IMPROVING APPROPRIATE TECHNOLOGIES FOR SMALL SCALE IRRIGATION IN SEMI-ARID AREAS: A CASE STUDY ON MABOTE DISTRICT OF MOZAMBIQUE

By

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CHAPTER I

GENERAL INTRODUCTION

Rain fed agriculture in Sub-Saharan Africa proved to be a challenge to many small scale farmers due to spatial and temporal variability in rainfall, which is acute in arid and semi-arid areas. This challenge is extended to all individuals, including engineers, who perform activities related to food production in these areas. The agricultural background of sub Saharan Africa paints a scenario composed by a significant number of “historically disadvantaged” farmers that produce in small scale and lack resources to pursue larger scale and more profitable agriculture. These farmers are often limited by geographical, climate and economical constraints of sub-Saharan countries. Those constraints dictate an uneven distribution of development in a given country and lead whoever wants to help these farmers to improve their productivity to stumble upon the realm of the ‘Appropriate Technologies’.

Appropriate technologies are defined as small scale, labor intensive, low cost, sustainable technologies that are appropriate for particular environmental, social and economic conditions (in www.villageearth.org/ Appropriate_Technology/). This vast menu of technologies has been used throughout the world to help farmers bridge from small scale to a more commercial agriculture.

During the author’s professional and academic journey in Mozambique, the author worked in the semi-arid region of the country and witnessed the use of such technologies for supplemental irrigation. The author noted ineffectiveness of some of the technologies due to implementation, thus the interest in researching such technology was born. The author believes that improvement in the effectiveness of such technologies can be accomplished by conducting “basic research”, which would allow the adoption of the technology to a specific region and demographic.

The master's thesis presented a research opportunity and an occasion to increase the author's knowledge on appropriate technologies. Therefore, the present thesis focuses in the improvement of two technologies currently in use for small scale irrigation in the Mabote district located in the semi-arid region of Mozambique: the use of runoff harvesting structures for water storage, and the use of human powered pumps for irrigation. Both subjects are discussed in the following chapters. The author hopes that the information produced herein helps to improve the implementation of these two technologies in Mozambique and in Sub Saharan Africa, in general.

CHAPTER II

IDENTIFICATION OF SITES FOR RUNOFF HARVESTING STRUCTURES

Introduction

Food production is a challenge in the developing world, and according to Critchley et al. (1991) more and more marginal lands are being used for this purpose in arid or semi-arid areas. Semi arid areas are characterized by erratic and low rainfall events that often result in low yields or crop failure for rainfed agriculture (Barron and Okwach, 2005). Droughts are considered a major cause of crop failure and could be reduced by the implementation of improved farming practices to increase rainfall infiltration and reduce runoff (Barron and Okwach, 2004) and also by the practice of supplementary irrigation (Critchley et al., 1991).

Supplementary irrigation is a practice that provides water to the crops in periods where soil water is not naturally recharged by rainfall. This practice requires the existence of a water source in sufficient volumes for effective crop irrigation. Sources include rivers, lakes, boreholes and underground water, but those sources may not exist or may not be evenly distributed in a specific region. For such cases, rainwater and runoff can be harvested and used (Ziadat et al. 2006 cited by De Winnaar et al. 2007).

Structures used for runoff water harvesting include dams. According to Nissen-Petersen (2006), the word “dam” is used for almost every type of water reservoir built of soil, added to the prefix that expresses the size, such as “small dams” as an example. Small dam classification applies to earth dams (Lasage et al. 2008), which are structures built by excavating a depression for water storage and using the removed soil to increase the storage volume by depositing it in the lower side of the water reservoir (Nissen-Petersen, 2006). These structures are used in several countries in drier areas of sub-Saharan Africa including Kenya and Tanzania (Nissen-Petersen, 2006; Lasage et al. 2008; Ertsen and Hut, 2009).

Mozambique is a country in sub-Saharan Africa, where a large area in the southern region (Inhambane and Gaza provinces) is classified as arid and semi-arid (Reddy, 1984). The Mabote district in Inhambane province is within this semi-arid area. Earth dams are currently in use in this district. Brito and Tamele (2008) reported the existence of three ground tanks in the district, where by 2009 only one was functional. Failure of these structures, characterized by non accumulation of runoff water, resulted in loss of money and time invested in their construction. The same authors hypothesized inadequate site selection and sizing as the main causes of failure, which resulting from installation on soils with high permeability and in oversized structures respectively. According to Forzieri et al. (2008) adequate sizing and site location are required for the effectiveness of such projects.

Site selection for earth dams could be facilitated by the use of geographical data where Geographic Information Systems (GIS) are tools widely used to produce and analyze such data. Padmavathy et al. (1993), Prinz et al.(1998), Zhan and Huang (2004) and De Winnaar et al. (2007), have successfully used GIS to assess the potential for runoff production and site selection for other regions of interest. Therefore, this project uses GIS as a tool to process landuse, soil and slope data to achieve the following objectives:

- Evaluate the Mabote district suitability for rainwater harvesting in general and for the installation of earth dams in particular.
- Create theoretical reference site selection maps of the Mabote district, for runoff harvesting purposes.

Study area

Mabote is a district of the Inhambane province, which is located in the southern region of Mozambique (Figure 1). It has an area of 14,577km^2 and a population of 45,101, according to the 2007 census (Governo do Distrito de Mabote - Mabote Government, 2008). Due to its geographical location, the climate is semi-arid with a dry and a rainy season. The dry season lasts 8 months and the rainy season is shorter; lasting for 4 months, with total annual rainfall ranging from 400-600mm. During the rainy season, a majority of the population pursues rainfed agriculture (Governo do Distrito de Mabote - Mabote Government, 2008). Rainfall is erratic and not uniformly distributed along the district increasing the risk of yield loss due to water stress and crop failure.

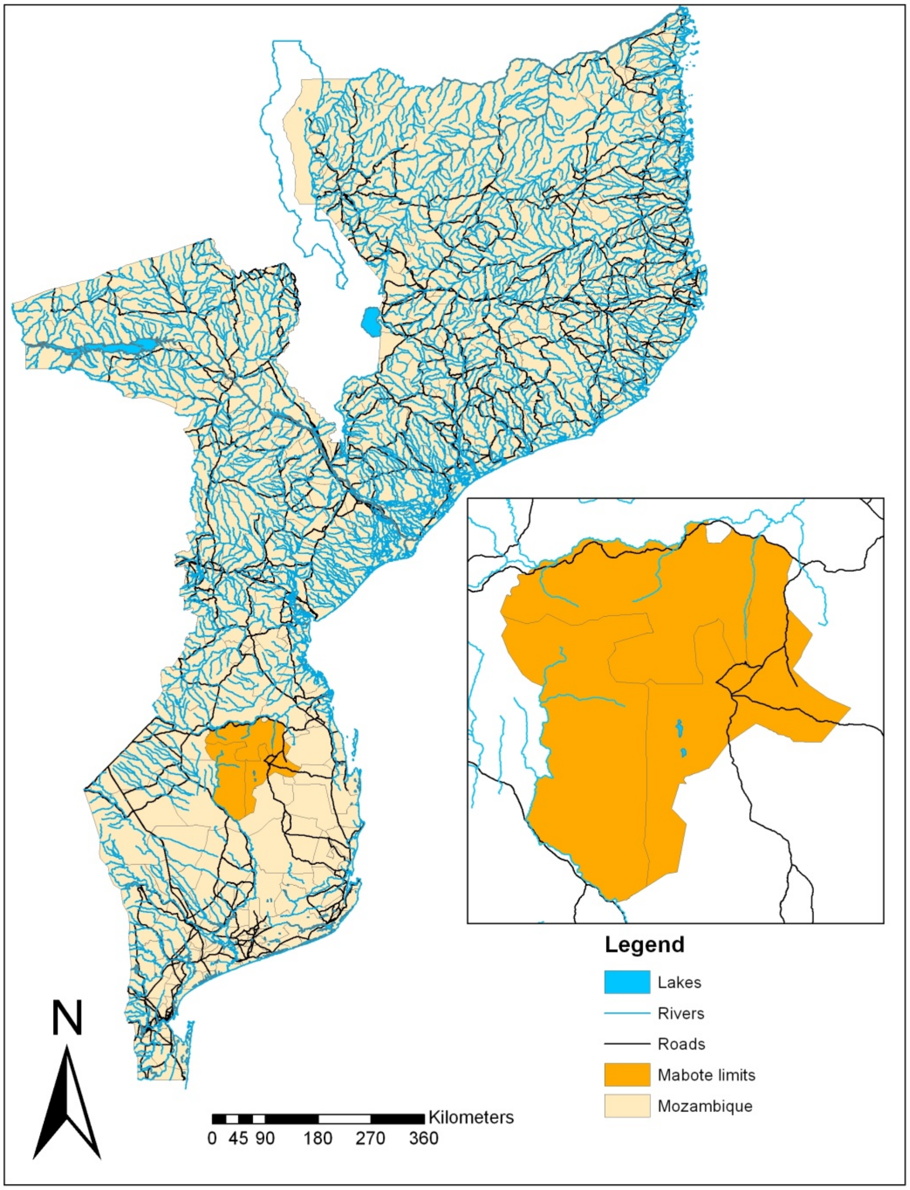

Figure 1: Mabote district in Mozambique.

Methodology

Creation of suitability maps for runoff harvesting has been explored by different authors (Padmavathy, 1993; De Winnaar, 2007; Forzieri, 2008). These authors have taken into account landscape factors that affect runoff production including soils, topography, land cover, geology and hydrogeography, and other criteria that affect site selection such as social factors, proximity to residential areas and roads. In this study, soils, landuse and slope were the main factors considered for runoff production, where other relevant factors taken into consideration were the proximity to water bodies and roads. The spatial interaction of all these factors was analyzed using ArcMap version 9.3 (ArcGIS, 2008), where a variety of tools and operations were used. The different steps are presented in Figure 2, where rectangles represent an input/output and ellipses represent an ArcMap operation. This study uses the curve number (CN) approach, developed by Soil Conservation Services (SCS-NRCS), to assess the potential that different combinations of soil and land uses have for runoff production. This parameters combined with the slope distribution of the study area provides a suitability ranking based on criteria explained further ahead. To calculate CN the HEC-GeoHMS extension for the ArcMap was used.

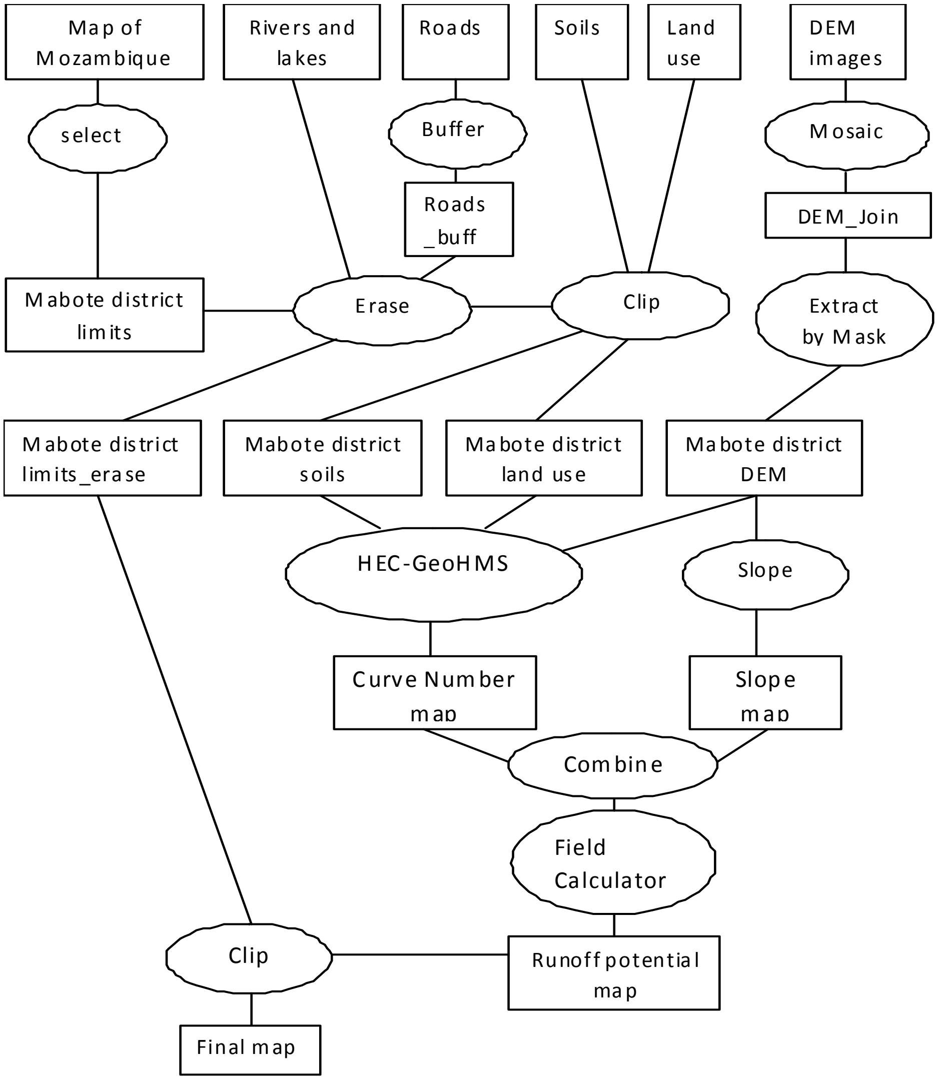

Figure 2: Flow diagram of the methodology used.

Data acquisition

Several internet sources were used to acquire data for this study. A description of the data and its sources is provided in Table 1.

Table1: Data description.

Layer	Description	Use	Source
Map of Mozambique	Format: Shapefile (polygon) with table of attributes. Scale: 1:250,000	Used to locate the Mabote district.	www.cenacarta.com
Lakes and rivers of Mozambique	Format: Shapefile (polygon and lynes) with table of attributes. Scale: 1:250,000	Used to locate rivers and lakes within the Mabote district. Suitable areas for rainwater will not be on areas with lakes or rivers.	www.cenacarta.com
Roads of Mozambique	Format: Shapefile (lynes) with table of attributes. Scale: 1:250,000	Used to locate roads within the Mabote district. Suitable areas for rainwater will not be on areas with roads.	www.cenacarta.com
Soil map of Mozambique	Format: Shapefile (polygon) with table of attributes. Scale: 1:250000	Used to determine Hydrological soil groups. Information needed to calculate runoff using the Curve Number method.	Mozambique national soils map-IIAM 1995
Land use map of Mozambique	Format: Shapefile (polygon) with table of attributes and lookup tables. Scale: 1:250000	Used to determine parameters of the Curve Number method	http://www.fao.org/geonetwork/srv/en/main.home
Digital Elevation Model (DEM)	Format: Satellite image Resolution: 30mx30m	Used to create a slope map of the Mabote district.	http://www.gdem.aster.ersdac.or.jp/search.jsp

A personal geodatabase, constituted by the data described above, was created and managed using the ArcCatalog ver 9.3 (ArcGIS, 2008). To maintain accuracy for data display and analysis, the spatial reference GCS_Tete (Datum: D_Tete) was used, which is the default for the map of Mozambique shapefile.

Slope map

DEM images covering the Mabote district were used to create a slope map using the spatial analyst tool in the ArcMap environment. This tool calculates the slope for each DEM cell based on the ratio between rise and run. The DEM images were downloaded with the grids in degree units. Aiming to obtain accurate slope calculations in percentage, the images were re-projected to the WGS_1984_UTM_zone_36S which is a Universal Transverse Mercator (UTM) spatial reference. The slope map produced is presented in Figure 3.

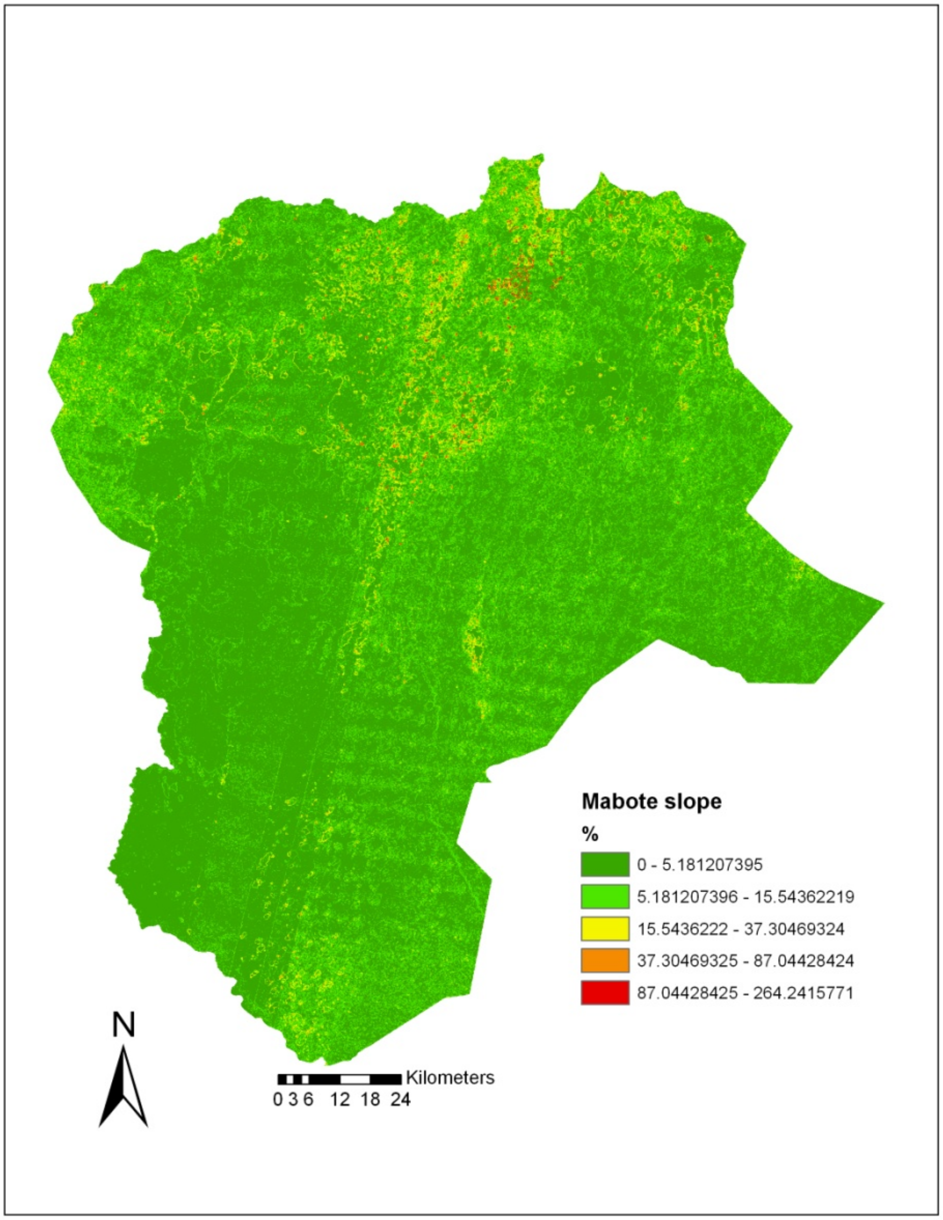

Figure 3: Slope map of the Mabote district.

