BOTSWANA UNIVERSITY OF
AGRICULTURE AND NATURAL RESOURCES

DESIGN AND DEVELOPMENT OF A BOREHOLE PUMPING AND WATER LEVEL MONITORING CONTROL SYSTEM IN BOTSWANA

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DECLARATION

I declare that the thesis has been composed by me and that the work has not been submitted for any other degree or professional qualification.

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DEDICATION

To my Fiancé, Evan Murimi, your trust, patience and unconditional love are cherished.

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ABSTRACT

Botswana experiences recurrent droughts and has limited surface water resources with the average annual rainfall varying from a minimum of less than 250 mm in the Southwest region and a maximum of about 650 mm in the Northeast area, which is below the world's average. Day time temperatures are very high, with a maximum of 43.9^{o}C, resulting in high average annual evaporation rates of up to 2000 mm. Globally, the agricultural sector is the main water user, with irrigation subsector accounting for most of it. Botswana, however, has a slightly different situation where the livestock subsector accounts for about 75% of agricultural water use. Most livestock farming takes place in rural areas, where water is normally pumped from boreholes and stored in storage tanks with no control automation. The same pumping-storage set up is also used to provide most rural areas with potable water for domestic use. Manual operation of these systems results in lots of water spillage from storage tanks and waste of energy involved in pumping. Such a scenario motivated the need to conduct a study where automatic water pumping and control system could be developed and be used to ensure that both water and energy are not only conserved but also used sustainably. In this regard, a study was undertaken to design, develop and test an automatic water level monitoring prototype with the ultimate aim of saving water and energy. The research further sought to determine the amount of water and energy savings that can be achieved through the use of such a system and also determine its economic viability. A prototype, typifying a Botswana rural farm, was developed following the engineering design process. Consequently, an arduino-controlled prototype consisting of a control unit, storage tanks and electrical energy supplies was assembled and tested. Magnetic float sensors were placed in tanks to measure the level of water and send the information to the arduino controller, which then made necessary decisions by sending an appropriate control signal to the pump through a relay switch. Tests carried out showed that the control prototype prevented overflow of water from the storage tank during a pumping process. Extrapolation on water and energy savings to the national level revealed that the automatic control system could potentially save 6,825,000 cubic metres of water and 3,627 MWh of electrical energy in a year. This translated to BWP 66,356,400 or USD 6,635,640 of annual monetary savings. When powered through solar energy, the system has been found to have a short payback period of about four years. The system is recommended for more extensive studies and tests in real farms in order to ascertain more accurately its merits and be ready for adoption by farmers in the country. Further, since the country has abundant solar energy with the annual average sunshine hours varying between 8.2 to 9.7 hours/day, the system would provide huge opportunities for sustainable use of both water and energy. This would then go a long way in improving the reliability of water supply, reducing greenhouse gas emissions from diesel-powered water pumping engines and consequently lower the overall farm operational cost.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background information

Water, the second most valuable natural resource following air, is vital for the existence of life on this planet and its depletion is a major concern in the current century (Sipes, 2010). About 71% of the earth's surface is covered by water but as Figure 1 shows, most of it is in places that are not easily accessible. For instance, about 96.5% is in the oceans and therefore unsuitable for daily domestic use (Gleick, 1993). With the world's growing population approximated at 9.4 billion people by 2050, it is a concern to scientists that current water reserves will not be enough to accommodate the water needs (Sipes, 2010). In response to the concerns mentioned, water wastage and conservation should be addressed comprehensively.

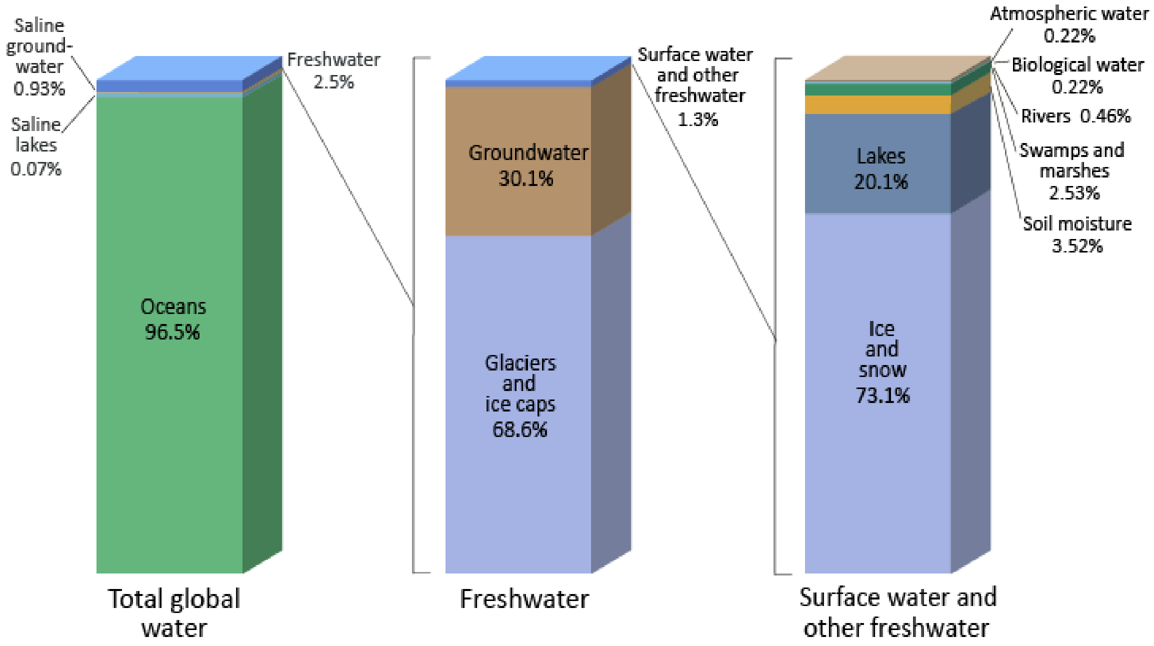


Figure 1: Water distribution on Earth (Gleick, 1993)

1.2 Water scarcity and governance in Botswana

Botswana’s climate is semi-arid as it remains dry for the major part of the year with a mean annual rainfall of 650 mm in the extreme Northeast and a minimum of less than 250 mm in the Southwest parts of the country (Bhalotra, 1984). It also experiences high evapotranspiration rates and poor groundwater recharge and yield (Bhalotra, 1984). This climate leads to limited stored surface and groundwater resources (Kumar, 2012), which is the main source of potable water supply in Botswana. Groundwater sources are indispensable to many individuals, companies and communities to supply water for mainly drinking, agriculture and sometimes industrial purposes.

Botswana Government estimates the demand will increase by 73.3% from 193.4 Mm^3/year in 2000 to 335.2 Mm^3/ year by 2020 (Swatuk & Rahm, 2004) and if the rate of groundwater extraction outweighs the rate of replenishment in the near future, then this finite resource will become non-renewable. With climate change causing progressive declines in rainfall, recharge rates are projected to be even lower (Department of Meteorological Services, 2009; Central Statistics Office, 2009), with some estimates further suggesting that groundwater could be exhausted by 2020 (Rahm, Swatuk, & Matheny, 2006). Despite the environmental constraints of climatically induced water scarcity and the inter-annual fluctuations which affect the natural freshwater supply, ways have to be found to improve quality of life and food security in Africa's semi-arid countries like Botswana (Jobson, 1999). One of the ways is to ensure institutional reform in water demand management and conservation.

Good governance is crucial to ensure a sustainable supply of water (Setlhogile & Harvey, 2015). In order to mitigate this life threatening disaster and ensure water security in Botswana, the government has prioritised dam construction, intra- and inter-basin transfer schemes and technological interventions, among other water conservation practices, to better utilize groundwater resources (Government of Botswana, 1992). In addition, the Government has come up with the National Water Master Plan which contains measures such as monitoring and evaluation of boreholes, aimed at conserving Botswana's water resources (Central Statistics Office, 2009). The two main legal mechanisms are the Water Act and Waterworks Act; and other legislations related to water resources include Aquatic Weeds Control Act Cap 34:04 and Public Health Act Cap 63:01 (Ministry of Minerals, Energy and Water Resources, 2012). The Water Utilities Cooperation (WUC) and Department of Water Affairs formulated initiatives which addressed issues that affected water resources in 2004 (Central Statistics Office, 2009). These included penalties and an increase in water charges; an effort meant to discourage the consumers from wasting water.

Despite the efforts to promote conservation, water losses and wastage is estimated at 46% (Ministry of Finance and Development Planning, 2010). The increasing demand for water has led to increased borehole sites across the country. Figure 2 shows the borehole water

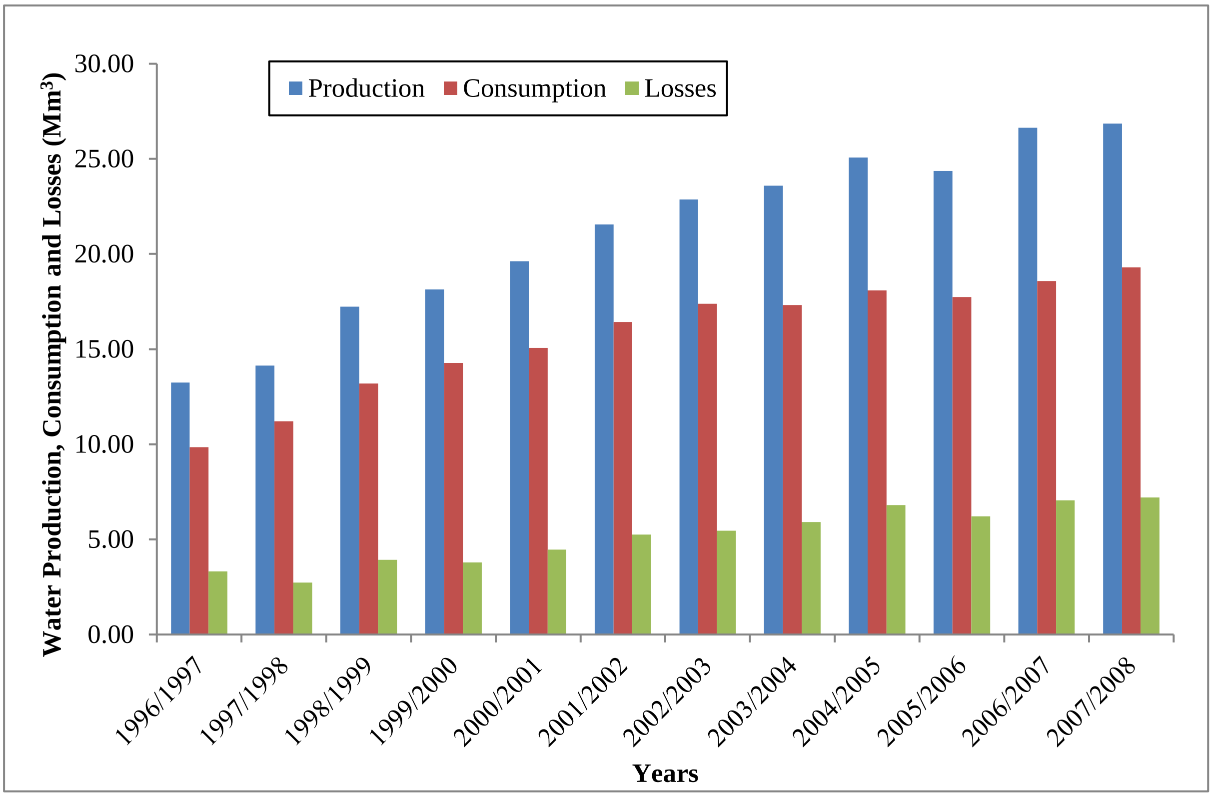


Figure 2: Borehole Water Abstraction, Consumption and Losses (m^3) for 17 major Villages in Botswana (1996/1997 to 2007/2008)-Source **(Central Statistics Office, 2009)**

production, consumption and water losses in the major villages in Botswana between the year 1996 and 2008. During this period, there was an increase in water abstraction from boreholes with proportionately increasing water losses due to inefficient water management. The Government aims to minimize these losses by monitoring the amount of water pumped from boreholes across the country and how it has been consumed (Centre for Applied Research, 2013). There is also a policy change moving away from supply to demand side management to minimize losses, increase efficiency and enhance conservation. Alternative strategies including incentives, regulations, tax rebate and targeted subsidies targeting water conservation should be considered (Arntzen, Masike, & Kgathi, 2000).

1.3 Water abstraction in Botswana

The term water abstraction defines the process by which water in its natural environment is artificially removed through the use of man-made structures or through the process of changing the flow of the water from its natural course to another course that the people in control of the diversion have set (Petts, 1996). Water abstraction dates back many centuries and can be achieved by various means, for various purposes. The way of abstraction depends on several variables that include the purpose for the abstraction, the location, the type of laws in place regarding the procedure, and the type of resources available for the extraction process.

In Botswana, the groundwater abstraction method commonly used is boreholes and wells from which water is pumped to the surface by mono or submersible pumps. There have been clear cases of groundwater over-abstraction due to high demand for this resource as illustrated in Table 1.

Table 1: Sustainable Groundwater Resource in Botswana (Source: Department of Water Affairs, 2015)

Wellfield	Available Developed resource (m^3/d)	Sustainable Resource (m^3/d)	Current Abstraction (m^3/d)	Annual Abstraction (Mm^3/y)
Dukwi	5700	600	6600	2.44
Mahalapye	7500	4000	4000	1.48
Ghanzi	1850	1850	1850	0.69
Kanye	3950	3950	6900	2.56
Letlhakane	1500	950	1500	0.56
Palapye	4000	2700	3200	1.19
Ramotswa	5000	5000	4000	1.48
Serowe	6200	3500	4500	1.67
Tsabong	2000	300	1600	0.59

For instance, the available developed water resources in Dukwi Wellfield are estimated at 5,700 m^3 per day as of 2008. The abstraction, on the other hand, was higher, estimated at 6600 m^3 per day in 2009 (Department of Water Affairs, 2015). The difference may have been inconsequential at that time, yet, predictions indicate that pumping at these high rates can be supported only up to 2020 (Central Statistics Office, 2009).

The factors to be considered when determining the sustainability of boreholes are porosity, permeability and the draw down in the well (Seward, Xu, & Brendonck, 2006). While porosity and permeability are limited by nature, the draw down can be maintained by avoiding over-abstraction and using a pump with a capacity that matches the borehole recharge rate. As seen from the above-mentioned causes of water scarcity, regulation is necessary to guide the abstraction of water through various sources due to the negative consequences associated with rampant removal or diversion of water. The impacts of over-abstraction and water table declines have been reported widely. It is important to note that over-abstraction can lead to various social, economic and environmental consequences. There can be critical changes in patterns of groundwater flow to and from adjacent aquifer systems (Hojjati & Boustani, 2010), and aquifer collapse due to reduction in pore pressure (Keqiang, Rulin, & Wenfu, 2010).

Besides, increased pumping head causes reduced pumping rates which implies that more pumping energy and associated cost are incurred. Over-abstraction also increases water insecurity in the agricultural sector, leading to food insecurity.

1.4 Causes of water scarcity and how to conserve it

Besides low annual rainfall and high evaporation rates, the country has one of the lowest storage capacities in dams due to its flat topography and sandy soil (Statistics Botswana, 2012). Several ways have been implemented to conserve water in Botswana. Water conservation methods used are discussed below.

1.4.1 Pollution prevention

The water we drink is essential for our wellbeing and a healthy life. During the last century, pollution of water has spread in large proportions estimated at 50%- 90% (Prager, 1993), due to increased toxic waste disposal resulting from increased economic activities and urbanization (Steiner, Martonakova, & Guziova, 2003). Large cities located on banks of rivers are directly disposing off different untreated wastes into such open water bodies. Likewise, tourism has increased pollution on lakes and sea coasts (Malik & Grohmann, 2011). This leaves humans to be greatly dependent on groundwater for their water related requirements, but still, some sources such as pit latrines, soak away pits and concentrated animal waste enclosures have also polluted this water.

In Botswana, causes of water pollution are mainly domestic, commercial and industrial waste mostly in urban areas where about 2.32 cubic m/person/year of waste is disposed (Kgosiesele & Zhaohui, 2010). These pollutants are either directly or indirectly discharged into water bodies without adequate treatment to remove harmful compounds causing environmental degradation. The polluted water can find its way to farms through irrigation. Groundwater on the other hand is polluted when water percolates to aquifers carrying farm chemicals and other pollutants with it (Mashhood & Arsalan, 2011). If water pollution is not prevented, soon there will be no fresh water for drinking or economic activities. The government of Botswana has put measures to help prevent water pollution through education and laws (Mogobe et al.,2014). For instance, the government acknowledges that some portion of pollution will occur synchronously with economic development; therefore it sets tradable pollution permits that will allow pollution within specific limits to tolerable change (United Nations Development Programme, 2012). Such a system has the benefit of motivating reduction in pollution as companies strive to make profits.

1.4.2 Population control

Water crisis in the world has assumed dangerous proportions due to fast increase in population, deterioration in measurable and qualitative aspects of water resources, expansion of industries and increasing urbanization. For instance, this demand increased 35 times from the year 1700 to the decade of 2000 (Easton, 2008). This crisis has been felt more in developing countries like Botswana (Central Statistics Office, 2009), where more people have moved into the cities and major settlements and the country has faced numerous droughts in the past.

Botswana's population may not be large compared to other countries in the world, with a population of about 2 million people as of 2011, projected to increase to 2.5 million by 2026. This population increase is expected to put pressure on the government to provide the required infrastructure such as housing, water and energy (Statistics Botswana, 2015). With Botswana being a drought prone country, the agricultural sector is largely affected by the climate. As of 2013, the livestock subsector had about 3.9 million livestock mainly consisting of cattle (2.1 million), goats (1.5 million) and sheep (0.3 million) (Statistics Botswana, 2013). A particular concern to Botswana is its heavy reliance on groundwater, estimated at 67% of water consumption, with most being used in the agricultural sector. In terms of economic benefits, the agricultural sector consumes most water and yet it contributes the least to the gross domestic product (GDP), BWP13/m^3, and employment at 2.2 jobs per 1000m^3 of water consumed in the country (WAVES & Department of Water Affairs, 2015). The demand for water is expected to increase with population increase and improving economic activity. Therefore, improving the efficiency of water in the agricultural sector as well as conservation is important for environmental benefit and lowering per capita consumption.

1.4.3 Increasing forest cover

According to the hydrological cycle, water is received through rainfall every year in different quantities on the surface of the earth, which then flows on the surface and reaches the seas and oceans. Some part of rainwater is stored in stable water reservoirs like lakes whereas some quantities of water infiltrate into the ground and percolates deeper into the underlying geologic formation to become part of groundwater (Naimpally & Rosselot, 2013). In the last century, most of the rainwater ran off to the saline seas without infiltrating into the ground due to increased deforestation.

In Botswana, the forest cover has been reduced from 24.2% in 1990 to 19.1% of the land area in 2015 (FAO, 2016). About two thirds of the country is covered by sandy soils which are infertile and have low water retention capacity (Government of Botswana, 2001). This combination coupled with low rainfall is not conducive because both factors do not favour water conservation, particularly groundwater which is widely used in Botswana (Bhalotra, 1984). Tree plantation should therefore be encouraged to increase forest cover that will help reduce surface runoff and also aid in the restoration of the hydrological cycle. Since trees withstand drought conditions for a long duration as compared to crops, more trees should be planted to help in reducing the demand for water especially during drought periods (Hudson, 1987).

1.4.4 Rational use of groundwater

Groundwater meets 25% of total supply of water in the world and the remaining 75% is supplied by surface water sources (United Nations Environment Programme, 2006). Demand for groundwater is increasing in Botswana while available quantity does not increase (Government of Botswana, 1992). This could partly be attributed to natural disasters like droughts. Since groundwater is recharged by surface water infiltration and subsequent deep percolation and thus takes a long time, groundwater exploitation should be in proportion to recharge rate. The major concern for Botswana is that, groundwater is increasingly becoming scarce due to low well yields of an average of $4m^3$/hour (Central Statistics Office, 2009), low recharge rates (4-20mm/year) (Center for Applied Research, 2005), water salinity that makes the water unsuitable for human consumption and farming (Masedi et al.,2000) and through losses. The exploitation should therefore be monitored to ensure no wastage occurs.

