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An Assessment of Hand Drilling Potential in Upland and Lowland Dambo Environments of Malawi

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An Assessment of Hand Drilling Potential in Upland and Lowland Dambo Environments of Malawi

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Abstract

Hand drilling methods can offer low cost, rapid access to shallow, unconsolidated aquifers typically found in dambo environments (seasonally waterlogged African wetlands). Three hand drilling techniques (augering, percussion drilling, and borehole jetting) were evaluated in regard to their suitability for groundwater supply in upland and lowland dambos in Malawi.

Through the drilling of 19 test boreholes, typical sub surface dambo geologies were assessed in terms of aquifer suitability to hand drilling applications. Drilling rates were recorded to examine the performance of a certain technique in particular ground conditions. A comparison between hand drilled boreholes and hand dug wells in dambos is also presented emphasizing the relative importance of implementation cost, convenience of construction and location.

Upland and lowland dambos are distinctly separate in terms of geology, hydrology and morphology. Lowland field area potential is constrained by geological variability over short distances. This is most likely due to initial fluvial mechanisms of aquifer deposition. Upland field area suitabilities are largely dictated by the proportions of clay weathering minerals in the underlying shallow bedrock, the presence of which can reduce aquifer permeability.

Drilling rates are generally determined by the depth of the borehole. Short term fluctuations in drilling rate can be attributed to grain size and clay content variations. Augering and percussion techniques performed well, while jetting was judged to be more limited in its application. The costs of hand drilled boreholes amount to 35% of the cost of hand dug wells. The lack of available hand drilling equipment at village level and the relatively high capital cost of drilling equipment may however, militate against the uptake of these techniques without external support.

Geological suitability is a primary determinant in the potential of hand drilling techniques. The variability of dambo geologies calls for a tighter fitting terminology that refers more specifically to aquifer characteristics. The choice of suitable drilling techniques can save on money and time, and enhance the overall ease of construction.

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Note: All figures and tables included in this work are of the authors own creation, unless otherwise stated

1. Introduction

Water borehole drilling is an essential process in establishing safe, sustained, accessible water supplies in many poor rural regions of the world. Hand drilled boreholes can provide access to groundwater reserves particularly for domestic and agricultural use. Hand dug wells offer similar access to groundwater supplies but often require strenuous and timely manual labour inputs, costly construction materials, and potentially unsafe construction practices. This project explores the potential of three hand drilling techniques as fast, cheap, and safe methods of accessing groundwater supplies.

Water-bore drilling encompasses a variety of techniques; methods span from simple hand augering to the use of conventional, truck mounted, hydraulic drilling rigs. Large rigs require more operational and maintenance expertise, and more expensive component parts. Poor access routes to potential drill sites can prevent such large rigs reaching remote rural areas. In contrast, simpler hand drilling tools are easier to transport and operate.

Hand drilling is a likely candidate to facilitate village level borehole implementation, affordability, and understanding; factors that when present, contribute towards achieving a sustainable borehole supply. Such participation levels are often unrealistic in larger scale, higher cost, deep borehole projects.

The application of hand drilling is limited to areas with soft unconsolidated geology, sufficiently shallow water tables, and high permeability aquifers. Many suitable areas of loose sediment and shallow water table exist in Malawi, for example dambos, alluvial[1] plains and lakeshore sediments. Fieldwork for this thesis focused on dambo environments. The term dambo is used widely throughout sub Saharan Africa to describe seasonally waterlogged grassland areas that form pronounced or discrete topographic depressions with poor drainage due to near surface clay units.

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[1] Stream or river derived, sedimentary deposits.

The hand drilling techniques used during this study were augering, percussion and jetting. Augering involved the cutting and collecting of sub surface material by rotating a cutting tool at the end of steel pipe extensions. Percussion used the same pipe extensions attached to a cylindrical sand-bailer fitted with a non-return flap valve. The bailer cut and collected material by continuous lifting and dropping of the steel pipe at the surface. Jetting used a pumped pressure jet of water to cut through ground material. These techniques and the equipment used are described in more detail in Chapter 2, Literature Review and in Appendix A, Drilling Equipment.

The overall aim of this study is to assess the potential of the three low cost hand drilling techniques as best end-user methods of accessing groundwater in upland and lowland dambo environment niches of Malawi.

Three specific objectives have been pursued to achieve this aim:

1. To determine the suitability of upland and lowland dambo geologies to the application of the low cost drilling techniques used during this study.
2. To assess the advantages and disadvantages of the three hand drilling techniques in a comparative and collective manner, and to provide an insight into which methods work best in certain ground conditions.
3. To compare hand drilled boreholes to hand dug wells as best methods for end-users to gain access to domestic and irrigation water supplies in dambo areas.

The work of this thesis follows a similar theme to the research carried out by Genis Duch (2006) that examines the potential of basement, alluvial and dambo aquifer varieties in Malawi to the application of low cost drilling techniques.

1.1 Malawi Country Profile

Malawi is located in the South East of Africa (Figure 1.1). It is one of the most densely populated countries in sub Saharan Africa with a population density of about 110/km^2 (Mines Country Profile, 2006). The sub-tropical climate consists of one rainy season lasting from November to May. Lake Malawi is the third largest lake in Africa and occupies 20% of the Malawi’s surface area (Mines Country Profile, 2006).

Figure 1.1 Map of Malawi (taken from Douglas & White, 2003)

Malawi has a Human Development Index ranking of 166 out of a total 177 countries (UNDP, 2006). It is estimated that 27% of Malawi's population do not have sustainable access to an improved water supply (UNDP, 2006). This figure is likely to be much higher in rural areas, where many village communities still rely on unlined and unprotected hand dug holes for their daily drinking and washing requirements. Figure 1.2 is an example of one such unprotected water source encountered during fieldwork in Sonda, near Mzuzu in Northern Malawi.

Figure 1.2 Water collection from an unprotected source in Northern Malawi

The majority of the country is in the form of gently undulating plateaus, suited to upland dambo formation. The topography of Malawi is largely influenced by the North-South orientated Malawi rift, a geological feature of crustal extension characterised by extensional faults. This rift system is thought to branch from the East African rift (Mines Country Profile, 2006). The Malawi rift is seismically active but generally non volcanic; thick (up to 3km) sedimentary sequences have accumulated in the Lake Malawi graben and in the Shire valley in the Southern Region (Figure 1.1).

The principal geological unit in Malawi is the metamorphic Basement Complex. Precambrian to lower Palaeozoic gneiss[2] and granulite[3] formations typically comprise this complex which directly underlies 85% of Malawi's land area (Mines Country Profile, 2006). Aquifers related to this metamorphic basement generally consist of 15-30m thick saprolite[4] units and occur in the plateau regions of Malawi (Mthunzi, 1999). These saprolite aquifers represent the weathered remnants of near surface Basement Complex rocks.

The younger Tertiary and Quaternary alluvial and lacustrine formations of the Post Karoo geological supergroup (Figure 1.3) occur close to the Western shoreline of Lake Malawi, and throughout the Southern part of the country near Lake Chilwa and in the Shire river valley (Mines Country Profile, 2006). Quaternary alluvial deposits of unconsolidated sand, silt, and clay sequences in these areas may represent aquifers with good potential for groundwater development (Mthunzi, 1999).

The fieldwork locations chosen for this study (Figure 1.3) represent two different types of shallow groundwater reserves within Malawi:

1. A lowland Post Karoo alluvial sediment aquifer in a dambo situated close to Salima.
2. Three upland Basement Complex saprolite aquifers occurring in dambos near Mzuzu.

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[2] A coarse grained, metamorphic rock with light (quartz - feldspar) and dark (biotite – hornblende - pyroxene) bands.

[3] A coarse grained, equi-granular, metamorphic rock, consisting of quartz, feldspar, pyroxene and garnet minerals.

[4] In-situ chemically weathered rock.

Figure 1.3 Geological map of Malawi with approximate field work locations (taken from Mines 2006)

2. Literature Review

2.1 Conventional Drilling: Scaling-Up of Low Cost Innovations

The use of conventional drilling rigs for deep borehole construction is necessary in many areas with deep water tables and solid rock aquifers. Conventional drilling rigs can be truck mounted or fitted with caterpillar tracks to improve mobility. However due to their bulky size, transport restrictions invariably occur in remote locations. Mthunzi (1999) describes attempts in Malawi to introduce and scale up the use of a smaller-than-conventional drilling rig that could offer better access to remote rural regions. The mobile *Port-a-rig* offered improved mobility and cheaper drilling costs, yet still retained sufficient conventional drilling power to penetrate reasonably hard rock formations. This engine-driven drilling rig was designed to fill the gap between hand drilling techniques and conventional drilling. However, a number of complicating factors can hinder the scaled uptake of such innovative specialized drilling technologies.

Commercial drilling contractors tend to invest in over-capacity rigs. This practice, although expensive, allows contractors more flexibility to bid for a variety of drilling jobs without the risk of using inadequate equipment (Robinson, 2006). The *Port-a-rig* was designed specifically to drill lower cost water boreholes in remote locations. Many contractors are unwilling to invest in such specialized equipment as it may narrow the market of biddable drilling jobs. Mthunzi (1999) acknowledges that specialized lower cost borehole drilling options may cause drilling businesses, with invested capital in large, one-size-fits-all, conventional rigs, to feel threatened by and lobby against such innovations.

Another hindrance to the introduction of innovative, lower cost, drilling technologies is over-subsidisation of borehole costs. Donor programmes can diminish public and private incentives to promote lower cost drilling. Large donor programmes (such as the World Bank) are willing to pay up to $15,000 per borehole in Malawi (Mthunzi, 1999). The Malawi government and private operators therefore have little incentive to uptake lower cost drilling options as long as such donations continue.

Specialised rigs such as the *Port-a-rig* can require unique component drilling parts that have to be imported (Mthunzi, 1999). This can potentially increase maintenance costs and undermine existing local markets.

Overly restrictive water borehole standards can also prevent the uptake of innovative lower cost drilling methods. Mthunzi (1999) describes how the Malawi Water Department initiated standard, countrywide guidelines to ensure quality borehole construction. In doing so, the excessive standards needlessly limited the application of the *Port-a-rig*.

The above resisting factors to innovative drilling in Malawi highlight some of the difficulties involved in scaling-up the use of appropriate but specialized technologies.

2.2 Hand Drilling Techniques: Scaling-Up of Hand Augering

In contrast to the problems faced in the scaling up efforts of the *Port-a-rig*, the uptake of hand drilling techniques can be less prone to as many hindrances. Danert (2006) provides optimistic evidence from Niger on how hand augered water boreholes, coupled with treadle pumps, have been introduced and scaled up to widespread use in the last thirty years.

Danert (2006) outlines how with on-going external support, subsidisation, and technical demonstrations, local hand drilling businesses have gained the capacity to provide good quality water boreholes for irrigation and agricultural use. One of the benefits of augered boreholes is that they can cost 15-20% of the cost of similar depth hand dug wells[5].

Price based competition has been emphasised in Niger; such competition can keep hand augered boreholes affordable for farmers. However a negative impact of competition is that drillers may have to travel further to find jobs. Non-local drillers may then be under

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[5] Danert, K. (2006) A brief history of hand-drilled wells in Niger.

less peer pressure to provide quality borehole construction as customers are less likely to be neighbours; quality can diminish as a result[6].

