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Optimisation of Irrigation and Fertigation Processes through Automated Control Systems: A Case of Maziwa Farm's Low-yielding Boreholes in Murewa, Zimbabwe

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***Abstract* - The aim of this research was to design an automated irrigation and fertigation system in low yielding boreholes at Maziwa farm, Murewa, Mashonaland East Province of Zimbabwe. The study focused on designing an automated controlsystem of irrigation and fertigation using the PIC18F4550 microcontroller. The work entailed the designing of a fertilizer and herbicide chemical plant and the simulation of the developed control system. An irrigation and fertigation control system program was developed using Mikro C Pro software and simulated using Proteus software. Key considerations in the fertiliser and herbicide chemical plant design included a drip irrigation system for optimised water, fertiliser, and herbicide distribution, featuring chemical tanks and solenoid valves for controlled injection. Emitters, laterals and the mainline pipes, a medium for the irrigation water and fertilizer or herbicides to the plants were also selected. The automated irrigation system employs a micro-controller that utilizes Global System for Mobile Communication (GSM) technology in facilitating operator communication. The system status updates were sent to the user via SMS (Short Message Service) with connection between the user and the system being possible also through text messages for action confirmation. The results of the research were validated using simulation with proteus software.**

Keywords: Irrigation optimisation, automated control systems, fertigation system, Maziwa farm, Murewa, Zimbabwe.

I. INTRODUCTION

Underground water serves as Zimbabwe's main water supply. Groundwater encompasses all water found beneath the surface, covering unsaturated and saturated regions. An aquifer is a geological establishment with capability to store and transferring considerable quantities of underground water, sufficient to meet public and irrigation needs[1]. Zimbabwean farmers rely on manually operated boreholes but the few who use electrical boreholes still manually operate and control them[2]. A borehole is defined as a deep vertical wall of minimum diameter drilled into the ground to access water, and it comprises of key components[3]. Mechanical seal degradation primarily occurs during dry running conditions, where insufficient lubrication between sliding surfaces causes raid destruction, severely impacting pump performance[4]. GSM modems are mostly used to provide internet connectivity for mobiles, and many of them are used for transmitting Short Message Service with Multimedia Message Service[5]. There is need for flexibility to people's lives and working systems to optimize their efforts in their daily operations[6]. The researcher identified the gap and hence the need to design an automated control system for the Maziwa farm.

1.1 Related Work

A GSM enabled irrigation system[7, 6, 8], controlled by a microcontroller, utilizes rain gun technology to optimise water usage, irrigating only when water is urgently needed, resulting in significant water conservation. This application leverages mobile phone technology to provide an innovative solution for irrigation control. The system's primary constraints are its restricted range and prohibitively high expenses, making it unsuitable for large-scale agricultural applications. A study by Yunseop *et. al,* [9, 8], presented on the distributed wireless sensor network for remote sensing and control. A robust and moderately effective framework is established, utilising a Windows application to monitor fields. The drip irrigation system is growing in popularity as it proves more effective in supplying nutrients and water to plant roots compared to conventional farming techniques [10]. Currently, researchers have made efforts to design and automated irrigation systems [11], but the effectiveness and feasibility of these systems in actual agricultural environments have yet to be thoroughly examined.

Researchers have initiated another study aimed at optimizing drip irrigation techniques[12]. This technique streamlines farming operations by automating fertiliser mixing, reducing time and labour requirements. The slow uptake of automated irrigation and fertigation technology can be attributed to factors such as limited awareness, inadequate technical expertise, and prohibitively high implementation costs, including advanced hardware requirements. Microcontroller based automatic irrigation plant systems are efficient and automated watering, results in significant water and financial savings [13]. The system's operations are governed by the programmable 851 microcontroller, ensuring uninterrupted signals to the sprinkler.

1.2 Aim

To design and implement an optimal automated control system for irrigation and fertigation processes.

1.3 Objectives

- To assess if the yield of the six boreholes meets the minimum threshold of seventy (70) litres per minute.
- To design an automated irrigation and fertigation control system using the PIC18F4550 microcontroller.
- To design an automated fertilizer and herbicide chemical plant.
- To simulate the irrigation and fertigation control system using Proteus software.

1.4 Research Hypothesis

Irrigation and Fertigation Process Optimisation: A Hypothesis Test for Automated Control.

H0: The optimisation of an automated irrigation and fertigation control system does not significantly improve water usage efficiency and fertiliser application at Maziwa farms low-yielding boreholes in Murewa, Zimbabwe.

H1: The optimisation of an automated irrigation and fertigation control system significantly improves water usage efficiency and fertiliser application at Maziwa farm's low-yielding boreholes in Murewa, Zimbabwe.

II. MATERIALS AND METHODS

2.1 Materials

PIC18F4550 microcontroller, moisture sensors, and level sensors, bore pumps, Chemical Injectors.

2.2 Methods

The research was carried out at Maziwa farm in Mashonaland East Province where faming activities are done through underground water which was harnessed through manual borehole pumps which the researchers sought to automate by designing a PIC18F4550 microcontroller. The component is a highly integrated, single chip computer system incorporating essential memory and peripheral functions to minimise external dependencies. To remove insulation problems associated with electrical equipment, submersible pumps made up of plastic were selected wherever possible [14]. The chosen submersible pumps feature a compact, close-coupled design with a fully enclosed motor cooled by surrounding water. To regulate water levels and automate pump operation, level switches were mounted inside the casting[15]. Submersible pumps exist both as low voltage ratings of 110V single phase rating of 240V and three phase rating of 380V[16]. Figure 2.1 shows the layout of Maziwa farm.

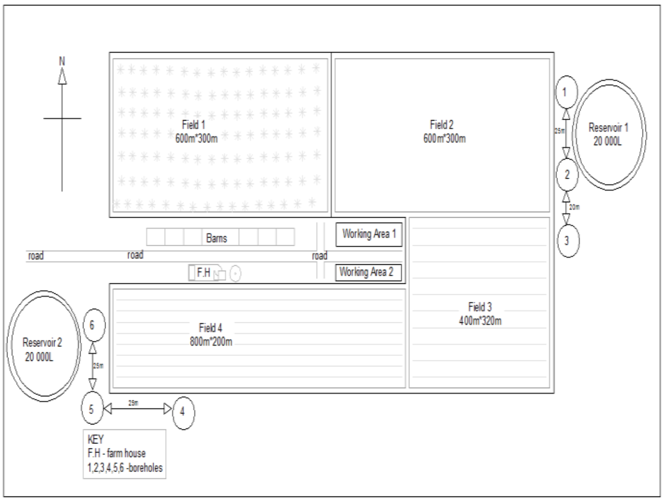

Figure 2.1: Maziwa Farm Layout

Figure 2.1 shows Maziwa farm layout, an $A2$ small-scale commercial farm of size $78ha$ located in Murehwa. The farm comprises of 6 boreholes which supply the farming water, two 20 000 $litre$ water reservoirs are installed at the farm where the water is pumped into before being pumped to the fields.

