Developing a Model for the Sustainable Use of Alluvial Aquifers for Small-scale irrigation: A Case study of Shashani River

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A Dissertation submitted in fulfilment of the requirements for the Degree of Master of Philosophy in the Department of Agricultural Engineering, School of Agricultural Sciences and Technology, Chinhoyi University of Technology, Zimbabwe

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Declaration

I, Tinashe Edward Justice Shumba, declare that the work presented here is a product of my work done at the Chinhoyi University of Technology and reference to work done by others is duly acknowledged in the report. This report has never been submitted to any other University for any related degree award.

Signed:…………………… Date: 24 OCTOBER 2025…………………………..

Supervisor .... Date: 24 OCTOBER 2025.....................................

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Abstract

Water resources are under increasing pressure globally. This is due to several factors, including changing weather patterns, population growth, and increased agricultural activity. Sustainable use of water resources is critically needed to conserve the resource and utilize the resource efficiently. Sustainable water resource management can be achieved through scientific study and demand management. In arid and semi-arid regions of Sub-Saharan Africa, some communities rely on water stored in alluvial aquifers within river channels (sand rivers) for dry season water supply. The main objective of this study was to develop a model for the sustainable use of the alluvial aquifer on Shashani River for small-scale irrigation. To achieve this, the study focused on three specific objectives: to quantify the potential water supply of the alluvial aquifer on Shashani River, to model its sustainable yield for small-scale irrigation, and to determine a suitable sand abstraction system to support its sustainable use. The volume of the alluvial aquifer was estimated using probing (mechanically driving a steel rod into sediment to measure depth and bedrock profile along three cross-sections) combined with satellite imagery (tracing river boundaries to estimate the river section). The sustainable yield was modelled based on literature and validated using field investigations. To validate the model, the sustainable yield was estimated for the Alluvial Aquifer on Shashani River. Satellite imagery and Geographical Information Systems were used for catchment sizing, rainfall-runoff modelling for runoff estimation, and field investigations and data collection for estimating alluvial aquifer abstraction. Desktop studies also estimated flow into and out of the river basin. To determine suitable abstraction technology, current methods were studied to inform the design of a sustainable system for irrigation. SolidWorks 2023 was used to design and simulate the performance of the abstraction technology. The volume of the Shashani Alluvial Aquifer was found to be 23.9 x 10^6 m^3. The sustainable yield rate was estimated to be 505 432 700 m^3/yr for a typical wet year, 329 404 000 m^3/yr, for a typical normal year and 135 730 800 m^3/yr for a typical dry year. This suggests that current abstraction can be safely increased by over 100% without exceeding sustainable yield or causing adverse environmental impacts. Therefore, users of these alluvial aquifers can safely utilize them sustainably for agricultural purposes. A suitable sand abstraction system for sustainable abstraction was modelled based on user demands in the catchment. SolidWorks 2023 software was used to model pump components and simulate their motion during operation. Simulations suggest that if the pump operates at a minimum of 50% efficiency, the flow rate will be 1.2 l/s. This would enable a farmer to pump approximately four cubic meters of water to a head of ±7m in an hour. If this water is discharged to and stored in a 4m^3 reservoir, it will be sufficient to meet the crop water requirements of one hectare of leafy vegetables for three weeks. The Shashani River alluvial aquifer can be sustainably utilized for small-scale irrigation, with the proposed sand abstraction system providing sufficient water to meet crop demands without exceeding environmental limits.

Keywords

Sand rivers , Aquifer potential , Sand Abstraction , Alluvial Aquifer, Manual Pump Design , Small-Scale Irrigation

Nomenclature

Parameter Notation	Parameter Definition	Unit
	Water Balance Parameters	
$Q_{in,s}$	Surface Water Inflow	m^3/unit time
$Q_{in,g}$	Groundwater Inflow	m^3/unit time
Q_{abs}	Abstraction	m^3/unit time
$Q_{out, s}$	Surface Water Outflow	m^3/unit time
$Q_{out,g}$	Groundwater	m^3/unit time
E	Net Evaporation from Saturated Sand	m^3/unit time
G	Seepage from the base of the alluvial aquifer	m^3/unit time
Q_{ed}	Exploitable dynamic groundwater reserve	m^3/unit time
Q_{dom}	Volume of water used for domestic use	m^3/unit time
Q_{irr}	Recharge due to irrigation	m^3/unit time
Q_{sew}	Sewage Return	m^3/unit time
S_y	Specific Yield	dimensionless
$P_{\in}$	Excess accumulated Rainfall	mm
P	Accumulated Rainfall depth	mm
I_a	Initial Abstraction	mm
S_r	Potential Maximum Retention	mm
CN	Curve Number	dimensionless
SY	Sustainable Yield	m^3/unit time
SYF	Safe Yield Factor	dimensionless
R	Runoff from Catchment Area	m^3/unit time
ET	Evapotranspiration	m^3/unit time
	Pump Design Parameters	
C	Spring Index	mm
d	Diameter of spring coil	mm
K	Wahl’s stress factor	Dimensionless
δ	Deflection	mm
G	Modulus of Rigidity	N/mm^2
n	Number of Active turns	no

CBM	Counterbalance Mass	kg
$\mathbf{M_0}$	Mass of the object to be lifted	kg
$\mathbf{D_0}$	Distance from object to the fulcrum	mm
$\mathbf{D_b}$	Distance from the counterbalance to the fulcrum	mm
$\mathbf{d_r}$	Piston Rod Diameter	mm
$\mathbf{F_w}$	Weight of Water	N
$\boldsymbol{\sigma_a}$	allowable stress which on piston rod	N/mm^2
$\boldsymbol{\rho_w}$	Density of Water	kg/m^3
g	Acceleration due to gravity	m/s^2
$\boldsymbol{S_l}$	Stroke Length	mm
$\mathbf{a_{rm}}$	rising main across sectional area	m
$\boldsymbol{P_w}$	Power	Watts
E	Output Energy	J
n	Cadence	Strokes/s
$\Delta\mathbf{H}$	Pump Head	m
$\boldsymbol{m_w}$	Mass of water lifted	kg
V	Swept volume per stroke	m^3
$\Delta\boldsymbol{p}$	Hydrostatic pressure at suction point	Pascal

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Chapter 1: Introduction

1.0 Introduction

Due to low precipitation experienced in the semi-arid regions of Zimbabwe, surface reservoirs usually become dry during dry spells and in the dry seasons (Morante-Carballo *et al.*, 2022; Mwadzingeni *et al*., 2022). This becomes problematic in Sub-Saharan Africa (SSA) where the bulk of the inhabitants rely on agriculture as their main source of livelihood and where water stress is intensifying with climate variability (Anghileri *et al.*, 2024; Siderius *et al.*, 2024). Access to water for agricultural production is poor due to unavailability of appropriate water sources and limited infrastructure for smallholders (Osisiogu *et al*., 2024). In order to increase access to water supply in semi-arid regions several adaptation systems such as artificial surface reservoirs and complementary small-scale storage have been designed to meet the domestic and agricultural water requirements of smallholder farmers (Ebrahim *et al.*, 2024).

Sand rivers have emerged as a reliable source of water supply in Sub-Saharan Africa. When all other water sources have dried up, water can still be found in riverbeds (Lazurko *et al.*, 2024; Prasad *et al*., 2024) . Sand rivers are defined as shallow unconsolidated alluvial deposits presently accumulating along active stream courses within which saturated basal sands form limited aquifers supporting dry-season supply (Prasad *et al.*, 2024). Alluvial aquifers, however, are groundwater units, generally unconfined, hosted in laterally discontinuous layers of sand, silt and clay and deposited by a river in a river channel, banks or flood plain (Xie *et al.*, 2024). Gwate (2012) suggested that sand rivers refer to the dry riverbed and the underlying alluvial aquifer, which usually contains groundwater throughout the year; recent work in Zimbabwe similarly treats these deposits as shallow, accessible nature-based storage (Chauruka *et al*., 2023; Prasad *et al.*, 2024). Soil erosion in many cases leads to large quantities of sand deposits into waterways and rivers; these unconsolidated sediments retain water in their pore spaces, offering buffered dry-season supplies (Prasad *et al.*, 2024). In this study, the terms sand river and alluvial aquifer have been used interchangeably because they use the same system of water storage.

The Shashani River, located in the semi-arid southern region of Zimbabwe within the Umzingwane Catchment, serves as a critical source of water for smallholder farming communities. Like many ephemeral rivers in the region, the Shashani exhibits seasonal flows, with most of the water stored underground in its sandy riverbed (Chisadza *et al.*, 2022; Dube *et al.*, 2024). During the dry season, the visible flow disappears, but significant volumes of water remain trapped in the underlying alluvial aquifer. Recent studies in the broader Shashe/Umzingwane system emphasize the role of subsurface and integrated storage in sustaining rural livelihoods, highlighting their potential for irrigation and drought resilience (Ebrahim *et al.*, 2024; Lazurko *et al.*, 2024).

Sand rivers have long played a crucial role in agricultural practices, serving as a valuable water source in various regions. Concurrently, significant progress has been made in developing and refining water abstraction technologies specifically designed for these unique riverine environments. The expertise to abstract water is a traditional talent in Southern Africa, and recent case studies in Zimbabwe and Kenya show that sand rivers can support smallholder irrigation as part of climate adaptation strategies (Prasad *et al.*, 2024). They have been used for domestic water supply for small towns, livestock watering, irrigated gardens, and commercial applications such as irrigation schemes and cattle production (Ebrahim *et al.*, 2024; Lazurko *et al.*, 2024). Many methods have been used to abstract water from sand rivers, including simple scoop holes, manual and hand pumps, and increasingly solar-powered pumps for smallholder irrigation (Chauruka *et al.*, 2023; Durga *et al.*, 2024).

Sustainability and affordability remain major considerations in the design of water projects. Many abstraction methods have been proposed and designed for abstracting water for irrigation. However, most authors agree that using readily available and low-cost materials, simple construction methods and local labour is beneficial for rural uptake (Prasad et al., 2024). The sustainability of alluvial aquifers is affected by high water demand for domestic use, irrigation and rising livestock populations, alongside growing climatic pressures (Anghileri *et al.*, 2024; Siderius *et al.*, 2024).In southern Africa, community-based efforts to utilise sand-river abstraction systems to alleviate rural water scarcity have revealed critical limitations when abstraction exceeds recharge, underscoring the need for robust monitoring and management (Ebrahim *et al.*, 2024; Prasad *et al.*, 2024). In Zimbabwe, the use of alluvial aquifers as an alternative to conventional groundwater and surface water is gaining attention but remains under-explored in terms of quantified sustainable yields and operational guidance (Lazurko *et al.*, 2024). The abstraction methods that are used will have to be reconsidered so as to ensure that the technology will not promote exploitation of the resource in an unsustainable way.

Abstraction from the sand rivers should be managed sustainably to ensure continuous supply of water. Russo *et al.* (2014) defined sustainable water management as meeting current water demand for all water users without impairing future supply. The sustainability of alluvial aquifers is affected by high water demand for both domestic, irrigation as well as increasing livestock population (Zume & Tarhule, 2011). In southern Africa, community-based pilot projects exploiting sand river abstraction systems to alleviate rural water scarcity have revealed critical limitations. For example, in Botswana it was found that aquifer recharge rates were substantially lower than abstraction rates, leading to over-pumping, falling water tables, and low drawdown (Clanahan & Jonck, 2005). In Zimbabwe, the use of alluvial aquifers as an alternative source to conventional groundwater and surface water remains under-explored and poorly understood (Mpala, *et al*., 2016). The abstraction methods that are used will have to be reconsidered so as to ensure that the technology will not promote exploitation of the resource in an unsustainable way.

In response to increasing water scarcity and the need for informed resource management, modelling of alluvial aquifers has emerged as a crucial tool for understanding hydrological dynamics and sustainable yield. Numerical groundwater models and coupled recharge–flow frameworks allow simulation of recharge, storage capacity, abstraction rates, and long-term impacts of different water-use scenarios (Balcha *et al.*, 2024; Condon *et al.*, 2021). Recent applications across arid and semi-arid alluvial settings demonstrate how calibrated models can estimate safe yield, evaluate pumping impacts, and test managed aquifer recharge options under climate stressors (Alelaimat *et al.,* 2023). Integrated approaches that couple watershed-scale recharge estimation with groundwater flow further strengthen planning for small-scale irrigation from sand rivers by linking climate variability, land use, and pumping to aquifer responses (Asrade *et al.,* 2024). These advances motivate the modelling undertaken in this study for the Shashani River system to support sustainable abstraction strategies for rural livelihoods.

Modelling enables researchers and decision-makers to simulate aquifer recharge, storage capacity, abstraction rates, and long-term impacts of different water use scenarios (Balcha *et al*., 2024; Turkeltaub & Bel, 2024). Various approaches have been employed in alluvial aquifer modelling, ranging from simple empirical calculations to more sophisticated numerical models such as MODFLOW and its derivatives (Christos *et al.*, 2025; Laoufi *et al.*, 2024). For small-scale irrigation schemes in semi-arid regions, developing tailored models that incorporate local hydrological and socio-economic conditions can enhance planning and promote sustainable use of alluvial aquifers (Alelaimat *et al.,* 2023; Asrade *et al.*, 2024)

1.1 Problem Statement

The full potential water supply of alluvial aquifers is still unknown, therefore, there is risk of under-exploitation or over-exploitation of the water resources, which could lead to unexpected environmental degradation, wastage of time and resources when irrigated crops fail (Mpala *et al*., 2016). Smallholder farmers in rural communities have limited access to water from alluvial aquifers for small-scale irrigation. Suitable technology for sustainable exploitation of alluvial aquifers has not been fully developed. Analysis of commercially available sand abstraction pumps reveals a consistent pattern of resource utilization imbalance. Specifically, their design and intended application often lead to under-exploitation of the resource when restricted to domestic contexts, or conversely, contribute to over-exploitation where the inherent ease of extraction encourages unsustainable practices.

1.2 Justification of the study

Zimbabwe has experienced increasingly erratic rainfall over the past three decades, which has contributed to persistently low agricultural productivity due to the country's reliance on rain-fed farming systems (Mugiyo *et al.*, 2023). In response, governments in Sub-Saharan Africa (SSA), non-governmental organisations (NGOs) and several donor-community agencies have intervened in these semi-arid regions. These efforts have included expanding access to water supply, sanitation, and hygiene (WASH) services, as well as promoting smallholder irrigation schemes and the adoption of solar-powered water abstraction technologies (Mupaso *et al.*, 2024; Mwadzingeni *et al*., 2023). All these activities mentioned are expected to increase the demand for water. While such programs have improved access to water, they have also significantly increased demand, placing additional pressure on available water resources. The growing reliance on these shallow alluvial aquifers raises serious environmental concerns, including groundwater depletion and degradation of groundwater-dependent ecosystems. Therefore, it is imperative to conduct research on the potential of alluvial aquifers to supply suitable water using suitable abstraction systems in a sustainable manner for irrigation

1.3 Aim

To develop a model for the sustainable use of the alluvial aquifer on Shashani river in Zimbabwe for small-scale irrigation.

1.4 Objectives

i. To quantify the potential water supply of the alluvial aquifer on Shashani river
ii. To develop a model for estimating the sustainable yield of the alluvial aquifer along the Shashani River to support small-scale irrigation.
iii. To design a sand abstraction system to support the sustainable use of the alluvial aquifer on Shashani river for small scale irrigation

1.5 Research Questions

1.1 What is the potential water supply of the alluvial aquifer on Shashani river?
1.2 How can the sustainable yield of the Shashani River alluvial aquifer be estimated through hydrological modelling approaches?
1.3 What sand abstraction system design is the most suitable for ensuring the sustainable use of the Shashani River alluvial aquifer for small-scale irrigation?

1.6 Scope and Limitations

This research is primarily focused on the sustainable utilization of water resources for small-scale irrigation systems. The central objective is to analyze and propose strategies that enhance the efficiency and longevity of these systems, ensuring their long-term viability. The study does not, however, extend to a comprehensive analysis of the associated socio-economic, human, or biophysical impacts. A detailed examination of community well-being, social equity, or the broader ecological effects of these irrigation practices lies outside the scope of this investigation.

A significant limitation encountered during this study was the dearth of contemporary primary data within the designated study area. The absence of up-to-date, empirical datasets necessitated a heavy reliance on historical records, secondary literature, and existing desk studies. Consequently, the findings and conclusions of this research are grounded in a synthesis of available historical information rather than current, field-collected data.

Chapter 2: Literature Review

2.1 Alluvial Aquifers

Alluvial aquifers are identified as ephemeral watercourses composed of sand that are flooeded by rain-run-off once or several times per year (Mpala *et al.*, 2020; Zarate *et al.*, 2025). During the rainy season, surface flow occurs for a short period, recharging these ephemeral channels (Mpala *et al.*, 2020). Groundwater continues to flow within the alluvial deposits even after surface flow ceases. The river's alluvial sediments provide temporary water storage that can be utilised to supplement water supply during dry periods. Even when other water sources have dried up, water can still be accessed in riverbeds (Mpala *et al.*, 2020).

Alluvial aquifers are referred to by different regional names, highlighting their widespread occurrence and exploitation. In East Africa, they are known as luggas; in North Africa and the Middle East, as wadis; and in the south-western United States, as arroyos. These terms are commonly used in the literature to describe sand-filled ephemeral channels exploited as water sources (Moyce *et al*., 2006). Historical references to the exploitation of alluvial aquifers in Zimbabwe date back to the late 19th century, with geophysical investigations documenting their use from around 1887 (Dahlin & Owen, 1998).

The alluvial aquifer is recharged through various channels. No river flow actually occurs until aquifer is saturated. Alluvial aquifers are recharged from replenishment by the intermittent surface flow as well as intermittent rainfall (Mpala, *et al*., 2020). De Hamer *et al*.,(2008) described the aquifer recharge and river flowing processes as simultaneous process rather than independent. As a flood travels down the riverbed, water infiltrates into the sandy and gravel alluvial deposits of the channel beds. The intensity, volume and duration of the flood determine the amount of recharge which should be factored in the calculations for recharge (Barbosa *et al.*, 2022). Alluvial aquifers have a direct relationship with the stream flow and can significantly contribute to the water balance because of their shallow depth (Jumbi *et al.*, 2025).

The storage capacity of an aquifer is determined by multiple interdependent factors. Coarse sand promotes faster recharge than finer sediments, owing to its larger pore spaces and higher hydraulic conductivity. This was evidenced in the Molototsi sand-river aquifer, which exhibits hydraulic conductivity between 20–300 m/day and porosity around 38–40% (Walker *et al.*, 2018). The extractable water volume, or specific yield, of coarse sands typically ranges between 20% and 35%, with average values around 27% (of the total sediment volume) (Kulkarni *et al.*, 2018). For Shashani River, historical studies have brought values in the range

16% (Jele, 2018) and 15% (Moulahoum, 2018). Additionally, aquifer geometry plays a crucial role: the thickness and lateral extent of alluvial deposits directly influence storage potential, and surface flows only occur once these sands achieve full saturation (Mpala *et al*., 2020; Mvandaba *et al.*, 2018).

Water losses from alluvial aquifers occur due to various factors, including evapotranspiration and seepage through fissures and fractures in the bedrock. Evapotranspiration is influenced by the depth to the water table, with significant losses occurring when the water table is shallow. For instance, a study by Zhang *et al.,* (2025) demonstrated that lowering the water table depth to 60 cm reduced evaporation rates to approximately 10% of those from an open-water surface. Additionally, groundwater seepage through bedrock fractures can lead to water losses from the aquifer. Research by Zhou *et al.,* (2023) highlighted that groundwater flow through fractured rocks is a significant mechanism of water loss in aquifers. These losses can be exacerbated by the presence of natural barriers, such as boulders and dykes, in the bedrock, which may impede downstream drainage and contribute to water retention within the aquifer (Nissen-Petersen, 2006).

Sand dams are also a significant part in the exploitation of alluvial aquifers. A sand dam is a reinforced concrete or rubble stone masonry structure built across the riverbed of a seasonal river to increase the accumulation of coarse sand upstream (Castelli *et al.,* 2022). Sand dams are artificial creations of alluviums in areas where there is limited accumulation of sediments. The main purpose of sand dams is to increase the volume of sand and water in the riverbeds (Gulduren *et al.*, 2021) . Sand dams also function in the same way as sand rivers as they retain water in the sediment and reduce evaporation of water from the channel (Hussey, 2007). Sand dams augment water supply throughout the year. However, Ritchie *et al.*, (2021) suggested that many sand dams do not retain water throughout the dry season, due to issues with low storage volumes (siltation), seepage (pervious streambed, water flow under or around the dam), and over-abstraction.

2.2 Quantifying the Storage potential of an Alluvial Aquifer.

For effective planning, it is essential to know the storage potential of the alluvial aquifer. The water storage potential of the aquifer can be taken as the capacity of the aquifer. The aquifer volume is a function of the length, width and height of the aquifer. However, the most difficult component to ascertain is the depth of the aquifer since it cannot be estimated by visual inspection and remote sensing. The depth (aquifer thickness) is determined using several methods so as to differentiate different layers of the soil in the aquifer.

2.2.1 Determination of Channel Depth

Nissen-Petersen (2006) stated that probing data can be used in estimating the volume of sand in the reservoir and the extractable volume of water from the sand. Probing involves inserting, a metal rod into the sands (usually by physically hammering) (Hussey, 2007). It is a quick and relatively easy method of gauging whether or not water is present below the sediment surface. Probing can also help in investigating the geology of the riverbed. Accuracy of the probing results can be increased by taking multiple readings at different positions on the riverbed. Walker *et al.,* (2018) suggested that probing is the most accurate method of determining depth to bedrock. This method was also used in a study by Mpala, *et al.,* (2016), (Jele, 2018) and by Walker *et al.,* (2018).

Vertical Electrical Sounding (VES) can also be used to determine the depth of the channel. VES uses an expanding array system to determine the thickness of the upper dry zone by recognising the resistivity contrast between it and the underlying saturated zone. The depth to bed rock is recognised by the marked resistivity contrast between solid rock and saturated sands (Kumar *et al.,* 2021). The VES data will be entered into various computer packages for analysis including RES1D (Mohammed Nazifi & Gulen, 2018), IPI2Win software (Ait Bahammou *et al.,* 2021). VES is frequently employed in groundwater studies, particularly in developing regions, because it offers a simple, rapid, and economical approach to subsurface characterization (Leborgne *et al.,* 2021) .This longitudinal resistivity survey can also indicate the consistency of sand aquifer thickness (Walker , *et al*., 2018). However VES provides thickness estimates only where layers are well defined (Walker , *et al*., 2018).

Electrical Resistivity Tomography (ERT) is another geophysical method used in assessing the dimensions of alluvial aquifers. The method is based on the apparent resistivity measurements along the earth surface. Recent advancements in data acquisition have led to the development of multi-electrode resistivity equipment, enabling detailed lateral and vertical imaging of subsurface structures through ERT (Takele *et al*., 2025). ERT has been successfully employed in groundwater exploration, providing valuable insights into aquifer properties and distribution (Hussein *et al.,* 2023; Ozioma *et al.,* 2022). The ERT has the advantage that it gives a 2D subsurface image (Ali *et al*., 2025).

Ground Penetrating Radar (GPR) is a geophysical method used to detect and map shallow subsurface features with high precision and can also be used to determine the sand depth of an aquifer (Ok, 2017). GPR utilizes short electromagnetic waves to reflect, refract, and diffract from subsurface targets. The eletrical properties of materials are controlled by water content and this variation will determine the velocity of the electromagnetic waves on the materials. The difference in properties will identify the material (Fediuk *et al.*, 2022). Recent studies have demonstrated the effectiveness of GPR in characterising aquifer properties and mapping subsurface features in various geological settings (Pena *et al.*, 2023).

Despite the advancement in technology and discovery of new methodologies of determining aquifer depth , probing has proven to be easier to use, financially less-burdening and the results are relatively more reliable (Walker , *et al.*, 2018). Table 2.1 shows the different methods of river channel assessment used on different sand rivers channels regionally.

Table 2.1 : A comparison of alluvial aquifer thickness regionally

Aquifer Thickness (m)	River Section	Measuring Method	Reference
1.48 – 2.45	Shashani River , Zimbabwe	Probing	(Mansell & Hussey, 2005)
1.5	Shashani River, Zimbabwe	Probing	(Mpala, *et al.*, 2016)
1.5 – 2.5	Shashani River, Zimbabwe	Probing, ERT , VES	(Moulahoum, 2018)
0 – 2	Molotsotsi River , Zimbabwe	Trial Pits, Probing, VES	(Walker *et al.*, 2018)
5 - 15	Umzingwane River, Zimbabwe	Continuos VES, GPR	(Dahlin & Owen, 2005)
10-20	Lower Mzingwane River , Zimbabwe	VES	(Masvopo *et al.*, 2008)
10	Kuiseb River , Namibia	Channel Borehole Depths	(Bate & Walker, 1993)
5 -10	Nhandugue River, Mozambique	Continuous VES	(Arvidsson *et al.*, 2011)

1.8 -10	Shashe, Tati, Motloutsi and Ramokgwebana, Botswana	Hammer seismics, probing , shaft excavation	(Davies *et al*., 1998)
4 - 6	Tati River, Botswana	Hammer seismics, probing, shaft excavation	(Herbert *et al*., 1997)
4 – 20	Mzingwane River , Zimbabwe	Resistivity, Dam Construction drawings	(Love *et al*., 2010)
1.4	Mnyabezi River, Zimbabwe	Probing	(De Hamer *et al*., 2008)
4 - 8	Runde and Sesami Rivers, Zimbabwe	Hammer Seismics	(Walker *et al*., 2018)

2.3 Determination of Abstraction rate

The rate of abstracting water from a water resource should be calculated with precision and accuracy. It is important to consider the input and output of a hydrological system before making the decision to use a water resource. Water budgeting is used to determine the relationship between several input and outputs in any hydrological system. In an alluvial aquifer system, it is used to determine all the water which will be stored in an aquifer at a certain period since the water is always in motion. There are several approaches to determine that the water is not depleted in a water system.

2.3.1 Alluvial aquifer modelling

A water budget is an accounting of water movement into and out of, and storage change within, a defined control volume (Moyers *et al.*, 2023). The first step in a water-budget analysis is to select one or more control volumes for study. A control volume may be any portion of the earth system or a hydrologic structure (for example, a laboratory soil column, a lake or stream, an aquifer, a watershed, a nation-state, or even the globe) and water budgets have been constructed across all these spatial and temporal scales. For an alluvial aquifer, Love *et al.* (2010) proposed a a conceptual budget equation for alluvial aquifers. They stated that :

$$Q_{in,s} + Q_{in,g} = E + Q_{abs} + G + Q_{out,s} + Q_{out,g} \pm \frac{\Delta S}{\Delta t} \quad \text{Equation [2.1]}$$

Where

$Q_{in,s}$ is surface water inflow

$Q_{in,g}$ is groundwater inflow

E is the net evaporation from saturated sand

Q_{abs} is abstraction

G is the seepage from the base of the alluvial aquifer

$Q_{out,s}$ is surface water outflows

$Q_{out,g}$ is groundwater outflows

$\Delta S / \Delta t$ is change in storage in the alluvial aquifer per time step

This approach considers most of the input and output parameters of an alluvial aquifer. Depending on the intention of the study, some of the parameters can be considered negligible. The approach developed in this study can be applied to evaluate the potential of alluvial aquifers. Notably, the conceptual understanding presented by Mansell and Hussey (2005) aligns with the later framework proposed by Love *et al.* (2010), suggesting a coherent theoretical basis for characterising flow dynamics in sand river systems. Hydraulically, the flow in a sand river system can be visualised as a closed conduit, which has a slope to its base approximating to the sand surface but more irregular (Mansell & Hussey, 2005). They developed a schematic illustrating the flow in an alluvium as shown in Figure 2.1.