In Botswana, the highest proportion of groundwater is utilized in agriculture (Central Statistics Office, 2009), which was responsible for about 45% of the total water consumption. Within the agricultural sector, the livestock sub-sector uses about 55.6 Mm^3/year against irrigation's 18 Mm^3/year (Department of Water Affairs, 2015), (Central Statistics Office, 2009). The government views accounting for ground water, especially in the agricultural sector where water accounting has not been taking place, as a priority towards ensuring its sustainable use (WAVES & Department of Water Affairs, 2015). Further, introducing efficient and adequate integrated water management practices, groundwater can be equitably conserved. For instance, instead of growing crops of commercial importance requiring more water and irrigation, farmers should consider drought resistant crops and those that match Botswana's agricultural climatic conditions. Secondly, avoiding accidental water overflows at the borehole sites in farms will go a long way in conserving water as water loss is one of the major factors contributing to water crisis (Abrar & Patil, 2014). It is therefore important to educate people on the importance of conserving water, as well as use technology such as the automatic water management system in curbing water losses and accounting for water pumped from the borehole.

1.4.5 Modern water management technologies

In the agricultural sector, use of water for irrigation and livestock has raised extensive concern leading to development of various water management technologies (Department of Water Affairs, 2015). A variety of sensing and transmission technologies that support agricultural real-time information gathering, such as, online crop water monitoring and decision-making simulation of crop growth have been developed (Gunturi, 2013). Computer management systems enable the management of irrigation water change from static to dynamic usage (Schaible & Aillery, 2012). Water management has been transformed to comprehensive decision-making that combines database, model base, knowledge base and geographic information systems (GIS) (Schaible & Aillery, 2012).

Aside from irrigation technologies, there are modern technologies that have been proposed and can be adapted by the government and farmers to help curb the accidental and careless water losses accrued in the small scale farms and cattle posts in Botswana. In (Reza et al.,2010), a water level sensing and controlling system was designed, using a microcontroller and iron and steel rod as the sensor unit. The system mainly used mains electricity and the sensors used were also not very reliable. An automated water level management system using a similar approach but incorporating an alert trigger communication link that sends an SMS via GSM modem and a buzz to alert the user on the critical water states was developed by (Teo & Tiew, 2015). The two studies however, mainly focused on using mains electricity as the source of power. In a study by (Krieger & Mohankumar, 2014), solar power, which is more desirable for remote farmers who are not connected, to the grid was used. The aforementioned systems concentrate on tank water management systems. They are, however, not designed for managing water pumping in boreholes which should include means of detecting presence of water in the borehole before pumping. Therefore, a suitable control system is developed in this study to also monitor the borehole water levels as well as using solar energy that is abundant in Botswana.

In this study, a reliable, simple and economic automatic system that can be used to prevent overflows from storage tanks at the farms is proposed. The system is expected to control and monitor the water level of the storage tank continuously and ensure that sufficient level of water is maintained at all times. Further, the system will continuously monitor the presence of water in the borehole while immediately notifying the farm owner in case the borehole runs dry. This is important to avoid over-exploitation of the boreholes and also acts as a protective measure against dry running of the pump. The intention of the research was to establish a flexible, economical and an easy to configure system to help solve the issue of water losses for rural farmers.

1.5 Problem statement

Traditionally, management of water resources across Botswana has focused on the supply-side approach. Regular supplies of water have been ensured using a combination of reservoirs, inter-basin transfers and increasing abstraction of both surface water and groundwater (Ministry of Minerals, Energy and Water Resources, 2012; Government of Botswana, 1992). The nineteenth and twentieth centuries, for example, were characterised by a rapid growth in the number of boreholes with about 25,000 boreholes across the country presently, serving about 80% of humans and animals in Botswana (Department of Water Affairs, 2013). The traditionally skewed emphasis provided no incentive to limit water use in any sector, leaving the major driving forces of use unchanged. As a result, it has promoted the excessive abstraction currently observed in many parts of Botswana and the associated harm to the environment. Continued expansion of supply is not, therefore, a viable management option in future, particularly given the anticipated increase in the frequency and severity of droughts across Sub-Saharan African countries (Dungumaro & Madulu, 2003). Botswana requires a sustainable, demand-led approach to water resource management, focusing on conserving water and using it more efficiently. Central to this is a more justifiable approach to water abstraction that discourses not only the desires of contending economic sectors but also the basic freshwater ecosystems and the environment (Swatuk & Rahm, 2004).

The need for a more sustainable and integrated approach to managing water resources in Botswana is already reflected in water-related policy and legislation. The Botswana Integrated Water Resources Management and Water Efficiency (IWRMWE) plan advocates for minimized or zero water losses. On the contrary, herd boys employed to manage most farms in Botswana pump water from boreholes to overhead tanks leading to frequent water losses. Water flows by gravity from the overhead tanks to troughs where livestock drink from. The whole operation is manual inconveniencing the livestock where often times, they have to wait for water to be available, as opposed to taking ad-lib, negatively affecting their productivity. When pumping starts, the herdsmen have no way of detecting whether the storage tanks are full or not, and at times they have to wait for the animals to drink enough before switching off the pump. In other cases, they go to attend to other chores as water continues to pump and will only come back when they either finish or estimate that water is enough. This normally leads to overflows from the overhead storage tanks where float valves are not installed resulting into the loss of water, as well as associated energy, two crucial and scarce resources. It also consequently leads to increased operational cost of livestock farming. Water resources are limited and could constrain future economic growth if inefficiently stored, conveyed and utilised. Importantly, there is no legislation which governs self-supply, that is, farmers are not charged for the amount of water consumed from their boreholes, hence there is no water metering at the farms. Water accounting and sustainable water use is therefore imperative.

Achieving sustainable water resource management will require the implementation of a number of policies and practices, including water pricing, efficient use of water, raising awareness, tackling illegal water abstraction and use of modern technologies. Botswana and her leaders can play vital roles in maintaining necessary infrastructure, promote technological innovation and incentivise behavioural change (Ministry of Minerals, Energy and Water Resources, 2012). Conventional borehole sites and pumping systems in Botswana have no way of avoiding overflows from overhead tanks and over extraction of water. Therefore, a solution that allows livestock farmers to pump water from boreholes without wastage, as well as monitor their extraction is required. As such, this research seeks to come up with a feasible and affordable solution that increases water use efficiency, eliminates overflows and monitors the borehole. Further, such a technological breakthrough is expected to lower the operational cost of pumping water as well as the labour costs needed to operate and monitor the pump. The system will also ensure that boreholes are not over exploited in accordance with the government's groundwater conservation policy.

1.5.1 Criteria for success

For the automatic water monitoring system to be considered successful; the design must be low cost, safe, particularly with no contamination of water, simple to operate with minimum human effort, environmentally friendly, should be adaptable to different power sources, easy to learn, structurally robust, adaptable to the environmental factors and aesthetically pleasing.

1.6 Justification

Integrated water resources management (IWRM) is fairly widely practised in Botswana, but not yet formally elevated as the foundation of water resources management. This is primarily due to the fact that the Water Act of 1967 has not been revised since its enactment in 1968 and the 2012 National Water Policy draft awaits approval by Parliament. However, the review of the Botswana National Water Master Plan clearly identifies the need to adopt IWRM, especially to shift focus towards water demand management, as well as reuse and recycling of treated wastewater (Centre for Applied Research, 2013). The proposed shift is based on environmental (water scarcity) and economic (cost) reasons. Water scarcity and escalating water costs could threaten economic development and livelihoods.

Historically, there have been massive difficulties in developing sustainable water resource management models in remote native communities, particularly for projects that give residents equal control of the economic benefits of such initiatives. This problem has persisted despite increased government awareness campaigns and funding to support remote areas in recent times. Optimization of currently available water and use of improved technologies and devices to help reduce water wastage is crucial for continued competitiveness of livestock production and agriculture in general.

Most water losses that are accounted for in Botswana occur due to leakages along distribution lines (WAVES & Department of Water Affairs, 2015). However, water losses in farms using boreholes are not well documented. Future water resource management plans, built on better data, need to ensure that groundwater is sustainably utilised, managed and well accounted for.

Water management at farms with boreholes using technology, is a concept that is not widely practised in developing countries like Botswana. There is an urgent need to adopt these systems in farms in order to manage water scarcity concerns mentioned earlier. Use of technology enhances knowledge generation and facilitates proper documentation and sharing to the benefit of both the farmer and government (World Bank, 2017). Most private boreholes or self-providers obtain groundwater rights from the Water Apportionment Board (WAB) but the major issue of monitoring their abstraction is still difficult and inadequate (Central Statistics Office, 2009). This is a major gap in the country's water management system, as self-providers account for the bulk of the abstraction. In this regard, part of this study seeks to use technology to automatically control and monitor water abstraction from boreholes in the country. The automatic water management system also monitors and controls the level of water in overhead storage tanks thereby eliminating overflows and over exploitation of groundwater, while also achieving energy efficiency. The proposed system in this study can be adopted by Water Apportionment Board (WAB) and be used to help reduce water wastage by making it mandatory for borehole owners to install them. The system is a simple, low cost device that is suitable for rural farmers in Botswana.

Most farmers in Botswana are in rural areas where grid connectivity is still low (12%) (Bhattacharyya, 2012). This forces them to use diesel or petrol which has disadvantages such as, greenhouse gas emissions (International Business Publications, 2015) and poor profits due to fluctuation in prices as Botswana relies on importation of these products. With an average of 31 MJ/m^2 of solar irradiation in December to 16 MJ/m^2 in June (Luhanga & Nijegorodov, 1997) in Botswana, solar is a suitable alternative to diesel and petrol pumps as well as in areas not connected to the grid. The automatic system is therefore designed for use in both grid connected areas as well as for those remote areas that would use solar. Further, economic analysis through determination of the payback period of the solar powered automatic water management system powered was carried out to determine if it is viable to implement in Botswana.

1.7 Research question

The purpose of this research is to develop a water management system which will minimize water loss through overflows on small-scale agricultural farms in Botswana. The water management system is based on automatically operating the pump depending on water level in the overhead storage tank and the borehole. The operation is carried out by monitoring water levels using sensors in the borehole and overhead storage tank. In addition, the specific opportunities and challenges related to automatic water monitoring and management are determined. The research hypotheses for this study were as follows;

H_O: There is no difference in amount of water overflows when both automatic and manual pumping is used.

H_I: There is a significant reduction in water overflow when automatic pumping is used as compared to manual operation.

This research involved development of a laboratory prototype, design of the control system and testing the complete system. Further, solar was incorporated into the automatic system where further tests were carried out.

1.8 Scope of the study

1. Due to resource limitations, the study mainly focused on testing the developed prototype at a laboratory scale. The normal water storage tank and borehole were typified using smaller tanks placed at different elevations.
2. The water and energy savings calculations limited to borehole pumping. Therefore, the losses concerned are due to overflows at the pumping site.

1.9 Study objectives

1.9.1 Main objective

To improve water management strategy on a typical small-scale farm in Botswana by designing an automatic water pumping system with emphasis on saving water and energy.

1.9.2 Specific objectives

The specific objectives are threefold**:**

1. To design, assemble and test the automatic water level control prototype unit and its related interface circuits.

2. To determine the water and energy savings realised as a result of utilization of the prototype using both grid and solar energy.
3. To perform an economic analysis of the solar powered prototype with the aim of determining the economic suitability.

CHAPTER 2 LITERATURE REVIEW

2.1 Relevant information

Botswana's per capita water consumption is considered low and is estimated at 95 m^3 per person per annum, compared to Namibia's and South Africa's 144 m^3 and 412 m^3, respectively (Lange, Mungatana, & Hassan, 2007). The trends in overall water consumption have been increasing in major villages in Botswana due to the increasing population and economic activities (United Nations Development Programme, 2012). For instance, there was an upward trend from 150 Mm^3 in 1991/1992 financial year to 194 Mm^3 in 2011/2012 (Department of Water Affairs, 2015). The agricultural sector consumed 37.2% of water in 2003 (Hambira W. L., 2007), that increased to about 45% in 2014 (WAVES & Department of Water Affairs, 2015). The internally renewable fresh water resources, both surface and groundwater, within the SADC region in 2014 is shown in Table 2 (The World Bank, 2017).

Table 2: Availability of fresh water and consumption in SADC region

	Amount of fresh water resources (x10^9 m^3)	**Annual freshwater abstraction (%)**			
		Internal resources	**Agriculture**	**Industry**	**Domestic**
Angola	148	0.5	21	34	45
Botswana	2.4	8.1	41	18	41
Congo, Dem. Rep.	900	0.1	11	21	68
Lesotho	5.2	0.8	9	46	46
Madagascar	337	4.9	98	1	1
Malawi	16.1	8.4	86	4	11
Mauritius	2.8	26.4	68	3	30
Mozambique	100.3	0.9	78	3	19
Namibia	6.2	4.7	70	5	25
South Africa	44.8	34.6	63	10	27
Swaziland	2.6	39.5	97	1	2
Tanzania	84	6.2	89	0	10
Zambia	80.2	2	73	8	18
Zimbabwe	12.3	29.1	82	6	12

It is evident that Botswana has the least amount of available fresh water in comparison to her neighbours, while Democratic Republic of Congo has the most fresh water resources. Only Angola, Lesotho and Democratic Republic of Congo use less water for agriculture, as these countries have reliable rainfall. In the rest of the region, the agricultural sector takes most of the water with the highest consumption being in Madagascar at 98%.

Figure 3 shows the long term trend in water consumption by the livestock subsector over the period 1990-2015 in million cubic metres. Botswana’s water sources consist largely of surface water (in rivers, pans and dams of various sizes) and groundwater in aquifers some of which are of a fossil nature and therefore not rechargeable. Notably, Botswana has more than 25000 officially registered boreholes (Department of Water Affairs, 2013), whose distribution is shown in Figure 4.

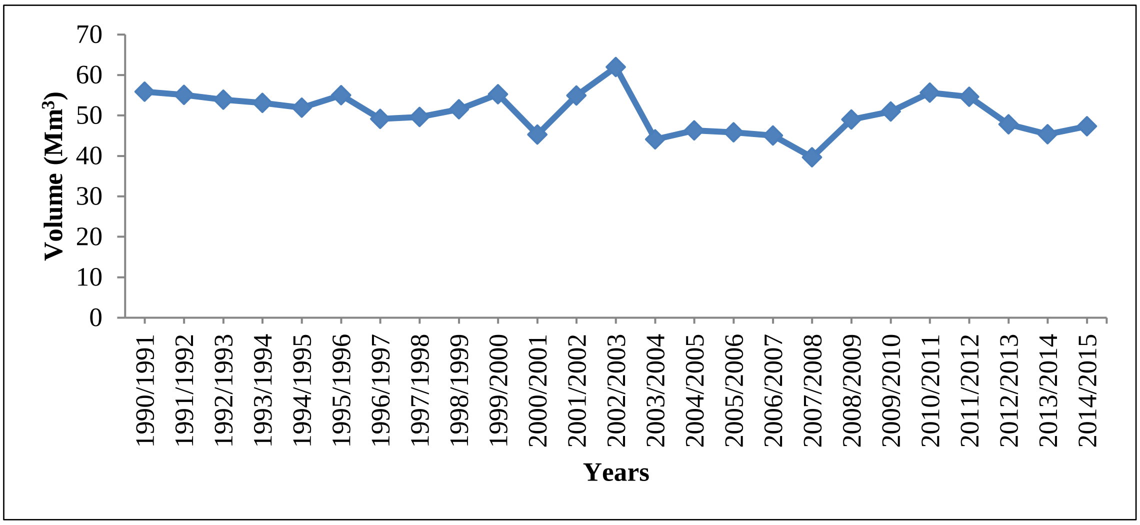


Figure 3: Trend in livestock water consumption (1990-2015) Mm3 (Center for Applied Research, 2015)

There were at least 21 major well fields providing groundwater in 2008 with several new others being developed (Central Statistics Office, 2009). Water yields from these well fields vary widely over the country with a large part of Botswana having poor to fair yields averaging 4 m^3/hour (Dietvorst, Vries, & Gieske, 1991). Botswana is a drought-prone country and the recharge rates of the boreholes drilled in the well fields are low. For example, the average

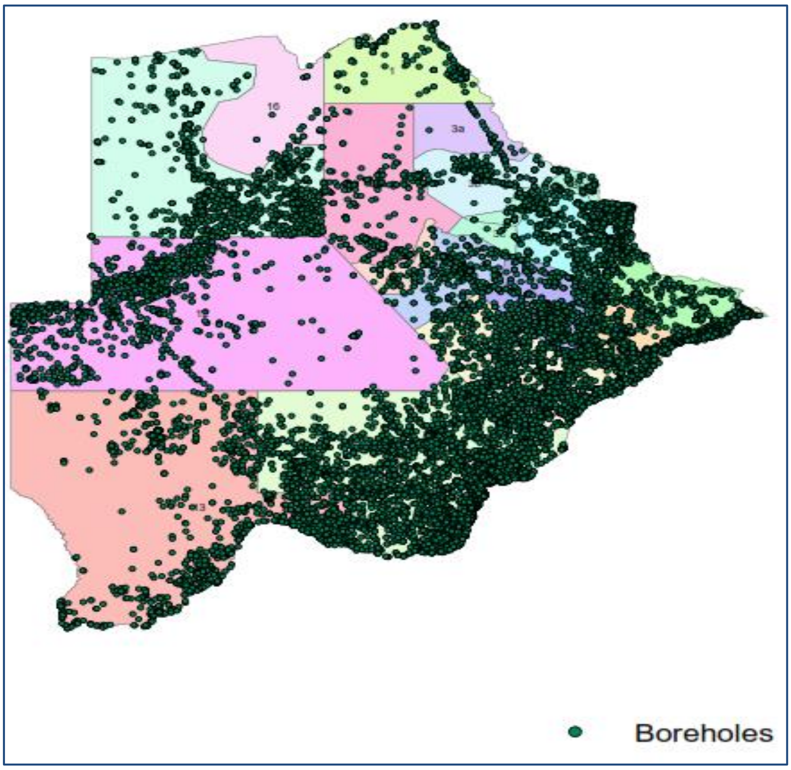


Figure 4: Borehole distribution in Botswana (Source: BUAN GIS Lab)

recharge rates are 1 mm/year for the northern region and 4-20 mm/year for the southern region (Center for Applied Research, 2005). The other major concerns of groundwater in Botswana include water salinity which is unsuitable for human and livestock consumption, low recoverable water proportion, groundwater mining and groundwater pollution (Masedi, Katai, Muzila, & Carlson, 2000). With increasing water demand from 193.4 Mm^3/year in 2000 to 335.2 Mm^3/ year by 2020 (Swatuk & Rahm, 2004), ways have to be established to conserve water and reduce wastage.

Water is a scarce and expensive resource that should be sustainably and efficiently used to ensure that the environment is protected while achieving sustainable development. In Botswana, groundwater is the main source of potable water supply with an estimated 80% of the human population and animals depending on it for drinking (Central Statistics Office, 2009), agriculture and industry (Moyo, O'Keefe, & Sill, 1993). The agricultural sector in Botswana consumes the highest amount of about 45% compared to mining and government sectors at 20% and 10%, respectively (Centre for Applied Research, 2013). Further, the livestock sub-sector uses about 55.6 Mm^3/year compared to 18 Mm^3/year used in irrigation (Department of Water Affairs, 2015).

Water loss is one of the major causes of water scarcity in Botswana (Arntzen, Masike, & Kgathi, 2000) and has a negative impact on the already-existing water crisis and national water security of the country (Eckardt et al.,2009). Borehole water demand and subsequent losses for major villages in Botswana between 1997 and 2008 is shown in Figure 5.