Table 2.1: Crops grown at Maziwa farm

Crop	Season
Maize	Spring
Bean	Spring
Carrot	All year round
Cabbage	All year round
Onion, bulb	Winter
Lettuce	All year round
Tomato	Summer, winter
Potato	Spring
Cucumber	Spring
Pepper	All year round

Table 2.1 shows the crops grown at Maziwa farm. During the dry season crops are irrigated, surface irrigation is employed at Maziwa farm, flood and furrow irrigation are employed in applying water to the crops, during the rainy season crops are also supplemented with irrigation water [13].

The yield rates for Maziwa farm boreholes' water supply capabilities are shown in Table 2.2.

Table 2.2: Maziwa farm boreholes water supply capabilities

Borehole	Borehole yield rate (l/hr)	Bore depth (m)	Static water level (m)
1	800	70	14.3
2	800	82	13.2
3	750	75	14.2
4	800	72	14.0
5	790	75	14.4
6	700	78	14.2

The concept development phase was the starting point of system design process. In this research the Pahl and Beitz design process was followed in carrying out the design process [17]. Concept development followed the subsequent activities: concept generation, concept screening, concept scoring and concept testing. The selected concept matrix was then developed. The Pahl evaluation matrix was used to evaluate the concepts in this study. Based on the customer requirements for the problem at hand a house of quality was constructed[18] The house of quality transformed the customer requirements into engineering characteristics which then helped with the development of the research study.

2.3 Concept Generation

This section reviews concepts for possible solutions to the problem.

2.3.1 Concept A

The concept comprises of water reservoir and differential pressure tank which injects chemicals into the irrigation system for crop production.

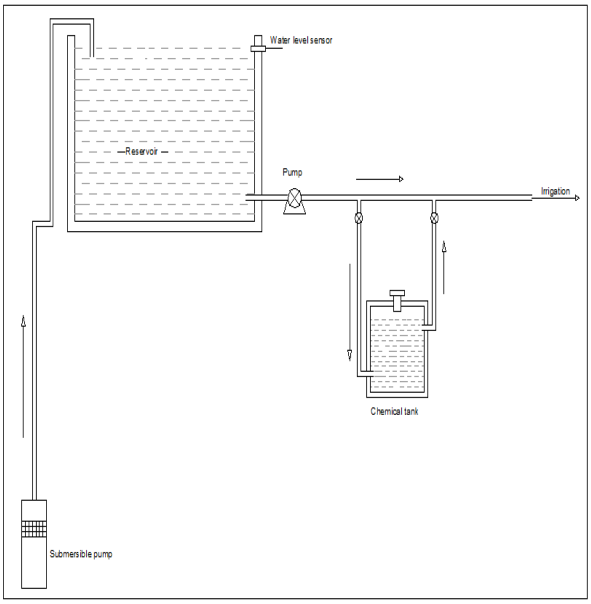

Figure 2.2: Water reservoir and differential chemical tank

2.3.2 Concept B

This concept comprises of the water reservoir and venturi injector linked to the drip irrigation.

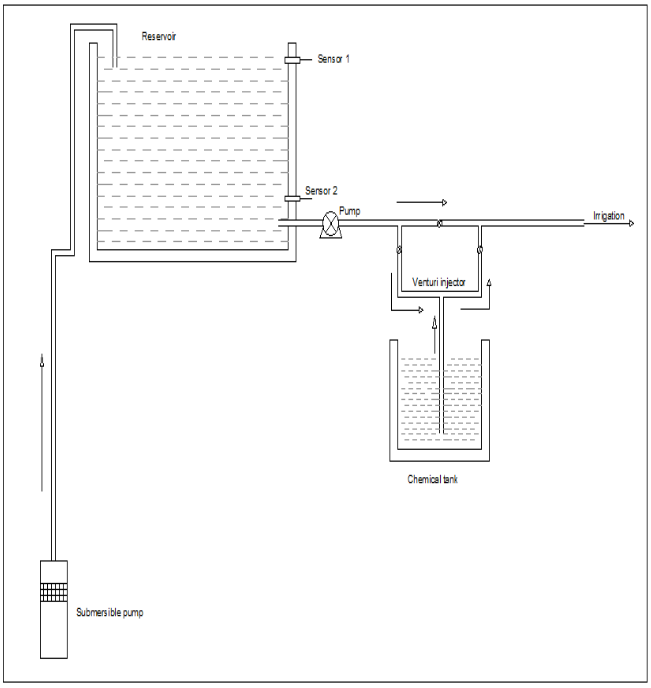

Figure 2.3: water reservoir and venturi injector

2.3.3 Concept C

This concept comprises of the water reservoir and the chemical tank linked to the drip irrigation.

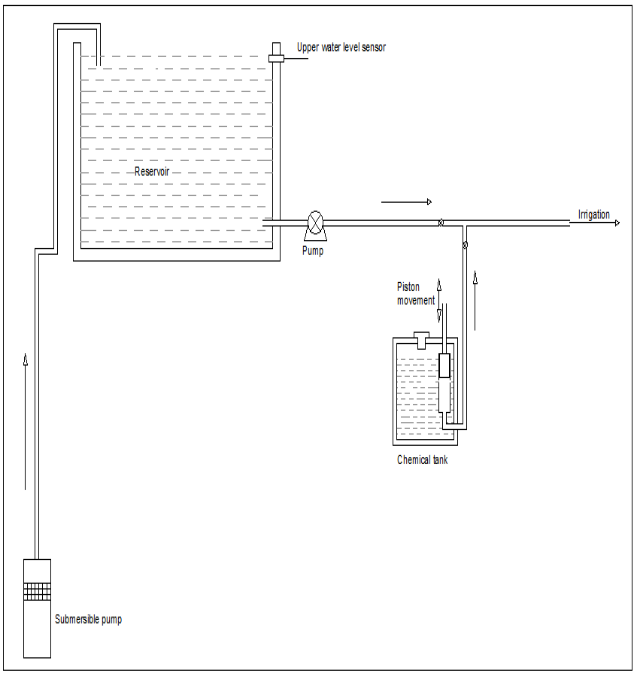

Figure 2.4: water reservoir and a chemical delivery system linked to the main line

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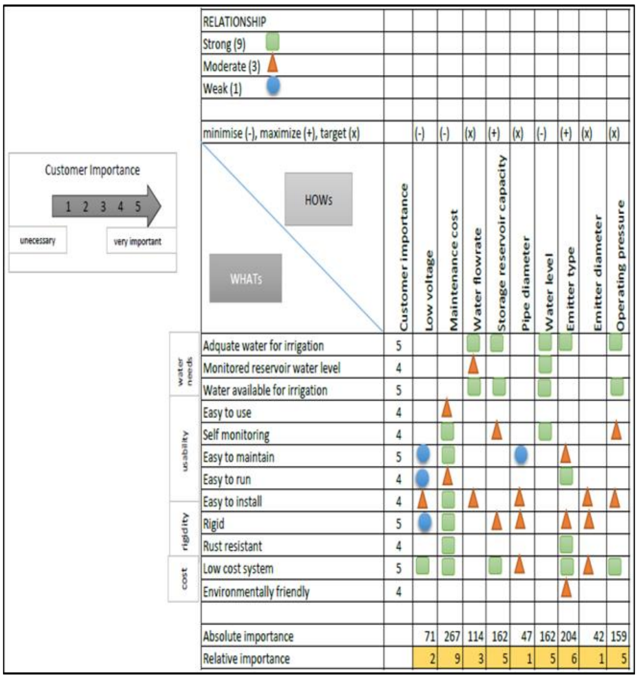
2.4 Concept Screening

Using customer feedback, a Quality Function Deployment (QFD) matrix was developed during the screening phase to translate customer needs into technical specifications.