Despite minor set-backs, the account of hand augering in Niger demonstrates the high potential for adoption of hand drilling techniques at country-wide levels. Hand augering alone is limited to non-collapsing sands and clays, and so Danert (2006) also suggests how hand percussion techniques could be introduced along with the use of rope pumps that can lift water from depths of up to 30m to increase the application of hand drilling techniques.

2.3 Hand Powered Drilling Techniques

Table 2.1 taken and adapted from Carter (2005) explains the hand drilling details for the techniques undertaken in this study.

Hand Drilling Method	**Cutting Mechanism**	**Material Removal Mechanism**	**Hole support Mechanism**
Hand Augering	Hand-rotated cutting tool (auger) on end of steel pipe.	Periodic removal of auger with drilling extension pipe.	Sometimes temporary PVC casing can be used.
Hand Percussion	Human-powered lifting and dropping of a bailer suspended at the end of steel pipe.	Periodic removal of the bailer to gather spoil as slurry.	Temporary PVC casing if needed
Jetting	Washing action of pumped water jet.	Flushing action of water pumped down drill pipe, flowing up annulus.	Hydrostatic pressure of water is usually sufficient. In collapsing sand, permanent or temporary casing can be installed during drilling.

Table 2.1 Human Powered Borehole Construction Methods and Mechanisms (from Carter, 2005)

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[6] Ibid.

Hand augering in Malawi has been carried out by Concern Universal using the Vonder rig (Mthunzi, 1999). This mechanism (as shown in Figure 2.1 taken from Penn 2006) involving the use of a tripod and winch, can reach depths of up to 115 metres (Penn 2006). The mechanism of drilling involves turning the T-bar handle at the surface to rotate the cutting tool at depth.

Figure 2.1 Sketch of a Vonder rig in action taken from Penn (2006)

Augering carried out in this study follows the same principle shown in figure 2.1, although a tripod and winch system was not necessary. Various auger head cutting tools exist, designed for use in certain ground conditions. Riverside augers (Appendix A) are specifically suited to hard stiff soils mixed with fine gravel (Eijkelkamp, No Date) whereas Edelman augers (Appendix A) are designed for clay, sand or coarse grained soils depending on the auger blade width. Edelman cutting blades are designed to enable minimum friction during drilling (Eijkelkamp, No Date). A common type of auger bit design is the corkscrew shape, used for cutting through very hard units; this variety of bit was not required for the purposes of this study.

Percussion drilling involves the constant lifting and dropping of a cutting tool or bailer which penetrates the sub surface units and excavates material from the hole. It has been used in China for over 3000 years (Penn 2006). Figure 2.2 (taken from Penn 2006) illustrates the percussion technique using a tripod and pulley mechanism.

Figure 2.2 Sketch of Percussion drilling in action taken from Penn (2006)

Jetting is the technique of cutting the sub surface unconsolidated formations with a pressurised jet of water. Cuttings are carried back to the surface, suspended in the return water flow travelling back up the borehole annulus. Figure 2.3 illustrates the technique being carried out using a treadle pump to jet water down the hole and a tripod and pulley system for supporting the drill casing.

Figure 2.3 Sketch of Jetting in action taken from Penn (2006)

It should be noted that all the techniques undertaken during the course of this study did not use a tripod, pulley or winch system. All holes were drilled to depths of less than 10m and so did not require the use of very heavy equipment or a tripod system.

2.4 Dambo Terminology and Shallow Aquifers

Duch (2006) presents an assessment of three shallow level aquifer environments in Malawi, namely weathered crystalline basement aquifers, alluvial plain deposit aquifers, and dambo associated aquifers. The potential for low cost drilling techniques in basement aquifers are described by Duch as variable depending on the composition of the underlying bedrock. Alluvial aquifers are portrayed as having reasonable potential, with river derived sand units being preferable to clayey lithologies. Dambos are detailed as complex and variable, but with proven potential at least at a localised level.

Von der Heyden (2004), in a review of dambo hydrology and hydrogeology, lists a set of variable dambo characteristics that, when constant, allow estimates of groundwater and surface water behaviour to be made. These characteristics are catchment size, dambo size, vegetation, rainfall, and sand-silt-clay interfluve[7] soil fraction. Von der Heyden also acknowledges the variability of dambo bedrock geology and topographical slope noting their potential to further influence hydrological behaviour. The changeability in such characteristics from place to place is likely to be a result of the loose classification criteria associated with the term dambo.

A definition of a dambos as being seasonally waterlogged African wetlands is too vague to issue definitive statements regarding hydrology and hydrogeology. In fact, such loose terminology gives rise to an overlap in the definitions of basement aquifers and dambos and also of alluvial aquifers and dambos. The separation of three distinct aquifer types: basement, alluvial and dambo aquifers outlined in Duch (2006) is not applied to this thesis. Basement aquifers may occur in areas defined as dambos (e.g. The Mzuzu field area of this study), similarly alluvial aquifers can also occur in locations classified as dambos (e.g. The Salima field area of this study).

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[7] A region of higher land separating two adjacent dambos, stream valleys or river valleys.

To analyse the overlap between basement aquifers and alluvial aquifers with dambos, a brief review of the geomorphological processes pertaining to dambo formation is necessary. Von der Heyden (2004) reviews two main models for dambo formation; the in-situ weathering model and the fluviatile model.

The in-situ weathering model is relevant to the overlap between basement aquifers and dambos. This model of dambo formation describes the processes of rainfall infiltration, leaching, and weathering of stationary bedrock to form colluvium[8], and an underlying clay-rich saprolite horizon that grades into fresher bedrock at depth. Many shallow level basement aquifers in upland areas of Malawi occur in narrow discontinuous seasonally water logged dambo depressions. Their upland geographical location and saprolite to basement ground profile are concordant with the in-situ weathering model of dambo formation.

The fluviatile model, in contrast, describes dambo origins as part of ancient river systems and can be applied to dambos found at lower elevations in Malawi, on or near alluvial plains. The gently sloping dambo topography is explained through processes of valley infilling during periods of reduced river energy and valley slope instability. Characteristic seasonal flooding then results from the gently undulating topography established during periods of valley infilling. Dambo areas formed in such a way contain alluvial sand aquifers of suitable permeability to shallow borehole development through hand drilling methods.

Acworth (1987, as cited in Wurzel, 2001) uses the following figure 2.4 to demonstrate a typical profile of an upland crystalline basement weathered aquifer. Zone B represents an impermeable to semi-permeable layer limiting the connection between shallow (Soil A and B) and deep (Zones C and D) aquifer regimes. The existence of this impermeable zone is also characteristic of a number of dambo hydrogeological models as described in von der Heyden (2004).

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[8] Loose weathered rock that has moved down-slope by surface wash or soil creep.

Figure 2.4 Vertical profile through weathered crystalline basement showing permeability and porosity (Acworth 1987, as cited in Wurzel, 2001)

The increase in permeability that occurs in the typical zone C is of particular interest for borehole drilling. It is likely that the clay fraction of zone B will be too high to reach sufficient levels of permeability for borehole recharge. This zone is more likely to be suited to the construction of larger diameter hand dug wells to allow the well storage capacity to compensate for low permeability. The relative permeability of zone C is likely to be high when compared with zone B. However, as Duch (2006) points out, the influence of the underlying bedrock composition is paramount in dictating the actual permeability value of this zone C and hence, influencing its potential for hand drilled boreholes.

Another important factor to consider is whether zone C as shown in figure 2.4, if suitable in terms of permeability, can actually be reached by hand drilling methods. The proportion and size of rock fragments in this zone could serve to hinder drilling progress.

3. Methodology

3.1 Equipment Sourcing

Two Edelman combination auger bits and two riverside auger bits (Appendix A) were used during the fieldwork of this study (Eijkelkamp, No Date). This equipment was made available from Cranfield University at Silsoe and Bundu College of Agriculture, Lilongwe. All four auger bits were designed to join to extension rods by conical screw thread connections (Eijkelkamp, No Date). An adapter (see Appendix A, Figure A5) was constructed to allow connection of the auger head conical screw thread to locally purchased and threaded, galvanised steel extension rod pipe.

A percussion sand bailer bit was also provided by Bundu College of Agriculture (Appendix A, Figure A7). This bailer, designed to drill through loose water logged sand, consisted of a 70mm diameter steel pipe fitted with a non return flap valve to allow sand to be drilled through without cuttings falling back down the hole. Again an adaptor part was constructed to allow this drilling tool to be connected to the locally purchased extension rod pipe (Appendix A, Figure A9).

The purchase of hand drilling equipment in Malawi was expected to provide an insight into both the in-country availability and cost. It should be noted that most of the hand drilling equipment bought was generally hardware designed for a different purpose. For example, one metre lengths of three quarter inch galvanised steel pipes (typically used in household plumbing) were used as the main extension rods for augering and percussion drilling. A full description of equipment purchased is given in Appendix A.

The majority of drilling equipment was purchased in Lilongwe over a period of 9 days from June 6th to 15th. An abundance of hardware stores geared towards metal work and plumbing exist in the capital city. Many of the larger enterprises are run by South African or Indian entrepreneurs. Smaller, locally run hardware markets can also be found, often with a limited stock of diverse hardware components. The price difference between the large foreign owned and small locally owned businesses was sometimes significant; material from smaller retailers commonly being two or three times cheaper. However, the uncertain quality of what was usually second-hand material, and the limited stocks of smaller retail outlets led to most equipment being bought from the larger scale providers. Promat, an international UPVC pipe retailer; Stewarts & Lloyds, a South African galvanised steel and UPVC pipe distributor with an outlet in Lilongwe; and Constantini Brothers Limited, a South African run general engineering/mechanics business proved to be the most useful sources of drilling equipment.

Table 3.1 provides the full costing of drilling equipment purchased in Lilongwe.

Drilling Equipment Expenses			
Date	**Description**	**Retailer**	**Price in Malawi Kwacha**
07/06/2007	Adjustable spanners (x2)	Shoprite Lilongwe	1,199.98
07/06/2007	Hacksaw	Shoprite Lilongwe	139.99
07/06/2007	Spirit Level	Shoprite Lilongwe	299.99
08/06/2007	PVC Pipe 75mm Grade 10 (x12m)	Promat Lilongwe	5,496.04
11/06/2007	Measuring tape (20m)	Shoprite Lilongwe	999.99
12/06/2007	PVC Casing cut and threads	Constantini & Co. Lilongwe	10,340.00
12/06/2007	Thread Tape (x3)	Stewarts & Lloyds Lilongwe	119.85
12/06/2007	Galvanised pipe (6m), cuts, threads, sockets	Stewarts & Lloyds Lilongwe	6,533.00
12/06/2007	Galvanised pipe (6m), and sockets	Stewarts & Lloyds Lilongwe	4,227.65
13/06/2007	One pipe cut	Stewarts & Lloyds Lilongwe	23.50
13/06/2007	Reinforced bolt and screw (x4)	Unique Supplies Lilongwe	752.00
13/06/2007	Adjustable wrenches (x2)	LMD Trading House Lilongwe	6,900.00
13/06/2007	High Temp copper compound (thread softener)	Automac Lilongwe	6,932.50
15/06/2007	75mm 3/4" Clamp Saddle (x2)	Promat Lilongwe	2,098.86
26/06/2007	Hacksaw	Shoprite Lilongwe	139.99
27/06/2007	PVC Pipe 75mm Grade 10 (18m) & Screen (6m)	Promat Lilongwe	10,264.60
		Total (Malawi Kwacha)	56,467.94
	1 GBP = 286 MWK	**Total (British pound Sterling)**	197.51
	1 EUR = 193 MWK	**Total (Euro)**	292.37

Table 3.1 Drilling Equipment Expenses

The cost of equipment bought for this project may not truly represent the budget for a local entrepreneur with greater knowledge of where cheaper yet comparable quality materials may reside.