Curve Number

The curve number (CN) method was developed by the Soil Conservation Services (SCS-NRCS) of the United States of America, and it is widely used for runoff estimation (Haan et al. 1994). For a given area, the CN indicates the runoff potential for different combinations of soils, land cover and treatments. Soil information is inputted in the form of hydrologic soil groups (HSG), which is a soil classification based on the minimum infiltration rate obtained for a bare soil after prolonged wetting. Several tables are available to extract CN for different combinations of HSG and land use descriptions. The HEC-GeoHMS extension was used to perform this task for all the study area. This ArcMap extension is available on the internet at http://www.hec.usace.army.mil/software/ and is capable of performing other analysis. Merwade (2008) provided a guide to perform CN calculation using this extension. To perform the analysis, this extension requires as inputs: HSG, land use, slope map and a CN lookup table.

Hydrologic Soil Groups (HSG)

HSG classification denotes four soil groups by the letters A, B, C and D. The infiltration rates decrease from type A to type B soils, and their general definition based in soil texture is presented in Table 2.

Table 2- HSG classification based on soil texture (source: Haan et al. 1994).

HSG	Soil texture
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

The HSG classification was developed based in soils from the USA, and therefore its application is limited when applied outside this country (Sartori et al. 2009). Sartori et al. (2009) provides an adaptation of hydrologic soil group classification for tropical soils, based on properties of tropical weathered soils from Brazil (restrictive layer, abrupt textural change, clay ratio, clay activity of subsurface horizon, acric property, iron oxide, histic horizon, water table and perched water table). Mabote has tropical soils, and the description available for these soils includes information about the texture, depth, geologic formation, topography, acidity, organic matter, and FAO (Food and Agriculture Organization) and USDA (United States Department of Agriculture) soil classifications. The distribution of soils in the Mabote district is presented in Figure 4, displaying the equivalent USDA soil classification. This description was used to reclassify the soils to HSG using the criteria provided by Sartori et al. (2009), and the result is presented in Figure 5.

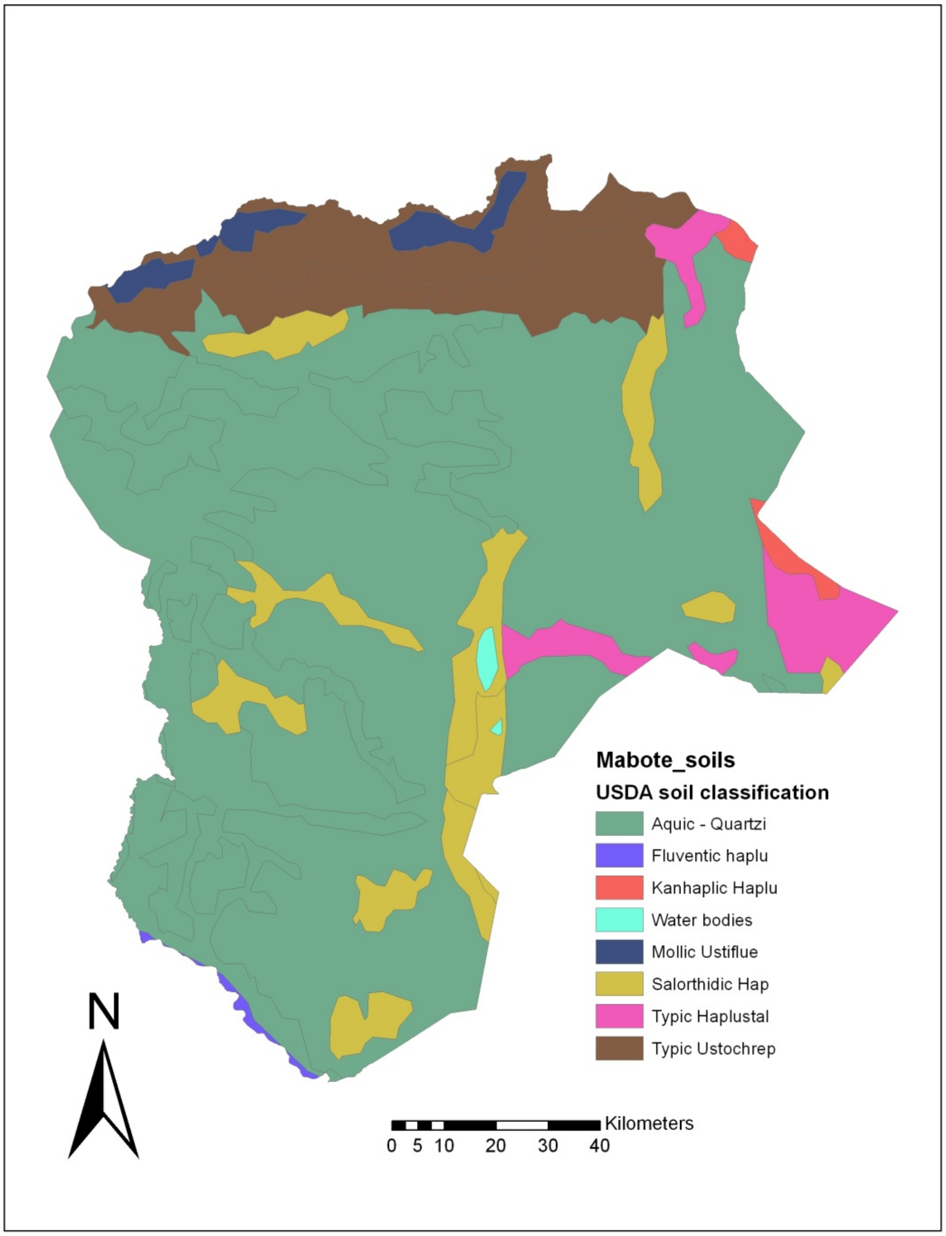

Figure 4: Soil map for the Mabote district.

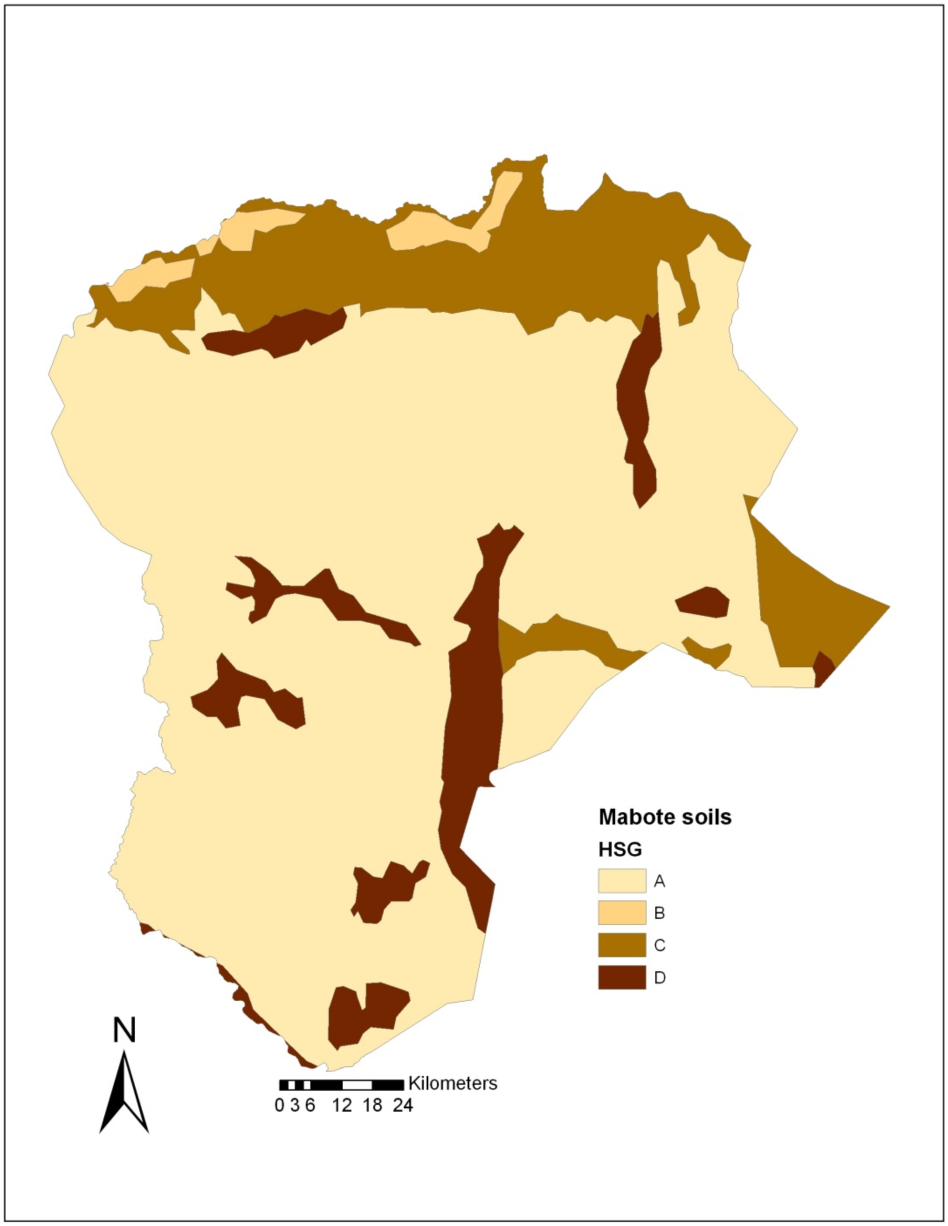

Figure 5: HSG for Mabote district.

Land use

The HEC-GeoHMS extension requires a land use classification input with the following groups: water, medium residential, forest and agricultural. The Mabote district has a variety of land uses

(Figure 6) that fall in the groups mentioned above, and therefore they were reclassified accordingly. A new land use map was created and is presented in Figure 7. Note the absence of a medium residential category. We believe that this was due to the fact that the data is from 1983, and therefore did not include the residential areas created in recent years.

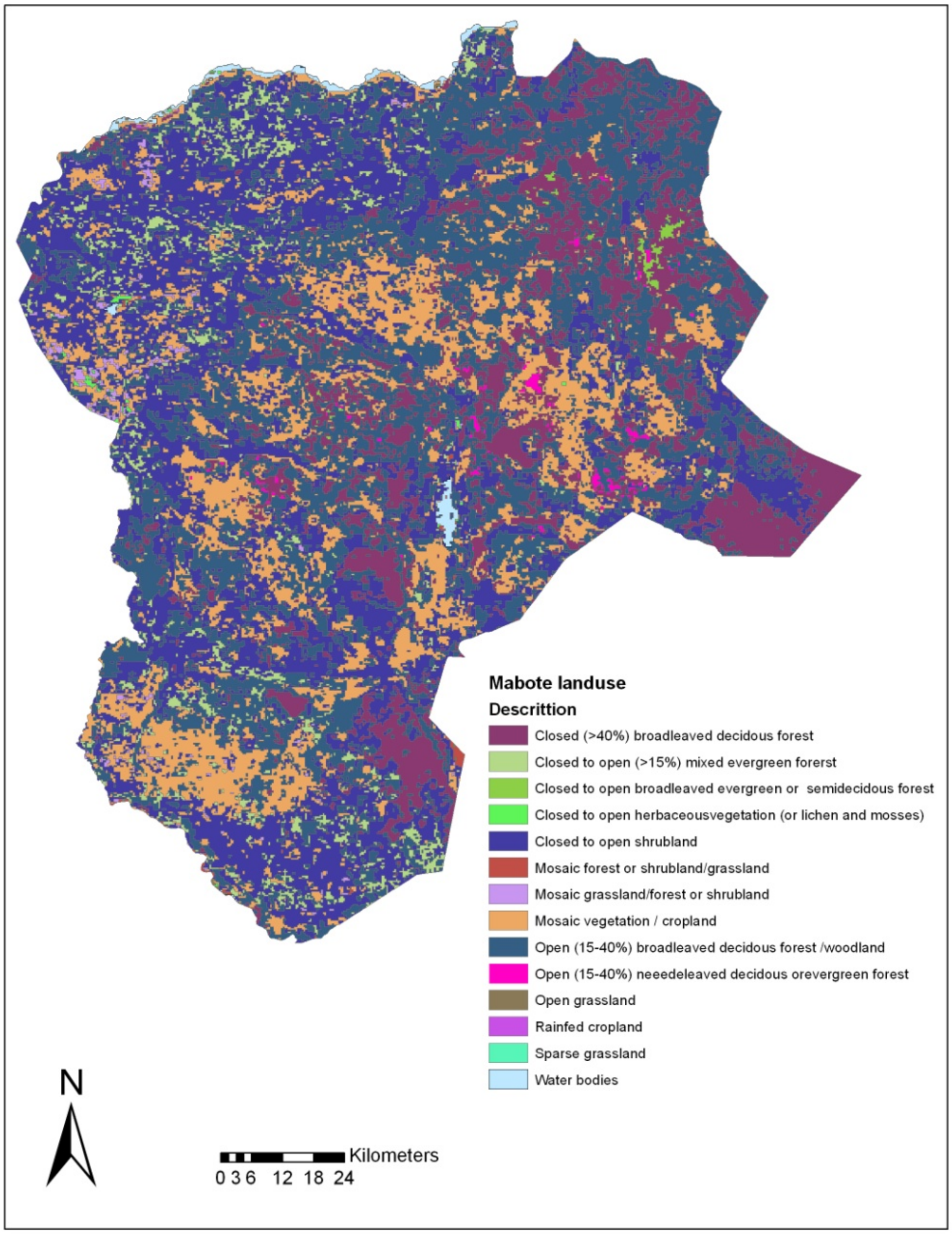

Figure 6: Land cover map for the Mabote district.

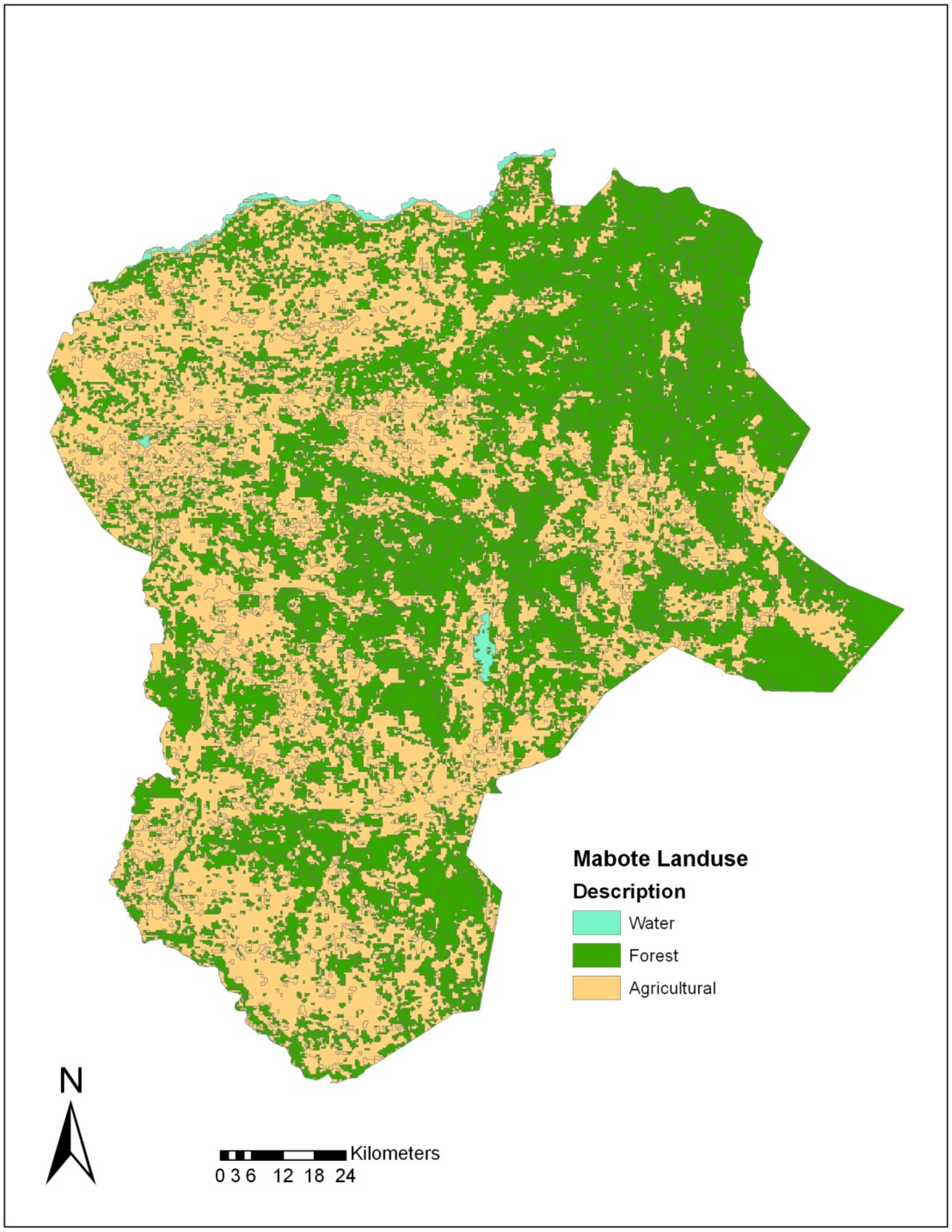

Figure 7: Land cover map after reclassification.

CN lookup table and slope categories

HEC-GeoHMS requires a lookup table to match the HSG to the land uses and provide an output with the CN. Table 3 provides the information contained in the look up table, where the CN numbers were obtained from the 1986 SCS TR55 (Merwade, 2008).

Table 3: CN lookup table (source: Merwade, 2010).

Description	A	B	C	D
Water	100	100	100	100
Medium residential	57	72	81	88
Forest	30	58	71	78
Agricultural	67	77	83	87

The slope map previously created was used for the CN calculation, and the CN output map is presented in Figure 8.

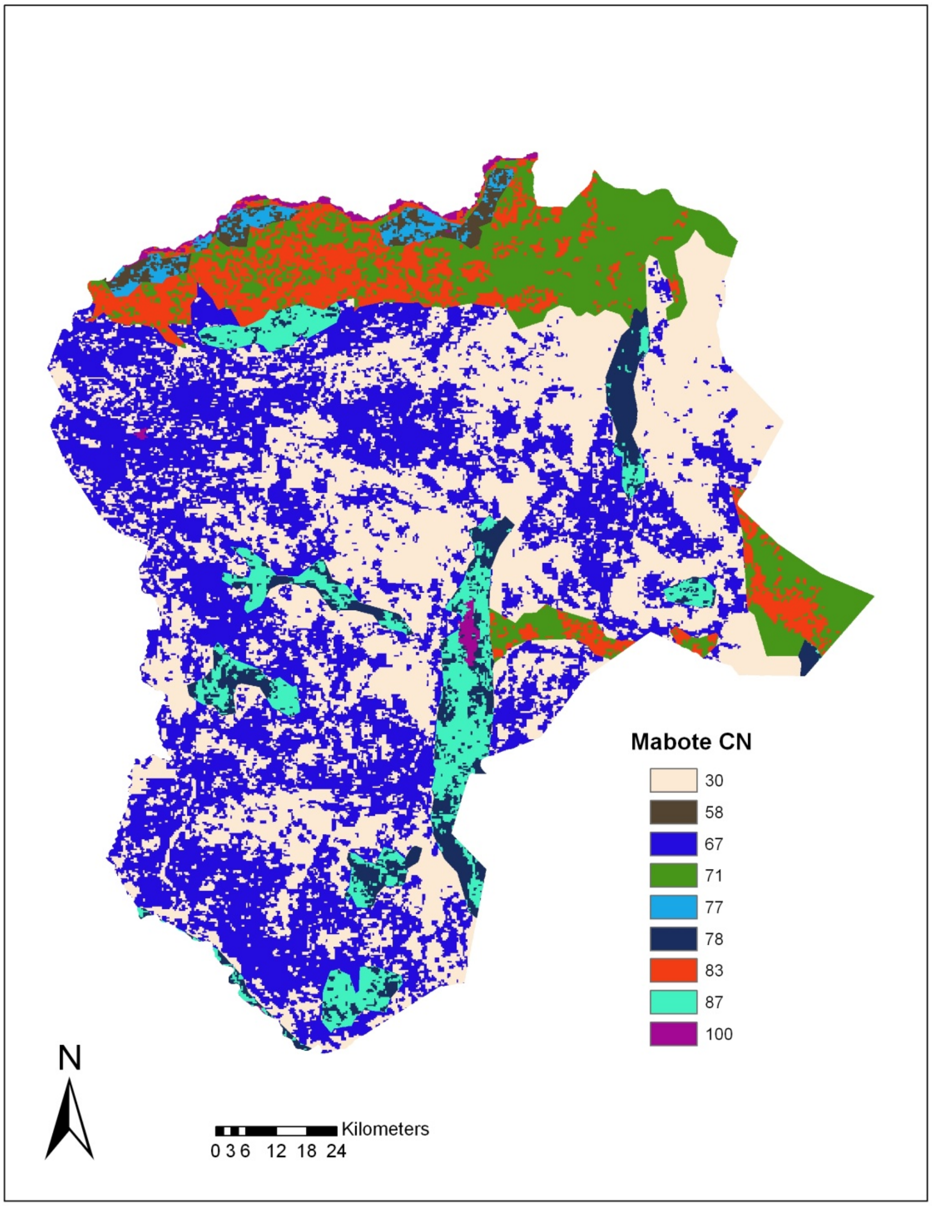

Figure 8: CN distribution in the Mabote district.