RELATIONSHIP

Strong (9) 🟩

Moderate (3) ▲

Weak (1) ●

		Customer importance	Low voltage	Maintenance cost	Water flowrate	Storage reservoir capacity	Pipe diameter	Water level	Emitter type	Emitter diameter	Operating pressure
	minimise (-), maximize (+), target (x)		(-)	(-)	(x)	(+)	(x)	(-)	(+)	(x)	(x)
water needs	Adquate water for irrigation	5			🟩	🟩		🟩	🟩		🟩
	Monitored reservoir water level	4			▲			🟩			
	Water available for irrigation	5			🟩	🟩		🟩			🟩
usability	Easy to use	4		▲							
	Self monitoring	4		🟩		▲		🟩			▲
	Easy to maintain	5	●	🟩			●		▲		
	Easy to run	4	●	▲					🟩		
	Easy to install	4	▲	🟩	▲		▲			▲	▲
rigidity	Rigid	5	●	🟩		▲	▲		▲	▲	
	Rust resistant	4		🟩					🟩		
cost	Low cost system	5	🟩	🟩		🟩	▲		🟩	▲	🟩
	Environmentally friendly	4							▲		
	Absolute importance		71	267	114	162	47	162	204	42	159
	Relative importance		2	9	3	5	1	5	6	1	5

Figure 2.5: Quality Function Deployment (QDF) for the irrigation control system

Figure 2.5 is the QFD matrix integrating the views of the customer to the engineering voice design attributes. The research showed that the chosen concept was the final design. Figure 2.6 is a design solution comprised of the water reservoir with an upper and lower-level sensors, a chemical tank to supply chemicals and fertilizers to the irrigation system, a centrifugal pump to push the chemicals[19], in solution and water from the reservoir to the drip line for irrigating crops and valves for backflow prevention.

2.5 Concept Selection

Table 2.3 shows Concept screening matrix where developed concepts were rated and screened using a set of selection criteria.

Table 2.3: Concept screening matrix

Selection criteria	Concepts		
	Concept A (reference)	Concept B	Concept C
Adequate water for irrigations	0	0	0
Water-level controlled reservoir	0	0	+
Easy to use	0	+	+
Easy to install	0	+	-
Self-monitoring	0	-	+
Maintainability	0	+	-
Whether it is rust resistant	0	0	0
Low-cost system	0	+	0
Summation +'s	0	3	3
Summation 0's	0	4	3
Summation – 's	0	2	2
Net score	0	2	1
Ranking	3	1	2
Continue	Discontinue	Yes	Continue

KEY	
Better than	+
Same as	0
Worse than	-

2.5.1 System Design: Chosen solution

Using the concept screening matrix, the chosen solution for the intended design is shown in figure 2.6 below:

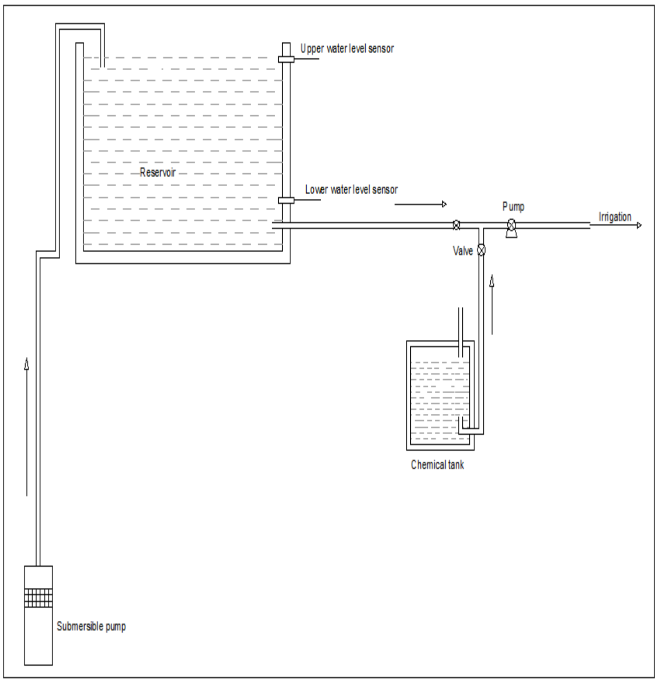


Figure 2.6: Chosen design solutions

2.6 Design Calculations

This section focuses on the design, selection and development of the various components of the irrigation and fertigation system at Maziwa farm.

2.6.1 Pump selection

With the starting operating parameters as given in table 2.4 below, the required pump power rating was selected.

Table 2.4: Required pump power rating

Parameter	Magnitude
Required water discharge (Q)	$1.6\,l/hr = 1600\,m^3/hr = 0.44\,m^3/s$
Water density	$1000\,kg/m^3$
Operating head	$0.8\,m$
Acceleration due to gravity (g)	$9.81\,m/s^2$

The output power of a pump is given by:

$$P_{out} = Q\rho_w gh \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (2.1)$$

Where

P_{out} = pump output power (W), Q = discharge (m^3s^{-1}), ρ_w = water density (kgm^{-3}), g represents the acceleration due to gravity, equals to 9.81 metres per second squared (m/s²), and h denotes the operating head in metres (m).

The pump's input power P_{in} must exceed its output power P_{out} , with the overall efficiency determined by pump, transmission, and motor.

$$P_{in}\eta = P_{out} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.2)$$

The efficiency (η) can often be in the range $0.4 - 0.6$.

The electrical submersible pump offers several benefits, including compact design, simplified installation and removal (with flexible rising main), quiet operation, flexibility in borehole alignment, and minimal surface infrastructure.

The electrical submersible pump has several drawbacks, including downhole motor placement requiring removal for repairs, dependence on stable electricity supply, necessary protection from overheating and dry running, requirement for dual electrical and mechanical expertise for maintenance, lower overall power efficiency compared to vertical turbine pumps, less tolerance of sand pumping [19].

2.6.2 Pipe network design

With water requirements of $5000l$ per watering cycle, with two watering cycles required per day, and a water reservoir with a capacity of $20000l$, the required water capacity (W_C) per day $10000 \leq W_C \leq 20000 litres$.