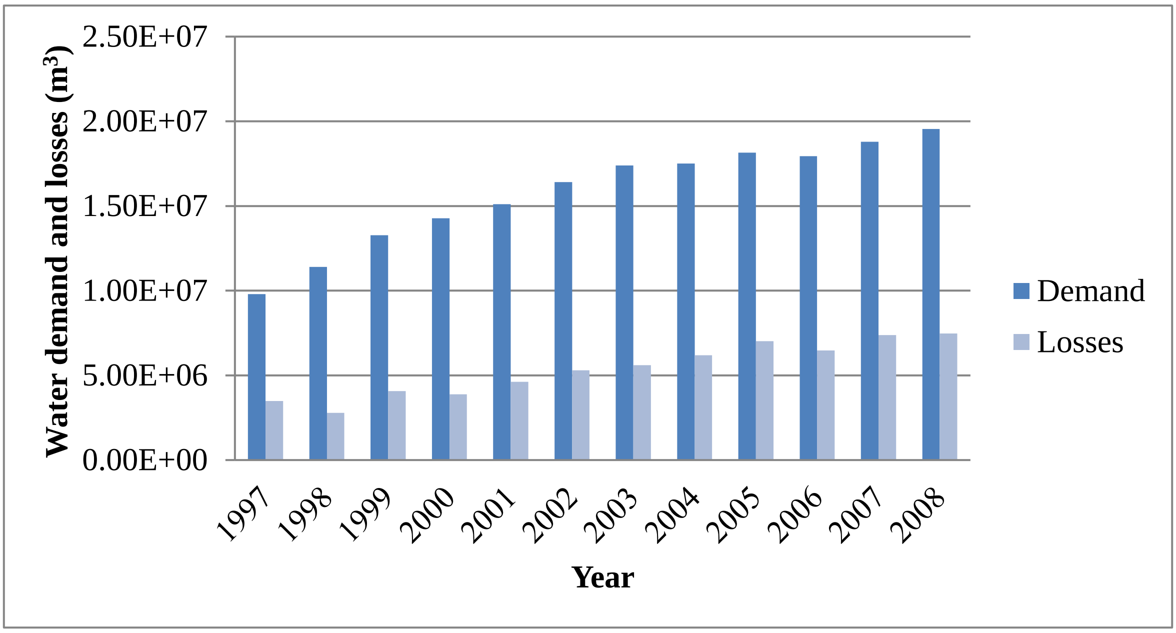


Figure 5: Average annual borehole water demand and losses (m3) for the 17 major villages in Botswana (1997-2008). Source: (Center for Applied Research, 2015)

Current abstraction from boreholes is unsustainable and therefore wastage should not be accommodated (Ministry of Finance and Development Planning, 2010). At the farms and cattle posts in rural areas where water is abstracted from boreholes, the major avenue through which this water is wasted is through overflow from (overhead) storage tanks followed by plumbing leaks. Figure 6 shows a typical case where water is wasted through overflows from the overhead storage tank as well as plumbing leaks in a farm in Gaborone. Considering that 2016 was a drought year as depicted by the dry vegetation of Figure 6, the green grass below the

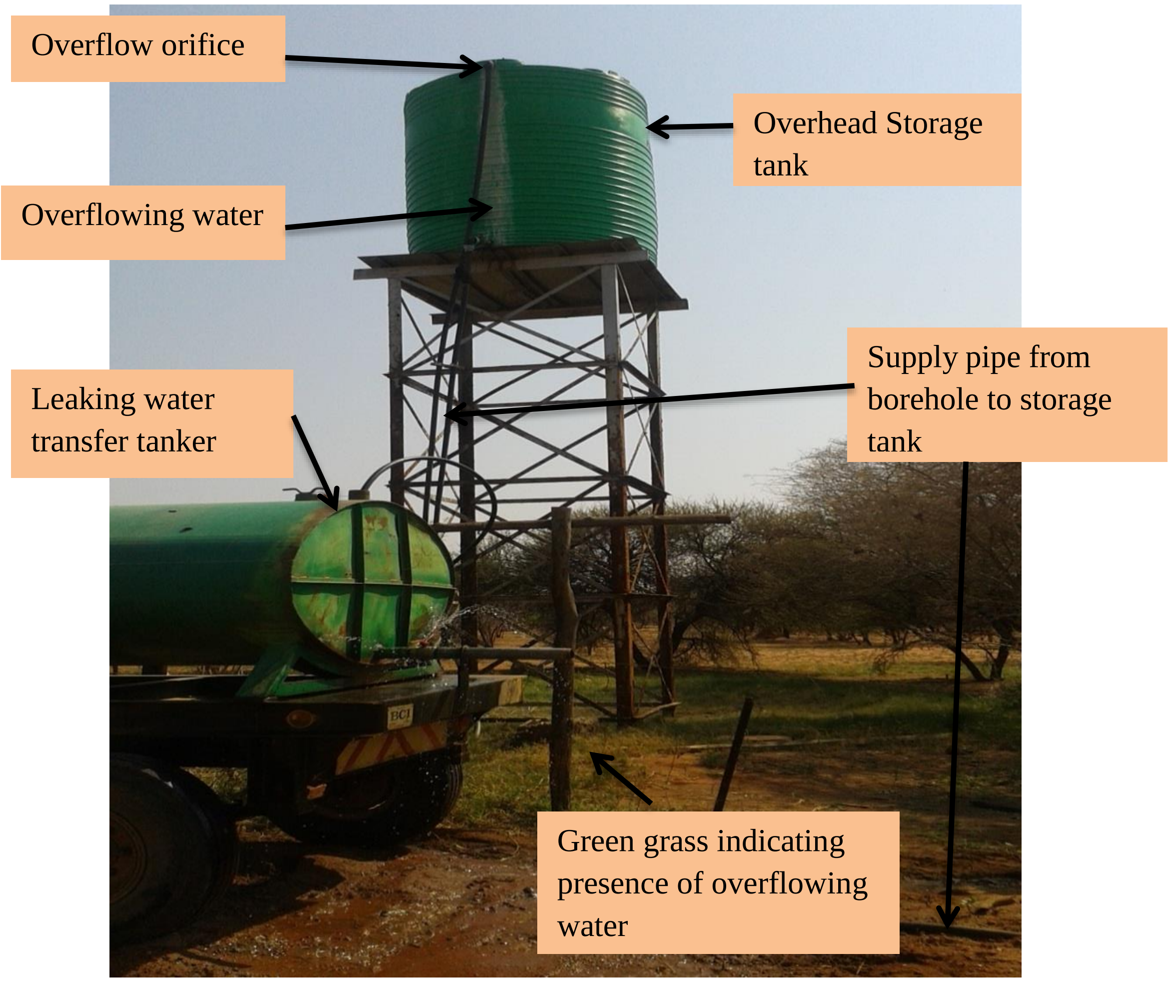


Figure 6: An example of water wastage due to overflow from overhead storage tank at Botswana University of Agriculture and Natural Resources (BUAN) farm

storage tank is evidence that water wastage has been taking place for a long time. This is against the Botswana government's policy to minimize or eliminate groundwater wastage.

Good governance is therefore needed to ensure sustainable supply of water in farms (Setlhogile & Harvey, 2015). The government of Botswana has planned to monitor the amount of water pumped from boreholes according to the Botswana National Water Policy in order to improve borehole water management (Centre for Applied Research, 2013). The National Water Master Plan Review in 2006 recommended that a series of institutional reforms were required within the water sector. Based on those recommendations, the Government of Botswana started a comprehensive effort in April 2008 to upgrade and extend water and wastewater services throughout the country (Ministry of Minerals, Energy and Water Resources, 2012). The use of improved technologies and devices that ensure that improved water use efficiency is achieved is of essence in both livestock and crop production (Government of Botswana, 1992). Further, behavioural change among farmers is important to minimize water wastage. In this regard, farmers in Botswana who efficiently and sustainably manage groundwater resources ought to receive incentives such as tax rebates from the government to encourage them to maintain the practice (Arntzen, Masike, & Kgathi, 2000).

Since overflow is the major cause of water wastage at the farms and cattle posts in Botswana, monitoring water level in storage tanks is an essential task to be done by the farmers and/or animal herdsmen. If incidences of water overflowing from storage tanks are allowed to continue unabated, they may result in reduced profits to the farmers as they lose money through diesel fuel cost for pumps, pump maintenance costs and increased labour costs. Operating diesel pumps, which are common in most farms and cattle posts, lead to continued greenhouse gas emissions which are known to contribute to climate change. The conventional method of managing water supply in farms and cattle posts in Botswana is to manually start the pump when water in the storage tank is at a low level and allow it to run until a higher water level is reached in the storage tank. The operators normally have no way of monitoring the level of water in the storage tank or knowing when it is full. Further, they normally go to carry out other chores in the farm while pumping is taking place resulting in water overflowing from storage tanks. In Botswana, livestock production is the major agricultural activity (Burgess, 2003) and water scarcity would directly result in food shortage due to livestock mortality. It is important to determine the volume and cost of water and energy lost in farms due to overflows so that farmers can understand the importance of saving water. One of the most effective solutions to minimizing losses is to use automatic pumping systems that will eliminate overflows.

2.2 Water management strategies

To sustainably meet water demand in Botswana farms, water demand management seeks to reduce the need to further expand existing supply infrastructure such as dams and boreholes. This can be achieved through non-conventional sources of water, water conservation technologies, reduction of losses and wastage, land-use planning, educational initiatives and water pricing (Segosebe & Parida, 2006). Non-conventional sources, such as water reuse and rain water harvesting, are measures on the supply side that increase supply of water without addressing water consumption behaviour. Furthermore, water reuse is still a challenge in the country as the general population is yet to accept it, and therefore, public educational initiatives are required. Water reuse could be useful in areas close to major urban centres. Rain water harvesting, on the other hand, is yet to confirm its reliability and cost effectiveness in the country, but a number of pilot projects are underway (Hambira, Moalafhi, & Mulale, 2011). Water pricing plays a crucial role in encouraging water conservation, but pricing in Botswana is applied uniformly across all consumers. This fails to capture the true value of the scarce resource and could indirectly encourage inefficiency (Hambira, Moalafhi, & Mulale, 2011).

Elimination of losses and wastage is one way of conserving water in farms that rely on boreholes. Globally, there are various technologies that are used in the agricultural sector and they fall in two broad categories. Water saving technologies maximize the use of available water consequently increasing productivity. There are also those technologies that make more water available such as storage to cope with seasonality. The use of any technology depends on local circumstances (UNCTAD, 2011). Water storage is known to have the greatest potential in improving water management. This technology has been exploited throughout history in form of dams, natural wetlands and subsurface storage accessible to plant roots, tanks and ponds. Water storage in tanks is generally a low cost option that is easily implementable by communities and individuals (McCartney & Smakhtin, 2010). Considering that most farmers and remote villages in Botswana rely on boreholes and wells for water supply, storage in overhead tanks has been useful for years. Just like water storage, there are various water lifting technologies available, mainly characterised by their energy source (Uhl et al., 2009).

2.2.1 Water lifting techniques and pumps

Human and animal powered water lifting devices have been used in various parts of the world. Though this form of energy is mostly used for surface water lifting, it has also been developed for lifting groundwater using rope and bucket, shallow well piston pump, treadle pump, rower as well as rope and washer pump. These water lifting devices have low flow rate, manually operated, labour intensive and are mostly suitable for shallow wells, with no overhead storage (The Schumacher Centre, 2008). In Botswana, groundwater aquifers are generally deep (Center for Applied Research, 2005), usually between 25 m and 125 m (Dietvorst, Vries, & Gieske, 1991). Numerous options exist for providing power to pump water from such deep wells and boreholes including; windmills, electric pumps, diesel pumps and solar pumps among others.

Pumps are essential in the water supply field, wooden pumps existed in the 1700s made from hollow logs with pistons made from wood too, to create suction and these were used to vacate the trash on ships (Oertling, 1996). In the early 1800s to mid, metal piston type pumps were developed and they were steam driven, but it was not till the introduction of electrically driven pumps that water system expansion became feasible on a large scale (Moyo et al., 1993). The first vertical turbine water pumps were developed by Layne Bowler in 1894 and first submersible pumps by Jacuzzi developed in the 1920s (Spann & Horgan, 2006).

Pumps move water by either by creating suction or by lifting water through the pipe. Suction pumps can only operate up to a depth of only 8 meters due to the limitations arising from atmospheric pressure. Beyond this depth, lift pumps must be used (Uhl et al., 2009). Pumps can generally be classified either as positive displacement pumps or variable displacement (kinetic) pumps. Positive displacement pumps discharge a fixed volume of water for each stroke or revolution while variable displacement pump discharges less water if the pumping head increases (US Department of Energy's Industrial Technologies Program, 2006).

Positive displacement pumps pressurize fluid with collapsing volume action. That is, squeezing a fixed amount of fluid with each stroke of the piston or shaft rotation. Reciprocating action pumps include use of pistons, plungers, diaphragms or bellows to lift water. Rotary action pumps use screws, internal gears, sliding vane, lobes or progressing cavities to lift water (Uhl et al., 2009).

Variable displacement pumps operate by adding kinetic energy to a fluid using a rotating impeller. This increase in kinetic energy is converted to a gain in potential energy (pressure) through Bernoulli’s principle. These pumps are more commonly used than positive displacement pumps as they are simple and safe to operate, require minimal maintenance and have long life cycle. Variable displacement pumps include radial, axial and mixed flow units. Radial flow pumps, also referred to as centrifugal pumps have the fluid entering along an axis, which is accelerated by the impeller to exit perpendicular to the shaft (radially). They generally operate at higher pressure and lower flow rates than axial or mixed-flow pumps. In axial-flow pumps, the fluid is pushed to move axially, operating at lower pressure and higher flow rate. Mixed-flow pumps are designed as a compromise between radial and axial-flow pumps (Garde, 1997).

2.2.2 Power supply

The power supply used to operate the pumps can be manual using humans or animals, or it can be converted from electricity, solar energy, and wind or from combustion of hydrocarbons. Manual pumping systems using humans or animals are slow and only suitable for shallow wells (Uhl et al., 2009).

Wind energy (windmill) have been used for centuries. The pumping system is attached to a windmill and lift water up to about 100 meters. Since wind may not be constant, water is normally pumped to a storage tank where it is stored for later use. This type of pumping system is suitable for regions with reliable wind (Baker, 2012). Windmills are rarely used in Botswana due to low prevailing wind conditions whereas a typical depth from which water must be lifted is quite deep. Actually, it is estimated that windmills may be economical in only 10% of Botswana’s rural areas (Bhalotra, 1984), while in many cases, wind energy serves as a secondary resource to diesel water pumps (Oladiran, 1995).

Diesel engines can be used to power pumps, mostly rotary or helical pumps that are submerged to the bottom of the wells. The pumps are driven by a drive belt or shaft connected to an engine on the surface. The drive belt or shaft is used to turn either an impeller or the screw of the pump (Uhl et al., 2009).

Electric power is normally used to drive motors that operate the pump. These pumps are located at the bottom of the well or borehole (submersible pumps), with the motor inside a waterproof casing that drives the impeller of the turbine pump. Electric power can be supplied from the grid lines, gas powered generators or solar panels. Although the government has a national electricity access target of 100% by 2030, national grid electrification in urban areas stands at 75% (Ketlogetswe, Mothudi, & Mothibi, 2007), while it is as low as 12% in rural areas (Bhattacharyya, 2012). Since many farms are in remote rural areas, the use of grid electricity to pump water is uneconomical due to high connectivity and operational cost (United Nations Development Programme, 2012). Farmers are therefore forced to use diesel or petrol-powered pumps. The use of these petroleum products to pump water is undesirable. First, Botswana relies on importation of these products exposing the agricultural sector to volatility in prices, which eventually affect the profits (Bruntrup, 2006). Secondly, the use of diesel or petrol water pumps increases Botswana’s greenhouse gas emissions which was at 2.32 metric tons per capita in 2011 (Braatz et al., 2013), and thirdly, the maintenance cost and repairs can be costly (Williams & Wilder, 1971). Solar panels, although expensive to buy and install, avoid the problem of fuel costs. They can either be connected to the pump or the power can be stored to a battery which is used to power the pump even when solar power is unavailable. Solar power is most cost effective in areas that are not connected to a power grid, and are otherwise forced to use gas powered generators (Uhl et., 2009). Table 3 shows the merits and demerits of each source of energy.

Table 3: Comparison of energy sources

Source	**Merits**	**Demerits**
Human	– Readily available resource	– Limited pumping capacity – Opportunity cost of work
Animals	– More powerful than humans – Lower wages than humans	– They require feeding – May be needed for other chores
Wind	– No fuel requirement – Low maintenance – Long life – Can be locally manufactured	– Water storage required when wind is low – High capital cost – Complex installation
Diesel or gas powered generator	– Quick and easy to install – Low capital cost – Can be portable	– Erratic fuel supply and prices – High maintenance cost – Short life expectancy – Noise and air pollution
Solar	– Unattended operation – Low maintenance – Easy installation – Long life	– High capital cost – Battery back-up recommended – Water storage required – Repair works require skilled personnel – Less power than diesel generators

Technical and economic suitability of renewable energy such as wind and solar mainly depend on conditions of the local environment. Windmills have been used to pump water for centuries and are mainly suitable in areas with persistent flow of wind (Baker, 2012). Solar power is suitable in remote areas with a high daily solar insolation and there is suitable land to mount the solar photovoltaic (PV) panels (Kelley et al., 2010). Botswana has a huge potential for solar energy as it has an excellent sun irradiation of over 3300 hours per year (Jain, Nijegorodov, & Kartha, 1994), with average daily solar radiation varying from 31 MJ/m^2 in December to 16 MJ/m^2 in June (Luhanga & Nijegorodov, 1997). The use of solar power has been proven as both economically and technically feasible in the agricultural sector (Kelley et al., 2010). Solar water pumping in remotely located farms provides the best opportunity for diversification of energy sources and reduction in the use of diesel and petrol (Hodgkin, McGowan, & White, 1987). It is not only environmentally friendly, but it also leads to lower operating and maintenance cost, as no fuel is transported to the pump station. However, in the solar energy sector, Botswana has only achieved 1% usage for agricultural use unlike diesel which is at 76% (Central Statistics Office, 2009).

2.2.3 Automatic control

Automatic control has been fundamental to the development of automation. Its origins lie in the ancient world of water level control, water clocks and pneumatics/hydraulics (Bissell, 2009). Automatic control can chronologically be divided into four main periods; early control (up to 1900), the pre-classical period (1900-1940), classical period (1935-1960) and modern control (post 1955) (Bennet, 1996).

Use of early control systems were preserved within Islamic culture in the Hellenic period. New inventions began to appear in the 18th century, such as float regulators in the tradition of Heron constructed in Baghdad in the ninth century AD. During the 19th century, a range of thermostatic devices were invented and sold (Bennet, 1996). They were mostly directly acting controllers; that is, the power required to operate the control actuator was drawn from the measuring system. Most of the inventions in this period conducted basic control activities such as controlling temperature, pressure, liquid levels and speed of rotating machines (Bissell, 2009).

During the pre-classical period, the early years of the 20th century saw rapid and widespread application of feedback controllers for voltage, current and frequency regulation. Applications included boiler control, electric motor speed control, ship and aircraft steering and auto-stabilization (Bandyopadhyay, 2002). The electronic negative feedback amplifier and pneumatic controller resulted from industrial problems (Bissell, 2009). More research was on going on analog calculating machines resulting in differential analyser that could simulate the behaviour of dynamic systems and obtaining numerical solutions to differential equations. It also led to the study of high performance of servomechanisms which provided the starting point for the next generation of control systems (Bennet, 1996).

During the classical period (1935 to 1950), advances in control systems sought to advance and design more complicated systems as well as theoretically understand these systems. A common terminology and design methods were developed through the formation of Industrial Instruments and Regulators committee that was the first body formed to specifically deal with automatic control in 1936 (Bennett, 1993). The Second World War demanded more complicated control systems such as aiming of anti-aircraft guns. The problem involved detection of position of aircraft, calculation of its future position, precise movement of a heavy gun and relaying of information from the radar devices to the gun controllers. By the end of the war, classical control techniques had been developed (Bennet, 1996). These designs were for linear single-input systems. However, there were still challenges on how to choose the control structure that would give the best performance and how to define best performance. Research on developing frequency response ideas and design methods continued throughout 1950s such as systems with nonlinearities (Bennett, 1993).