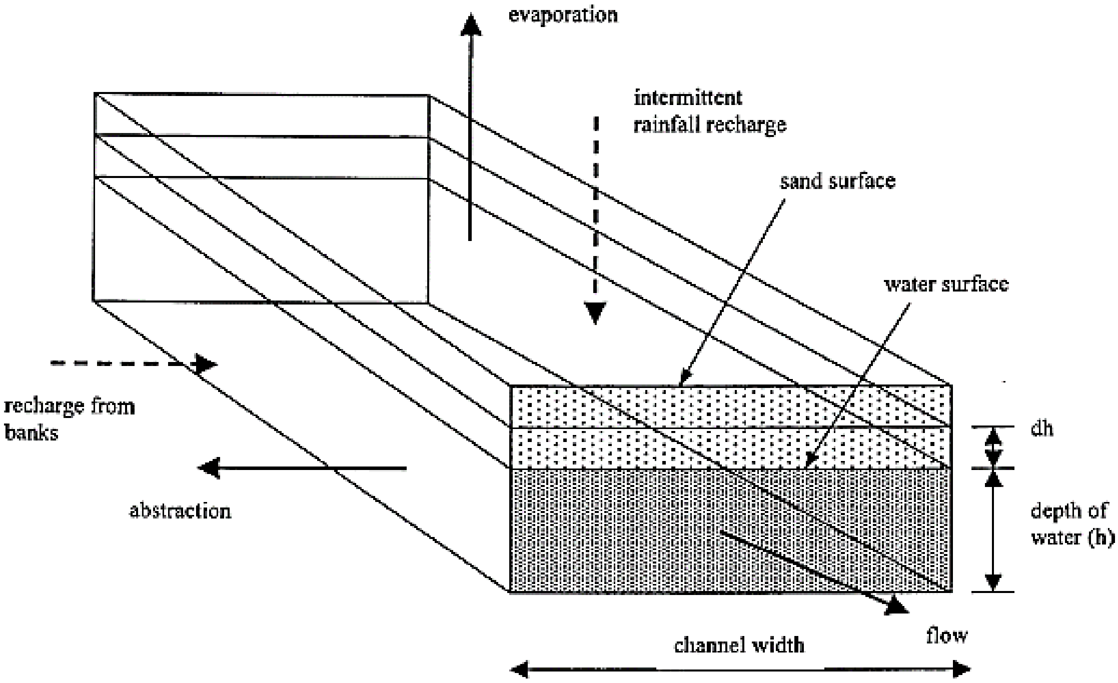

Figure 2.1: A schematic of the flow in a sand river system (Source: Mansell & Hussey, 2005)

2.3.2 Safe Yield

The safe yield concept has been extensively used in water research through the years (Karandish et al., 2025; Tapia-Villaseñor et al., 2022). Originally it focused on the relationship between the size of a surface water reservoir and its safe yield defined as the maximum quantity of water that could be supplied from the reservoir during a critical period (Alley & Leake, 2004). Gebreslassie *et al.,* (2025) defined safe yield as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge. Any withdrawal in excess of safe yield is an overdraft (Tizro *et al*., 2010). Al Atawneh *et al.,* (2024) suggested that safe yield of a groundwater basin is the long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge. Many suggestions for improving the safe-yield concept have focused on considering the yield concept in a socioeconomic sense (Woldeyohannes & Waqar, 2017).

Safe yield should be less than the average annual recharge to compensate for minor groundwater losses (Tizro *et al*., 2010). Anim-Gyampo *et al.* (2012) suggested using a factor of safety of 0.6- 0.9 based on the local hydrogeology experience to account for minor groundwater losses. Some of the disadvantages of the safe yield are that it assumes an even distribution of discharges or withdrawals across a watershed (Anim-Gyampo et al., 2012). Tizro *et al.,* (2010) suggested that changes in vegetation, land use, urbanisation, location of pumping wells, incorporation of new water supplies or climate change would require calculation of the safe yield. Several methods have been postulated on how to determine safe yield , however Naik & Awasthi (2003) developed an emprical relationship given in equation 2 :

$$Safe\ Yield = Q_{ed} + Q_{dom} + Q_{irr} + Q_{sew} \qquad \text{Equation [2.2]}$$

Where:

$Q_{ed} = exploitable\ dynamic\ groundwater\ reserve$ [m^3/unit time]

$Q_{dom} = volume\ of\ water\ used\ for\ domestic\ use\ in\ the\ rainy\ season$ [m^3/unit time]

$Q_{irr} = recharge\ due\ to\ irrigation$ [m3/unit time]

$Q_{sew} = sewage\ return$ [m3/unit time]

To determine the exploitable dynamic groundwater reserve, Naik & Awasthi (2003) suggests using equation [2.3] below:

$$Q_{ed} = A \times S_y \times DL_d \qquad \text{Equation [2.3]}$$

Where:

$S_y = Specific\ Yield$

$A = Effective\ Area\ of\ groundwater\ recharge$ [m^2]

$DL_d = Average\ water\ level\ decline\ in\ the\ dry\ season$ [m]

In this study the safe yield is going to be taken as the annual recharge and an average safety factor of 0.75 is going to be used for water budgeting purposes based on the suggestions by Anim-Gyampo *et al.*(2012).

The safe yield concept is a good concept to use in water economics. However, it suffers multiple drawbacks in that it assumes an even distribution of withdrawals across each watershed and are not necessarily indicative of localised impacts to base flow (Chilaka *et al.*, 2024). Sophocleous (2000) posited that the safe yield ignores the fact that over the long term under natural or equilibrium conditions, natural recharge is balanced by discharge from the aquifer by evapotranspiration or into streams, springs, or seeps. Okten and Yazicigil (2005) asserted, the traditional concept of safe yield is flawed because it fails to account for other significant components of the hydrological cycle, such as evapotranspiration and base flow. Consequently, management policies based solely on this metric can result in unintended ecological and environmental consequences, including the desiccation of streams and wetlands, loss of associated ecosystems, and potential contamination of groundwater through interaction with polluted surface water.

Sophocleous (2000) stated that the conventional safe-yield approach is limited and restrictive, and that it fails to address the beneficial impacts of natural ground-water discharge on related groundwater-dependent ecosystems, and on the surface-water system in general. He further explained the assertion stating that there is no one value which can be pointed to affect safe yield since the water quality, water quantity and changes in vegetation can affect safe yield. This was supported by Tizro *et al*., (2010) who stated that changes in vegetation, land use, urbanisation, location of pumping wells, incorporation of new water supplies or climate change would require recalculation of the safe yield hence many factors affect the safe yield of a water source.

2.3.3 Sustainable Yield

The sustainable concept is developed in early 1980s with the idea of limited availability of resources and how to regenerate for coming generations (Woldeyohannes & Waqar, 2017). Meyland (2011) defined sustainable water resource systems as systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity. Hays (2000) defined sustainable yield as the volumetric rate of water that an aquifer can provide while maintaining desirable aquifer conditions (primarily water levels and water quality) such that the aquifer remains a viable resource for long-term use. Sustainable management of alluvial aquifers requires balancing abstraction with natural recharge, maintaining aquifer health, and adopting practices that prevent overexploitation (Jele, 2018). Integrating hydrological modelling and optimized pump technology can help communities use these aquifers efficiently while supporting long-term agricultural productivity

2.3.4 Determination of modelling parameters

An accurate determination of the parameters affecting the water balance is key to accurately determine the sustainable yield Several approaches can be used for different parameters and this section discusses the approaches to determination of different parameters used in this study.

Determination of Surface Runoff

Surface runoff is the water flow that occurs when soil is infiltrated to full capacity and excess water from rain, melt water, or other sources flows over the land (Pal & Samanta, 2011). Several approaches can be used to determine surface runoff including Soil Conservation Services-Curve Number (SCS-CN) method, hydrologic models, physical methods and tracer techniques which will be discussed in this section.

Soil Conversation Services – Curve Number (SCS-CN) method

The Soil Conservation Service Curve Number (SCS-CN) method, developed by the U.S. Soil Conservation Service, is an empirical approach that remains widely applied for estimating direct runoff from rainfall, particularly in ungauged and rural catchments (Cronshey, 1986). It relates total rainfall (P), initial abstraction (I_a), and potential maximum retention (S) using a set of standard equations. Recent research continues to validate and enhance this method in various contexts. Bahrami *et al*. (2021) evaluated the SCS-CN model in an ungauged watershed in Iran and found it effective for predicting flood volumes, especially when baseflow separation is considered. Similarly, Ibrahim *et al.* (2022) applied the SCS-CN method in humid tropical environments and demonstrated that local calibration of Curve Numbers significantly improved runoff estimation accuracy.

The method's simplicity, minimal data requirement, and compatibility with GIS-based applications have contributed to its continued relevance in contemporary hydrological modelling (Singh & Khare, 2021). The core relationship used in the method is expressed as shown in equation 2.4 below (Cronshey, 1986):

$$P_{\in} = \frac{(P-I_a)^2}{P-0.8S} \qquad \text{Equation [2.4]}$$

Where:

$P_{\in}$ Is the accumulated rainfall excess at time t ($P_{\in}$ = 0 if $P < 0.2S$)

P is the accumulated rainfall depth at time t

I_a Is the initial abstraction

S_r is the potential maximum retention. (Cronshey, 1986)

A further empirical relationship defines initial abstraction as:

$I_a = \lambda S$ (Where λ =0.2) Equation [2.5]

Substituting Equation 2.5 into Equation 2.4 yields the commonly used form;

$$P_{\in} = \frac{(P-I_a)^2}{P-I_a+s} \qquad \text{Equation [2.6]}$$

Additionally, the retention parameter S is related to the Curve Number (CN) by:

$$S_r = \frac{(1000)}{CN} + 10 \qquad \text{Equation [2.7] (Cronshey, 1986)}$$

These formulations form the basis of runoff estimation in a wide range of hydrological studies, including those incorporating remote sensing and land use classification to refine CN values.

Physical methods of determining groundwater recharge

The physical methods as pointed out by Healy (2010) are the most used to determine groundwater recharge. A good estimate of recharge can also be determined by taking measurements in the saturated zone of the aquifer. Healy and Cook (2002) identified the Water Table Fluctuation (WTF) method as one of the most widely used techniques for estimating groundwater recharge, primarily due to its simplicity and minimal data requirements. Recent studies continue to apply the WTF method, especially in unconfined aquifers where water level data are available and recharge mechanisms are relatively well understood (Webster *et al.,* 2023). The water table fluctuation method (WTF) is applicable to unconfined aquifers. This method has been used in unconfined aquifers through time and it formed the basic foundation of the method used in alluvial aquifers by Love *et al.* (2008). It is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Masvopo (2008) and De Hamer *et al.* (2008) successfully used the method in trying to assess the potential of alluvial aquifers. However, these physical methods suffer some drawbacks because they do not account for steady rate of recharge and external effects on groundwater level (Islam, 2016).

Measurement of downward water flux or change in water storage within the unsaturated zone can also be used to obtain a good estimate of recharge (Healy, 2010). These methods assume that the draining water will eventually reach the water table (Scanlon *et al.,* 2002). However they can be costly to implement and require intensive instrumentation that is susceptible to measurement inaccuracies (Healy and Cook, 2002). Furthermore, they can only give a localised value of the recharge which cannot be a representative of the whole zone (Healy and Cook, 2002). Under certain circumstances, these methods have a unique ability to provide detailed insight into recharge processes and factors that influence recharge rates (Healy, 2010). (Becke *et al*., 2024) stated that these methods produce estimates of drainage rates below the depth of measurement, and they are applicable to a wide range of temporal scales.

The other physical method is based on the relationship between surface water and groundwater. Streamflow data are commonly used to estimate recharge rates in humid and subhumid regions, in part because of the abundance of streamflow data and the availability of computer programmes for analyzing those data (Healy, 2010). Winter *et al.* (1998) suggested that measuring the magnitudes of exchange between the two sub-systems can help in determining the recharge or discharge. This method, however, requires careful analysis of the underlying assumptions (Healy, 2010) and since the method does not take into account evapotransipiration, it ussually gives estimates greater than other methods.

Tracer techniques of determining surface groundwater recharge

The techniques based on the heat or chemical isotopic tracers are gaining much importance in the estimation of groundwater recharge (Sajil Kumar *et al.,* 2022). Tracers have a wide variety of uses in hydrologic studies: providing quantitative or qualitative estimates of recharge, identifying sources of recharge, providing information on velocities and travel times of water movement, assessing the importance of preferential flow paths, providing information on hydrodynamic dispersion, and providing data for calibration of water flow and solute-transport models (Healy, 2010). Scanlon (2000) stated that the tracer methods are highly technical but they are cost-effective compared to other methods if applied effectively. A successful application of the tracer techniques in alluvial aquifers was done by Mansell and Hussey (2005) at Dongamuzi and Wenlock in southern Zimbabwe.

Hydrological models of determining surface runoff

Due to the complexity of the processes in recharge and the calculations involved in the process, computer models have been adopted into the process. The water models are based on the water balance equation, while some empirical methods take the form of simple estimation equations that define the annual recharge as a function of precipitation and possibly other climatic data or watershed characteristics (Healy, 2010). Islam *et al.* (2016) suggested that models can also be used to predict distribution of recharge in temporal and spatial scales based on the geologic properties and rate of recharge. De Hamer *et al.* (2008) and Love *et al.* (2010) successfully used the modelling approach in quantifying recharge and modelling the aquifer processes. Despite being complex, the models offer accurate results in a shorter space of time (Healy, 2010).

Quantification of flow along the river channel

In attempting to produce a comprehensive water balance the natural flow processes along the river channel have to be considered whether it be surface flow or groundwater flow (in the alluvium). The riverbed might appear dry for the larger portion of the year, there is perennial groundwater flow within the sand (Mpala *et al*., 2016). Accurate measurement of the remaining groundwater will be critical to ensure proper quantification of the water in the sand river system. Several methods have been proposed in literature to quantify the flow and these include direct measurements of water flux, heat tracer, and methods based on Darcy's Law.

Heat tracer methods

The heat tracer methods involve tracing temperature changes along the river bed. Temperature changes are measured in the streambed at many locations within a short time period. The underlying assumption is that variations in temperature are attributed to spatial variations in water flux through the streambed (Kalbus & Schirmer, 2006). Mathematical functions such as the one developed by Becker *et al*., (2004) can then be used to develop a model of the streambed and estimate the flux changes along the streambed. This offers its own set of advantages including the fact that it is quite inexpensive and temperature measurements are quick and easy to perform (Kalbus & Schirmer, 2006). These methods, however, suffer drawbacks with regards to their usage in alluvial aquifers. They offer limited applicability as they are applicable to shallow groundwater aquifers and temperature observations using heat tracers are typically limited to short durations. This restricts their ability to capture long-term changes in groundwater movement patterns (Rau *et al*., 2014). Furthermore, interpreting heat tracer data relies on complex mathematical models that require accurate estimates of thermal properties (conductivity, capacity) of the aquifer material. Uncertainties in these values can lead to significant errors in flow velocity calculations (Rau *et al*., 2014). They are also susceptible to external factors beyond groundwater movement and they typically provide only localized information about the groundwater making them in applicable for large river basins (Halloran *et al*., 2016).

Darcy's law based methods

Methods based on Darcy's Law are generally similar to the methods used to study groundwater movement in terrestrial aquifers (Kalbus & Schirmer, 2006). The determination of water flux in the alluvium will require information on the hydraulic gradient and hydraulic conductivity, or groundwater velocity and porosity. Piezometers are the standard method used to measure to determine hydraulic head in alluvial aquifers (Kalbus & Schirmer, 2006). They have their own set of drawbacks in their usage in groundwater measurement and these include the fact that piezometers provide data only at a specific point. In heterogeneous aquifers like alluvial deposits, with varying grain sizes and permeability, a single piezometer might not capture the full picture of groundwater flow and pressure variations (Fetter, 2018). Furthermore, most piezometers measure a single water level, representing an average pressure across a certain aquifer thickness. This can be misleading in layered alluvial aquifers, where hydraulic conductivity can vary significantly with depth (Freeze & Cherry, 1979).

Every method that is applicable can introduce its own set of drawbacks, it is therefore prudent to use the methods with extra caution and appropriate measures to ensure that the results that are produced represent the intended picture.

Evapotranspiration

Evapotranspiration, which combines the processes of transpiration from plant leaves and evaporation from the surrounding land and water surfaces, constitutes a primary mechanism for water discharge from a watershed system.. The water is used up by the vegetation and lost through evapotranspiration. Evapotranspiration (ET) is a crucial component of the hydrologic cycle, representing the combined water loss from a watershed through evaporation (from soil and water bodies) and transpiration (from plant surfaces). Accurately estimating ET is essential for water resource management, irrigation planning, and understanding climate change impacts on watersheds.

Weighing lysimeters are widely recognized as among the most accurate and direct instruments for estimating actual evapotranspiration in watershed-scale studies, serving as reference benchmarks for validating methods such as eddy covariance and energy-balance models (Bian et al., 2024). These are large weighing scales with embedded soil columns that directly measure the weight of water transpired by plants and evaporated from the soil surface (Sołtysiak & Rakoczy, 2019). Although lysimeters are widely regarded as one of the most accurate methods for directly measuring actual evapotranspiration, their high installation and maintenance costs, along with their limited spatial representativeness, often constrain their applicability at the watershed scale (Bian *et al.*, 2024).

Remote sensing is another method of measuring evapotranspiration in a watershed (Bhattarai & Wagle, 2021). Spectral reflectance data from satellites can be used to estimate vegetation health and surface temperature, which can be related to ET through various models (Kimball & Running, 2016). However , despite remote sensing offering good spatial coverage it requires complex models and validation with rigorous ground truthing (Kiptala *et al*., 2013).

Metereological methods are also valid methods to estimate evapotranspiration. These use equations like the Penman-Monteith Equation, Priestley-Taylor Equation and the crop coefficients. The Penman-Monteith Equation is a widely used equation which estimates potential ET based on meteorological data like temperature, humidity, radiation, and wind speed. However, it requires accurate weather data and doesn't account for specific vegetation characteristics (Walter *et al*., 2012). The Priestley-Taylor Equation is a simpler equation which uses temperature data to estimate potential ET. While easier to apply, it has limitations in arid and semi-arid regions which our study area (Moorhead *et al*., 2017). Crop coefficients relate potential ET (calculated using methods like Penman-Monteith) to actual ET for specific vegetation types. Accurate estimation of crop water requirements and evapotranspiration at the watershed scale requires information about the dominant plant species, as different crops have distinct water use patterns and canopy characteristics (Allen et al., 1998). This method requires knowledge of dominant plant species within the watershed and the usage of software such as Cropwat (1992) and Climwat (1993) help in increasing the accuracy of the findings (Gabr, 2022). These software programs have been further developed with other versions being released.

2.3.5 Modelling the sustainable usage of Alluvial Aquifers

Modelling the sustainable use of alluvial aquifers has evolved significantly over the years, adopting integrated approaches that consider physical, climatic, and socio-environmental dimensions. Water budget and water balance models remain foundational in these modelling situations. Mpala *et al.* (2020) constructed a water-level model for an ephemeral river's alluvial aquifer in South-western Zimbabwe, incorporating recharge from intermittent flows, evapotranspiration beneath sand, and abstraction. The model revealed that pore characteristics and evaporation coefficients critically influence storage dynamics and recharge efficiency. In agricultural regions, Nawale & Mategaonkar (2024) demonstrated how coupling GIS, remote-sensing data, and MODFLOW simulations can quantify artificial recharge contributions to sustain groundwater reservoirs.

Interactions between surface water and alluvial groundwater have been modelled to assess threshold behaviour during floods and droughts. These coupled approaches help determine sustainable abstraction limits linked to aquifer recharge cycles. Engineering interventions such as sand dams are being modelled for their sustainability benefits. Nawale and Mategaonkar (2024) assessed artificial recharge scenarios incorporating such structures, showing potential for enhancing storage while maintaining sustainable abstraction levels. One outstanding case is the Mississippi Alluvial Plain (USA), where Leaf *et al.*, (2023) implemented a MODFLOW-6 model linked with climate scenarios and irrigation demand projections. Their simulations forecast that under dry or warming scenarios, drawdowns could exceed 10 m in parts of the aquifer by mid-century. This underscores the urgency of management based on robust, scenario-driven modelling.

2.4 Design of suitable abstraction technology for sustainable use of Shashani alluvial aquifer

The design of technology to abstract water from sand rivers is not very different from that of groundwater abstraction. However, in this study the objective is to determine the appropriate pump technology to support the sustainable use of the alluvial aquifer on Shashani river for small scale irrigation. The major factors considered in the design of the suitable abstraction technology were whether the abstraction technology promotes sustainable abstraction and if the technology is friendly to the users.

Sustainable abstraction requires water demand management techniques to be put in place. One of the techniques in water demand management is investing in water saving technology (Kampragou *et al.*, 2011). Women are the major users of water and they make the most important decisions regarding subsistence agriculture in the basin (Kativhu *et al*., 2021). This was considered in this study to determine the pumping methodology. The other pumps with similar objectives were reviewed to understand the improvement that can be done in the system.

2.4.1 The Treadle pump

A treadle pump is a foot-operated device that uses a bamboo or a PVC for suction to pump water from surface water bodies or shallow aquifers (Shah, *et al.*, 2000). The treadle pump consists of a sheet metal or cast-iron pump box, a bamboo frame with two treadles, and a bamboo frame with two treadles and or PVC strainer (Orr *et al.*, 1991). The pump has two cylinders and pistons that are joined into a single suction pipe. Above each cylinder is a beam that is hinged at one end and at the other connects to a piston (Hussey, 2007). Water penetrates the filter and rises up through the suction pipe to the dynamic ground water level. From there it is lifted in a pulsating stream following the strokes of the two pistons. The action of the two cylinders provides a virtually continuous stream of water (Shah, *et al*., 2000).

The treadle pump has various advantages over other pumps in the industry. Orr *et al.,* (1991) posited that the action of two cylinders provides a virtually continuous stream of water making the treadle pump more efficient than single cylinder pumps. This is because in single cylinder pumps more energy is required to reacclerate the water after the longer pause in the change between strokes. Hussey (2007) and Orr *et al.,* (1991) pointed out that the design of a treadle pump is less tiring to use and has a higher potential output because of leg operation. Shah, *et* *al.*, (2000) suggested that the treadle pump was relatively easier to maintain compared to other pumps used by small scale irrigation farmers.

The treadle pump has few disadvantages. Hussey (2007) mentioned that the construction of the treadle pump was complex and the skill was limited to a few organisations which had taken up the task of assembling the system at commercial scale. The treadle pump also requires specialist machine tools and parts to ensure production of efficient, reliable units and this might bring an unexpected level of dependence on others (Kay and Brabben, 2000). However, the introduction of the treadle pump has brought substantial impacts including increased land area under irrigation, reduced work time, full irrigation of fields, less strainous irrigation compared with bucket irrigation, additional and new crops and increased number of growing cycles (Kay and Brabben, 2000).

2.4.2 The rope and washer pump

Rope and washer pumps are still widely recognised as a low-cost, simple, and locally maintainable option for rural water supply, particularly in self-supply or community contexts. Recent studies confirm that properly installed rope and washer pumps can offer reliability comparable to standardized hand pumps in terms of robustness and water quality (Bazaanah & Dakurah, 2021). The rope and washer pump has small plastic washers lined up on a rope. The rope is pulled through a plastic rising pipe over a crank-operated drive wheel. The rope runs through a PVC pipe and, as the wheel is turned, water is drawn up the pipe by suction (Kadlowec *et al.*, 2013). The Rope and washer pump is a very effective and low-cost pump option for water supply and irrigation that is used by families and small communities (Mkandawire et al., 2019). It was observed that the presence of the rope and washer pump increases family income, and increases food security as is the case in countries like Nicaragua (Mkandawire et al., 2019). Modifications have been done to the operation of the rope and washer pumps have been done however the operating principle remains the same.

The Rope and washer pump has many advantages compared to other pumps used in sand-abstraction. Mkandawire *et al*.(2019) stated that a rope and washer pump has the advantage of easy operation and maintenance since local communities can maintain it. They further stated that the rope and washer pump has relatively low cost and possibility of local manufacture because of its simplicity. The rope and washer pump can reach greater depths in practical applications compared to the treadle pump however for sand abstraction it might not be necessary since the alluvial aquifers are shallow. In Kenya, after the introduction of the rope and washer pump, there was a decrease in the number of typhoid infections (Hughes *et al*., 2004). A study by Mkandawire *et al*. (2019) also indicated that the presence of rope and washer pumps increased the water quality in Malawi.

The rope and washer pump made tremendous impact in the field of domestic water supply. Hussey (2007) mentioned that the rope and washer pump is only suitable for installation on offset sand wells and collector wells that are fed by infiltration-galleries. Haanen & Holtslag (2016) mentioned several shortcomings of the rope relative to piston pumps including that it cannot pump higher than the pump outlet, it requires frequent maintenance like oiling the brushes and that it splashes more than piston indicating low efficiency. According to a survey by Kamanga *et al.*, (2018), 70% of the respondents mentioned that frequent breaking of the rope and the handle was the main problem experienced in the use of the Rope and washer pump technology. They also discovered that the rope and washer pumps were abandoned because of turbidity and odour in the abstracted water.

2.4.3 The Rower pump

The Rower pump is a hand pump technology which has proved to be well-suited to the irrigation needs of small farmers (Hussey, 2007). It is a suction pump in which the suction pump is directly activated. The Rower pump is a reciprocating-action handpump with the cylinder inclined at 30 degress for simplified construction and maintenance (Harder, 1995). Hussey (2007) described the Rower pump as a direct-lift bucket pump. He further posited that the Rower pump is suitable for drawing water for both sand abstraction well systems but for well point systems. The water is lifted using the rowing action and, water is discharged on the pull, or 'up' stroke as it flows from the open end of the pump cylinder (Hussey, 2007; Harder, 1995). Hussey (2007) also stated that Richard Cansdale of SWS Filtration manufactures the pump and pump componets that can be fitted into appropriate Upvc of ABS piping

The Rower pump has been accepted for sand abstraction in Zimbabwe because of several advantages. The Rower pump offers the advantage of cheaper construction than most reciprocating suction and lift pumps (Olley, 2008). The Rower pump is a basic system that allows easy operation, maintenance and repair of wearing parts (Hussey, 2007). Harder (1995) also mentioned that the Rower pump is easy to repair since local farmers can still repair it and local materials can be used to repair the pump. Olley (2008) further mentioned that the Rower pump allows faster delivery of water since it has a long stroke. These advantages make the

Rower pump suitable for sand abstraction and use in small-scale farming in Zimbabwe and worldwide.

Despite the advantages of the Rower pump it also suffers a few disadvantages. Harder (1995) and Olley (2008)mentioned that the Rower pump has disadvantages of limited depth. However for the purposes of sand abstraction it might not be necessary since most of the alluvial aquifers have shallow depths. Olley (2008) stated that the pump has a risk of water contamination since there is pump priming and the upward facing delivery pipe.It also has the disadvantage of limited capacity since it can be limited to 50 people a day. Despite the disadvantages it suffers the Rower pump has been accepted and is still being applied in sand abstraction.

2.4.4 Sediment and water separation

The method used in the abstraction affects the sustainability of the water resource, physical and chemical properties of the water. The success of sand-abstraction systems installed is dependent on the level of separation of water from sand sediment which are created by a graded barrier within the sediment at the point of water abstraction (Hussey, 2007). Depending on the use of the water being abstracted and the equipment being used on the river which is bearing the water, a filter needs to be installed (Hussey, 2003). The properly designed system will result in a graded filter zone developing around each well-point or caisson. Sand abstraction systems as elaborated by Hussey (2003) comprise mainly of a screened well-point system, infiltration gallery system, caisson system and a sand well system.

