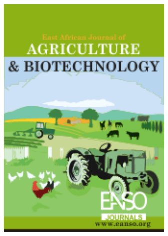

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Original Article

Optimized Designing of Solar Powered Direct Pumping Small Scale Sprinkler Irrigation Pipe Networks.

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ABSTRACT

Today, the agricultural sector world over is confronted with a water scarcity crisis and the related numerous challenges. Harnessing the scarce water resources to meet the irrigation water requirement in a more economical way without compromising sustainability is very vital. The present study aims at applying EPANET2.2, a hydraulic modelling tool, in the optimization design of a solar-powered direct pumping sprinkler irrigation system. This study has shown that the designed solar-powered sprinkler irrigation system capacity is 20.88 m3/hr per shift with a precipitation rate of 6.02 mm/h. A submersible pump, Grundfos SP17-13, shall be installed, operating at a maximum head of approximately 85 m to deliver water up to 20.88 m3/hr. 48 in number, 250 Watts monocrystalline panels shall be installed, and, are more than sufficient to meet the peak water irrigation requirement of 5.72 mm/day for tomato crop thus, sufficient to meet the water demands of other horticultural crops. Choice of solar energy was majorly ascribed to proven efficiency in addition to low costs involved in operation and maintenance. Hydraulic simulation results from the EPANET2.2 model indicate that the minimum pressure within the systems is 33.10 m observed at the last sprinkler of the farthest plot while the maximum pressure is 82 m of water observed at the node next to the pumping station. The velocity of flow within the system ranges from 0.67-2.37 m/s which is within the acceptable limit. The transmission pipeline shall be made of OD75 mm HDPE pipe of pressure rating PN10 of 500 m length. The sub-main shall be OD63 mm UPVC pipes of pressure rating PN 6, 210 m length. The sprinkler laterals shall be OD25 mm HDPE pipes of pressure rating PN6 spaced at 12 x 12 m.

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INTRODUCTION

Water is the ultimate vital resource for all life forms to exist on earth (Sonaje & Joshi, 2015; Obura, Kimera, & Khaldi, 2022). It is not only required for existence but also needed to live a very fine quality and contented life (Garg, 2005). Recent studies show that scarcity of water impacts over 40 % of the general public world over, and the status quo is likely to worsen due to climate change. Despite this, by 2050, the global population is estimated to reach about 9.6 billion according to the latest UN (2013) projections. In Africa alone, the population will have grown twice by 2050 reaching about 2.1 billion (Bongaarts, 2009; Wanyama et al., 2017). This demands an over 60 % growth in agricultural food production globally and 100 % more in developing countries (Alexandratos & Bruinsma, 2012).

In Uganda, food production remains the pillar for the country's food security at both the household and national levels. Agriculture has been a major benefactor to Gross Domestic Product (GDP) (about 24 %), to export revenues (about 48 %) as well as employing over 70 % of the population (UBOS, 2015; Wanyama et al., 2017). Water is a key ingredient in crop production. Currently, crop growing in Uganda is overly dependent on rain. This conventional rain-fed food production is presently threatened by climatic changes resulting in poor crop and livestock production Wanyama et al. (2017) and reducing livelihood revenues accruing from the agricultural sector. In 2010, alone, 38 % and 36 % loss in production for beans and maize correspondingly was attributed to drought. Furthermore, Uganda recorded about shillings 2.8 trillion (8 %) loss of GDP and 87 % loss to agro-industries in 2014 (MAAIF & MWE, 2017).

Uganda's Vision 2040 and National Development Plan II (NDP II) identify agriculture as a vital area to the nation's food security, economic growth, income enhancement, and employment (MWE, 2019). One of the vital responses the Uganda government has undertaken towards meeting food security has been solar-powered small-scale irrigation development by the Ministry of Water and Environment (MWE) through the Water for Production (WfP) department. Investment in Small Scale Irrigation Schemes (SSIS) is attributed to lower total capital investment, shorter development lead time, and less complex designs in comparison with larger schemes. Since the pipe network of an irrigation system accounts for about 70 % of the total capital investment, oversizing the pipes is most likely to increase the investment costs. Hence, a reduction in total investment cost would require an optimized design of an irrigation network using a hydraulic simulation tool. This study, therefore, aims at applying EPANET2.2, a hydraulic modelling tool, in the optimization design of solar-powered sprinkler irrigation pipe networks. A hydraulic model such as EPANET2.2 helps to find the optimal pipe diameter for each pipe in an irrigation system network thus, reducing investment cost. A direct pumping system was opted for to reduce the cost of erecting an overhead storage system. The choice of solar energy was majorly ascribed to proven efficiency in addition to the low costs involved in operation and maintenance.