Although some modern control developments were influenced by findings during the war period, the rapid development of modern control was catapulted by two factors; first, governments needed to control the launch, manoeuvring, guidance and tracking of missiles and space vehicles and secondly, by the advent of digital computers (Ceruzzi, 2003). The first problem required detailed physical models in terms of differential equations, measuring instruments and other equipment of great accuracy and precision. Digital technologies led to replacement of servomechanisms that had been developed using analog computing. First digital control systems were supervisory systems in that individual loops were controlled by conventional electrical, pneumatic or hydraulic controlled but monitored and optimized by a computer (Bennet, 1996). In the second half of 1960s, specialized process control computers offered direct digital control (DDC) as well as supervisory control. Such computers were expensive and had programming problems (Bandyopadhyay, 2002). They were soon superseded by cheaper minicomputers in 1970s, and later the microcontroller had the greatest effect. Microprocessor-based digital controllers were compact, reliable and had a wide selection of control algorithms, ease of use of programming and diagnostic tools as well as good communication with supervisory computers (Ceruzzi, 2003). Another milestone was the development of programmable logic controllers (PLCs) in mid 1960s to replace individual relays. Digital computers have enabled the use of more advanced control techniques such as adaptive control, fuzzy control, optimal and robust techniques (Bennet, 1996).

Pumping and storing groundwater for use in farm and abundance of solar energy in Botswana form part of motivation for this research. Reduction of operation cost by automating the system thereby minimizing the labour cost and curbing wastage of water due to overflows forms further motivation for the research. Various control methods are applicable. Suitable microcontrollers that can be used include; PIC and Atmel microcontrollers (Reza, Tariq, & Reza, 2010). Other platforms include 555 timer (Boopathi, 2013), Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA) (Das et al.,2013) and arduino (Baraka et al.,2013), just to mention a few. Some of these platforms come with open source software which has become very important in engineering education in recent years. The choice depends on, among others, complexity, availability in local market, adaptability and compatibility to associated interface circuits. Among these platforms, arduino is highly regarded because of its adaptability and compatibility to different interface circuits, low cost and ease of programming. As a result, it was selected for use in this study.

The arduino is an open-source prototyping platform based on easy-to-use hardware and software. Arduino boards are able to read inputs and translate them into outputs. Its strengths are on the ease of programming as well as low cost of implementation with a free Integrated Development Environment (IDE) that runs on the computer (D'Ausilio, 2012). Further, the arduino is used for writing and uploading computer code onto the physical board. Arduino Uno, which is a microcontroller board based on the ATmega328 microcontroller (Blum, 2013), has 14 digital input/output pins, 6 analog input pins, a 16 MHz ceramic resonator, a USB connection, a power jack, an In-Circuit Serial Programming (ICSP) header and a reset button. It also has In-system programming (ISP), also called ICSP, which allows some programmable logic devices, microcontrollers, and other embedded devices to be programmed while installed in a complete system, rather than requiring the chip to be programmed prior to installation into the system.

2.3 Summary

Therefore, the need to autonomously manage the pumping process from boreholes while eliminating wastage of water and associated energy is the major motivation for this research. Most of the available technologies are expensive and complicated to implement. For instance, PLCs and SCADA systems are mainly suitable for complex process like manufacturing and large water systems. Most microcontrollers are not easily programmable, and they are also quite costly when the cost of associated electronics is taken into account. In this regard, the arduino controller is found suitable for autonomously managing the pumping process in boreholes. However, no research has been carried out on arduino-based water management systems incorporating renewable energy. This research therefore seeks to design, assemble and test a low cost automatic water pumping and water level monitoring prototype suitable for rural farmers in Botswana. The prototype could use either grid or solar energy.

CHAPTER 3 THE DESIGN PROCESS OF THE WATER PUMPING AND MONITORING PROTOTPYPE

3.1 The design process

The design process normally involves five basic steps; Problem definition, literature review and pertinent information, generation of multiple solutions available, analysis and selection of a solution and finally testing and evaluation of the chosen solution.

Prior to choosing the concept prototypes for an appropriate automatic water level controller, it was necessary to define the essential characteristics concerning the structure and functionalities of such system. To assist with the identification of these characteristics, a group of farmers that would be using the automatic system were identified and their perceptive needs were explored through administration of questionnaires. This led to formulation of the problem statement discussed in Section 1.5. The next step in the design process was to conduct an extensive literature review on existing systems available in the market or under development, which is discussed in Chapter 2. After enough information about the users and existing technologies had been acquired, a list of design features covering the requirements for an automatic water level monitoring system conceptual model was identified and described. The remaining steps in the design process are discussed in the following sections.

3.2 Multiple solutions

During the design process, investigation and analysis of various components required to design the automatic water level monitoring and control system was critical in coming out with a feasible solution. These components were classified as controllers, water level detection sensor and pumps.

3.2.1 Controllers

Various controllers can be used in level monitoring of water in various applications around the world. These controllers include;

3.2.1.1 PIC 16F84A microcontroller

Peripheral interface controller (PIC) is a family of RISC (Reduced instruction set computing) microcontrollers made by Microchip Technology. PIC was originally developed by General Instrument's Microelectronics Division as an integrated circuit meant to control peripheral devices and alleviating the load from the supervisory central processing unit (CPU) (Microchip, 2016).

Reza (2010) designed a water level sensing and controlling system using a PIC 16F84A microcontroller and iron and steel rod as the sensor unit. The intention of the research was to establish a flexible, economical and a system that is easy to configure to help solve the issue of water losses. The basic operation of the system was such that if there was no water in the reserve then the system switched off for a given time till the reserve had enough water again. If the sensors in the storage tank were in or out of contact with water, the input pins got signals and communicated to the PIC 16F84A to act accordingly by either stopping or starting to pump according to the programmed codes.

3.2.1.2 PIC 18F4520 microcontroller

An automated water level management system was developed using a similar approach to level sensing method adopted in (Reza, 2010) with a PIC 18F4520 microcontroller as the control unit (Teo & Tiew, 2015). The system demonstrated an enhanced water sensing and control mechanism with an alert trigger communication link that sends an SMS via GSM modem and a buzz to alert the user on the critical water states: when the main tank is full or empty or when the water level in the reserve drops below the minimum level.

3.2.1.3 Atmel 89C52 microcontroller

Atmel 89 series microcontroller are single chip microcontrollers developed by Intel company for use in embedded systems, that is, they are meant for dedicated functions within a large mechanical or electrical system requiring real-time computing (Atmel Corporation, 2016).

Taking advantage of electrical conductivity properties of water, copper conductors have been used as water level sensor (Ebere & Francisca , 2015) . When water made contact with the copper sensor positioned at a particular level in the tank, voltage was transferred to the copper electrodes. The voltage was then transferred to the comparator circuit for further processing. The LM324 comparator, with a pre-set resistance, was used to compare the inputs from the electrodes in the tank and output a HIGH or a LOW with respect to the result from the contrast. The HIGH or LOW signal received was then fed into the microcontroller to control the water pump and display the proper status on an LCD screen. The programmable Atmel 89C52 microcontroller that was used as the processor to control the functionalities of the entire system was programmed in Assembly Language (Ebere & Francisca , 2015) .

3.2.1.4 555 Timer IC

The 555 integrated circuit (IC) is a timer that was first manufactured in 1972 by American company, Signetics. The 555 timer is the most popular integrated IC ever manufactured, and is still widely used due to its low cost, ease of use and stability (Berlin, 1976).

The use of a 555 timer as the control unit was demonstrated by (Boopathi, 2013). Whenever the level of water in the tank went either low or full, the output pins of the controller were given the necessary voltage by the controller, that is, either 0 or 1, thereby affecting the position of the relay and hence the pump is either on or off.

3.2.1.5 Atmega 32PDIP

Atmega 32 is an 8-bit high performance microcontroller of Atmel’s Mega Advanced Virtual RISC (AVR) family (Atmel Corporation, 2016).

In an attempt to reduce energy costs, (Krieger & Mohankumar, 2014) designed an automated remote solar powered water pump using Atmega 32 microcontroller, a float sensor and a 433MHz transceiver and a water pump. The system is aimed at obtaining water for small scale use from a pond or other water resources and transports it over a distance of about 100m to a water storage container without any wastes. The pump drew water when there was enough sunlight and only if the storage tank is not full. The transmitter was used to communicate the state of the container wirelessly.

3.2.1.6 PLC and SCADA system

A Programmable Logic Controller (PLC) is a ruggedized digital computer adapted for control of complex processes such as assembly lines and robotics requiring high reliability, ease of programming and process fault diagnosis. Supervisory Control and Data Acquisition (SCADA) is a high level process supervisory management that uses peripheral devices such as PLCs to interface to the process plant (Mehra, 2012).

To control and monitor the liquid level of a tank continuously and ensure that a sufficient level of water is maintained, a system which can be used universally in industrial applications has been developed (Das et al., 2013). The proposed system can be used to prevent overfilling of any open or closed containers thereby preventing overflows or creating overpressure conditions. The system was made using the SIEMENS S7- 300 PLC and four inductive proximity level sensors which were used to detect the presence of water. The readings of the sensors are used by the PLC to take the required decision which is implemented by the PLC through a relay switch.

Baranidharan, (2015) proposed an automated water distribution system that was used to distribute the municipal water equally to all street pipe line by setting a fixed amount of water for each pipe. The set amount is measured with the aid of a flow sensor and a solenoid valve. The project used a PLC to control the pump via an RS232 cable and three solenoid valves which were switched ON or OFF by a relay.

3.2.1.7 Arduino

Arduino is an open source electronics platform based on easy to use hardware and software. The arduino board is based on Atmel AVR microcontroller with a lot of integrated peripherals (Arduino, 2016). It supports high level programming languages and yet runs with minimal support circuitry. Arduino comprises of both a physical circuit board that is programmable (which is frequently known as a microcontroller) and a piece of software, or Integrated Development Environment (IDE) that runs on the computer and they are used for writing and uploading computer code onto the physical board. The board's strengths are ease of programming as well as low cost of implementation (D'Ausilio, 2012).

3.2.1.8 Selection of a controller

The choice of a suitable controller for use was based on ease of use, adaptability, skills required to programming and maintenance, cost and durability. The PLC and SCADA system are very costly and also suitable for huge and complex processes like manufacturing plants. The microcontrollers (PIC and Atmel) and the 555 timer IC are much cheaper than the PLC and SCADA systems and arduino boards and also locally available. Despite these advantages, programming these microprocessors requires skilled technicians. Furthermore, for starters, the cost of programming isn't that low, as one has to buy the relevant programming kit as well as design relevant circuits to make the microcontroller compatible with peripheral devices such as sensors and the actuator (pump). With the additional components, the cost of these microcontrollers almost approximates the cost of arduino (Blum, 2013).

Over and above the availability of arduino locally, they are inexpensive than some microcontrollers. Technically, arduino software runs across various platforms such as Windows, Linux and Macintosh OSX operating systems unlike most microcontrollers that run on Windows only (Arduino, 2016). They also have simple and clear programming environment that requires little skills to learn, and considering that both arduino software and hardware are open source, experienced and creative programmers and circuit designers can freely extend and improve the C++ libraries as well as design an extension of their own modules. This flexibility allows arduino to be versatile to many uses than other microcontrollers (Schmidt, 2011).

3.2.2 Sensors

A sensor is a transducer that converts a physical stimulus from one form into a more useful form to measure the stimulus. Any sensor is based on a simple concept that physical property of a sensor must be altered by an external stimulus to cause that property either to produce an electric signal or to modulate (to modify) an external electric signal. Quite often, the same stimulus may be measured by using quite different physical phenomena, and subsequently, by different sensors (Bishop, 2002). The sensing process is as shown in Figure 7.

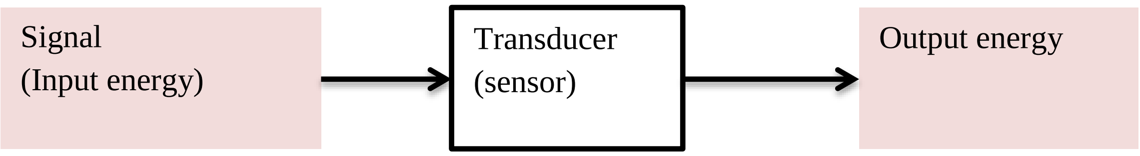


Figure 7: The sensing process

A wide variety of instruments are available for measuring the level of liquids. Small changes in liquid levels in a container or any other vessel can be detected using level sensors. Mostly such sensors are linked or connected to some kind of an output system that sends notifications to a technician at a monitoring station or sometimes the connection is to a sounding alarm (Bishop, 2002). Level sensors have been used years back to date often for detection of dangerous levels of liquid build-up within a closed system in various industries, to alert the technicians of the danger (Yoshikawa, 2013). Today, refined digital electronics has made level sensors more user-friendly, reliable and more applicable to industries like agriculture for managing water waste through overflows. To achieve this objective, these technologies make use of recent electronic techniques and they incorporate embedded microprocessor-based digital computers for control, analysis, and communication functions as shown in Figure 8 (Bishop, 2002). Some of the locally available level sensors that can be used for the prototype are briefly discussed below;

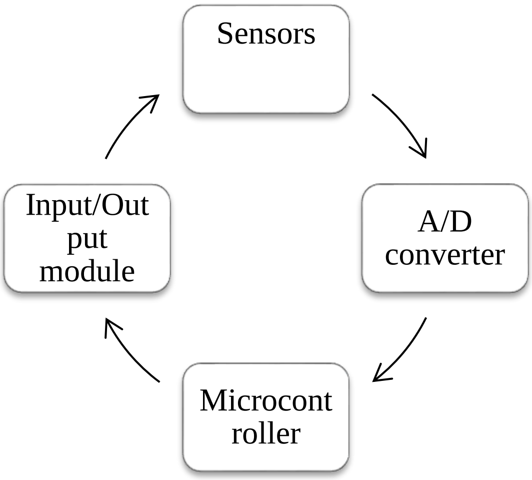


Figure 8: Relation between electronics and communication functions

3.2.2.1 Radar microwave/antenna methods

This non-contact measuring technique involves directing a constant-amplitude, frequency modulated microwave signal at the liquid surface as shown in Figure 9. The phase difference between the reflected signal and the original signal transmitted directly through air to the receiver is linearly proportional to the liquid level (Morris, 2001).

Therefore the level of liquid is obtained using Equation 1. Programming of the transmitter is done using the bottom of a tank or container as the reference gauge height. The level is then calculated by the microprocessor in the transmitter. The major advantage of these sensors is that they can provide successful level measurement in applications that are otherwise very

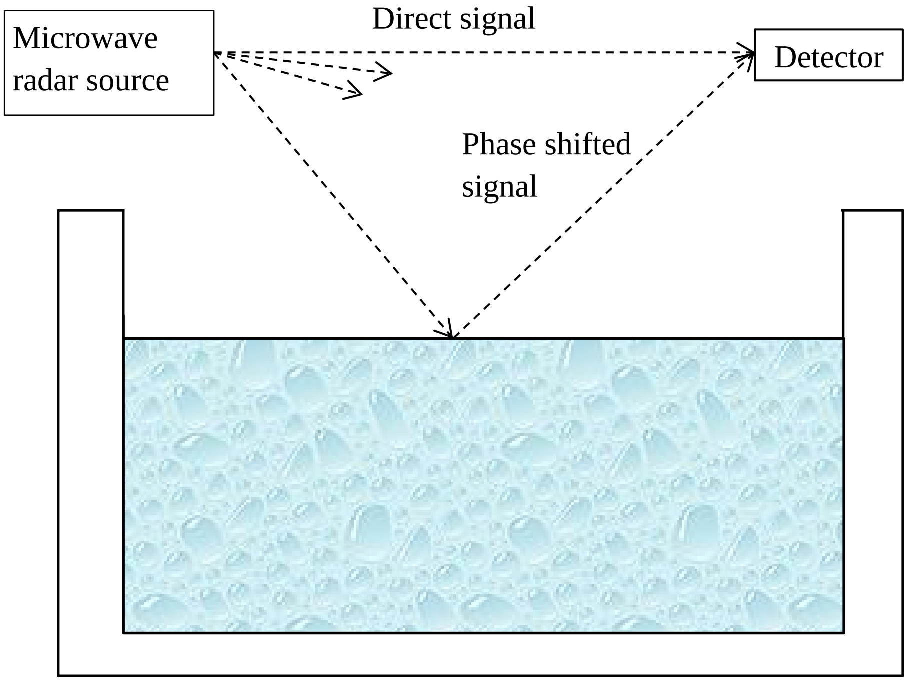


Figure 9: Radar level detector

difficult, such as measurement in closed tanks, where the liquid is unsettled and in the presence of obstacles and condensation.

$$\text{Distance} = \frac{[\text{Speed of light} * \text{ Time delay}]}{2} \qquad (1)$$

3.2.2.2 Ultrasonic level transmitters

Ultrasonic level sensors, shown in Figure 10, send ultrasound pulses from the transducer to the surface. The time required for the pulse to travel to and back is then used to determine the level of the liquid in the container (US Patent No. 4063457 A, 1977). They are capable of monitoring many liquids remotely without the need for any part of the sensor to actually contact the liquid (US Patent No. 5747824 A, 1998). The time travelled by the ultrasonic pulse is calculated, and the distance of the object is found using Equation 2. Temperature, pressure, and humidity are the sources of error for these types of sensor.

$$\text{Level} = \frac{\text{Speed of sound in air} \times \text{Time Delay}}{2} \qquad (2)$$

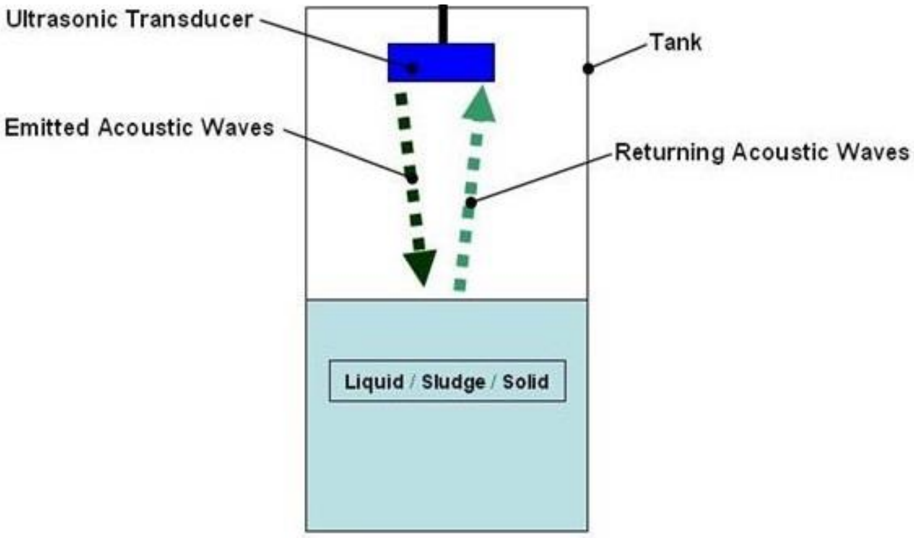


Figure 10: Ultrasonic level gauge

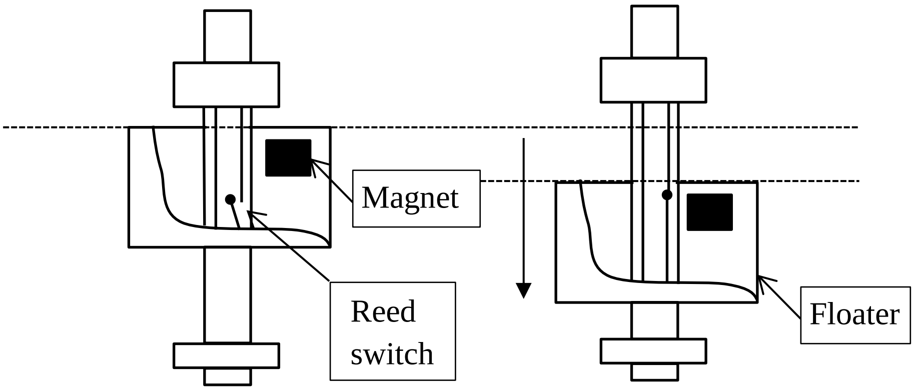
3.2.2.3 Tape level devices

Float and tape gauge (or tank gauge) has a tape attached to the float that passes round a pulley situated vertically above the float. The other end of the tape is attached to either a counterweight or a negative-rate counter-spring. The amount of rotation of the pulley, measured by either a synchro or a potentiometer, is then proportional to the liquid level (Kayser & Liptak, 2003).