The purpose of a sand-abstraction system is to extract water while minimizing the intake of fine sediments from the alluvial aquifer. Most sand-abstraction systems are dependent on screened well-points to separate water from the alluvium. Flow into a well-point is created by a pump which reduces the pressure within the pipe to less than that of the atmosphere, so that atmospheric pressure forces water into the well-point. This prompts a filtration system which uses filter packs. The filter pack should be many times more permeable than the aquifer material, but the filter pack must not be coarse enough to allow the fine particles of the aquifer material to continue to wash through the pack. Water is drawn through the screen to the point of discharge (Hussey, 2003). The screened well point system suffers from multiple drawbacks itself, it can be considered relatively complex to install, the availability of repair material and not being able to get the draw-off pipe deep enough into the sediment to preclude damage during subsequent river flow (Hussey, 2007).

An infiltration gallery system uses the natural hydraulic pressure to separate the alluvial sediments from the water. Jazayeri & Werner (2025) described and infiltration gallery as a permeable, horizontal or inclined conduit into which water infiltrates from an overlying or adjacent source. This agrees with what Hussey (2007) posited stating that an infiltration gallery is a slotted or perforated pipe installed horizontally into the alluvium in a riverbed. Water will flow from the sediment using the aquifer hydraulic head into the gallery. The gallery then conveys the water from the aquifer into a collection well or tank in the river bank where it can be pumped to the surface (Hussey, 2007). This method of abstraction has the advantage that it offers good preliminary treatment should there be need (Kusuma *et al.*, 2018). It also suffers the disadvantage that most gallery systems require a filter pack to be cleaned or unblocked, which might require complete reconstruction of the system rendering it expensive to maintain (Zou et al., 2019).

A caisson can be viewed as a well shaft that does not reach the surface (Hussey, 2007). Water is abstracted through a slotted base of a large (1.0 to 1.5m diameter) flat, cylindrical or slightly conical tank which is connected by pipes to a suction pump on the river bank. (Hussey, 2007). The caisson is then connected by pipes to an atmospheric pump on the riverbank (Hussey, 2003). This system has the disadvantage that there is need to continually dig the caisson into the alluvium to have access to water. As the caisson goes further down the alluvium it reaches the silt layer that are likely to impede the flow of water into the abstraction zone of the caisson. This can limit the success of the caisson (Hussey, 2003).

A sand well system uses an upgrade to the traditional scoop-hole system. The sand well is an open depression excavated in the river sediment, referred to as a sand-well or scoop-well (Hussey, 2003). Sand wells are thus best installed into alluvial riverbanks close to the river channel where they can draw water from the river alluvium or dug into the side of the riverbank where they can interface directly with the sediment in the river channel (Hussey, 2007). The sand well has the disadvantage that if a flood of high intensity occurs there is high probability that they system might be destroyed (Hussey, 2003). Nissen-Petersen (2006) however improved the system in 2000 by introducing concrete cylinders to lower the centre of gravity and increasing stability of the system

2.5 Research gaps

Several authors have done studies along Shashani River, however little research has been concerning the water budget and how it can be used sustainably. The water resource is being used by several stakeholders, however, it is needful to do a water budget and obtain the sustainable yield. The project seeks to investigate the sustainable yield of the aquifer so that any further developments done in the district will cause minimal damage to the environment.

The main objective of the project is to develop a model for the sustainable use of alluvial aquifers to support small-scale irrigation. This includes modelling the sustainable abstraction of groundwater and evaluating technologies that enhance long-term aquifer use. The project will also focus on designing abstraction technologies based on principles that improve pumping efficiency while reducing installation and maintenance costs.

2.6 Conclusion

Alluvial aquifers have been used for a long time; however, their usage has often been unsustainable. Sustainable usage still emerges as a critical issue , emphasizing the need for practices that balance abstraction with natural recharge and maintain aquifer health. Developing models to analyse hydrological systems, such as alluvial aquifers, using proper catchment hydrological analysis and water balance techniques, can provide guidance for sustainable management and long-term resource use.

In addition, it was observed that the abstraction technology which has been in use does not promote the agricultural endeavours of the small-scale farmers. Technology should solve the problem of costly maintenance and installation as well as promote sustainable agriculture. Some rural communities in Sub-Saharan Africa use manually driven pumps for their agricultural activities. Given the limitations of electric pumps such as dependence on unreliable power supply and higher maintenance costs there is a need to improve manually operated pumps (Foster et al., 2018). Studies show that optimizing mechanical design (stroke length, suction pipes, valves) can significantly increase flow rates without additional physical effort (Shah et al., 2024).

This research is expected to create a model of using alluvial aquifers in a sustainable manner and this can be achieved by using models of input and output parameters of the alluvial aquifer system. This can then be used as a model of proper analysis of catchments and sand river usage in the world. In the review of literature, it was also discovered that the pumps that are in operation in the industry are either expensive to maintain and install or they do not offer the required output for successful irrigation and small-scale farming.

Chapter 3: Study Area

This section describes the characteristics of the study area, Shashani Catchment. The introductory section deals with the general characteristics of the Shashani River. The remaining part of the section describes the climatic and hydrogeological characteristics of the catchment.

Shashani River is a tributary of the Limpopo River located in Matabeleland South Province in Zimbabwe. The Shashani sub-catchment (Figure 3.1) is estimated to be 2 826 km^2 (Mpala *et al*., 2016) and is situated in the northern-part of the Limpopo Basin. Shashani River flows in the southward direction and it is 206 km long. The upstream third of the river passes through a commercial farming region and is dammed at two sites. The Shashani Dam is located 37 km downstream of the source and the larger Gulati Dam is located 92 km downstream from the source. The middle and lower third of the river pass through a communal farming area and a conservation zone, respectively, with most sand abstraction practised in this area (Mpala *et al.*, 2016). The focus of this study was on the lower section of the area from Antelope Dam to Shashe Confluence. The Shashani River was chosen for this study because of the availability of both satellite and weather data.

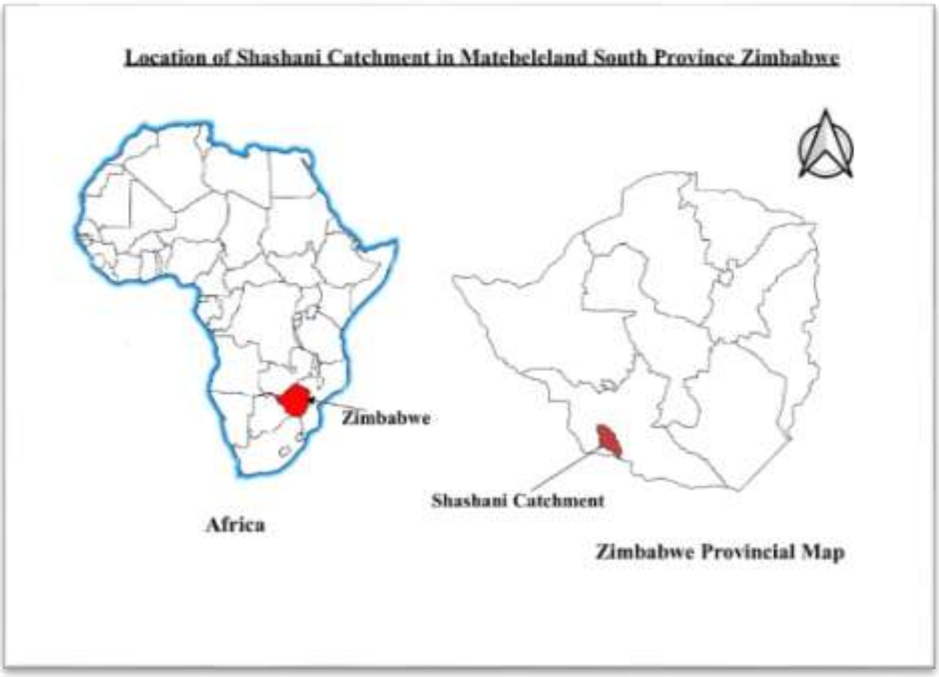

Figure 3.1: Shashani Catchment relative to Zimbabwean Boundaries (Source: QGIS, Landsat 8, images)

3.1 Background to Limpopo River Basin

Extreme drought in the Limpopo River Basin is a regular phenomenon and has been recorded for more than a century at intervals of 10-20 years (Mazibuko *et al.*, 2021). The mean annual rainfall of the basin varies considerably (200-1500 mm) with much of the northern and western parts of the basin receiving less than 500 mm annual rainfall (Mosase & Ahiablame, 2018). Love *et al*., (2010) reached the same conclusion about the climate of Zimbabwe stating that the region is a semi-arid area receiving annual rainfall varying from 360 mm in the south to 630 mm in the north. A study of part of the basin concluded that there is strong spatial variability in rainfall, and ephemeral, disconnected discharge events, even in a season with above-average rainfall (Love *et al*., 2010)

Limpopo riparian countries depend heavily on food grown within its borders to meet national goals of food security (Petrie *et al.*, 2015). In the rural communities, men generally use the water for livestock (Hussey, 2003). However, the fact that the basin has approached water resource closure (Petrie, *et al*., 2014) does not help in the livelihood of the rural community who are trying to eke a living using the water. Mosase and Ahiablame (2018) reached a contrasting conclusion that there is increased availability of water in the basin, however, population increase, changes in land use, and intensification of agriculture activities continue to put pressure on water resources in the basin

3.2 Hydrogeology in Shashani catchment

Jones *et al.*, (2013) described the Shashani catchment having dominantly luvisols and leptosols in its upper reach and luvisols and lixisols in its lower reach. Arenosols are sandy, rapid-draining soils whilst leptosols are shallow, free-draining soils that typically overlie hard rock. Luvisols and lixisols have an accumulation layer of clay at some depth below the surface and are free-draining, but the latter is more weathered. The dominating soil type in the catchment is free-draining sand and the soils are mostly between 50 and 100 cm deep, with areas as shallow as less than 30cm around the greenstone belt (ISRIC, 2005), thus water is lost rapidly to lower lying areas.

Mansell & Hussey (2005) posit that there is weathered material which settles in the base of the sand river since the catchment is hilly. According to Mansell & Hussey (2005) the average permeability of soils in Shashani catchment is 4.07m/h (97.68m/d), the average porosity of the soils is 41.9% and the channel slope of Shashani River is 0.201%.

3.3 Shashani climate

Shashani sub-catchment is in a grassland of intermediate altitude (Mpala *et al.*, 2016), the mean annual precipitation of 450 to 475mm (Mansell and Hussey, 2005). According to De Hamer *et al.*, (2008). This area experiences one rainy season per year, typically extending from late October to early April with the most precipitation falling between November and March. A typical meteorological year in Zimbabwe is divided into four seasons, the cool season (Winter) occurring in Mid-May to August, Hot season occurring between September and Mid-November, the rainy season Mid-November to mid-March and the post rainy season occurring from Mid-march to mid-May.

3.4 Shashani evapotranspiration

The daily average evapotranspiration for the study area for the year 2021 are shown in Figure 3.2 below. West Nicholson has approximately the same elevation as the Shashani catchment (861 m above sea level) and is located about 70 km eastwards. According to the data gathered from FAO Climwat , the average value for evapotranspiration in the study area was 4.02 mm/day. The highest value for evapotranspiration is in the month of October with a value of 5.31 mm/day whilst the lowest value of evapotranspiration was 2.39 mm/day. Figure 3.2 shows the graphical comparison of the evapotranspiration values for the year 2021

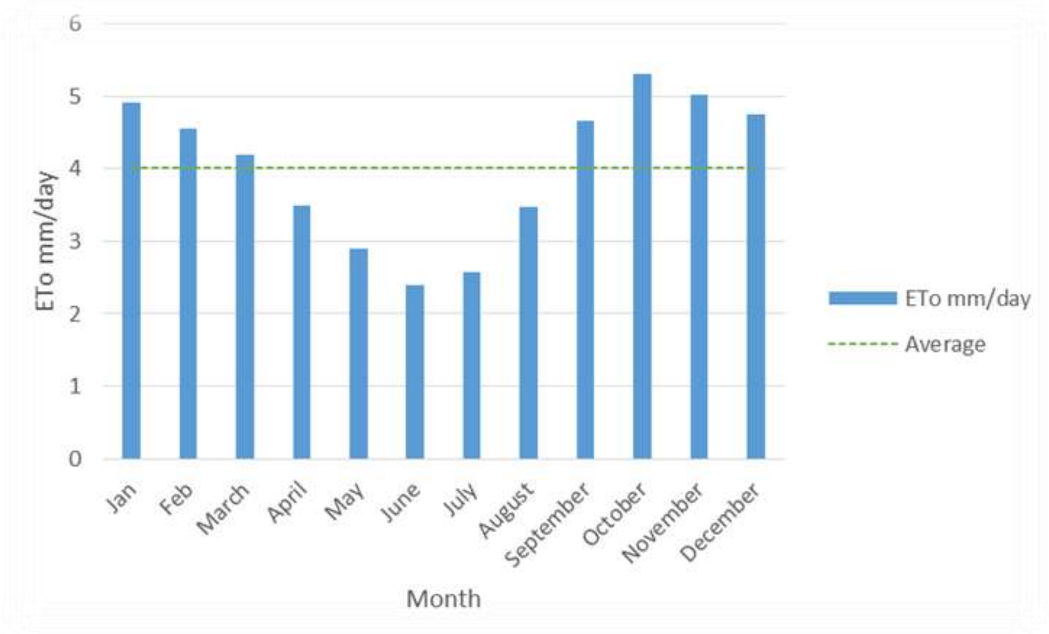

Figure 3.2: The estimated evapotranspiration values for the study area for 2021, Source: FAO Climwat

Chapter 4: Methodology

4.0 Introduction

This chapter describes the data collection procedure and methods used in the collection and processing as well as the assumptions and the limitations of the study. The first section explains the process of determining the alluvial aquifer volume (the determination of alluvial aquifer depth, length and width). Methods used to calculate the volume after getting the dimensions are described. The second section describes the methods used develop a model for estimating the sustainable yield of the alluvial aquifer along the Shashani River to support small-scale irrigation as well as the procedures used in testing the model. The last section gives a detailed description of the procedure in the design of a sand abstraction system to support the sustainable use of the alluvial aquifer on Shashani river for small scale irrigation.

4.1 Determination of potential water supply of the alluvial aquifer

The potential water supply of the alluvial aquifer can be taken as the capacity of the sand river alluvium. In this study, probing was used to determine the depth (thickness) of the alluvial aquifer and profile of the bedrock along three cross sections of the river. Probing is the process of mechanically driving a steel rod into the sediment of a sand river. In the context of studying sand rivers, the process of probing was used to estimate the depth to the bedrock of the alluvial aquifer. It was also used to estimate the water level at that point. This is done by measuring the wet surface of the steel rod after removing it from the river bed. Three probing points were chosen randomly to cover a wider section of the river. A 3m steel rod was manually driven into the sand river until it reached a hard surface (assumed to be the bedrock). The section of the steel rod which had been successfully driven into the riverbed was then measured using a measuring tape. The measured value was the alluvial aquifer thickness at that particular probing point. The probing points were located at the banks of the river as well as the middle of the river to get a better picture of the river channel. Figure 4.1 shows the location of the probing points relative to Shashani Catchment.

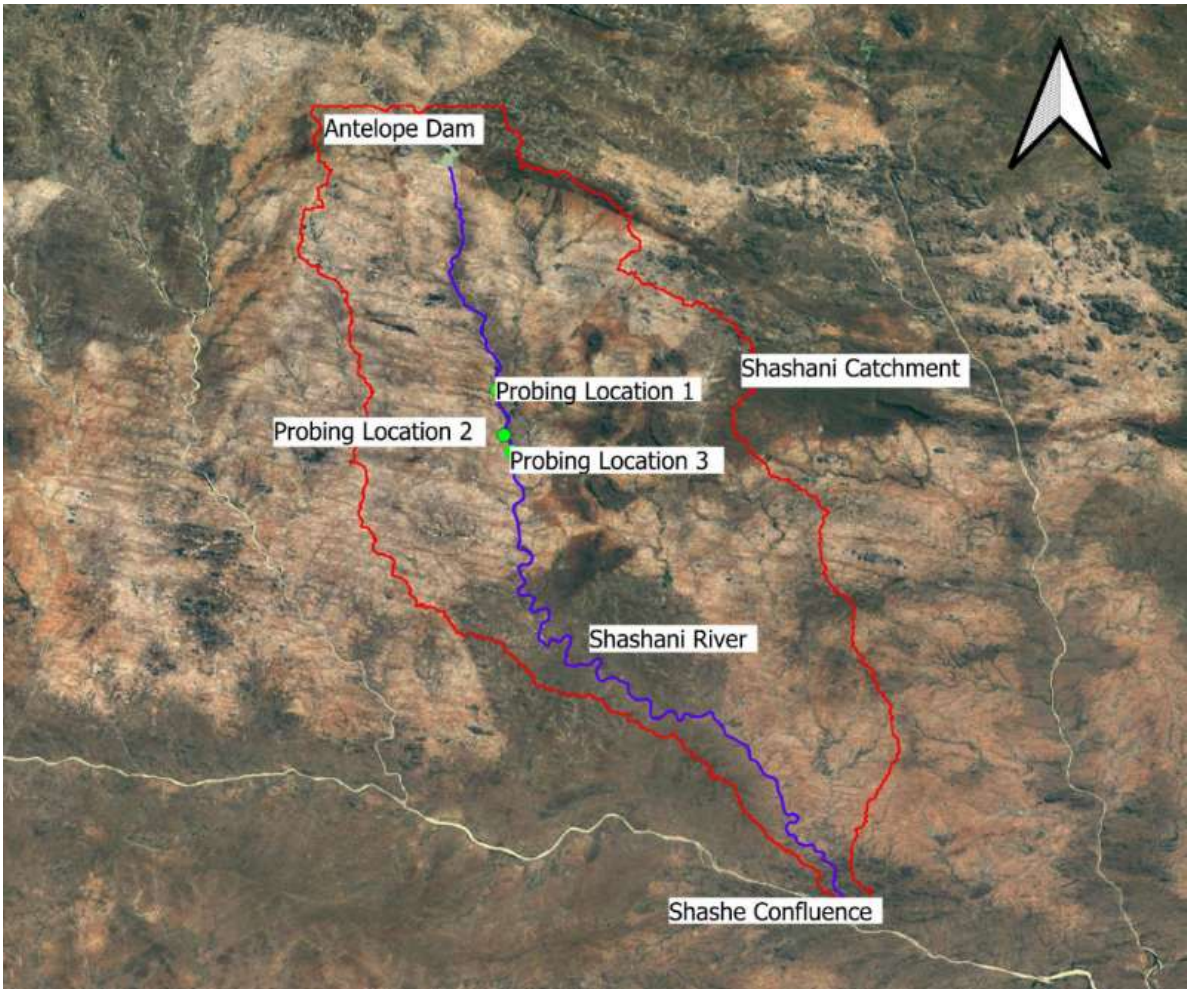

Figure 4.1 The location of the probing points relative to Shashani river and study area (Source: Google Earth)

A topographical survey was performed to gather detailed data on the terrain's geometry. The survey method involved using a Total Station Theodolite to measure the coordinates and elevations of specific points. This was systematically done across different sections of the river under study to create a comprehensive profile. These sections are where the probing points were located. A Global Positioning System (GPS) with an accuracy of ±3m was used to record the coordinates and elevation of the initial starting point of the survey.

The area of the river channel was calculated using a tool embedded in GOOGLE Earth Software. These results were then used to determine the volume using Equation [4.1]. The product of the average depth of the sand river and the calculated area was taken as the volume of Shashani Alluvial Aquifer which is its potential water supply.

$\text{Volume} = \text{Area} \times \text{Average depth}$ ……………………………………………Equation [4.1]

Since only a certain percentage of the alluvial aquifer stores water , the potential water storage was determined using the equation [4.2] below :

Potential Water Storage = Volume x Average Porosity of the Sand ....Equation [4.2]

4.2 Modelling the sustainable yield of the alluvial aquifer on Shashani river

This section describes the determination of all the parameters needed to model the sustainable yield of an alluvial aquifer. For each parameter this section describes the data which was gathered and the procedure used to test the sustainable yield model.

Hays (2000) defined sustainable yield as the volumetric rate of water that an aquifer can provide while maintaining desirable aquifer conditions (primarily water levels and water quality) such that the aquifer remains a viable resource for long-term use. To model the sustainable yield of the alluvial aquifer it was necessary to ascertain the parameters that affect the sustainable yield of the alluvial aquifer (Hays, 2000). The sustainable yield of an alluvial aquifer depends on the recharge it receives and its distribution in time, the geometry of the sand river deposits, the hydraulic properties of the sand and the amount of water abstraction, evaporation and other losses (Mpala *et al.*, 2020). The sustainable yield model was developed taking all of these factors into consideration. All of the above mentioned factors were determined individually. The net annual recharge was determined basing on the alluvial aquifer model postulated by (Mansell & Hussey, 2005) and the factors stated by (Mpala *et al.*, 2020). The net annual recharge into the alluvial aquifer was estimated using Equation [4.3] below:

$$\frac{\Delta s}{\Delta t} = Q_{in,g} + \left(P + R - Q_{in,s}\right) - Q_{out,in} - ET - Q_{abs} \qquad \text{Equation [4.3]}$$

Where:

$\Delta s/\Delta t$ = the rate of change in storage (m^3/day)

$Q_{in,g}$ = groundwater inflow (m^3/day)

$Q_{in,s}$ = surface flow (m^3/day)

$Q_{out,g}$ = groundwater outflow (m^3/day)

P = Precipitation (m/day)

R = Runoff from catchment Area (m^3/day)

ET = Evapotranspiration (m^3/day)

Q_{abs} = the abstraction rate (m^3/day)

The sustainable yield was taken as the safe yield of an alluvial aquifer. The sustainable yield was modelled as the volume of water that can be safely abstracted from the alluvial aquifer without adverse environmental impacts. This implied that a safe yield factor was to be applied on the net annual recharge. The sustainable yield was modelled by applying a factor of safety on the net annual recharge as shown in equation [4.4] below:

$$\boldsymbol{SY} = SYF[Q_{in,g} + (P.A + R - Q_{surf}) - Q_{out,g} - ET - Q_{abs}] \qquad \text{Equation [4.4]}$$

Where:

SY = Sustainable Yield (m^3/day)

SYF = Safe Yield Factor

$Q_{in,g}$ = groundwater inflow (m^3/day)

Q_{surf} = surface flow (m^3/day)

$Q_{out,g}$ = groundwater outflow (m^3/day)

P = Precipitation (m/day)

A = Surface Area of River Channel

R = Runoff from catchment Area (m^3/day)

ET = Evapotranspiration (m^3/day)

Q_{abs} = the abstraction rate (m^3/day)

4.2.1 Testing and validation of the sustainable yield of the alluvial aquifer

To test and validate the model, a scenario analysis was conducted to assess the behaviour of the model under different scenarios. The study was conducted on Shashani alluvial aquifer. Three characteristic years were chosen for study and the parameters were input into the model to assess the parameters which the model was sensitive to most under different climatic conditions. The sustainable yield was determined for a typical wet, dry and normal year and then compared.

Based on the findings of Knapp *et al*. (2015) a typical wet year was taken as a year with annual rainfall at least 30% greater than the normal annual rainfall and a typically dry year as a year with annual rainfall at least 40% less than the normal annual rainfall. The normal rainfall was taken as the statistical average of rainfall over 38 years (Knapp *et al.*, 2015). These characteristic years were selected from the daily rainfall data sets (1983 to 2021 inclusive) downloaded from the Centre for Hydrometeorology and Remote Sensing (CHRS) Data Portal (www.chrsdata.eng.uci.edu). The parameters for the sustainable yield model for each typical year were then determined as described in the sections as follows:

i. $Q_{in,g}$ = groundwater inflow (m^3/day)

To test the model, it was acknowledged that the groundwater outflow is influenced by the hydraulic gradient. However, the hydraulic conductivity of the material influences the rate at which the water flows along the river section. The Darcy Equation was also adopted for the groundwater inflow to determine the specific discharge along the river channel. The slope of the water table was calculated from the difference in water levels for the upstream and downstream across sections of the study area. The hydraulic conductivity of the alluvial material was determined in-situ using the Hooghoudt auger test which was obtained from the desktop study. The volume of the water was then determined by multiplying the discharge with the average cross sectional area obtained from the field studies using equation [4.5] below:

$$q = -k \frac{\partial h}{\partial x}$$ Equation [4.5]

Where:

q = specific discharge (m/s)

k = hydraulic conductivity (m/s)

$\frac{\partial h}{\partial x}$ = Slope of the water table (m/m)

ii. Q_{surf} = surface flow (m^3/day)

In testing the model, the surface inflow was assumed to be negligible since the river is dammed upstream. There was no available record indicating a dam spilling event at the time of the research therefore the assumption was considered to be valid.

iii. $Q_{out,g}$ = groundwater outflow (m^3/day)

In testing the model, it was also acknowledged that, the groundwater outflow is also influenced by the hydraulic gradient just like groundwater inflow. Similarly, the hydraulic conductivity of the material influences the rate at which the water flows along the river section. The Darcy Equation was adopted for both groundwater inflow and outflow to maintain consistency. The slope of the water table was calculated from the difference in water levels for the upstream and downstream across sections of the study area. The same results from the Hooghoudt auger test in the desktop study was used as the hydraulic conductivity and equation [3] was used to determine specific discharge. The volume of the water was determined by multiplying the discharge with the average cross sectional area obtained from field studies.

Lateral Inflow and Outflow

Lateral inflow and outflow occurs when the alluvial aquifer recharges the riverbanks and vice versa. This results from groundwater connectivity and differences in water table heights (Hussey, 2003). The rate of lateral inflow and outflow is dependent on the type of soil which is dominant on the riverbank and the hydraulic gradient between the riverbank and the sand river. From field observations along Shashani River, the riverbanks were made up of compacted clay and hard-rock in some areas. Using this observation and supported by findings from Moulahoum (2018), it was assumed that the lateral inflow and outflow were negligible.

Seepage into groundwater aquifers

According to Lovell *et al.*(1994) the depth of the underlying groundwater aquifers is in the range of 50 m to 70 m for most of the Matabeleland region. Manual probing and observations from scoop holes along the riverbed revealed that the riverbed consisted of rock hence seepage losses were neglected in this study. The recharge from underlying groundwater aquifers was also considered to be negligible basing on this assumption.

iv. *R* = Surface runoff (m^3/day)

The Soil Conservation Service (SCS) method (USDA-SCS, 2021) method was chosen as the method to determine runoff as the study area is predominantly rural. A rainfall-runoff model was used to estimate the surface water runoff caused by precipitation. The area that was modelled is a micro catchment which covers the river section from Antelope Dam to Shashe confluence (Figure 4.1). The catchment delineation was done using QGIS software.

The land use and land cover data were determined using remote sensing. Land use cover types were determined using data from Environmental Systems Research Institute (ESRI) land cover maps. The map is derived from ESA Sentinel-2 imagery at 10m resolution. It is a composite of

LULC predictions for 10 classes throughout the year in order to generate a representative snapshot of a typical year.

