Investigation on Centre Pivot to improve its water consumption in agriculture

Arian Bahadori

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Project Advisor: Dr Keri Collins, School of Engineering, Faculty of Science and Engineering, University of Plymouth

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Abstract

This paper investigates the performance of a Centre Pivot (CP) Irrigation System and attempts a theoretical modelling to enhance its water consumption efficiency.

Primarily, the performance of a CP with sprinklers is compared to a theoretically developed, CP with subsurface irrigation on the basis of water usage. Although this report concentrates on the water consumption under different weather conditions, it additionally measures the electricity consumption and overall costs of running the systems for five years. This is to evaluate the overall aspects of both models and whether the theoretical model is a suitable method of irrigation.

Excel was initially used to create a template for the basis of the calculations, which clarified the overall picture to understand the concept thoroughly. Excel was efficient for producing the estimates close enough to the real-life results. To develop the theoretical modelling, Solidworks was the most suitable option as it provides a 3D design. Although Solidworks was not the best option for buckling analysis, it supported the handwritten calculations by providing a safety factor.

The water consumption of each model has been thoroughly discussed and values from the excel calculations have been compared against real-life examples in this report. It was found that the theoretical CP has the potential to improve the water consumption and reduce the overall costs, but it will increase the electricity consumption instead. Further work is required to support this theory since this new model has not been practically proven. This is because the size of the CP is far beyond that which can be reproduced in a laboratory.

Acknowledgements

I would like to thank Dr Keri Collins for all her help and efforts. As my project supervisor, she continuously supported me in every way possible and made this project truly enjoyable.

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Notation and Acronyms

Symbol	Definition
A	Area
B	Width of foundation of pipe (diameter)
CP	Centre Pivot
Cp	Specific heat at constant pressure
D	Outer diameter of pipe
E	Energy
$E(cp)$	Efficiency of CP
$ET0$	Reference crop evapotranspiration
ETc	Crop evapotranspiration
$E(ym)$	Young's modulus
F	Force
G	Soil heat flux density
Gsc	Solar constant
H	Total dynamic head
I	Moment of inertia
J	Day number in a calendar year
L	Length of pipe
La	Latitude (all in north direction)
N	Day light hours
Nc	1st capacity factor
Nq	2nd capacity factor
Nr	3rd capacity factor
P	Power
$Patm$	Atmospheric pressure
$P(cp)$	Percentages of irrigated land by CP
Q	Flow rate
Qu	Soil capacity for a circular footing
Ra	Aerodynamic resistance
$Ra1$	Extraterrestrial radiation
Rh	Relative humidity
R_n	Net radiation at crop surface
Rnl	Outgoing net longwave radiation
Rns	Net shortwave radiation
Rs	Shortwave radiation
Rso	Adjusted Rs for specific elevation
T	Temperature (Average)
$Tmax$	Maximum air temperature

$Tmean$	Mean air temperature
$Tmin$	Minimum air temperature
V	Volume
W	Diameter (width of circle)
WHP	Water horsepower
$as + bs$	Amount of radiation absorbed on a clear sky
c	Cohesion of sandy soil
d	Inner diameter of pipe
do	Zero plane displacement height
dr	Inverse relative distance of sun
$e^0(T)$	Saturation vapour pressure at (T)
ea	Actual vapour pressure
$es - ea$	Saturation vapour pressure deficit
es	Saturation vapour pressure
exp	Exponential
g	Gravitational constant
H	Average crop height
k	Von Karman's constant
kc	Crop coefficient
m	Molar mass
n	factor accounting for the end conditions
t	Time of operation
u_2	Wind speed at 2 meters above the ground
v	Speed
z	Elevation above sea level
zh	Height of measurement
zoh	Roughness length governing transfer of heat and vapour
zom	Roughness length governing momentum transfer
Δ	Slope vapour pressure curve
Δt	Time step
α	Albedo
γ	Psychrometric constant
γ(w)	Bulk unit weight
δ	Solar radiation
ε	Ratio molecular weight of water vapour/dry air
λ	Latent heat at constant pressure
ρ	Density
φ	Latitude
ωs	Sunset hour angle

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1.0 Introduction

Fresh water is an essential need for humans, animals and plants, yet only 2.5% of all the water on the planet earth is fresh water (Perlman, 2019). Climate change impacts the freshwater directly by increasing its temperature and changing the hydrological cycle.