Extraction map

This study took into account the existence of roads and water bodies in the Mabote district, whose areas should be excluded from the analysis. Therefore a map to serve as the final extraction layer for the produced suitability map was created. This map was produced by erasing the water bodies (lakes, rivers) and roads from the Mabote limits map. It used a buffer of 500m from the water bodies and of 100m from the roads, which resulted in the map presented in Figure 9.

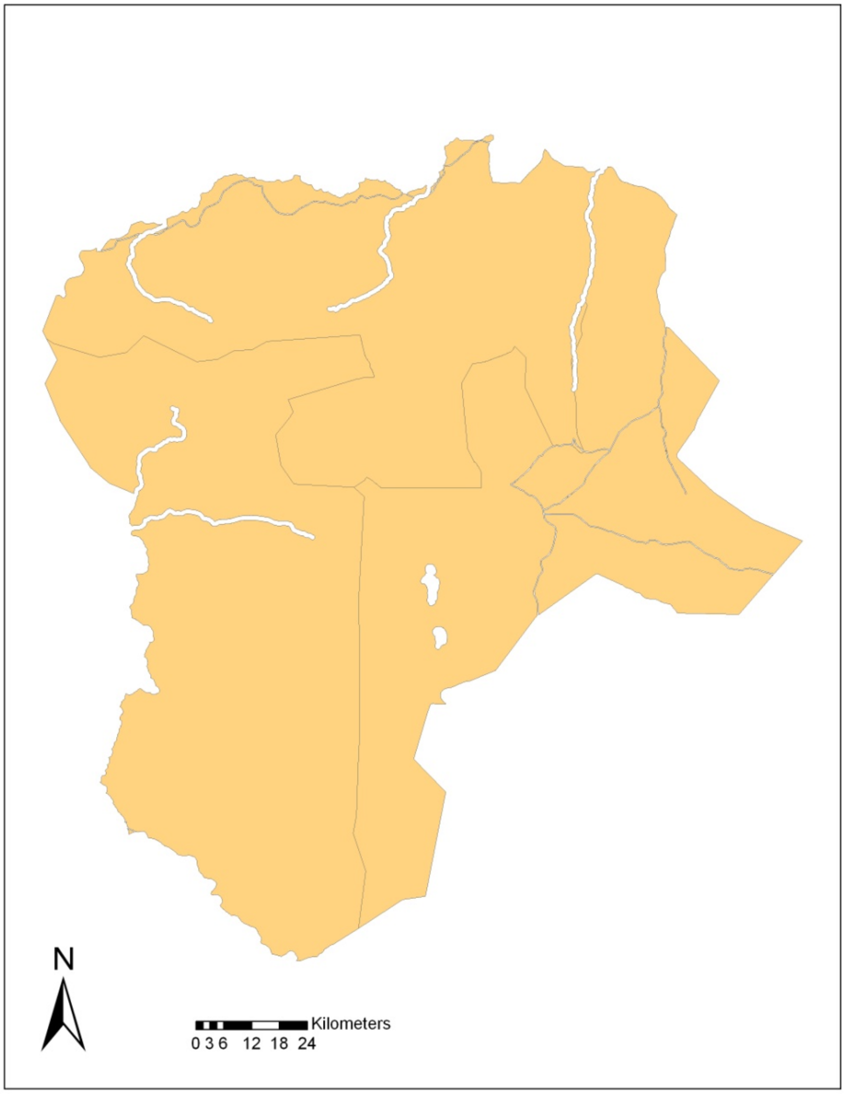

Figure 9: Extraction map of the Mabote district.

Suitability criteria

Suitable slopes and CN are necessary for the production of usable amounts of runoff from precipitation. Different criteria for the combination of these parameters were used in similar studies (Prinz et al., 1998; De Winnaar, 2007). For the purposes of this study, the slopes were divided into three categories (as suggested by Prinz et al., 1998): low (<8%), medium (8<%<30) and high or steep (>30%) as presented in Figure 10.

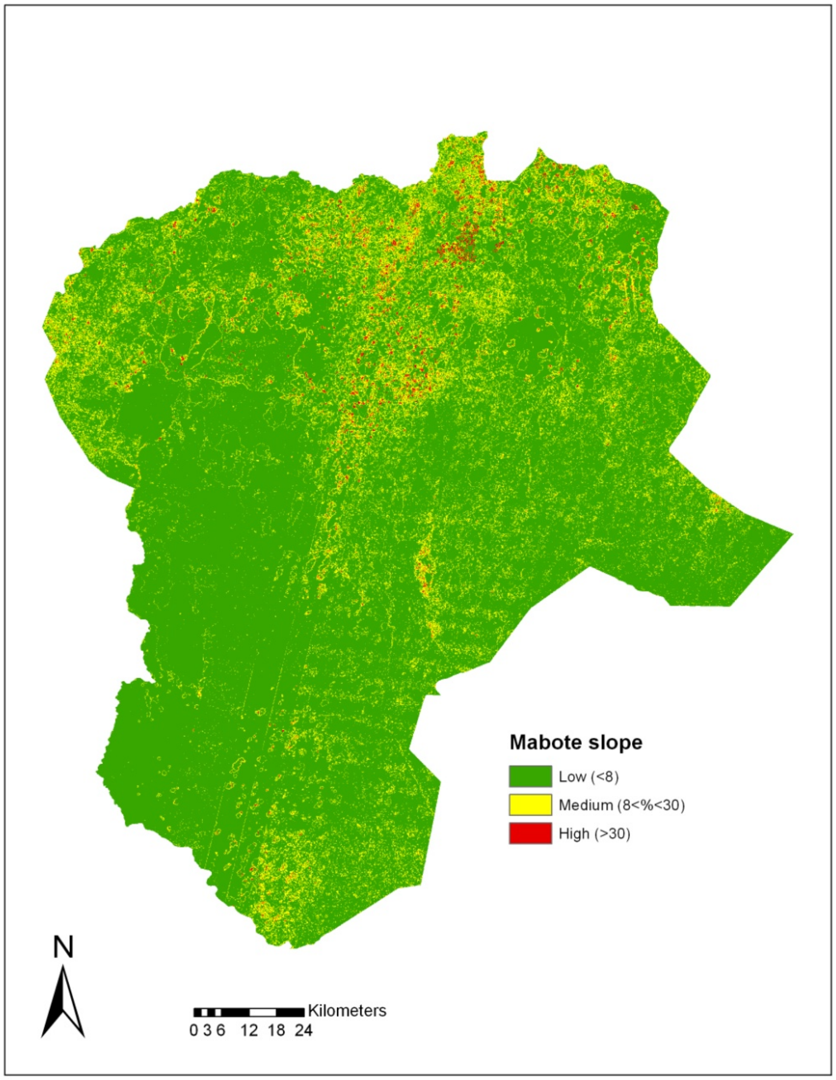

Figure 10: Slope classification of the Mabote district.

The curve numbers were also divided into three categories: low (<60), medium (60<CN<80) and high (>80), as presented in Figure 11.

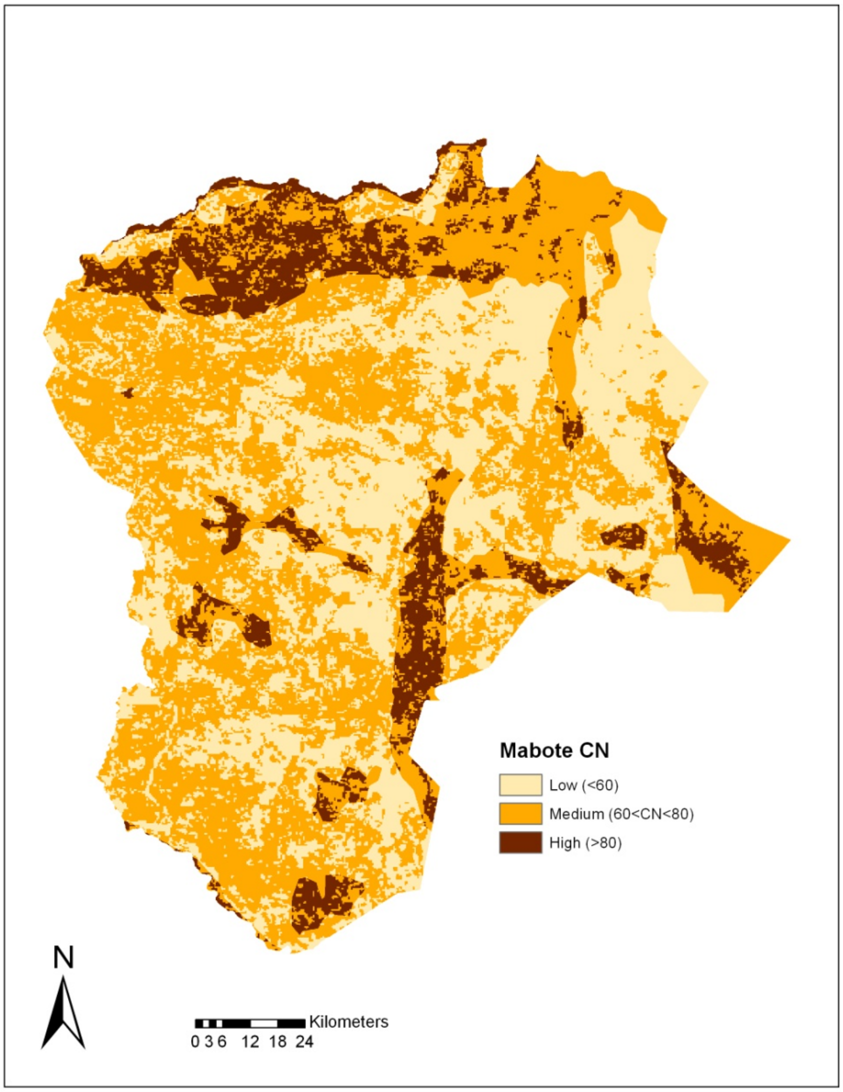

Figure 11: CN classification for Mabote district.

The final suitability map was created by overlapping the categories described for slope and CN where:

- High suitability: slope >=30% and CN>=80.
- Medium suitability: slope 8<%<30 and 60<CN<80.

- Low suitability: slope =<8% and CN=<60.

Each suitability level was set based on the knowledge that steep slopes and high CN would produce runoff to recharge an earth dam before it infiltrates to the soil. Considering that the rainfall for the Mabote district is low and erratic, the highly suitable area for installation of earth dams should meet the above criteria for high suitability. Areas where the criteria were not met were labeled as not applicable (N/A), and the result is presented in Figure 12.

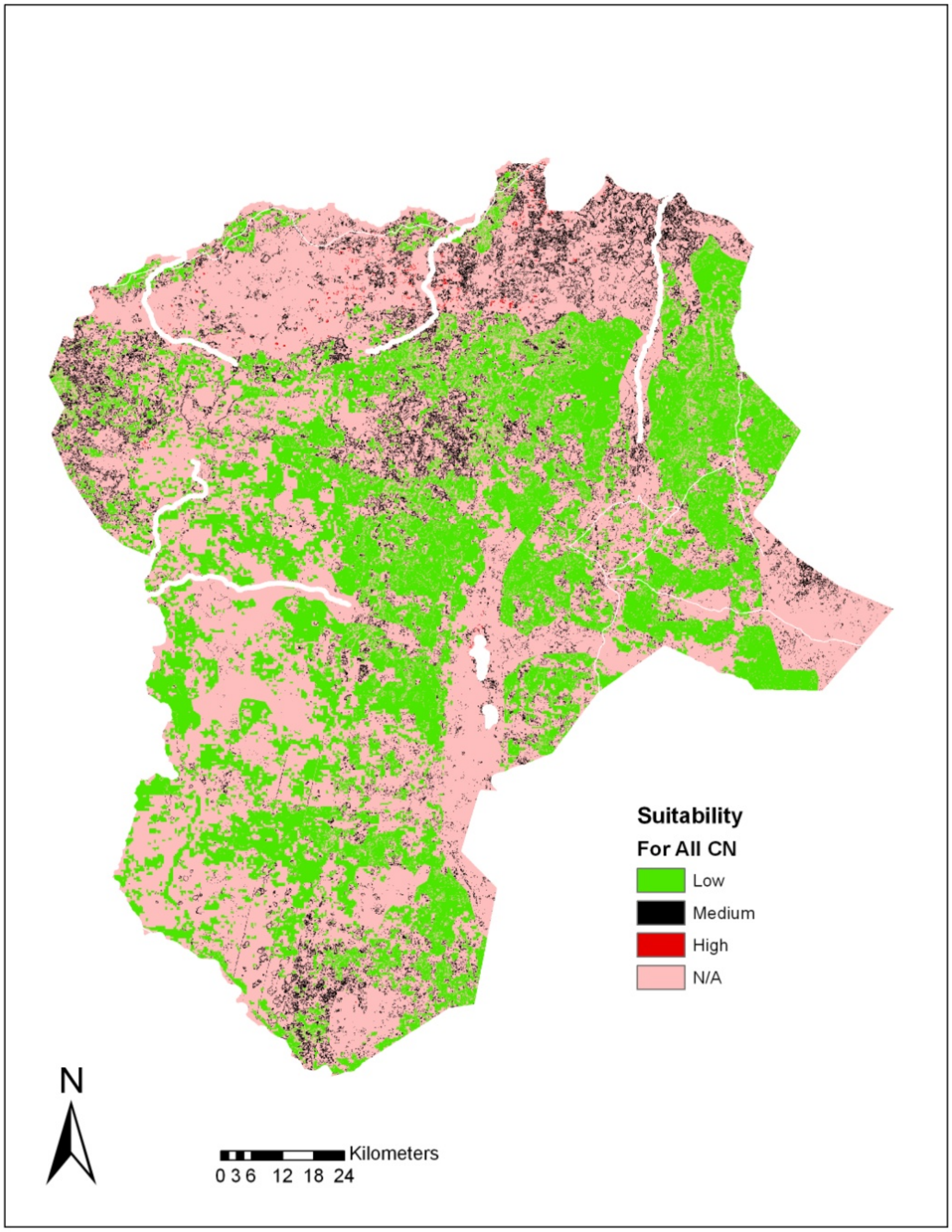

Figure 12: Suitability map for all the CN categories.

To overcome the data loss derived from N/A areas, each individual CN category was overlapped to the three slope categories providing the maps presented in Figures 13 to 15.

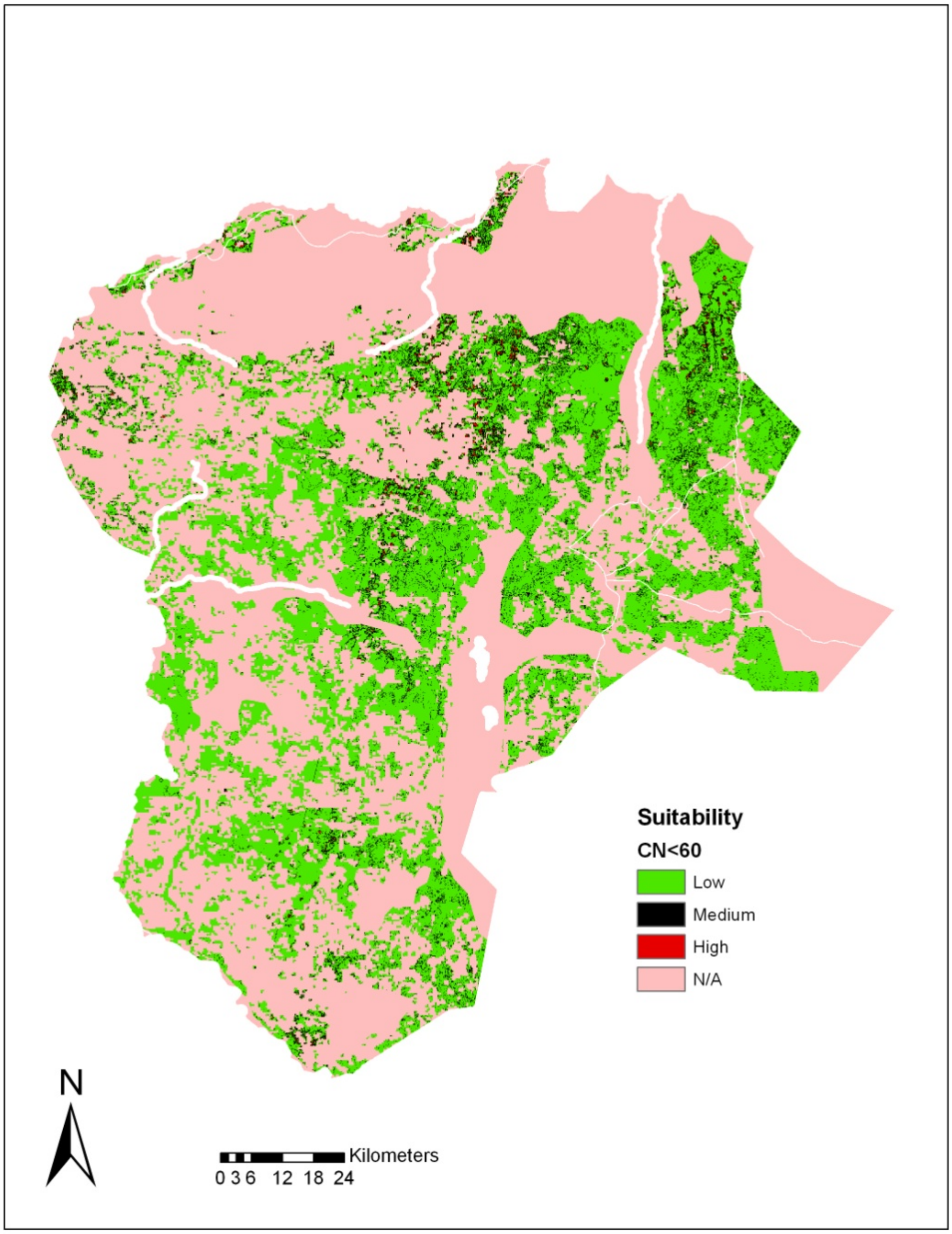

Figure 13: Suitability map for CN<60.