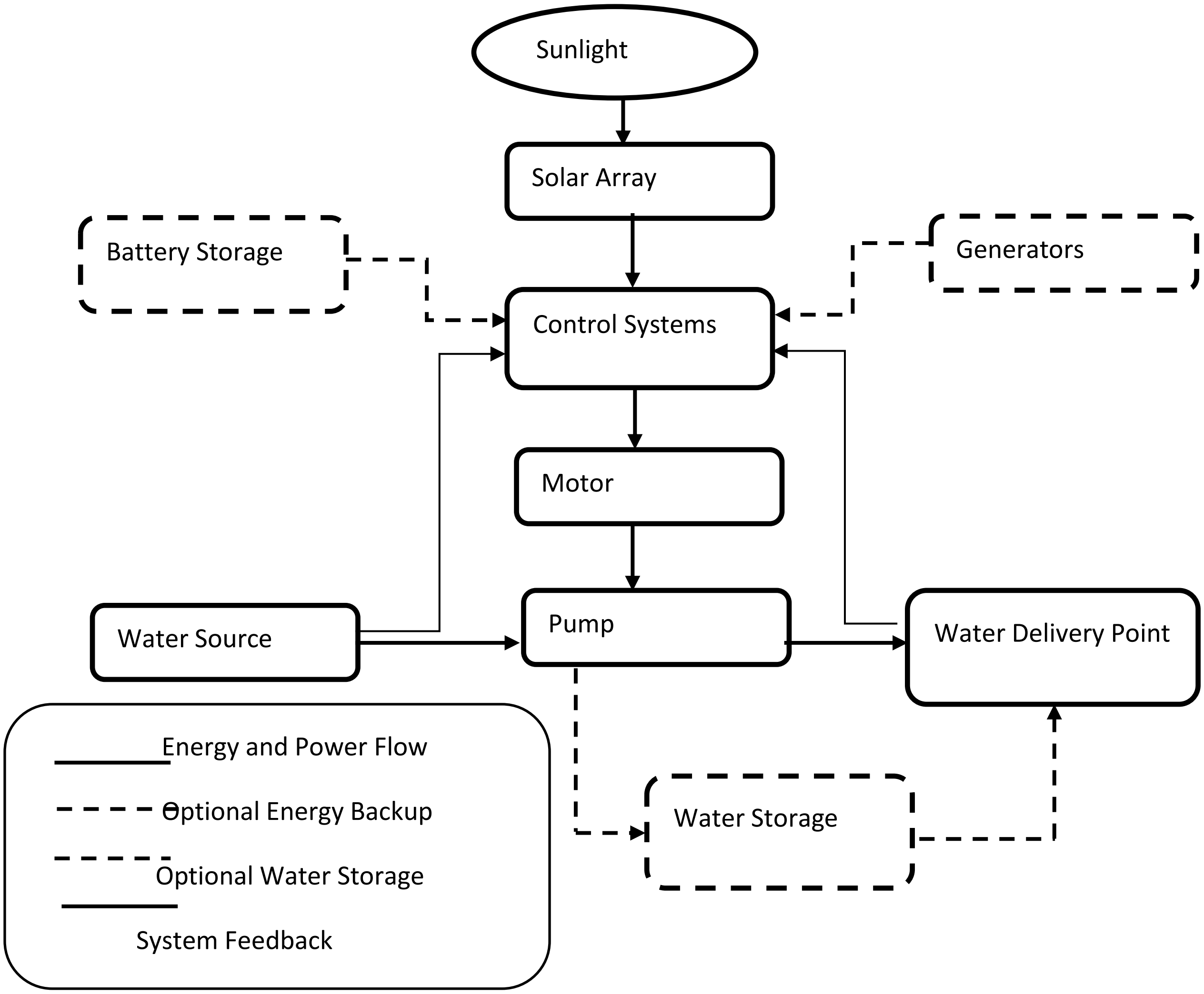
Proposed Irrigation Site Description

The proposed project site is located in Tumba village, Namika parish, Lwabiyata Sub County in Nakasongola district, a cattle corridor district situated in upper central Uganda. The Land coverage of the district is approximately 3,737.6 km^2 with about 4.6 % being permanent wetland. The proposed project area can be described as relatively moist, warm, and dry in terms of climatic conditions. About 100 mm is estimated to be the mean monthly rainfall received in the area with the mean annual rainfall between 600 to 1000 mm. Despite the close proximity to Lake Kyoga, frequent droughts are observed in the area consequently disturbing soil cover and agricultural productivity. Approximately 30^0 C and 17.5^0 C can be stated as the mean maximum and minimum temperatures observed in the area. According to the 1991 Agriculture and Livestock census, the total arable land in Nakasongola was approximated at 913 km^2 however, cultivation was carried out on only 235 km^2. The topographical survey conducted on the proposed irrigation site indicated the gross command area as 28 acres of which the proposed irrigable area comprises 10 acres. The source of water is Lake Kyoga, being the most feasible water source for the project area. The site is located on GPS coordinates 36N 433217 m E, 171510 m N.

Solar-Powered Irrigation System Concepts

Achieving the most reliable and affordable on-farm energy is so practical with solar energy. This is usable energy obtained from irradiation. In solar pumping solutions, photovoltaic panels produce the current used to run the pumps that lift and supply water to the gardens as elaborated in *figure 1* below.

Figure 1: Solar-powered irrigation system concepts



Source: (Ahmed A. , 2017)

Solar Powered Sprinkler System Design Steps

A solar-powered sprinkler irrigation system design steps can be broken down into two phases:

- Preliminary design phase and
- Final design phase

Preliminary Design Phase

The parameters considered under the preliminary phase are reference evapotranspiration (ETo), crop water requirement (ET_{crop}), net depth of water application (d_{net}), gross depth of water application (d_{gross}), irrigation frequency (IF), irrigation duration (t), and system capacity (Q).

Reference Evapotranspiration (ETo)

The reference evapotranspiration epitomizes the evapotranspiration from a standardized vegetated surface. Meteorological data is required to estimate ETo using different formulae developed. The most acclaimed standard method that can be used to define and calculate the ETo is the robust FAO Penman-Monteith equation adopted after an Expert Consultation held in May 1990. CROPWAT model implements this vigorous method which requires radiation, air temperature, air humidity and wind speed data. The Penman-Monteith formula is mathematically represented as (Allen, Pereira, Raes & Smith, 1998a);

$$\mathrm{ET}_o = \frac{0.408\ \Delta(\mathrm{R}_n - G) + \gamma \dfrac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.3U_2)} \quad (1)$$

Where;

$ET_0 =$ reference evapotranspiration [mm day^{-1}], $R_n =$ net radiation at the crop surface [MJ m^{-2} day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = mean daily air temperature at 2 m height [^{0}C], U_2= wind speed at 2 m height [m s^{-1}], $e_{s=}$ saturation vapour pressure [kpa], $e_{a=}$ actual vapour pressure [kpa], $(e_s - e_a) =$ saturation vapour pressure deficit [kpa], $\Delta =$ slope vapour pressure curve [kpa ^{0} C^{-1}], and$\gamma =$ psychometric constant [kpa ^{0} C^{-1}].

Crop Water Requirement (ET$_{\text{crop}}$)

The crop water requirement, ET$_{\text{crop}}$ (mm/day) denotes the depth of water necessary to replace soil water lost by the plant during transpiration and that lost from the root zone through evaporation. ET$_{\text{crop}}$ is expressed as (Doorenbos & Pruitt, 1977; Allen, Pereira, Raes & Smith, 1998a):

$$\mathrm{ET}_{\mathrm{Crop}} = \mathrm{K}_{\mathrm{C}} \times \mathrm{ET}_{\mathrm{O}} \quad (2)$$

Where; where **Kc** is the crop coefficient. The value of the crop coefficient Kc depends on the stage of growth and different crops have different Kc values.