In their recent research on the effect of global warming on fresh water, Pletterbauer, Melcher and Graf (2018), claim that as a result of global warming, the frequency of drought increases, run-offs from snow and ice covers reduces, therefore, water quality becomes deteriorated. Thus, it is vital to save water.

Globally, over 70% of fresh water is used for agriculture as shown in Fig. 1, (Khokhar, 2017). This value changes to 80% in the Mediterranean and 85% in Middle Eastern countries, where water is more scarce. Khokhar (2017) also claims that the moisture content of soils will continue to drop based on the current rate of climate change and that demand for water will only continue to rise in these countries.

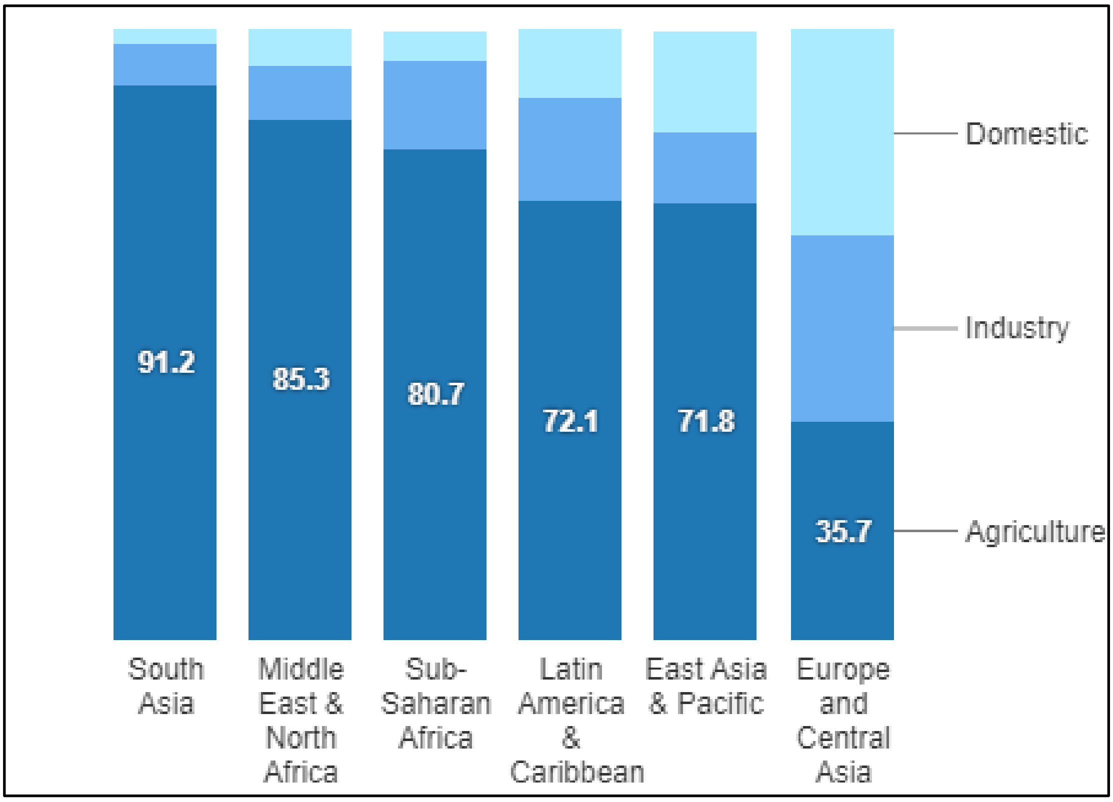

Figure 1. *Percentage share of freshwater withdrawals in 2014 (Khokhar, 2017)*

In 1946, Frank Zybach, an inspired farmer, invented the first CP Irrigation system (Anderson, 2018). CP revolutionised the agricultural industry. The system increased in popularity due to reduction of water consumption, time spent on the field and money spent on labour. The technology has also become popular as it can be used even in extreme weathers. Figure 2 shows a picture of a modern-day CP.

Figure 2. *Centre Pivot (Folvonic, 2019)*

1.1 Aim

The aim of this paper is to improve the water consumption of CP Irrigation system and see its impact on the costs and electricity consumptions.

1.2 Objectives

- To use mathematical modelling on a CP to calculate its water losses, electricity consumption and the costs of running it for a year

- To make an alternative design to reduce the evaporation losses in irrigation and find theoretical evidence to see if the design is viable by using Computer-aided Drawing (CAD)

- To calculate, by using the same procedure as before, the water saved, electricity consumption and costs of operating the new design

- Finally, to compare the difference between the original CP and the new design and to discuss the advantages and disadvantages of each model.

