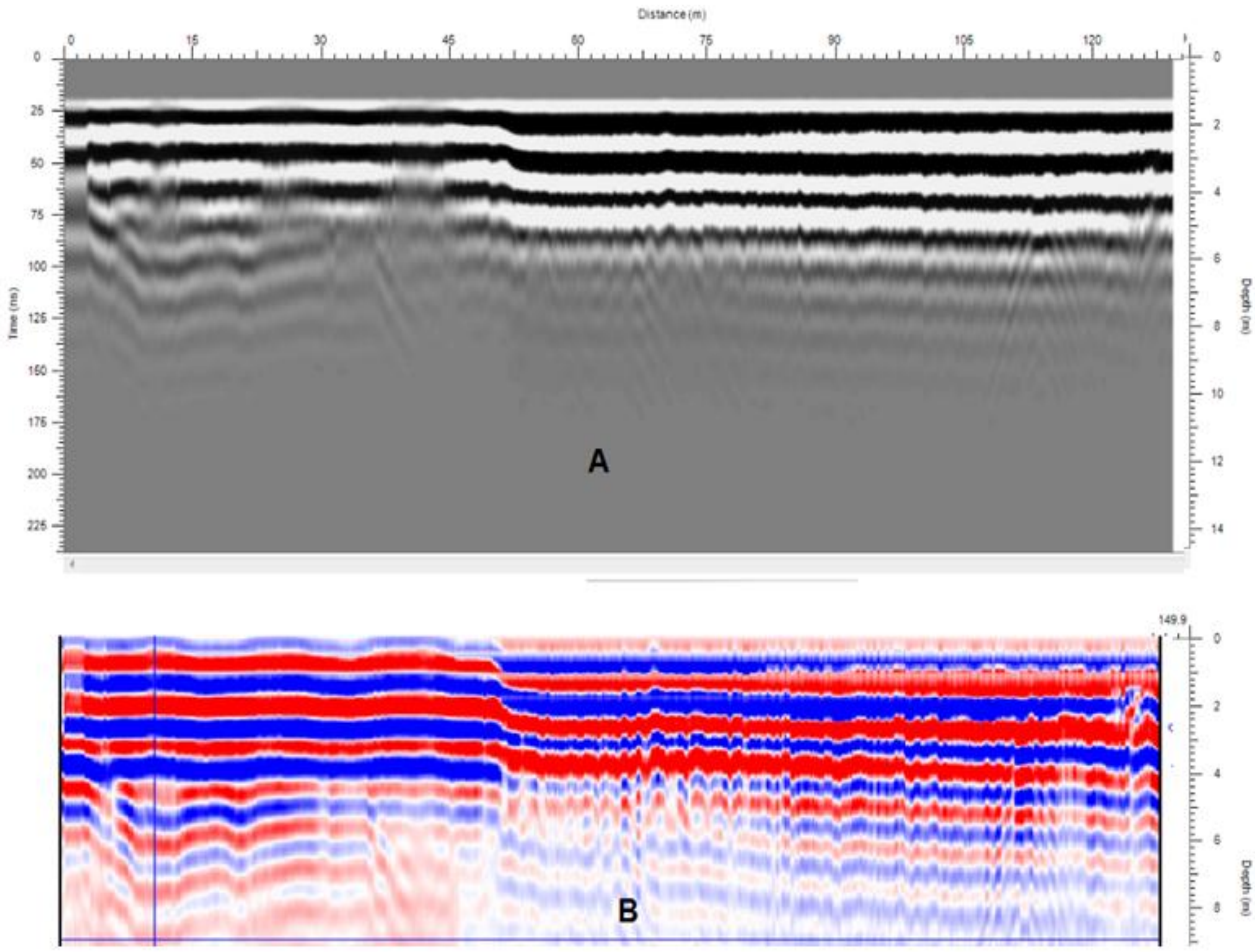

Figure-5. A) The raw radar image before migration; B) The migrated radar image.
Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

3.2. Aquifer Parameters
Porosity

Porosity was found to be 40% determined from the Ground Penetrating Radar. This high porosity value is expected for river sands and for clays and silts from riverbank samples. It is also within the range of values reported in the literature for such materials. Representative porosity values for various unconsolidated sedimentary materials, sedimentary rocks and crystalline reported by Morris and Johnson [20] stated that the range of porosity for coarse sand to clay is from 31 % to 57%. According to Freeze and Cherry [12] the range of porosity values for sand, silt and clay is from 25% to 70%. Nord [21] obtained a porosity of 35% for Motloutse River sand.

Specific Yield

Table-1. Computation of specific yield.