The classification was further done using 30 random soil samples gathered from the catchment. Soil samples were randomly collected from the catchment, for each land cover type to enable the assignment of hydrologic soil groups based on the soil type. To classify the soil samples collected into specific hydrologic soil groups, the data was gathered from the Atlas of SOTER-derived maps of Zimbabwe (ISRIC, 2005). The classification was based on the (USDA NRCS, 2007) as shown in table 4.1 below:

Table 4.1: Hydrologic Soil Groups Classification

Hydrologic Soil Group	Soil Type
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 curve number was determined using the hydrologic soil groups, land treatment or land cover type, the hydrological condition and antecedent moisture conditions for each land cover type. The hydrologic conditions and land treatment were assessed during a field survey. The average curve number of the catchment was calculated from the various land cover types. The formula to determine the average curve number is shown in equation [4.6] below:

$$CN = \frac{\sum CN_i A_i}{\sum A} \quad \text{Equation [4.6]}$$

Where:

CN = Average Curve Number for the whole catchment

A = Total Catchment Area, m^2

CN_i = Curve number for each land cover type

A_i = Area of each land cover type, m^2

The surface runoff was then determined using the SCS- Curve number method as shown in equation [4.7] below:

$$P_{\in} = \frac{(P-0.2S)^2}{P+0.8S} \qquad \text{Equation [4.7]}$$

Where the retention parameter S_r is mapped to the curve number CN as shown in Equation [4.8] below :

$$S_r = \frac{(1000)}{CN} + 10 \qquad \text{Equation [4.8]}$$

Where:

$P_{\in}$ = Accumulated excess runoff

The surface runoff for each typical year was then determined by adding the excess runoff for each day.

v. *P* = Precipitation (m^3/day)

In testing the model, the precipitation was determined The climatic data for the study area was downloaded from the CHRS data portal from 1983 – 2021. The same characteristic years used for surface runoff determination were used to determine the direct rainfall to maintain accuracy. To determine the volume of water that went directly into the alluvial aquifer, the surface area of the river had to be determined. The surface area of the river was calculated using the GOOGLE Earth Software. The volume of water was then determined using Equation [4.9] below:

Precipitation =Rainfall × Total Surface Area of the river .... Equation [4.9]

An average permeability of 4.07 m/hour for the Shashani River has been given by authors (Mansell and Hussey, 2005; Mpala *et al.*, 2016), suggesting that the recharge from rainfall is nearly instantaneous and it can be assumed that all direct rainfall recharges the alluvial aquifer before river flow starts (Mansell and Hussey, 2005). It was assumed that the recharge from rainfall was almost instantaneous, therefore all rainfall recharges the alluvial aquifer until it is saturated.

vi. *ET* = Evapotranspiration (m^3/day)

The daily average evapotranspiration for the study area for the year 2021 were obtained from the FAO Climwat software. West Nicholson has approximately the same elevation as the Shashani catchment (861 m above sea level) and is located about 70 km eastwards. It was assumed that based on the relative elevations and proximity, that the climatic conditions of the two areas are similar. De Hamer *et al*.(2008) used a similar approach in studying Mnyabezi Catchment. The evapotranspiration from the alluvial aquifer was assumed to come from the riparian vegetation in the vicinity from the river. The riparian vegetation was assumed to cover a 3m wide area along each of the banks, it excludes the water usage from tributaries and other micro catchments. The volume of water lost through evapotranspiration was calculated by multiplying the evapotranspiration rate by the total area covered by the riparian vegetation represented by equation [4.10] below.

ET = Evapotranspiration rate x Area covered by riparian vegetation Equation [4.10]

vii. Q_{abs} = the abstraction rate (m^3/day)

To determine the abstraction rate, a cumulative volume was calculated by aggregating the water consumption data from three distinct categories: garden irrigation, domestic use, and livestock consumption. This methodology is f expressed in Equation [4.11] below:

Q_{abs} = Garden Irrigation + Domestic Usage + Livestock Abstraction Equation [4.11]

The garden irrigation was determined by using the crops that are planted in the region. To achieve this, a survey was done along the Shashani River with the motive of estimating the number of gardens, the size of each garden and also the crops being planted in each garden. This was collected via informal interviews, questionnaires as well as observations during field surveys.

The data was then used to estimate the average area used for irrigation. The irrigation water requirements were based on an annual water requirement of 15,000 m^3/ha/year (Mpala *et al.*, 2020; WorldBank, 2017). The total area for irrigation for the gardens in the vicinity of the Shashani river was estimated using Equation [4.12] below:

$\text{Annual Garden Irrigation} = \text{Total Irrigated Land x 15 000m}^3/\text{ha}$ ....Equation [4.12]

The total abstraction for domestic usage was estimated from the population of the study area that was obtained from the census data produced by ZIMSTAT (2022). The Shashani River passes through Wards 2, 3, 5, 6, 7 and 19 in Matobo District. The population data of these wards was used to estimate population of people using the Shashani River as a water source. The assumption made was that all the people use water from the source. Average water use per capita per day was obtained from the WHO guidelines (WHO, 2017). The domestic usage was determined using equation [4.13] below:

$$\text{Domestic Usage} = \text{Human Population x Daily usage per capita} \qquad \text{Equation [4.13]}$$

The water abstraction for livestock was calculated using data from livestock production departments. The water requirements for the different animals were adopted from the World Health Organisation (WHO, 2017). The livestock abstraction was estimated by multiplying the animal population by the water requirements for the respective animals as shown in Equation [4.14] below:

$$\text{Livestock Abstraction} = \sum (\text{Animal population } \times \text{Water Requirements}) \qquad \text{Equation [4.14]}$$

The total annual abstraction from the alluvial aquifer was estimated by adding the livestock abstraction, domestic usage and garden irrigation as follows.

Q_{abs} **= Garden Irrigation + Domestic Usage + Livestock Abstraction**

viii. Safe yield factor

To determine the safe yield for testing an average safety factor was used. Anim-Gyampo *et al.* (2012) suggested using a factor of safety of 0.6- 0.9 based on the local hydrogeology experience to account for minor groundwater losses. For this study an average safety factor of 0.75 was applied since there was no known local hydrogeology experience.

4.3 Design of sustainable abstraction technology

It was necessary to design a suitable abstraction technology so as to promote sustainable abstraction of the alluvial aquifer. In designing the abstraction technology, it was assumed that the abstraction methodology and abstraction tools are directly linked to the rate of abstraction. This is because the water use patterns and water use behaviour are determined by accessibility. Several steps were taken to select and determine the suitable abstraction technology from the alluvial aquifer. To select the suitable pump, the rate of abstraction, cost, ease of maintenance, its effect on the environment and the way a pump mechanism influences water use was taken into consideration. The design process involved data collection and multi-criteria decision making to select the most optimal pump. Several design options were suggested, compared and the final choice was then designed based on the decision making tools.

4.3.1 Data collection

To design a pump that was acceptable in the small holder farmer community it was necessary to understand the preference of the targeted end-users. This was achieved through a desk study and interactions with some of the small holder farmers along Shashani River. The data was collected through a field survey from farmers along Shashani River mainly through informal interviews. Interviews were also conducted with stakeholders who regularly interact with the farmers along Shashani River. The objective of this exercise was to get a clearer picture of the necessity and probability of acceptance of the pump. The other objective of the desk study was to determine the power requirements of the pump taking into consideration the age and gender distribution of the farmers in the study area and the ergonomic considerations.

The data which was collected included the age and the sex of the anticipated end-users of the pump. The age and sex were required to determine the power options of the existing farmers. Since the pump would use manual labour, the strength capacity of the people using the pump would have to be determined to decide on the volume of water to be abstracted per stroke. This activity was done during a field visit in Matobo District in June 2021 and September 2021 by means of questionnaires and field interviews

The design parameters of existing pumps were reviewed to justify why they were operating at the current rates. The review specifically looked at the cylinder sizes, pipe diameter, and average stroke length. This information was done to ensure that the design of the pump will improve on the existing pumping capacity.

4.3.2 Design concepts

Four pumping mechanisms were then proposed and compared using the criteria in Table 4.2. The pumping mechanism options were then proposed, and the design formulae are shown for every option on the specific sections. The different pumping mechanisms have different components to improve ergonomics, ease of operation and improve on the flow rate. The components for a specific pump option are described in the section of that pump. The orientation of different components of the pump assembly was also studied to ensure minimum ergonomic hazards. These were considered since these are the major determinants of the pumping capacity of the manual pump.

A. Design Concept A: Hand Pump Mechanism

The concept of a Hand pump mimics the concepts from the Rower pump (Haque et al., 1996). In the design of the new hand pump option there was an increase in the manifold size and the sizes of major components.

Principle of operation

The hand pump option would be a manually operated pump which would require the user to push and pull the piston rod using their hands. The hand pump will have to be installed at angle of 30º to minimise head losses. On the suction stroke, the user moves the piston downward, creating a vacuum in the cylinder. The atmospheric pressure outside the pump forces fluid through the inlet valve and into the cylinder. On the discharge stroke the user moves the piston upwards. The piston moves upward, compressing the fluid in the cylinder. The inlet valve closes, preventing fluid from flowing back into the source. The outlet valve opens, allowing the fluid to be pushed out of the pump.

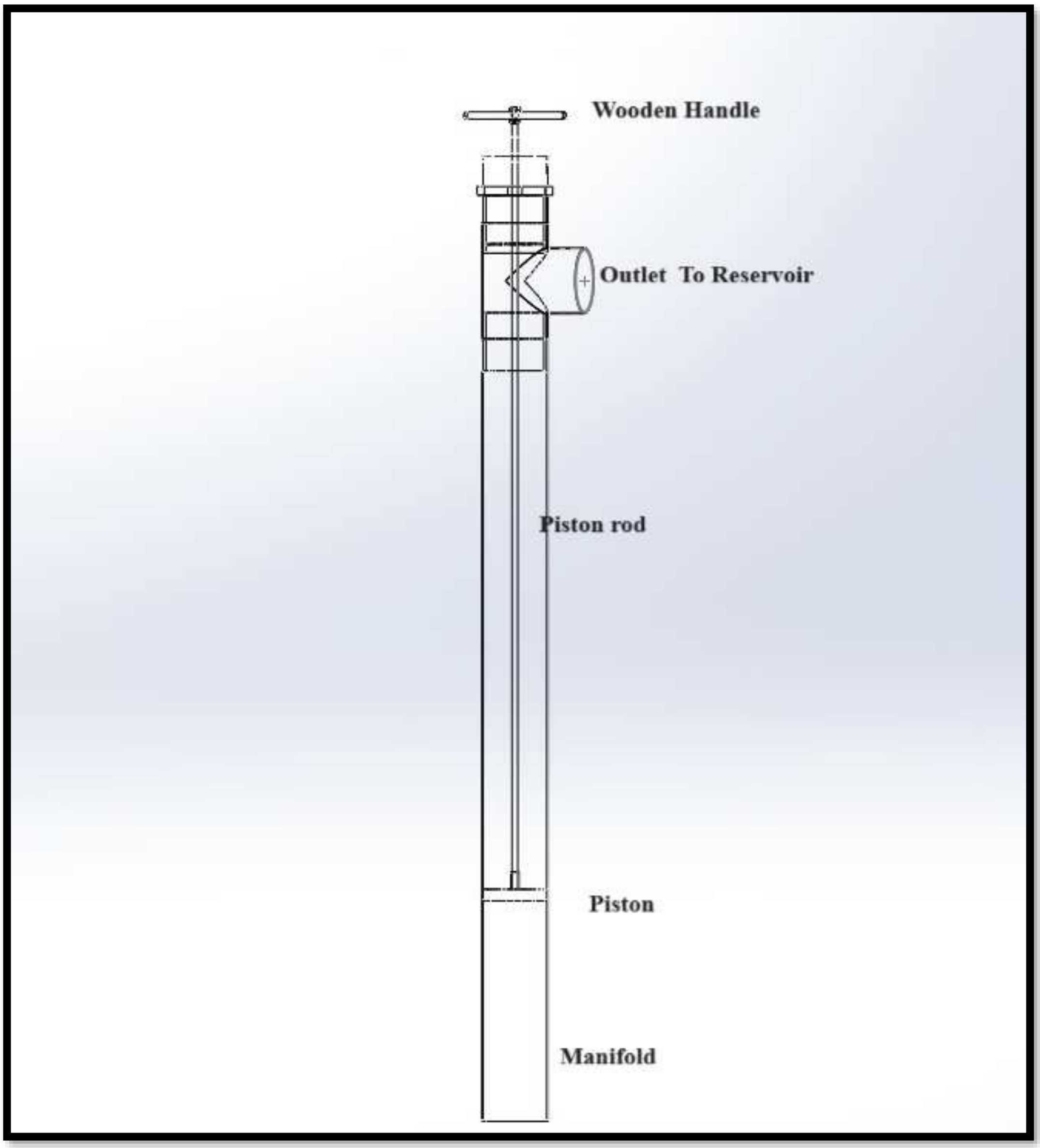

Figure 4.2: Side view of Hand Pump Concept (Source: Solidworks 2023)

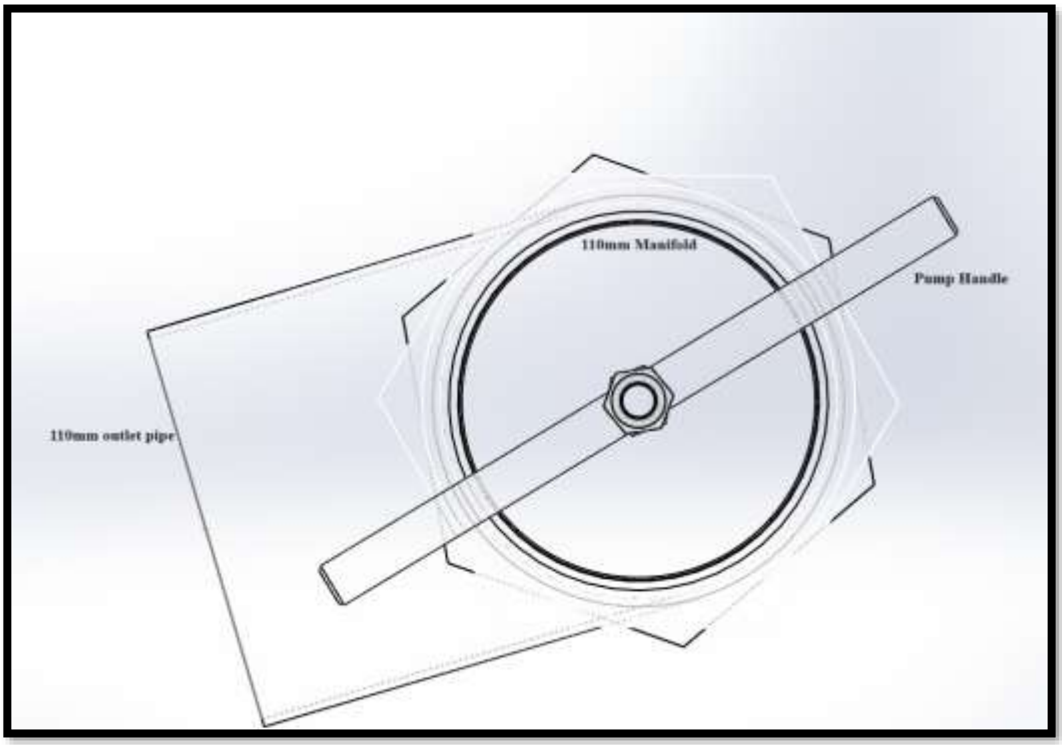

Figure 4.3: Plan View of Design Concept A , Hand pump Option (Source: Solidworks 2023)

Advantages

1. Easy fabrication
2. Village level Operation and Maintenance
3. Parts can be disassembled for security reasons

Disadvantages

1. Human powered
2. Labour Intensive

B. Design Concept B: Springboard mechanism

This mechanism was designed in a way that the upstroke is powered by the compression spring and the down stroke is powered by the operator.

Principles of design & operation

The operator would use the feet to push the piston down whilst creating a vacuum in the manifold and compressing the spring in the process. During the upstroke the compressed spring would be released and using the stored energy would lift the water into the manifold which would be conveyed to the farmer for use. Using the feet would ensure that they would be less tiresome effort and possibility of greater pumping rate.

The springboard pumping mechanism would use lesser energy and at a higher speed. In this pumping mechanism a spring-board mechanism would be designed to support pumping using the feet instead of hands like most pumps. The design was done using principles from (Bhandari, 2007) and (Gupta, 2005). The equations used in the design for the components associated with the pumping mechanism are as follows:

The mean diameter of spring coil

$D = C.d$

Where:

C = spring index (mm)

d = diameter of spring coil (mm)

$Wahl's\ stress\ factor, K = \frac{4C-1}{4C-4} + \frac{0.615}{C}$ Equation [4.15]

Where:

C = Spring index

The wire diameter (d)

$\boldsymbol{\tau} = K\left(\frac{8FC}{\pi d^2}\right)$ Equation [4.16]

Where:

F = The maximum load to be sustained by the spring, N

C = The spring Index

d = Diameter of spring wire, (mm)

Number of turns in the spring:

$\delta = \frac{8.F.C^3.n}{G.d}$ Equation [4.17]

Where:

F = The maximum load to be sustained by the spring, (N)

C = The spring Index

d = Diameter of spring wire, (mm)

G = Modulus of rigidity of the material, (N/mm^2)

δ = deflection, (mm)

n = number of active turns

Free length of the spring

$$\text{Free length} = n.d + \delta + 0.15\delta \qquad \text{Equation [4.18]}$$

d = Diameter of spring wire, (mm)

δ = deflection , (mm)

n= number of active turns

Pitch of the coil

$$\text{Pitch of the coil} = \frac{\text{Free Length}}{n-1} \qquad \text{Equation [4.19]}$$

n= number of active turns

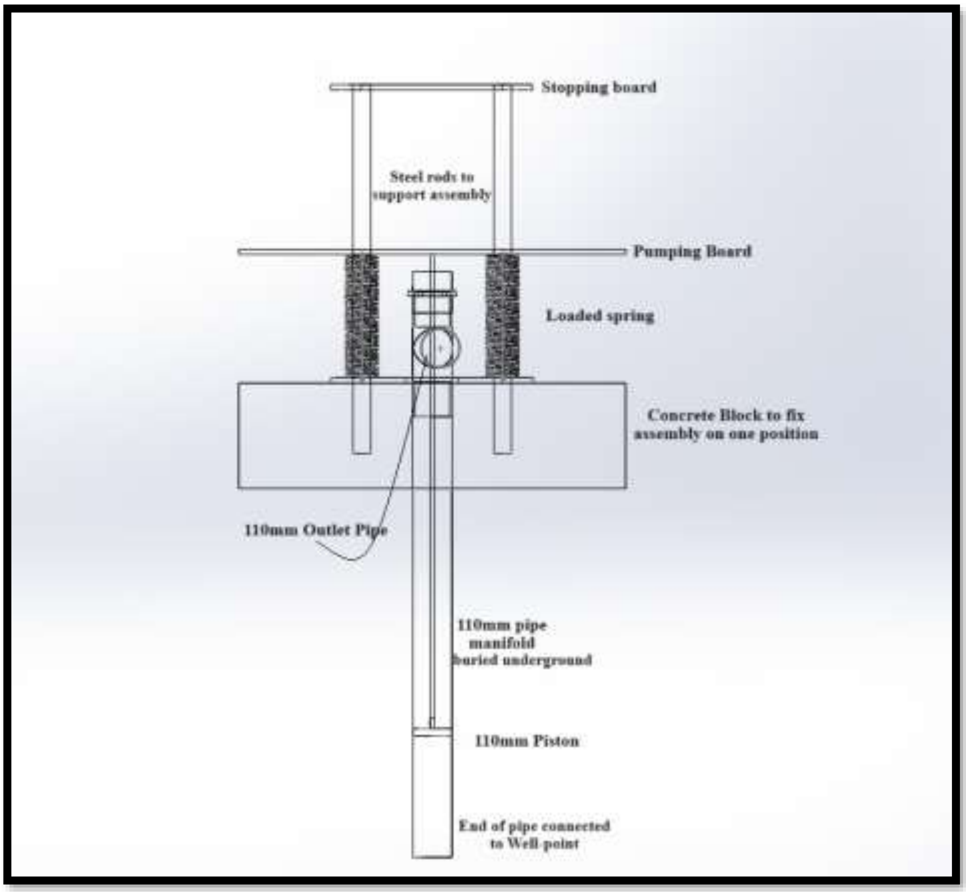

Figure 4.4:A schematic of the Springboard Mechanism, Side View (Source: Solidworks 2023)

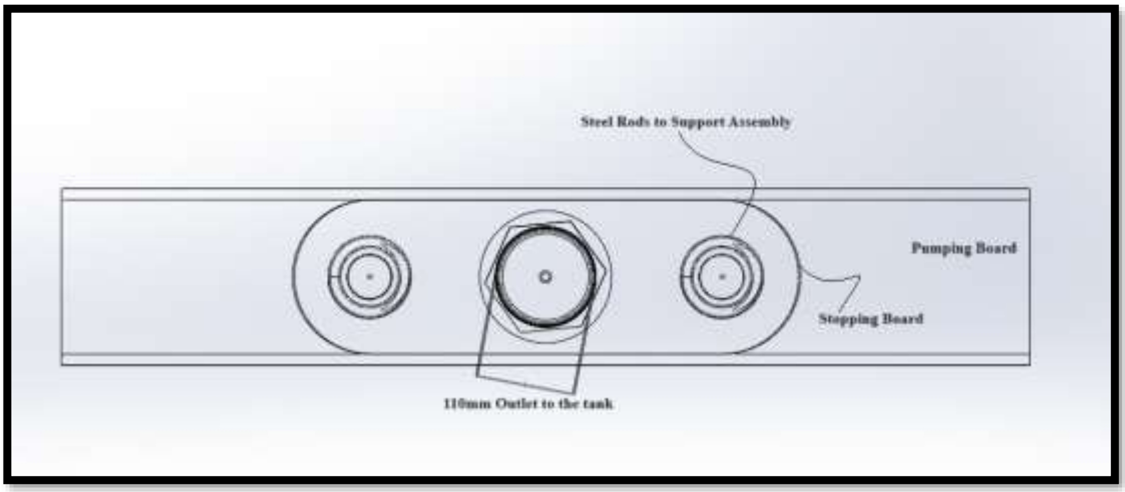

Figure 4.5: Plan view of the springboard mechanism (Source: Solidworks 2023)

Advantages

1. Easy fabrication
2. Village level Operation and Maintenance

3. Parts can be disassembled for security reasons
4. Relatively reduced labour

Disadvantages

1. Human powered
2. Labour Intensive

C. Design concept C: Counterbalance option

The design of the counterbalance system also had the intention of reducing the effort used by the user in the sand abstraction process.

Principle of operation

The design of the counterbalance system had the intention of reducing the effort used by the user in the sand abstraction process. A counter balance is a weight, when placed at a certain distance, equals the same torque as another object at a different distance from the fulcrum part. The use of the counterbalance would significantly reduce the effort applied and also reduce the risk of injury since the other stroke would be automatically done by the counterweight.

The counterbalance would operate by ensuring that during the upstroke the user is assisted and on the down stroke when less effort is required the user will use their own effort. The user would push down the piston rod using their hands whilst lifting a weight on the opposite side and on the upstroke the lifted weight would fall under gravity and in the process assist the user to lift the water into the manifold.

The determination of the counterweight was done using principles postulated by Hibbeler (2010). The objective was to ensure that the counterweight will be able to lift the water on the upstroke assisting the user. The counterweight was made with the objective of Village Level Operation and Maintenance (V.L.O.M). Hence, it was made by concrete since it can be locally made using available resources.

$$CBM = \frac{M_0 \: x \: D_0}{D_b}$$ Equation [4.20]

Where:

M_0 = mass of the object, (kg)

D_0 = distance from object to the fulcrum, (mm)

D_b = distance from the counterbalance to the fulcrum, (mm)

The length of the supporting pipe and the lengths of the angle irons used in the assembly of the setup.

Design of the piston rod diameter

$d_r = (\frac{4F}{\pi\sigma_a})^2$ ………………………………………….. Equation [4.21]

Where:

F = Weight of Water (N)

σ_a = allowable stress which is limited to $45 N/mm^2$

The weight of water can be calculated using this equation

$F_w = (A_p S_l + a_{rm} \Delta H) \rho_w g$ ………………………………………. Equation [4.22]

Where:

ρ_w = density of water (1000 kg/m^3)

g = accelaration due to gravity (m/s^2)

S_l = Stroke length (m)

a_{rm} = rising main across sectional area (m)

Power required

The equations which were used to determine the power requirements were successfully used by Nasir *et al.*, (2004) and Nwaoha (2016). To determine the power required for the operation of the pump the following equation was considered:

$P_w = E.n$ Equation [4.23]

Where:

P_w = Power (Watts)

E = Output Energy (J)

n = cadence in strokes per second

$E = mg\Delta H$ Equation [4.24]

Where:

m = mass of water lifted per cycle , (kg)

g = accelaration due to gravity (m/s^2)

ΔH = pump Head, (m)

$m_w = V\rho_w$ Equation [4.25]

V = swept volume per stroke, (m^3)

ρ_w = density of water , kg/m^3

At the suction point the hydrostatic pressure Δp will be

$\Delta p = \rho_w \times g \times \Delta H$ Equation [4.26]

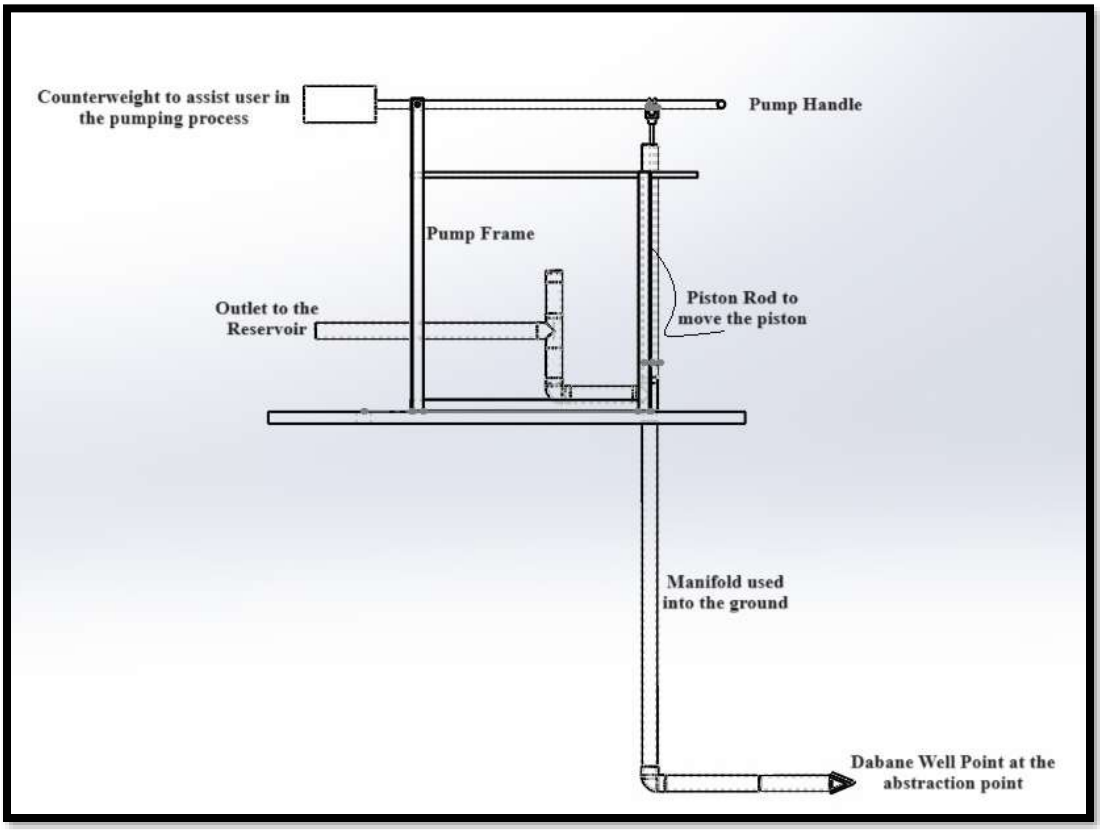

Figure 4.6: A schematic of the counterbalance option (Source: Solidworks 2023)

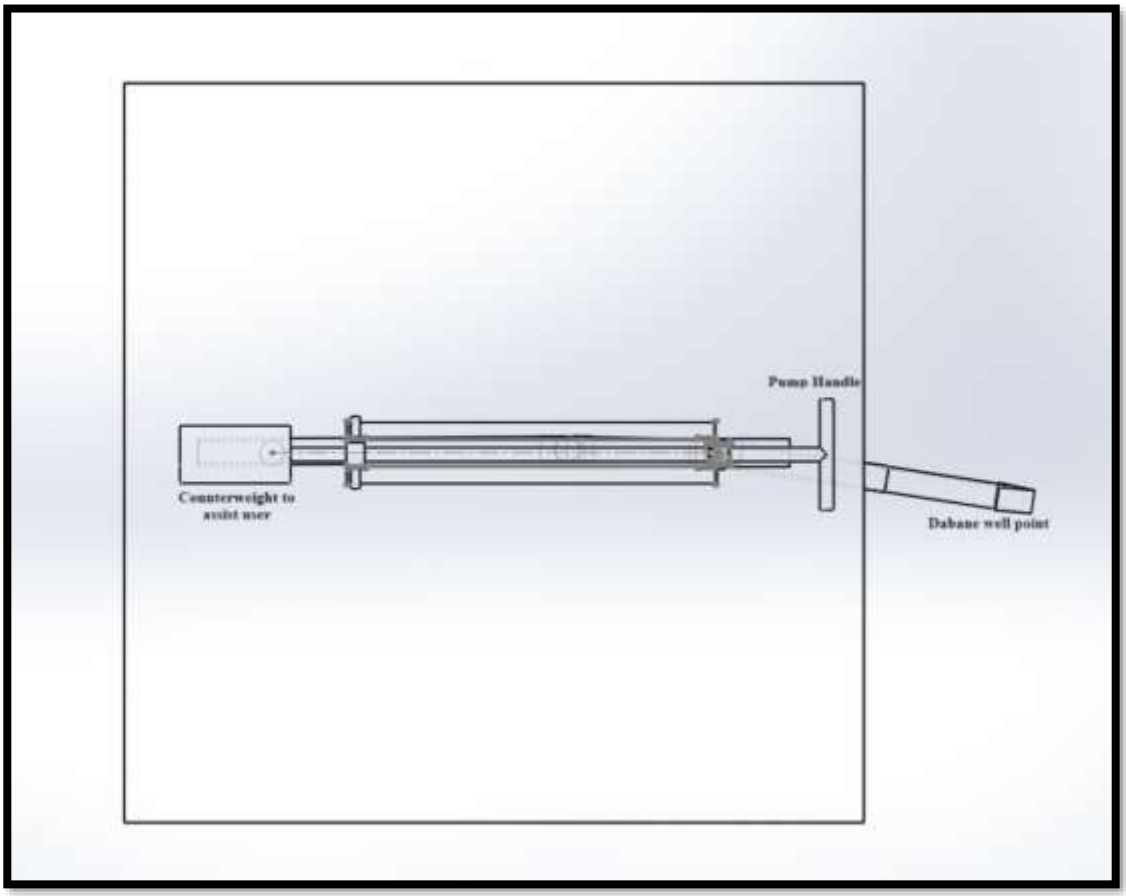

Figure 4.7: A Plan view of the proposed counterbalance pumping system

(Source: Solidworks 2023)

Advantages

1. Reduced labour requirements on the user
2. Increased discharge
3. High durability
4. Village level Operation and Maintenance

Disadvantages

1. Human powered
2. Labour Intensive

4.3.3 Multi-criteria decision analysis

The choice of the proposed design was based on the multi-criteria decision analysis. The factors were considered based on their contribution to sustainable exploitation of the alluvial aquifers. The factors which were considered were pumping rate, purchasing, installation and maintenance cost, expected life span, user friendliness and water demand management. The factors were ranked and given a contribution score to the final choice. The scoring criteria was based on the perceived performance of the pump considering that factor. A Likert scale, as presented in Table 4.3, was employed to convert qualitative data into numerical scores for grading purposes. The resulting scores were categorised as either beneficial or non-beneficial. it is crucial to distinguish between beneficial criteria and non-beneficial criteria to effectively compare different models.