The auger bits and percussion bailer were not manufactured locally. The main factor deterring against local manufacture of these specialised equipment was time. The fieldwork for this thesis lasted seven weeks and so the sourcing of equipment had to be rapidly carried out. Had more time been available, local manufacture of auger bits and a percussion bailer may well have been possible.

3.2 Field Area Backgrounds and Hand Drilling Procedures

For the purposes of this study, two type field areas were selected. Both areas fall under the term “dambo” but differ in geology and morphology. In Salima, the field area environment has been termed a “lowland dambo” for the purposes of this study. In Mzuzu, “upland dambo” is the name used to describe the field locations.

The potential of low cost drilling in the Salima field area was assessed by means of a cost-time comparison with hand dug well construction, and the use of drill-hole logs and sections to determine suitable and unsuitable groundwater-geological conditions. Pumping tests were carried out on three constructed boreholes during the study (See Appendix C for details) to further establish aquifer suitability for hand drilled boreholes.

In Mzuzu, the potential for low cost drilling was carried out using drill-hole logs, geological cross sections and typical sediment profiles. No pumping tests were carried out on constructed boreholes in this field area; the sub surface material intercepted appeared unsuitable in all cases.

In both field areas the three hand drilling methods used were examined by comparing their drilling rates relative to the ground conditions intercepted. It should be noted that external factors such as the stamina of the drilling operator can also influence drilling rate. Possibilities for such variations in drilling rate were taken into account during field work and every effort was made to ensure that operator speed remained constant. Time taken during breakdowns and repairing equipment has been removed from the drilling rate dataset so as not to distort the true rate of each drilling technique. However, where breakdown and a long set up time are consistently associated with a certain technique, the correlation was noted.

3.2.1 Salima Field Area

The Salima field area is located approximately 100km East of Lilongwe and less than 10km West of Lake Malawi. It is located on a vast lakeshore plain with little or no topography except for the granitic intrusions[9] that form the Senga Hills to the East (Figure 3.1). The plain comprises superficial deposits of alluvium and colluvium (Walter, 1972). Dambo boundaries are difficult to identify in the dry season due to the flat landscape and lack of characteristic flooding. No bedrock or saprolite units were intercepted at the depths reached by hand drilling (up to 7m); it is likely that erosion of upland basement rock to the East has resulted in thick sediment deposits being accumulated in this area (Figure 3.2). Figure 3.1 shows the view looking East across the lakeshore plain towards the Senga hills in the distance.

Figure 3.1 View to the East over the Salima Lakeshore plain towards the Senga Hills

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[9] Light coloured coarse grained igneous rocks consisting of quartz, feldspars and mica.

3.2.2 Salima Field Area Drilling Procedure

Hand drilling was carried out beside a rural village named Simaiwa, located 5km north of Salima town. Sixty two farmers share and manage an Irrigation Cooperative on a plot of land roughly five hectares in size (Figure 3.4) which forms the boundaries of the field area. No drilling was carried out beyond the boundaries of the Cooperative. Nine hand dug wells have been constructed in this area for irrigation use. Approximately ten treadle pumps are available in the village for pumping at any one time. Plans are in place to construct a total of twenty eight hand dug wells to be shared between farmers. Sufficient numbers of extra treadle pumps are available from the Ministry of Agriculture in Salima town. The expected outputs of a hand drilling study in this area were threefold;

1. A comparison between the suitability of hand drilled boreholes and hand dug wells in the area
2. A comparison between the three hand drilling techniques (drilling rate relative to soil type)
3. A typical sub surface profile across the "lowland dambo" area

Fieldwork in Salima began with a reconnaissance trip to Simaiwa village and the surrounding area. An understanding of the surrounding geology and topography was established and overview maps were created (Figures 3.2 and 3.3).

Figure 3.2 The Geology of Salima and the surrounding region

Figure 3.3 The Geology of Salima and the surrounding region overlain on Google Earth

A meeting was then held with the Simaiwa Cooperative committee members to discuss the expected outputs of the study and potential benefits of hand drilled boreholes in the area. During this stage of fieldwork, a sketch map of the actual field area was drafted by combining the use of a hand-held Global Positioning System (GPS) with a community mapping exercise undertaken by the Cooperative farmers. The map illustrates the size and shape of the Cooperative with the approximate locations of landholder plots (Figure 3.4).

Figure 3.4 Outline of the Salima Field Area with Landowner Plots and Drilled Holes

Drilling was carried out, initially with the Edelman auger bits and then progressing to the riverside auger bits and percussion bailer tool as ground conditions varied. Where the auger and percussion methods failed to work or progressed at a very slow rate, well jetting was attempted using 75mm, Class 10, UPVC casing and a treadle pump drawing from a nearby hand dug well. The rate of each hand drilling technique was recorded in metres per minute and the subsurface material was recorded under the headings Colour, Grain Size, Grain Shape, Clay content, Moisture Content and Grain Sorting. The standard guide shown in Figure 3.5 was used to ensure consistent recording of data throughout the fieldwork.

Figure 3.5 Standardization Guide for geological logging (available from most standard geology textbooks)

Details of time and cost of hand dug well construction were attained through discussions with the Cooperative chairman and secretary. A comparison of hand dug wells and hand drilled boreholes was undertaken in terms of cost components and construction time (Section 4.1).

The drilling rate and subsurface material data collected were used to compare the rates of certain drilling techniques in particular soil conditions (Appendix D). The down-hole logs of intercepted material (Appendix B) were used to create cross section soil profiles across the dambo field area.

3.2.3 Mzuzu Field Areas

Three potential field areas were visited; Doroba, Sonda and Muzgola. All three sites are located in upland hill and valley terrain within 20km of Mzuzu city (Figure 3.6). Although no geological map data was readily available for the field areas, a brief reconnaissance study indicated the underlying bedrock to be schistose[10] basement or granitic intrusives. In many areas this underlying bedrock is within 2m of the surface (Figure 3.7).

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[10] Fine-medium grained metamorphic rocks often defined by their aligned platy mica and elongated quartz-feldspar mineral textures.

Figure 3.6 Google Earth image with Mzuzu Field Area Locations

Figure 3.7 Bedrock close to ground surface in Upland Areas around Mzuzu

The underlying bedrock in many cases is weathered to saprolite with high clay content. This is most likely due to the weathering of feldspar minerals present in the bedrock formations.

The topography of the field areas near Mzuzu is that of upland hills with minor dambos and valleys, up to 50m wide, often feeding into larger river valleys. The dambo boundaries in most cases are well defined by the valley sides (Figure 3.8).

Figure 3.8 Well defined dambo boundaries in Muzgola Field Area

3.2.4 Mzuzu Field Area Drilling Procedure

The expected outcomes of the Mzuzu fieldwork remained the same as those in Salima (mentioned in section 3.2.2). The sub surface profile however in this case was to be of an “upland dambo” area.

Initial stages of fieldwork involved mapping the three field areas to establish where the greatest need for water was and thus, potential locations of hand drilled boreholes. In order to combine the best interests of local villagers with the project outputs it was decided to initially choose drilling locations based on villager’s need for water. Need was quantified based on:

1. The number of people in a village
2. The distance from a village to the nearest water source
3. The type of water source used by the village

Three maps were created (Figures 3.9, 3.10 & 3.11) using a handheld GPS and consultations with local inhabitants and chiefs. The number of people at each settlement, the distance and type of water source available, as well as the relative altitude of settlements and water sources were recorded. GPS recordings of altitude can be inaccurate and so altitude data presented in the maps should not be taken as actual values, but instead as a means of roughly showing the relative change in altitude from one point to another.

Once recorded, the data was transferred to computer and reproduced graphically using Adobe Illustrator 10® software. This software does not produce geographically referenced images and so the maps shown may be subject to a small degree of error in scale and location. Potential deviations that may have arisen from graphically reproducing the maps are too small to be noticeable; they do not diminish the usefulness of the maps in locating the areas most in need of water. The maps proved to be invaluable tools for planning an initial fieldwork strategy; to hand drill in the areas most in need of a protected water supply in the limited time available.

Figure 3.9 Map of the Doroba field area; Water sources, Village settlements and Valley/Dambo outlines

Figure 3.10 Map of the Sonda field area; Water sources, Village settlements and Valley/Dambo outlines

Figure 3.11 Map of the Muzgola field area; Water sources, Village settlements and Valley/Dambo outlines

Initial stages of the fieldwork revealed a scarcity of suitable permeable sand at depth to facilitate pumping from boreholes. Upon this realisation, later drilling locations were chosen in areas where the interception of suitable sand was deemed most likely and less according to where the need for a clean water source was greatest. Ideal locations included areas of convergence between two dambos, and sites recommended by local villagers as to where sub-surface sands were most likely to reside.

As was the case in Salima, drilling began using the Edelman auger bits. Auger heads were then interchanged according to the sub surface material intercepted. Drill holes were logged to record geology, augering technique and drilling rates. Hand percussion and jetting techniques were not used in the Mzuzu field areas; ground conditions remained suited to the augering technique in all holes drilled.

4. Results and Analysis

4.1 Cost Comparison between hand dug well and hand drilled borehole water sources in Simaiwa, Salima Field Area

The farming cooperative committee at Simaiwa village provided valuable insight into the cost components of the nine uncovered hand dug wells already constructed for irrigation. Two sizes of locally available bricks were used to construct the wells. Upon consultation with the cooperative chairman and secretary, it was possible to compare the construction costs of hand dug wells built with small bricks, large bricks and hand drilled boreholes. A 6.5m deep hand dug well, 1.5m in diameter, was used as the standard hand dug well size. This was compared to a standard hand augered and percussion drilled borehole 6.5m deep, and 90mm in diameter. The technique of jetting was omitted from the cost comparison for simplification purposes and also due to the limited applicability of the technique in Simaiwa (Section 4.5). Tables 4.1 and 4.2 outline the cost components of the three water source types developed in Simaiwa.

The components of cost are broken down into the sub-headings of materials, transport, labour and equipment. The cost of equipment is weighted to portray the proportion that is effectively spent during the construction of one well or borehole. In the case of hand dug wells it is estimated that after the construction of 10 wells the replacement of some or all equipment would be necessary. Therefore the proportion of equipment cost spent per well is 10% of the total equipment cost. In a similar manner, it is estimated that some components of the hand drilling equipment would need replacement after the construction of 25 boreholes, thus the proportion of equipment cost per hand drilled borehole is estimated at 4%.