Sample ID	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
S1-1	476.40	33.80	442.6	464.24	430.44	12.16	7.49
S1-2	521.07	32.65	488.42	486.65	454.00	34.42	20.09
S1-3	494.06	32.65	461.41	460.78	428.13	33.28	20.60
S1-4	452.32	33.80	418.52	434.04	400.24	18.28	12.10
S1-5	480.35	33.80	446.55	467.05	433.25	13.3	8.14
S2-1	527.38	32.65	494.73	501.62	468.97	25.76	14.56
S2-2	476.96	33.80	443.16	464.35	430.55	12.61	7.76
S2-3	501.43	33.80	467.63	476.25	442.45	25.18	5.69
S2-4	485.96	32.65	453.31	455.01	422.36	30.95	7.33

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

Specific gravity of sand was taken as 2.65 because river sand has the main component as quartz and this value is applicable to sands that are not packed. An average specific yield of 13.68% for samples collected only on the riverbed was found (Table 1), which is low for this river section as compared to that derived by Nord [21] of 20% and very low for a typical sand formation which has a range of 21 to 27% [22]. An average specific yield for the river bank sediments is much lower than the riverbed one. However, both these values will give a conservative estimate of the groundwater resource.

Hydraulic Conductivity

In the analysed sediment samples, the grain size ranges from 0.008mm to 10 mm in diameter as can be seen in Figure 6, which is a very wide range attesting to the poorly graded sand and the heterogeneous nature of the aquifer. The median (d_{50}) and effective grain diameter (d_{10}) are 1.6 and 0.4, respectively. According to the Unified Soil Classification System [22] the Motloutse sediment is poorly graded sand with gravel or gravelly sand.

Table-2. USCS classification of aquifer material samples.

Sample ID	S1-1	S1-2	S1-3	S1-4	S1-5
Per cent fines	0.14	0.1	0.1	0.3	0.2
Per cent sand	95.8	81.8	79.1	97.3	81.1
Per cent gravel	3	7.7	16.3	1.4	18.7
C_c	1.16	0.89	0.98	0.89	0.88
C_u	3.2	4.5	4.7	3.2	4.3
USCS classification	SP	SP	SP	SP	SP

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

WhereC_c is coefficient of curvature; C_u is coefficient of uniformity; and, SP is poorly graded sand. Coefficient of curvature, Cc, is the ratio $(D_{30})^2/(D_{10} \text{ x } D_{60})$,where D_{60}, D_{30}, and D_{10} are the particle sizes corresponding to 60, 30, and 10 % finer on the cumulative particle-size distribution curve, respectively.

Coefficient of uniformity, Cu, is the ratio D_{60}/D_{10}, where D_{60} and D_{10} are the particle diameters corresponding to 60 and 10 % finer on the cumulative particle-size distribution curve, respectively.