3.2.2.4 Magnetic float sensors

Float switches are set to open or close a circuit once the level of a fluid rises or falls. Magnetic float switches utilize a magnetic reed switch that is hermetically enclosed in a stem. The float houses the magnet which moves up and down along the length of the stem tracking the level of the fluid. As the magnet passes the reed switch, the attractive force of the magnet causes the switch to close as shown in Figure 11 (Webster & Eren, 2014). Float sensors can be designed for almost any liquid if there is a high chemical compatibility with the materials used to construct it.

Float switches are used in such diverse applications as home appliances and automotive. Certain float switches are suitable for reservoirs and large tanks, while others are for chambers



(a) Open float switch (b) Closed float switch

Figure 11: Magnetic float switch

of a few millilitres. There are many physical and application variables that affect the selection of the optimal level monitoring method for industrial and commercial processes. The major factors include temperature, pressure, vibration, density (specific gravity) of the medium and environmental conditions particular to a given application. Material and safety standards are also critical factors (Webster & Eren, 2014). The choice for an application depends on the physical arrangement of the tank, the available mounting positions, tank wall thickness, and whether access is available to the inside of the tank.

3.2.2.5 Sensor selection

Liquid level sensors play an important role in the detection, measuring, and monitoring of water in the reservoirs. Various factors were considered in selection of the appropriate level sensors for the prototype. They include: cost, availability, ease of use, compatibility with the controller and reliability. Radar and ultrasonic level sensors are much more expensive than magnetic and tape level sensors. Further, magnetic level sensors have a float that moves with the level of the fluid and therefore provides a digital output of either 0 or 5V. This makes the design easier as it eliminates the need for an analog to digital converter.

In addition, the magnetic level sensor has relatively high accuracy, reliability, durability, availability and ease of incorporating with the rest of the system. The BTH PSA-381/1-P magnet float level sensor used is a standard liquid level sensor mounted vertically for best results. A tape level sensor was modified to be used as a physical gauge that the owner can use to see the level of water in the tank.

3.2.3 Pumps and energy source

Various types of submersible water pumps could be used to build the laboratory prototype. Relatively small electric pumps are applicable. Those locally available include a suction pump, fountain pump and bilge pump. Both the suction and fountain pump are AC powered and are much more expensive than the DC powered bilge pump (Pumps for Africa, 2016). As discussed in the literature, various options are available to produce electricity to power the pumps. Botswana is well endowed with a lot of sunshine and less wind energy, while farms close to urban areas are connected to the grid.

Therefore, solar photovoltaic and grid power were used and compared to power the DC bilge pump in this prototype.

3.3 Selection of the solution for the prototype development

From multiple solutions, the next step in the design process involves selection of the most feasible solution that will have the prototype developed from. The prototype should ensure that the storage tank is never empty for continuous water supply, prevent overflows whenever the tank is full and monitor the borehole water levels. The suitable prototype is schematically shown in Figure 12 including the flow of information between various components. The features of this system are as follows;

1. The magnetic float sensors send a signal to the controller indicating the level of water in the overhead storage tank as well as the borehole to the arduino controller.
2. The arduino controller processes the information from the sensors using the program loaded in its microprocessor.

3. The controller then sends a signal to the bilge pump through a relay directing it to take appropriate action.

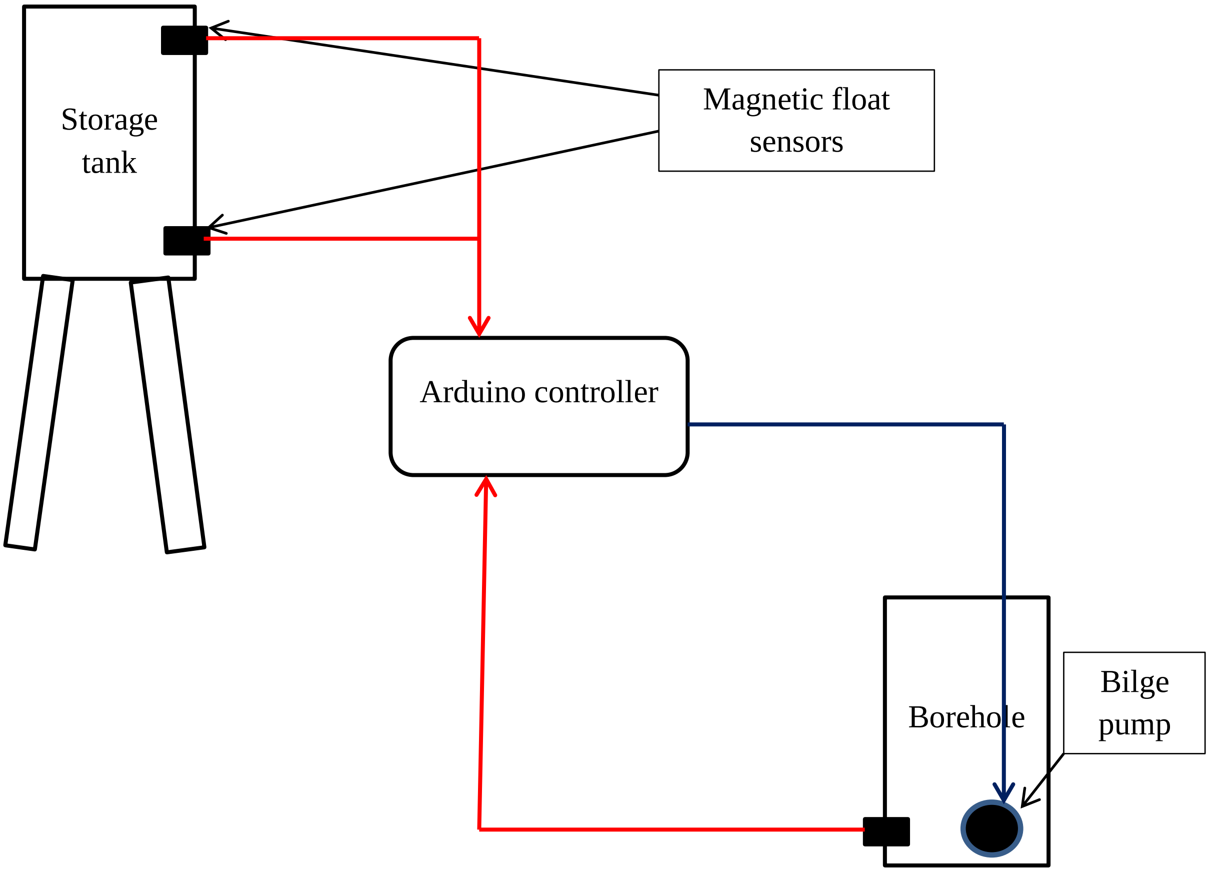


Figure 12: Information flow between various components

The system can be powered using solar as well as grid power. Further, the borehole and storage tank were represented with the use of two tanks in the prototype. Testing and analysis of this prototype design was conducted as described in detail in Chapter 4.

CHAPTER 4 MATERIALS AND METHODS

This section is divided into three parts. Each part represents the methods undertaken to answer a particular Objective.

4.1 Design, development and testing of the prototype and related interface circuits

To develop the automatic pump control and water level prototype, the controller components were identified as an outcome of the design procedure discussed in Section 3.1 and assembled before setting up the whole system to typify the farm water pumping scenario. To simulate the water pumping at the farm or cattle post, the setup consisted of two tanks: the upper tank elevated using a stand and the lower tank placed on the ground. The upper tank represented the overhead storage tank (ST) and the lower tank represented the borehole (BH). The ST had two water level sensors: the upper level sensor (STUL) for sensing when ST was full and lower level sensor (STLL) for sensing when ST was empty. The BH was also fitted with the safety level sensor (BHSL) placed just above the pump to prevent the pump from dry pumping.

4.1.1 The system architecture of the Arduino controller

The arduino controller was made up of five main unit systems, namely: (1) The control unit (2) The magnetic sensor unit (3) The power supply unit (4) The Light Emission Diodes (LED) display unit, and (5) The pump actuation unit. These are described in detail below.

4.1.1.1 The control unit

The control unit used was the arduino Uno (Model UNO R3, Smart Projects, Italy) shown in Figure 13, which is a microcontroller board based on the ATmega328 microcontroller (Blum, 2013). The microcontroller embedded in the arduino board was programmed using the Arduino programming language to control the pump operation. The program logic is shown

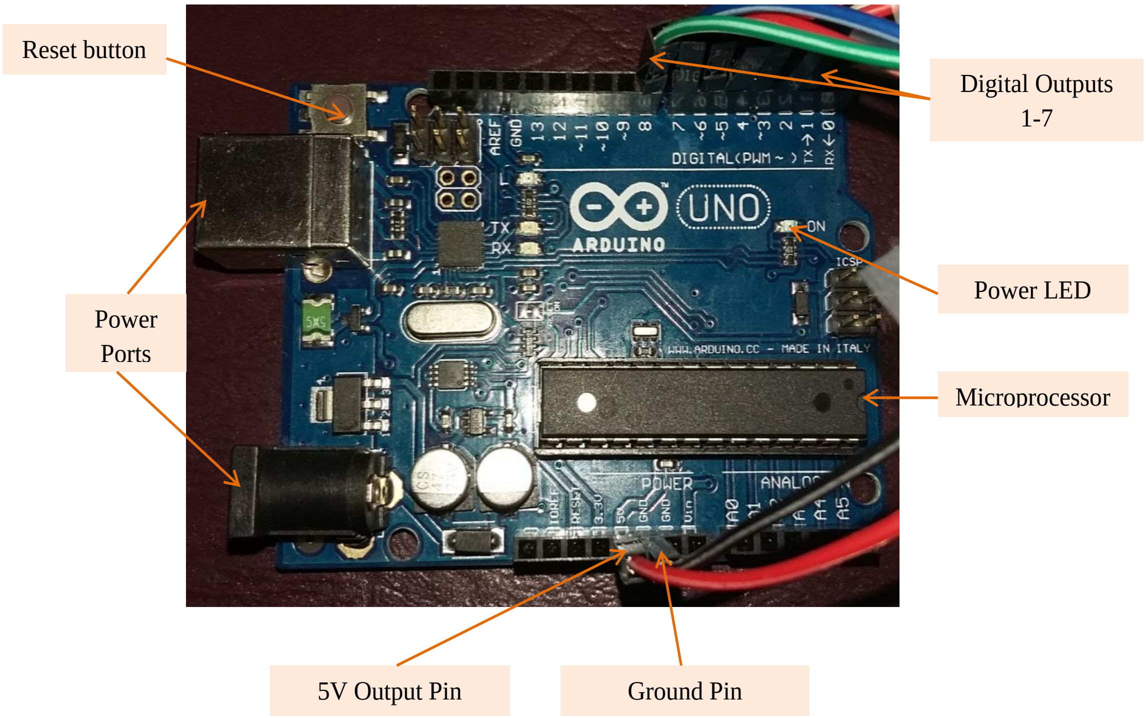


Figure 13: The Arduino Uno used as the control unit

in

Figure 14 and the program code is shown in Appendix A.

4.1.1.2 The magnetic sensor unit

The magnetic float level switches (Model BTH PSA-381/1-P, Parma and Parma Pvt Ltd, India) shown in Figure 15 were used to monitor the water levels in the borehole (BH) and storage tank (ST). They were selected due to their high accuracy and durability, ease of operation, cost effectiveness, availability, reliability and compatibility with the arduino controller. These sensors detected the level of water in ST and BH using Archimedes' principle (Patrick & Fardo, 200). When the water level rose or lowered, the hermetically sealed-in-glass reed switch located inside the stem of the sensor was activated or deactivated by the upward or downward movement of the strong magnet in the tailpiece of the float thereby generating a Low or High signal, respectively. The red cable of each sensor was connected to a corresponding input port of the arduino board and the black cable was connected to ground of the arduino board.

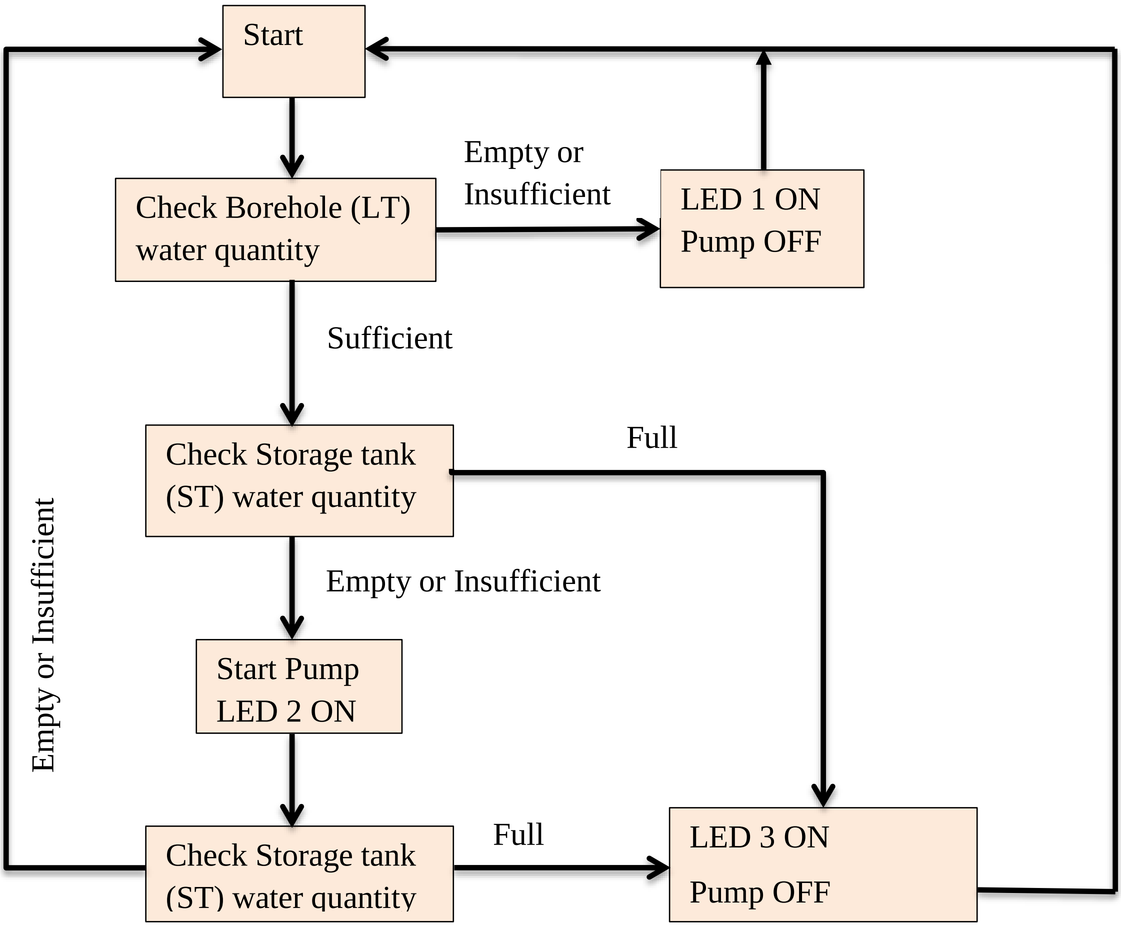


Figure 14: The program operation logic for the pump control

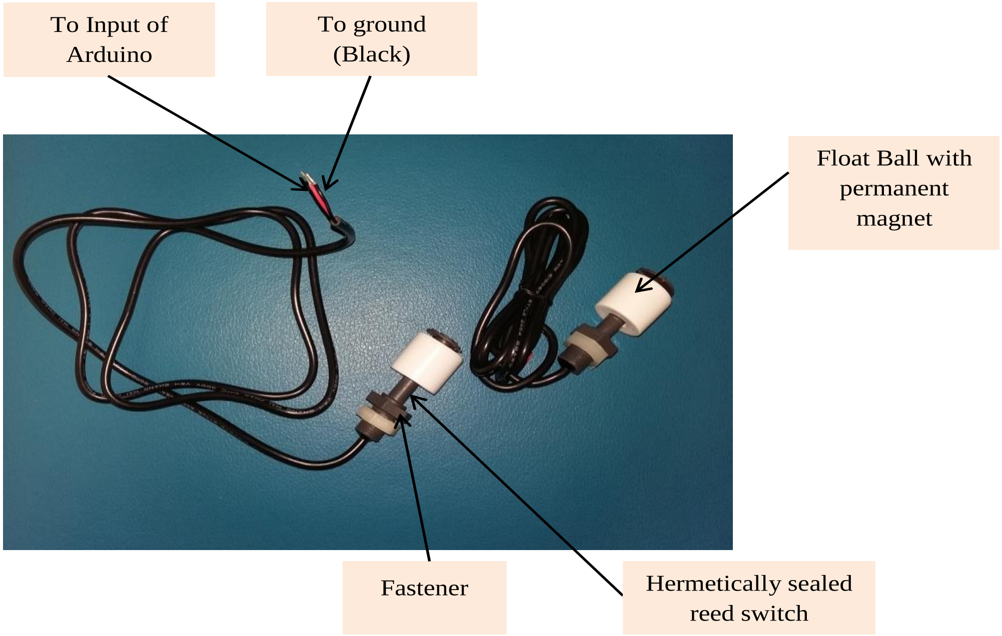


Figure 15: The vertical magnetic float sensors used to detect water levels in the borehole and storage tank. Two units are displayed.

4.1.1.3 *The power supply unit*

The pump and arduino board system were powered by solar and the connection array is shown in Figure 16. Solar power was chosen because it is free and abundant in Botswana and all farmers have free access to it. The initial investment would involve purchase of the solar power system and all system components are readily available in cities, towns and major villages. Solar power was provided by one 160W solar panel (Model SW 150 poly R6A, SolarWorld Industries, Germany). The panel supplied 18V DC through the solar charge controller (Model CML 10-2.2, Phocos, Germany) which regulated the voltage and current from the solar panel to protect the batteries from overcharging. Two batteries (Model Deltech 1250, South Africa), each with a capacity of 12V, were connected in series to provide 24V DC which was supplied to the 24V inverter (Model A301-1K7-F3, Mean Well, Taiwan). Since the pump needed 12V DC, one battery would have been sufficient to supply the required voltage. However, due to lack of a power jack for direct connection to the battery, an inverter was used to convert the voltage to AC first then to the pump using an adapter. Additionally, the available inverter was a 24V DC inverter which required to be powered with two 12V batteries connected in series.