Simaiwa Village: Hand Dug Well (6.5m deep, 1.5m diameter) Cost Components			
Materials	***Amount per well***	***Unit Cost in Malawi Kwacha (MK)***	***Total Cost in Malawi Kwacha (MK)***
Cement	10 bags (25kg each)	1,700	17,000
Small Bricks	2950 bricks	3	8,850
Large Bricks	1200 bricks	5	6,000
River Sand	4 trailer loads	0	0
Materials Total (Using Small Bricks)			**25,850**
Materials Total (Using Large Bricks)			**23,000**
Transport	***Amount***	***Unit Cost (MK)***	***Total Cost (MK)***
River Sand	4 journeys (round trip)	1,500	6,000
Bricks	1 journey	1,500*	1,500*
Transport Total			**7,500**
Labour	***Amount***	***Unit Cost (MK)***	***Total Cost (MK)***
Unskilled	5 labourers, 11 days	100 MK per day*	5,500*
Skilled	1 mason, 4 days	250 MK per day*	1,000*
Labour Total			**2,100**
Construction Equipment	***Amount***	***Unit cost (MK)***	***Total Cost (MK)***
Shovel	3*	150*	450*
Bucket	3*	100*	300*
Trowel	2*	50*	100*
Construction Equipment Total			**850**
Assuming Construction Equipment Lasts for 10 hand dug wells **Construction Equipment Total (weighted per well)**			**85**
TOTAL HAND DUG WELL COST (SMALL BRICKS)			**35,535 MK**
TOTAL HAND DUG WELL COST (LARGE BRICKS)			**32,685 MK**

Note: Overheads of implementing agency are not included
** Denotes an estimated cost component, not directly recorded during fieldwork*

Table 4.1 Hand Dug Well Cost Components

Simaiwa Village: Hand Drilled Borehole (6.5m deep, 90mm diameter) Cost Components			
Materials	***Amount per well***	***Unit Cost in Malawi Kwacha (MK)***	***Total Cost in Malawi Kwacha (MK)***
PVC Pipe (75mm diameter, Class 10)	6.5m	458 per 1m length	2,977
Screened PVC pipe	2m	50 per 1m length	100
Local Sand: Formation Stabiliser	2 wheelbarrow loads	0	0
Local Clay: Sanitary Seal	0.5 wheelbarrow loads	0	0
Cement	0.5 Bags (25kg each)	1,700	850
PVC Borehole Cap	1	130	130
Materials Total			**4,057**
Transport	***Amount***	***Unit Cost (MK)***	***Total Cost (MK)***
PVC Pipe	1 round trip to Salima	1,500*	1,500*
Drilling Equipment	1 round trip to Lilongwe	5,000*	5,000*
Transport Total			**6,500**
Labour	***Amount***	***Unit Cost (MK)***	***Total Cost (MK)***
Unskilled	2 labourers, 1.5 days	100 MK per day*	300*
Skilled	1 driller, 1.5 days	250 MK per day*	375*
Labour Total			**675**
Construction Equipment	***Amount***	***Unit Cost (MK)***	***Total Cost (MK)***
Edelman Auger head (if constructed in Salima)	1	1,000	1,000
Percussion Bailer head (if constructed in Salima)	1	2,000	2,000
Dilling Extension Rod Kit	1	25,488**	25,488**
Construction Equipment Total			**28,488**
Assuuming Construction Equipment lasts for 25 Boreholes **Construction Equipment Total (wighted per borehole)**			**1,139.50**
TOTAL BOREHOLE COST			**12,372 MK**

Note: Overheads of implementing agency are not included
** Denotes an estimated cost component, not directly recorded during fieldwork*
***Includes extension poles, connectors, handle, wrenches, bolts, screws and copper grease*

Table 4.2 Hand Drilled Borehole Cost Components

The total cost of a hand drilled borehole in Simaiwa village was found to be approximately 35% of the total cost of a hand dug well. Converting Malawi Kwacha to Euro the total cost of a hand dug well is roughly 180 Euro, whereas the total cost of a hand drilled borehole is about 65 Euro.

Hand dug wells are considerably more expensive, primarily because of the large amounts of cement and bricks needed for their construction. Additionally, the longer time required for hand dug well construction results in higher labour costs.

The materials needed to construct hand drilled boreholes were not locally available and had to be procured from Salima or Lilongwe. This increases the transport costs involved in hand drilled borehole construction. Hand dug well materials, although locally available, are also subject to high transport costs because of the large volumes required. Particularly, the need to transport significant amounts of river sand for cement mixing drives up the transport costs associated with hand dug well construction.

Construction subsidies can diminish the importance of cost relative to convenience. The need for long distance transport of hand drilling materials and equipment may be viewed as a greater inconvenience by end users, than the need to transport larger volumes of hand dug well material over shorter distances. Conversely, the shorter construction time associated with hand drilled boreholes would attract end-users towards this option, especially if external support was in place to facilitate the local availability of drilling materials and equipment.

The method of weighting equipment costs is based on best estimates of how long the weakest equipment part would last without needing to be replaced. This simplification should be noted; weighting is based on the first part of equipment to need replacing and not on the entire equipment set. This weighting method is particularly likely to overestimate the weighted cost of hand drilling equipment per well; the threaded steel extension poles would likely need replacing after about 25 boreholes, however the auger and percussion heads may last for up to 100 boreholes. Hand dug well equipment such as shovels and buckets would be more prone to breakdown at similar stages; after the construction of about 10 wells.

4.2 The Suitability of Geological Units intercepted in the Salima "Lowland Dambo" Field Area

Drill-hole logs were used to construct inferred cross sections of the dambo field area. These sections illustrate the internal variations of sub-surface conditions within the field area. They also provide an insight into the occurrence of suitable sub strata for hand drilled borehole water sources. All drill hole logs are included in Appendix B. Three section lines were drilled (Figures 4.1, 4.2 and 4.3), they are presented in order of location from East to West; the section traces are illustrated in plan view in Figure 3.4.

Figure 4.1 Simaiwa Cross Section: Holes 1, 2, 3, and 4

The bright yellow units indicate medium-coarse grained sand, thought to be of sufficient permeability to enable successful borehole pumping. As can be seen in Figure 4.1, Holes 1 and 4 intersect suitable sands at depths of around 4 to 6 metres. Both these holes were tested for pumping, however neither proved to be successful (See Appendix C for detailed accounts of the pumping tests and analysis of the results). This was most likely due to the insufficient thickness and limited lateral extent of both intersected units.

Figure 4.2 Simaiwa Cross Section: Holes 9, 10 and 11

Figure 4.2 illustrates the sub-surface geology inferred from the last three holes drilled during fieldwork in Salima. No holes along this section appeared to be suitable to carry out pumping tests. Hole 11 was discontinued at 2.77m due to time constraints and slow drilling rates through collapsing sands. This section clearly illustrates the lateral discontinuity of the sub-surface sand, clay, and silt units encountered. Such internal variation within short distances (less than 50m along the surface) prolonged the process of finding suitable sub-surface conditions for the construction of a pumped borehole water source.

Figure 4.3 Simaiwa Cross Section: Holes 5, 6 and 7

The laterally discontinuous nature of sub-surface units is again evident from the section shown in Figure 4.3. Hole 6 intersected an almost 4m thick unit of permeable sand below the water table. A pump test was successfully carried out on this hole (Appendix C).

The shallow water table and thick accumulations of unconsolidated sediment throughout the Salima dambo indicated a high potential for hand drilling techniques to be successfully used to construct water sources. However, the three sections presented illustrate the high level of internal variability of sub-surface conditions in the Salima lowland dambo field area. Such inconsistent geology hindered the search for suitable permeable sand units, and the identification of suitable borehole sites located conveniently near to beneficiaries' homes or land.

4.3 Pumping Tests in the Salima Dambo Field Area

Pumping tests were carried on Holes 1, 4 and 6 drilled in the Salima dambo. Out of the eleven holes drilled in Simaiwa, these three holes were deemed to have the highest potential for successful borehole development and establishment of a water source. Each of the three holes intercepted at least 1.8m of reasonably permeable, medium to coarse grained sands at levels of about 2m below the water table. Three separate pumping reports for each hole are presented in Appendix C complete with results and analysis.

The tests conducted on Holes 1 and 4 proved to be unsuccessful primarily because the aquifer units intercepted were less than two metres thick in both cases. The lateral extent of these aquifer units are thought to be on the scale of 50-100m (Figure 4.1). In both cases, transmissivity values of the aquifers were low and excessive drawdown occurred during pumping (See Appendix C for details and explanations of terminology). A suction hose length of 4m limited the depth from which a treadle pump could lift.

A successful variable time, pumping test was carried out on hole 6 (Appendix C, Table C2). Discharge rates proved to have a greater effect on drawdown than pumping duration in this hole; maximum drawdown levels of 30cm occurred after pumping at a discharge rate of 1.80 l/s for only one minute, whereas ten minutes of pumping at a lower average discharge rate of 1.48 l/s produced a steady state drawdown level of just 10cm. The aquifer thickness intercepted in Hole 6 was 3.6m with an approximate lateral extent of 50m. A transmissivity value of 16m^2/day was calculated for the aquifer unit intercepted.

Pumping tests were carried out on the three likeliest holes, all of which intercepted reasonably thick permeable aquifer units. The failure of two pumping tests highlights the importance of intersecting aquifer material below the water table, with over 2m thickness, and with a lateral extent at least on the scale 50-100m. The results of the tests reiterate the point mentioned in section 4.2; that the variability of geology encountered in the Salima field area impedes the process of locating suitable hand drilled pumping borehole sites conveniently located according to the preferences of beneficiaries.

4.4 The Suitability of Geological Units intercepted in the Mzuzu “Upland Dambo” Field areas

Although drilling conducted in the Mzuzu field areas followed a less step-by-step transect approach than that carried out in Salima, a number of the resulting holes still provided enough data to create inferred dambo sections. Drilling locations were first chosen according to where a successful borehole would be best located to meet the needs of local inhabitants. Upon intersection of unsuitable geology in these areas, drilling locations were then chosen according to where suitable coarse sand aquifer units were most likely to occur. Despite this approach, none of the eight holes drilled in the Mzuzu upland dambo field areas revealed suitable sub surface aquifer units for the construction of pumped boreholes.

The borehole logs recorded for each hand drilled hole (Appendix B) were used to construct cross section profiles across two upland dambo areas in the Sonda field area (See Figure 3.10 for their location), and a typical stratigraphic sequence for the Muzgola field area. No holes were drilled in the Daroba field area. Based on preliminary mapping of the three areas, a greater need and potential for pumping boreholes existed in the Sonda and Muzgola areas.

Sonda Holes 1 and 2 were used to create the first section profile across an upland dambo (Figure 4.4).

Figure 4.4 Sonda Cross Section: Holes 1 and 2

Reasonably thick topsoil was encountered in the two holes drilled in the first Sonda dambo (Figure 4.4, see Figure 3.10 for section location). The sandy nature of this topsoil in places provided, on first impressions prior to drilling, an optimistic outlook as to the possibility of suitable permeable sands being present below the water table. However, as can be seen from the cross section, no such sands were encountered at depth. Instead a sequence of fine-medium grained sandy topsoil grading to clay and then to clay rich saprolite was encountered. Both holes on this section were drilled at locations chosen primarily because of their convenient location near the village of Unyoro (Figure 3.10). The inhabitants of Unyoro currently collect water from an unprotected water hole dug into clay. A secondary factor affecting hole location in this dambo was ensuring that the site looked to have a reasonable possibility of hitting permeable sands at depth. Potential sites displayed the characteristics of sandy topsoil with no clay visible at the surface. They were commonly located close to, but not in, dry stream beds (to maximise the potential of aquifer sand interception while avoiding flooding during the wet season).

Sonda holes 4 and 5, which form the second dambo section profile (Figure 4.5), were drilled in locations where it was deemed most likely to intersect permeable sand units below the water table. Hole 4 was drilled in a location advised upon by the inhabitants of Sonda (Figure 3.10). Hole 5 was chosen, again with advice from the people of Sonda, in an area of particularly sandy topsoil. Both hole locations also fulfilled what was now a secondary consideration for drilling in this dambo; being conveniently located for beneficiary access.