Reservoir 1 is filled by boreholes $1, 2, 3$ and reservoir 2 is filled by boreholes $4, 5, 6$, the water supplied to the different reservoirs by the different boreholes in a time period of an hour is as given in Table 2.5.

Table 2.5: Reservoir water availability

Reservoir	Boreholes number	Borehole yield (l/hr)	Available water (l/hr)
Reservoir 1	1	800	2350
	2	800	
	3	750	
Reservoir 2	4	800	2290
	5	790	
	6	700	

Pipe network for water discharge:

To analyse pipe flow, the continuity equation is applied, specifically for steady circular pipe flow with diameter D:

$$Q = \frac{\pi}{4} D^2 V \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.3)$$

Where,

V (average velocity of flow in ms^{-1}), Q (rate of flow, in m³/s), D (pipe diameter in metres).

The steady flow equation of motion is:

$$z_1 + h_1 + \frac{V_1^2}{2g} = z_2 + h_2 + \frac{V_2^2}{2g} + h_L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. \dots\dots\dots\dots . (2.4)$$

Where

$z_1$and z_2 = centerline elevations (m) from a reference datum and h_1 and h_2 as pressure heads (m), V_1 and V_2 = average velocities at the two different sections (m/s), g = gravitational acceleration m/s^2 and h_L = head loss (m).

Head loss consists of two components: friction loss (surface resistance), and minor loss (form resistance), which occurs due to changes in pipeline shape [14].

The head loss is given by:

$$h_L = h_f + h_m \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (2.5)$$

Where

h_L = Head loss (m), h_f = resistance losses (m) and h_f = head loss due to friction resistance (m).

Assuming a pipe with a uniform cross-sectional area:

$$h_2 = h_1 + z_1 - z_2 - h_L \dots\dots\dots\dots\dots\dots (2.6)$$

Friction loss due to surface resistance is calculated using the Darcy-Weisbach equation:

$$h_f = \frac{fLV^2}{2gD} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

Where

$L =$ pipe length (m), $f =$ coefficient of surface resistance (friction factor)

For tumultuous flow, the surface resistance coefficient is influenced by the average height of roughness projections (ε) on the pipe wall, with typical values for commercial pipes provided in table 2.6.

Table 2.6: Mean surface roughness values

Material for the pipe	Average height of roughness, mm
Asbestos cement	0.05
Asphalted cast iron	0.13
Wrought iron	0.04
Polyvinyl chloride	0.05
Ductile iron	0.25
Steel	0.05
Steel riveting	4.05
Galvanised iron	0.15
Concrete	1.35

In addition to roughness, the surface resistance coefficient relies on the Reynolds number, R, given by:

$$R = \frac{VD}{v} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Where

$v =$ kinematic viscosity of fluid

For turbulent flow $(R \geq 4000)$, the coefficient of surface resistance is given by

$$f = 1.325\left[\ln\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{R\sqrt{f}}\right)\right]^{-2} \ldots\ldots\ldots\ldots (2.9)$$

Where

$\varepsilon =$ the roughness height of materials (mm).

When flow is laminar $(R \leq 2000)$, friction factor, f, depends exclusively on Reynolds number, R, as defined by the Hagen-Poiseuille equation:

$$f = \frac{64}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

Form-resistance losses, caused by fittings (e.g., bends, valves) and interior pipe irregularities, can substantially impact overall head loss in pipe networks, contradicting the notion of minor losses [14].

Form loss is expressed as:

$$h_m = k_f \frac{V^2}{2g} = k_f \frac{8Q^2}{\pi^2 gD^4} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.11)$$

Where

$k_f =$ form loss coefficient,

For pipe bends, the loss coefficient k_f is a function of the bend angle α and bend radius R, the form loss coefficient is given by:

$$k_f = \left[0.0733 + 0.923\left(\frac{D}{R}\right)^{3.5}\right]\alpha^{0.5} \ldots\ldots\ldots (2.12)$$

For near zero bend radius form loss coefficient for elbows should be used, elbows are utilised to proof against the impact of sharp bends in pipelines, the loss coefficient for an elbow is given by:

$$k_f = 0.442\alpha^{2.17} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.13)$$

Where

$\alpha =$ elbow angle in radians.

Head loss accrued by it valves have head losses associated with them. Table 2.7 gives the k_f for fully open valves.

Table 2.7: Loss coefficient k_f for fully open valves

Valve type	Form loss coefficient (k_f)
Sluice valve	0.15
Switch valve	2.4
Angle valve	5.0
Globe valve	10.0

Knowing the various loss coefficientsk_{f1}, k_{f2}, k_{f3}, ..., k_{fn}, the total loss coefficient k_f in a pipeline is determined by summing the individual loss coefficients:

$$k_f = k_{f1} + k_{f2} + k_{f3} + \cdots + k_{fn} \ldots\ldots\ldots (2.14)$$

To determine the net head loss h_L, add the surface resistance loss head loss h_f and form loss h_m, as:

$$h_L = \left(k_f + \frac{fL}{D}\right)\frac{V^2}{2g} = \left(k_f + \frac{fL}{D}\right)\frac{8Q^2}{\pi^2 gD^4} \ldots\ldots (2.15)$$

2.6.3 Borehole water pumping analysis

As water is being pumped, the water level drops, this phenomenon is known as well drawdown. Drawdown is typically expressed in metres, representing the difference between the static water level and the level during pumping. Drawdown measurements are vital to determine if a water source is being depleted and to evaluate the effectiveness and efficiency of wells. A well that yields abundant water, recovers swiftly, and exhibits low drawdown may only necessitate periodic inspections, whereas wells with lesser performance require constant surveillance [20].

Well yield represents the quantity of water pumped from a well per unit time, usually quantified in gallons per minute (gpm) or gallons per hour (gph).

The specific capacity of a well is expressed as the well yield per unit of drawdown, it is expressed as:

$$s_c = \frac{Q}{h_0 - h} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.16)$$

Where

s_c =Specific capacity(m^2/day), Q = pumping rate(m^3/day), $h_0 - h =$ the drawdown(m).

The specific capability of a water source, such as a well, derive significantly from the applied rate of pumping. It is also influenced by non-linear losses in the well specific capacity which decreases with elevated pumping rates. This impediment makes the complete worth of specific capacity become less significant though it is beneficial for comparison of the well efficiency over the passage of time [21].

The drawdown measured in a pumping well consists of two fundamental components that are related.

$$s = BQ + CQ^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.17)$$

With

$$Q = AV \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.18)$$

Where

$s =$ drawdown (m), $Q =$ pumping rate (m^3/day), $B =$ aquifer loss coefficient, $A =$ pipe area (m^2), $V =$ water velocity (m/s), $C =$ well loss coefficient.

The equation's first term (BQ) represents the linear drawdown component, while the second term (CQ^2) accounts for non-linear well losses, quantification requires testing at multiple flow rates.