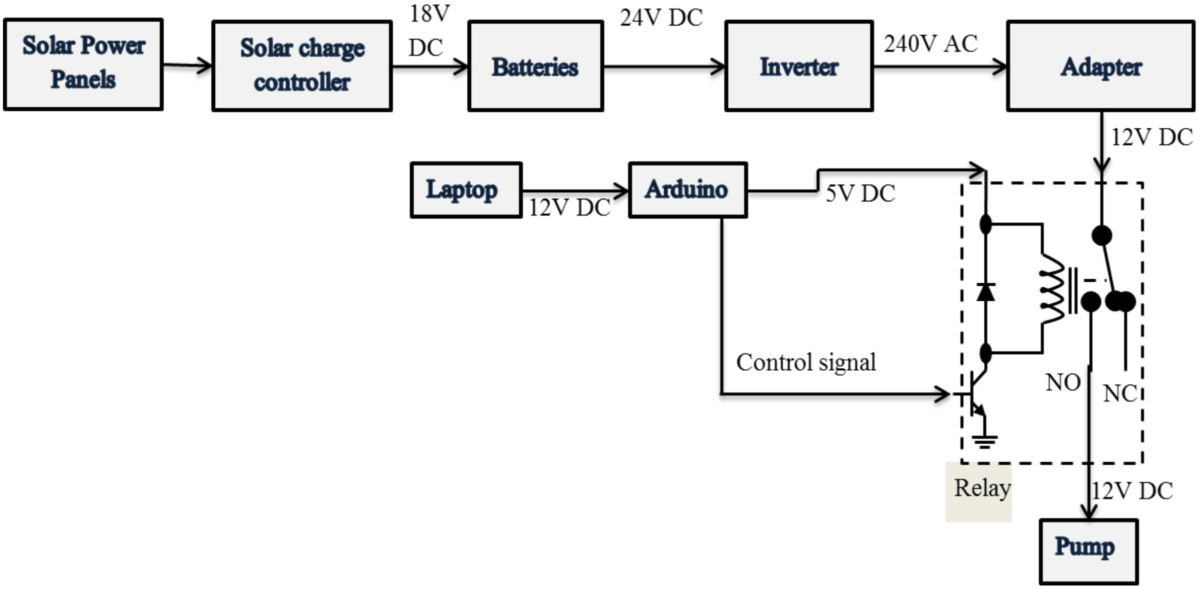


Figure 16: The layout of the solar power system supplying power to the submersible pump

The inverter in turn converted the 24V DC input to 240V AC output. A 12V DC adapter (Model MRE11a, Pioneering Power Supplies, India) was connected to the 240V AC output of the inverter to convert the AC power to 12 V DC which then powered the small submersible pump (Model SFBP1-G750-01, SEAFLO, West Midlands, England) via the relay switch (Model HK3FF-DC5V-SHG, Huike, China).

4.1.1.4 The LED display unit

The display unit was made of three Light Emitting Diodes (LEDs) (Model COM-09264, SparkFun Electronics, Niwot, Colorado, USA) that indicated the state (full or empty) of the ST and the borehole. The LEDs 1, 2 and 3 were connected to the arduino board via a breadboard (Model AD-01, Maplin Electronics, England).

Table 4 shows the expected state of the system depending on the status of the three LEDs. Whenever the three LEDs were OFF, it was an indication that no pumping was required as ST was full even though BH was insufficient. Whenever LED 1 turned ON, it indicated that the BH had insufficient water and was running at the risk of being emptied and dry-running the pump. In this instance, the pump was immediately switched OFF by the controller irrespective of the status of water in ST. After BH recharged and ST had insufficient water, then pumping took place and LED 2 simultaneously went ON to indicate that pumping was in progress. Finally, when both BH and ST had sufficient water, LED 3 turned ON and in this state, no pumping was required.

Table 4: The Light Emitting Diodes (LED) sequence vs water level in the storage tank (ST) and borehole (BH)

LED 1	**LED 2**	**LED 3**	**ST status**	**BH status**	**Comments**
ON	OFF	OFF	Empty	Empty	Both ST and BH do not have sufficient water: LED 1 ON to alert operator that pump is off and should not be switched on manually. It is not system failure.
OFF	ON	OFF	Empty	Full	BH has recharged, ST is empty: LED 2 indicates pumping is in progress.
OFF	OFF	ON	Full	Full	Both ST and BH are full: LED 3 indicates pumping stopped because ST is full.
OFF	OFF	OFF	Full	Empty	BH is discharged to minimum level and ST is still full: all LEDs are OFF. No pumping is required.

4.1.1.5 The pump actuation unit

The pump actuation unit was made up of a compact size submersible pump (Model SFBP1-G750-01, SEAFLO, West Midlands, England) and a relay switch (Model HK3FF-DC5V-SHG, Huike, China). When running, the pump was silent, did not vibrate and had anti-airlock protection by design. The pump required 12V DC power supply and had a rated flow rate of 2.8 m^3/h (750GPH), maximum head of 3 m and power rating of 30 W. This pump was selected due to its low cost, adaptability to the ST and BH sizes used in the study and the arduino controller, low power consumption and compatibility to both grid and solar power.

The relay switch was electromagnetically operated and had a complete protection circuit with its power flow shown in Figure 17. It was used to isolate the arduino board from the pump thereby protecting the arduino board against stray voltages and current from the pump. Since the arduino provided an output signal of 5V DC, it was not enough to power the 12V DC pump. Therefore, the 5V DC signal fed to the relay through the transistor made the transistor saturated, which energised relay's coil that closed the normally open (NO) switch. This allowed 12 V to flow from the adapter to the pump thereby switching it on. If the 5V signal from the arduino board was cut out, the relay's NO switch became open thereby cutting off power to the pump which would then switch off.

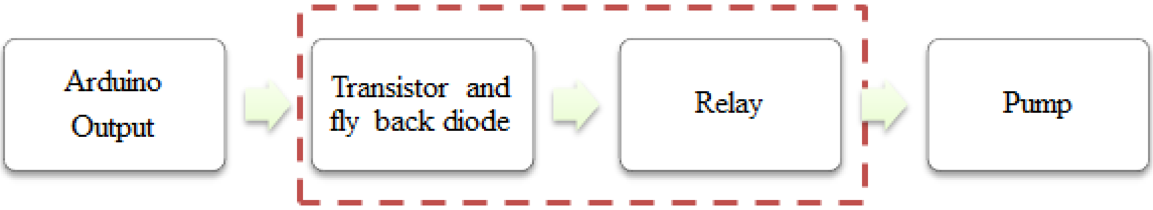


Figure 17: Block diagram for the interface circuit of the pump actuation unit.

4.2 Determination of water and energy savings from using the prototype

Due to the scope and resource limitations in this project, an experimental setup was put together to exemplify the actual water pumping scenario at the farms or cattle posts in Botswana and data on power consumption collected.

Figure 18 shows the schematic diagram of the experimental setup. The borehole (BH) was represented by the lower tank placed on the ground while the upper tank was elevated using stands to represent the storage tank (ST). Both tanks had magnetic level sensors (Model BTH PSA-381/1-P, Parma and Parma Pvt Ltd, India) to monitor the level of water and send the information to the controller (Arduino Uno- Model UNO R3, Smart Projects, Italy) which turned the pump ON or OFF. The BH had one magnetic level sensor to act as the safety level

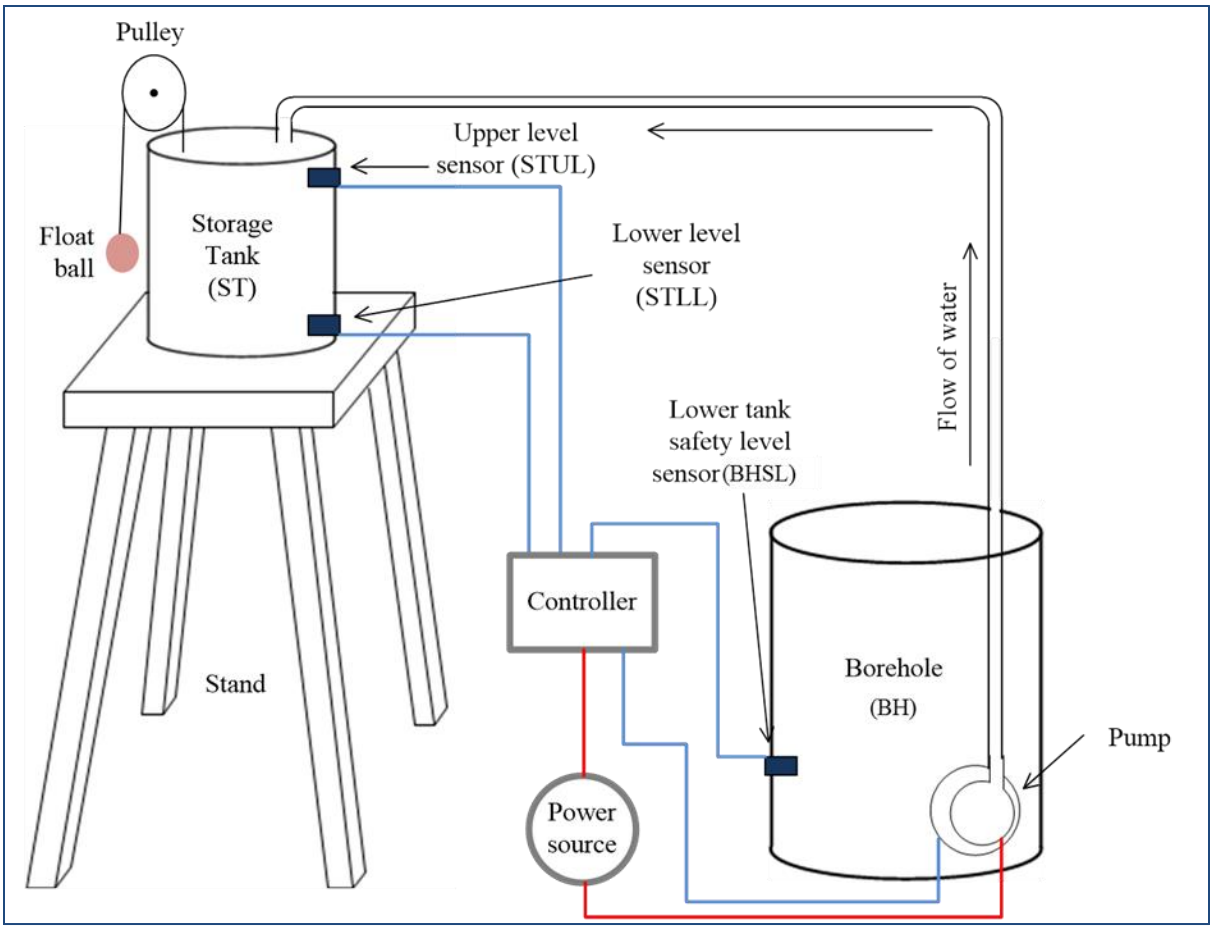


Figure 18: Schematic diagram of an automatic water pumping system setup to exemplify the actual pumping at the farm or cattle post in Botswana.

sensor (BHSL) and was placed just above the pump in order to prevent the pump from dry running. On the other hand, the ST had two magnetic level sensors – the Lower and Upper level sensors. The Lower level sensor (STLL) was placed at a position where the water level was not allowed to fall below thereby ensuring that the ST never became completely empty. The Upper level sensor (STUL) was placed at the maximum allowable level where the ST was considered full without overflowing. These sensors were sending corresponding signals to the arduino-based controller which then sent an appropriate signal to the submersible pump (Model SFBP1-G750-01, SEAFLO, West Midlands, England) through a relay switch (Model HK3FF-DC5V-SHG, Huike, China). A ST water level gauge is used by few farmers to visually monitor the level of water in the ST. In this model, such was achieved using two floats connected through a pulley as shown in Figure 18.

Preliminary tests on the pump were carried out to determine its flow rate. The pump was powered using grid power, and the time used to pump water from the BH tank until the water level was just above the pump was recorded. This experiment was repeated 10 times to ensure the accuracy of the results. Once the system performance was satisfactory, actual measurements were carried out with data collected for later analysis.

Two power sources, grid and solar, were used to power the pump and the power and energy consumptions were monitored during each pumping session. One pumping session was made by filling the ST from empty to full. The submersible pump's average flow rate and energy consumption were measured at various heads of 1.0, 1.3, 1.6, 2.0, 2.2 and 2.6m. The head was taken as the height between the suction inlet of the pump and the water level in the ST. The pumping heads were achieved by placing the ST on various stands and measuring the height from the pump inlet to the top of the water level in the ST using a tape measure. The pump's rated maximum head was 3.0m. The flow rate at each head was obtained by recording the time taken to fill the ST tank, whose capacity was 25 *l*. In order to calculate the energy consumed at each height or head, the voltage across and current through the pump were measured. At each head, 10 repeated measurements were taken so as to ensure the reliability of the results. Further, the procedure was repeated over a 5-day period while powering the pump using grid and solar power on each day.

The amount of energy, $E\ (Wh)$, consumed was calculated as,

$$E = V \times I \times t \tag{3}$$

Where:

V = measured voltage (V)

I = measured current (A)

t = the amount of time taken for the pump to fill the ST (seconds)

4.2.1 Measurements with grid power

The grid power was obtained from the regular mains power from a nearby University laboratory. The schematic of the connection and how power consumed by the pump was measured is shown in Figure 19. Digital multimeters (Model 179, Fluke Corporation, USA) were used. One meter was set to measure voltage across the pump while the other was connected in series between the adapter and pump to measure the current that the pump was drawing from the power source. Since the pump used in this study was a DC pump, the adapter

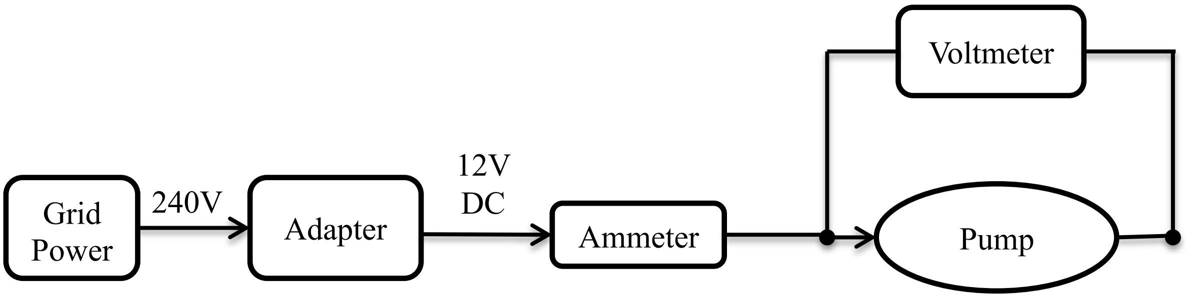


Figure 19: Schematic representation of the grid power consumption measurement.

(Model MRE11a, Pioneering Power Supplies, India) was used to convert the grid 240VAC power to 12V DC.

4.2.2 Measurements with solar power

Figure 20 shows the schematic diagram of powering the automatic pumping system using solar power. The solar panel was used to charge two batteries, each with a capacity of 12 V, through a solar charging controller. The two series-connected batteries were connected to a 24V inverter which converted the batterys' 24V DC to 240V AC. Although each battery could drive the pump, the lack of an appropriate direct connection jack dictated the use of an inverter. However, only a 24V DC inverter was available at the time of experiment hence the use of two 12V DC batteries. An inverter was then connected to an adapter which had a 240V AC input and 12V DC output and powered the 12V DC submersible pump. Similar to measurements using grid power, two meters were used to collect data, with one measuring current to the pump while the other measured voltage across the pump.

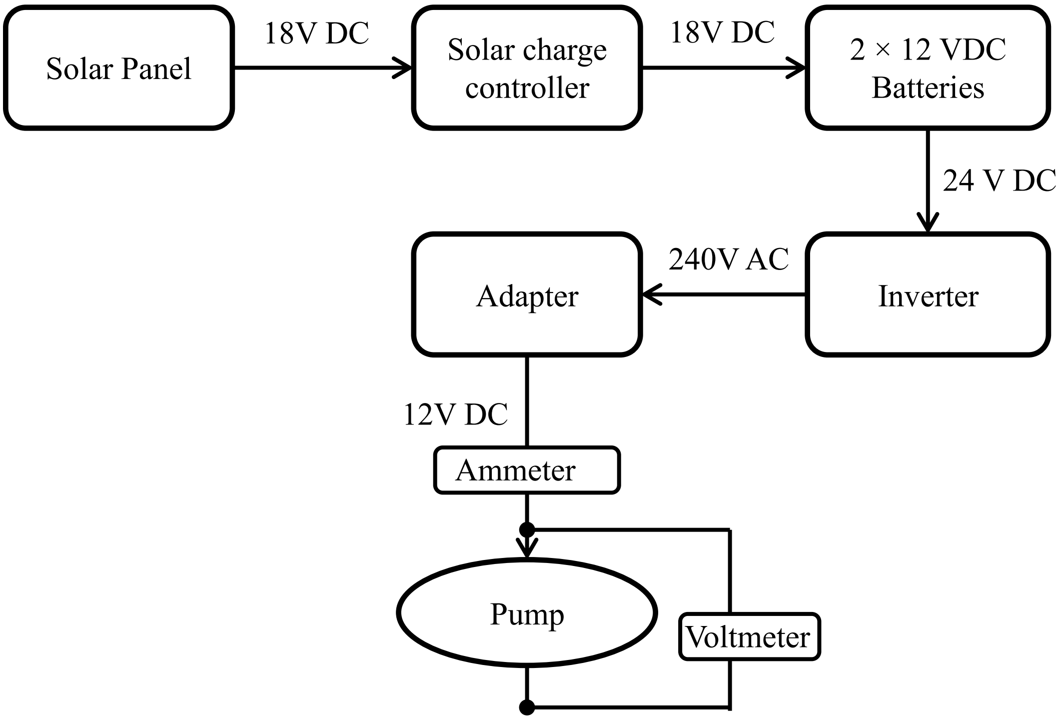


Figure 20: Schematic connection of the pump to solar power system

4.2.3 Experimental data projections to real farm situation

To obtain a realistic farm operation, a synoptic survey was carried out among borehole owners at Botswana University of Agriculture and Natural Resources (BUAN) by using a questionnaire shown in Appendix B. The results from the questionnaire were used as baseline to enable projection to a real farm scenario. The survey provided information on the average borehole depth, water pumping pattern, volumes of water wastage due to overflows and energy consumption on pumping. An extrapolation was done on the pump parameters namely energy consumption, flow rate and head, in order to obtain an ideal approximation for a pump that can perform at the given average head. To determine the water and energy savings accrued annually in Botswana, the savings obtained from the prototype data were multiplied by the number of boreholes in Botswana and the proportion of borehole owners who reported to be experiencing water losses in the survey. At present there are around 25,000 officially registered boreholes in Botswana (Centre for Applied Research, 2013), with about 17,700 being used for domestic and livestock watering (Center for Applied Research, 2005). Additionally, the borehole water pumping tariff charged by Botswana Power Corporation (BPC) was used to determine the amount of money saved from energy savings while the current water tariff charged by Botswana's Water Utility Corporation (WUC) was used to calculate the amount of money saved by eliminating overflows.

4.2.4 Calculations for projected water savings

Assuming that all pumps operated at the prototype's extrapolated flow rate and power, the volume, V_{pump}, of water pumped during a pumping event was calculated as

$$V_{pump} = Q \times t_{pump} \tag{4}$$

Where

t_{pump} is the duration of each pumping event (h)

Q is the flow rate of the pump (l/h).

From the survey, the average time that water spills, t_{spill} (h) is used to obtain the volume of water overflowing from the storage tank in a pumping event as follows,

$$V_{spill} = Q \times t_{spill} \tag{5}$$

The automatic system ensures that no water loss takes place through overflowing. Therefore, the amount of water saved per borehole in a pumping event was V_{spill} (l). It subsequently follows that the annual water saved per borehole, V_{s-BH}, is;

$$V_{s-BH} = \sum_{i=1}^{n} V_{spill}(i) = \sum_{i=1}^{n} Q \times t_{spill}(i) \tag{6}$$

Where

n is the number of pumping events in a year for that particular borehole.

Therefore, the total amount of water saved annually in Botswana, V_s (l), was calculated as,

$$V_s = \sum_{j=1}^{Bo} V_{s-BH}(j) = \sum_{j=1}^{Bo} \sum_{i=1}^{n} Q(j) t_{spill}(i,j) \tag{7}$$

Where

Bo is the total number of boreholes in Botswana that experience overflows.

4.2.5 Calculations for energy savings

The electrical energy used in pumping during water overflow or wastage without the automatic system installed, E_{spill} (kWh) was given by,

$$E_{spill} = P_{pump} \times t_{spill} \tag{8}$$

Where;

P_{pump} is the pump's power rating (kW).