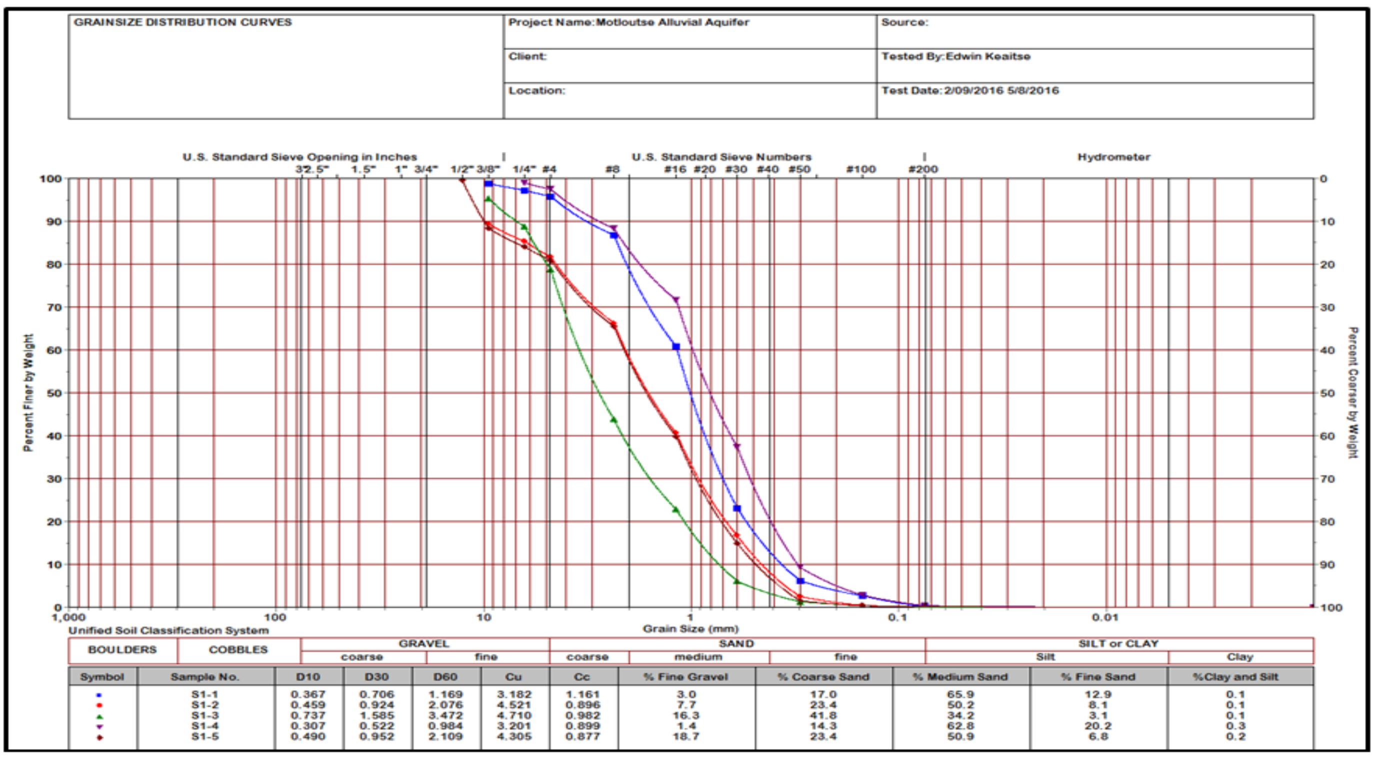

Figure-6. Grain size distribution curve of the Motloutse sediments.

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

Hydraulic conductivity using Alyamani-Sen formula

Table-3. Computed hydraulic conductivity values using Alyamani-Sen formula.

Sample ID	d_{10}	d_{30}	d_{60}	C_u	C_c	Io	Hydraulic conductivity (m/day)
S1-1	0.3	0.7	1.1	3.2	1.1	0.3	113.9
S1-2	0.4	0.9	2.1	4.5	0.9	0.3	144.8
S1-3	0.7	1.6	3.4	4.7	0.9	0.5	443.1
S1-4	0.3	0.5	0.9	3.2	0.8	0.3	89.6
S1-5	0.4	0.9	2.1	4.3	0.8	0.3	161.9
K mean = 160.4							

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

An average hydraulic conductivity value of 160m/day (1.856 x 10^{-3}m/sec) for gravelly sand was determined using Alyamani-Sen formula. This value is within a reasonable range of values of hydraulic conductivity for gravelly sand. Representative values of hydraulic conductivity for various unconsolidated sedimentary materials, sedimentary rocks, igneous and metamorphic rocks complied by Freeze and Cherry [12] shows that the values of hydraulic conductivity for gravelly sand is ranging from 1.157 x 10^{-4} to 1.157 x 10^{-1} m/sec.

Hydraulic conductivity from Slug test

Table-4. Hydraulic conductivity from Slug test.

Sample ID	Radius(m)	h(m)	T(s)	H(m)2	K(m/s)	K(m/d)
S2-1	0.01	0.76	29	0.24	0.000166776	14.40947992
S2-2	0.01	0.76	2000	0.24	0.000378298	32.68491787
S2-3	0.01	0.76	3500	0.24	0.000534835	46.20971147
S2-4	0.01	0.76	6000	0.24	0.000143613	12.40816327
K mean						**26.43**

Source: Edwin O.K., M.Sc. thesis, University of Botswana, Gaborone, Botswana, 2016.

Slug test produced a mean value of 26.43m/day (3.059 x 10^{-4}m/sec) for the riverbank sediments. This value is also within a reasonable range of values of hydraulic conductivity for sand that comprises of a lot of silt and clay.

4. Conclusions

A one-layered aquifer, riverbank alluvial and riverbed deposits, was studied to characterize their hydraulic properties. Geologically the area is consisting of alluvial deposits overlying the granite, which is the bed rock of the area. The alluvial deposits or the Motloutse sand river consists mainly of sand and gravel at variable depth, with coarse sand along the middle of the river and silt and clay banks occurring adjacent to river banks. Geophysics method have been applied to resolve depth to bedrock using GPR, and it is found that the range of the thickness of the alluvium varies from 9 – 12m, and GPR also provided reasonable estimates of porosity of the sediments, which is 40%.

The grain size analyses of the riverbed sediments revealed that the Motloutse sediments are poorly graded gravelly sand. The laboratory test resulted in an average specific yield of 13.68% for the riverbed sediments and 8.84% for the river bank sediments. A slug test performed in the riverbank yielded estimates of hydraulic conductivity of 26.43m/day (3.059 x 10^{-4}m/sec). An average hydraulic conductivity value of 160m/day (1.856 x 10^{-3}m/sec) for gravelly sand was determined using Alyamani-Sen formula.

This difference in hydraulic properties of the riverbed sediments and the riverbank sediments is likely a result of sediment heterogeneity as more fine grain sediments are found together with sand in the riverbank sediments.

These combined hydraulic properties estimation using empirical formula, geophysical survey, laboratory test and slug test greatly enhanced the understanding of the hydrologic properties of the single layered alluvial aquifer system in the Motloutse River catchment. For those who want to continue further studies in the studied area, these determined aquifer parameters can be used to determine the groundwater potential of the aquifer using groundwater modeling techniques.

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