2.6.4 Drip irrigation design

Drip irrigation, also referred to as trickle or micro irrigation, is a water-conserving method that delivers water directly to a plant's root zone through a network of pipes, tubing and emitters.

With trickle irrigation, the crop water requirements is given as:

$$ET_{crop-loc} = ET_{crop} K_r \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.19)$$

Where

$ET_{crop-loc}$ = Crop water requirements(mm/day), ET_{crop} = crop evapotranspiration (mm/day)

The estimated ET_{crop} at peak demand for localized irrigation is given by:

$$T_d = U_d[0.1(P_d)^{0.5}] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.20)$$

Where

T_d = The estimated ET_{crop} at peak demand for localized irrigation(mm/day), U_d = conventional estimated peak ET_{crop} (mm/day), P_d = percentage ground cover.

The irrigation requirements are calculated as:

$$IR_n = [ET_{crop} K_r] - R + LR \dots\dots\dots\dots\dots\dots (2.21)$$

Where

IR_n = net irrigation requirements (mm/day), ET_{crop} = crop evapotranspiration (mm/day), K_r = reduction factor for ground water, R = water sources for irrigation other rainfall (mm/day), LR = amount of water required for the leaching of salts (mm/day).

$$IR_g = \frac{ET_{crop} K_r}{E_a} - R + LR \dots\dots\dots\dots\dots\dots (2.22)$$

Where

E_a = Field application efficiency

The field application efficiency are as given in Table 2.8

Table 2.8: Field application efficiencies

Climate	Efficiency value
Hot dry climate	0.85
Moderate climate	0.90
Humid climate	0.95

The field application efficiency is given by:

$$E_a = K_s EU \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.23)$$

With

$$K_s = \frac{\text{average water stored in root volume}}{\text{average water applied}} \dots\dots (2.24)$$

Where

$EU =$ coefficient reflecting the uniformity of application, $K_s = 0.95$ for silt, $EU \geq 0.90$.

The irrigation requirement is the additional net amount of water required to meet crop water demands plus leaching requirements. The leaching requirements is given as:

$$Y_r = \frac{maxEC_e - EC_w}{maxEC_e - minEC_e} \dots\dots\dots\dots\dots\dots\dots\dots\dots (2.25)$$

Where

$Y_r =$ relative yield, which is expressed as the ratio of estimated reduced yield to the full potential, $EC_w =$ electrical conductivity of irrigation water (ds/m), $minEC_e =$ electrical conductivity of the saturated soil extract that will not decrease the crop yield (ds/m), $maxEC_e =$ electrical conductivity of the saturated soil extract that will reduce the crop yield to zero (ds/m).

For horticultural crops electrical conductivities values are as given in table 2.9

Table 2.9: Electrical conductivity

Maximum	12.5
Minimum	2.5

The leaching requirement ratio under drip irrigation is given as:

$$LR_t = \frac{EC_w}{2[maxEC_e]} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.26)$$

Where

$LR_t =$ the leaching requirement ratio under drip irrigation, $EC_w =$ the electrical conductivity of irrigation water (ds/m).

$$LR = LR_t \left[\frac{IR_n}{E_a}\right] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.27)$$

The percentage of wetted area and the number of emitters per plant are calculated as:

$$Emitters\ per\ plant = \frac{area\ per\ plant * P_w}{A_w} \dots\dots (2.28)$$

Where

$P_w =$ percentage wetted area (%), $A_w =$ wetted area by a single emitter (m^2), and area per plant is the space allocated to each plant (m^2).

The emitter spacing is given by:

$$S_e = \frac{S_p}{N_p} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.29)$$

Where

$S_e =$ emitter spacing (m), $S_p =$ plant spacing (m), $N_p =$ the number of emitter.

The percentage wetted area is given by:

$$P_w = \frac{100 N_p S_e W}{S_p S_r} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.30)$$

Where

$W =$ wetted width (m), $S_r =$ distance between plant rows (m), $S_e =$ emitter spacing (m), $S_p =$ plant spacing (m), $N_p =$ the number of emitter.

The area wetted by the emitter is given by:

$$A_w = \frac{\pi D^2}{4} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.31)$$

Where

$A_w =$ wetted area by emitter (m^2), $D =$ diameter of irrigated area (m).

The irrigation frequency and duration are calculated from:

$$T_a = \frac{IR_g}{N_p q} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.32)$$

Where

$T_a =$ duration of irrigation per day (hr), $IR_g =$ gross irrigation requirement (mm/day), $N_p =$ number of emitters per plant, $q =$ emitter discharge (l/hr).

2.6.5 Fertilizer injection

Fertigation is an advanced and efficient technique that combines fertiliser application with irrigation, delivering dissolved mineral fertilisers directly to crop roots, resulting in higher yields and better quality.

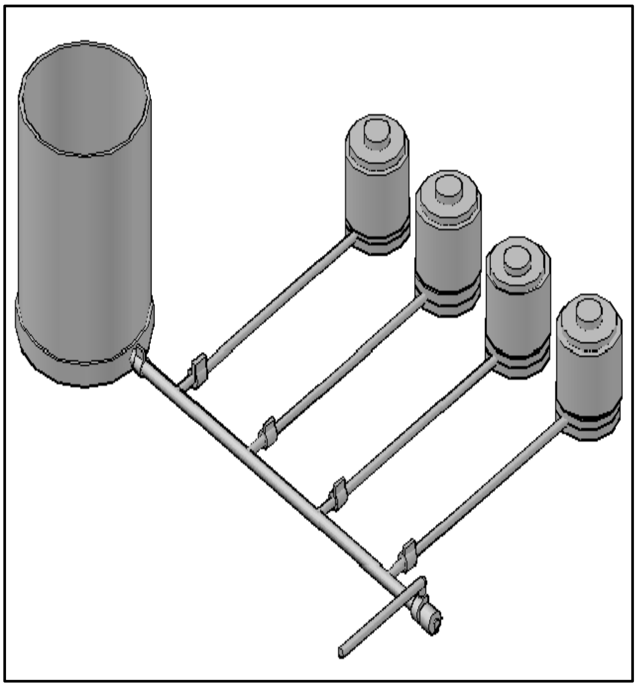


Figure 2.7: Multiple tank fertilizer and herbicide injection system

The fertigation process involves calculating the chemical injection rate using the following equation:

$$g = \frac{fA}{ct_2 t_r} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.33)$$

Where $g =$ rate of injection (L/hr), f = chemical dosage (kg/hectare), A= wetted area $(hectare), c =$ amount of chemical per unit volume (kg/ltr), $t_2 =$ fertigation time (hrs) and $t_r =$ irrigation duration (hrs).