With the automatic water management system in place, no spillage would occur and therefore, energy saving per borehole per pumping event was E_{spill} (kWh). The energy saving in a year for the same borehole, E_{s-BH} in a year was therefore obtained by;

$$E_{s-BH} = \sum_{i=1}^{n} P_{pump}\, t_{spill}(i) \tag{9}$$

Therefore, the total energy saved annually in Botswana, E_s (kWh), was expressed as;

$$E_s = \sum_{j=1}^{Bs} E_{s-BH}(j) = \sum_{j=1}^{Bs} \sum_{i=1}^{n} P_{pump}(j) t_{spill}(i,j) \tag{10}$$

Where;

Bs is the total number of boreholes in Botswana not using solar energy that experience overflows.

The cost savings from arising from water savings (p_{W_saved} (BWP)) and energy savings (p_{E_saved} (BWP)) through elimination of water overflow or wastage were calculated as,

$$p_{W\_saved} = V_s \times p_w \tag{11}$$

$$p_{E\_saved} = E_s \times p_e \tag{12}$$

Where;

p_w is the cost of water in (BWP/m^3) and p_e is the price of electricity in (BWP/kWh) .

The projected amount of water and associated energy wasted were calculated on annual basis. These amounts were separated into winter and summer values as pumping pattern differ between the two periods.

4.3 Economic analysis of the use of solar energy in powering the prototype

The government of Botswana is encouraging the use of clean energy to reduce over reliance on petroleum products in future. This automatic water management system shall lead to a reduction in the use of diesel pumps in future. Hence, an economic viability was carried out on the solar power system to provide insight information to the farmers who would take the solar option to power their pumping operations.

The discounted payback period method was used in this analysis since it accounted for the time value of money. It was obtained from the net present value (NPV) of the cumulative cash flow. The present value of the cash flow during the i-th year, $PV(i)$, was:

$$PV(i) = \frac{CashFlow(i)}{(1+r)^i} \tag{13}$$

Where

$CashFlow(i)$ is the cash flow of the i^{th} year (BWP) and r is the discount rate (%)

Having obtained $PV(i)$, the net present value was calculated as :

$$NPV_{i=1}^{n} = \sum_{i=1}^{n} PV(i) - CC \tag{14}$$

Where

CC is the initial capital cost of the project (BWP).

The discounted payback period was calculated as (Fabrycky & Blanchard, 1991):

$$Payback\ period = n_y + \frac{-NPV_{i=1}^{n}}{PV(n_y+1)} \tag{15}$$

Where

n_y is the last year with a negative NPV.

In order to calculate the time it would take for a farmer to recoup the investment or the payback period, the following assumptions were made.

1. A discount factor of 2.7% was used to reflect the time value of money and the 2.7% was indicative of the annual inflation rate in Botswana for June 2016 (Southern Africa Customs Union, 2016).
2. The solar benefit and maintenance costs were assumed to remain constant throughout the period.

CHAPTER 5 RESULTS AND DISCUSSION

This section is divided into three parts. Each part represents the results and discussions related to a particular Objective.

5.1 Design, development and testing of the prototype and related interface circuits

5.1.1 Assembled Pump Control and water level system

The schematic representation of the assembled automatic water pumping and level control device is shown in Figure 21. The red terminals of STUL, STLL and BHSL sensors were connected to digital input ports 2, 3 and 4 of the arduino board, respectively, while the black terminals of the three sensors were connected to the ground (GND) Port of the arduino board. The three magnetic sensors gave a high signal of 5V whenever the float ball moved down and

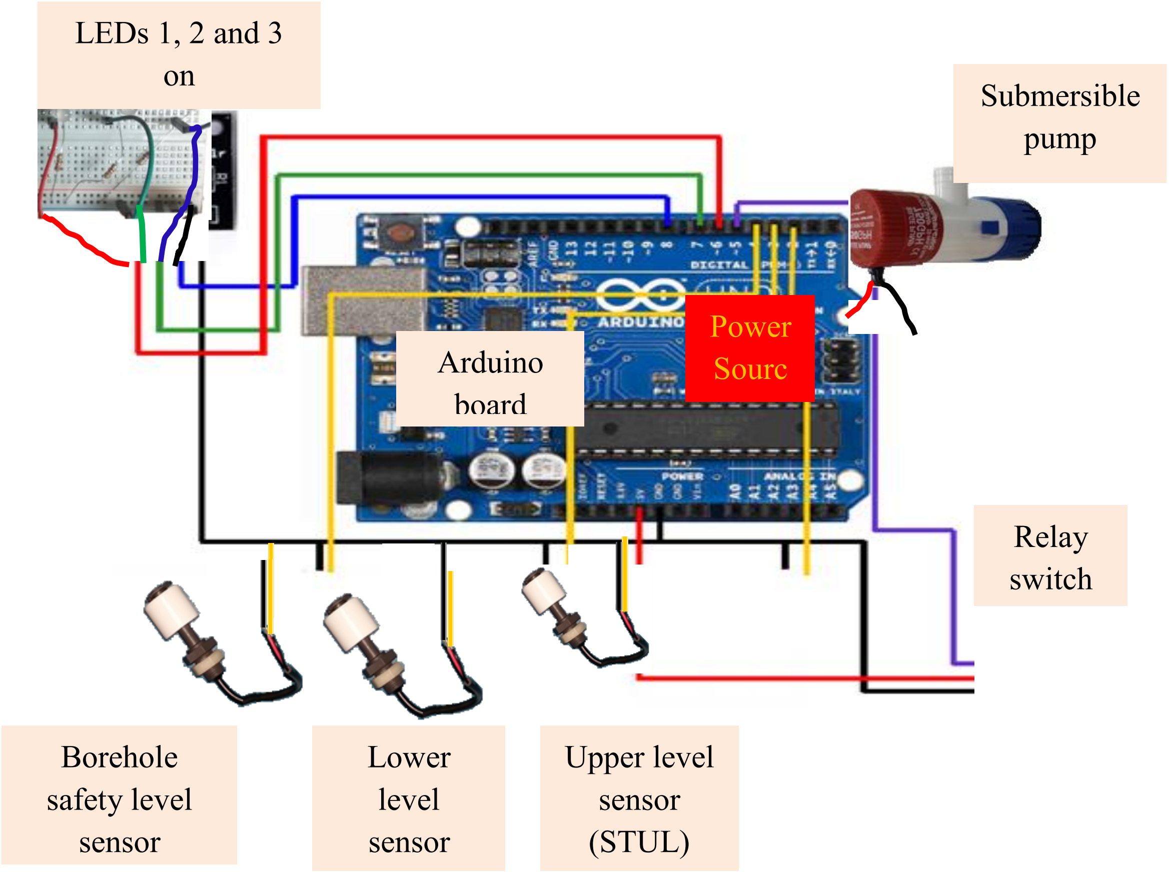


Figure 21: Physical schematic view of the complete pumping and water level control prototype showing all the five major units

0V if the float ball moved up. The downward motion of the float ball of the sensors opened the reed switch circuit while the upward motion closed the circuit sending the aforementioned signals. The three Light Emission Diodes (LEDs) giving the status of the system had each of their input terminals connected to digital output ports 6, 7 and 8 of the arduino board.

Further, output port 5 was connected to the signal port of the relay switch. The relay's Vcc port, which supplied 5V signal to the relay from the arduino board, was connected to the 5V port of the arduino board and the ground terminal of the relay was connected to the ground port (GND) of the arduino board (Godse & Bakshi, 2009). On the other side of the relay, the common (COM) port was connected to the neutral (black terminal) of the pump while the normally open (NO) port was connected to the neutral terminal of the adapter. The red terminal of the pump was directly connected to the adapter. Finally, the arduino board was powered using a laptop via USB port and the system was run to test if it performed the intended functions as described below.

5.1.2 The hand-testing of the ON and OFF operation of the pump

The testing process started when both the storage tank (ST) and the borehole (BH) were empty. In this condition, the float ball of BHSL was down the stem of the sensor and a 5V signal was sent to the arduino board. LED 1 turned ON indicating that no pumping could take place since the BH had insufficient water. This was used to test the dry run protection mode. The float ball of BHSL was pushed up the stem of the sensor by hand to symbolize when the BH had water. However, the float ball of STLL was still down the stem of the sensor indicating that ST was empty. Therefore, the arduino board continuously received a 5V signal from both STLL and STUL which then sent a positive signal (5V) to the relay effectively switching ON the pump. In addition, LED 2 was turned ON by the arduino board indicating that pumping was taking place. To achieve a full ST status, the float ball of STUL was pushed up to send a 0V signal to the arduino board which sent 0V to the relay de-energising the coil and opening the NO terminal of the relay switch. Consequently, the pump was switched OFF and LED 3 was turned ON to indicate that the ST was full. This sequence worked successfully as intended.

5.1.3 Water pumping system setup and operation

The system was constructed such that the magnetic float level sensors were accurately placed to sense the level of water in the storage tank (ST) and borehole (BH) and send the information to the arduino board controller. In order to ensure that the sensors were stable and always vertical in the ST, storage tank upper level (STUL) and storage tank lower level (STLL) sensors were fastened on a flat wooden plank using a metal flange as shown in Figure 22. This flange was then fastened onto the wall of the ST to ensure that it did not move as water level rose.

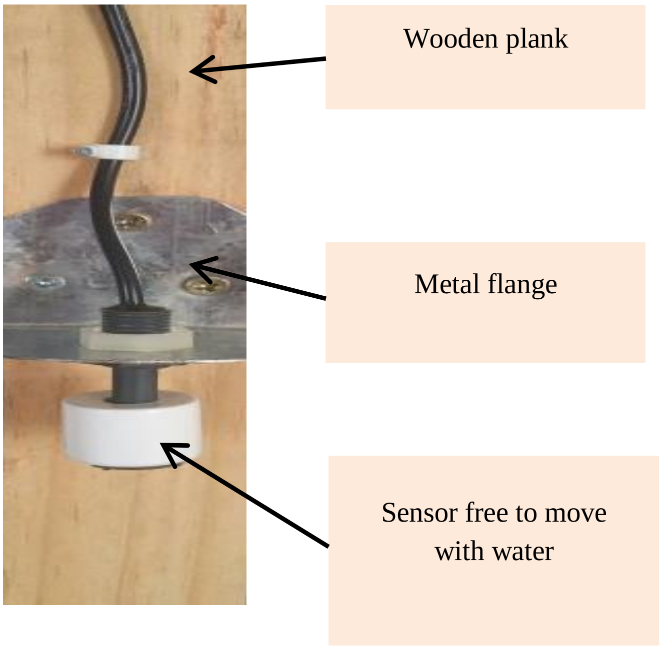


Figure 22: The magnetic sensor placement in the storage tank affixed onto a plank with a metal flange.

However, the sensing part was free to move up or down with the water level.

The borehole safety level sensor (BHSL) was fastened on the pump's discharge hose just above the pump, with its sensing part vertical and free to move. The STUL sensor was placed at 5 cm below the top of the ST to give a signal when the ST was full just before it could overflow and this represented the full tank status. STLL was placed 5 cm above the base of ST to give a signal when the ST was almost empty representing the ST empty status. Further, BHSL sensor was placed just above the submersible pump such that whenever the level of water was just above the submersible pump position, then BH was considered empty and if it was above this level then BH was considered to as having sufficient quantity of water to allow pumping. This sensor ensured that whenever BH was almost running dry, pumping stopped thereby saving the pump from dry running because such an occurrence may damage the pump.

The control unit (arduino board) was used to control the overall system automatically with minimum complexity. The arduino control unit used the information from the sensors, processed it and turned it into output control action that was sent to both LED display and pump actuation units. The control action corresponded to the current status of water level in the ST and BH. The flow of information from the inputs to the controller which sent necessary commands to the outputs in the prototype is schematically shown in Figure 23.

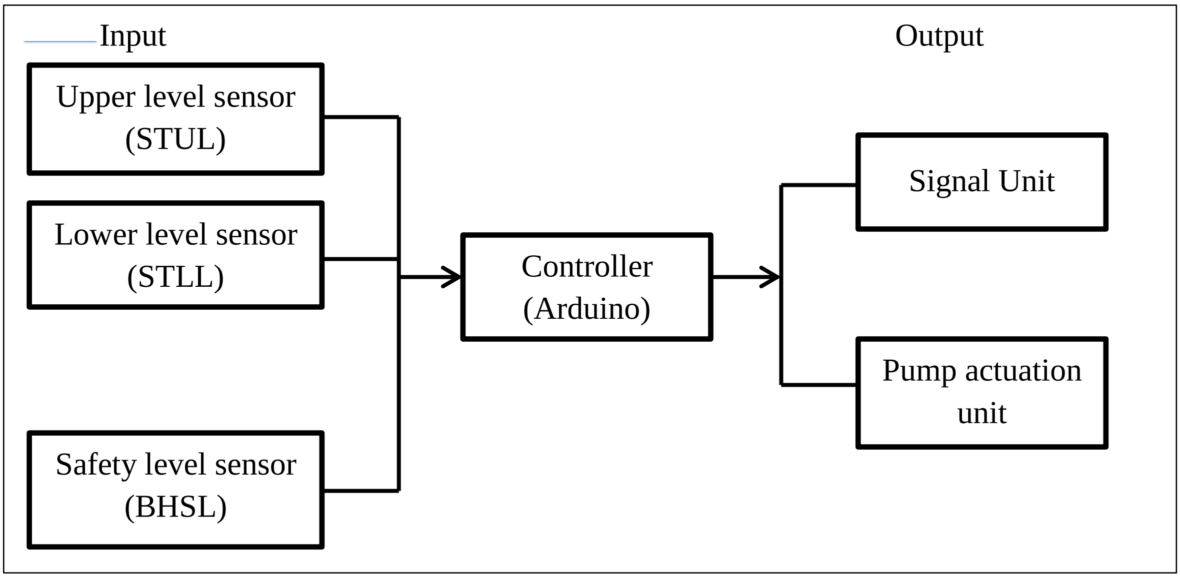


Figure 23: The flow of information in the water pumping system

5.1.4 The water pumping system test results

The process started when both the ST and the BH were empty. The BHSL became open and sent a 5V signal to the arduino board. LED 1 turned ON indicating that no pumping could take place until the BH had recharged sufficiently. This was the dry run protection mode. When the BH had sufficient water and the ST was empty, the arduino board continuously received a 5V signal from both STLL and STUL which then sent a 5V signal to the relay switch closing the normally open (NO) terminal. This allowed the 12 V to flow to the pump thereby switching it ON. In addition, LED 2 was also switched ON by the arduino board indicating that pumping was taking place. When the water level rose above STLL in the ST and the ST was not full, pumping continued and LED 2 stayed ON. When the ST filled up, STUL sent a 0V signal to the arduino board which opened the NO terminal of the relay switch. Consequently, the pump was switched OFF and LED 3 was switched ON to indicate that the ST was full. If pumping was taking place and the BH ran dry, BHSL sent a 5 V signal to the arduino board which turned the pump ON. In this case, LED 1 turned ON indicating that the BH ran dry while pumping was still taking place. Therefore, similar to hand-testing operation, the prototype performed as expected and the tests were successful.

5.1.5 Summary

The pumping and water level monitoring prototype has demonstrated that the automatic borehole water management system has a potential to ensure availability of water in the storage tank whenever the borehole has water while also ensuring that the storage tank never overflows thereby saving water. The system was tested to ensure that whenever the level of water in the storage tank reached the pre-set maximum level the pumping was stopped. The system was also tested to ensure that whenever the water level in the borehole was below the pre-set minimum, the pump went OFF to protect the pump from pumping dry which could potentially damage it. There are many pumps being used which do not have protection against dry pumping. When there was enough water in the borehole and the storage tank was empty, the pump went ON. Other than saving water and electrical power, this system can potentially reduce labour costs required for livestock management. This would further contribute to reduction in operating costs.

5.2 Determination of water and energy savings from using the prototype

Figure 24 shows the pictorial view of the experimental set up of the automatic water management system. The borehole tank (BH) used was a 210-litre tank, placed on ground level while the storage tank (ST) was a 25-litre container which was considered full at the 20-litre mark. The ST was elevated using stands to achieve a head of 1.0m, 1.3m, 1.6m, 2.0m, 2.2m, and 2.6m.

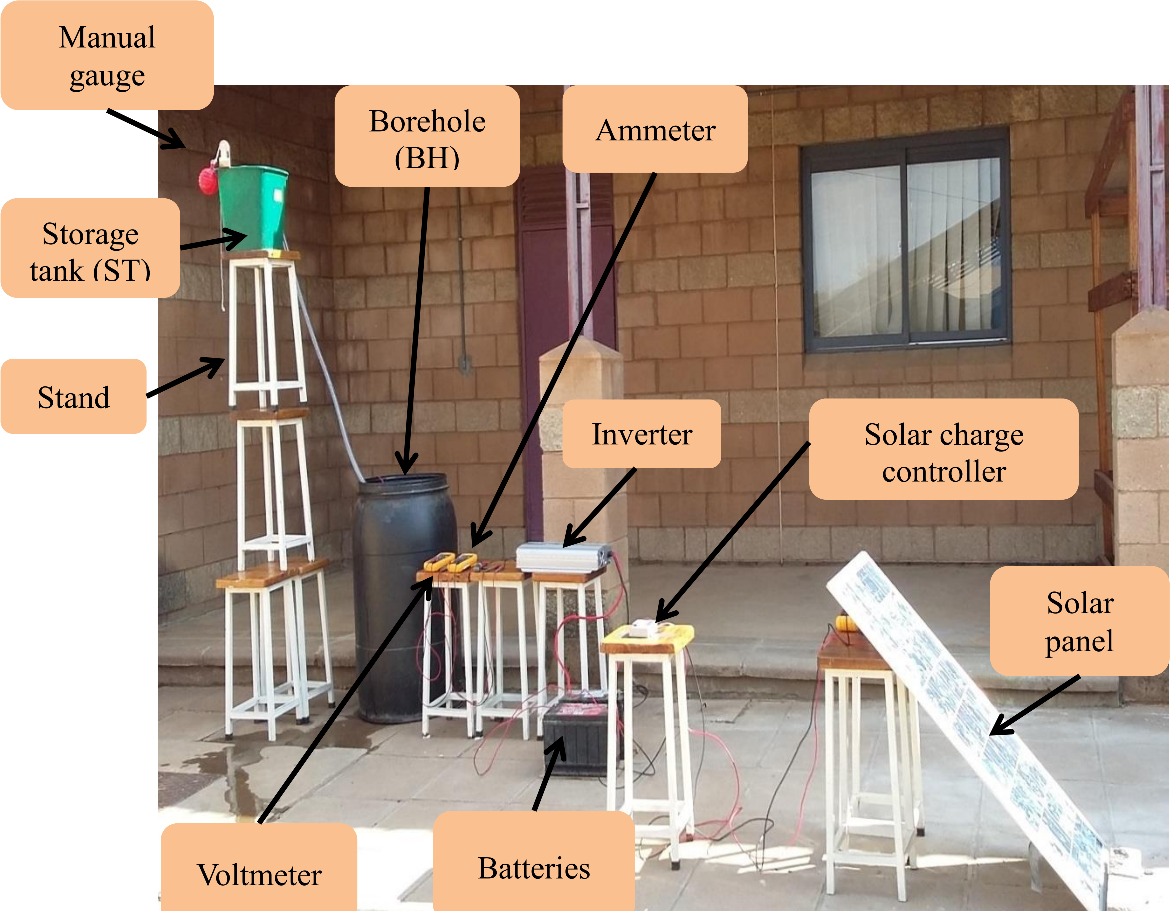


Figure 24: Laboratory set up at 2.6 m data collection on solar power

5.2.1 Determination of the pump flow rate

Table 5 shows the results for the determination of the average flow rate of the submersible pump for comparison with the manufacturer’s rated value.