2.0 Literature review

CP is an automated machine that moves slowly in a circular pattern whilst irrigating the land (Folvonic, 2019). As shown in Fig. 3, CP has a central tower called the pivot. The pivot is anchored to a fixed point where water is pumped from the underground sources into the system. Then, water travels through a long horizontal pipe, and then sprayed on the surface of the ground using sprinklers (Evans, 2001).

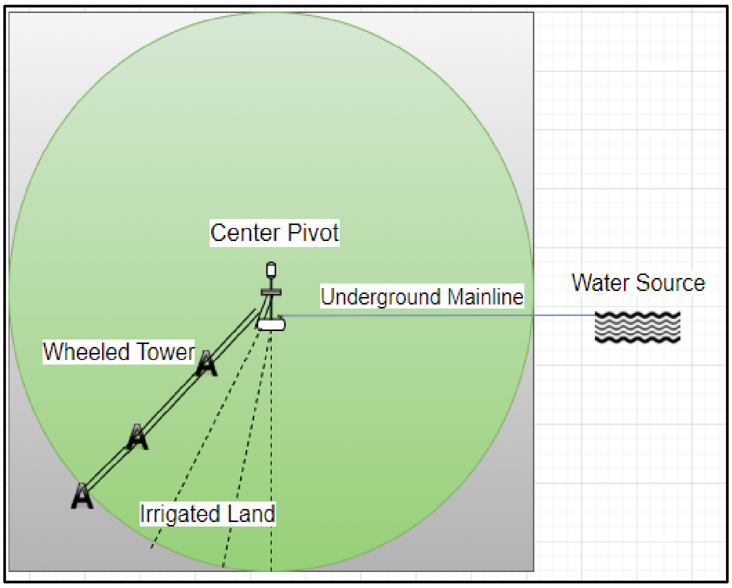

Figure 3. *Irrigating pattern of a Centre pivot (Barbosa and Colombo, 2018; Flowchart Maker & Online Diagram Software, 2020)*

As labelled below on Fig. 4, the main pipe of a CP is supported above the ground by a series of "A" shaped beams which are known as wheeled towers. The system moves in a circular pattern with the help of wheels that are attached to these towers and the power generating motor within each tower (Evans, 2001). The main pipe also has a series of smaller tubes hanging loosely from them. Each tube has a sprinkler attached at the end of it to distribute water (Barbosa and Colombo, 2018).

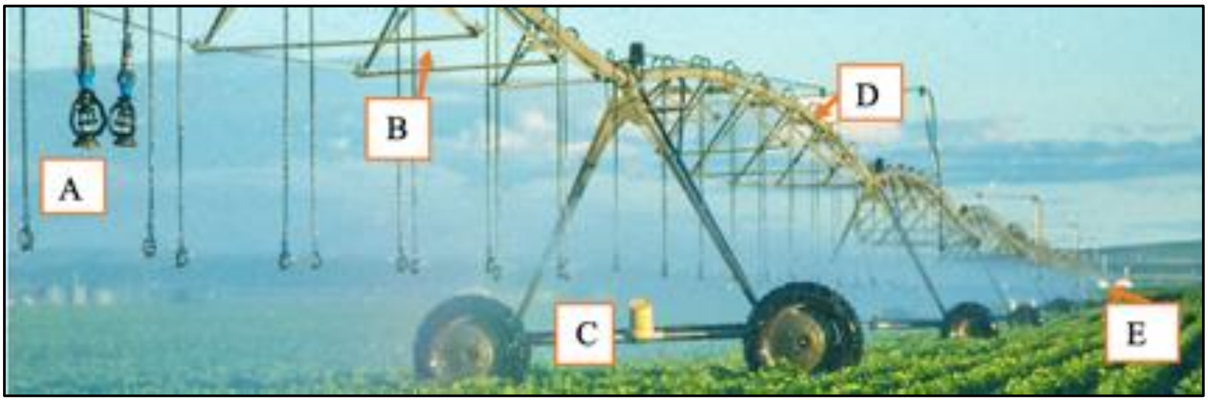

Figure 4. *Labelled diagram of a CP, (Folvonic, 2019)*

Table 1 provides definitions for the labels in Fig. 4.

Table 1. *Description of CP components*

Letter	Component of the system with description
A	Sprinklers that spray water on the land.
B	Structure to support the span due to high water pressures.
C	Wheeled tower works as a drive unit by a geared motor.
D	Main water pipe (span), transporting water to the sprinklers.
E	Fixed central pivot, where underground water is pumped into initially.