2.6.6 Complete Irrigation System Design

Figure 2.8 shows complete irrigation system design architecture. The water source being borehole water which is pumped into a reservoir tank using a submersible pump, water level both the upper level and lower level are monitored by water level sensors, when reservoir is at the required upper water level borehole water pumping is stopped and when the water level has reached the lower level (lower-level sensor) the borehole pumps are activated to pump more water into the reservoir. A centrifugal pump pumps the chemicals in solution and the water from the reservoir to the drip line for irrigation; valves are installed for backflow prevention and for controlling the volume of chemicals passing per given time. Water supply with dissolved chemicals in solution flows in the main line which then branches into the drip lines where the irrigation water together with dissolved chemicals are then delivered to the plant roots by means of emitters.

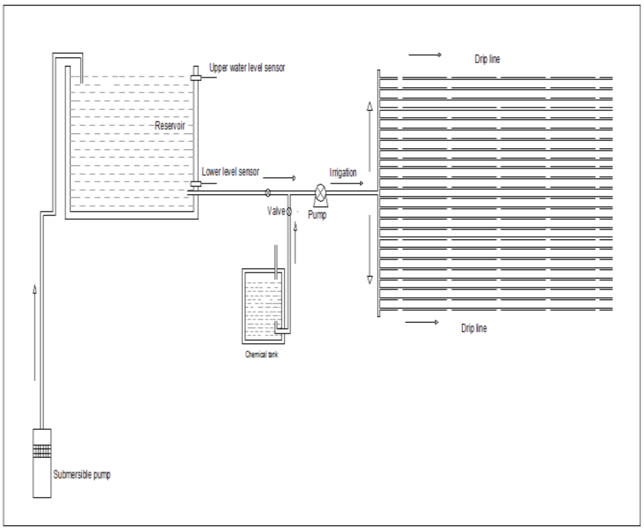


Figure 2.8: Complete irrigation system design

The existing design only incorporates one chemical tank, one chemical tank results in more time being required to manage the system, the tank needs to be frequently replenished, consideration must be given to allowing sufficient time for one fertilizer to be flushed through the system before another fertilizer is introduced into the same tank, this resulted in the author coming up with a system of four chemical tanks in parallel which allows up to four different fertilizer mixes in a single irrigation but at different times during the irrigation.

2.7 Control System Development

The controller be used is the PIC18F4550 microcontroller. The controller has digital or analogue input-output pins on which all the other sensors, electronic components and external circuitry are interfaced. It reads the sensor values at its input pins and executes instructions based on the inputs.

The PIC18F4550 microcontroller offers cost-efficient solutions for technical applications written in C+, that use a real-time operating system (RTOS) and require a complex communication protocol stack such as USB. This device provides in size of 128Kbytes and data memory from 256 to 4Kbytes flash program memory, operating from a supply of 5V at speeds up 96MHz. The PICs use a full static design for clock frequency up to maximum of 48MHz external or 96MHz internal.

The integrated system allows for the pumping and delivery of underground water into reservoir and also the pumping of the water from the reservoir together with fertilizer or herbicides from the fertilizer tank to irrigate the crops. Water level in the reservoir is controlled by two water level sensors, the upper and lower-level sensors, when reservoir is at the upper level (full) power to the submersible pump is cut and when water level has dropped to the lower-level power is supplied to the submersible pump thus having water being pumped into the reservoir. Fertilizers or herbicides are supplied into the irrigation water by means of timed solenoid valves to constantly supply fertilizers or herbicides from the different four dedicated tanks. The moisture level is detected by moisture sensors, when below the desired level a signal is sent to the microprocessor to start the irrigation process which only stops when the required moisture level has been reached.

The sensor algorithm for the water level sensors to be used for submersible pump protection and reservoir water level monitoring is as given in Table 2.10. The sensors are open when there is no water and closed when there is water.

Table 2.10: Sensor algorithms

	Pump protection		Reservoir empty		Reservoir full		Soil moisture	
Digital	1	0	1	0	1	0	1	0
meaning	Protect	Normal	Empty	Not empty	Not full	Full	Wet	Not wet

The truth table for the borehole water control system is as given in Table 2.11.

Table 2.11: Borehole water control system truth table

PP	RE	RF	Result	Pump	Backflow valve	Valve A, B, C and D
0	0	0	Sensor OK	OFF	OPEN	Usable (green light)
0	0	1	Sensor OK	OFF	OPEN	Usable (green light)
0	1	0	Faulty sensors	OFF	CLOSED	Not usable (red light)
0	1	1	Sensor OK	ON	CLOSED	Not usable (orange light)
1	0	0	Sensor OK	OFF	OPEN	Usable (green and orange light)
1	0	1	Sensor OK	OFF	OPEN	Usable (green and orange light)
1	1	0	Faulty sensors	OFF	CLOSED	Not usable (red light)
1	1	1	Sensor OK	OFF	CLOSED	Not usable (orange light)

Where

PP	Pump protection pin
RE	Reservoir empty pin
RF	Reservoir full pin

The flow chart for the irrigation and fertigation system is shown in figure 2.9.

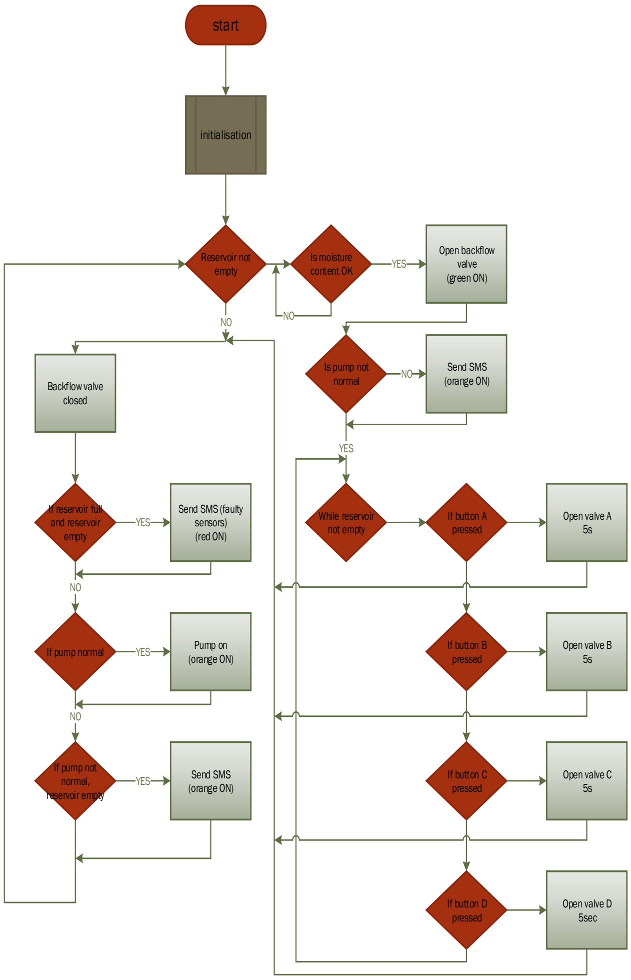


Figure 2.9: Irrigation and fertigation control system flowchart

Figure 2.10 is a circuit block diagram for the irrigation and fertigation system.