Net Depth of Water Application (dnet)

This refers to the quantity of water in (mm) that desires to be delivered to the soil to take it back to field capacity. It is computed by the following expression (Doorenbos & Pruitt, 1977; Andreas & Karen, 2001):

$$\mathrm{d}_{\mathrm{net}} = (S_A).Z.f \quad (3)$$

Where; d$_{\text{net}}$ = Net depth of water application per irrigation for the selected crop (mm), $S_A = (S_{FC} - S_{PWP}) =$ Available soil moisture, mm/m soil depth, FC = Soil moisture at field capacity mm/m, PWP = Soil moisture at the permanent wilting point (mm/m), Z = Soil depth exploited effectively by plant roots (m), f = Allowable available soil moisture depletion fraction before the next irrigation.

Gross Depth of Water Application (dgross)

The gross depth of water per irrigation is obtained by dividing the net depth of water (d$_{\text{net}}$) by efficiency (Doorenbos & Pruitt, 1977; Andreas & Karen, 2001):

$$\mathrm{d}_{\mathrm{gross}} = \frac{d_{net}}{E_a} = \frac{(S_A).Z.f}{E_a} \quad (4)$$

Where; d$_{\text{net}}$ = Net depth of water application per irrigation, $E_a =$ Water application efficiency, fraction.

Irrigation Frequency (IF)

This is the time a plant takes to drain the soil water at a given diminution fraction and it is expressed as (Doorenbos & Pruitt, 1977; Andreas & Karen, 2001):

$$IF = \frac{d_{net}}{ET_{crop}} \quad (5)$$

Where; IF = Irrigation frequency (days), d$_{\text{net}}$ = Net depth of water application (mm), ET$_{\text{crop}}$ = Crop evapotranspiration (mm/day)

Preliminary System Capacity (Q)

This is mathematically expressed as (Doorenbos & Pruitt, 1977):

$$Q_p = \frac{10.A.d_{gross}}{T} \quad (6)$$

Where; Q_p = Preliminary system capacity (m^3/hr), T = supply duration (hr.), A = Acreage (ha), d$_{\text{gross}}$ = Gross depth of water application (mm)

System Operation Time

To achieve the maximum degree of equipment utilization, the time each set of sprinklers should operate at the same position in order to deliver the gross irrigation depth (d_{gross}) needs to be determined (Doorenbos & Pruitt, 1977; Andreas & Karen, 2001).

$$T = \frac{.d_{gross}}{P_r} \tag{7}$$

Where: T= set time (hours) and P_r = sprinkler precipitation (discharge) rate (mm/h)

Final Design phase

The final design phase considers the selection of the sprinklers' characteristics and spacing and final flow rate. According to (Andreas & Karen, 2001), the subsequent steps may be trailed to reconcile the preliminary design factors (Rasheed & Al-Adil, 2015):

Sprinkler Selection and Spacing

The opening step in the final design phase of the sprinkler irrigation system is sprinkler selection and spacing. The choice of the sprinkler depends on a number of factors for instance soil infiltration rate, irrigation water requirement, and frequency. In order to avoid a runoff, the sprinkler selection should be in such a way that the precipitation rate is less than the soil infiltration rate (Andreas & Karen, 2001). Manufacturers' tables such as table 1 can be used to rightly select sprinklers and their spacing.

Table 1: Manufacturers' sprinkler performance table

Nozzle (mm)	Nozzle (inch)	Pressure		Coverage Diameter		Discharge Rate	
		Kg/cm^2	Psi	mtr.	ft.	LPM	GPM
2.38	3/32”	2.0	28.44	20.5	67.24	5.40	1.43
		2.5	35.55	21.0	68.88	5.95	1.57
		3.0	42.66	22.0	72.16	6.50	1.72
		3.5	49.77	23.0	75.44	6.90	1.82
		4.0	56.88	24.5	80.36	7.40	1.95
		4.5	63.99	25.0	82.00	7.90	2.09
2.77	7/64”	2.0	28.44	21.0	68.88	7.50	1.98
		2.5	35.55	21.5	70.52	8.35	2.21
		3.0	42.66	22.5	73.80	8.95	2.36
		3.5	49.77	23.5	77.08	9.90	2.61
		4.0	56.88	24.0	78.72	10.35	2.73
		4.5	63.99	24.5	80.36	10.85	2.87
3.17	1/8”	2.0	28.44	21.0	68.88	9.58	2.53
		2.5	35.55	22.5	73.80	10.80	2.85
		3.0	42.66	23.0	75.44	11.60	3.06
		3.5	49.77	24.0	78.72	12.80	3.38
		4.0	56.88	25.0	82.00	13.40	3.54
		4.5	63.99	25.0	82.00	13.90	3.67
3.57	9/64”	2.0	28.44	21.5	70.52	11.80	3.12
		2.5	35.55	22.5	73.80	13.20	3.49
		3.0	42.66	23.0	75.44	14.45	3.82
		3.5	49.77	24.0	78.72	15.55	4.11
		4.0	56.88	25.0	82.00	16.70	4.41
		4.5	63.99	25.5	83.64	17.25	4.56

Source: AQua impact sprinklers catalog (2015)

Final System Flow Rate

The final flow rate can be mathematically expressed as (Andreas & Karen, 2001):

$$Q_f = N_c . N_s . q$$

(8)

Where; $Q_f =$ Final system flow rate (m^3/h), $N_c =$Number of laterals operating per shift, $N_s =$Number of sprinklers per lateral, q = Sprinkler discharge (from the manufacturer's *Table 1*) (m^3/hr).

Allowable Pressure Variation

Researchers such as (Keller, 1989) advise that for practical reasons, 23.4 % of the required average pressure may be taken on to approximate the allowable pressure loss due to friction. For a similar purpose, keeping minimal friction losses in laterals is necessary. Other sources recommend an allowable pressure variation of not more than 20 % of the sprinkler operating pressure (Andreas & Karen, 2001).

Sprinkler Irrigation Pipe Size Determination

Determination of pipe size is dictated by a design flow, allowable velocities, and allowable residual heads. It is paramount to maintain the maximum flow velocities within the range of 0.6 - 2.5 m/s (Azenkot, 2004). Head loss calculations can be computed using the Hazen-Williams equation or using flow charts.

Pipe Diameter

The continuity equation for calculating pipe diameter can be expressed as:

$$V = Q/A = 4Q/(\Pi D\hat{}2)$$

(9)

Where A, is the pipe cross-sectional area in m^2, D is the internal diameter in m and Q is the flow rate (m^3/s).