The main pipe and wheeled towers are made of high tensile galvanized steel or aluminium pipes (Evans, 2001). These materials are corrosive resistant, and they can withstand the systems operational pressures.

Roy (2019) reports that the sprinklers on the system come in a variety of sizes and to ensure uniform distribution of water, smaller sprinklers are used at the mouth and larger sprinklers at the tail of the pipeline. This is because the further away from the pipe, the more separated the tubes become, as shown in Fig. 5 (Barbosa and Colombo, 2018). At the end of the pivot, the "tail," which is another larger sprinkler is installed to increase the area of irrigated land.

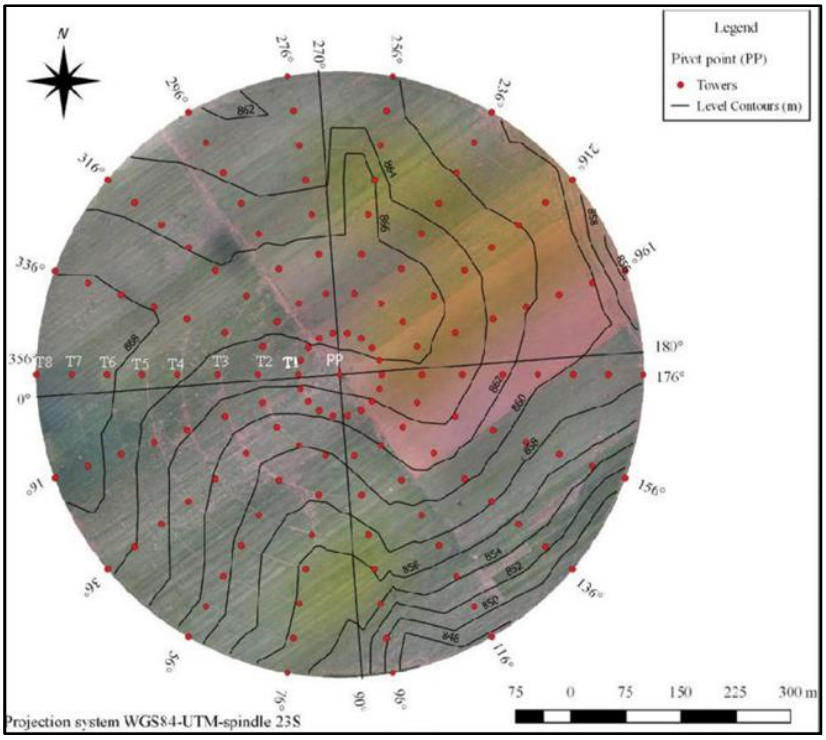

Figure 5. *Angular positions of the CP movable lateral line (Barbosa and Colombo, 2018)*

Currently, countries such as the United States and Canada are developing CPs for bigger farms (Roy, 2019). These systems have certainly helped to reduce water and energy consumptions as they can be used in extremely warm countries such as Jordan and Saudi Arabia. Figures 6 and 7 show pictures of irrigated lands by CP in Saudi Arabia and Jordan, respectively.

Figure 6. *CP irrigation in Saudi Arabia (Roy, 2019)*

By researching the papers of Anderson (2018), Riyo (2018), Roy (2019) and Zazueta (2018), evaluations are made on the advantages and disadvantages of CP using sprinklers. The advantages and disadvantages are given in Table 2 and Table 3, respectively.

Table 2. *Advantages of CP*

Advantages
No labour required
Uniform application of water
Irrigation of large areas in a short period of time
20 years of service life
Can be used in very hot countries
An automated machine, hence, it saves time for farmers
Adjustable rate of water delivery
Efficient use of water

Table 3. *Disadvantages of CP*

Disadvantages
High capital cost (£80k – £100k)
Requires flat surface
Hard to use on a rectangular field
Uneven irrigation on a windy day
Water evaporation from the surface of the land

Figure 7. *Satellite view of CP irrigation in Jordan (Roy, 2019)*

As reported by Folvonic (2019), CP water efficiency can be up to 80%. However, this value may decrease in warmer countries. The major cause of this cause is water evaporation from the surface of the land. Hence, in theory, by replacing the sprinklers with a pipe that is able to gently penetrate the ground to irrigate the subsurface layer of the land, the efficiency of CP should improve. Figure 8 illustrates the original method with the potential new method.