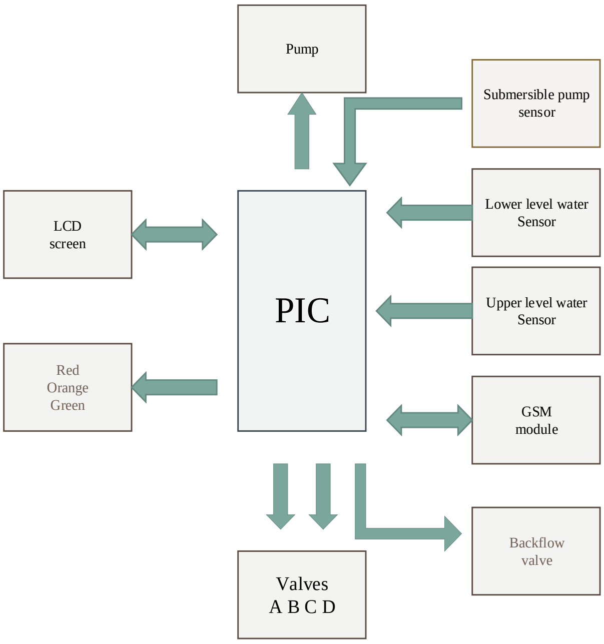


Figure 2.10: Circuit block diagram

Figure 2.11 is showing simulation of irrigation and fertigation supply system.

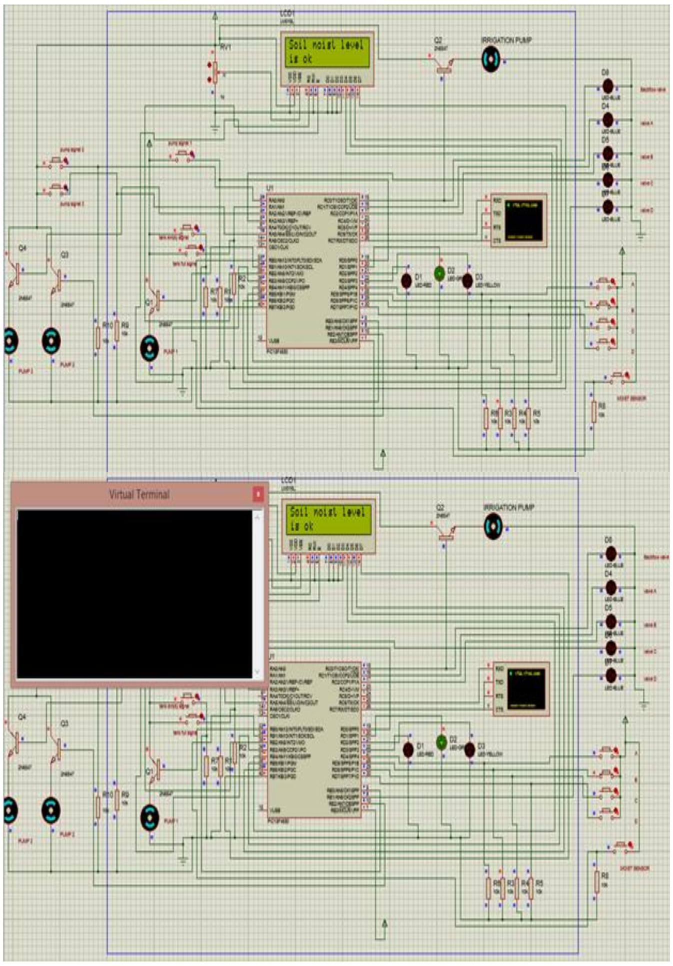


Figure 2.11: Irrigation and fertigation supply system

III. RESULTS

This chapter shows research findings from the objectives, related work, and materials and methods.

3.1 Trickle Irrigation Components

The results for the trickle irrigation components include the design results of the emitters, lateral line design, submain line design, main line design and pump selection.

3.2 Lateral line design results

Polyethylene pipes were selected as they are flexible which allows for some flexibility in making turns without using 90° elbow fittings, they also have ultraviolet stabilizers mixed with plastic material which makes it less susceptible to the deteriorating effects of sunlight, as shown in the Table 3.1.

Table 3.1: Lateral line design results

Parameter	Value
Diameter	$12mm$
Wall thickness	$0.8mm$
Dripper spacing	$200mm - 2000mm$
Working pressure	$1bar$
Bursting pressure	$6bar$
Flow rate	$1.6\,l/hr$

3.3 Submain line design results

PVC pipes were selected for carrying the fluid from the reservoir and the chemical tank to the laterals, PVC pipes are immune to corrosion and durable which translates into a longer lifespan saving on costs and reducing environmental impact, PVC pipes have less failures and thus a much lower life cycle cost compared to other materials such as steel, cast iron and ductile iron and also ease of handling and installation together with toughness and flexibility.

Table 3.2: Submain line design results

Parameter	Value
Diameter	$45mm$
Wall thickness	$1.5mm$
Dripper spacing	$200mm - 2000mm$
Working pressure	$1bar$
Bursting pressure	$6bar$

3.4 Main line design results

PVC pipes were selected for carrying the fluid from the reservoir and the chemical tank to the laterals, PVC pipes are immune to corrosion and durable which translates into a longer lifespan saving on costs and reducing environmental impact, PVC pipes have less failures and thus a much lower life cycle cost compared to other materials such as steel, cast iron and ductile iron and also ease of handling and installation together with toughness and flexibility.

Table 3.3: Main line design results

Parameter	Value
Diameter	$45mm$
Wall thickness	$1.5mm$
Dripper spacing	$200mm - 2000mm$
Working pressure	$1bar$
Bursting pressure	$6bar$

3.5 Pump selection

A centrifugal pump was selected for pumping irrigation water and fertilizers to the plants as it has the capability to work medium to low head, small in size hence space saving and it is easy to maintain.

Table 3.4: Design results for the irrigation pump

Parameter	Value
Power rating	$350W$
Voltage	$240V$
Total head	$2m$
Flow rate needed	$1.6l/hr$

A submersible pump was selected, boasting a self-contained design that prevents leaks and electrical issues, ideal for submerged operation.

Table 3.5: Design results for the borehole pump

Parameter	Value
Power rating	$1792W$
Voltage	$240V$
Static head	77m
Dynamic head	1.82m
Total head	$78.82m$
Flow rate needed	$0.15m/s$

3.6 Pipe network design

PVC pipes were selected for carrying the fluid from underground into the reservoir, PVC pipes are resilient against corrosion and are durable which translates into a longer lifespan saving on costs and reducing environmental impact, PVC pipes have less failures and thus a much lower life cycle cost compared to other materials such as steel, cast iron and ductile iron and also ease of handling and installation together with toughness and flexibility.