Energy Head Loss in a Pipe (Friction)

When water is flowing in a pipeline, the frictional energy loss is proportional to the flow length (Azenkot, 2004).

$$S = \Delta H/L$$

(10)

Where; L is a pipe section length, ΔH is the frictional head, S is head loss (in % (percentage) or ‰ (parts per thousand)

$$\boldsymbol{S}\% = \left(\frac{\boldsymbol{\Delta H}}{\boldsymbol{L}}\right)\boldsymbol{x100}$$

(11)

$$\boldsymbol{S}\text{‰} = \left(\frac{\boldsymbol{\Delta H}}{\boldsymbol{L}}\right)\boldsymbol{x1000}$$

(12)

The Hazen-Williams equation for head loss is mathematically expressed as (Azenkot, 2004):

$$S = 1.131\ x\ 10^{12}\ x\ (Q/C)^{1.852} x\ D^{-4.87}$$

(13)

Where, S = head loss, (‰); Q = flow rate, (m^3 /h), D = Pipe diameter, (mm), C = Hazen-Williams Constant. This varies from 100-150 for commercial pipes.

The frictional loss computation by Hazen-Williams equation for a robust network may not be so practical, except one applies a hydraulic modeling tool or a slide ruler or monograph based on the Hazen-Williams principle. Azenkot (2004) submitted that "monograph is more practical and common, however, it is not so accurate as precise calculation".

Basic Principles of Hydraulic Modelling

Two basic principles govern network hydraulics: (1) conservation of mass at nodes; and (2) conservation of energy around the loops (Lee. 1983).

The mass conservation at nodes uses linear algebraic equations expressed as (Khamkhan, 2000);

$$\sum Q_{in} - \sum Q_{out} = C_j$$

(15)

Where; Q_{in} and Q_{out} are discharges into and out of the junctions respectively and; C_j represents external consumption or input flow rates at the junction (Izinyon & Anyata, 2011).

The energy conservation around the closed loops is based on non-linear equations (Khamkhan, 2000) written in terms of flow rate.

$$h_f = KQ^n \tag{16}$$

The values of K and n depend on the friction head loss equation adopted (e.g., Hazen-Williams or Darcy-Weisbach) (Ahmed I., 1997; Izinyon & Anyata, 2011; Moosavian & Jaefarzadeh, 2014)

DEVELOPING SPRINKLER IRRIGATION NETWORK MODEL IN EPANET2.2

The hydraulic modelling tool used in sprinkler irrigation pipe network analysis was EPANET2.2 software. The following reasons justify the choice for selecting the EPANET2.2 simulation tool; First of all, it is a window-based public domain model that one can copy and dispense without restrictions. Furthermore, it offers diverse ways of modelling the hydraulic network. For instance, the designer can actually draw the network given the drawings and the dimensions, or else the user can import files from AutoCAD. Using this tool, the irrigation system designer is expected to follow the below-tabulated steps to simulate any irrigation system network (Rossman, 2000):

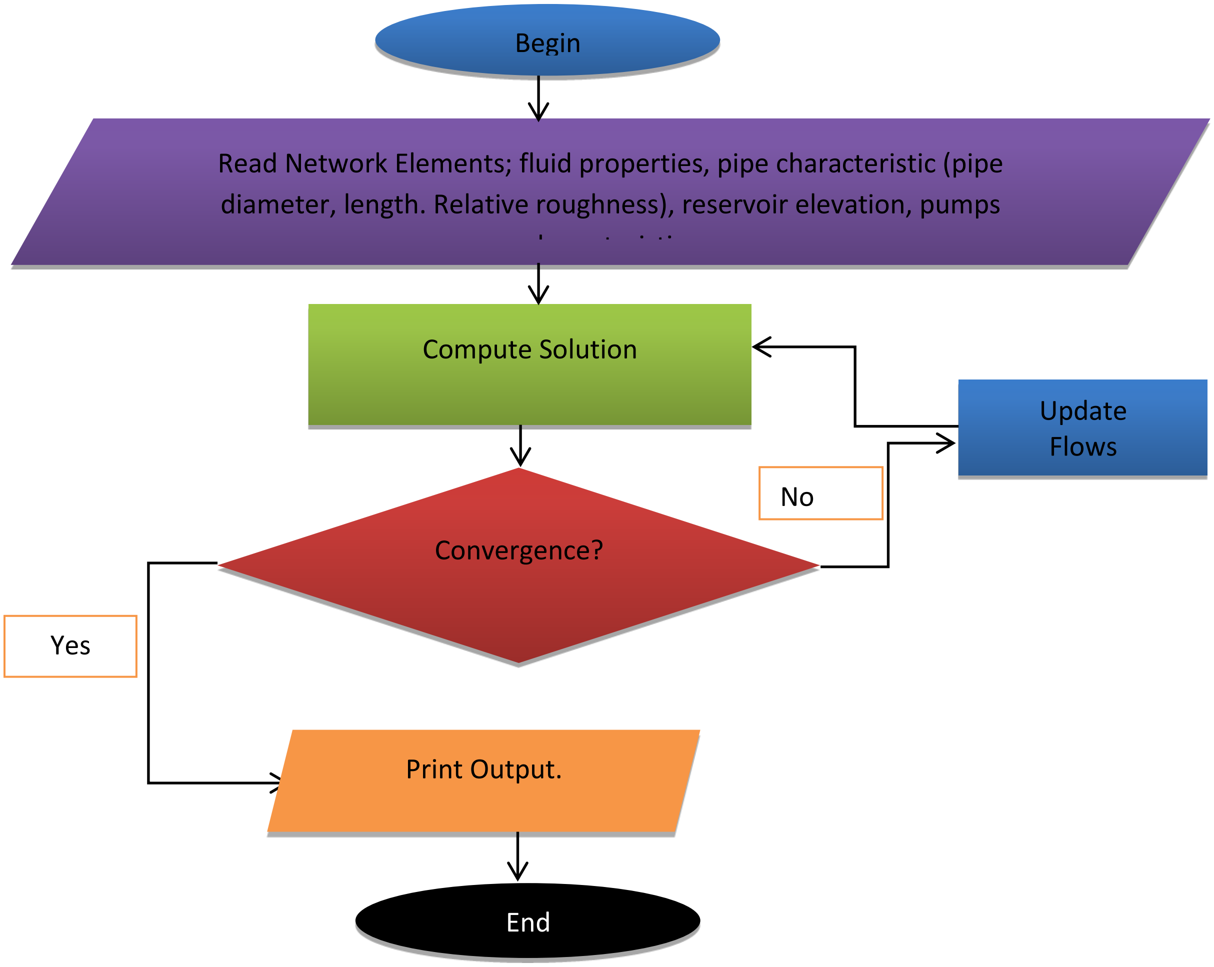
Table 2: Steps executed when simulating an irrigation system network in EPANET2.2

1.	Physically draw the pipe network or import a text file describing the network.
2.	Edit the objects' properties of the network system.
3.	Define the operation of the system.
4.	Choose a set of analysis options.
5.	Run a hydraulic/water quality analysis.
6.	Observe the outcomes of the analysis.