Figure 4.5 Sonda Cross Section: Holes 4 and 5

The topsoil encountered in this dambo was much thinner and graded to clay or clay rich sand in places. Then the familiar sequence of clay grading down-hole into clay rich saprolite was encountered. No suitable permeable sand units were encountered in either of the Sonda dambos.

Sonda holes 3 and 6 were drilled in upland dambo areas located at high elevations close to the onset of interfluve high ground (Figure 3.10). Both of these holes were chosen at sites of convenient access (hole 3 for Unyoro village, and hole 6 for Blamsaka village). Both holes revealed similar sequences of sandy topsoil grading to clay and to clay rich saprolite. The water level in hole 3 was recorded at a depth of 3.75m and no water was encountered in hole 6 (drilled to a depth of 4.20m).

The inhabitants of the Muzgola region rely on an unprotected water hole and a slow flowing river for their drinking water supply. Two boreholes were hand drilled in this field area (see Figure 3.11 for their locations) at sites where it was deemed most likely to encounter permeable sand aquifers. Hole 1 was drilled near to the intersection of a dambo and a river valley, hole 2 was located beside a dry sandy stream bed at the intersection of two dambos. Neither hole intercepted a suitable aquifer unit. The typical geologies encountered in Muzgola are illustrated in Figure 4.6.

Figure 4.6 Muzgola Typical Down-hole Sequence

The saprolite horizons encountered both in the Sonda and Muzgola field areas contained significant amounts of clay (likely to be weathered feldspar minerals), minor quartz fragments and platy muscovite mica minerals. The remnant rock texture was sometimes visible, as can be seen in figure 4.7 from Muzgola hole 2 at 4m depth. Upon intersection of the clay rich saprolite horizons, significant further drilling was discontinued. It was believed that because of the high clay content, no permeable medium-coarse grained sands of sufficient thickness and lateral extent could be encountered before the onset of semi-solid bedrock. Drilling rates slowed through the saprolite zone due to the presence of embedded quartz stone fragments up to 5cm in size.

Figure 4.7 Close up view of schistose saprolite from Muzgola hole 2

4.5 A comparison of the three hand drilling techniques

Hand augering, hand percussion and treadle pump jetting techniques were analysed and compared by recording the drilling rates of each. Appendix D illustrates in graphic form the variation in drilling rate relative to sub surface geology intercepted in each of the 19 holes drilled.

Recurring trends in the data are noted and listed in Appendix D. The most significant trends observed were as follows:

- Edelman auger bits in most cases, drill at faster rates through unconsolidated dambo units than riverside auger bits.
- Treadle pump jetting rates were significantly faster than augering or percussion rates, however jetting requires a long equipment set up time (up to 1.5 hours)

and is limited in its applicability (can only cut through medium grained sands) when a treadle pump is the most powerful pump locally available.

- An increase in the hole depth will in many cases, decrease the overall drilling rate. This is primarily due to the extra time needed to remove equipment from the hole as well adding and removing extension poles.
- Variations in grain size and clay content of sub surface units can have more immediate short term effects on drilling rates than depth; a clay content decrease and/or a grain size increase often correlates immediately to an increase in percussion and auger drilling rates.

5. Discussion

5.1 Geological Suitability of Dambos to Hand Drilling Techniques

Sub surface geological units in the Salima lowland dambo are discontinuous over horizontal distances of as little as thirty metres. Some permeable sand units exist at depths that are suited to hand drilled borehole water source development. The problematic issue is locating suitably thick and laterally extensive aquifer units within this discontinuous geological environment. It is difficult to state actual measurements of suitable aquifer thickness and lateral extent required for borehole development, due to the variations in a given sand unit's permeability from place to place. Nevertheless, results from the Salima field area suggest that a vertical thickness of at least 2m of medium-coarse grained aquifer sand is preferable with a lateral extent of 50m upwards.

This lowland dambo may fit into the fluviatile category of dambo formation reviewed by von der Heyden (2004). Given the channelised nature of the suitable sand units intercepted in Simaiwa, it could be argued that the aquifer units, now located in a dambo environment, were initially fluvial in origin. Figure 5.1 presents a possible outline trace of the existence of a now buried river channel that forms permeable sand units at depth.

Figure 5.1 Possible river channel outline inferred from down-hole data of intercepted fluvial sands

Fluvial channel sands can form suitable permeable aquifers but they are limited in three-dimensional extent by the width and length of the original river channel, and by the duration of meandering channel flow over time. Other depositional environments such as alluvial fans and river deltas may give rise to thicker and more laterally extensive sand deposits. Areas containing such deposits may have a higher potential for the widespread application of hand drilling techniques for shallow borehole water sources.

Walter (1972) describes the majority of clays in the Salima area as montmorillonite. The existence of such swelling clays can serve to produce truncated geological units. Such clays continuously expand when wet and contract when dry. Prolonged periods of swelling in a wet dambo environment may produce thick discontinuous units of swollen clay surrounded by unconsolidated sands and silts. The laterally discontinuous thick clay deposits intercepted in Simaiwa hole 9 (illustrated in figure 4.2) may be an example of such a swelling clay unit.

The Mzuzu field area dambos differ from the Salima dambo in terms of size, conspicuousness, geology and elevation. The sole features common to both are a gentle gradient and seasonal flooding. The in-situ dambo formation model (von der Heyden, 2004) appears to be more applicable in the Mzuzu field areas. The typical sub surface sequences intercepted near Mzuzu (described in section 4.4) are reminiscent of weathering profiles caused by rainfall infiltration and leaching.

As predicted by Duch (2006) the suitability of such basement related aquifer types is very dependant upon the composition of the hard rock geology from which the unconsolidated, weathered units are derived. In the case of Mzuzu the predominant underlying bedrock appeared to be granitic (Sonda field area) or garnet-mica bearing schist (Muzgola field area). In both cases it is likely that the high feldspar content of the bedrock has weathered to unsuitably high clay levels within the unconsolidated horizon. Despite the high quartz content in granitic bedrock near Sonda, the resulting weathered saprolite zone displayed a high clay content. This clay can reduce permeability and prevent borehole recharge during pumping.

During the fieldwork carried out in Mzuzu, upon intersection of the clay rich saprolite zone with occasional rock fragments, it was deemed unnecessary to continue drilling to deeper depths. Given the clay rich nature of the saprolite horizon and the high feldspar content of underlying bedrock it was decided that the clay fraction would remain constantly too high and a suitable aquifer of permeable material would not be intercepted.

A feature, not fully covered in this study that may warrant further investigation, is the ease at which greater depths can be drilled to in upland dambo areas similar to those near Mzuzu. Results of such a study may provide insight into which hand drilling techniques can best reach the potentially high permeability zone C (Figure 2.4) in upland basement-dambo aquifers. Ideally a study of this nature would be carried out in a field area of suitable bedrock composition that would produce a high permeability saprolite-bedrock transition zone. Quartz rich basement rocks with minimal feldspar content would, on first impressions, be suitable candidates.

5.2 Hand Drilling Equipment: Availability for End-users

The drilling equipment used in this study was a combination of in-country purchased and university provided equipment. The availability of hand drilling equipment within Malawi is potentially very good given the number of hardware businesses within Lilongwe, Mzuzu and to a lesser extent in Salima. However, the in country availability of material alone cannot ensure successful uptake of a drilling technique in an area of suitable geology.

Throughout the fieldwork, transporting of equipment from urban centres to rural drilling locations was challenging. Without the use of a car or jeep, transport of equipment from Lilongwe to Salima and Mzuzu would have been severely restricted. Routes from Mzuzu and Salima to the more remote rural field areas were in some cases accessible only by motorbike, bicycle or by foot. Transporting PVC pipe, auger and percussion bits, and galvanised steel extension rods along such routes tended to be difficult without at least the use of a motorbike. Transport restrictions would surely be exacerbated by muddy conditions during the wet season.

The capital cost of a sufficient drilling kit amounts to almost 28,500 Malawi Kwacha, roughly 150 Euro (Table 4.2). Recurrent costs during the seven weeks of fieldwork amounted to 200 Malawi Kwacha (about 1.05 Euro) for fixing two broken threads on auger extension pipe and unscrewing one un-greased stuck thread joint.

Given the lack of transport available to rural village inhabitants (usually restricted to travelling by bicycle or by foot) and the lack of cash flow in rural villages it is unlikely that end-user beneficiaries would be able to raise sufficient capital to cover equipment and transport costs. Village level implementation of hand drilling projects would be very difficult without a certain level of ongoing external government, charity or NGO support.

5.3 Hand Drilling Techniques: Suitability for End-Users

Fast drilling rates and equipment set-up time can save on money, and energy spent during borehole construction. From a beneficiary point of view it is sometimes the case, especially in projects where capital costs are partly subsidised, that the energy and time required for the construction of a water source is a stronger factor influencing choice of technique than the cost. Experience from Simaiwa showed that end-user interest focused more on the ease and speed at which the water table could be penetrated by hand drilling techniques rather than the cheaper cost of construction when compared with hand dug wells. Additionally, issues of equipment availability, ease of transport, and geological suitability were not held in any great importance by end-users. This is most likely due to insufficient levels of community sensitisation to hand drilling techniques prior to implementation.

Field studies, such as this thesis, often result in the compromise of community mobilisation in order to complete an academic study within the time-frame available. This pro-active field study focuses on a particular development aspect of water sources without prior consideration to what the immediate needs and demands of the beneficiaries may be. This can be problematic; the dependency and expectancy of the community upon external support to provide new techniques and water sources can become unrealistic, understanding of how a technique works and confidence to operate a technique amongst end users can be low without external support. Also, end-user motivation to address their own most pressing needs can become limited without high levels of external guidance. It is important, throughout the course of a study of this nature, to constantly explain and remind potential end-users of the true purpose of the study: to assess the suitability of the technology in that particular place. In doing so less confusion will arise over the distinction between an academic field appraisal of hand drilling technologies and a community development project facilitating beneficiaries to address their most urgent needs.

The limited number of field locations in which hand drilling techniques could be successfully applied and the low availability of local PVC and borehole screens were important factors supporting the preference of hand dug wells. The ability of end-users to implement hand dug well projects themselves with minimal external support demonstrates how the technique is suitable in Salima and Mzuzu.

In potential areas of widespread geological suitability to hand drilling, with sufficient community mobilisation it is likely that implementation of hand drilling techniques would have a number of advantages over hand dug wells. Lower costs and faster and easier construction would be the advantages of adopting hand drilling techniques. However, ongoing support would be needed to ensure local availability of hand drilling equipment and materials for operation and maintenance purposes.

Field work experiences showed high levels of end-user enthusiasm towards the introduction of hand drilling technologies. Beneficiary viewpoints of the suitability of hand drilling techniques were in some cases unrealistically high. This was the case at times, in Simaiwa. However, in a number of situations the opinions of end-user beneficiaries proved to be insightful and innovative. A suggestion was made in the Muzgola field area, near Mzuzu, to use hand drilling techniques to test water table levels in order to identify suitable hand dug well locations in clay rich ground conditions. Such end-user enthusiasm for apply innovative technologies, even in areas of limited potential, illustrates the importance of beneficiary motivation in ensuring successful uptake.