Beneficial criteria are factors where a higher value is preferred. In this study beneficial criteria were:

1. Pump Rate: A higher flow rate is beneficial because it means the pump can move a larger volume of water in a shorter time, improving efficiency for irrigation tasks .
2. Expected Life Span: A longer expected lifespan is beneficial as it indicates greater durability and reduces the frequency of replacement, leading to long-term cost savings.
3. User-Friendliness: A pump with a higher user-friendliness rating is beneficial, as it means easier installation, operation, and maintenance.
4. Water Demand Management: In this study, a higher score in water demand management was beneficial, as it indicates a more effective system that better conserves water and reduces waste.

Non-Beneficial Criteria are factors where a lower value is preferred. In this study non-beneficial criteria were:

1. Costs: Lower initial purchase cost and lower long-term operating costs (e.g., energy consumption) are beneficial, as they reduce the financial burden.

To ensure comparability across all criteria, data normalisation was subsequently applied. The pumps with a score of 3.5 or higher were considered to be good for the sustainable usage of the Shashani alluvial aquifer

Table 4.2: Multi-criteria decision Analysis Template

	Hand Pump	Pedal Pump	Springboard	Counterbalance	Sunflower Pumps	Mechanical Pumps
Pump Rate						
Costs						
Expected Life Span						
User-friendliness						
Water demand management						

Table 4.3: Likert Scale Grading System

Opinion	Score
Very Good/Very High	20
Good/High/	16
Acceptable/Neutral	12
Poor/Low	8
Very Poor/Very Low	4

The scores were classified into beneficial and non-beneficial. To make all the criteria comparable normalisation was done using Equation [4.27] and Equation [4.28]:

For non- beneficial criteria:

$$\text{Normalised Score} = \frac{\text{Min}\ (X_{ij})}{X_{ij}}$$ Equation [4.27]

For beneficial criteria

$$\text{Normalised Score} = \frac{X_{ij}}{\text{Max}\ (X_{ij})}$$ Equation [4.28]

4.3.4 Design and drawings

Except for the solar pumping mechanisms, all the pumping mechanisms that were proposed required a pumping rod and a piston, therefore, the design of piston rod, manifold and piston were the same for all the pumping mechanisms. The design calculations are shown in Appendix II. From the desk studies it was observed that the manual pumps in operation were using a pipe size of 63mm diameter. The diameter that was chosen was 100mm to improve on the existing work. The designs and the components required for the successful operation of the pump were drawn using Solidworks 2023 software.

4.3.5 Modelling and simulation of the designed model

The modelling and simulation of the designed abstraction technologies was done in three stages. Wu *et al.*,(2019) states that Solidworks software can be used to test agricultural models and provide a powerful practical tool for the sustainable development of agriculture. There, the first stage was the motion simulation in the Solidworks environment, the second stage was the flow simulation in Solidworks and thirdly the modelling of the expected discharges in Microsoft Excel (2016).

Motion Study

Motion study is a simulation that shows how parts of a design move and interact with each other over time. A motion study in SolidWorks is a simulation used to test and visualize how a design's parts move and interact under real-world conditions. In this study, motion study was performed in SolidWorks 2023 to verify that the designed suction pump components would produce the desired motion upon assembly. The simulation process involved:

1. Assembling all designed components in the SolidWorks environment according to the intended configuration.
2. Applying relevant mechanical constraints to reflect the real-life assembly conditions.
3. Fixing all static components and allowing only the moving parts to move under simulated operating conditions.
4. Tracking the piston rod displacement using the SolidWorks Motion Study displacement analysis tool to determine the maximum achievable stroke length before any mechanical interference or undue stress occurred.

Flow Simulation

The flow simulation was conducted to estimate the expected fluid flow once the pump is fabricated. The motion of fluid within the pipes is influenced by parameters such as friction, gravitational force, and changes in the geometry of the control volume. The simulation tracked the fluid behaviour from its entry into the pump manifold to the outlet, assuming that water has already been separated from the soil sediment.

The pump geometry for the flow simulation was generated directly from the final design model in SolidWorks 2023, incorporating all internal flow paths from inlet to outlet to replicate the actual pump configuration. The Flow Simulation module was used to assess the hydraulic performance of the pump under the assumed design operating conditions.

The following boundary conditions were applied:

- Inlet: Volumetric flow rate of 3.8 L/s.
- Outlet: Static pressure set to atmospheric pressure (101.325 kPa).
- Fluid: Water at 20°C.
- Wall condition: No-slip.

The simulation tracked velocity distribution throughout the manifold and delivery pipe during a simulated upstroke, with the piston displacement set to the maximum stroke length obtained from the motion study.

Discharge modelling

The discharge modelling was done to test how the discharge per stroke would be sufficient to meet the desired demand by the farmer. An excel spreadsheet was designed to estimate the expected volume of water that can be discharged per hour if the user uses different stroke lengths. The volume of water discharged per hour was estimated for each stroke and the expected volume was obtained.

Chapter 5: Results and Discussion

5.1 Determination of potential water supply of the alluvial aquifer

Due to the size of the catchment under study, multiple measurements were taken at different locations of the sand river to obtain a more accurate representation of the alluvial aquifer capacity. In that regard three sections of the river were selected for assessment to estimate the average aquifer thickness of Shashani Alluvial Aquifer. The geographical location of the sections is shown in Figure 4.1.

5.1.1 Dimensions of the alluvial aquifer

A mechanical probe was used to determine the depth to bedrock or the clay layer, and results are presented in Appendix I. The maximum sand depth recorded along the Shashani sand river was 3.0 m, while the minimum was 1.51 m. Field measurements conducted in this study produced an average depth of 2.04 m, reflecting localised variations across the river section sampled. To derive a regionally representative estimate of average depth for volumetric calculations, depth data from related studies were also considered. Moulahoum (2018) reported sand depths ranging from 1.5 to 2.5 m, while Mpala *et al.* (2016) documented an average depth of 1.5 m along another section of the Shashani River. Taking these values into account, and to ensure comparability and avoid overestimation, an adjusted average depth of 1.9 m was adopted. This approach balances the findings from previous studies with this study's own observations and provides a conservative yet representative estimate for calculating aquifer volume. The estimated length of the river channel from Antelope Dam to Shashe Confluence as estimated from the Google Earth digital elevation map was 113 334 m. The area of Shashani sand river was found to be 12.6 x10^6 m^2. These results were used to determine the volume of the alluvium from Antelope dam. The alluvial aquifer volume was estimated to be 23.9 x 10^6 m^3. The potential water storage of the alluvial aquifer was found to be 7.17 x10^6 m^3 which is sufficient to support large scale irrigation. Table 5.1 presents the probing results from the field studies conducted for this project.

Table 5.1: The average depth at the different locations where probing was done

Probing Location	Average Depth
1	1.77
2	1.57
3	2.77
Average	**2.04**

5.2 Modelling the sustainable yield of an alluvial aquifer

The sustainable yield was modelled by the following equation :

$$\mathbf{SY} = \mathrm{SYF}[Q_{g,in} + (PA + R - Q_{surf}) - Q_{g,out} - ET - Q_{abs}] \quad \text{Equation [5.1]}$$

Where:

SY = Sustainable Yield (m^3/day)

SYF = Safe Yield Factor

$Q_{g,\,in}$ = groundwater inflow (m^3/day)

Q_{surf} = surface flow (m^3/day)

$Q_{g,\,out}$ = groundwater outflow (m^3/day)

P = Precipitation (m/day)

R = Runoff from catchment Area (m^3/day)

ET = Evapotranspiration (m^3/day)

Q_{abs} = the abstraction rate (m^3/day)

5.2.1 Testing of the sustainable yield model

A scenario analysis done in order to see the behaviour of the model for a typical wet, dry and normal years. The results of the modelling and the steps taken to develop the model are shown in the sections following:

Table 5.2: The results from the testing of the sustainable yield model

Parameters	Normal Year	Dry year	Wet year
INPUTS	**Value (m^3)**		
Direct Rainfall	5 700 286	3 407 601	7 410 385
Surface Runoff	544 749 349	224 253 194	836 420 227
Upstream Groundwater Inflow	18 805.22	18 805.22	18 805.22
River Surface Inflow	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
Recharge from underlying aquifers	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
Base flow from the catchment	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
TOTAL	**550 468 440**	**227 679 600**	**843 849 417**
OUTPUTS			
Surface outflow	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
Evapotranspiration	998 016.3756	998 016.3756	998 016.3756
Seepage	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
Lateral outflow	Assumed to be negligible	Assumed to be negligible	Assumed to be negligible
Downstream groundwater outflow	17 534.87	17 534.87	17 534.87
Total Abstraction	890 578.2	890 578.2	890 578.2
TOTAL	**1 906 129**	**1 906 129**	**1 906 129**
Annual recharge	**548 562 310.6**	**225 773 470.6**	**841 943 287.6**
Sustainable Yield	**329 137 386**	**135 464 082**	**505 165 972**

The results of the model testing show that the sustainable yield in a normal year was 329 137 386m^3 whilst in a dry year the sustainable yield is 135 464 082m^3 and in a wet year the sustainable yield was 505 165 972m^3. This showed that in a dry year the sustainable yield reduces by 58.8% and in a wet year the sustainable yield increases 53.5%. This suggests that the alluvial aquifer is still being underutilised. Walker *et al*., (2018) had similar observations whilst doing a similar study in South Africa.

From the scenario analysis it can be argued that the sustainable yield is highly sensitive to the rainfall and to the surface runoff since the other parameters were assumed to be constant in the study. This was in agreement with the findings of Mpala *et al*. (2020) in their study. The surface runoff volume is highly influenced by the surface texture of the catchment. The sustainable yield of an alluvial aquifer depends on the recharge it receives and its distribution in time, the geometry of the sand river deposits, the hydraulic properties of the sand and the amount of water abstraction, evaporation and other losses.

The results of the testing also revealed that the model was sensitive the abstraction. Amongst all the influencing parameters the abstraction was the one which was highly influenced by human activity. Innovative approaches are required to sustainably increase creative use of this resource to improve the livelihoods of people in the vicinity of the resource (Duker *et al*., 2020). That shows that as people increase their farming efforts the rate of abstraction is going to increase since the water demand is going to increase. The model will then be useful in estimating the effect of the increase in number of farmers. There is therefore need to establish sustainable abstraction technology to ensure that the resource is used sustainably.

The model was limited in its ability to determine certain hydrological parameters such as seepage losses, lateral inflows, and lateral outflows, and it relied on historical data for some inputs. To calibrate the model and assess its performance accurately, a long-term study with adequate resources would be required to quantify these specific parameters under varying hydrological conditions. Improved data on these factors would enhance the model's predictive reliability and overall accuracy.

5.2.2 Determination of model parameters

Determination of wet, dry and normal year

The climatic data for the study area was downloaded from the CHRS data portal from 1983 - 2021. The variation of rainfall in the study area is shown in Figure 5.1. For this study a typical wet year was taken to be 2017, the dry year was taken to be 2015 and the normal year was taken to be 2021. The rainfall values for the typical wet, dry and normal year were found to be 621.12mm, 295.01mm and 439.35 mm, respectively. These years were specifically chosen because they are more recent and are a better representative of the current weather patterns.

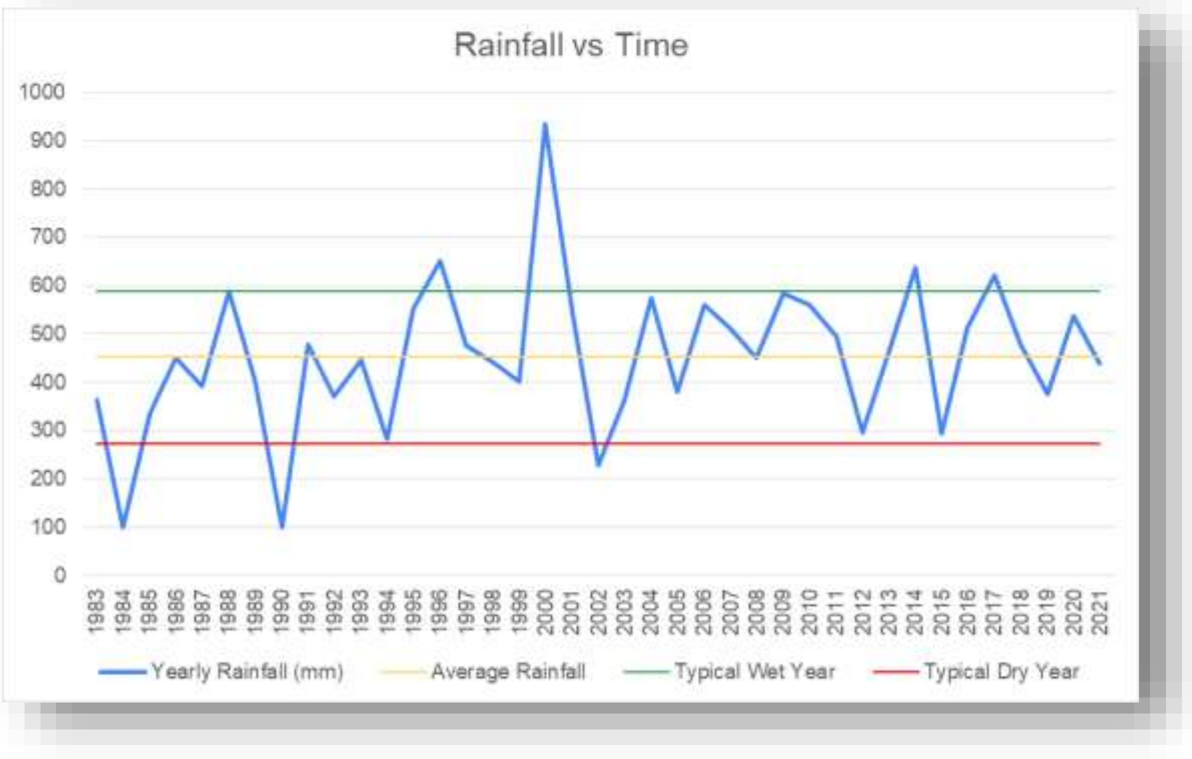

Figure 5.1 The variation of annual rainfall with time from 1983 - 2021, Source: CHRS Data Portal

Determination of Curve Number

The curve number was determined by taking samples of different surfaces in the catchment area. Soil tests were done on the different samples around the catchment Results show that Shashani catchment consists of sandy clay and silt clay soils, thus the soils are classified as hydrologic soil group “C” and “D” respectively in accordance to guidelines given by the USDA NRCS (2007). The results of the curve number determination are as shown in Table 5.3 below.

Table 5.3: Different soil classifications and curve numbers for Shashani catchment

Land Cover	Area (km^2)	Hydrologic Condition	HSG	CN
Communal Area	871.565	82	C	82
Commercial Area (Meadow/Pasture)	646.055	73	D	73
Commercial Area (Grassy Woodland)	644.379	65	C	65
Average				**74.2**

Using this data, the accumulated runoff for the typical wet, dry, and normal years was estimated at 386.75 mm, 251.89 mm, and 103.69 mm, respectively. These values are notably higher than the range reported by Ncube et al. (2010), who suggested annual runoff volumes between 21 mm and 40 mm. The discrepancy may be attributed to differences in climatic data sources, temporal scale, and methodological approaches used in estimating runoff, particularly the application of the SCS curve number method. The SCS-CN is known to be sensitive to soil classification and land-use assumptions. This significant variance highlights the need for further research, including model calibration, validation, and long-term data collection, to refine runoff estimates for the Shashani catchment. These results were used to find the volume of water in Shashani river for the typical years under study. The results of the volumetric contribution are shown in Table 5.4 below:

Table 5.4: Volumetric contribution of runoff to water supply in Shashani Sand River

Year	Volumetric Contribution (m^3)
Wet Year	836 420 227
Normal Year	544 749 349
Dry Year	224 253 194

Downstream Groundwater Outflow and Upstream Groundwater Inflow

Due to limitations of the study, piezometers could not be installed in the study area. However, historical data indicated that the values for upstream groundwater inflow and downstream groundwater outflow in the study area were 18 805.22 m^3 and 17 534.87 m^3, respectively. This was used as an estimate of the data used in this study.

Evapotranspiration

Evapotranspiration for Shashani catchment was estimated based on climate data from West Nicholson weather station (sourced from ClimWat), using the Penman-Monteith equation in FAO Cropwat. Riparian vegetation was assumed to cover a 3m wide area along each of the banks. The amount of water lost as evapotranspiration in the study area would be:

Total annual evapotranspiration = 998 016.3756 m^3

Abstraction from the alluvial aquifer

From the field visit, it was found out that the people in the study area mainly use the sand river for irrigation of vegetables such as, carrots, onions and tomatoes. There are 390 gardens along the river channels with average garden size of 750 square metres. The total irrigated land was 292 500m^2 (29.25 hectares). The total volume of water required was 438 750m^3. This was added to the irrigation water requirements from already established community gardens whose abstraction requirements were recorded as shown in Table 5.5 below.

Table 5.5: Community Gardens Irrigated with water Abstracted from the Study Area

Name of Garden	Ward Number	Village	Size of Garden (Ha)	Beneficiaries
Shashane 5	2	Mazwi	0.75	13
Siyazama	2	Singangatsha	0.75	12
Madlelo Aluhlaza	6	Mazwi	0.75	12
Thembani	7	Halawupha	0.75	16
Vusanani - Toloki	7	Silonkwe	0.75	13

Based on interviews conducted with garden members, it was concluded that each garden had an estimated abstraction of 1m^3 per week. The total volume of water abstracted from Shashani Sand river by these gardens was calculated to be 260 m^3 annually.

Total abstraction for garden irrigation was estimated to be: 439 010 m^3/year

The abstraction for livestock watering was obtained from livestock population data sourced from the Livestock Production Department (LPD) Matobo District and water requirements for the different animals are given in the Table 5.6. this was used to estimate the remainder of the river section as shown in Appendix III. The Annual livestock water requirement was estimated to be 213 047.8599 m^3

Table 5.6: Livestock water requirements for a 5km stretch along Shashani

	Cattle	Donkeys	Calves	Goats	Kids
Water Requirements (l/day)	25	20	10	5	2
Population	462	263	329	921	523
Total	11550	5260	3290	4605	1046

The total population of people in the wards under study was: 32 674 people. The daily water usage per capita = 20 litres (WHO, 2000). The annual domestic water demand was estimated as shown in Appendix III. The total abstraction was estimated to be 452 366.20m^3

Direct rainfall

From the desk studies it was observed that the permeability of Shashani river is about 4.07 m/hr. This suggests that the recharge is instantaneous hence the direct rainfall was assumed to recharge the alluvial aquifer. The surface area of the river was calculated using the GOOGLE Earth digital elevation map. The total surface area of the alluvial aquifer was estimated to be 12 573 060.27m^2. The total contribution of direct rainfall for the respective years would be as shown in Table 5.7.

Table 5.7: Volumetric contribution of rainfall to Shashani Sand river water supply

Year	Volumetric contribution (m^3)
Wet Year	7 410 385
Normal Year	3 407 601
Dry Year	5 700 286

5.3 Design of sustainable abstraction technology

From the field investigations it was observed that in the study area the most common manual pump in usage is the Rowa Pump. At its optimum operation the Rowa pump abstracts water at an average rate of 0.6 l/s. This has however limited the usage of this resource to domestic usage with limited agricultural yield. Interventions have been done by multiple organisations to improve the usage however sustainability of the resource has not been prioritised. From field investigations it was observed that the head was about ±7m. The results of the design calculations are shown in Appendices II. The calculations for the proposed Abstraction Technology are shown in Appendix VII.

5.3.1 Hand pump

Since the intention was to have a manual pump with attributes that are better than the one existing on the market, the average flowrate required was 1 l/s. The proposed design was an adjustment to the Dabane Rowa Pump. The manifold that are in operation would be changed to 110 mm and this would double the flowrate on every stroke. The other components of the pump would have to be redesigned to ensure that they can handle the change, Based on the calculations, the minimum diameter of the piston rod was 2.79 mm if it is a steel rod. However, to allow for easier assembling and availability of steel rods a steel rod of 10mm was adopted in the design. The other parts which were used were based on those which are readily available on the market and to allow for Village level operation and maintenance. The results of the design calculations are detailed in Appendix VI.

The Hand pump option would however introduce an ergonomic hazard because of the rowing action and the increase in weight. This anticipated hazard prompted the use of an easier pumping mechanism. The pedalling option was introduced instead.

5.3.2 Springboard mechanism

The springboard mechanism was another idea to improve the abstraction process. The spring board mechanism involves the use of a compression spring. In the design the piston rod would be extended by approximately 1 meter to allow for the free length of the spring. The sitting position of the operator would be elevated by 500 mm to allow easier operation. Instead of a hand-operated mechanism, the pump is actuated by the operator's feet. A spring-assist mechanism reduces the required effort, making the pumping process more efficient and less physically demanding. The results of the design are detailed in Appendix II. The springboard mechanism however had challenges since the maintenance might be high cost. The spring might require greasing and consistent replacement. This prompted for other options discussed below.

5.3.3 Counterbalance option

The counterbalance required for smooth operation of the system was calculated to be 26 kg, based on static load analysis and system performance requirements. For the final design, a counterweight of 30 kg was selected to provide a safety margin, accounting for potential increases in operational resistance caused by friction, mechanical wear, or minor misalignments during prolonged use. The additional mass also ensures adequate momentum to sustain consistent motion under varying load conditions, thereby enhancing the reliability and efficiency of the system. This counterweight option was innovative in that it utilised a combination of existing components reconfigured to function as a pump, without the need for extensive modification or replacement of parts. The orientation of these components made the design particularly suitable for the operating environment. While periodic lubrication may be necessary to maintain performance, this was considered the most practical and reliable configuration for the intended application.

The counterbalance option would introduce a different driving mechanism. The user will still use the upper body strength, however, the orientation is different. Instead of operating the machine whilst sitting they will be standing. The upstroke which is the most critical stage will be assisted by a weight. This would significantly make the pumping process easier since the heavier stroke is assisted by the counterweight. The following image show the designed components for the designed pump and the final assembly as simulated in Solidworks 2023.

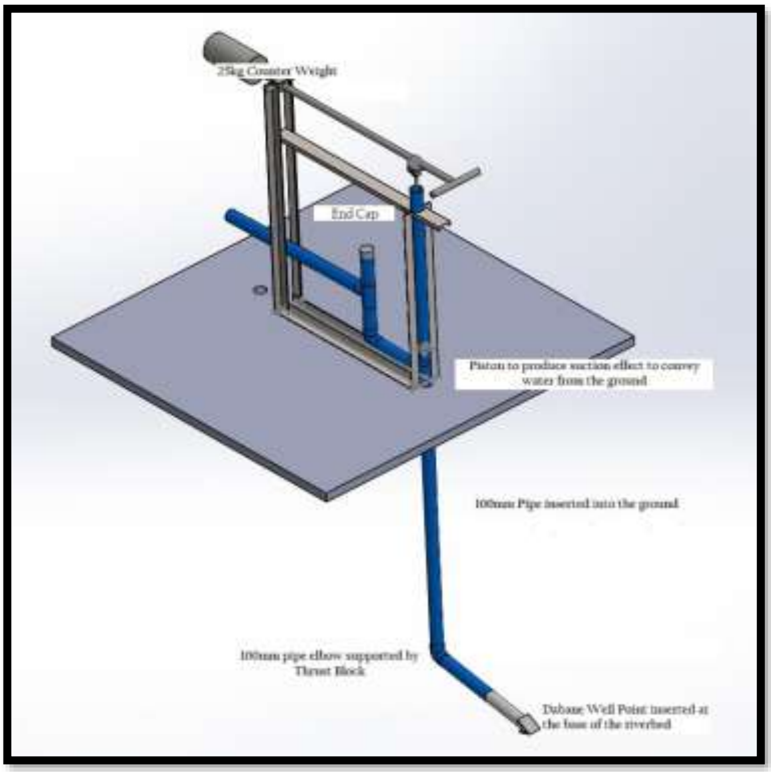

Figure 5.2 Illustration of the sand Abstraction System that was designed (Source: Solidworks 2023

5.3.4 Comparison of different technology for final selection

To design the final product, the different proposed technologies was compared from both a social and engineering vantage point. Table 5.9 shows the different advantages and disadvantages of the several proposed designs. The comparison and ranking of the different design options are shown in Table 4. The design options were then compared as shown in Table 5.8 and Table 5.11 and the chosen option was the counterbalance option.