Flow Chart for Irrigation Network Modelling in EPANET2.2

EPANET2.2 can be thought of as one of the most widely used programs for the modelling of water distribution networks. EPANET2.2 iteratively calculates the nodal heads and pipe flows by resolving instantaneously the mass conservation equation for each node and the energy loss equation for each pipe in the network. EPANET2.2 uses the "Gradient Algorithm" to calculate the nodal heads by iteratively resolving a linearized set of equations up until some convergence criterion that may be user-defined is fulfilled (Rossman, 2000) see *Figure 2* below.

Figure 2: EPANET2.2 simulation flow chart



RESULTS AND DISCUSSION

This section aims at discussing the findings after the design process and results after hydraulic modelling of the solar-powered sprinkler irrigation system network.

Computed Reference Evapotranspiration (ETo)

Climate data for the nearby station of Masindi district was generated using CLIMWAT 2.0. The data was imported into CROPWAT8.0 to compute ETo as in *Table 3* below.

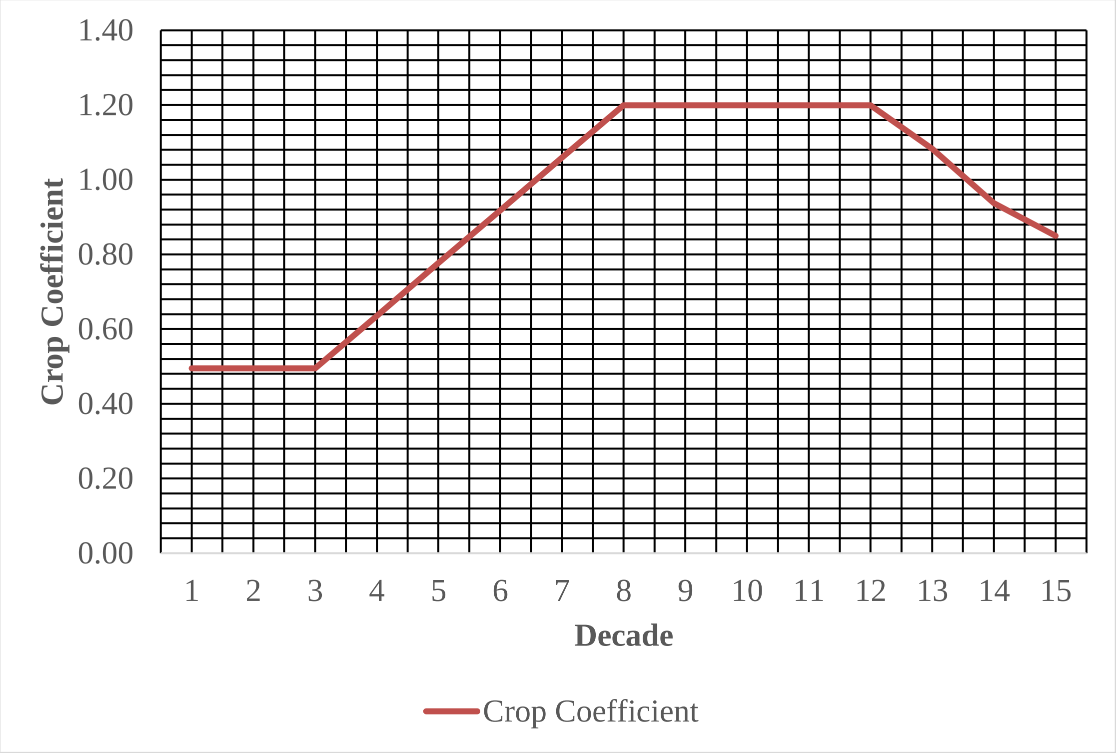
Table 3: Calculated reference evapotranspiration, ETo

Month	Min Temp (^{0}c)	Max Temp (^{0}c)	Humidity (%)	Wind (Km/day)	Sun (hours)	Rad (MJ/m^2/day)	ETo (mm/day)
January	16.6	31.0	59	216	5.0	16.4	4.71
February	17.1	31.0	59	199	5.4	17.6	4.85
March	17.1	30.0	67	199	5.2	17.6	4.52
April	17.7	29.3	71	173	5.3	17.4	4.15
May	17.1	28.2	77	173	5.4	16.7	3.75
June	16.6	28.2	75	156	5.1	15.7	3.58
July	16.0	27.1	77	156	5.1	17.4	3.66
August	16.0	27.1	78	173	5.6	17.4	3.70
September	16.0	27.7	78	173	6.0	18.6	3.94
October	16.6	28.8	73	190	7.2	20.4	4.47
November	16.6	28.8	71	190	7.3	19.9	4.44
December	16.6	29.3	66	190	8.6	21.3	4.77
Average	16.7	28.9	71	182	6.0	18.0	4.21

Computed Potential Crop Evapotranspiration (ETc)

For the design purpose, the tomato plant was chosen since it has the highest crop water requirements among the vegetable plants. Thus, Kc ini, Kc dev, Kc mid, and Kc end values of tomato were first determined and adjusted before proceeding to compute the crop water requirement (ETc) at different stages of growth as shown in table 4 below. A distinctive crop coefficient curve (Kc curve) for the tomato plant was then constructed as shown in *figure 3* below. Four-point values for Kc were needed to define and create the curve.

Figure 3: Crop coefficient curve drawn for tomato crop



Once the Kc values were derived, the crop evapotranspiration (ETc) was got by multiplying the adjusted Kc values by the equivalent ETo values (see *Table 4* below). Weekly, ten-day, or monthly values for Kc are essential when ETc calculations are done on a weekly, ten-day, or monthly time basis respectively. A common process is to create the Kc curve, overlap the curve with the length of the weeks, decades, or months, and graphically obtain from the curve the Kc value for the considered period. The ETc values were established per day and for ten days assuming that all decades have a duration of 10 days, which enables finding Kc and inserts minor errors into the scheming of ET_{Crop}.