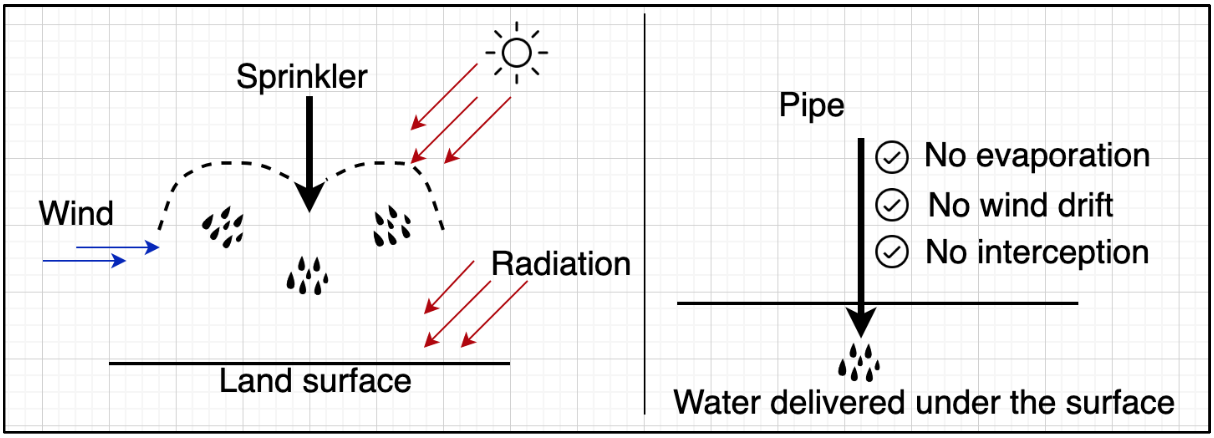

Figure 8. *Sprinkler vs Subsurface irrigation diagram (Flowchart Maker & Online Diagram Software, 2020)*

Therefore, it is important to calculate the water consumption. Using the studies of Licht and Archontoulis (2017), it is clear that between 25-40% of evapotranspiration of a plant is made of evaporation from the soil, depending on which month of the year it is. Therefore, it is required to calculate the evapotranspiration of a plant at a specific period first. Raes (2009) and Whycos (2008) provide the first equation (Eq. 1), evapotranspiration from the crop:

$$ETc = Kc * ET0 \qquad Eq.\ 1$$

Where;

$ET0$: *Reference crop evapotranspiration* Kc: *Crop coeficient*

ETc: *Crop evapotranspiration*

Evaporation from the surface in a normal CP is, therefore, going to be the total amount of water saved from the subsurface irrigation. Figure 9 shows a perfect example of how water is sprayed aimlessly on the land.

Figure 9. *Sprinklers Irrigation of CP (Folvonic, 2019)*

To determine the electricity consumption of CP, research by Roy et al., (2018) shows that the electricity used to pump the water through the system is calculated using:

$$Daily\ electricity\ use = \frac{WHP * t}{performance\ criteria} \qquad Eq. 2$$

This is where;

$WHP: Water\ Horsepower$ $\qquad t: Time\ of\ operation$

CP requires a capital cost of $2000 to $5000 per hectare, (Alibaba, 2020; Harris, 2011). Consequently, knowing that an average CP can easily irrigate 50 hectares of land, the total costs would estimate around $100,000, which is equivalent to approximately £80,000. This suggests that by improving the efficiency of this machine, the total value can go even higher.

3.0 Centre Pivot Modelling

3.1 Evapotranspiration Calculations

Evapotranspiration is the sum of all the evaporations plus the transpiration of the plant (Licht and Archontoulis, 2017). To measure the rate of evaporation from the soil surface, crop evapotranspiration must be calculated first. Thus, the evapotranspiration equation is rearranged and labelled as *Eq. 3.* Figure 10 illustrates the ET0.

$$ETc = Kc * ET0 \qquad Eq. 3$$

This is where;