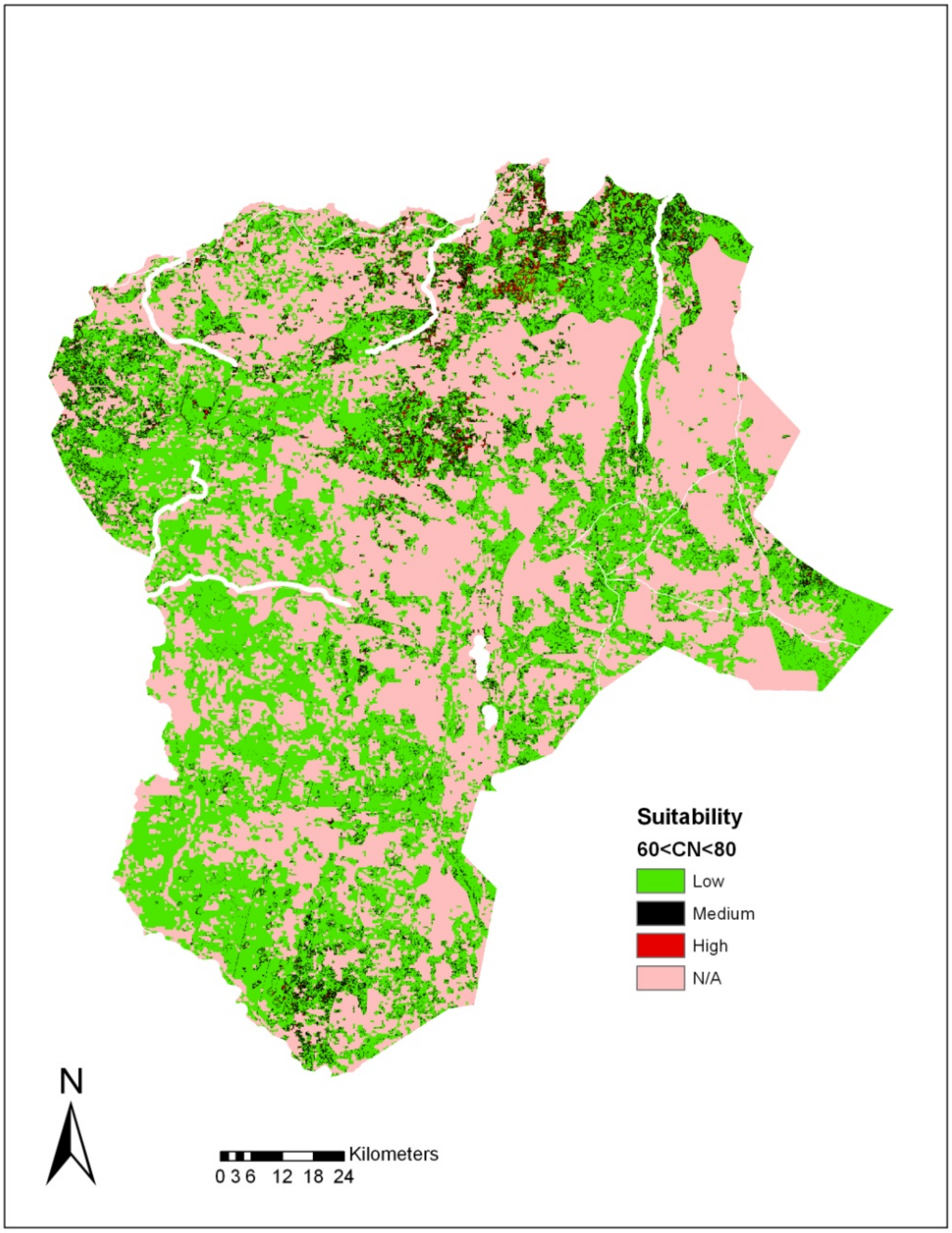

Figure 14: Suitability map for 60<CN<80.

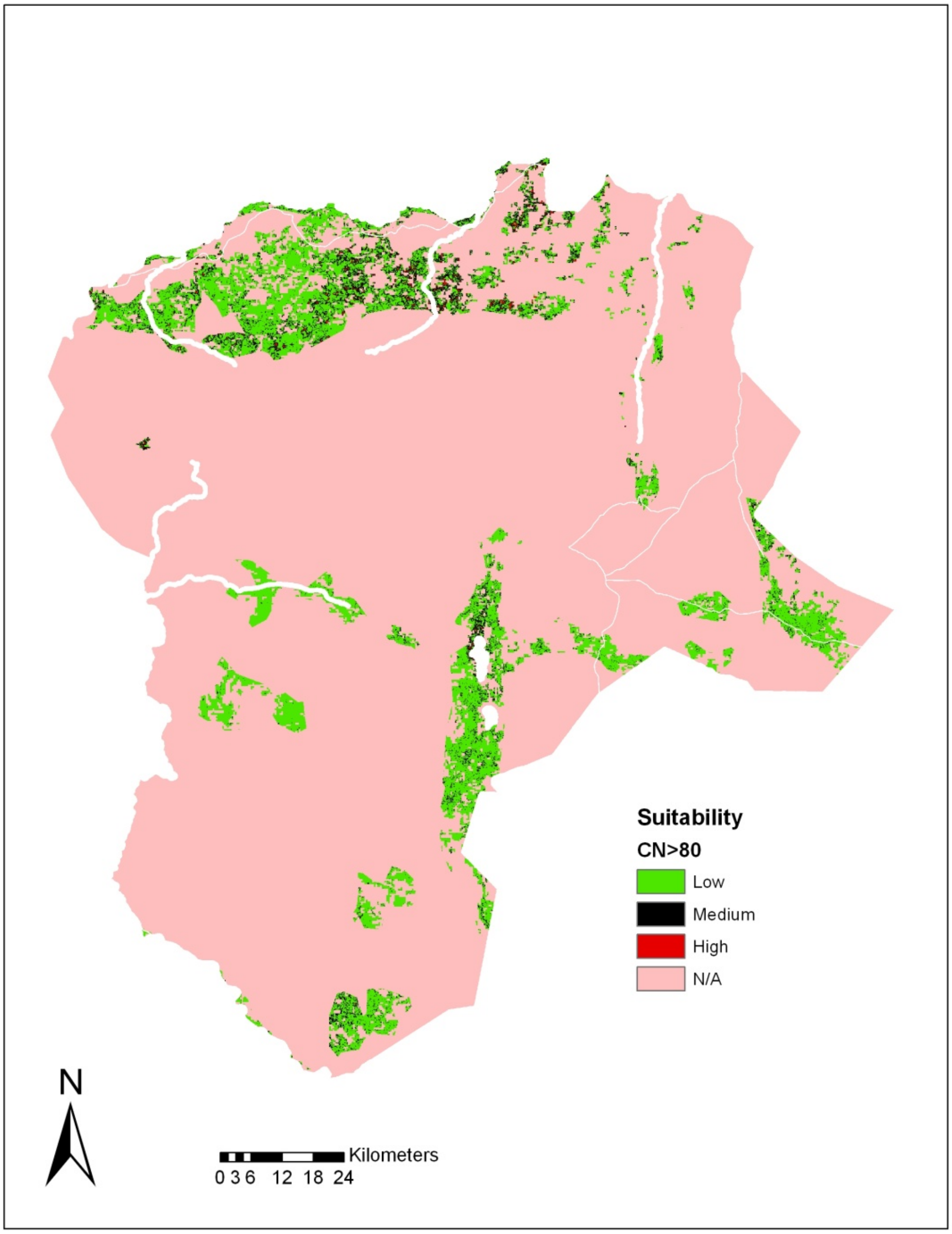

Figure 15: suitability map for CN>80.

Results and discussion

A summary of the areas calculated for each suitability criteria is presented in Table 4.

Table 4: Areas for the different suitability criteria.

	Area (km^2)			
Criteria	Low	Medium	High	N/A
ALL CN	4229 (28.3%)	1001 (6.7%)	21 (0.14%)	8967 (60.1%)
CN<60	4229 (28.3%)	716 (4.8%)	37 (0.25%)	9236 (61.9%)
60<CN<80	6470 (43.3%)	1001 (6.7%)	83 (0.56%)	7364 (49.4%)
CN>80	1379 (9.2%)	282 (1.9%)	21 (0.14%)	13236 (88.7%)

Note: Percentage of the total area is presented in parenthesis.

Information from Table 4 shows that a small percentage (<1%) of the area has high suitability for installation of earth dams, and most of the area is not applicable. Low slopes are predominant in the Mabote district, and as a result, the second largest area falls in the Low suitability category, for all suitability classification approaches.

These results suggest that overall the district has a low potential for the installation of earth dams, and therefore site selection should be made carefully to avoid failure of these structures. Earth dams can be installed in medium slopes, but that will require higher amounts of rainfall to produce enough runoff to fill the dam, because more infiltration will occur before runoff is produced. Therefore, these slopes should be associated with soils with low infiltration, where 1.9% to 6.7% of the districts area meets these criteria.

The results may have been affected by the procedure used to classify the Mabote soils to HSG. This procedure may be a source of error because it requires matching several soil characteristics to the description provided by Sartori et al. (2009), where some of the required information was not presented in the description of the Mabote district soils. Another source of error is the land use information that is outdated because it was produced in the eighties. We believe that addressing these two issues would improve the assessment provided herein.

Different suitability analysis can be made based on the runoff harvesting technology to be implemented. Other technologies used for drought mitigation include in-situ water harvesting, where the rainfall water is collected by a catchment area and conducted to the plant (Critchley et al., 1991). Critchley et al. (1991) discusses the use of in-situ water harvesting techniques, where according to this author, this technique is not recommended for slopes greater than 5%; and soils with high infiltration rates and high water holding capacity are preferred. Therefore using this technology as the purpose of analysis, low slopes and medium CN would be preferred, providing a high suitability area that covers 43.3% of the Mabote district, as calculated in Table 4 (Low and 60<CN<80).

Due to limited availability of temporal and spatial precipitation data for the Mabote district, this study did not include an evaluation of the distribution of precipitation. Precipitation is an important aspect to consider for sizing of these structures because it can provide an estimate of runoff volumes available for use. Precipitation available from internet sources as the CLIMWAT 2.0 software (CLIMWAT for CROPWAT, FAO irrigation) is limited to monthly averages for a single year, which limits it applicability for the evaluation of temporal variability of precipitation.

Conclusions

GIS has been applied as a tool to aid in the identification of sites for runoff harvesting. The analysis made in this study aimed to evaluate the suitability of the Mabote district for rainwater harvesting, where the results showed that the highly suitable areas represent less than 1% of the total area of the Mabote district. These results suggest that the district has low suitability (small suitable area) for the installation of rainwater harvesting structures as earth dams. Using in-situ water harvesting as the technology for analysis, resulted in an estimated 43.3% of the district area classified with high suitability for the use of this technology. Therefore, the author suggests this technology as an alternative for the areas with low suitability for earth dam installation.

Theoretical reference maps for site selection based on suitability for runoff harvesting were successfully created, though applicability needs to be verified due to data quality related issues. Land use and soil information data are considered the main sources of error for this study, where the author believes that the use of recent land use information and a HSG soil classification based on more information may provide more accurate results

The current study did not evaluate the rainfall distribution in the district which is suggested by the author as an objective to be taken into account in future studies.

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CHAPTER III

HUMAN POWERED PUMPS FOR SMALL SCALE IRRIGATION

Introduction

Agriculture is a common practice in developing countries. A significant part of the population in those countries practice subsistence rainfed agriculture, which is characterized by dependence on precipitation. Therefore, droughts and erratic rainfall can result in reduced crop yield (Biswas, 1986), which may in turn lead to food insecurity for the farmer. Alternatives to reduce the potential of reduced crop yield under drought and reduced rainfall conditions include the use of drought tolerant crops and irrigation (Biswas, 1986).

Irrigation is possible where water sources (e.g. rivers, lakes, underground water) are available, and creates the possibility of year round production and diversification of crops (Stickney et al. 1985). Therefore, micro-scale irrigation, which focuses on the single farmer, has been recommended as a good option for the beneficial use of water resources in developing countries (Lambert and Faulkner, 1991). The technology in use for micro-scale irrigation (e.g. watering can, pump) may limit the cropped area size. Proof of cropped area increases as a result of using irrigation machinery, have been provided by Lambert and Faulkner, 1991, and, Faulkner and Lambert, 1991.

The use of powered irrigation machinery, such as solar pumps and other power-driven pumps, are prohibitive for a large number of farmers, mainly due to their purchase and operational costs (Lambert and Faulkner, 1991; Lambert, 1992). The use of human powered pumps has been highlighted as the best alternative in micro-irrigation (Islam, 1983; Stickney et al. 1985; Lambert and Faulkner, 1991; Faulkner and Lambert, 1991; Lambert, 1992).

Several definitions of human powered pumps are provided by different authors. Islam (1983) defined man(human)-powered pumps as shallow tubewells used to lift water, with a suction head limit of 7.4 m(≈24ft). However, Lambert (1992) reported a depth limit of 10m for a human powered pump (the rope washer pump). Raghuvanshi (1986) defined a hand pump as an appliance used for lifting ground water, which is classified as shallow or deep well depending on cylinder and plunger location. That is perhaps the best definition found, which can be broadened by removing the limitation to ground water.

Several types of human powered pumps exist for different applications. Stewart (2003) provided a list of human powered pumps including those used for potable water supply, and characterized them by type (operating principle), depth range and distinguishing characteristics. Some pumps used for domestic water supply have been denoted by Lambert (1992) as unsuitable for irrigation due to operational limitations, cost and insufficient flow rate. From Stewart's (2003) pumps list, the rope washer, rower and treadle pumps have been described by several authors (Islam, 1983; Stickney et al. 1985; Lambert and Faulkner, 1991; Lambert, 1992) as pumps suitable for irrigation purposes which satisfy the Village Level Operation and Maintenance (VLOM) requirements, which are important for the successful use of human powered pumps (Colin, 1999; Akinbaode and Ogwuagwu, 2002; Stewart, 2003). To satisfy VLOM requirements a pump would need to be: simply maintainable at village level (using minimal skills and few tools), manufactured in country (to guarantee the availability of spare parts), tough and dependable (under field conditions) and cost effective (Colin, 1999). The authors that described the rope washer, rower and treadle pumps assessed their performance, although little information has been provided about the overall lifetime of the pumps and their parts. Kay and Brabben (2000) reported a study where the Masvingo (Zimbabwean design) treadle pump piston and seals durability were assessed.

Pump durability becomes an issue when breakdown occurs during the cropping season and in remote areas where pump repair may be troublesome due to lack of resources. As an example, the author observed broken treadle pumps in the Mabote district, an inland district from the Inhambane province of Mozambique (Figure 16).

(source:IP Consult/Ambero-ProGRC).

Figure 16: Broken treadle pumps in farmer fields in Mabote district, Mozambique.

The author also found that the reasons for pump failure were unknown to the farmers, and as a result, crop production capacity was reduced because the pumps stayed non-operational for a long period. Therefore, it is believed that determining durability for human powered pumps built with newly available materials will be useful for the implementation of maintenance plans and improved pump design, contributing to reduce pump breakdown.

Therefore, the objectives of this study are:

- Estimate the cost of pumps built with materials that meet VLOM requirements.
- Follow variations on pump performance (flow and pressure) throughout the testing period.
- Assess the lifetime and durability of selected human powered pumps.

Methodology

This study focuses on testing human powered pumps that are used for irrigation purposes for situations where high flow is needed (e.g. furrow irrigation), and for situations where pressure is needed (e.g. drip irrigation associated with elevated tanks). Therefore, two pumps were tested: a treadle pump (to deliver pressure) and a rower pump (high flow). These two pumps are piston pumps and the theoretical maximum volume (V) per stroke is given by:

$$V = \pi R^2 L \qquad (1)$$

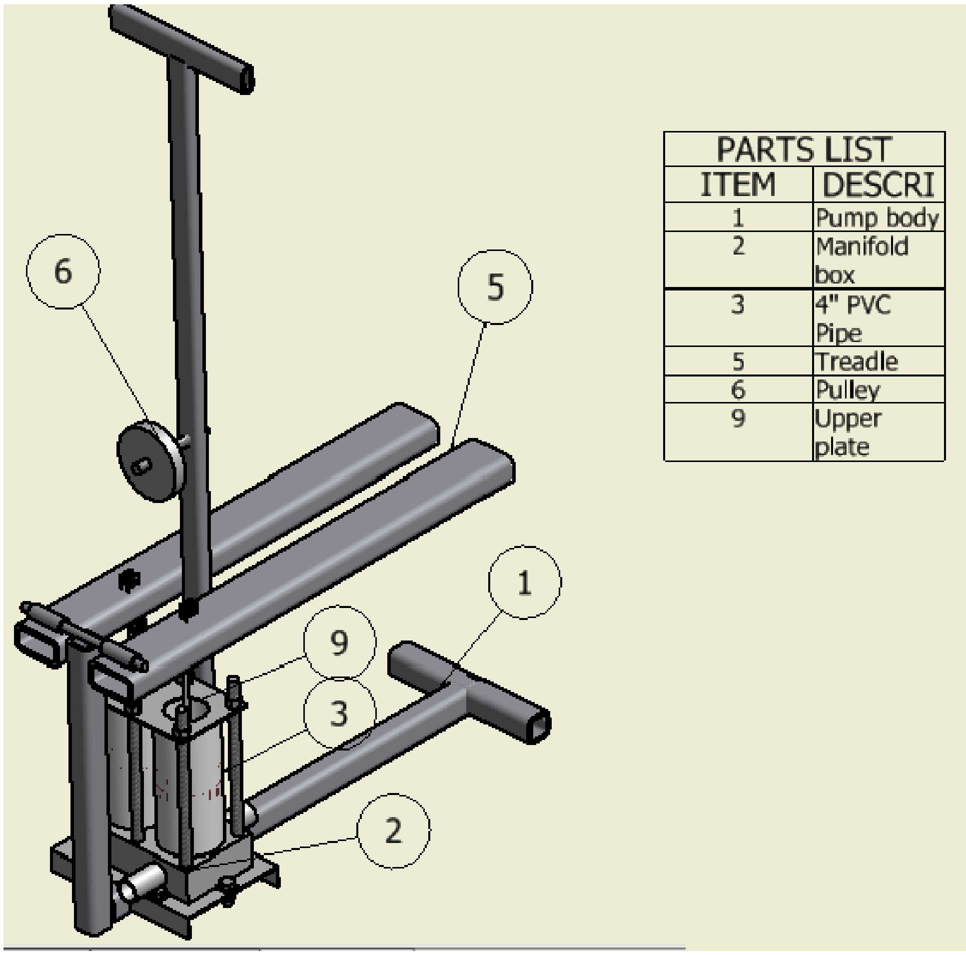
Where R is the pump cylinder radius and L is the pump cylinder height.

Taking into account that these pumps are human operated, it is expected that the operation speed varies depending on the operator and operation process (hand or foot). Lambert and Faulkner (1991) reported that whether the pumps are operated by hand or foot the favored operating speeds range from 30 to 50 rev/min.

To simulate pump operation, the pump levers (treadles or handles depending on the operation method) were connected to an apparatus that simulated human operation. This apparatus was conceived to provide continuous operation under a desired operating speed. Details about this apparatus are presented in the section that addresses pump design.