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Table 4: Calculated seasonal irrigation water needs for tomatoes

Design Parameters	**Months**															
	November			**December**			**January**			**February**			**March**			**[1]**
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**[2]**
ETo(mm/day)	4.4	4.3	4.2	3.8	3.7	3.9	4.4	4.6	4.7	4.8	4.7	4.6	4.5	4.4	4.2	[3]
Kc-stage	Ini.	Ini.	Ini.	Ini/Dev	Dev.	Dev.	Dev.	Mid	Mid	Mid	Mid	Mid	Late	Late	Late	[4]
Kc	0.50	0.50	0.50	0.64	0.78	0.92	1.06	1.20	1.20	1.20	1.20	1.20	1.08	0.94	0.85	[5]
ETc(mm/day)	2.16	2.12	2.06	2.39	2.91	3.55	4.67	5.51	5.65	5.72	5.66	5.49	4.84	4.09	3.61	[6]
ETc(mm/dec)	21.6	21.2	20.6	23.9	29	35.5	46.7	55.1	56.5	57.2	56.6	54.9	48.4	40.9	36.1	[7]
Eff. Rain (mm/dec)	29.0	29.0	29.0	8.7	8.7	8.7	8.7	3.1	3.1	3.1	7.9	7.9	7.9	22.6	22.6	[8]
Net irrigation requirement (mm)	0.0	0.0	0.0	15.3	20.4	26.8	38.0	52.0	53.4	54.1	48.7	47.1	40.6	18.3	13.5	[9]
Gross irrigation requirement (mm)	0.0	0.0	0.0	20.4	27.2	35.7	50.7	69.4	71.2	72.2	65.0	62.8	54.1	24.3	17.9	[10]
Rooting depth(m)	0.1	0.2	0.3	0.40	0.50	0.60	0.70	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	[11]
Depletion fraction p	0.51	0.52	0.52	0.50	0.48	0.46	0.41	0.38	0.37	0.37	0.37	0.38	0.41	0.44	0.46	[12]
RAW (mm)	43.2	43.3	43.5	42.4	40.6	38.5	34.7	31.9	31.4	31.2	31.4	31.9	34.1	36.7	38.3	[13]
max. net application depth (mm/application)	3.5	6.9	10.4	13.6	16.3	18.5	19.4	17.9	17.6	17.5	17.6	17.9	19.1	20.5	21.4	[14]
Number of applications	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	[15]
Irrigation depth (mm)	0.0	0.0	0.0	10.2	13.6	17.9	25.3	34.7	35.6	36.1	32.5	31.4	27.1	12.2	9.0	[16]
Water application duration (hr)	0.0	0.0	0.00	1.69	2.26	2.97	4.21	5.76	5.91	6.00	5.40	5.21	4.49	2.02	1.49	[17]
Volume of water for the decade of 10 days (m3)	0.0	0.0	0.0	82.4	110.1	144.5	205.0	280.8	288.1	292.2	263.0	254.0	219.0	98.5	72.6	[18]

From *Table 4* above, it can be observed that at the initial stage, there is zero irrigation water applied to the soil because November is one of the wettest months in the project area thus, no need to irrigate as rainfall is sufficient to replace the water lost during evapotranspiration. January is the driest month; thus, one can easily observe a higher crop water requirement compared to the rest of the considered months.

Table 5: Computed net and gross irrigation water requirements for tomato crop

	Gross irrigation requirement IR_g			**Net irrigation requirement IR_n**	
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**
	(mm)	**(mm/day)**	**days**	**(mm)**	**(mm/day)**
Water Requirement (init.)/period (30 days)	0.00	0.00	30.00	0.00	0.00
Water Requirement (dev.)/period (40 days)	133.93	3.35	40.00	100.40	2.51
Water Requirement (mid.)/period (50 days)	340.5	6.81	50.00	255.40	5.11
Water Requirement (late)/period (20 days)	78.40	3.90	20.00	58.80	2.94
Water Requirement (late)/period (10 days)	17.90	1.80	10.00	13.50	1.35
Average Irrigation Water Requirement		3.20	150.00		2.40

Table 5 has been clarified as below:

- Column [2] = summation of gross irrigation requirement for tomato plant at different stages of growth in row [10] of table 4 above.
- Column [3] = Column [2] Column [4]
- Column [5] = summation of net irrigation requirement for tomato plant at different stages of growth in row [9] of table 4.
- Column [6] = Column [5] Column [4]

Based on the seasonal crop water requirements computations in table 4, the peak ETc was obtained as 5.72 mm/day in the month of February (mid-season) and effective rainfall of about 0.31 mm/day which leaves a net irrigation requirement of 5.41 mm/day. The Gross Irrigation requirement was obtained as 7.2 mm/day.

The total available soil water [mm] was obtained as 84 mm. A depletion factor of 0.37 was adopted at peak ETc = 5.72 mm/day resulting in readily available water (RAW) of 31.18 mm. The irrigation interval was then obtained as 5.43 days. Five days shall be adopted as the irrigation interval.

Sprinkler Irrigation System Daily Water Demand

Since the irrigation frequency is 5 days, the number of acres to be irrigated per day =

$$10/5 = 2.0 \text{ acres/day} = 0.809 \text{ ha/day}$$

Table 6: Daily scheme operation procedure

Scheme operation							
Day	**Operation**	**Net Area (Ha)**	**Appl. Rate (mm/h)**	**Set Time (T) (h)**	**Total Q (m^3/h)**	**Total Q (m^3/duration)**	**Req. per day (m^3)**
1	1	0.405	6.0	0.53	24.30	13.0	
	2	0.405	6.0	0.53	24.30	13.0	25.9
2	1	0.405	6.0	0.53	24.30	13.0	
	2	0.405	6.0	0.53	24.30	13.0	25.9
3	1	0.405	6.0	0.53	24.30	13.0	
	2	0.405	6.0	0.53	24.30	13.0	25.9
4	1	0.405	6.0	0.53	24.30	13.0	
	2	0.405	6.0	0.53	24.30	13.0	25.9
5	1	0.405	6.0	0.53	24.30	13.0	
	2	0.405	6.0	0.53	24.30	13.0	25.9
	Total	4.05		5.3			

From *Table 6*, the preliminary system capacity was obtained as 24.3 m^3/h per shift command area of 0.405 ha which is higher than the final system capacity of 20.88 m^3/h. Thus, taking into consideration the economic aspect, the system capacity of 20.88 m^3/h was chosen for sizing the network pipes.