$ETc: Crop\ evapotranspiration$ $\qquad$ $Kc: Crop\ coefficient$

$ET0: Reference\ crop\ evaporanspiration$

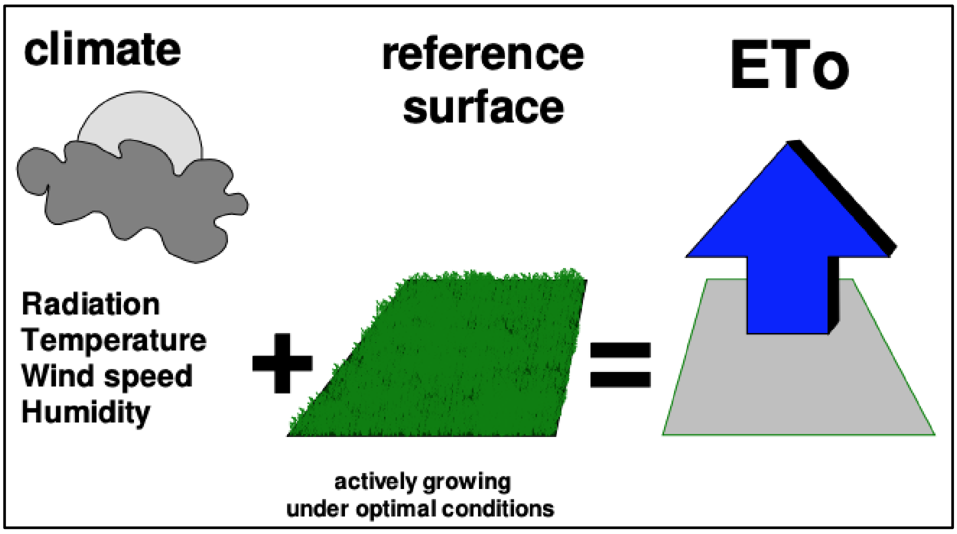

Figure 10. *Diagram of reference evapotranspiration (Raes, 2009)*

Pereira et al. (1998) provided Eq. 4 for the reference evapotranspiration:

$$ET0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(es - ea)}{\left(\Delta + \left(\gamma(1 + 0.34u_2)\right)\right)} \qquad Eq.\ 4$$

This is where;

$\gamma: Psychrometric\ constant$ $\qquad$ $R_n: Net\ radiation$

G: Soil heat flux density $\qquad$ T: Average temperature

u_2: Wind speed 2 metres above the ground $\qquad$ es: Saturation vapour pressure

ea: Actual vapour pressure

Assumptions made:

- All the data inputs are assumed to be all happening on the 15th of May
- T, u_2, are provided from the same source (weatherspark, 2020)
- Soil heat flux density to be zero to simplify the calculations. This is because Net radiation of the sun is so large that in comparison it does not make much of a difference (Raes, 2009)

Therefore, γ, es, ea and R_n are to be calculated.
Starting with the Psychometric constant, which is provided in the studies of Pereira, Allen, Raes and Smith (1998):

$$\gamma = \frac{Cp\ (Patm)}{\varepsilon\ \lambda} \qquad Eq. 5$$

Where

$Patm$: Atmospheric pressure

Cp: Specific heat at constant pressure

ε: Ratio molecular weight of water vapour

λ: Latent heat of vaporization

Cp is assumed to be 0.001013 MJ/kg °C in all calculations. This is because the differences are very small. And as atmospheric pressure, $Patm$, varies at different heights above sea level z. it is therefore calculated by:

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad Eq. 6$$

The obtained value is put back into Eq. 5 and therefore Eq. 4.
Saturation vapour pressure, es, is calculated using:

$$es = \frac{e^0(Tmax) + e^0(Tmin)}{2} \qquad Eq. 7$$

Where $e^0(T)$, Saturation vapour pressure at maximum and minimum temperatures is given by;

$$e^0(T) = 0.6108 \exp\left[\frac{17.27\ T}{T + 237.3}\right] \qquad Eq. 8$$

Relative humidity, Rh, is provided by Weatherspark (2020) to assist with the calculation of actual vapour pressure ea:

$$ea = \frac{e^0(Tavg)\ Rh}{100} \qquad Eq. 9$$

And finally, Slope vapour pressure curve, Δ is calculated using Eq. 10;

$$\Delta = 0.6108 \exp(e^0 T) \qquad Eq. 10$$

Again, these values are substitute back into Eq. 4.

Average Net radiation value obtained is 16 $MJ\ m^{-2}\ day^{-1}$. The calculations are provided in Appendix A.

Figure 11 illustrates the $ET0$ and shows what the calculated values mean.