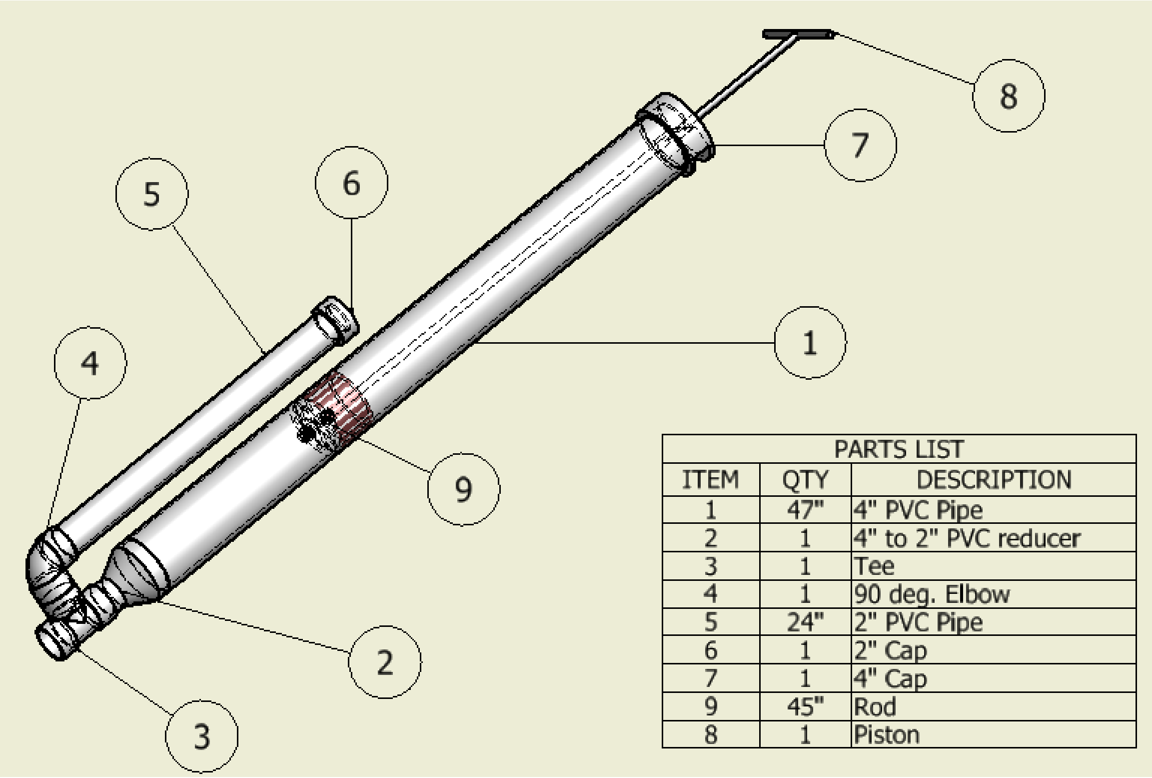
Pump design

A treadle pump was built based on existing designs presented by Lambert (1992) and Kay and Brabben (2000), and a rower pump design was created using sketches provided by Islam (1983), Lambert and Faulkner (1991) and from several internet resources. The drawings for the treadle and rower pumps are presented in Figures 17 and 18 respectively.



PARTS LIST	
ITEM	DESCRI
1	Pump body
2	Manifold box
3	4" PVC Pipe
5	Treadle
6	Pulley
9	Upper plate

Figure 17: Treadle pump layout.



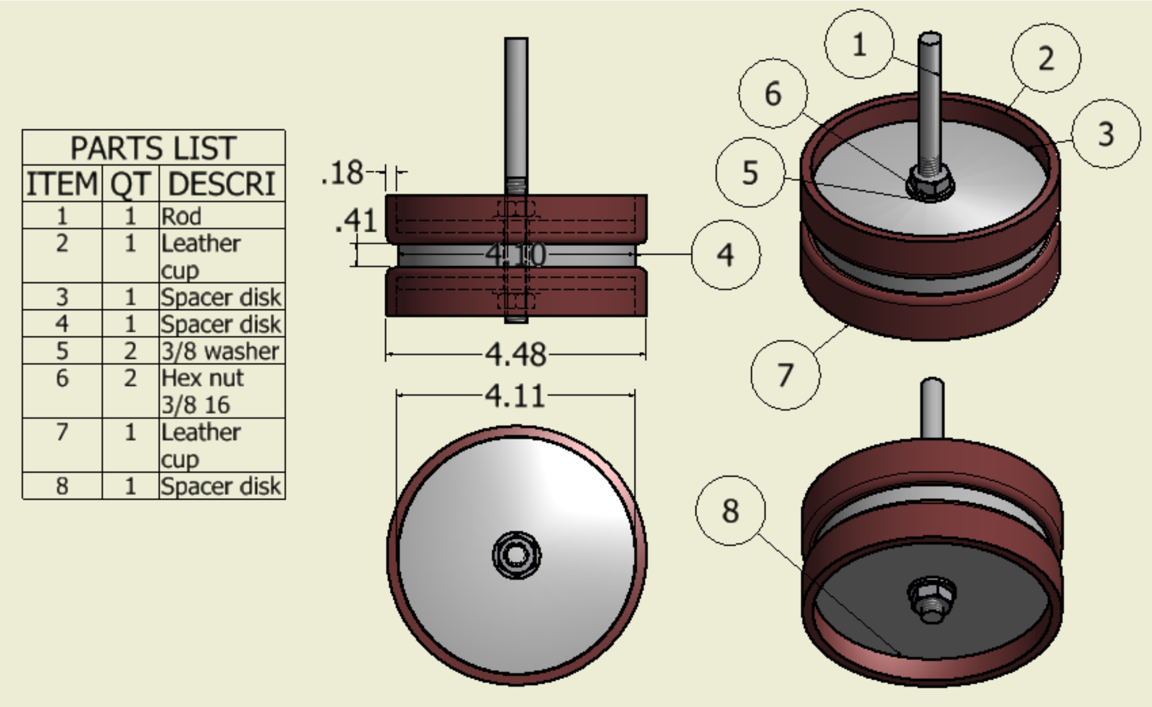
PARTS LIST		
ITEM	QTY	DESCRIPTION
1	47"	4" PVC Pipe
2	1	4" to 2" PVC reducer
3	1	Tee
4	1	90 deg. Elbow
5	24"	2" PVC Pipe
6	1	2" Cap
7	1	4" Cap
9	45"	Rod
8	1	Piston

Figure18: Rower pump layout.

More details on the pumps designs are presented in the appendix. All materials used for pump assembly were listed and their prices recorded. The objective was to use durable and low cost materials that are easily available to farmers living in remote areas.

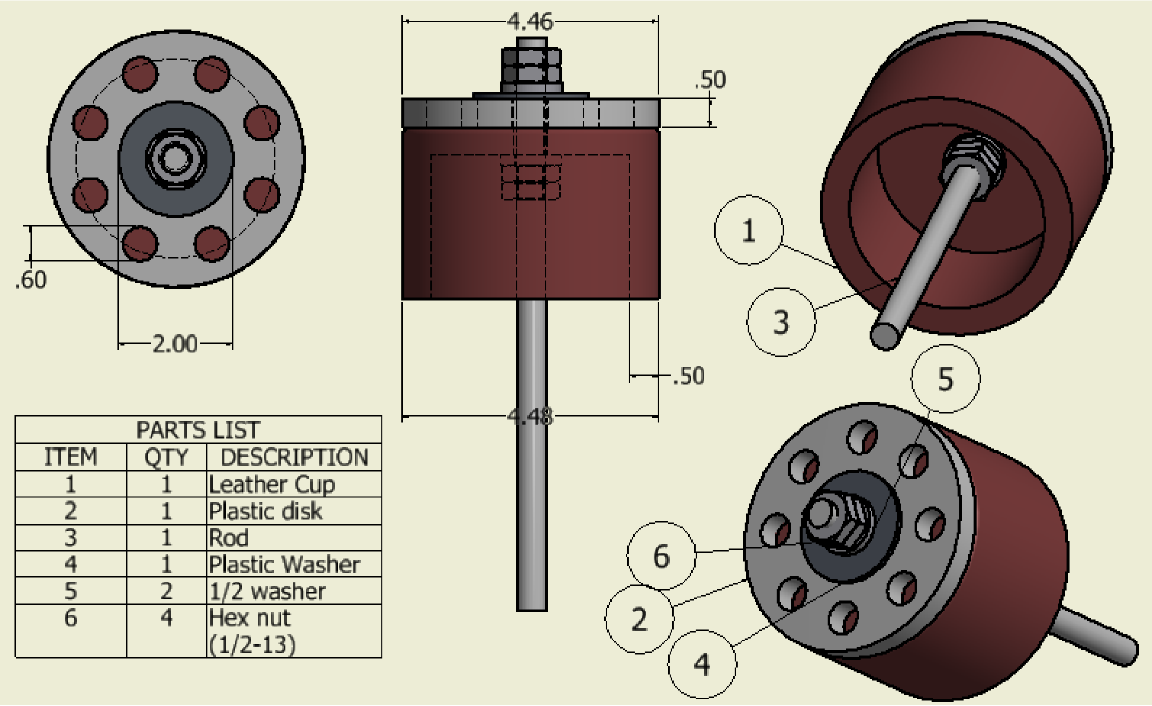
For both pumps, 4 inch nominal size (schedule 80) PVC (Polyvinyl chloride) pipes were used for the cylinders, with lengths of 25cm (9.8inch) and 119 cm (47inch) for the treadle and rower pump, respectively. Using Equation 1, the theoretical maximum volume per stroke are 1.9 and 9.7 liters for the treadle and rower pumps, respectively.

The piston layout for the treadle and rower pumps are presented in Figures 19 and 20 respectively.



PARTS LIST		
ITEM	QT	DESCRI
1	1	Rod
2	1	Leather cup
3	1	Spacer disk
4	1	Spacer disk
5	2	3/8 washer
6	2	Hex nut 3/8 16
7	1	Leather cup
8	1	Spacer disk

Figure 19: Treadle pump piston layout (dimensions in inches).



PARTS LIST		
ITEM	QTY	DESCRIPTION
1	1	Leather Cup
2	1	Plastic disk
3	1	Rod
4	1	Plastic Washer
5	2	1/2 washer
6	4	Hex nut (1/2-13)

Figure 20: Rower pump piston layout (dimensions in inches).

Generally pumps are described by their hydraulic performance (output, discharge and pressure), which is difficult for these type of pumps due to the difficulty of standardizing the power input that depends on human performance (Kay and Brabben, 2000). To work around this problem an apparatus was used to simulate human operation and provide continuous power input.

To provide continuous pump operation a “Continuous Pump Operation Apparatus” (hereafter called CPOA) was created. The CPOA had to provide operating speeds ranging between 30-50rpm (preferred operation speeds according to Lambert and Faulkner, 1991). Therefore, the apparatus included an electrical motor with a gear reduction and a rotation speed controller connected to parts (e.g. chains and sprockets) that converted the rotational motion of the motor to the linear motion needed to operate the pumps. CPOA’s connected to the pumps are presented in Figures 21 and 22 for the treadle and rower pumps, respectively.

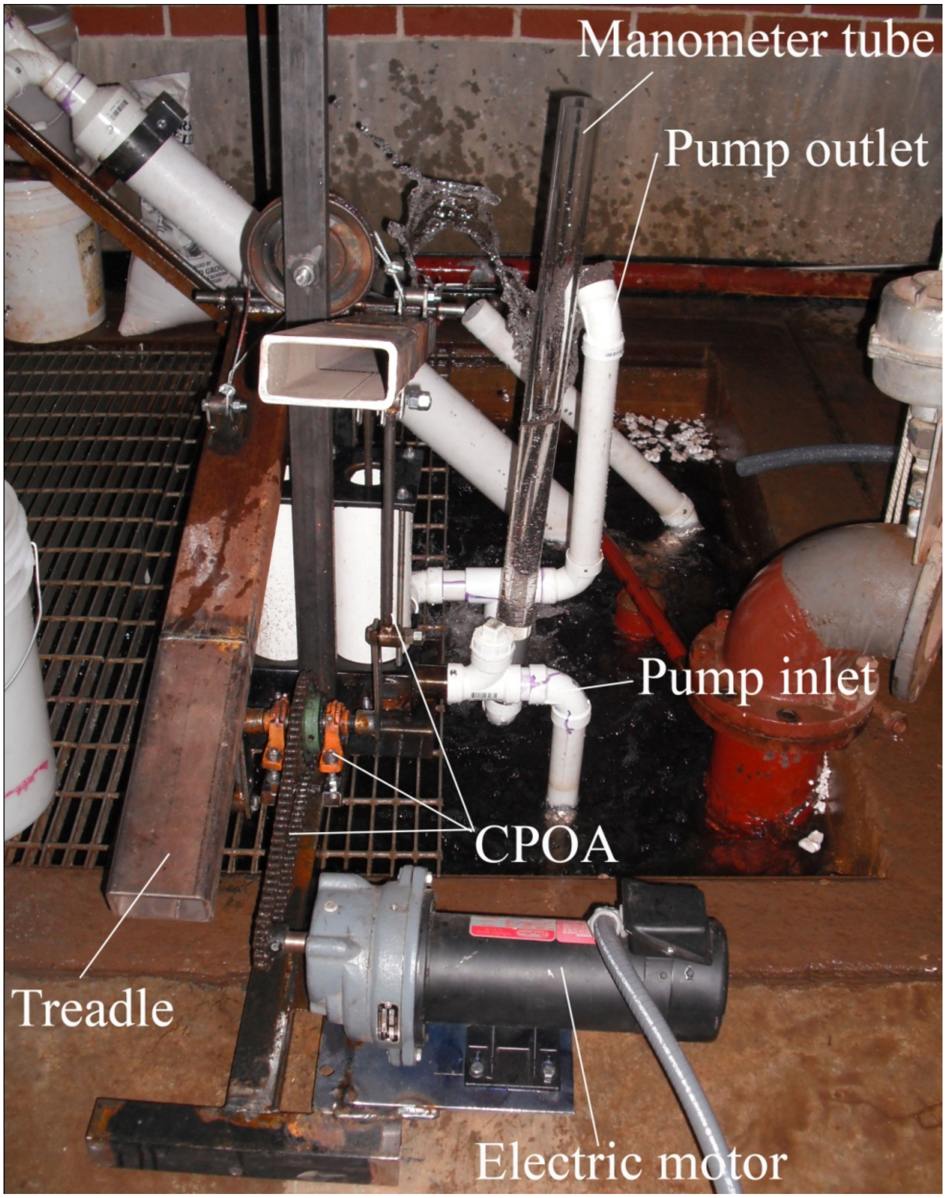


Figure 21: Treadle pump connected to CPOA at the BAE lab.

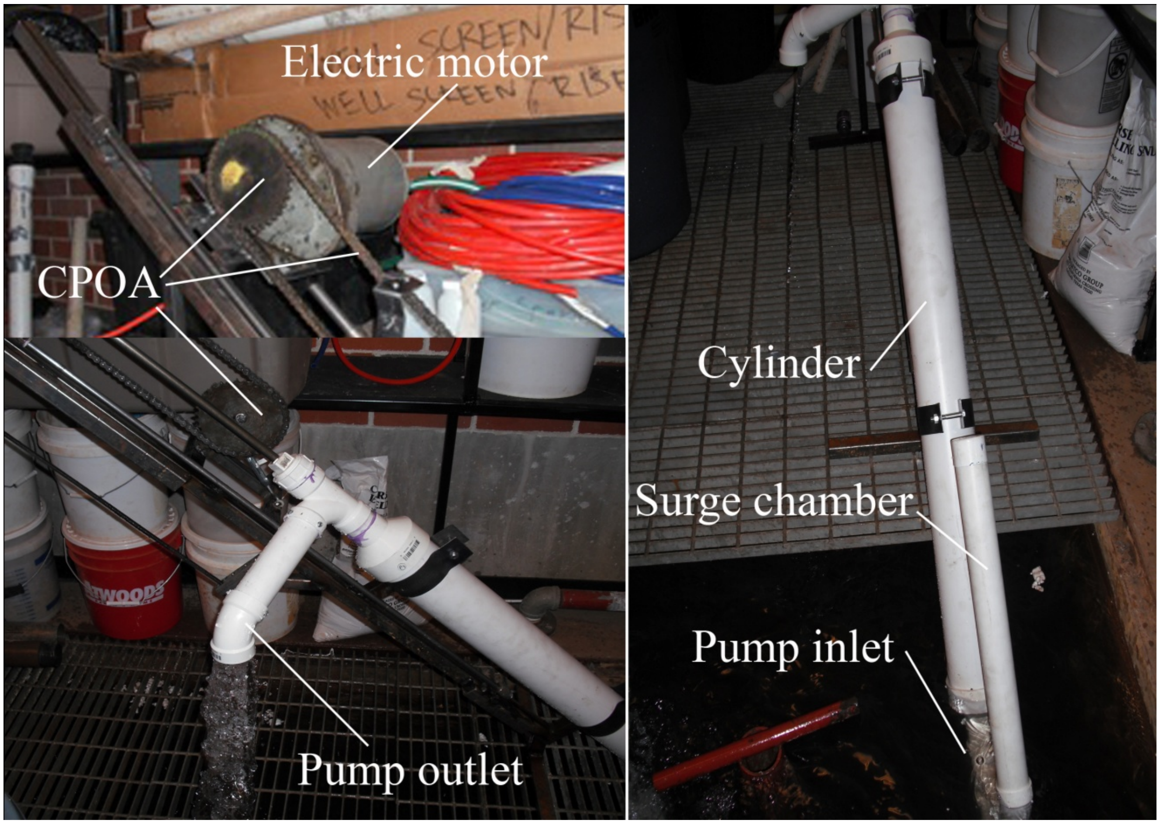


Figure 22: Rower pump connected to CPOA at the BAE lab.

Measured parameters

Frequency: Data collection took place at least twice in each 24 hour period.

Flow: The flow provided by the pumps was recorded to evaluate the suitability of the pumps for different irrigation scenarios (different suction lifts) and to identify changes in pump performance, which were interpreted as an indicator of parts failure/fatigue. To achieve this, the pumps were tested under laboratory conditions, in the BAE laboratory at OSU, using the setup presented in Figure 23.

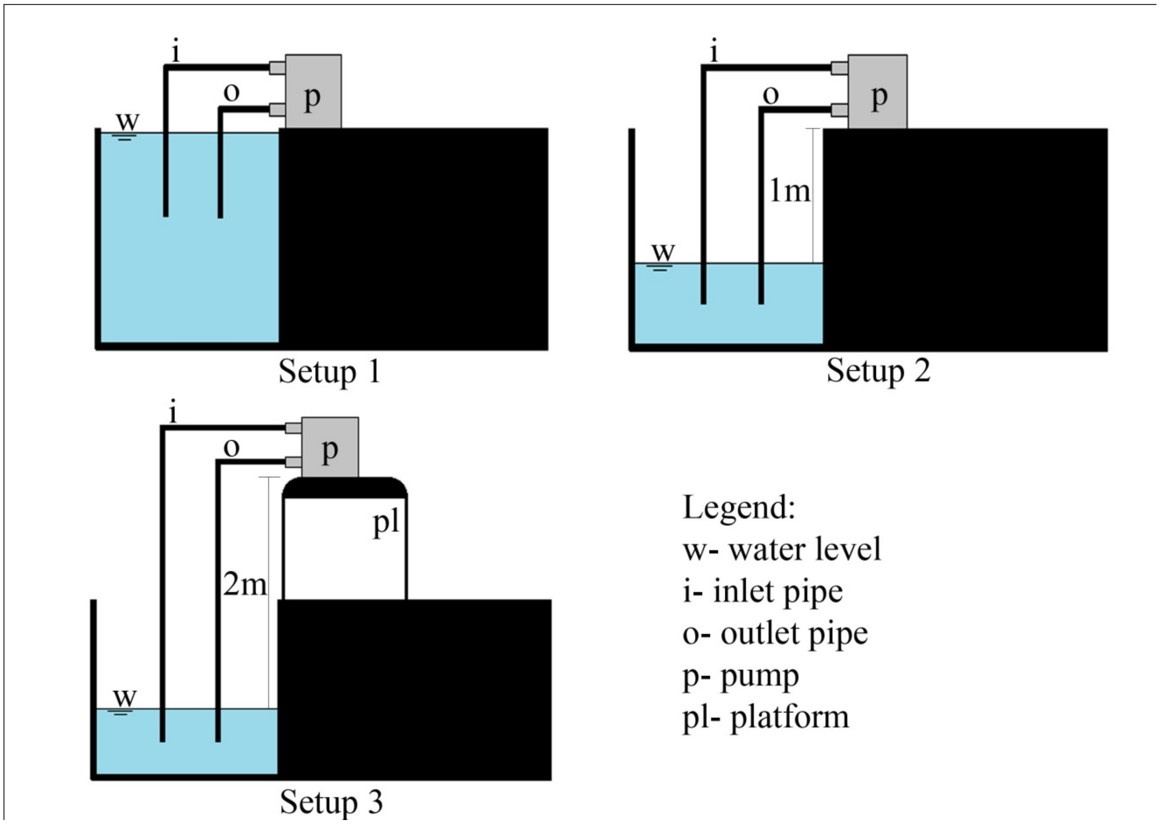


Figure 23: Laboratory setups for pump testing.