Proposed Shifts for System Operation.

The entire sprinkler system (10 acres) shall be operated by two (2) shifts in 5 days to achieve water distribution optimization, improve efficiency, and cut down on system costs. Every single shift considers irrigation of 2 plots (1 acre) for approximately 32 minutes. There will be two shifts conducted in the morning and evening. On a given day, irrigation is conducted in the morning from 9:00 a.m. to 9:32 a.m. for 2 plots when the solar energy can run the pump. Farmers may then be engaged in other agronomy activities till 4 pm. The second shift should be carried out from 4: 30 pm for about 32 minutes.

Sprinkler Selection & Spacing

An AQ-5N25 overhead impact sprinkler of nozzle diameter 3.57 mm with a discharge(q) of 14.45 l/min, and a pressure head of 30 m at a spacing of 12 x 12 m was selected from Aqua impact sprinklers catalogue 2015 (see *table 1* above). The sprinkler lateral shall be 38 m long yielding 3 sprinklers in number per lateral. The precipitation rate of the sprinklers was obtained as 6.02 mm/h which is less than the 15 mm/h maximum rate of flow for clay loam.

Modelling the Sprinkler Irrigation Network in EPANET2.2

Optimization is necessary to have the right pipe sizes operating at the required pressures. Hydraulic modelling to optimize the design and avoid negative pressures was carried out using EPANET2.2. Since the solar-powered sprinkler system has been designed to irrigate two plots per shift, simulation was carried out for two plots (01 & 20), plot 20 being the farthest. For plot 01, the observed minimum sprinkler pressure is 35.63 m of water (see *figure 4* below) while as for plot 20, the observed minimum sprinkler pressure is 33.10 m of water (see *figure 4* below). Generally, modelling results show that all nodes from the transmission to the field laterals have positive pressures within the range of 33.10 m to 77 m. The system velocity ranges between 0.67 m/s to 2.37 m/s which is within the acceptable limit (see *figure 4* below). The optimal pipe diameters obtained from the simulation model are presented in table 7 below.

Figure 4: Plots 01 & 20 sprinkler system simulation in EPANET2.2

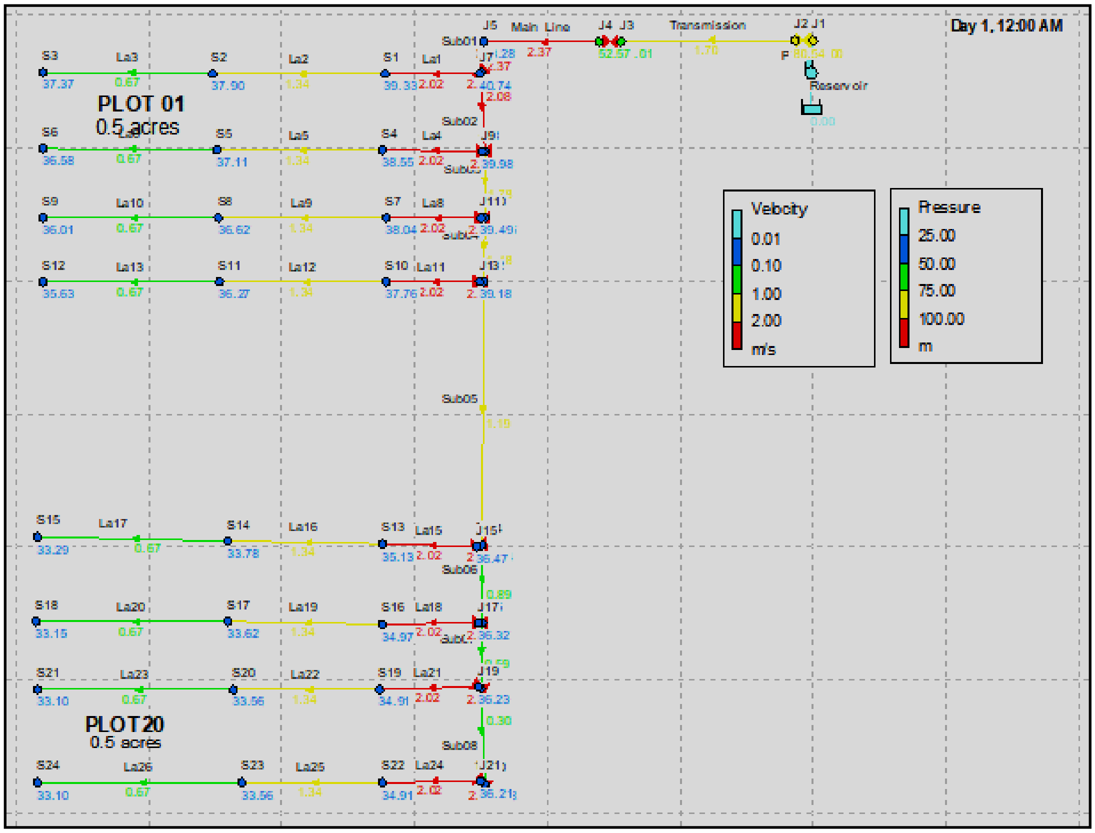


Table 7: Optimized sprinkler system pipe network specifications

S/N	Description	
1.	Supply line from the pump house to the fields	
	• Pipe Material Type	HDPE
	• Pipe Class	PN10
	• Maximum segment pipe Length	500 m
	• Nominal diameter	66 mm
	• Velocity	1.70 m/s
	• Discharge	20.88 m^3/h
2.	Mainline to the gardens	
	• Pipe Material Type	uPVC
	• Pipe Class	PN6
	• Pipe Length	86.7 m
	• Outer Diameter	63.0 mm
	• Velocity	1.70 m/s
	• Discharge	20.88 m^3/h
3.	Sub main/manifold	
	• Pipe Material Type	uPVC
	• Pipe Class	PN 6
	• Pipe length	210 m
	• Outer Diameter	63.0 mm
	Laterals	

S/N	Description	
	• Pipe Material Type	uPVC
	• Pipe Class	PN 6
	• Pipe Length	30 m
	• Outer Diameter	25 mm
4.	Pump station specifications	
	• Number of pumps in parallel	1 No.
	• Unit Pump discharge	20.88 m^3/h
	• Pumping head	85.0 m

Sprinkler Field Layout Configuration

The sprinkler irrigation system consists of 10 acres made up of 20 plots each of 0.5 acres (50 m by 40 m). The actual layout of the system was taken as a rectangular pattern. Additionally, to preclude any chances of runoff, the sprinkler application rate chosen was checked to ensure it does not exceed the basic soil infiltration rate. Overall, each plot shall contain 12No. sprinklers. For each plot, 4 lateral lines of OD25 mm PVC PN 6 pipes direct water from OD63 mm manifold to the sprinklers on 0.8 m risers. There shall be 240 sprinklers installed on 20 plots in total.