Table 3.6: Borehole pipes design results

Parameter	Value
Material	PVC
Diameter	$100mm$
Flow rate	$0.15m/s$
Safe working pressure	$6bar$
Length needed	$107m$

3.7 Fertilizer and herbicide dosing system design results

Low Density Polyethylene (LDPE) tanks were selected for fertilizer and herbicide storage, LDPE offers good chemical resistance, very tough and rigid, weatherproof, has a low water absorption and is of low cost.

Table 3.7: Design results for the fertilizer herbicide tank

Parameter	Value
Capacity	500l
Diameter	820mm
Height	1075mm
Material	LDPE

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3.8 Flow control design results

For backflow prevention and fertilizer and herbicide injection valves as given in Table were selected.

Table 3.8: Flow control design results

Parameter	Specification
Directional control	One way ball valves
Fertilizer, herbicide injection	Solenoid valves

3.9 Control system development results

Simulations results for the control system development are shown below. Figure 3.1 shows the control system with fertiliser input ready.

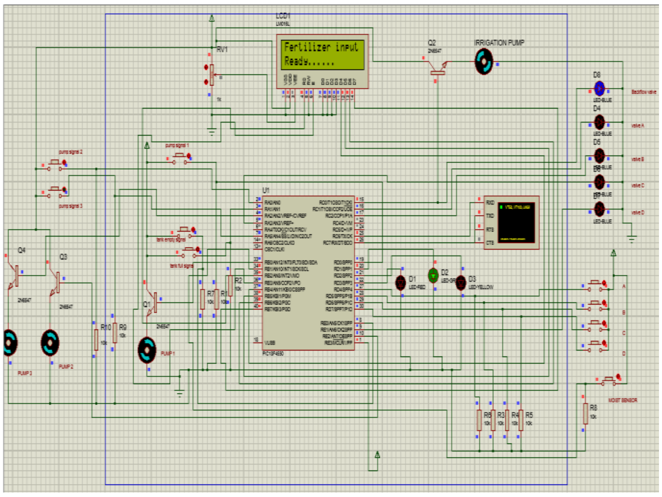


Figure 3.1: Control system with fertiliser input ready

Figure 3.2 shows the simulation results for the Control system with soil moisture content at desired level is shown in below:

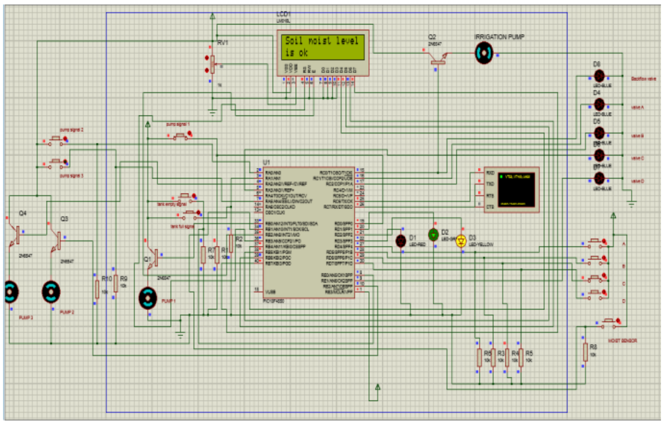


Figure 3.2: Control system with soil moisture content at desired level

Simulation of the Control system with irrigation water being supplied together with fertilizer from fertilizer tank C is shown in figure 3.3.

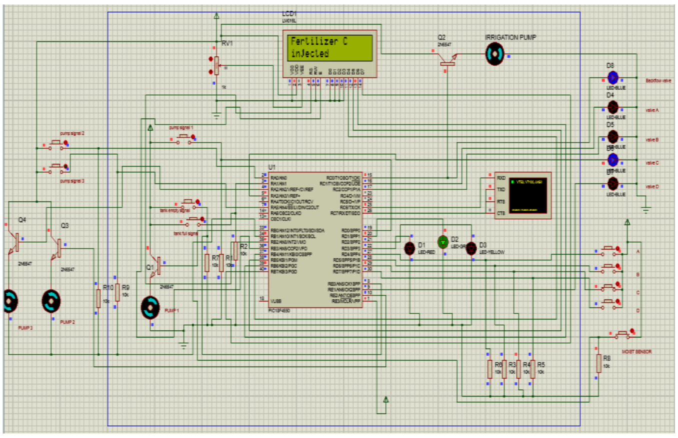
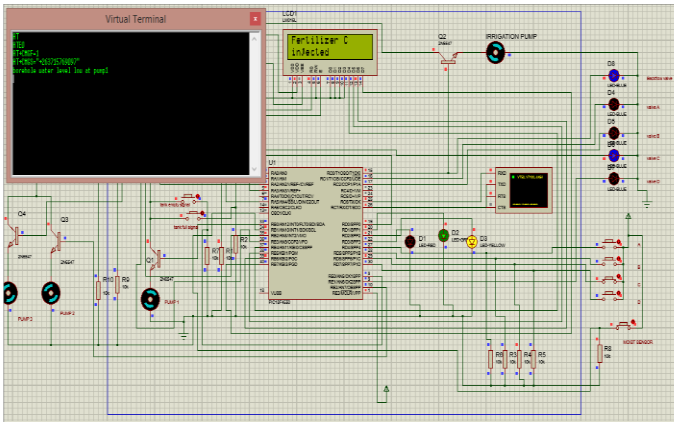


Figure 3.3: Control system with irrigation water being supplied together with fertilizer from fertilizer tank C

Simulation of the control system with an SMS sent to the user (virtual terminal) is shown in figure 3.4.



```
AT
ATE0
AT+CMGF=1
AT+CMGS="+263715769097"
borehole water level low at pump1
```

Figure 3.4: Control system with an SMS sent to the user (virtual terminal)

IV. DISCUSSION

In line with Sustainable Development Goal (SDG) 9, the research results revealed that, the moisture level is detected by moisture sensors. When the desired level reaches the desired preset level a signal is sent to the PIC18F4550 microcontroller to start the irrigation process which only stops when the required moisture level has been reached and this protects the borehole pumps from running dry. The chosen solution comprises of the water reservoir with an upper and lower-level control and monitoring sensors, a chemical tank to supply chemicals and fertilizers to the irrigation system, a centrifugal pump to pump the chemicals in solution and water from the reservoir to the drip line for irrigating crops and valves for backflow prevention.

V. CONCLUSION

In consultation with prior art in literature review and application of design principles, the author was able to design an automated irrigation and fertigation control system, design a fertilizer and herbicide chemical plant and simulated system. On the fertilizer and herbicide chemical plant design the author focused on the pumping medium selection, valve selection for fertilizer or herbicide injection into the irrigation water and the sizing of the fertilizer or herbicide tank and selecting the tank material. A control program for controlling the pumping of water and injection of fertilizer or herbicides into the irrigation water was developed, the control system consists of water level sensors, moisture sensors, pumps and solenoid valves and action confirmation on the desired system events. The design calculations and developed program simulation have proven that the system of this nature is feasible.

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