Table 5.8: Multi-criteria decision analysis of different pumps

	Hand Pump	Pedal Pump	Springboard	Counterbalance	Sunflower Pump	Mechanical Pumps
Pump Rate	High	High	Acceptable	High	Very High	Very High
Costs	High	Very High	High	Very Low	Low	Very High
Expected Life Span	Very High	Acceptable	Acceptable	High	High	Very low
User-friendliness	low	Acceptable	Acceptable	Very High	Very High	acceptable
Demand Management	Very High	Very High	Very High	Very High	Very High	Very low

Table 5.9: The scores of different pump options based on the five-point likert scale

	Hand Pump	Pedal Pump	Springboard	Counterbalance	Sunflower Pumps	Mechanical Pumps
Pump Rate	16	16	12	16	20	20
Costs	16	20	16	4	8	20
Expected Life Span	20	12	12	16	16	4
User-friendliness	8	12	12	20	20	12
Water Demand Management	20	20	20	20	20	4

Table 5.10: The normalised scores of the different pump options for comparison

	Hand Pump	Pedal Pump	Springboard	Counterbalance	Sunflower Pumps	Mechanical pumps
Pump Rate	0.8	0.8	0.6	0.8	1	1
Costs	0.25	0.20	0.25	1	0.5	0.25
Expected Life Span	1	0.6	0.6	0.8	0.8	0.2
User-friendliness	0.4	0.6	0.6	1	1	0.6
Water Demand Management	1	1	1	1	1	0.2
Total	**3.45**	**3.20**	**3.05**	**4.6**	**4.3**	**2.25**

Selected Option:

The sunflower pumps option and the counterbalance option met the criteria to be used for the sustainable usage of Shashani alluvial aquifer. They both had a score which is above 3.5 making them both suitable for the intended purpose. The counter-balance option was the final recommended option for modelling and testing.

5.3.5 Modelling and simulation of the Counter-Balance Pump

The testing of the system was done digitally mainly because of the high cost of fabrication and the time constraints. However, the testing and simulation that were done showed that if fabricated the pump would behave satisfactorily.

Motion study

The motion study revealed that the assembly of the designed components would operate smoothly when fabricated. Based on the SolidWorks 2023 piston rod displacement analysis, the achievable stroke length was determined to be 0.55 m. This limit was set to prevent mechanical interference between components and to avoid overstressing the manifold, which could result in reduced operational efficiency or potential failure of the pump.

Flow simulation

The flow simulation results showed that each upstroke would produce outlet velocities within the range 0–0.725 m/s (Figure 5.3), consistent with the inlet boundary condition of 3.8 L/s. This corresponded to an equivalent continuous discharge of approximately 3.11 L/s. Figure 5.7 illustrates the spatial velocity distribution of the fluid during an idealized upstroke. This model assumes a closed system, where there is no mass transfer or leakage to the surrounding environment. These findings confirm that the pump is capable of operating efficiently within the design parameters.

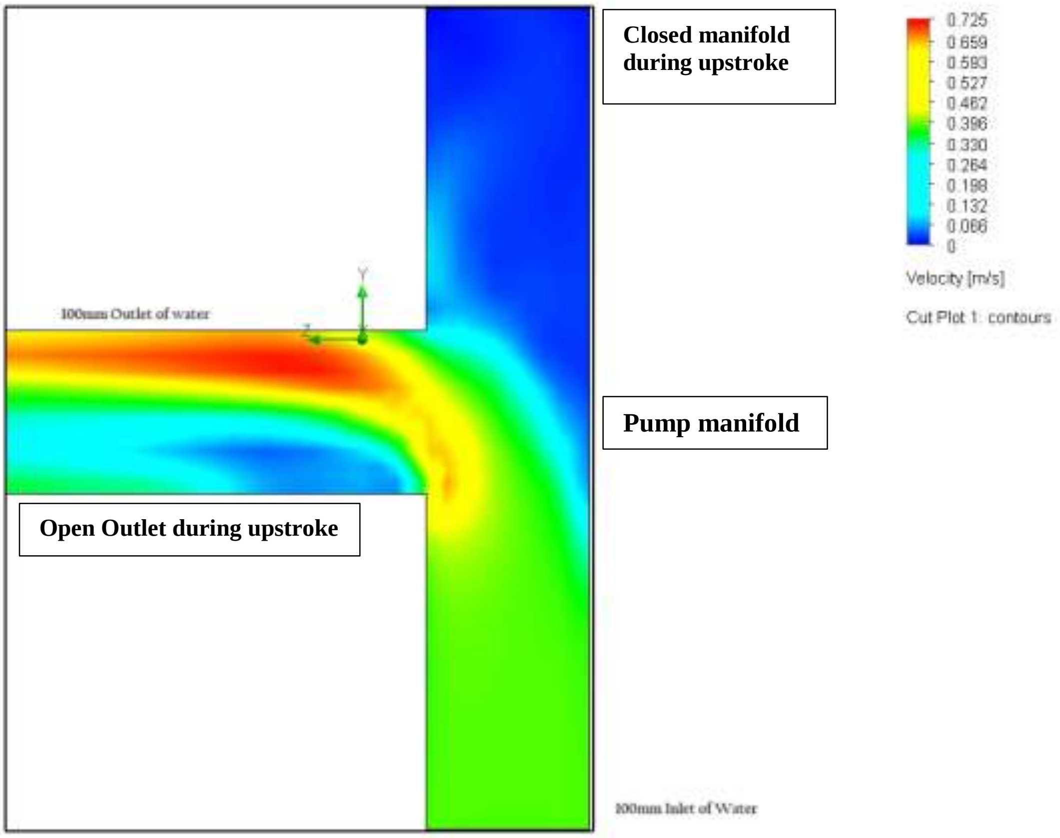

Figure 5.3: Results of the flow simulation showing different flow velocities at different points during the upstroke of the Counterbalance Pump (Scale: Not to Scale)

Discharge Modelling

The results of the discharge modelling showed that the pump would be able to support the small scale farmer satisfactorily when used at different rates per minute. When using minimum stroke of 100mm the user would take one hour to fill up a $1m^3$ reservoir. The results of the discharge modelling are shown in Appendix VI. Appendix VI show the discharge modelling results. These show how variation in stroke would affect the pump output.

5.3.6 Comparison of the Counter-balance pum with Pumps Existing on the market

The Counterbalance pump was compared with the hand Pump to observe the significance of the change. The pump rate of the modelled pump depends on the stroke length and the rate at which the operator of the pump is operating. It was assumed that an average operator will do a maximum of 30 strokes per minute. Depending on the stroke length the volume of water pumped by the modelled pump was compared to that of a hand pump a locally used pump. The results indicate that the modelled pump delivers a higher water output than the hand pump across all tested stroke lengths. This increased efficiency demonstrates that farmers can operate the pump more productively, reducing effort while achieving greater water delivery. This would improve the farmers output significantly.

5.3.7 Cost-Benefit Analysis

The cost-benefit analysis was conducted using cabbages as the representative crop, as their selling price is well-established and allows for a reliable estimation of potential income. The results indicate that a farmer would need at least three farming sessions of cabbages to recover the cost of the pump. This corresponds to a payback period of approximately 1 to 1.5 years, assuming consistent and productive farming throughout the year. The cost-benefit analysis is shown in Appendix V. While other vegetables such as carrots, onions, and tomatoes are also cultivated in the area, their variable market prices make it difficult to provide a precise payback estimate. Therefore, using cabbages offers a clear and practical reflection of the pump's economic viability under typical agricultural conditions.

5.4 Conclusion

The developed water pump is capable of delivering water at a rate suitable for vegetable farming. Water can be pumped into a reservoir of height 0.5 m to 1 m, sufficient to support furrow or bucket irrigation for a small-scale farmer. Using an average stroke length of 0.3 m, the counterbalance pump can fill a 4 m^3 reservoir in approximately one hour. For reference, the minimum stroke length of 0.1 m would fill a 1 m^3 reservoir in the same time, while the maximum stroke length of 0.55 m would increase the pumped volume proportionally. This demonstrates that the volume pumped is roughly proportional to the stroke length, and if the water is stored and budgeted, it would be adequate to irrigate one hectare for a month.

The drip irrigation system is one of the most efficient irrigation methods for small-scale, gravity-fed applications. This system requires a minimum head of approximately 1 meter, which means the water tank needs to be elevated to that height above ground level for optimal performance. Simulations demonstrated that the designed pump can supply water to a reservoir, which in turn discharges water through a drip irrigation system. This improved mechanism is capable of raising water to a sufficient height to accommodate drip irrigation. Therefore, the drip irrigation system is recommended to ensure sustainable water resource management.

The adoption of such a sand abstraction system will ensure proper exploitation of the sand river. If the pump is fabricated and adopted it has the potential to improve the agricultural efforts and the livelihood of farmers in Shashani. It assists the small-scale farmer to gain access and benefit from the sand river water without over-exploiting the resource.

Chapter 6: Conclusions and Recommendations

Conclusions

The first objective was to quantify the storage capacity of Shashani sand river. The alluvial aquifer volume was 23.9 $x10^6$ m^3. The sand river has the capacity to keep 7.17 $x10^6$ m^3 which is sufficient to support large scale irrigation.

The second objective was to model the sustainable yield for Shashani Sand river for small scale irrigation for Shashani alluvial aquifer. The sustainable yield was modelled and a scenario analysis was done for a typical normal, wet and dry year. The results showed that the sustainable yield was sensitive to the surface runoff, rainfall and abstraction. This prompts the development of sustainable abstraction technology which will ensure sustainability of the resource.

The third objective was to determine the appropriate pump technology to support the sustainable use of Shashani Sand River for small scale irrigation. Three options were designed to improve the abstraction of water from sand rivers. Two options were finally selected based on the objectives of the pump. The manual was modelled and compared to assess its performance. If the operator is using an average stroke length of 0.3 m, the counterbalance pump can fill a 4 m^3 reservoir in approximately one hour which is a significant improvement compared to some pumps existing on the market.

Recommendations

Water authorities could also consider adopting a water resources policy that will see to the conservation and quality protection of the water in the alluvial aquifer. This may be achieved through community capacity building and the encouragement of stakeholder participation through community-based management of the resource.

The model was limited in the determination of other parameters such as seepage, lateral inflow and outflow and the dependence on historical data for some parameters. To calibrate the model and assess its performance a long term study with adequate resources would be needed to ascertain certain parameters. A long term further study is recommended to improve the decision making process and also inform the measures that can be taken to ensure sustainable usage of the water resource.

It is also recommended that further investigations be done on the river banks to accurately determine the extent of groundwater connectivity between the sand river and other groundwater sources in the region. Further studies in the region can be done using geo-electrical methods to identify cracking and fissures at the base as this might be another unaccounted for output of water. The accuracy of the findings of the study were limited by data unavailability. The installation of weather stations in the region will greatly increase the accuracy of any studies. The effectiveness of the pump might need to be assessed over a longer period of time. Implementation and studying the usability and effectiveness of the pump will be necessary to see its effectiveness over a long period of time as well as its acceptability amongst the users.

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APPENDIX I: DETAILED WATER BALANCE

An overview of the Water Balance for the Wet Year (2017)

Parameters	Value	unit	Assumptions	REF
INPUTS				
Direct Rainfall	7 410 385	m^3	All the direct rainfall recharges the alluvial aquifer	
Surface Runoff	836 420 227	m^3	Runoff Generated from catchment adjacent to Study Area	
Upstream Groundwater Inflow	18 805	m^3		(Jele, 2018)
River Surface Inflow	-	m^3	Considered to be negligible since it is dammed Upstream	
Recharge from underlying aquifers	-	m^3	Considered to be negligible	
Base flow from the catchment	-	m^3	Considered to be negligible	
TOTAL	**843 849 417**	m^3		
OUTPUTS				
Surface outflow	-	m^3		
Evapotranspiration	998 016.3756	m^3	Riparian vegetation assumed to cover a 3m wide area along each of the banks, it excludes the water usage from tributaries and other micro catchments	
Seepage	-		Considered to be negligible	
Lateral outflow	-		Considered to be negligible	
Downstream groundwater outflow	17 534.87	m^3		(Jele, 2018)
Total Abstraction	890 578.2	m^3	Abstraction from the areas in the vicinity of the main river, it excludes the water usage from tributaries	
TOTAL	**1 906 129.45**	m^3		
Annual recharge	**841 943 287.6**	m^3		
Sustainable Abstraction Rate	**505 165 972**	m^3	Assumed to be 60% of annual recharge	

An overview of the Water balance for the normal year (2021)

Parameters	Value	unit	Assumptions	REF
INPUTS				
Direct Rainfall	5 700 286	m^3	All the direct rainfall recharges the alluvial aquifer	
Surface Runoff	544 749 349	m^3	Runoff Generated from catchment adjacent to Study Area	
Upstream Groundwater Inflow	18 805	m^3		(Jele, 2018)
River Surface Inflow	-	m^3	Considered to be negligible since it is dammed Upstream	
Recharge from underlying aquifers	-	m^3	Considered to be negligible	
Base flow from the catchment	-	m^3	Considered to be negligible	
TOTAL	**550 468 440**	m^3		
OUTPUTS				
Surface outflow	-	m^3		
Evapotranspiration	998 016.3756	m^3	Riparian vegetation assumed to cover a 3m wide area along each of the banks, it excludes the water usage from tributaries and other micro - catchments	
Seepage	-		Considered to be negligible	
Lateral outflow	-		Considered to be negligible	
Downstream groundwater outflow	17 534.87	m^3		(Jele, 2018)
Total Abstraction	890 578.2	m^3	Abstraction from the areas in the vicinity of the main river, it excludes the water usage from tributaries	
TOTAL	**1 906 129.45**	m^3		
Annual recharge	**548 562 310.6**	m^3		
Safe Yield	**329 137 386.3**	m^3	Assumed to be 60% of annual recharge	

An overview of the Water Balance for the Dry Year (2015)

Parameters	Value	unit	Assumptions	REF
INPUTS				
Direct Rainfall	3 407 601	m^3	All the direct rainfall recharges the aquifer	
Surface Runoff	224 253 194	m^3	Runoff Generated from catchment adjacent to Study Area	
Upstream Groundwater Inflow	18 805	m^3		(Jele, 2018)
River Surface Inflow	-	m^3	Considered to be negligible since it is dammed Upstream	
Recharge from underlying aquifers	-	m^3	Considered to be negligible	
Base flow from the catchment	-	m^3	Considered to be negligible	
TOTAL	**227 679 600**	m^3		
OUTPUTS				
Surface outflow	-	m^3		
Evapotranspiration	998 016.3756	m^3	Riparian vegetation assumed to cover a 3m wide area along each of the banks, it excludes the water usage from tributaries and other micro - catchments	
Seepage	-		Considered to be negligible	
Lateral outflow	-		Considered to be negligible	
Downstream groundwater outflow	17 534.87	m^3		(Jele, 2018)
Total Abstraction	890 578.2	m^3	Abstraction from the areas in the vicinity of the main river, it excludes the water usage from tributaries	
TOTAL	**1 906 129.45**	m^3		
Annual recharge	**225 773 470.6**	m^3		
Safe Yield	**135 464 082.4**	m^3	Assumed to be 60% of annual recharge	

APPENDIX II: DESIGN CALCULATIONS

Spring Board Mechanism

PARAMETER	RESULT	Source
Minimum Operating Power	250 Watts	
Deflection	350mm	Average Stroke Length = 350mm
Maximum permissible shear stress for steel	$460\text{N}/\text{m}^2$	
Modulus of rigidity of the material, G	$81.370\text{kN}/\text{mm}^2$	
Spring Index	7	Assumed
Load	1000 N	
Output of Design		
Wahl's factor, K	1.213	
Diameter of Spring Wire	7mm	
Mean diameter of Spring coil	49mm	
Outer diameter of spring coil	56mm	
Number of active turns	80	
Free length	962.5mm	
Pitch of Chain	12.1mm	

Hand Pump Option

PARAMETER	RESULT
Pump rate	1.2l/s
Minimum Operating Power	832.11W
Cadence	18 strokes/minute
Output of Design	
Inside diameter of pump	100mm
Stroke length	900mm
Cadence	0.3 strokes / second
Diameter of the piston rod (minimum)	2.79mm

Counterbalance Option

PARAMETER	**RESULT**
Target Pump rate	1.2l/s
Minimum Operating Power	832.11W
Output of Design	
Inside diameter of pump	100mm
Stroke length	400mm
Cadence	1 strokes / second
Diameter of the piston rod (minimum)	1.15mm
Minimum Weight of Counterbalance	67N

APPENDIX III: ABSTRACTION CALCULATIONS

Total Daily Livestock water requirement: 25 751l

Annual water requirement = $Total\ daily\ livestock\ requirement\ \times 12\ months$

= **9399115 litres**

$$Annual\ livestock\ Water\ requirement\ for\ the\ study\ Area = \frac{d}{e} \times f$$

Where:

d = length of river

e = length of the studied section

f = Annual water requirement for the study Area

Using the formula above the Annual livestock requirement = **213 047 859.9 litres**

$= \mathbf{213\ 048\ m^3}$

The total abstraction for domestic use was obtained using the formula below:

$$Daily\ water\ usage = Population\ \times daiy\ water\ usage\ per\ capita$$

: $= 32\ 674\ \times 20$

$= \mathbf{653\ 480\ litres}$

$$Annual\ Domestic\ water\ Demand = Daily\ Domestic\ Water\ Demand\ \times 365$$

$= 653\ 480\ \times 365$

$= \mathbf{238\ 520\ 200\ litres}$

$= \mathbf{238\ 520.2\ m^3}$

$\boldsymbol{Total\ Abstraction}$

$= Domestic\ water\ demand + Water\ for\ Irrigation + Livestock\ water\ supply$

$= 238\ 520.2 + 439\ 010 + 213\ 048$

$= \mathbf{890\ 578.2\ m^3}$

APPENDIX IV: PUMP COSTING

	Components	Materials	Unit of Measure	Quantity	Unit Costs	Total Costs (USD)
1	**Pump Body**	PVC Tees-plain	110mm	3	4.34	39.06
2		PVC Elbows – plain	110mm	5	2.05	51.10
3		VSP	110mm	1	6.05	6.05
4		MIFP	110mm	1	5.72	5.72
5		End Cap	110mm	1	6	6
6		PVC Reducer	100-50mm	1	1.50	1.50
7		PVC Pipe Class 16	110mm	5.55	10.73	59.55
8	**Pump handle and rods**	25mm Steam Pipe	m	2.95	7.75	7.75
9		40x40mm Square Bar	m	2.25	0.25	13.53
10		Pump Rod (12mm bright Steel)	m	1	0.90	0.90
11		Pivot rods	m	0.26	4.66	1.21
12		12mm Nyloc nuts	mm	2	0.09	0.18
13	**Pump frame**	Lynch Pins	no.	2	1.83	3.66
14		50x50x4mm angle iron	m	10	31.54	315.4
15		19mm Steam pipe	m	0.25	3.29	0.83
16		10mm round bar	m	0.9	7.75	7.75
17		16x45mm hex bolts and nuts	no.	4	0.86	3.44
18	**Pump Components**	Foot Valve	no.	2	6.27	12.57
19		Cup Seals	no.	6	1.47	8.82
20		Piston Body	no.	1	5.14	5.14
21		Dabane Well Point	no.	1	600	600
22	**Production Costs**	Fabrication , Production and Installation Costs				800
	Total					**1950.16**

APPENDIX V: COST-BENEFIT ANALYSIS

ITEM	VALUE	UNIT	ASSUMPTIONS & REFERENCES
Garden Size	750	m^2	Average garden size for small scale farmers in Shashani is 750m^2
Cabbage Plants per hectare	200	no	(Cervenski *et al*., 2018)
Total plant population per garden	1500	no	none
Selling price	0.5	$	Informal Interviews
Overhead expenses	0	$	The small-scale farmers are using local resources (manure, pesticides)
Total profit per season	750	$	
Approximate Payback Period	**3**	Farming Session	-Profitable season -Products are fully purchased in the market - People are buying from the source - They only plan to plant and sell cabbages only

APPENDIX VI: DISCHARGE MODELLING RESULTS

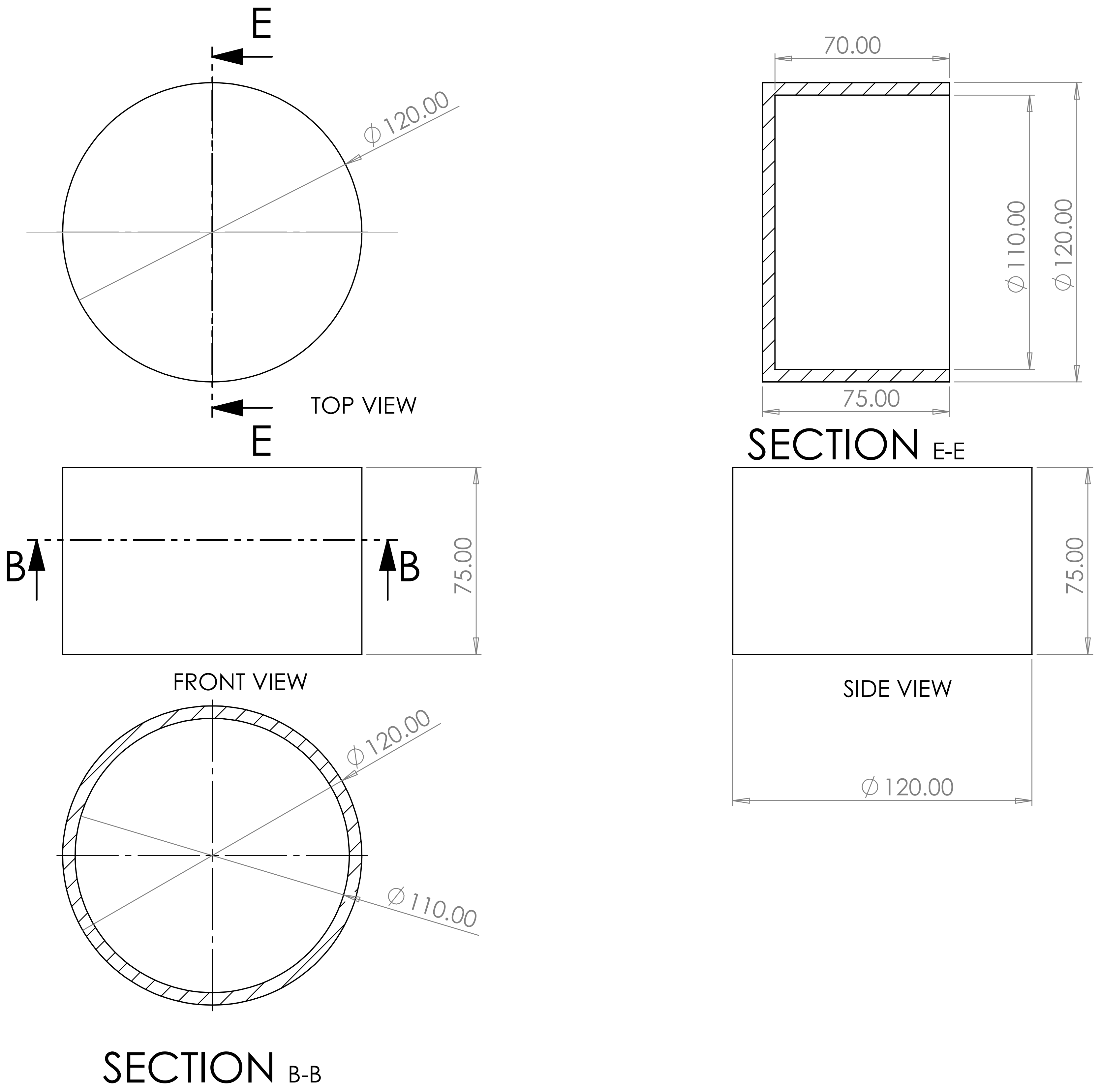
				Number of Strokes/minute																
Stroke Length	**Q/stroke(m3/s)**	**Discharge (l/s)**		**2**	**4**	**6**	**8**	**10**	**12**	**14**	**15**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**Max Hrly Discharge (litres)**
0.1	0.000785	0.785	**Cumulative Discharge per minute (l/s)**	1.57	3.14	4.71	6.28	7.85	9.42	10.99	11.775	12.56	14.13	15.7	17.27	18.84	20.41	21.98	23.55	**1413**
0.2	0.00157	1.57		3.14	6.28	9.42	12.56	15.7	18.84	21.98	23.55	25.12	28.26	31.4	34.54	37.68	40.82	43.96	47.1	**2826**
0.3	0.002355	2.355		4.71	9.42	14.13	18.84	23.55	28.26	32.97	35.325	37.68	33.27615	47.1	51.81	56.52	61.23	65.94	70.65	**4239**
0.4	0.00314	3.14		6.28	12.56	18.84	25.12	31.4	37.68	43.96	47.1	50.24	56.52	62.8	69.08	75.36	81.64	87.92	94.2	**5652**
0.5	0.003925	3.925		7.85	15.7	23.55	31.4	39.25	47.1	54.95	58.875	62.8	70.65	78.5	86.35	94.2	102.05	109.9	117.75	**7065**

APPENDIX VII: DESIGN CALCULATIONS AND ENGINEERING DRAWINGS

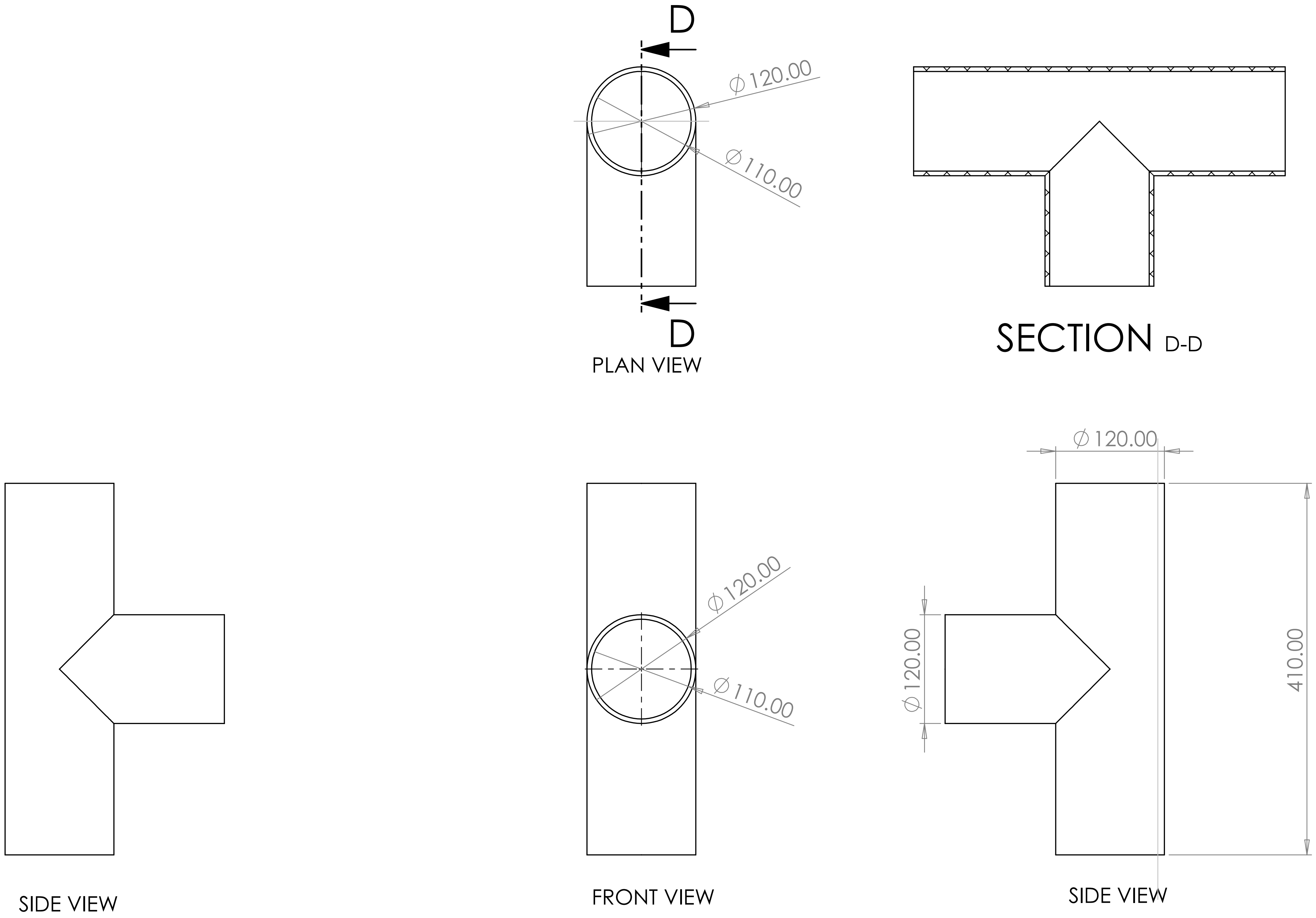
Source	Calculations	Output
	<u>Design of Piston Rod</u> $d_r = (\frac{4F}{\pi\sigma_a})^2$ Stroke Length = 0.4mm Pipe Diameter = 100mm **<u>Design Volume of Water per Stroke</u>** Design Volume = $\frac{\pi d^2}{4} \times$ Stroke Length $= \frac{\pi \times (0.1)^2 \times 0.5}{4}$ = <u>0.0039m^3/stroke</u> $d_r = (\frac{4 \times 39}{\pi \times 45})^2$ = **<u>1.28mm</u>** **<u>For usability and workability, the 12mm diameter steel rod was used for design</u>**	**<u>12mm Steel Rod</u>**