5.4 Social Factors and the Uptake of Hand Drilling Techniques

The potential for sustainable village-level uptake of hand drilling techniques, if geological conditions proved to be suitable and sufficient levels of external support were available, would also rely, to a degree, on the levels of co-ordination and initiative within the villages, communities or farming co-operatives themselves. Little time was spent during fieldwork examining such social structures and levels of end-user motivation. However, some general impressions gained from impartial observation and informal questioning are outlined below. These initial observations may form the basis of a more in-depth study of social structure in areas of Malawi with high potential for hand drilling techniques.

The existence of successful government-supported irrigation farming co-operatives, such as that in Simaiwa, demonstrate a good level of co-ordination in some areas of

Malawi between government irrigation officers and farmers. Within the Simaiwa co-operative itself two broad informal groups of landowners were identifiable; a core group who work on their land in the co-operative on a daily basis and a peripheral group who visit their land two or three times a week.

Levels of co-ordination within the core group of about twenty farmers were high. These land-owners included the Simaiwa village chief, the irrigation co-operative chairman and the secretary, most of whom lived close to the co-operative. On a daily basis this group of farmers would attend to their land and share irrigation responsibilities such as treadle pump operation.

The peripheral group were generally farmers who did not live as close to the farmland, and so did not visit their crops on a daily basis. This group of farmers seemed content to operate on a more individual basis sharing irrigation duties only when necessary with neighbouring landowners within the co-operative.

During the implementation of hand drilling techniques, assistance was offered from the core group of farmers. Peripheral farmers also showed an interest in the techniques but were not regularly involved in the drilling operations. The core group of individuals could be described as the so called ‘movers and shakers’ of the cooperative in that they seemed to show the most initiative by voluntarily participating in the hand drilling field-work, carrying out joint irrigation responsibilities and discussing problems and issues with the district irrigation officer. If village level uptake of the hand drilling techniques introduced were to take place, it would most likely be initiated by this core group of individuals.

Two ethnic groups were distinguishable amongst the sixty two Simaiwa Co-operative land-owners; Chewa and Yao. On first impressions it is difficult for an outsider to notice ethnic differences, although the languages used between the two groups are quite different; Chichewa and Chiyao. There did not seem to be a relationship between a particular ethnic group and whether an individual could be broadly classified as core or peripheral to the co-operative set up. However, little field time was spent examining this social aspect of the co-operative community and so no definite conclusions can be made.

In contrast to Salima, the more dispersed nature of village settlements surrounding Mzuzu meant that less time was spent working within a particular community. The accounts of social structure for the Mzuzu field areas are based on impressions gained from about four separate, half-day to day long, visits to each of the areas. The field areas of Daroba, Sonda and Muzgola all consisted of large land areas within which a number of smaller settlements (usually about 20 people in each) were located (Figures 3.9, 3.10 and 3.11). Each area had a male chief who knew many of the inhabitants within the area.

No government supported farming co-operatives were encountered in the Mzuzu field areas. Three irrigation schemes were visited that had been initiated or improved upon with support from the Irish Organisation “Wells for Zoë”. The schemes were built upon reasonable levels of community spirit and co-operation that seems to exist within clusters of settlements in the three areas. Where external support was given, many inhabitants appeared motivated towards the pooling of time and labour to produce a mutually beneficial result. The activity of dam construction for irrigation co-operatives is a good example this.

A number of small irrigation dams had also been constructed in the Mzuzu field areas on an individual basis, without external support, for the benefit of just one or two landowners within the community. It may be the case, that in the absence of an external, motivating force, farmers with sufficient resources are more willing to invest in self benefit schemes than to participate in the pooling of resources for the good of the ‘community’.

5.5 Hand Pump Suitability

Pump suitability, although beyond the main scope of this thesis, is an important consideration in the development of both hand dug well and hand drilled borehole water sources. In the Simaiwa field area of the Salima district it was evident that pressure treadle pumps were robust, locally available and easy to operate. However, limitations of these treadle pumps were pointed out by the village chief. Oil used to lubricate the pump pistons contaminated the water supply and so the pumps were only used for irrigation purposes and not for domestic water supply. The lack of an available piston lubricant alternative limited the scope of treadle pump application.

Pressure treadle pumps did prove to be useful in the process of borehole development, an important part of borehole construction prior to pumping. Their ability to pump air as well as water allowed borehole surging to be carried out (Appendix C, Figure C3) significantly reducing the time and energy needed for the removal of fines around the borehole screen.

In the Mzuzu field areas, the potentially robust Canzee pump was in limited operation with a current lack of spare parts available in the area. The alternative widespread, but more prone to breakdown, Church of Central Africa Presbyterian (CCAP) Mach 5 pump was the main type of shallow well pump in the region with a significant store of spare parts in Mzuzu. There is scope for further research into methods for scaling up the easier to maintain, Canzee pump to widespread use and establishing the long term local production of spare parts.

6. Conclusions and Recommendations

6.1 Geological Conclusions

The primary factors contributing to the success of constructing a viable water source, through hand drilling methods, are the sub surface aquifer conditions. Without the interception of a sufficiently permeable aquifer, at least 2m thick, suitably located below the minimum water table level, and with a lateral extent of over 50m, the likelihood of hand drilling producing a working water source is very low.

Lowland dambos in Malawi tend to have thick accumulations of unconsolidated sediments. Fluvial deposits within these sediment sequences can form units of coarse permeable sands ideal for borehole development. However, geological variability can prolong the search for suitable sand aquifers. Initial investment into field reconnaissance and pilot-hole drilling is needed in such areas. Investment is problematic as it will have uncertain levels of success depending on the degree of geological variability of the particular lowland dambo area studied.

Bedrock geology is extremely important in upland dambos, as it influences the levels of clay that may be found in unconsolidated aquifers. Clay rich formations restrict the rates of groundwater flow and borehole recharge. Geologies rich in clay weathering minerals such as feldspars should be avoided. In the absence of significant bedrock quartz content, it is unlikely that suitable weathered sand units will be present in upland dambo-basement aquifers.

6.2 Drilling Rate Conclusions

Drilling rate efficiency is an important secondary consideration in the process of developing and constructing water sources. Drilling rates of the three techniques tested, vary primarily according to the amount of sub surface clay, grain size and borehole depth. A good knowledge of what drilling technique works best under certain conditions can save significant amounts of time, energy and money during fieldwork. Such information can be gained from drilling experience and through the ongoing analysis and results of field studies.

By using the methods of augering and percussion in combination an efficient means of rapid borehole construction can be established with minimal equipment. Augering and percussion techniques can be efficiently interchanged by means of a simple drill bit change. Treadle pump jetting is limited to fine-medium grained sand formations and requires a long equipment set up time. However, with suitable pump availability, jetting may reduce the amount of drilling time and energy that is spent when using the more laborious percussion technique to penetrate collapsing sands.

6.3 Best Method Conclusions: Hand Drilled Boreholes vs. Hand Dug Wells

In regions of Malawi and indeed throughout sub Saharan Africa distance to water source is a critical factor in determining how and where water is collected. Distance to water can influence levels of energy and time spent during collection. A site specific technique of safe water source construction such as hand drilling can only be effectively applied in areas where the overall geology is favourable to the technique. In cases where one has to search for suitable ground conditions it is probable that the protected borehole water source will be further away from end-users homes than alternative unprotected water sources.

In the case of the dambo field areas of this study, hand dug wells present a method of water source construction that is less limited by geological conditions and can be more widely used than hand drilled boreholes. The extra labour, higher construction cost, and longer time spent for the construction of hand dug wells are cancelled out by the ability to construct water points closer to beneficiary’s homes or land.

6.4 Recommendations: Further testing of Upland Dambo Hand Drilling Potential

Further study is needed in identifying areas where hand drilling techniques can have widespread use. Areas of sufficiently permeable, laterally continuous aquifers within 20m of the ground surface and a year-round high water table are most suited to hand drilling techniques. Such areas may occur near ancient large fluvial systems or in upland areas of quartz rich bedrock with minimal clay content. Where suitable geology is discovered over large areas, the advantages of cheaper, safer and faster hand drilling will outweigh the need for hand dug well construction.

6.5 Recommendations: Niche Environment Terminology and Classification

The term “dambo” is perhaps used too generally and describes too wide a range of seasonally flooded topographical lows. A need exists for more site specific terminology to be used when describing areas of certain geology and aquifer occurrence. A tighter fitting terminology would enable more meaningful assessments to be carried out regarding the suitability of certain hand drilling techniques in particular niche environments.

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9. Appendices

9.1 Appendix A: Drilling Equipment

9.1.1 Hand Augering Equipment

Figure A1. Edelman Auger Bit (External Diameter 65mm)

Figure A2. Edelman Auger Bit (External Diameter 95mm)

Figure A3. Riverside Auger (External Diameter 60mm)

Figure A4. Riverside Auger (External Diameter 88mm)

Figure A5. Auger Bit Conical Screw Thread to locally threaded extension pipe adapter

Figure A6. Reducing Connector: ¾ inch to ½ inch

9.1.2 Hand Percussion Equipment

Figure A7. Steel Sand Bailer with extension rod adaptor attached

(External Diameter 70mm)

Figure A8. Non return flap valve at the cutting end of the Steel Sand Bailer

Figure A9. Adaptor bit to attach Steel Sand Bailer to extension pipe

Figure A10. Loose Steel Sand Bailer Adaptor Bit

Figure A11. Strengthened Nut and Bolt for adaptor attachment to Steel Sand Bailer

9.1.3 Extension Poles for Augering and Percussion

Figure A12. Two ¾ inch galvanised steel extension rod pipes attached using a ridged ¾ inch connector

Figure A13. Ridged ¾ inch extension pipe connector

Figure A14. Auger and Percussion drilling handle made from ¾ inch galvanised steel pipe and a T connector

Figure A15. ¾ inch T connector

9.1.4 Borehole Jetting Equipment

Figure A16. Borehole Jetting Equipment set up.

Treadle pump hose attached to 75mm PVC casing using a plastic bottle secured tightly with rubber band. Casing handle constructed from a 75mm – ¾ inch clamp saddle and two equal lengths of ¾ inch galvanised pipe

Figure A17. The cutting edge of PVC casing used for borehole jetting.

Serrated using a hacksaw to help the PVC casing grip into the down-hole sands.

Figure A18. Casing Handle consists of two clamp saddle and galvanised pipe sections screwed together

9.1.5 Other Drilling Equipment

Figure A19. Copper Grease used to soften all threaded connections and ensure easy opening.

Figure A20. Two adjustable wrenches used for extension rod connection and disconnection.

Figure A21. Two adjustable spanners used for auger bit disconnection.

Figure A22. Drilling plate designed to fit over the borehole while drilling.

Used to keep extension rods straight, and to allow easy connection and disconnection of extension rods.

Figure A23. Hand Augering equipment in action in the Salima Field Area, Simaiwa.

9.2 Appendix B: Drill Hole Geological and Drilling Rate Logs

This Appendix is a collection of the drill-hole geological and drilling rate logs for all boreholes constructed during fieldwork. The logs shown are scanned neat copies of the original field logs.

Figure B1. Simaiwa Borehole 1, down hole geological and drilling rate log.

Figure B2. Simaiwa Borehole 1 re-drill, down hole geological and drilling rate log.

Figure B3. Simaiwa Borehole 2, down hole geological and drilling rate log.

Figure B4. Simaiwa Borehole 3, down hole geological and drilling rate log.

Figure B5. Simaiwa Borehole 4, down hole geological and drilling rate log.

Figure B6. Simaiwa Borehole 5, down hole geological and drilling rate log.

Figure B7. Simaiwa Borehole 6, down hole geological and drilling rate log.