Pump and Solar Panel Selection

From the pump characteristics of; Q = 20.88 m^3/hr and TDH = 85.0 m, Grundfos SP17-13 (Grundfos data booklet) solar submersible pump with the power rating 7.5 KW, full load current 17.6 A was selected as the best match in this study. Sun inverter 2, SV2/7.5T, rated voltage 3x415 V and output current 18 A for solar powering AC motors. Table 8 below presents a summary of the required pumping system specifications.

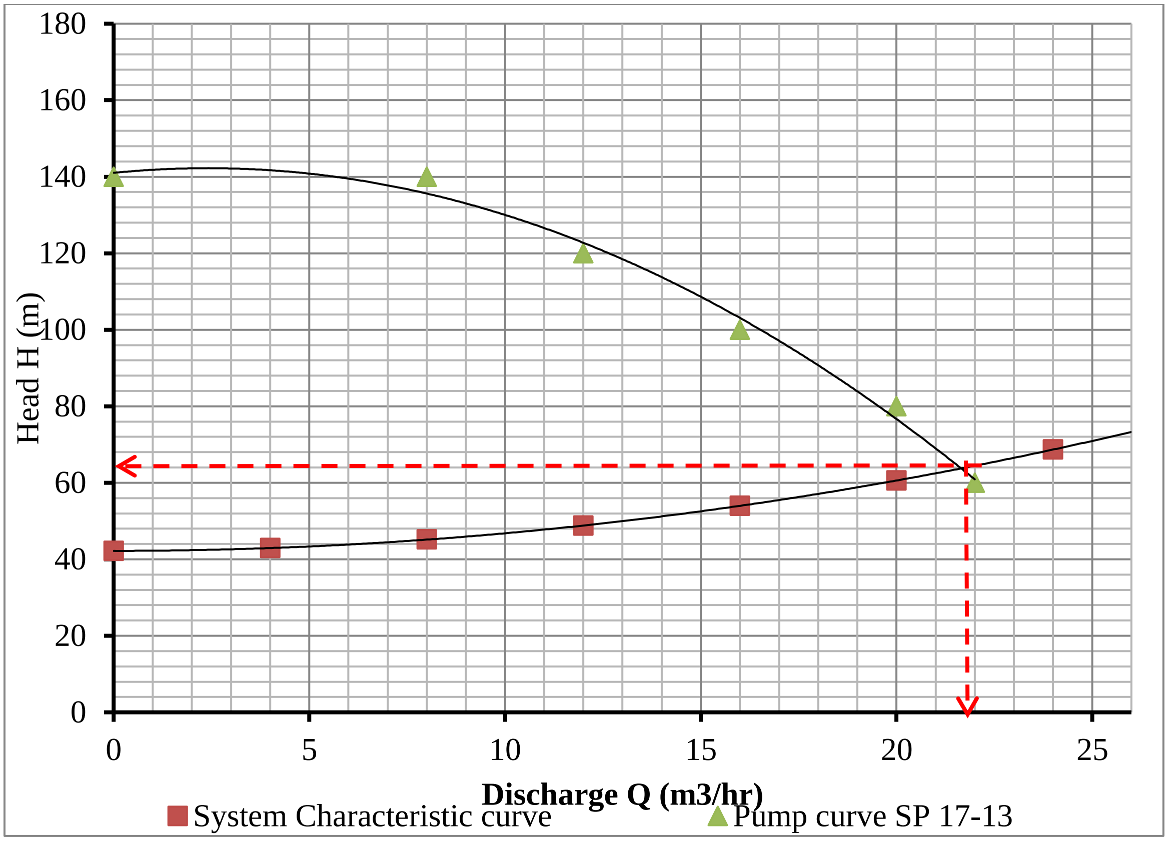
Table 8: Summary of the required pumping specifications

Parameter	Specification
A)- Proposed Pump	
Model	Grundfos SP17-13
Required Discharge	20.88 m^3/hr.
TDH	85 m
Motor Rated Power	7.5 kW
Full Load Current	17.6 A
B)- Proposed Solar Panels	
Model	YL275
Power Rating	250 W
Optimum Operating Voltage	31.9 V
Optimum Operating Current	9.4 A
Open Circuit Voltage	39.1 V
Short Circuit Current	9.96 A
Total Number of Solar Panels	48
C) Proposed Sun inverter 2	
Model	SV2/7.5T
Motor Rated Power	7.5 KW
Rated Voltage	3x415 V
Output Current	18 A
Max DC input Voltage	850 V
Dimensions [H x W x D]	425x415x205 mm
Weight	17 kg

Pump Duty Point

A duty point refers to the point in terms of head and discharge at which a pump normally operates. The pump operates at a duty point where the head supplied by the pump precisely matches the head requirements of the system at the same discharge; i.e., where the pump and system characteristics intersect. The pump characteristic data of Grundfos SP17-13 together with the system characteristic were plotted on the same graph and the duty point was obtained at Q = 21.8 m^3/h and H = 64 m.

Figure 5: Pump and system characteristics curve



CONCLUSION

The simulation results indicate that the required pump to run the sprinkler system should be of capacity 20.88 m^3/hr operating at a minimum head of 85 m and maximum head of 120 m. However, there is a need to install a pressure reducing valve on the mainline before the manifold to make sure the pressure within the laterals does not exceed the pressure of 60 m that can be withstood by the lateral pipes. The laterals have been designed to withstand pressure up to a maximum of 60 m of water, beyond which the pipes would burst. The minimum pressure within the systems is 33.10 m observed at the last sprinkler of plot 20 while the maximum pressure is 82 m of water observed at the node next to the pumping station. The velocity of flow within the system ranges from 0.67 m/s to 2.37 m/s which is within the acceptable limit.

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