Source	Calculations	Output
	Design of Counterweight	
	Diameter of Piston = 100mm	
	Assumed Speed = 60 Strokes/min	
	Suction Head = 5m	
	Delivery Head = 2m	
	Efficiency of Pump = 50%	
	Design Volume of Water per Stroke	
	Design Volume = $\frac{\pi d^2}{4} \times$ Stroke Length	
	$= \frac{\pi \times (0.1)^2 \times 0.5}{4}$	
	= 0.0039m^3/stroke	
	Mass Flow Rate = 3.9kg/s	
	Weight Lifted per Stroke = **39N**	
	Calculation of Counterbalance Mass	
	C.B.M = $\frac{M_0 \times D_0}{D_b}$	
	Where:	
	M_0 = Mass to be lifted	
	D_0 = Length of Stroke	
	D_b = Length of lever	

Source	Calculations	Output
	Design of Counterweight C.B.M = $\frac{3.9\times10\times1}{0.3}$ = 130N = 13kg **Considering the Estimated 50% Efficiency of the Assembly** Counterweight = $\frac{13}{0.5}$ = **26kg** **30kg Counterweight was selected**	**30kg Counterweight**



CHINHOYI UNIVERSITY OF TECHNOLOGY **SCHOOL OF AGRICULTURAL SCIENCES AND TECH** **DEPARTMENT OF AGRICULTURE**	**TITLE:**	110 MM - END CAP	DETAILS:	110 MM - END CAP
	DRAWN BY:	TINASHE SHUMBA	MATERIAL	POLY-VINYL-CHLORIDE
	CHECKED BY :		SCALE:	1:100



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SCHOOL OF AGRICULTURAL SCIENCES AND TECH

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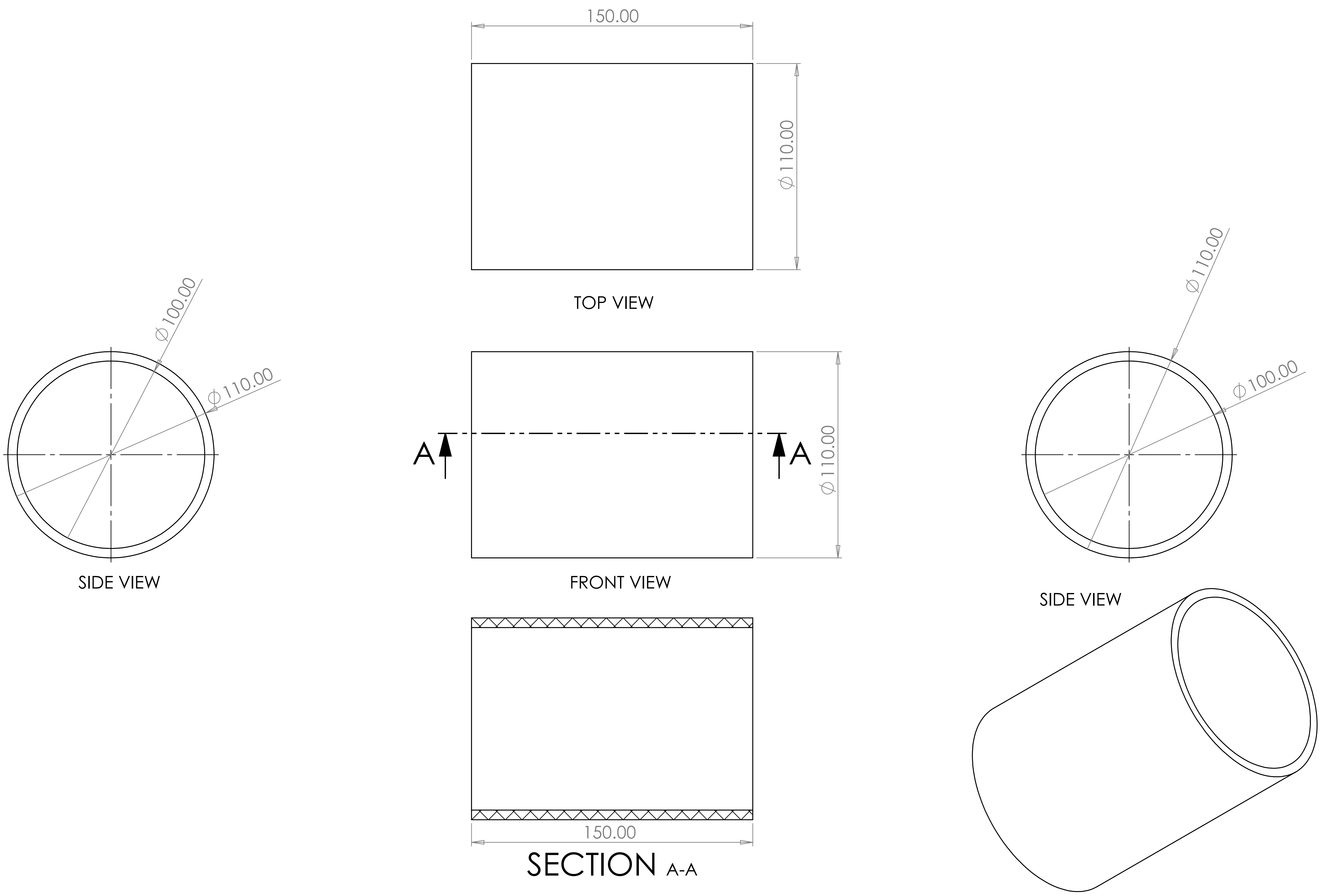
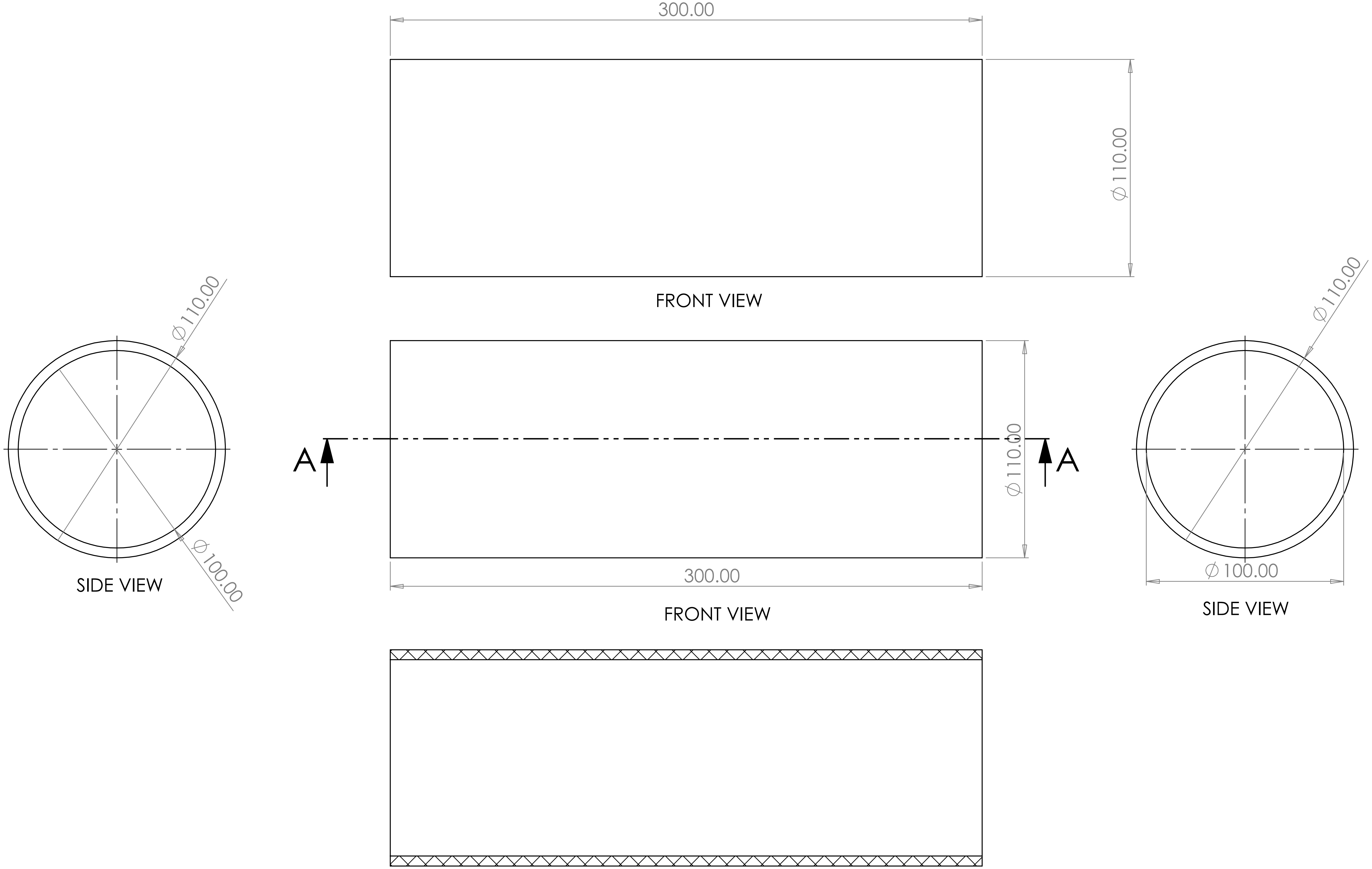
TITLE:	110 MM -EQUAL-TEE	DETAILS:	110 MM -EQUAL-TEE
DRAWN BY:	TINASHE SHUMBA	MATERIAL	PVC
CHECKED BY :		SCALE:	1:100



CHINHOYI UNIVERSITY OF TECHNOLOGY
SCHOOL OF AGRICULTURAL SCIENCES AND TECH
DEPARTMENT OF AGRICULTURE

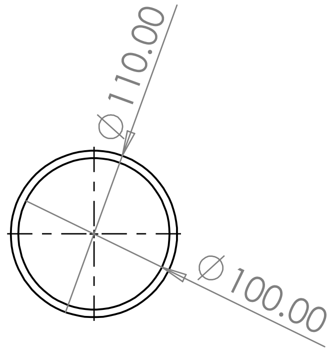
TITLE:	150 MM PVC PIPE	DETAILS:	150MM PVC PIPE
DRAWN BY:	TINASHE SHUMBA	MATERIAL	POLY-VINYL-CHLORIDE
CHECKED BY :		SCALE:	1:100



SECTION A-A

CHINHOYI UNIVERSITY OF TECHNOLOGY
SCHOOL OF AGRICULTURAL SCIENCES AND TECH
DEPARTMENT OF AGRICULTURE

TITLE:	300MM-PVC-PIPE	DETAILS:	300MM-PVC-PIPE
DRAWN BY:	TINASHE SHUMBA	MATERIAL	POLY-VINYL-CHLORIDE
CHECKED BY :		SCALE:	1:100



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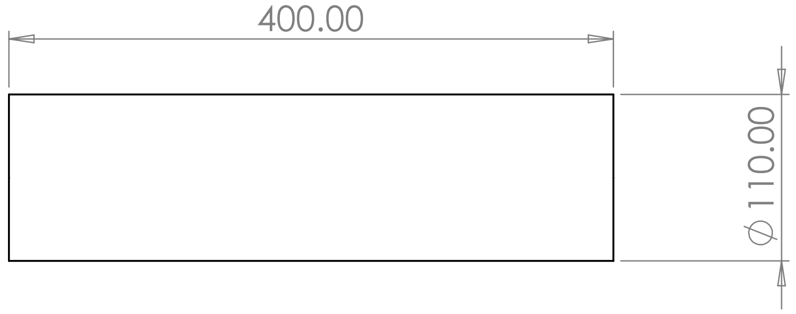
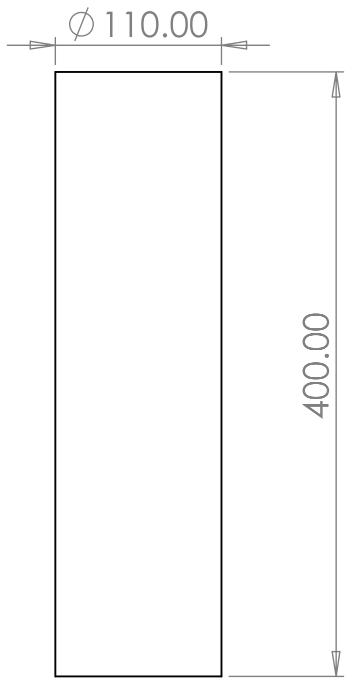
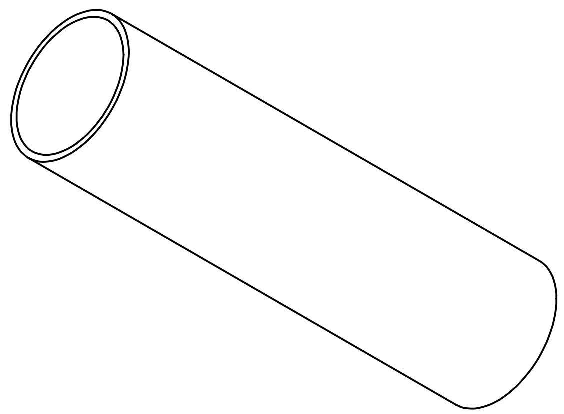


SIDE VIEW



BOTTOM VIEW



ISOMETRIC VIEW

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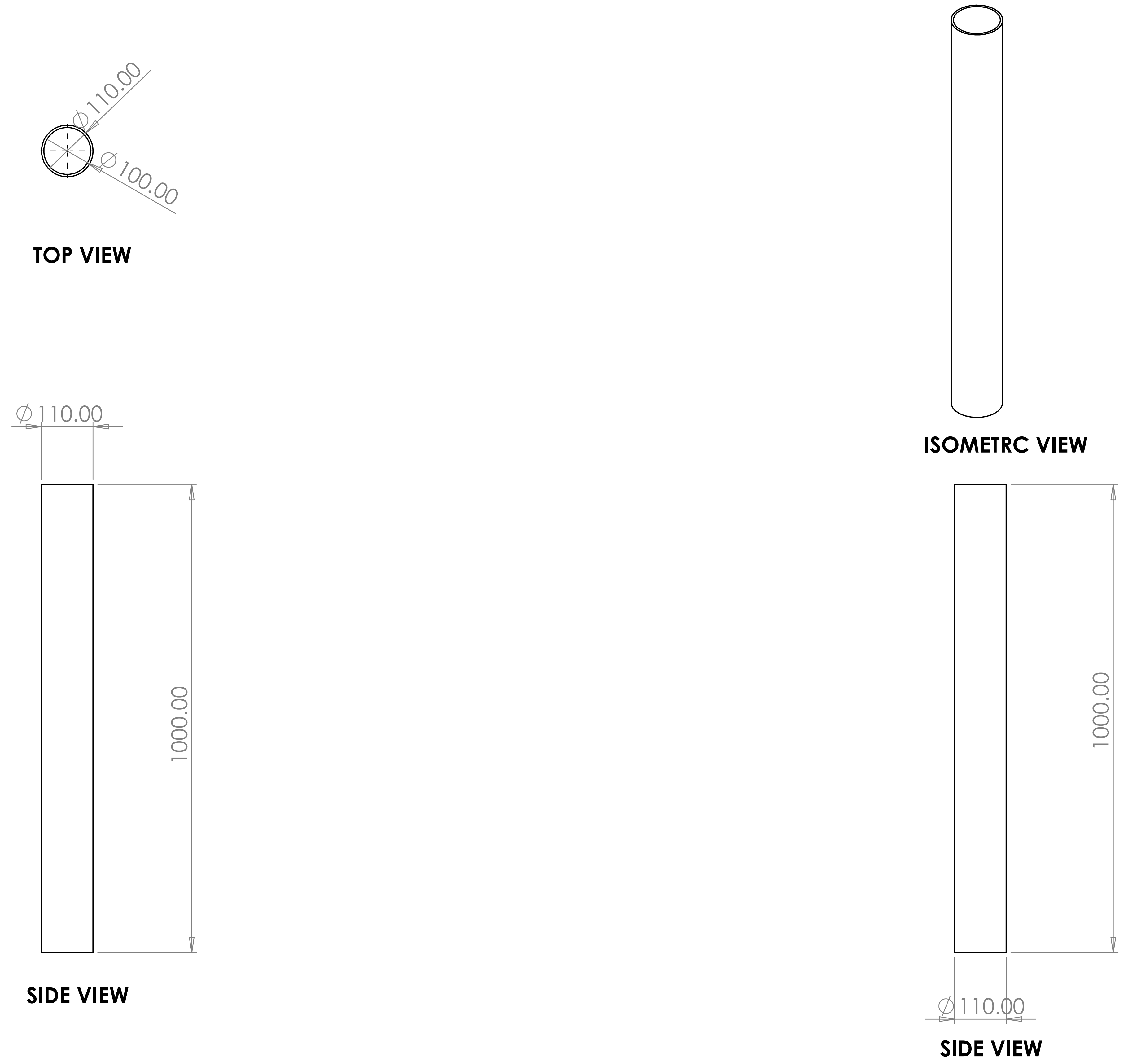
	DRAWN BY:	**TINASHE SHUMBA**	MATERIAL	**POLY-VINYL-CHLORIDE**
	CHECKED BY :		SCALE:	**1:100**



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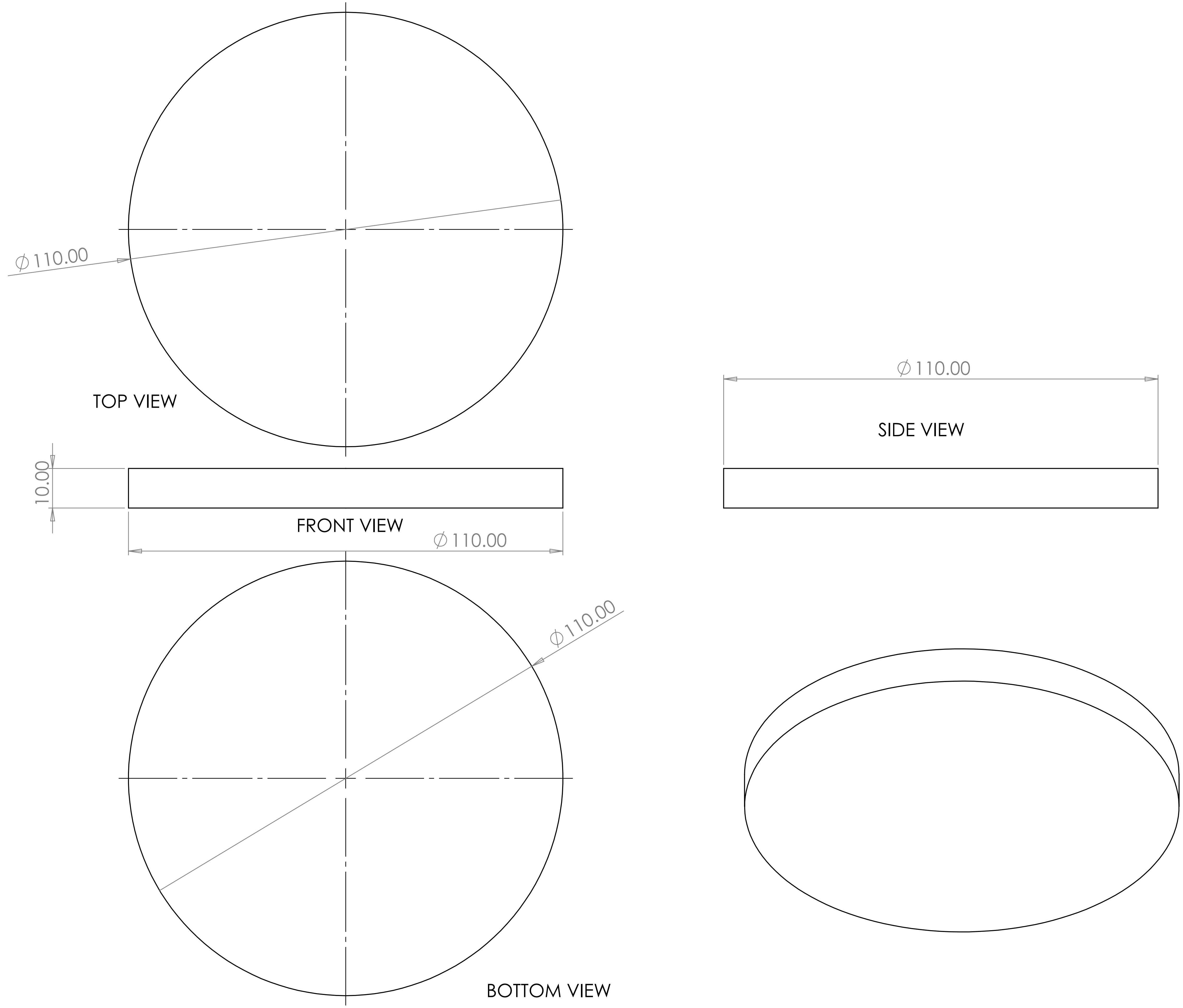
	DRAWN BY: **TINASHE SHUMBA**	MATERIAL **POLY-VINYL-CHLORIDE**
	CHECKED BY :	SCALE: **1:100**



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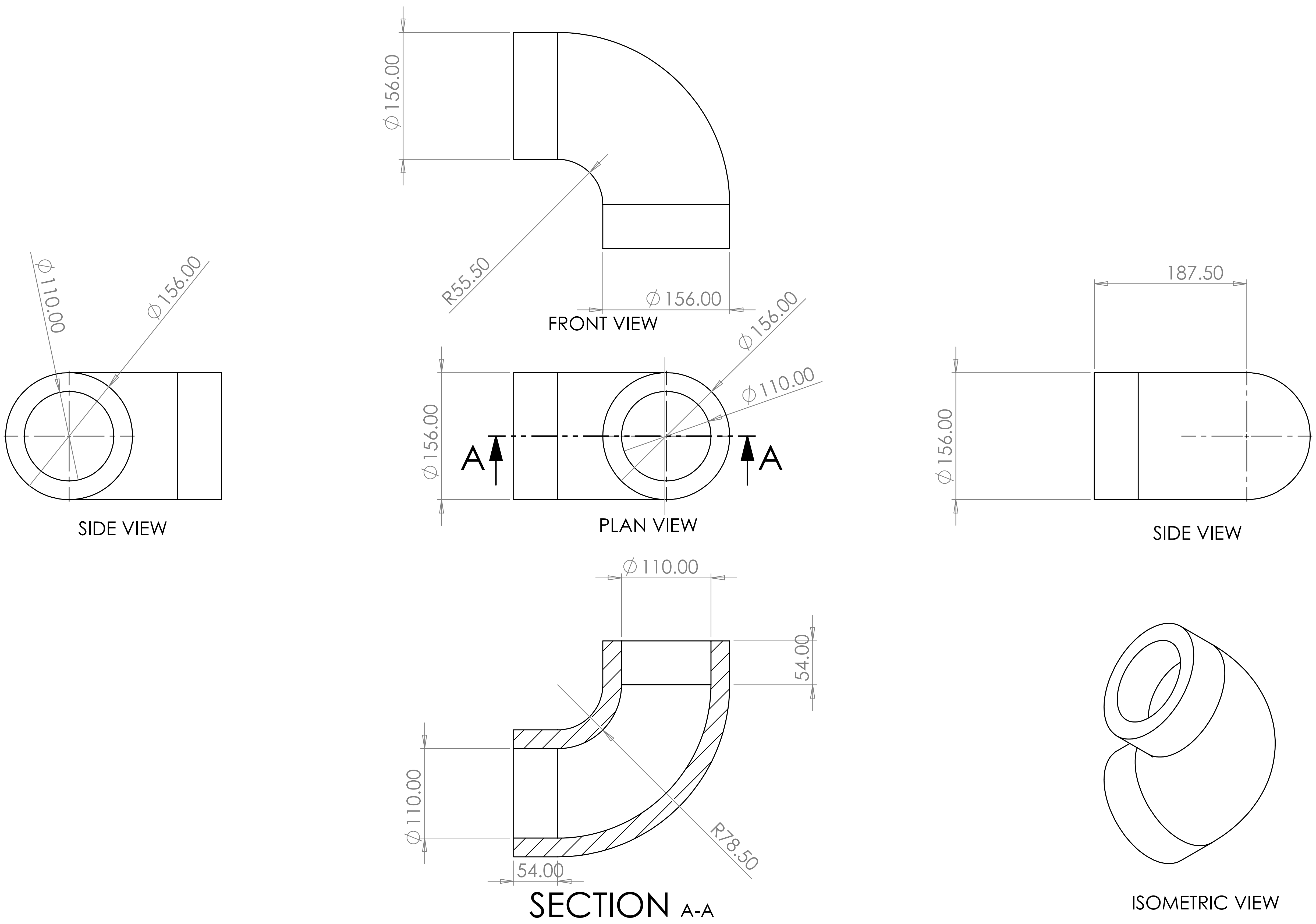
	DRAWN BY: TINASHE SHUMBA	MATERIAL RUBBER
	CHECKED BY :	SCALE: 1:100