Figure B8. Simaiwa Borehole 6 re-drill, down hole geological and drilling rate log.

Figure B9. Simaiwa Borehole 7, down hole geological and drilling rate log.

Figure B10. Simaiwa Borehole 8, down hole geological and drilling rate log.

Figure B11. Simaiwa Borehole 9, down hole geological and drilling rate log.

Figure B12. Simaiwa Borehole 10, down hole geological and drilling rate log.

Figure B13. Simaiwa Borehole 11, down hole geological and drilling rate log.

Figure B14. Sonda Borehole 1, down hole geological and drilling rate log.

Figure B15. Sonda Borehole 2, down hole geological and drilling rate log.

Figure B16. Sonda Borehole 3, down hole geological and drilling rate log.

Figure B17. Sonda Borehole 4, down hole geological and drilling rate log.

Figure B18. Sonda Borehole 5, down hole geological and drilling rate log.

Figure B19. Sonda Borehole 6, down hole geological and drilling rate log.

Figure B20. Muzgola Borehole 1, down hole geological and drilling rate log.

Figure B21. Muzgola Borehole 2, down hole geological and drilling rate log.

9.3 Appendix C: Simaiwa Pumping Test Reports

The pumping tests reports presented in this appendix are given in chronological order. This does not follow the chronological order of drilling that took place in Simaiwa.

9.3.1 Simaiwa Hole 4 Data

Hole 4 was identified as a potential pumping hole as it intercepted 2.5m of sand at a depth of 3.5m to 6m. The water table at the time of drilling was 1.97m. The main units intercepted down hole were as follows:

0.0m – 0.3m	Topsoil	
0.3m – 3.3m	Clay	
3.5m – 6.0m	Sand	(Fine to medium grained. Coarse grained at 4.6 – 5.4m)
6.0m – 6.4m	Clay	

The 2.5m thick sand unit intercepted, appeared very similar in grain size and grain distribution to type sand intercepted in Simaiwa Hole 7. A sample was taken from Hole 7 at a depth of 5 -6m. A volumetric grain size analysis was carried out on this type sand sample; a transparent plastic container of known volume was used in which the sand sample was settled out in water. The volume proportions of different grain sizes were measured upon settling out of the sample (after two days). The particle size distribution curve for this type sand is shown in Figure C1.

Figure C1. Particle Size Distribution Curve for Type Sand Sample in Simaiwa Hole 7

The Uniformity Coefficient (D_{60}/D_{10})[11] for the type sand is 1.35, with a D_{10} grain size value of 200um. In light of these measured values, geo-textile[12] installation was deemed necessary prior to the pumping test on Hole 4.

Estimations of drawdown levels were calculated using Jacob's Equation[13]. Drawdown[14] estimates ranged from 2.06m to 8.79m. Estimates were based on 6 hours continuous pumping, a confined aquifer storativity[15] value of 0.001, a medium sand conductivity[16]

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[11] A value used to quantify the distribution of particle sizes in a sample: the 60% finer-than value divided by the 10% finer than value, calculated using the particle size distribution curve in Figure C1.

[12] Rot-proof, permeable fabric used to prevent the intake of fine grained material into the borehole during pumping.

[13] An analytical groundwater flow equation that can be used to predict drawdown levels and the lateral extent of drawdown on the water table surface (radius of influence) during pumping.

[14] The lowering of the water table that occurs during borehole pumping. Drawdown values in this study are stated in metres below the water table level, unless otherwise specified.

[15] The volume of water that an aquifer can release from storage per unit surface area of the aquifer per unit change in head (Todd, 1980).

[16] The rate at which groundwater can move through the pore spaces of an aquifer.

range of 2.5 – 12m/day (Todd, 1980), and an average discharge of 2.5l/s typical of suction treadle pumps (Kay & Brabben, 2000) that has been applied to pressure treadle pumps for the purposes of these estimations..

9.3.2 Simaiwa Hole 4, Methodology and Results of Pumping test

On the 28th of June, 75mm, Grade 10, PVC borehole casing was installed to 6m depth in Simaiwa Hole 4 (the bottom 40cm of the hole had filled with down-hole caved material). The bottom 2m of casing (from 4m to 6m down hole) were screened and wrapped with synthetic filter material (an oven filter) acting as a geo-textile. The water level inside the casing was measured at 1.7m and the water level outside the casing was 1.65m. The reference rest water table level during pumping tests was taken as 1.7m as all drawdown measurements were taken inside the casing. Coarse sand taken from a nearby hand dug well spoil heap was used as the formation stabiliser[17]. The sanitary seal[18] was then constructed using locally available, near surface, clay.

Borehole development[19] was conducted using the percussion bailer (Appendix A, Figure A7). Bailer flushing involved rapidly lifting and lowering the bailer tool to surge the borehole. This procedure was carried out for 30 minutes.

Pumping using a pressure treadle pump was then attempted. Three short pumping tests were conducted (Table C1).

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[17] Permeable material used to backfill the borehole annulus used to stabilize the zone around the borehole casing.

[18] Impermeable material used to backfill the borehole annulus close to the surface to prevent contaminants seeping from the surface into the groundwater borehole water supply.

[19] The act of removing fine grained material from the aquifer proximal to the borehole screen in order to maximize the yield and lifetime of the borehole.

Simaiwa Hole 4 - Pumping Test Records		
Pumping Time (mins)	***Water level immediately after pumping***	***Discharge l/s***
0.08 mins (5 secs)	2.6m	1.10
0.33 mins (20 secs)	3.4m	1.10
0.33 mins (20 secs)	3.2m	1.10

Table C1 Simaiwa Hole 4 Pumping Test Records

Pumping could not be carried out for longer than 20 seconds as the treadle pump continuously began to pump air. The water level in the borehole consistently fell below 4m (the length of the treadle pump suction hose) and thus rendered further pumping impossible.

9.3.3 Simaiwa Hole 4, Analysis of pumping test results

Two possible reasons for excessive drawdown levels (over 2.3m below the rest water table level) were identified. The transmissivity[20] and lateral extent of the aquifer was either too low or the geotextile material was unsuitable and may have become blocked.

Reasonably rapid recovery of the water level (consistently returned to a level of 2.3m below the ground surface within 3 minutes of the pumping test) suggested that the geotextile was not blocked and that low aquifer transmissivity and limited lateral extent were the main factors contributing to excessive drawdown.

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[20] A measurement of aquifer groundwater water yield to wells or boreholes taking into account aquifer thickness and permeability.

9.3.4 Simaiwa Hole 6 Data

Hole 6 was originally drilled to 3.95m. At this depth coarse waterlogged sand caused the hole to collapse. Further drilling was postponed until permanent casing with a screened section was obtained. The water table at the time of initial drilling was 2.05m. Percussion drilling inside casing was the main drilling method used. The treadle pump jetting technique was attempted, however poor water circulation, due to highly permeable sand units down-hole, rendered this technique unsuitable.

One week later, on the 29 June, this hole was re-drilled to a depth of 6m. The starting depth at the time of re-drill was 2.90m (hole caving had reduced the depth by 95cm). Open-hole percussion drilling was conducted to a depth of 4.50m. In order to insert casing down the hole, the large riverside auger was used to ream[21] the hole to a wider diameter of 88mm. At this depth excessive caving occurred and so the screen and casing were inserted. Percussion drilling inside the casing was continued to 5.9m, as drilling progressed the casing and screen were reamed down to the same level as the percussion bailer . Further drilling would have been possible but was discontinued because a depth of almost 4m below the water table had been achieved. The 4m treadle pump suction hose that was locally available, rested at an ideal level just above the 2m screened section of PVC casing.

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[21] To enlarge the borehole diameter using a larger diameter auger head.

The summary of down-hole intercepted strata is as follows:

0.00 – 0.35m	Topsoil
0.35 – 1.72m	Clay / Sand
1.72 – 3.65m	Medium to Coarse grained Sand
3.65 – 3.80m	Very Coarse Sand
3.80 – 5.00m	Medium Sand
5.00 – 5.90m	Coarse Sand

The almost 4m thick, sand aquifer unit was taken as a type sample for medium to very coarse sand in the Simaiwa area. As the grains tended to be rounded, occasionally graded and moderately sorted it was likely that the material is fluvial in origin. An estimate of the particle size distribution for this aquifer material was made, as shown in Figure C2.

Figure C2 Particle Size Distribution Curve for Type Sand Sample in Simaiwa Hole 6

The Uniformity Coefficient is estimated at 2.05, and D10 is approx. 215um. Both of these criteria suggest a geo-textile or gravel pack[22] should be used. The hole diameter was not large enough to use a gravel pack. No geo-textile was used; it would have been damaged as casing was reamed down-hole.

Using Jacobs Equation, drawdown estimates range from 0.96m to 3.89m, based on 6 hours continuous pumping, an unconfined aquifer storativity of 0.1, a conductivity range of 2.5 – 12m/day (Todd, 1980), and a design discharge of 2.5l/s typical of suction treadle pumps (Kay & Brabben, 2000) which is also applied to pressure treadle pumps for the purposes of these calculations.

9.3.5 Simaiwa Hole 6, Methodology and Results of Pumping Test

Coarse sand left over from the digging of a nearby hand dug well, was used as formation stabiliser. This material filled the hole annulus to a depth of 45cm below the surface.

Borehole development of Hole 6 involved three stages. Firstly bailer surging was carried out for 30 minutes, this proved to be very strenuous as it involved lifting and dropping the percussion tool within the water filled screened section. Following bailer surging, water was rapidly removed from the borehole using a bailer for 15 minutes. No change in rest water level was recorded during bailing; the 2.20m rest water level observed during re-drilling the hole was maintained. The water remained sediment rich during these first two stages. Finally, a pressure treadle pump was reversed (suction hose at the surface and discharge hose down-hole) and used to surge air down the hole. This method of borehole development was used for 30 minutes and proved to be highly effective in the removal of fines close to the borehole screen and the establishment of clear water in the borehole (Figure C3).

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[22] Well rounded gravel particles placed down the hole, around the borehole screen. It is used to minimize the pumping of fine grained material into the borehole, and improve the borehole yield.

Figure C3 Reverse treadle pump air surging borehole development

The bottom of the borehole was sealed with a coarsening up sequence of rock (gneiss) fragments. A pumping test was then carried out using the treadle pump to determine drawdown levels and aquifer material transmissivity. Five pumping durations (from 20 seconds to 10 minutes) were tested. In each case the rest water level was recovered within 1.5 minutes of pumping. The water level was recorded immediately after pumping by rapidly removing the suction hose from the hole and inserting a long bamboo to act as a dipstick from which the water level mark could be measured. The results of the variable time, pumping tests are shown in Table C2.

Simaiwa Hole 6 - Pumping Test Records		
Pumping Time (mins)	***Water level (metres below surface) measured immediately after pumping***	***Discharge l/s***
0.33 mins (20 secs)	2.20m	1.25
1 min	2.50m	1.80
2 min	2.45m	1.50
5 min	2.40m	1.64
10 min	2.30m*	1.48

* Data subject to error during measuremnt due to delay between end of pumping and measurement

Table C2 Simaiwa Hole 6 Pumping Test Records

An average discharge rate of 1.53l/s was calculated. In most cases, a lower discharge rate resulted in reduced levels of drawdown. Longer pumping durations required more energy to operate the treadle pump, this lead to a slightly lower average discharge over a longer period of time, and thus smaller levels of drawdown occurred.