In Figure 23, setups 1, 2 and 3 correspond to suction lifts of 0, 1 and 2m, respectively. Suction lifts greater than 2m could not be implemented due to limited vertical space available at the laboratory. The same factor limited the maximum suction lift of the rower pump to 1.6m. Flow measurements were obtained by measuring the time necessary to fill an 18.9 liter (5US gallons) container. The time used was the average time obtained from three measurements recorded for each data collection event.

Pump pressure: A manometer was connected do the treadle pump outlet with the purpose of monitoring pressure changes. The manometer was made of a 3.81cm (1.5 inches) diameter plastic tubing. A measuring tape was used to measure the height of the water column using the pump outlet as the datum. The pressure was then calculated using the following relationship:

$$P = \gamma \frac{h}{100} \qquad (2)$$

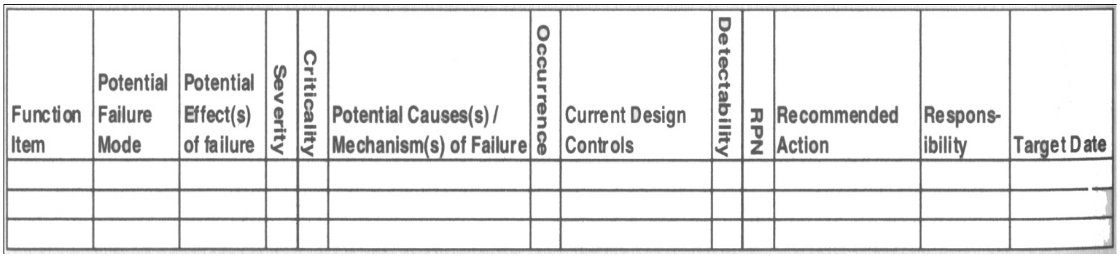
Where P is the pressure in N/m^2 or Pa, γ is the specific weight of water in N/m^3 and h is the water column height in cm.

Parts that needed replacement: During pump operation, information about the parts that failed was recorded. These parts were replaced and the pumps were submitted to further work in order to obtain information about the overall pump durability. The methodology used is presented next.

Lifetime estimation

The durability of the pumps was defined by the number of growth seasons that the pump can stand, where the hours of testing mimic the hours of operation for a complete growth season. The pumps were operated for a total period of 720hrs, value estimated based on the analogy provided by Lambert and Faulkner (1991) whom reported that pump operation can be sustained for 4 h/day which, assuming crop water requirements of 25mm/day, would allow to irrigate 0.24ha (≈0.6acre). Assuming a total crop growing period of 180 days (e.g. growing period of corn and tomato, according to Allen et al.(1998)) a period of operation of 720hrs was calculated.

Because the lifetime of the pump would be influenced by the durability of the pump parts, the Design Failure Mode Effects Analysis (DFMEA) was used to assess the different possibilities for pump failure. Porter (2004) defined DFMEA as a “disciplined analysis of potential failure in the design” which when conducted properly “the process will identify the key functional items, potential failure modes, their root causes and any corrective action”. This procedure allows for improving the design and can be helpful in conduction of tests. Figure 24 presents a sample of the standard DFMEA format used for the thought process.



Function Item	Potential Failure Mode	Potential Effect(s) of failure	Severity	Criticality	Potential Causes(s) / Mechanism(s) of Failure	Occurrence	Current Design Controls	Detectability	RPN	Recommended Action	Respons-ibility	Target Date

Figure 24: Standard DFMEA format - Source: Porter (2004).

The terms Potential Failure Mode and Potential Effect(s) of Failure are defined as the mechanism by which a failure occurs (e.g. fatigue, temperature) (Tawancy et al. 2004) and “the results of the failure on the function or behavior of the product” (Porter, 2004) respectively. The format presented in Figure 24 was adapted to achieve the desired objectives and was used during data acquisition.

Results and discussion

Overall, the testing was successfully completed and the operating periods were reached. Due to breakdown of some of the electric motors used for the CPOA, the testing for suction lifts of 1 and 2m had to be redesigned. Both lifts were implemented for a single testing period of 720hrs, where each lift was used for half of the testing period. This procedure was used for both pumps. The results obtained and a discussion of the findings are presented below.

Pump materials and cost

Pumps were successfully assembled with relatively inexpensive and easily available materials that met VLOM requirements. The detailed list of materials used and cost estimation is presented in the appendix. Pump costs differed for both pumps where the rower pump provided the lower cost (47 USD) when compared to the treadle pump (165 USD). The higher number of moving parts and the diversity of materials that constitute the treadle pump are the main reasons for its higher cost. Overall, the cost of both pumps is considered low when compared to the cost of commercially available diesel pumps, and it is within the price ranges for human powered pumps that can be obtained from internet sources. Note that the prices do not include the cost of labor needed for their assembly. This cost will vary based on the artisan, and it is believed that it would not exceed the cost of the materials. Therefore the overall cost is considered low, even if doubled.

Pump flow

Measured pump flows for the treadle and rower pumps, for both testing periods and for the different lifts, are presented in Figures 25 and 26.

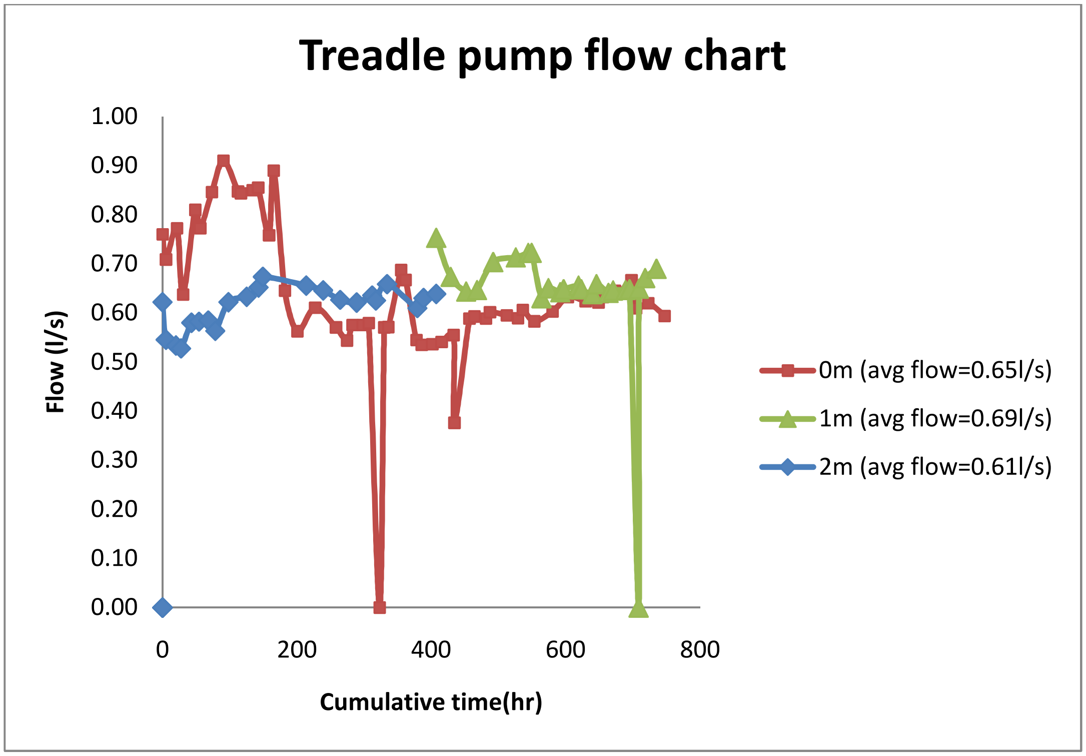


Figure 25: Flow chart for the treadle pump – 0m, 1m and 2m suction lifts.

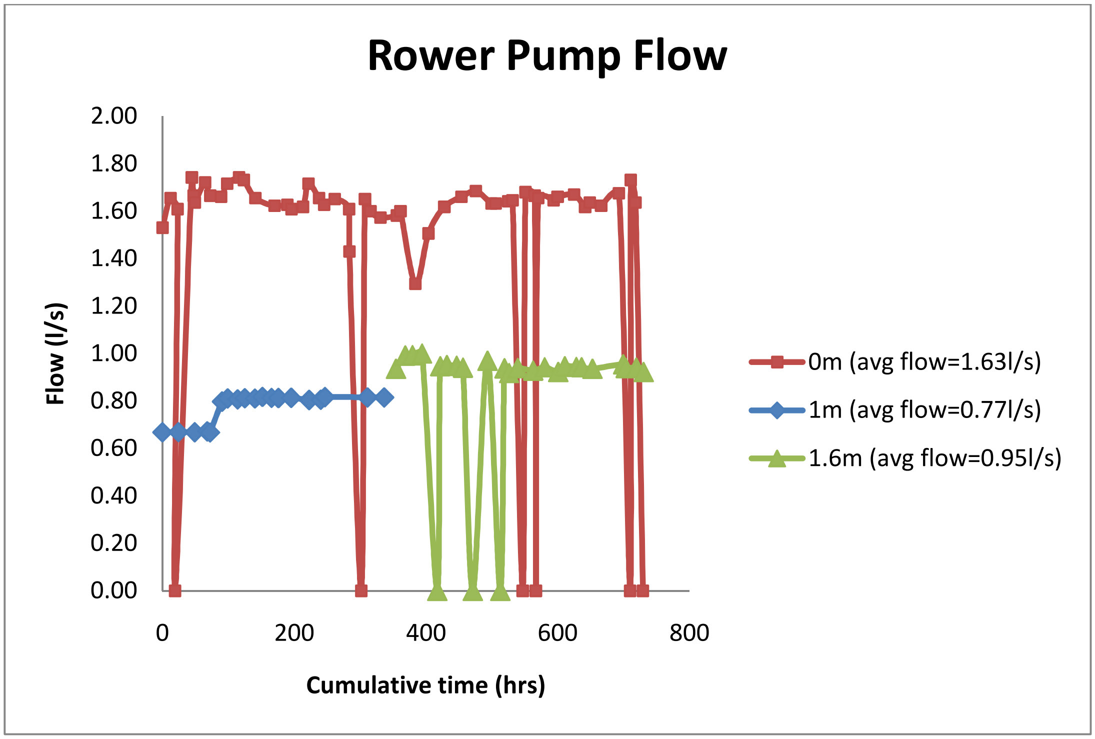


Figure 26: Flow chart for the rower pump – 0m, 1m and 1.6m suction lifts.

Figure 25 shows that the flow provided by the treadle pump differed between all suction lifts, though the pump was tested at 33-35rpm for all of them. The lower suction lift provided the lower flow after a flow drop from ≈0.80l/s to ≈0.60l/s, after approximately 200 hours of operation. This goes against the results provided by Faulkner and Lambert (1991) and Faulkner (1991) that showed that flow decreases as the suction lift increases. 1m suction lift provided higher flow when compared to the 2m suction lift, which agrees with the results obtained by the same authors.

The electric motor used (which provided 13rpm) with the CPOA for the rower pump broke down at the end of the first testing period and was replaced by an electric motor that provided a lower rpm (6.5rpm). As a result, the testing for 1m and 1.6m suction lifts were performed on a different rpm and therefore the flow readings had to be adjusted for analysis. Because the rpm reduced by half, the flow readings were multiplied by a factor of two.

Figure 26 shows that the flows provided by the rower pump were overall stable for all the testing periods and suction lifts. Similar to the treadle pump results, the higher flow obtained for the 1.6m lift, when compared to the 1m lift, goes against the results obtained in other studies. Overall, the results show that the flow reduces as suction lift increases, which follows the findings from other authors. This pump performed better than the treadle pump when we look at the stability of the flow throughout the testing periods.

Both pumps provided average flows below those reported by Faulkner and Lambert (1991) and Faulkner (1991). That may be due to the operating conditions with regard to the operating speed and the length of the stroke provided by the CPOA. Because these pumps are positive displacement pumps, the output is directly proportional to the operating speed and to the percentage of the cylinder volume that is used.

The main purpose of the flow measurements, besides pump output evaluation, were to observe variation on pump performance, whose events are represented by the flow drops presented in Figures 24 and 25. These events are evaluated and explained in the results and discussion sub section that addresses pump failure analysis.

Pump pressure

Variation in pump pressure at the treadle pump outlet was recorded. The results are presented in Figure 27.

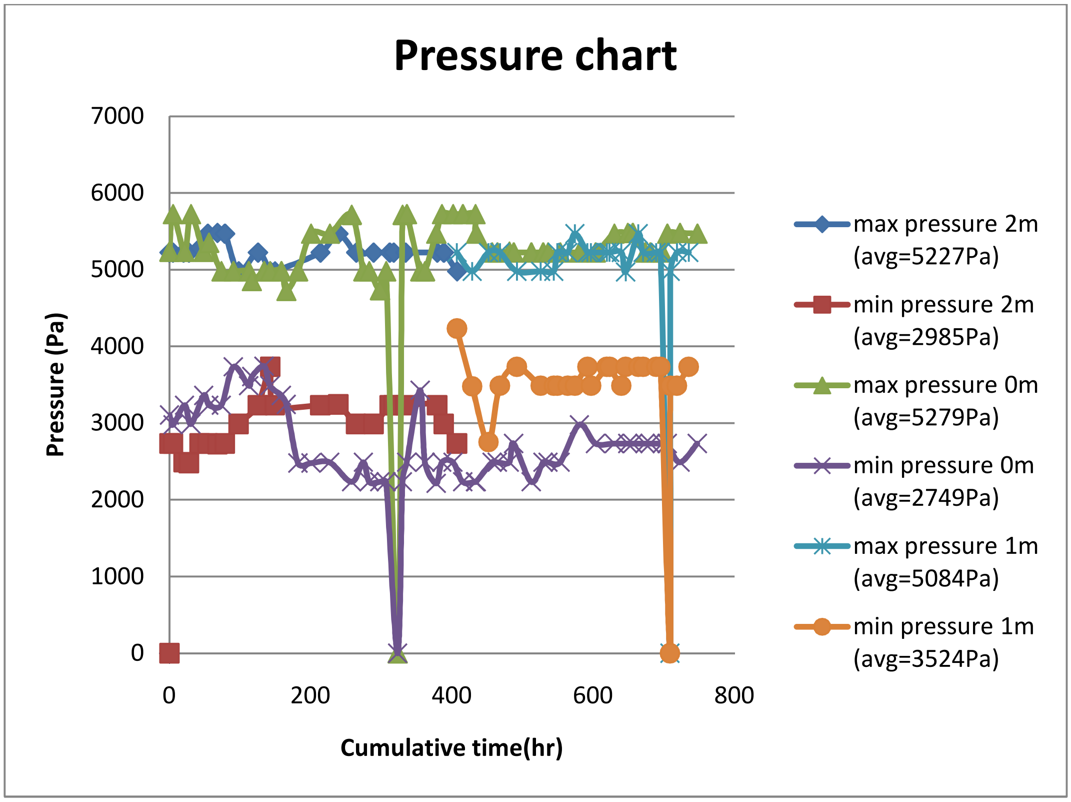


Figure 27: Treadle pump pressure – 0m, 1m and 2m suction lifts.

During pump operation it was noted that the water height in the manometer varied throughout strokes. As a result, the minimum and maximum values were recorded at each data collection event. From Figure 27 we can extract that the pressure differed for each suction lift, but the maximum pressure varied slightly when compared to the variations in flow. On the other hand, the minimum lift followed the same variation pattern as the flow measurements, and therefore, we can assume that this is the real pressure delivered by the treadle pump. The minimum pressure showed that the pump was able to create enough suction to move the water from the water source to the outlet and provided enough pressure at the outlet to provide pressurized discharge. Though the pressure was maintained throughout testing, it was noted that more effort was needed for 2m suction lift, where pump priming required a higher operation speed. The pressure drops presented in Figure 27 also indicate changes in pump performance and part failure, which are discussed next.

Pump failure analysis

Design Failure Mode Effects Analysis (DFMEA) was used to assess the possibilities for pump failure. The thought process imbedded in this method led to focus on the moving parts of the pumps and the parts subject to abrasion. Thus, the parts that were considered potential sources for pump failure were: seals, pistons, valves and cylinders.

Though the interruptions on pump operation due to failure could be listed chronologically, a significant part of the breakdown events were related to problems with the CPOA which include burned motors, broken chains, broken sprockets, etcetera. Therefore, Table 5 presents a list of broken pump parts, its frequency of occurrence and cause of failure.

Table 5: List of broken parts for the treadle and rower pumps.

Treadle pump					
Function item	Failure mode	Effect of failure	Causes and mechanisms of failure	Number of Occurrences Period 1	Number of Occurrences Period 2
Piston	Inoperative piston/cylinder	Reduction in flow and pressure. Pump breakdown	Cup wear	1 (@≈200hrs)	1 (@≈150hrs)
Pulley	Inoperative treadles	Pump breakdown	Pulley cable wear	1 (@≈450hrs)	0
Pump chassis	Damaged pump body	Pump breakdown	Broken pulley cable. Body fatigue	1 (@≈450hrs)	0
Rower pump					
Function item	Failure mode	Effect of failure	Causes and mechanisms of failure	Number of Occurrences Period 1	Number of Occurrences Period 2
Piston	Inoperative piston	No flow. Pump breakdown.	Broken piston disk	1 (@≈19hrs)	0

According to Table 5, though the number of occurrences was low, the parts that failed were the pistons for both pumps and the pulley wire for the treadle pump resulting in damage to the treadle pump body. All these events resulted in pump breakdown, excepting the second piston failure for the treadle pump which led to a drop in pump flow due to leakage in a piston. Note that the piston cups were made of leather, a good alternative material considering that it is a byproduct of cattle production, and therefore, its availability could be guaranteed, as opposed to rubber cups whose assembly and purchase can be difficult in remote areas. The cups failed at around 150-200hrs of operation which is below the time found in a study reported by Kay and Brabben (2000), where different leather cup pistons were evaluated. In that study, the leather cups needed to be replaced after 400hrs of operation.