Table 5: Results of the flow rate test of the submersible pump

Readings	Volume (l)	Time (sec)	Flow Rate (l/h)
1	170	385	1587.7
2	170	352	1738.7
3	170	411	1489.1
4	170	357	1714.3
5	170	391	1565.2
6	170	454	1347.8
7	170	342	1790.9
8	170	388	1575.4
9	170	443	1382.3
10	170	356	1716.7
Average	170	388±12	1590.8±47.9

The average flow rate determined was 1590.8±47.9 *l/h* at a head of about 1 m, the height of the tank representing the borehole. This flow rate was comparable to the pump's rated flow rate of about 1760 *l/h* at the same head, whose performance curve is shown in Appendix C. The conditions under which the pump was operating in this experiment could have caused the difference when compared to those of the manufacturer which are usually ideal conditions.

5.2.2 Experimental results

Table 6 shows the average day-time weather conditions experienced during the 5-day period when the measurements were carried out.

Table 6: Weather conditions

Weather parameter	**Average value**
Cloud cover	No clouds
Temperature	30.3^{o}C
Relative Humidity (RH)	64.74%
Solar Radiation	489.7 W/m^2

It was generally sunny, with no cloud cover and the solar panel continuously charged the batteries which provided adequate power to the pump throughout the experiment.

The effect of varying the elevation of the ST or pumping head on energy consumption of the pump was investigated and the results are shown in Table 7 when using grid power and Table 8 when solar power was used. Several measurements were carried out for each head, and the standard error is included in the results for each measurement.

Table 7: Average grid power consumption with varying elevation of the storage tank above the ground

Elevation	Average grid power consumption				
(m)	Current (A)	Voltage (V)	Power (W)	Time (s)	Energy (Wh)
1.0	1.81±0.01	11.75±0.01	21.26±0.03	42.38±0.08	0.25±0.01
1.3	1.80±0.01	11.74±0.01	21.11±0.03	53.13±0.37	0.31±0.01
1.6	1.78±0.01	11.74±0.01	20.89±0.11	53.70±0.41	0.31±0.01
2.0	1.70±0.01	11.79±0.01	20.05±0.06	67.17±0.22	0.37±0.01
2.2	1.63±0.01	11.80±0.01	19.26±0.10	87.53±0.57	0.47±0.01
2.6	1.47±0.01	11.87±0.01	17.42±0.11	88.62±1.03	0.43±0.01

Table 8: Average solar power consumption with varying elevation of the storage tank above the ground

Elevation	Average solar power consumption				
(m)	Current (A)	Voltage (V)	Power (W)	Time (s)	Energy (Wh)
1.0	1.80±0.01	11.73±0.01	21.14±0.04	48.46±0.07	0.28±0.01
1.3	1.80±0.01	11.74±0.01	21.09±0.02	52.55±0.12	0.31±0.01
1.6	1.78±0.01	11.75±0.02	20.85±0.03	53.96±0.20	0.31±0.01
2.0	1.70±0.01	11.78±0.01	20.05±0.06	74.15±0.19	0.41±0.01
2.2	1.63±0.01	11.81±0.01	19.22±0.05	81.23±0.16	0.43±0.01
2.6	1.49±0.01	11.86±0.01	17.68±0.07	90.58±0.08	0.44±0.01

It was observed that as the ST elevation increased, the energy consumed by the pump, using either power source, increased. This was in line with the energy consumption curve of a pump (Takacs, 2009). It was also noted that the time taken to fill ST increased and consequently the flow rate of water decreased with an increase in head. The pump had a rated maximum head of 3 m. During the experiment, it was not possible to pump water at this height as the water resistance was very high.

The average time taken to fill the ST at the maximum elevation of 2.6m was 88 and 90 seconds for grid and solar power respectively, at a flow rate of 818.2 l/h and 800 l/h, respectively. At this head, $17.42 \pm 0.11\ W$ and $17.48 \pm 0.07\ W$ of grid and solar power were consumed by the pump, respectively. Therefore, the amount of energy consumed was $0.43 \pm 0.01\ Wh$ and $0.44 \pm 0.01\ Wh$ from grid and solar, respectively, in pumping 20 litres of water into the storage tank (ST). The automatic water management system effectively stopped pumping when the storage tank (ST) was full and started the pump when ST was empty. This confirmed that the system can effectively stop water wastage through overflows in farms.

5.2.3 Survey results

Upon carrying out the survey among borehole owners in BUAN, 15 responses were received with 87% of the farmers reporting that they do not have monitoring systems for the borehole or the storage tank. Therefore, pumping is normally carried out manually by the operators who only switch off the pumps when they either have finished working with water or they think the tank is full. These farmers further agreed that water overflow normally takes place from the storage tanks as the operators normally switch on the pump and go to attend to other chores. Further, the monitoring system used by 13% is manual operation of pumping operation to store water in two tanks fitted with float valves such that when water fills one tank, the float closes the valve and water is redirected to the other tank. However, they still have no way of establishing whether all the tanks are full or monitoring the borehole. The use of float valves and manual pump operation could be detrimental to the plumbing when all the tanks are full and yet the pump is still operating. This would arise as the pump's motor would continue to run the impeller. Since there is no water outlet, it would continue to spin the same volume of water, eventually exceeding the amount of pressure the plumbing can hold causing the pipes to burst. Additionally, lack of low level sensors causes the high risk of dry running that leads to cavitation and damage of the impeller and bearings (Edison & Rob, 2016). All the farmers interviewed do not have a way of monitoring the borehole water level. Some of the farmers indicated that they do not experience overflows as a result of low borehole yields and recharge rates. 13% of the farmers interviewed indicated the properties of their pump to have an average rated flow rate of 35 l/min, while the overflows happen for an average of 30 minutes. The other farmers could not remember the properties of their submersible pumps used. In addition, most farmers indicated that they cannot accurately establish how long water overflows before the operator switches off the pump, as there is normally no one to monitor the overflow. The boreholes were found to have an average depth of 90 m.

The feedback from the farmers ascertained the importance of the automatic water management system for pumping water into the overhead storage tanks while also monitoring the status of the borehole water level.

5.2.4 Water and energy savings

The automatic water management system has shown its ability in eradicating water overflows in farms saving both water and associated energy. Since the energy consumed by the pump in the experiment at a head of 2.6 m was 0.44 Wh, then by extrapolation, the energy required to pump water at a head of 90 m would be 11.81 Wh. From the survey, the average flow rate of the pump considered was 35 l/min and the average time for overflow was 30 minutes. This means that about 1050 litres of water is lost in one farm through storage tank overflow during one pumping event. Again, if for a head of 90 m, pumping 20 litres of water would require 11.81 Wh, then, 1050 litres would lead to associated pumping energy loss of 0.62 kWh in a single pumping event. However, the automatic system prevented overflow meaning that there is no volume of water and associated energy lost. From the survey, pumping was recorded to take place an average of 4 times a week during winter and 6 times during summer. Taking that summer and winter last six months each, then each borehole had 260 pumping events in a year. The total amount of water and energy that could be saved in one year in Botswana was therefore found to be 6,825,000 cubic metres and 3,627 MWh of energy respectively. The total annual water saved in Botswana was obtained using all the registered boreholes while energy saved was obtained using the boreholes that do not use solar power. Water is priced as a block tariff by (Water Utilities Corporation, 2015) as shown in Table 9, while electricity is priced as 21.96 BWP/month fixed charge and 0.8828 BWP/kWh per month by (Botswana Power Corporation, 2016).

Table 9: Monthly water tariff

Amount (kL)	0-5	5-15	15-25	25-40	>40
Cost (BWP)	2.00	8.00	13.00	20.00	25.00

From the tariffs provided, the amount of money saved in Botswana through water savings and associated energy is shown in Table 10.

Table 10: Annual savings due to overflow elimination

Annual Quantities		
Water saving	Amount(Kilo-litres)	Value (BWP)
	6,825,000	57,225,000
Energy saving	Amount (kWh)	Value (BWP)
	3,627,000	9,131,400
Total savings (BWP)		**66,356,400**

At a national level, about 6,825 million litres of water can be saved by eliminating overflows with associated energy of 3,627 MWh annually as shown in Table 10. The loss of such huge amounts of these rare resources is of great concern and ways to eliminate them should urgently be developed in order to ensure sustainability. The solar powered automatic water management system is a perfect candidate as it has shown its ability in eliminating the losses while also monitoring the borehole. Botswana can save a total of about 66 million BWP as a result of abolishing overflow of the scarce underground water.

5.3 Economic analysis of the use of solar energy in powering the prototype

5.3.1 Economic viability

Table 11 shows the 2.7% discounted cash flows using the inflation rate for Botswana in June 2016 over a period of eight years. The results were then used to calculate the payback period and are presented in Table 12. The payback period was obtained as the year when the cumulative cash flows changed their sign from negative (represented in brackets) to positive values. The results show that automatic solar water management system would take about 4 years and 4 months for a farmer to pay back their investment cost. This showed that the system is indeed economically viable to implement in Botswana in order to enhance both water and energy use efficiency, while effectively incorporating environmentally friendly measures.

The solar automatic water management system has also shown that it is economically viable for implementing in Botswana. The payback period obtained was about 4 years and 4 months after which a farmer will have recouped his investment back. Various stakeholders should therefore be encouraged to adopt this system in order improve the efficiency of water pumping while also lowering the amount of manpower needed to monitor the system.

Table 11: Discounted Cash flows over 8 years

Years	0	1	2	3	4	5	6	7	8
Solar pump	(9 940.00)								
Solar panels	(2 216.00)								
Arduino controller	(4 000.00)								
Installation cost	(1 000.00)								
Maintenance cost		(1 000.00)	(1 000.00)	(1 000.00)	(1 000.00)	(1 000.00)	(1 000.00)	(1 000.00)	(1 000.00)
Solar benefit (Grid power not used)		3 000.00	3 000.00	3 000.00	3 000.00	3 000.00	3 000.00	3 000.00	3 000.00
Arduino controller benefit (saved costs on water & energy)		3 550.00	3 550.00	3 550.00	3 550.00	3 550.00	3 550.00	3 550.00	3 550.00
Cash flows	(17156.00)	5 550.00	5 550.00	5 550.00	5 550.00	5 550.00	5 550.00	5 550.00	5 550.00
Discount factor @ 2.7%	1.00	0.97	0.95	0.92	0.90	0.88	0.85	0.83	0.81
Discounted cash flows	(17156.00)	5 404.09	5 262.02	5 123.68	4 988.97	4 857.81	4 730.10	4 605.74	4 484.66

Table 12: The calculated payback period for a solar power system

Discounted Payback Period	Years	Discounted cash flows	Cumulative cash flows
	0	(17 156.00)	(17 156.00)
	1	5 404.09	(11 751.91)
	2	5 262.02	(6 489.90)
	3	5 123.68	(1 366.22)
	4	4 988.97	3 622.75
	5	4 857.81	8 480.57
	6	4 730.10	13 210.67
	7	4 605.74	17 816.41
	8	4 484.66	22 301.07
Payback is :	**4 years, 4 months**		
Year Four	4 988.97		
Each month of year four	415.75		
Months in year 4 to get to 0	3.29	Approx. 4	

CHAPTER 6 CONCLUSIONS

For each specific Objective, the following conclusions have been drawn.

Objective 1

An automatic water level monitoring and control prototype was successfully designed, assembled and tested. The arduino-controlled prototype consisted of a control unit, storage tanks representing water storage tank and borehole, and electrical energy supplies. The complete assembly was tested at a laboratory scale and it performed according to expectations.

Objective 2

The water and energy savings as a result of the use of the prototype were determined at a laboratory scale and extrapolations were made at a national scale considering all registered boreholes in Botswana. On a yearly basis, it was revealed that the use of prototype system could save 6,825,000 cubic metres of water and a corresponding 3,627 MWh of corresponding energy. This translated to BWP 66,356,400 (USD6, 635, 640) of monetary savings per year.

Objective 3

The discounted payback period method applied on the solar energy system revealed that when powering the prototype with solar energy, it would take about 4 years to return the investment made by a farmer. The system could therefore be considered suitable for use by rural farmers in Botswana.

In summary, the automatic borehole water management system could be very useful in Botswana in sustainably managing the rare water resource through elimination of water wastage through overflows and consequent energy losses. The system could further eliminate the need for use of diesel generators to pump water and alternatively use the abundant solar energy. Finally, the solar powered system is financially feasible as it pays back within a period of 4 years. This study therefore disapproved the first hypothesis while at the same time proved the second hypothesis that automatic pumping system leads to significant reduction in water losses due to overflow.

CHAPTER 7 RECOMMENDATIONS

The objectives set out in this research were achieved albeit with room for further improvement. Various opportunities were identified to improve the system. They include;

1. A more detailed survey of water consumption and overflows from storage tanks in Botswana farms should be carried out. This would help researchers with necessary information on water consumption, associated energy consumption and cost implications. The survey would also help in identifying the market penetration of solar water pumping systems.
2. Information on seasonal water consumption in the farms should be sought. This would be important in determining a more accurate payback period of the use of solar energy in water pumping.
3. The automatic system could be improved to include water metering and logging of water extraction quantities from boreholes and electrical energy consumption patterns. Further, remote monitoring capability such as through the use of mobile phones which are widely distributed in Botswana could be considered for incorporation into the system.
4. The prototype should be tested more in a real farm setup. Tests would help in finding out the reliability of the system in controlling the water abstraction from the borehole. Upon successful tests and exposure to users (farmers) through organised field days, the automatic system could be rolled out to farmers.

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APPENDICES

Appendix A: Program code for the pump control unit

The following program is written using Arduino Programming Language

```
// improving water management on farm
//INPUTS
int tankFull = 2;
int tankEmpty = 3;
int boreEmpty = 4;

int tankFullStatus;
int tankEmptyStatus;
int boreEmptyStatus;

//OUTPUTS
int relay = 5;
int redLed = 6; //LED 1
int greenLed = 7; // LED 2
int blueLed = 8; //LED 3

void setup()
{
  pinMode(tankFull, INPUT);
  pinMode(tankEmpty, INPUT);
  pinMode(boreEmpty, INPUT);
  pinMode(relay, OUTPUT);
  pinMode(redLed, OUTPUT);
  pinMode(greenLed, OUTPUT);
  pinMode(blueLed, OUTPUT);
```

```
  digitalWrite(tankFull, HIGH);
  digitalWrite(tankEmpty, HIGH);
  digitalWrite(boreEmpty, HIGH);
}
//SYSTEM BEHAVIOR
void loop()
{
  //Read all sensors
  tankFullStatus = digitalRead(tankFull);
  tankEmptyStatus = digitalRead(tankEmpty);
  boreEmptyStatus = digitalRead(boreEmpty);
  //delay(5);

  //SENSORS SIGNAL MANIPULATION
  if (boreEmptyStatus == HIGH)
  {
    digitalWrite(relay, LOW);
    digitalWrite(redLed, HIGH);
    digitalWrite(greenLed, LOW);
    digitalWrite(blueLed, LOW);
  }
    if (tankFullStatus == LOW)
  {
    digitalWrite(relay, LOW);
    digitalWrite(redLed, LOW);
    digitalWrite(greenLed, LOW);
    digitalWrite(blueLed, HIGH);
  }
   if (boreEmptyStatus == LOW && tankEmptyStatus==HIGH && tankFullStatus ==
```

Appendix B: Questionnaire for the borehole synoptic information survey

Date: …………………….. Your Name: ……………………..

<u>Section A: Borehole and Pump Information (</u>*Tick where appropriate*)

<u>Borehole</u>

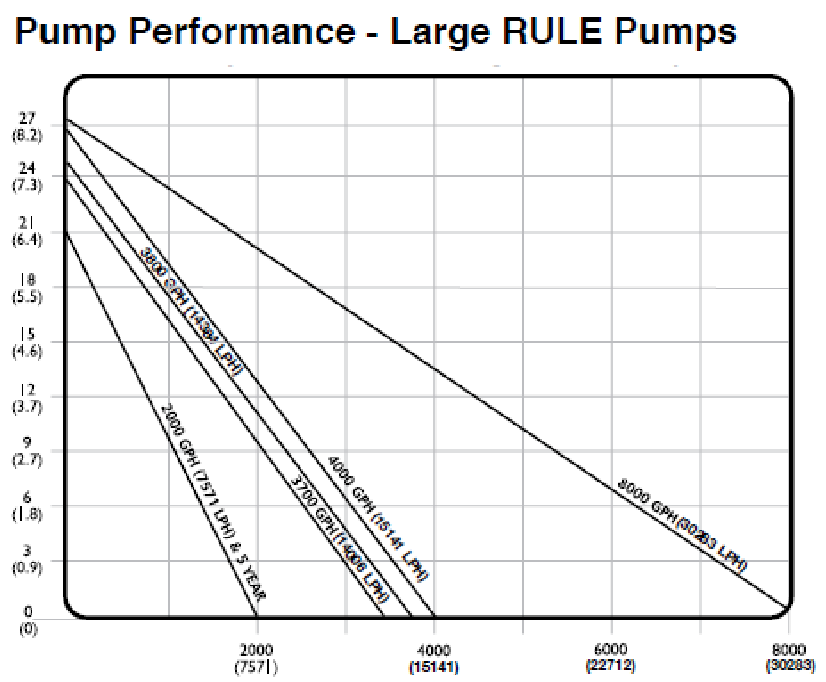
- In which district is the farm situated? : ………………………………….
- Name of the location: ………………………………….
- Depth of Borehole (m): ………………………………….
- Approximate yield (m^3/hr OR Litres/hr): ………………………………….

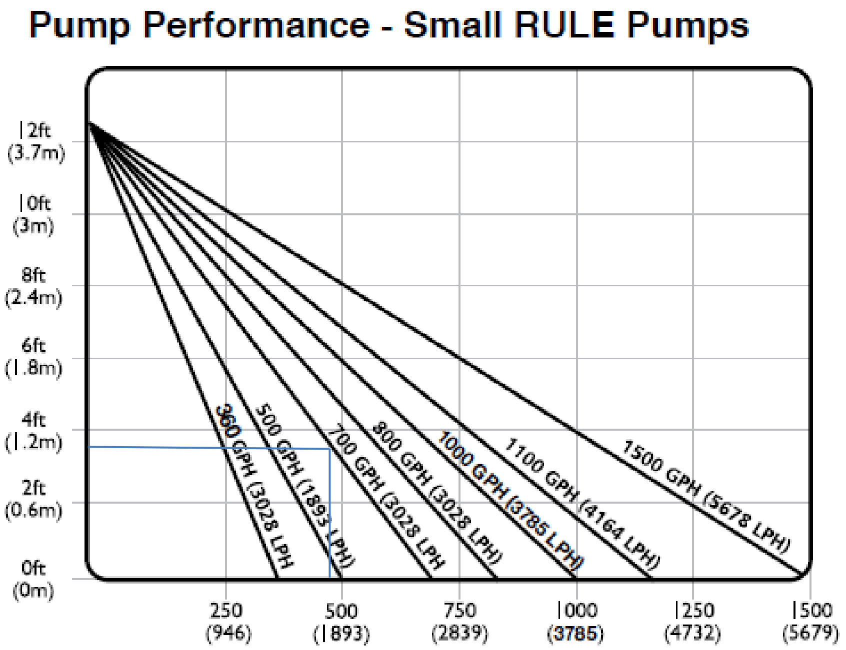
<u>Pump</u>

- Type: Mono OR Submersible (tick)
- Power rating (kW): ………………………………….
- Pump Flow rate (litres per hour) ………………………………….
- Power supply source: Diesel/Petrol OR Solar OR Grid (Tick)
- Your storage tank Capacity (l): ………………………………….
- On average, how long do you run the pump per each pumping event? (hours/ pumping event): ………………………………….
- Do you experience any overflow from your storage tank? YES or NO (tick)
- If Yes, on average how long does the overflow take per each pumping event before turning of the pump? (minutes per pumping event) ………………………………….
- What is the approximate volume of overflow per pumping event (litres or m^3) ………………………………….
- Pumping frequency per week in each season: ………………………………….
- Do you have a water level monitoring system? YES or NO (tick)
- Are there other forms of water wastage in the water distribution system, like leakages? YES or NO (tick)

Thank You

Appendix C: Pump’s performance curve


Pump Performance - Large RULE Pumps


Pump Performance - Small RULE Pumps