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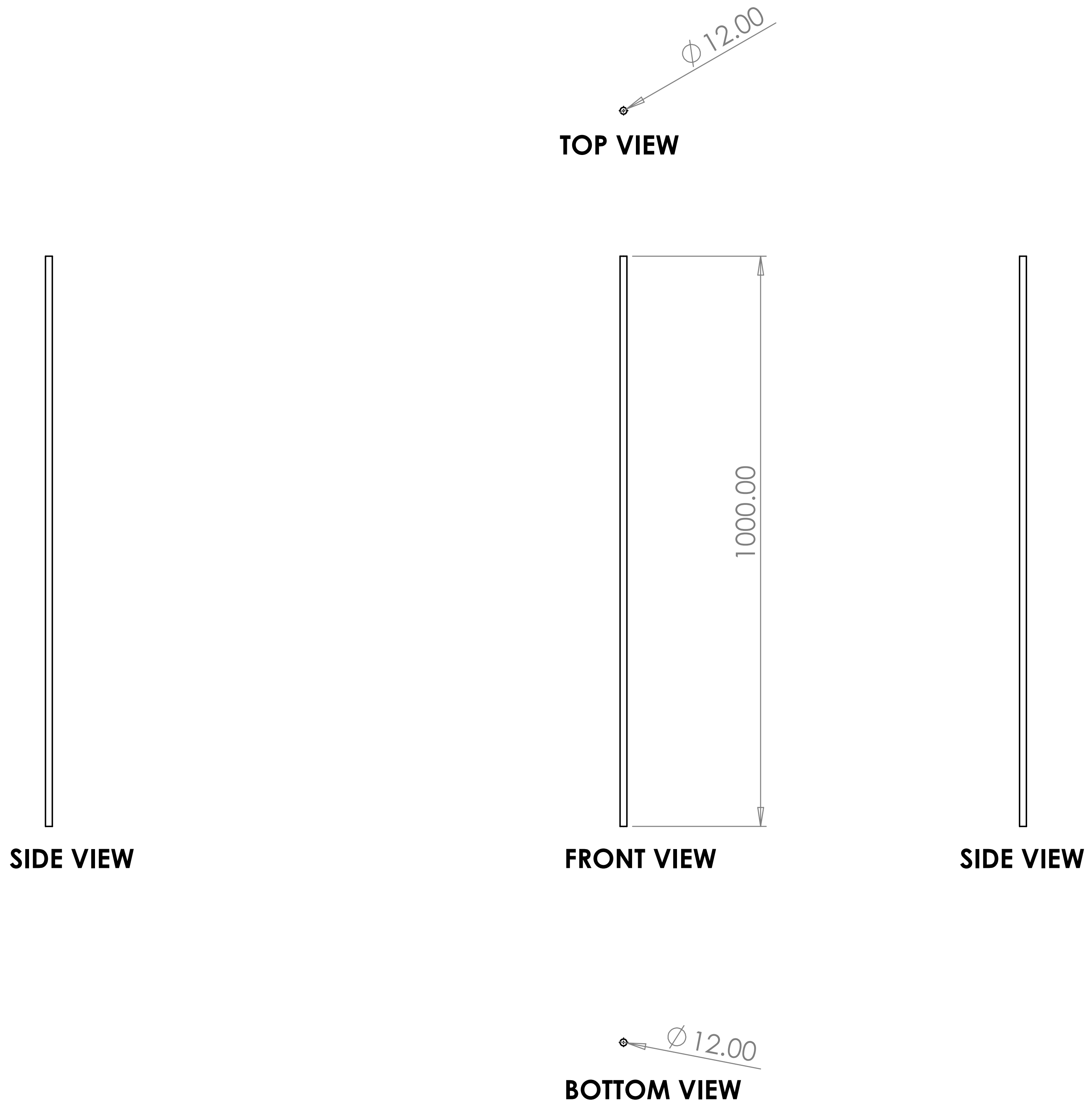
	CHECKED BY :		SCALE:	1:100



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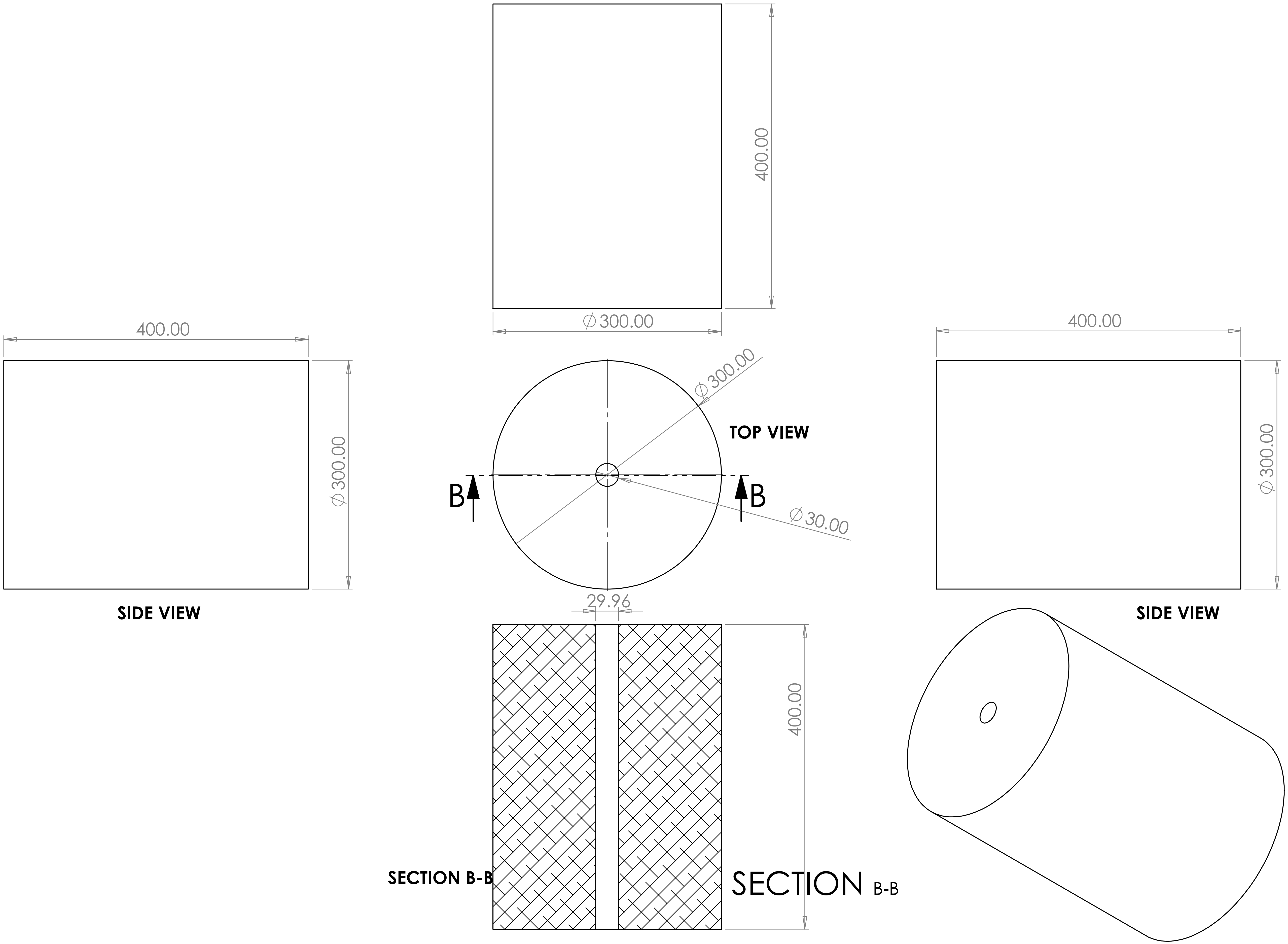
SCHOOL OF AGRICULTURAL SCIENCES AND TECH	DRAWN BY:	**TINASHE SHUMBA**	MATERIAL	**STEEL**
DEPARTMENT OF AGRICULTURE	CHECKED BY :		SCALE:	1:100



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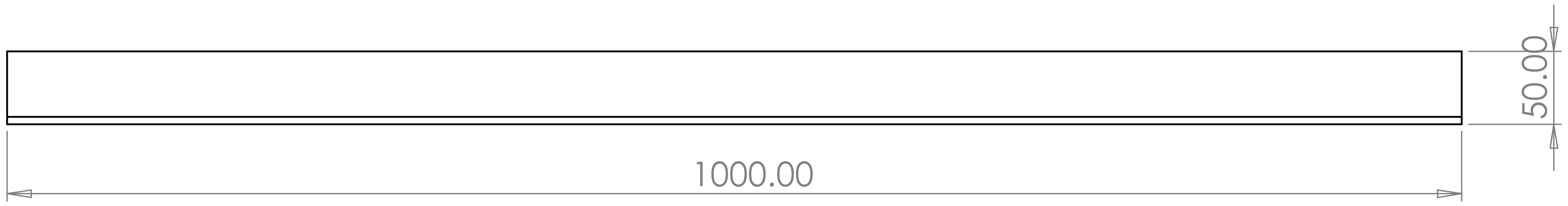
SCHOOL OF AGRICULTURAL SCIENCES AND TECH	DRAWN BY: **TINASHE SHUMBA**	MATERIAL **CONCRETE**
DEPARTMENT OF AGRICULTURE	CHECKED BY :	SCALE: **1:100**



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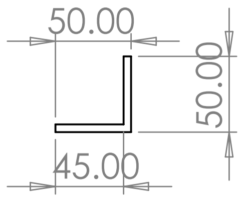

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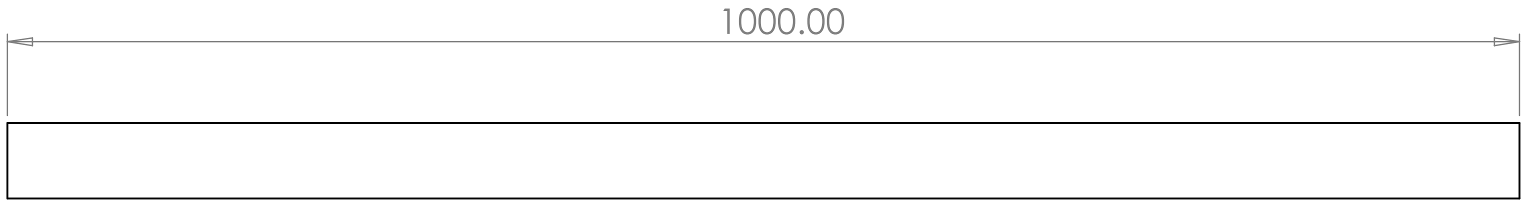
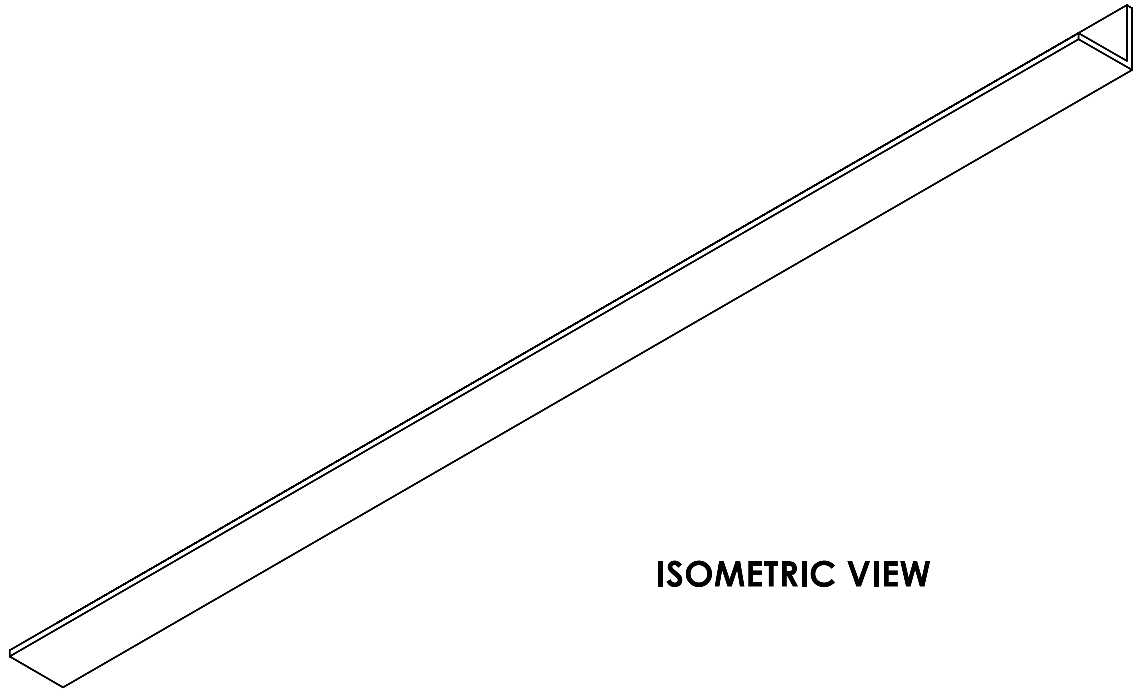


BACK VIEW



ISOMETRIC VIEW

1. All Dimensions are in mm
2. Drawings are for fabrication purposes

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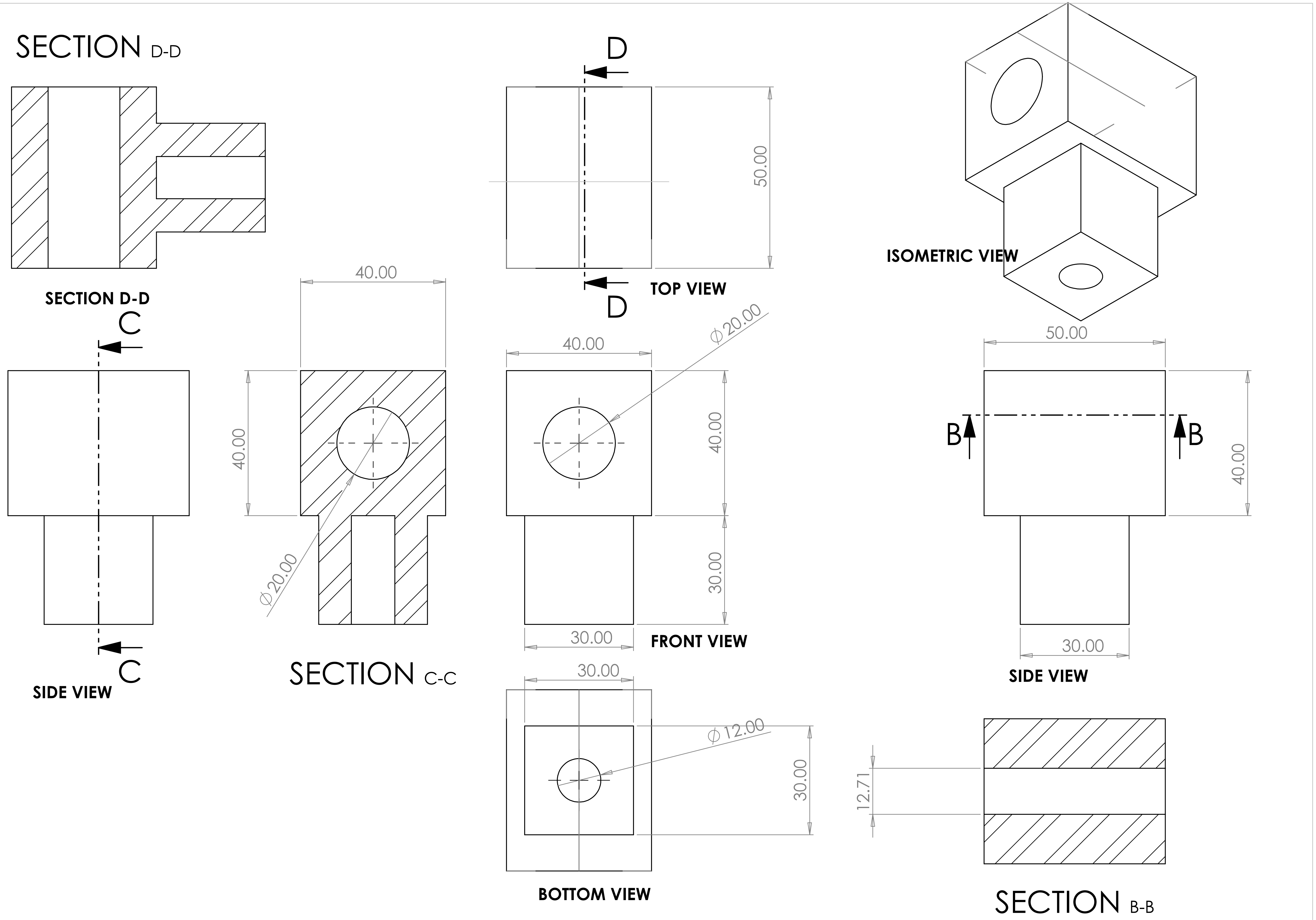
	DRAWN BY: TINASHE SHUMBA	MATERIAL : Steel
	CHECKED BY : P,RWAKATIWANA	SCALE: 1:100



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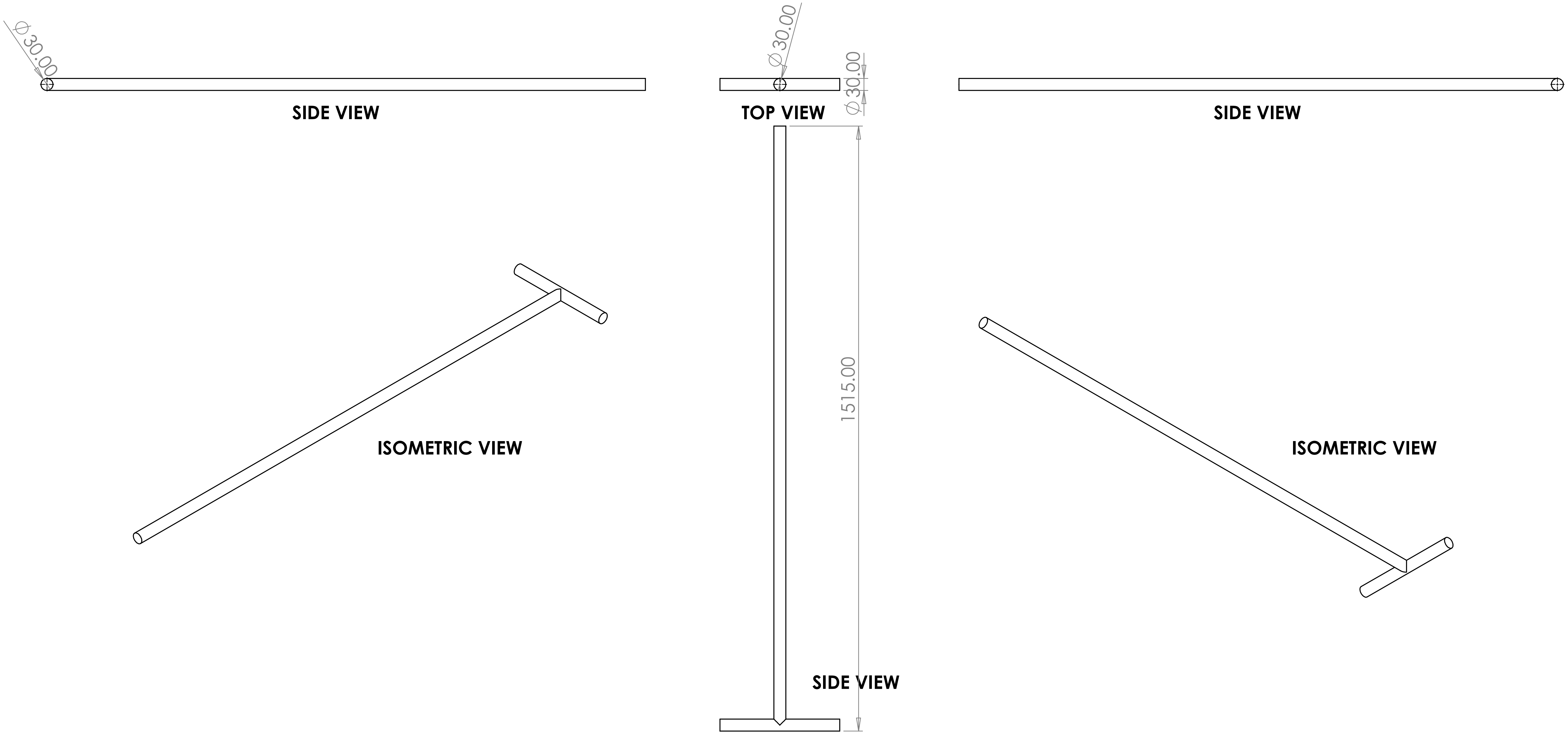
	DRAWN BY: **TINASHE**	MATERIAL **STEEL**
	CHECKED BY :	SCALE: **1:100**



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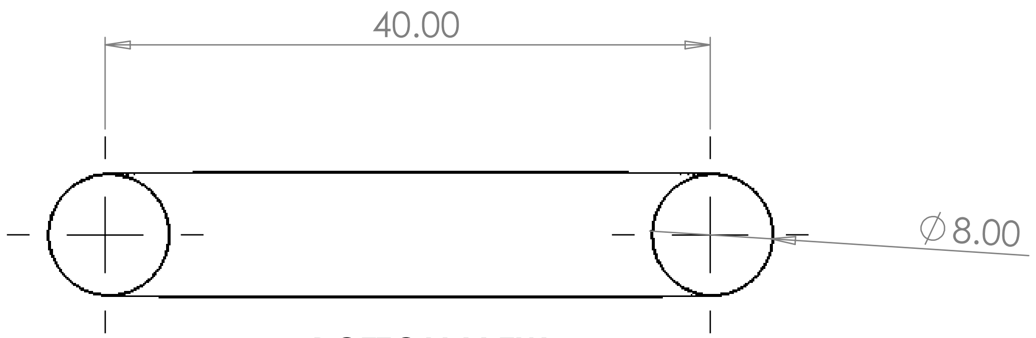
	DRAWN BY:	**TINASHE SHUMBA**	MATERIAL	**STEEL**
	CHECKED BY :		SCALE:	**1:100**



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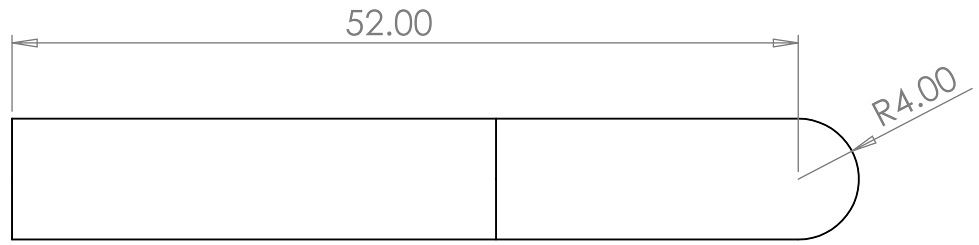
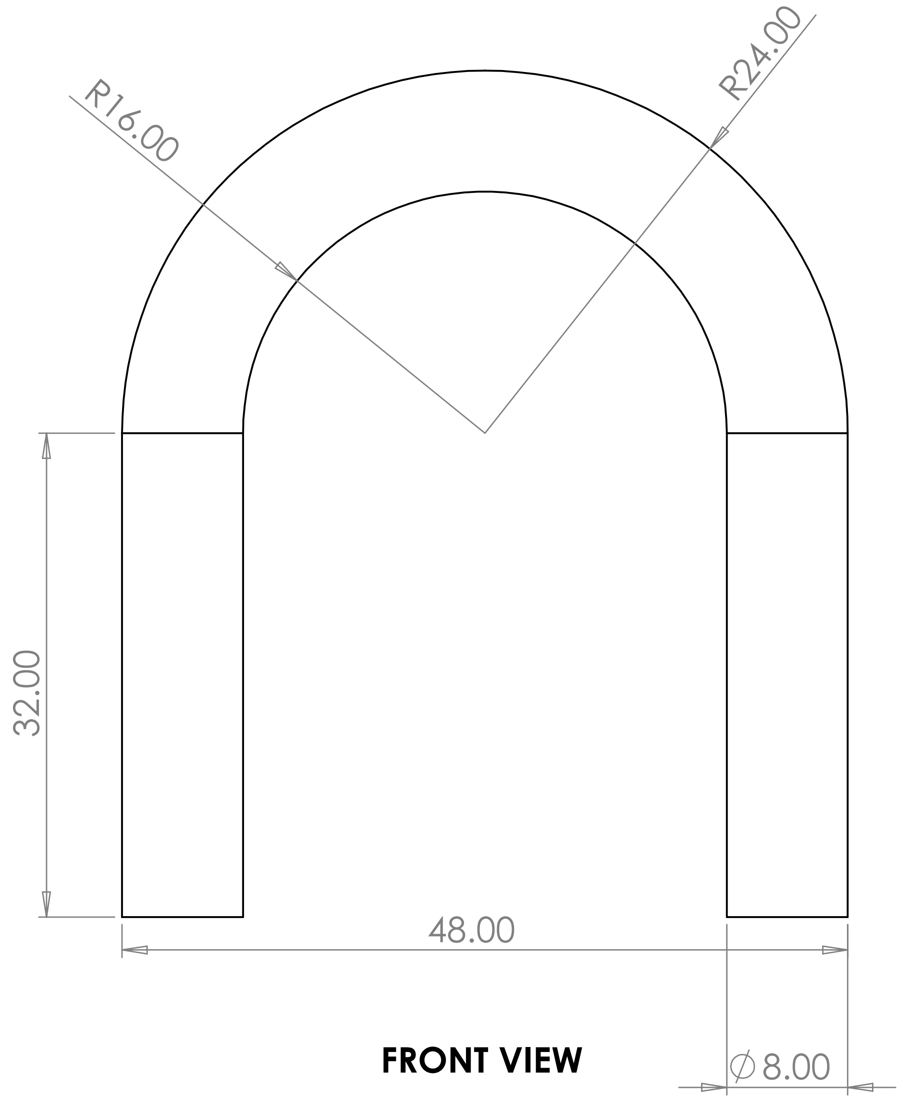
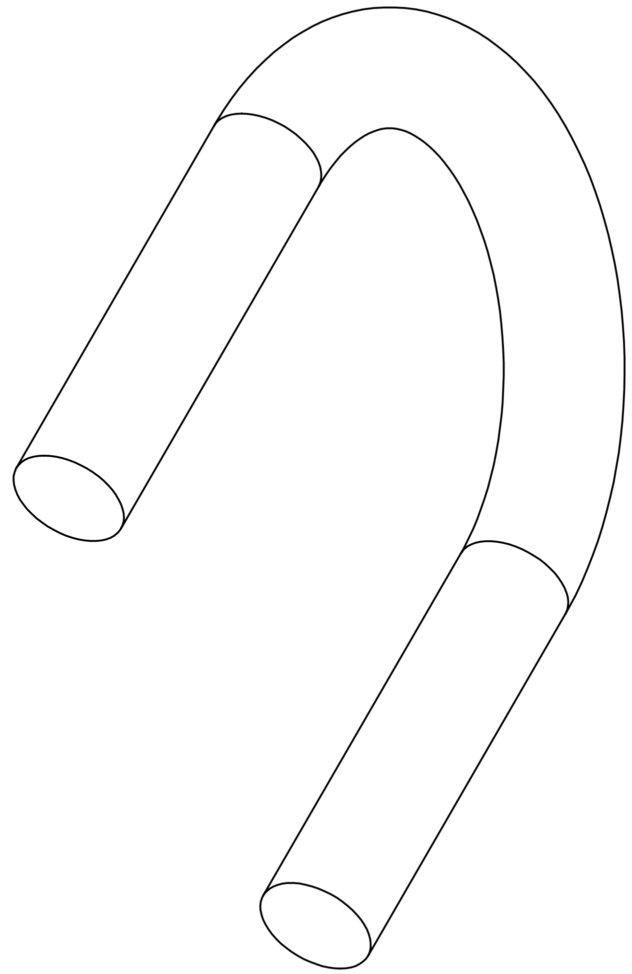


SIDE VIEW



FRONT VIEW



ISOMETRIC VIEW

CHINHOYI UNIVERSITY OF TECHNOLOGY **SCHOOL OF AGRICULTURAL SCIENCES AND TECH** **DEPARTMENT OF AGRICULTURE**	TITLE:	**U-BOLT**	DETAILS:	**U-BOLT TO HOLD ROWING BAR IN PLACE**
	DRAWN BY:	**TINASHE SHUMBA**	MATERIAL	**STEEL**
	CHECKED BY :		SCALE:	**1:100**

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