For the rower pump, piston failure was caused by a broken disc (see piston schematics for details). This problem was determined to have been caused by an assembly error where a washer with a wrong size was used, resulting in more stress to the disc which led to its failure. This problem was solved by replacing the disc and assembling it with a suitable washer. This occurrence supports Kay and Brabben (2000) findings, who stated that evaluation of such devices can be hindered by differences in design, materials used, dimensions of components and manufacture standards.

Valves and seals performed well for both pumps during both test periods, which is a good result when we take into consideration the simplicity of the designs used. Figure 28 shows a composition with the different parts that broke.

Figure 28: Broken parts: 1-treadle piston with damaged leather cups; 2- treadle pulley assembly with broken cable; 3-treadle body with broken support; 4- rower piston with broken disk.

The rower pump performed better than the treadle pump, for providing fewer breakdown events and for maintaining the flow during the test periods. We believe that this pump bests the treadle pump due to the fact that it is composed by fewer moving parts.

These results support the hypothesis that the pump lifetime would be determined by the durability of the moving parts. Meaning we can assume that, regardless of the quality of the materials used for the pump body, the nature of pump operation will lead to wear of pistons and pulleys during each operation period, which would lead to pump failure. For this study, the pump durability/lifetime is estimated to be within one cropping season. Therefore, focusing on these parts during pump operation, with regard to its maintenance, would considerably improve the performance and durability of these types of pumps.

Conclusions

Human powered pumps are an appropriate technology for small scale irrigation in developing countries and in remote areas where the social, economical and infrastructural conditions may limit the use of other pump types. The problem of pump failure in this kind of scenario was addressed in this study through an evaluation of the durability and lifetime of a treadle and a rower pump.

Pumps were built with materials that meet VLOM requirements and the costs were estimated to be low (165 USD for the treadle and 47 USD for the rower pump) when compared to diesel/electricity powered pumps. The pump costs were within the price ranges that can be found for human powered pumps using internet sources.

Flow and pressure (for the treadle pump) were measured for both pumps, and the results showed variability in pump performance for the different suction lifts. These results showed that the rower pump performed better than the treadle pump with regard to maintenance of flow throughout the testing periods, where the treadle pump flow and pressure varied considerably. Overall, the performance of both pumps was within the range of results found in other studies.

The results showed that pump durability is influenced by the pump parts, where the pistons are the main concern followed by the pulley assembly (for the treadle pump). Though the pump structure is made of durable materials, in this study, these parts limited pump lifetime/durability to a single cropping season. Therefore, the author recommends special care for these parts during pump operation, which could be achieved by scheduling routine inspections and not exceeding 200-400 hours of operation. Due to variability inherent to the manufacture process of these devices, assuming that artisanal methods would be used, the author advises manufacturers to include spares of the listed parts in the ‘new pump kit’. This measure would avoid prolonged pump inoperability due to breakdown during cropping seasons, because the farmer would be able to replace the parts immediately after failure. Designers are also encouraged to improve the designs, with regard to making the access to these parts easier, and to allow maintenance to be conducted using the fewest possible number of tools.

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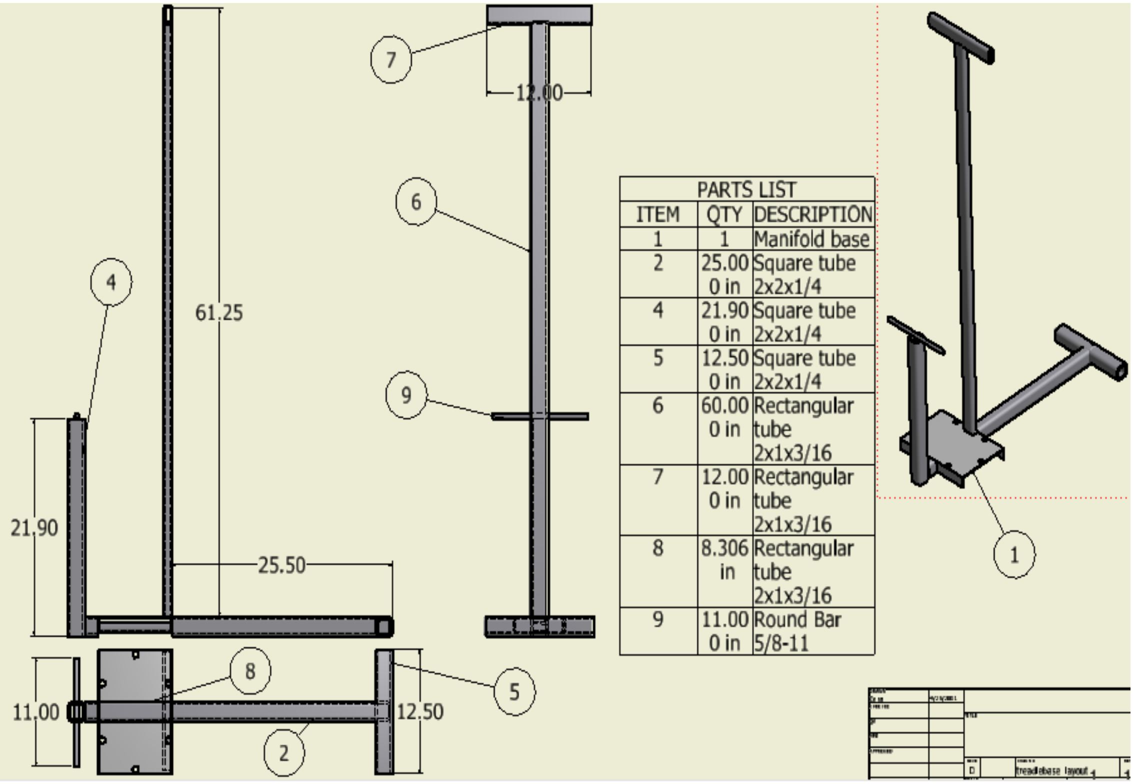
APPPENDIX

Supplemental Pump Information

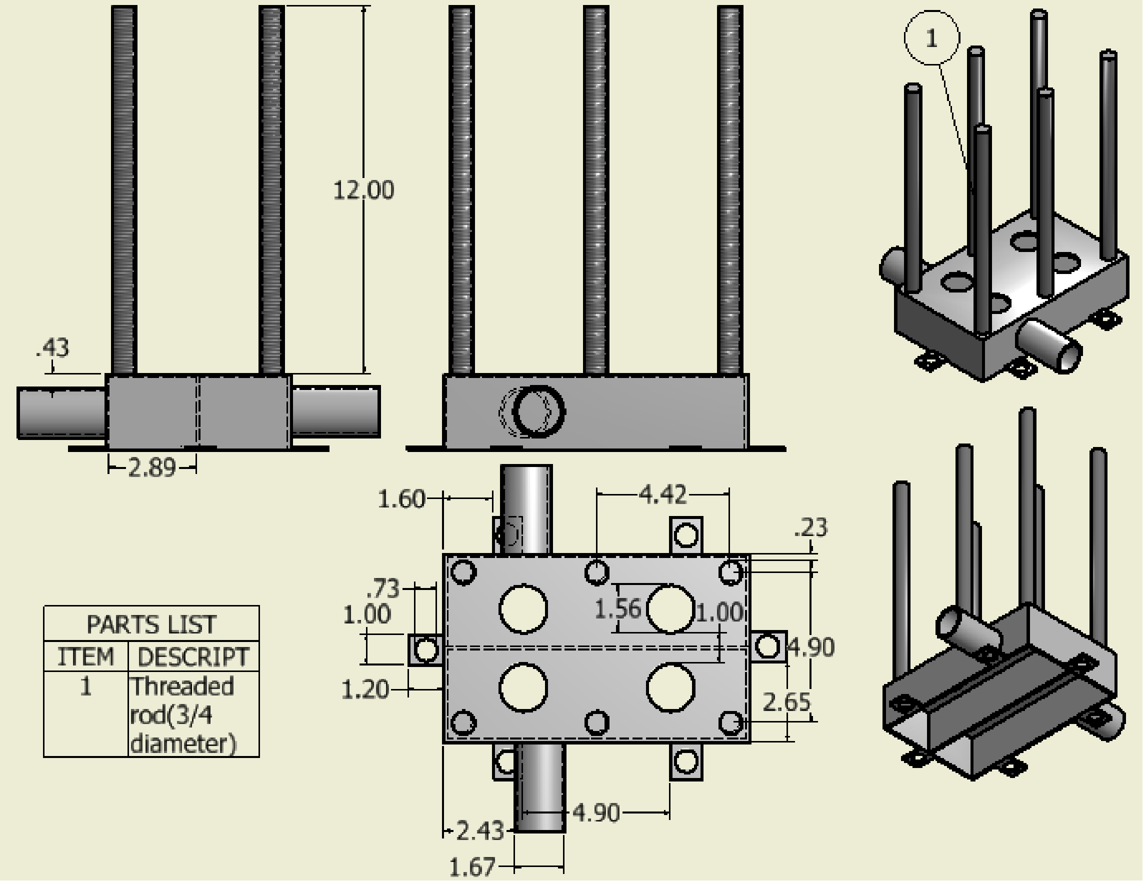
Treadle pump drawings (Dimensions in inches).

Figure A: Treadle pump base.



PARTS LIST		
ITEM	QTY	DESCRIPTION
1	1	Manifold base
2	25.000 in	Square tube 2x2x1/4
4	21.900 in	Square tube 2x2x1/4
5	12.500 in	Square tube 2x2x1/4
6	60.000 in	Rectangular tube 2x1x3/16
7	12.000 in	Rectangular tube 2x1x3/16
8	8.306 in	Rectangular tube 2x1x3/16
9	11.000 in	Round Bar 5/8-11

Figure B: Treadle pump manifold box.



PARTS LIST

ITEM	DESCRIPT
1	Threaded rod(3/4 diameter)

Figure C: Treadle pump manifold base.

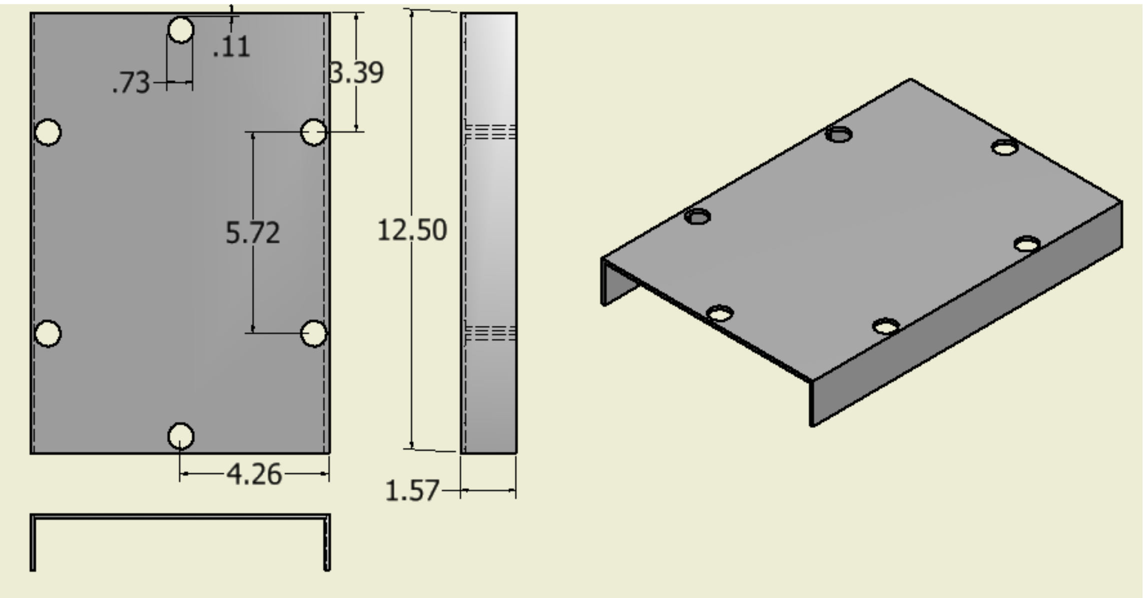


Figure D: Treadle pump upper plate

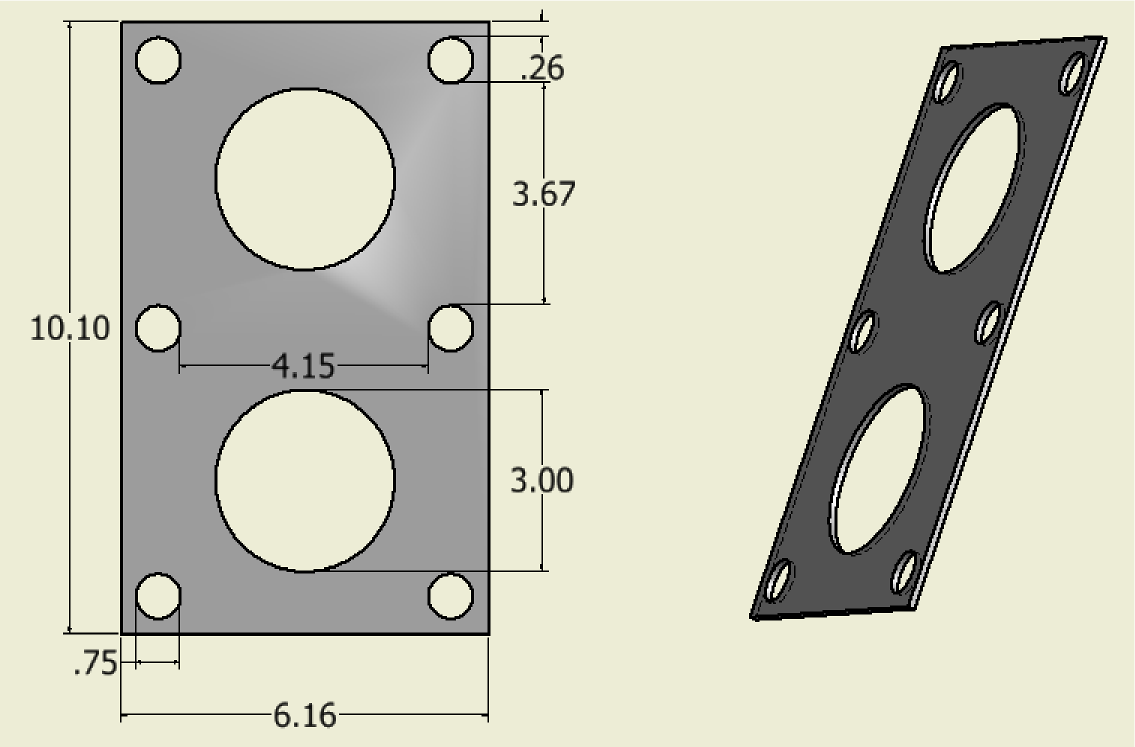
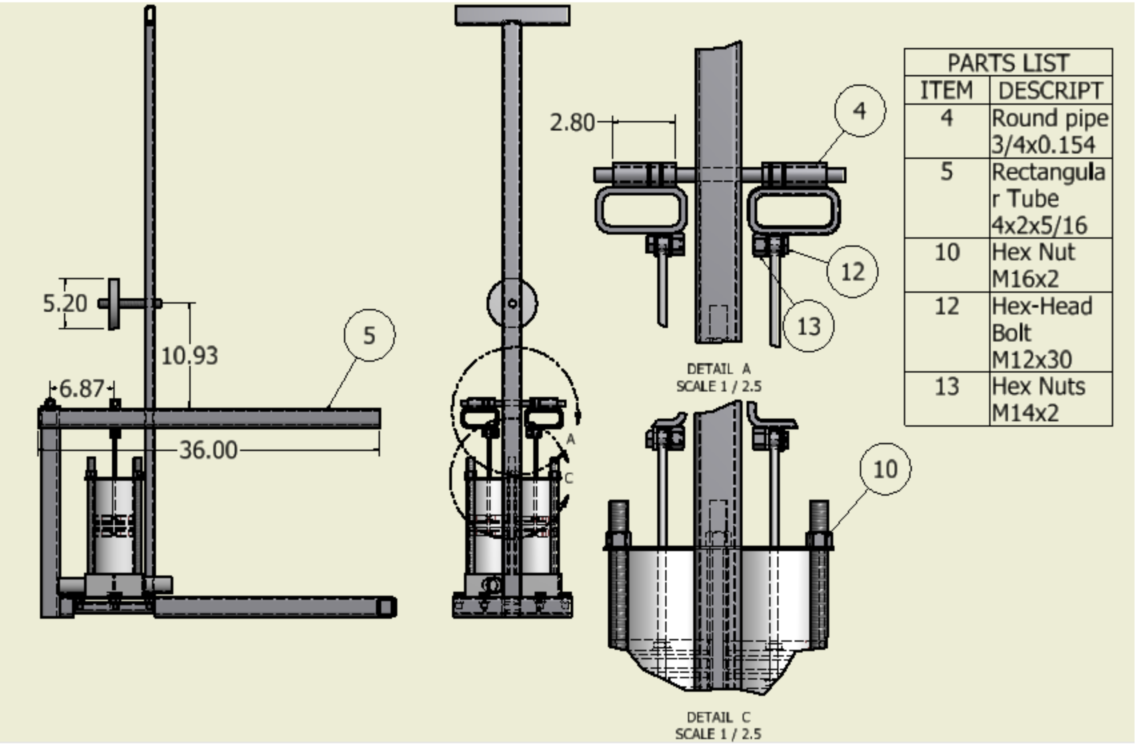


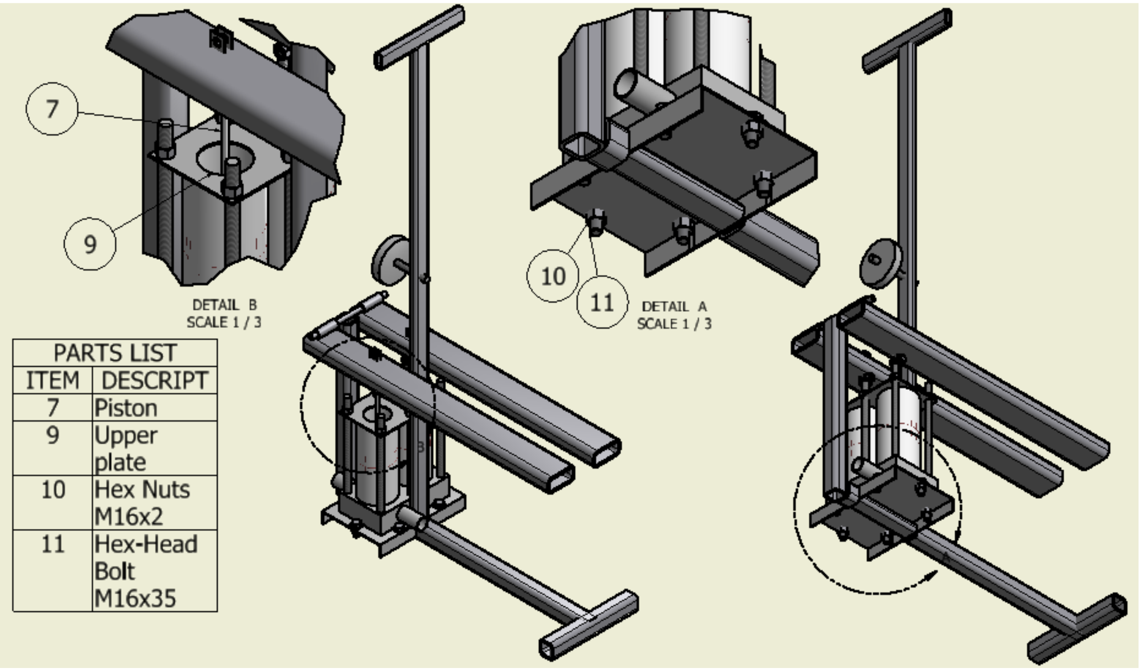
Figure E: Treadle pump views 1.