Using Jacob's equation with a maximum drawdown value of 30cm, the actual transmissivity value for the 3.8m thick aquifer is calculated as 16m^3/day, with a radius of influence of 3m (see footnote 13).

9.3.6 Simaiwa Hole 6, Analysis of Pumping Test Results

Despite the absence of a geo-textile and gravel pack, the medium to very coarse aquifer material intercepted in Simaiwa Hole 6 formed a viable water source yielding an average discharge of 1.53l/s using a pressure treadle pump. The aquifer is judged to be unconfined and so its high storativity gives rise to a small (3m) radius of influence. Borehole 6 has provided a successful alternative irrigation water source to hand dug wells for the farmers of the Simaiwa cooperative (Figure C4).

Figure C4 The successful use of hand drilled borehole 6 for irrigation in Simaiwa

9.3.7 Simaiwa Hole 1 Data

Hole 1 was originally drilled to a depth of 4.25m. A combination of Edelman and riverside augering as well as open and cased hole percussion drilling was used to reach this depth. Medium to coarse grained collapsing sands were encountered at 3.5m to 4.25m and so further drilling was postponed. The water table level during initial drilling was measured at 1.72m.

Two weeks later on June 30th, drilling recommenced from a starting depth of 3.1m (down-hole caving had reduced the hole depth by 1.15m). A combination of open hole and then cased hole percussion drilling was used to reach a final depth of 5.8m. Further drilling was not possible due to the very slow rate of progress through very coarse grained sand (up to 2000um). The water table level had risen to 1.55m since the initial stages of drilling; this suggested that the down-hole aquifer was confined with groundwater stored under slight pressure.

The down-hole units intercepted are summarised as:

0.00m – 0.50m	Topsoil
0.50m – 1.20m	Medium grained Sand
1.20m - 1.80m	Silt / Clay
1.80m – 3.10m	Medium grained Sand
3.10m – 5.50m	Coarse grained Sand (minor Clay at 4.50m – 4.80m)
5.50m – 5.80m	Very Coarse grained Sand

The 4m of aquifer material intercepted from 1.8m to 5.8m consisted of similar grain sized sand to the type sand sample taken from Simaiwa Hole 6. Therefore the grain size analysis data used for Hole 6 (Figure C2) was also used for this hole. A geo-textile or gravel pack again was not used as the borehole diameter was not wide enough for gravel pack installation and the method of percussion drilling inside casing would have damaged a geo-textile during screen installation.

Using Jacob's equation, drawdown estimates range from 1.39m to 5.97m, based on 6 hours continuous pumping, a confined aquifer storativity of 0.001, a conductivity range of 2.5 – 12m/day (Todd, 1980), and a design discharge of 2.5l/s typical of suction treadle pumps (Kay & Brabben, 2000) applied to pressure treadle pumps for the purposes of these estimations.

9.3.8 Simaiwa Hole 1, Methodology and Results of Pumping test

Again coarse sand from a nearby hand dug well spoil heap was used as the formation stabiliser with near surface clay used as the sanitary seal. Formation stabiliser was inserted and filled up to 2.15m depth from the surface (after settling out of material), the sanitary seal was then used to backfill the remaining borehole annulus to the surface.

Borehole development was conducting using a combination of the treadle pump to surge air down hole and the percussion bailer to remove sand from the borehole. The bottom of Hole 1 was sealed with a PVC cap; no stone fragments were needed to seal the hole.

Treadle pump air surging was carried out for 1 hour, no colour change in the sediment rich water was observed. The percussion bailer was then used to remove 1m of clay and fine sand that had entered the hole through the screen. Treadle surging was then continued for a further 2.5 hours. No water colour change was observed; the water remained sediment rich.

A brief pumping test yielded a water level drop to 3.25m after 15 seconds of pumping with a discharge of less than 0.5 l/s. Pumping could not continue for longer as the sediment rich water could not be pumped using the treadle pump. Continued pumping also caused the water level to drop below the level of the suction hose.

9.3.9 Simaiwa Hole 1, Analysis of pumping test results

Upon closer examination of the borehole log it is evident that although 4m of sand was intercepted, it is only the bottom 2m of sand in the borehole that is sufficiently coarse enough to achieve the permeability levels needed for borehole pumping. It is likely that the transmissivity value of this thin permeable aquifer unit was too low to prevent excessive drawdown levels occurring. It also seems that a significant fine sand and clay fraction continuously entered the borehole through the screen during pumping. The use of a geo-textile may have prevented this occurrence but would not have prevented the excessive drawdown levels from re-occurring.

9.4 Appendix D: Drilling Rate Analysis

Three broad techniques of hand drilling were used in this study; Hand augering, hand percussion and treadle pump jetting. The particular drilling techniques used are categorised as follows:

- Hand Augering with 65mm external diameter, Edelman Auger Bit
- Hand Augering with 95mm external diameter, Edelman Auger Bit
- Hand Augering with 60mm external diameter, Riverside Auger Bit
- Hand Augering with 88mm external diameter, Riverside Auger Bit
- Hand percussion in open hole with 70mm external diameter bailer
- Hand percussion in cased hole with 70mm external diameter bailer
- Treadle pump jetting with 75mm, Class 10 PVC casing and serrated PVC bit

The following set of 21 graphs each illustrate the change in drilling rate according to the down-hole geology intercepted and the drilling technique used for each borehole.

The blue dotted-lines, visible on the graphs, indicate the water table level at the time of drilling. Where one drilling technique was used continuously, data points are joined with a trend-line to illustrate the progressive change in drilling rate for that technique. A trend-line has not been used to join different data-sets from different drilling techniques, in doing so would have falsely represented a progression in drilling rate without considering the time taken to change the equipment from one technique to another.

Water Table

Figure D1. Simaiwa Borehole 1 Drilling Rate and Geological Data

Water Table

Figure D2. Simaiwa Borehole 1 Re-drill Drilling Rate and Geological Data

Water Table

Figure D3. Simaiwa Borehole 2 Drilling Rate and Geological Data

Water Table

Figure D4. Simaiwa Borehole 3 Drilling Rate and Geological Data

Water Table

Figure D5. Simaiwa Borehole 4 Drilling Rate and Geological Data

Water Table

Figure D6. Simaiwa Borehole 5 Drilling Rate and Geological Data

Water Table

Figure D7. Simaiwa Borehole 6 Drilling Rate and Geological Data

Water Table

Figure D8. Simaiwa Borehole 6 Re-drill Drilling Rate and Geological Data

Water Table

Figure D9. Simaiwa Borehole 7 Drilling Rate and Geological Data

Water Table

Figure D10. Simaiwa Borehole 8 Drilling Rate and Geological Data

Water Table

Figure D11. Simaiwa Borehole 9 Drilling Rate and Geological Data

Water Table

Figure D12. Simaiwa Borehole 10 Drilling Rate and Geological Data

Water Table

Figure D13. Simaiwa Borehole 11 Drilling Rate and Geological Data

Water Table

Figure D14. Sonda Borehole 1 Drilling Rate and Geological Data

Water Table

Figure D15. Sonda Borehole 2 Drilling Rate and Geological Data

Water Table

Figure D16. Sonda Borehole 3 Drilling Rate and Geological Data

Water Table

Figure D17. Sonda Borehole 4 Drilling Rate and Geological Data

Water Table

Figure D18. Sonda Borehole 5 Drilling Rate and Geological Data

Figure D19. Sonda Borehole 6 Drilling Rate and Geological Data

Water Table

Figure D20. Muzgola Borehole 1 Drilling Rate and Geological Data

Water Table

Figure D21. Muzgola Borehole 2 Drilling Rate and Geological Data

The hand drilling rates achieved in this project ranged from about 0.001m per minute to 0.2 metres per minute, with an average rate of 0.06m per minute.

It is difficult to draw definitive conclusions from the graphs shown. A number of unaccounted for, external factors can also influence drilling rates, such as drilling operator experience and weather conditions (a very hot day can reduce the drilling rate significantly).

Every effort has been made during fieldwork to ensure a constant level of drilling operator speed was maintained. In spite of such effort, it is likely that increased drilling efficiencies, due to a build up in experience of using the technique over time, will have resulted in faster drilling rates in the later holes drilled (e.g. The Sonda and Muzgola holes in the Mzuzu field areas).

The number of drill operators can also affect drilling rates; generally an absolute maximum of four drilling operators is needed at any one time (two drillers, one depth measurer and time keeper, one bit cleaner and extension rod connector). Larger numbers of operators can lead to confusion and slower drilling rates.

The number of external variables affecting the drilling rate dataset collected is too great to realistically embark on a statistically rigorous quantitative analysis. Instead, a more qualitative approach has been adopted. The graphed data has been examined and general recurring trends have been noted below.

1. The Edelman augers, in most cases, drill at faster rates than the Riverside augers through similar dambo geological units. (E.g. Simaiwa Holes 6, Sonda hole 4 & Muzgola hole 1).

2. Percussion drilling rates increase with larger grain size. (E.g. Simaiwa Holes 1 & 6 Redrill).

3. The jetting technique proceeded at the fastest rate, however its long set-up time (usually 1.5 hours) and limited applicability to just medium grained sands (when using a pressure treadle water pump) slows down the overall drilling operation rate. (E.g. Simaiwa Holes 4 & 6).

4. The effect of depth on drilling rate is usually an overall gentle decreasing trend in the measured rate. This trend is often obscured or hidden by more sudden short term drilling rate variations that correlate to changes of drilling technique, and alterations in grain size, clay content and sand content of the sub-surface material. (E.g. Simaiwa Holes 4, 5, 9, Sonda holes 1, 3, 4, 6, Muzgola holes 1 &2).

5. An increase in grain size and/or a decrease in clay content often correlate with an increase in augering or percussion drilling rate. (E.g. Augering: Simaiwa holes 5 at 3m, 6 at 2.5m. Percussion: Simaiwa holes 1 & 6)

6. The Edelman auger tends to proceed at faster rates in sand than it does in clay. That is, provided the clay content within the sand is sufficient (10-25%) to act adhesively with the auger head. (E.g. throughout Simaiwa holes 3, 8 & 9, and Simaiwa hole 5 below 4m).

7. Edelman auger rates within clay units tend to display a decrease that often coincides with the interception of the water table. (E.g. Simaiwa holes 2, 4 & 9).

8. Edelman drilling rates through loose topsoil are often slower than through deeper more cohesive units. (E.g. Simaiwa holes 5, 10 & 11).

9. Augering rates generally decrease upon intersection of saprolite units. (E.g. Sonda holes 1, 3, 4 & 5, Muzgola holes 1 & 2).

10. Percussion drilling in open hole is generally faster than percussion drilling inside casing. It is necessary to point out however, that percussion drilling inside casing was only undertaken in unstable sand units, whereas open hole percussion was used in stable sand formations. (E.g. Simaiwa holes 1, 1 Redrill & 6).

The time interval over which drilling rate is measured has a significant influence on the values recorded. Long time intervals between recordings will give rise to a gradual, gently changing drilling rate dataset. Shorter time intervals will result in a more pronounced, sharply fluctuating drill rate dataset; due to the number of external variables that can immediately influence short term drilling rates.

The set of ten observations listed above are by no means conclusive. Their purpose is to document the general correlations of geological variables and drilling techniques with the recorded drilling rates. In some cases, exceptions to these general observations occur. The graphs in this appendix have been purposely left blank of any interpretation so as not to hinder the reader from drawing further interpretations of the data presented in combination with other datasets.