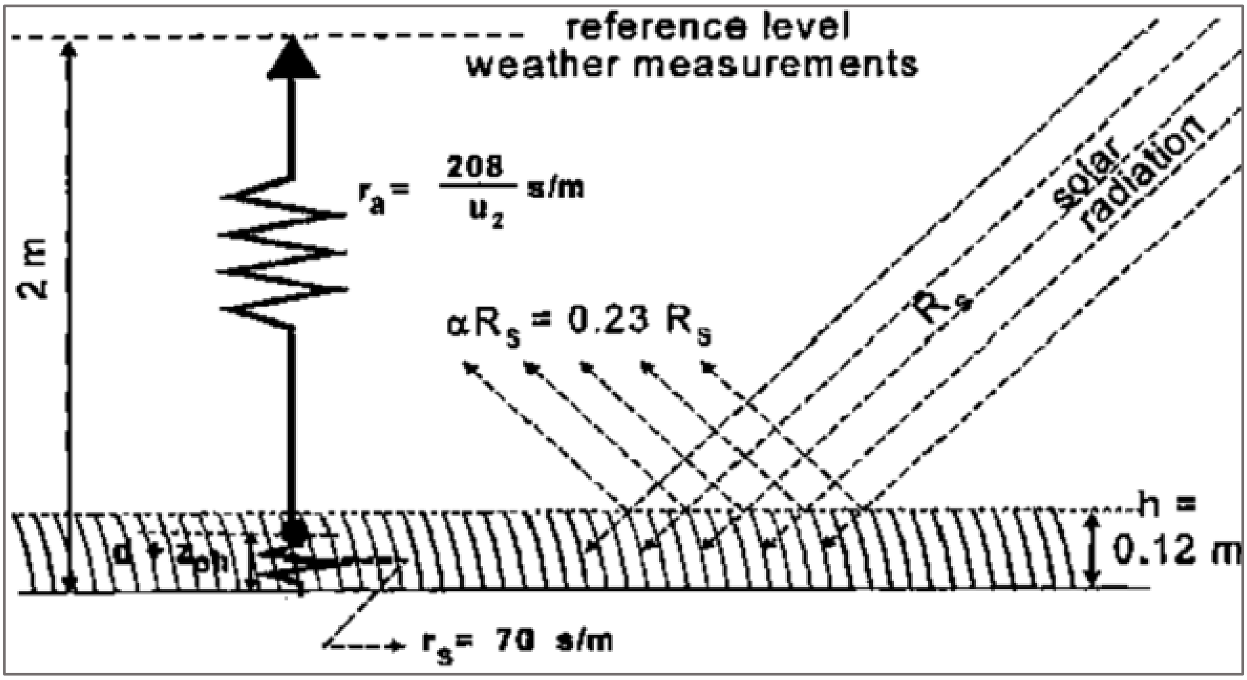

Figure 11. *Characteristics of the hypothetical reference crop (Pereira et al., 1998)*

To emphasise the results of evapotranspiration and as evidence that the calculations are accurate, 3 different locations are chosen to be examined. These 3 locations are; Montana – USA, Riyadh – Saudi Arabia, Gloucester – UK. The results are compared at the end of the calculations.

Other assumptions made:

- Height of the crops: 0.12 m for all crops
- Ratio molecular weight of water vapour/dry air: 0.62 for all areas
- Height of measurement of wind and temperature: 2m above the surface
- Roughness length governing the transfer of heat and vapour: 0.0014m
- Roughness length governing momentum transfer: 0.0147m
- Von Karman's constant: 0.41
- Solar Constant: 0.082 MJ m^2 min^-1
- The surface resistance of all plants: 0.12 s/m
- Albedo: 0.23
- Boltzmann constant: 4.9E+09 MJ k^-4 m^-2 day^-1

Evapotranspiration calculation was achieved by following the studies of Pereira et al. (1998). Therefore, it was a rational choice to keep the assumptions the same as the studies. Another reason for these assumptions is that they make very little changes to the final results. For example, the temperature at 2 metres above the ground is very similar, if not the same temperature as 1.5 metres above the ground.