PARTS LIST

ITEM	DESCRIPT
4	Round pipe 3/4x0.154
5	Rectangular Tube 4x2x5/16
10	Hex Nut M16x2
12	Hex-Head Bolt M12x30
13	Hex Nuts M14x2

Figure F: Treadle pump views 2.



PARTS LIST	
ITEM	DESCRIPT
7	Piston
9	Upper plate
10	Hex Nuts M16x2
11	Hex-Head Bolt M16x35

Other relevant images.

Figure G: Piston cup.

Figure H: Piston cup in PVC cylinder.

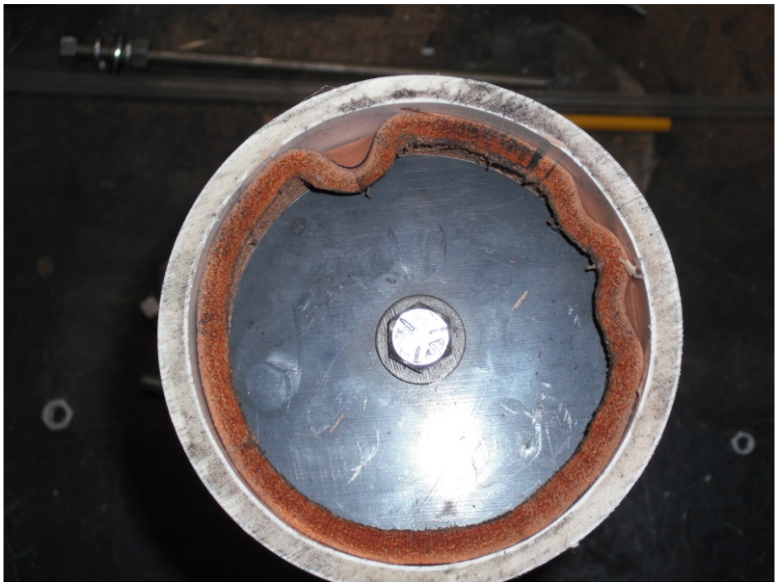


Figure I - Treadle pump base.

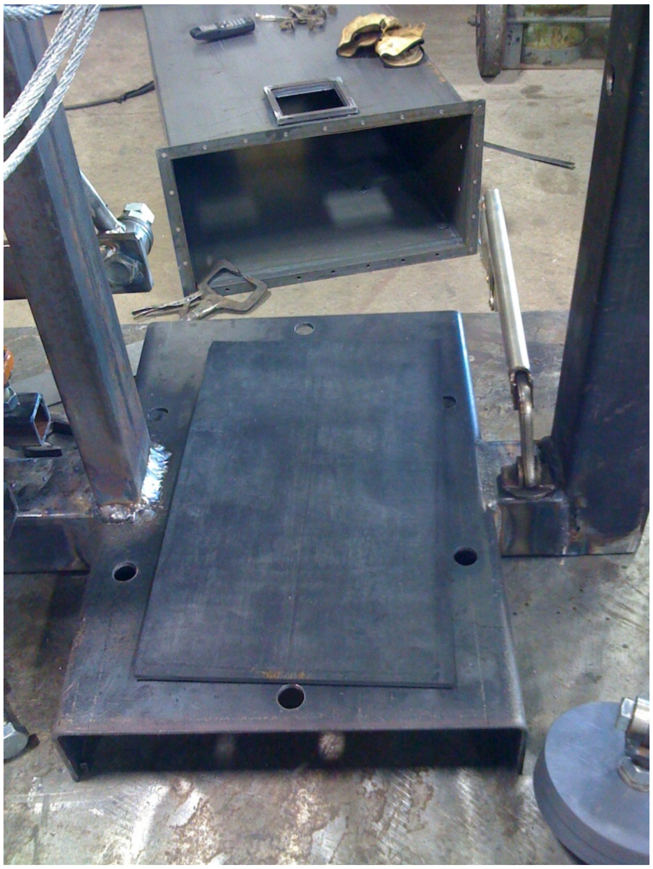


Figure J: Treadle pump manifold box.

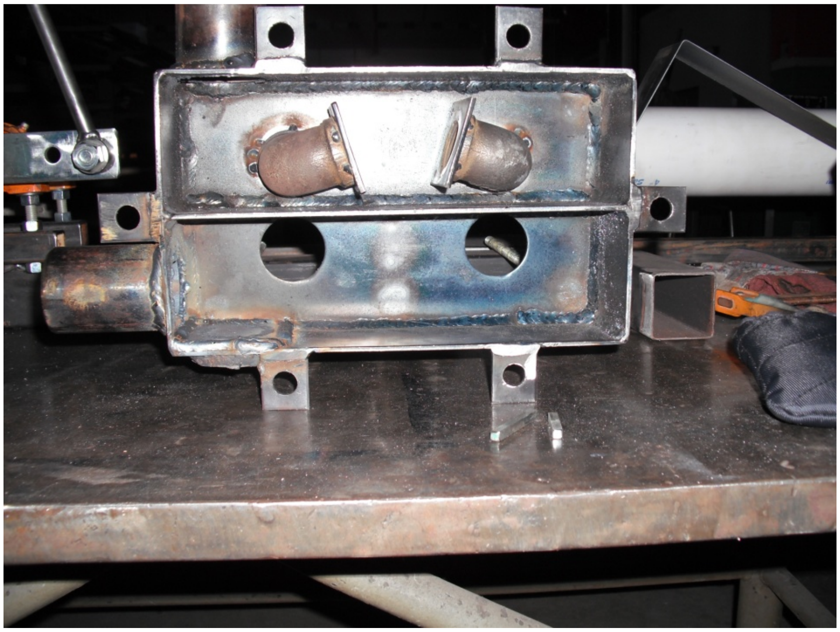


Figure K: Treadle pump manifold box (after 100 hours of operation).

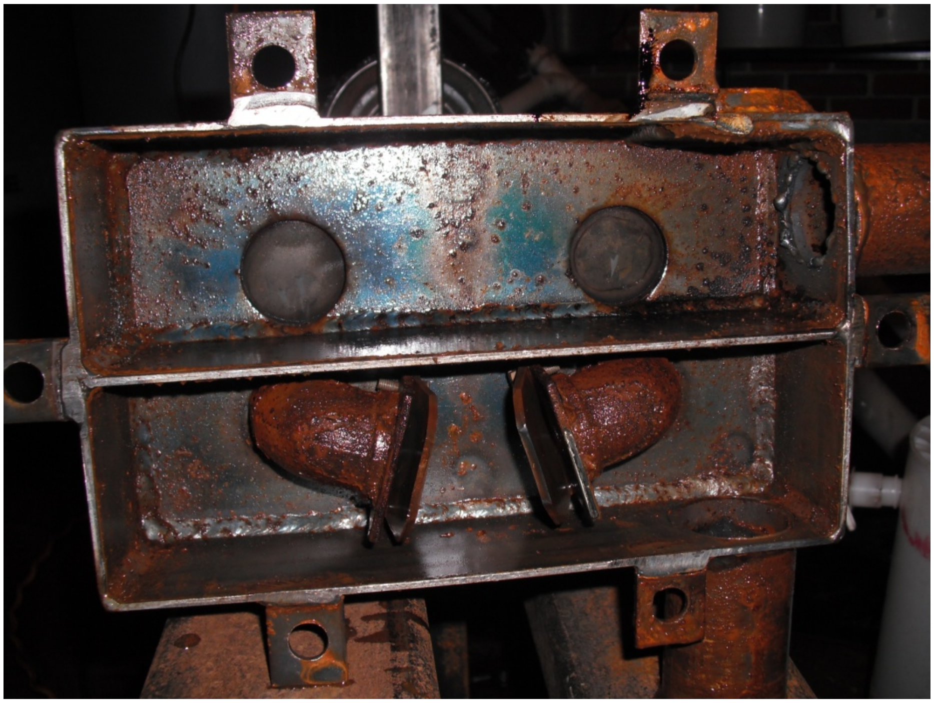


Figure L: Treadle pump valves.

Figure M: Treadle pump manifold box with upper valves.

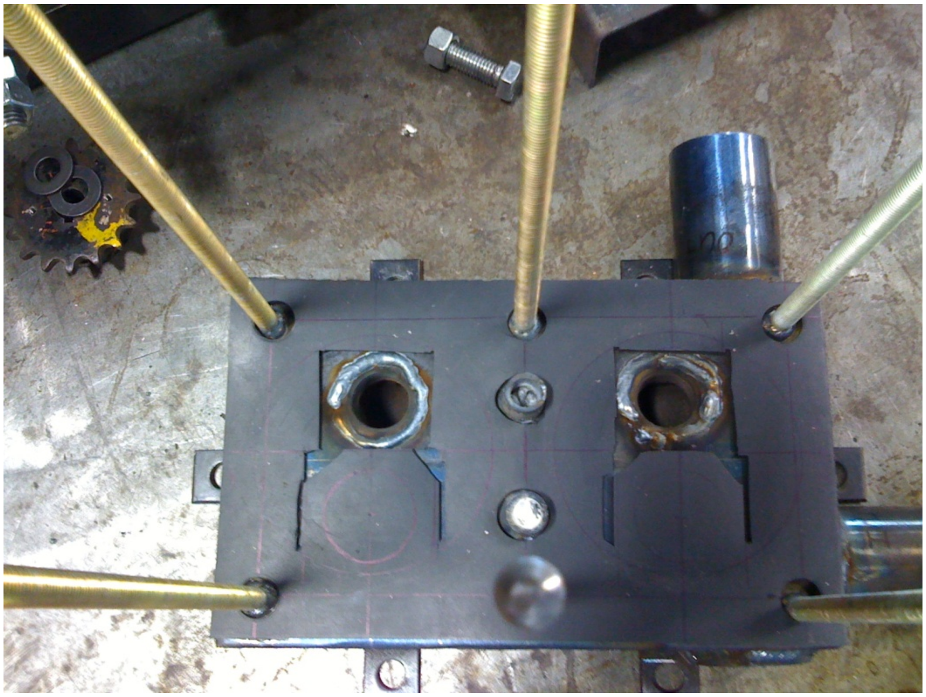


Figure N: Treadle pump assembly.

Figure O: Rower pump.

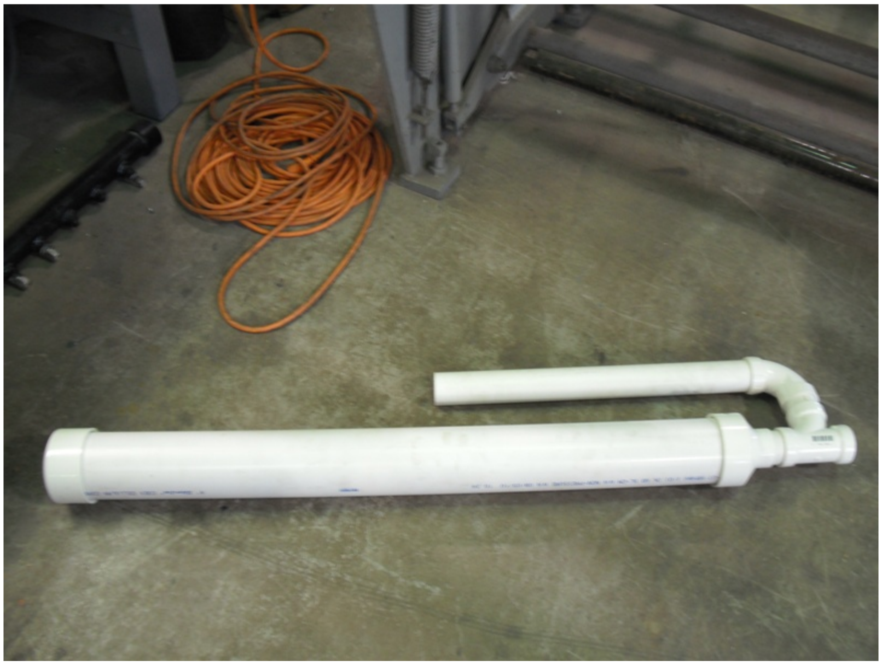
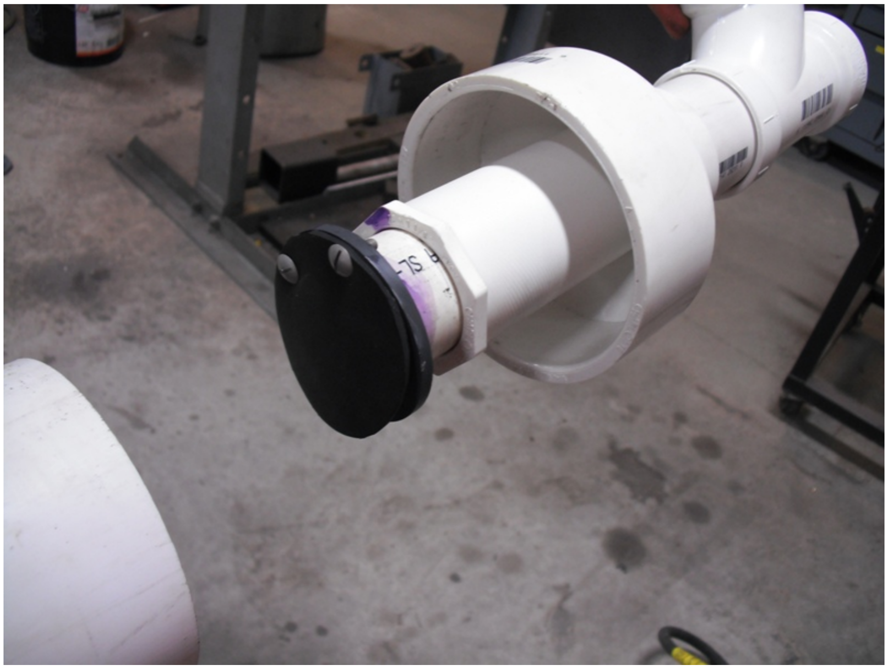


Figure P: Rower pump valve.



Pump costs.

Table A: Cost estimation for the treadle pump

Item	Unit	quantity	price/unit (USD)	Cost (USD)
2x4x8" rectangular tubbing	ft	3.0	6.8	20.3
2x2x16 square tubbing	ft	7.1	3.8	27.1
1/4" thick mild steel plate	sq ft	1.5	15.0	22.9
1 1/4 black pipe	ft	0.5	5.6	2.8
1 1/2 PVC tubbing	ft	10.8	0.8	8.8
1x2x11 rectangular tube	ft	1.8	3.0	5.5
6" diameter pulley	unit	1.0	20.0	20.0
5/8 diameter shaft	ft	0.5	1.7	0.9
5/8 nuts	unit	2.0	0.2	0.4
5/8 washers	unit	2.0	0.2	0.4
iron cable (3/16)	ft	5.0	0.7	3.4
cable clamps	unit	2.0	2.5	5.0
1/2" pipe	ft	1.3	2.9	3.9
3/8 2" long bolt	unit	1.0	0.7	0.7
3/8 nuts	unit	9.0	0.1	1.1
3/8 diameter rod	ft	0.7	1.0	0.6
3/8 16 thread	ft	1.0	1.9	1.9
1/2"x1 1/2 bolt	unit	2.0	0.5	1.0
1/2"x1 1/2 nuts	unit	2.0	0.2	0.3
3/8 diameter, 3/4" long bolt	unit	4.0	0.3	1.1
8" rubber	sq ft	1.5	6.7	10.2
90o steel elbow	unit	2.0	13.1	26.3
			Total cost (USD)	**165**

Table B: Cost estimation for the rower pump

Item	**Unit**	**quantity**	**price/unit (USD)**	**value(USD)**
4" pvc pipe	ft	4.0	3.0	12.0
4" to 2" pvc reducer	unit	2.0	8.7	17.5
2" pvc pipe	ft	1.0	1.1	1.1
2" pvc Y	unit	1.0	4.3	4.3
2" 45o pvc elbow	unit	1.0	1.8	1.8
0.5" diameter rod	ft	5.0	1.2	5.8
PVC plate	sq ft	0.1	6.6	0.6
nuts	unit	4.0	0.3	1.0
washers	unit	2.0	0.1	0.2
ruber	sq ft	0.1	6.7	0.6
PVC cap	unit	1.0	1.0	1.0
Leather	sq ft	0.2	6.0	1.2
			Total cost (USD)	**47**

VITA

Celso Miguel Abdala Tamele

Candidate for the Degree of

Master of Science

Thesis: IMPROVING APPROPRIATE TECHNOLOGIES FOR SMALL SCALE IRRIGATION IN SEMI-ARID AREAS: A CASE STUDY ON MABOTE DISTRICT OF MOZAMBIQUE .

Major Field: Biosystems Engineering.

Biographical:

Education:

Completed the requirements for the Master of Science in Biosystems and Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2011.

Completed the requirements for the Bachelor of Science in Agronomic Engineering at Eduardo Mondlane University, Maputo, Mozambique in 2007.

Experience:

- From April 2008 to July 2009 I worked as an Assessor for Risk Management (Assessor de Gestão de Risco de Calamidades) for the PRO-GRC (Projecto Institucionalização da Gestão de Risco de Calamidades em Moçambique) project, ruled by IP Consult (GTZ) in partnership with Instituto Nacional de Gestão de Calamidades –INGC (National Institute for Disaster Management).
- From September 2007 to March 2008 I worked as a Research Assistant for the Challenge Program on Water for Food (CP17) ruled by the Faculty of Agronomic Engineering and Forestry from the Eduardo Mondlane University.
- From April to August 2007 I worked as a Research Assistant for MTT Agrifood Research Finland (Animal Production Research, Maaninka Research Station).
- From 2004 to 2006 I worked as a Lecturer Assistant for the Faculty of Agronomy and Forestry Engineering in the following subjects: Climatology, Hydrology and Forestry Handling of Hydrological Basins, Irrigation and Drainage.

Professional Memberships: N/A

Name: Celso Miguel Abdala Tamele Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: IMPROVING APPROPRIATE TECHNOLOGIES FOR SMALL SCALE IRRIGATION IN SEMI-ARID AREAS: A CASE STUDY ON MABOTE DISTRICT OF MOZAMBIQUE.

Pages in Study: 65 Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study:
Chapter II addresses the use of earth dams as an appropriate technology for rainwater harvesting for small scale irrigation. The effectiveness of this technology in the Mabote district has been hindered by incorrect site selection resulting in non operational structures. This chapter focuses in the identification of suitable areas for the installation of earth dams using geographic information system (GIS) techniques. GIS was also used to evaluate rainwater harvesting in general, including small scale, in-situ applications. Chapter III addresses the use of human powered pumps as an appropriate technology for small scale irrigation. Failure of human powered pumps has been reported in the Mabote district, where farmers had difficulties in maintaining such devices. Therefore, in this study, two human powered pumps were submitted to continuous operation and their durability was evaluated.

Findings and Conclusions:
GIS modeling showed that less than 1% of the Mabote district area is highly suitable for the installation of earth dams. Therefore, correct site selection, using reference maps produced herein, would reduce losses of resources due to ineffective dam installation. However, the results showed a comparatively large potential (43% of the district area) for the use of in-situ water harvesting techniques.
A treadle pump and a rower pump were evaluated, where the last performed better. Pump durability was influenced by the moving parts, where the pistons are the main concern followed by the pulley assembly. Routine maintenance is recommended, which should not exceed 200-400 hours of operation. The author suggests that human powered pump manufactures include spares of the listed parts in the ‘new pump kit’. Human powered pump designers are also encouraged to improve designs to make access to parts easier, during maintenance operations.

ADVISER’S APPROVAL: Dr. Glenn O. Brown