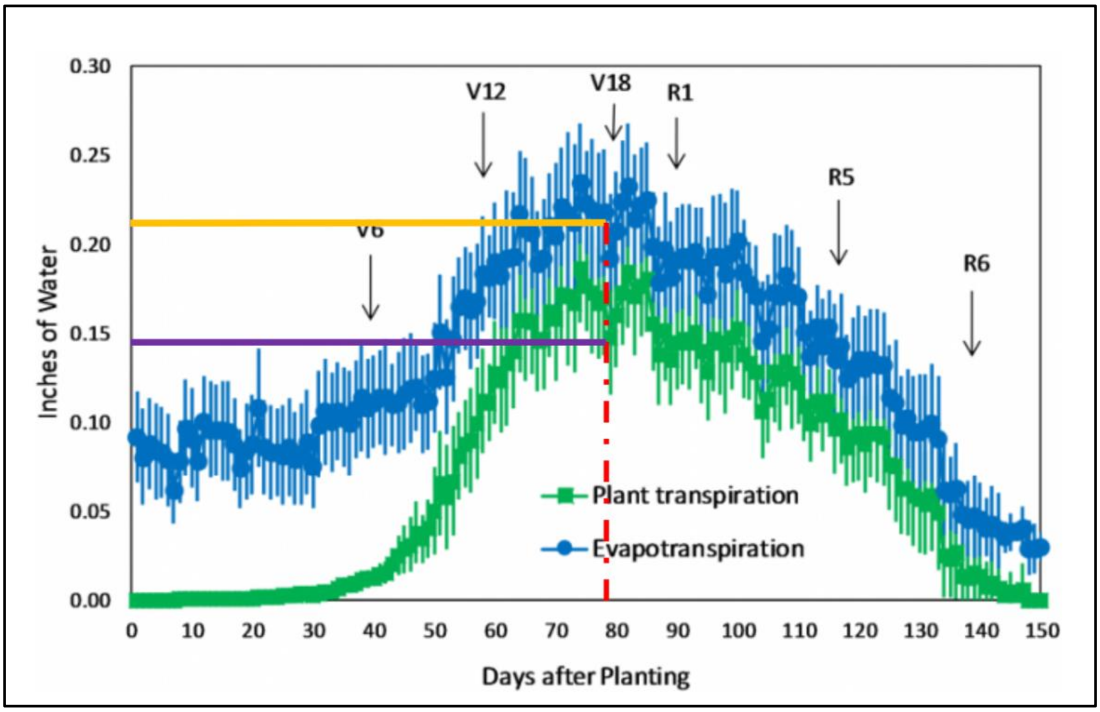

Figure 12. *Relationship between plant transpiration and evapotranspiration (Licht and Archontoulis, 2017)*

3.1.1 Evaluation of water losses

The critical assumption in these calculations are the crop co-efficient, kc, and the percentage of evaporation that is in evapotranspiration. Therefore, for crop coefficient, for a newly planted vegetation, kc is 0.4 (Pereira et al., 1998). Also based on the studies of Licht and Archontoulis (2017), the percentage of evaporation from crop evapotranspiration is assumed to be the average of 35% in these calculations. Table 4 shows the calculations that have been done to measure the evapotranspiration at three different locations.

Transpiration added with evaporation gives the total value of evapotranspiration. Using the graph on Fig. 12, the assumption was based on having two points on the same day once the plant has grown. The percentage difference is therefore the constant for evaporation. By dividing 0.15 by 0.225 on day 78 after planting, produced a constant of 0.67. eventually, that was taken away from the total of 100 to produce the constant of 0.35. Thus, it is assumed 35% of evapotranspiration is made of evaporation.

Table 4. *Reference evapotranspiration and evaporation calculations*

	Symbol	Montana	Riyadh	Gloucester	Unit
Reference evapotranspiration	ET0	4.052	8.344	4.045	mm / day
Net radiation at crop surface	Rn	16.93	15.07	17.02	MJ m^-2 day^-1
Soil heat flux density	G	0	0	0	MJ m^-2 day^-1
Mean temperature at 2m	T	9.915	26.05	11.46	°C
Wind speed at 2m	U2	1.8	3	3.9	m /s
Saturation vapour pressure	es	1.221	3.371	1.353	kPa
Actual vapour pressure	ea	0.708	0.742	0.907	kPa
Saturation VP defecit	es-ea	0.513	2.630	0.447	kPa
Slope VP curve	Δ	0.082	0.199	0.090	kPa / °C
Psychometric constant	γ	0.065	0.063	0.067	kPa / °C
Crop Height	h	0.12	0.12	0.12	m
Atmospheric pressure	P	97.76	94.27	101.02	kPa
Elevation above sea	z	304	612	24	m
Latent heat of vaporization	λ	2.45	2.42	2.47	MJ /kg
Specific heat at constant pressure	Cp	0.001013	0.001013	0.001013	MJ / kg °C
Ratio molecular weight of water vapour/dry air	ε	0.62	0.62	0.62	
Mean air temperature	Tmean	9.915	26.05	11.46	°C
Maximum air temperature	TMax	16.5	37.4	15.7	°C
Minimum air temperature	Tmin	3.33	14.7	7.22	°C
Crop evaporation		0.567	1.168	0.566	mm/day
Saturation vapour pressure at T	e°(T)	1.221	3.371	1.353	kPa
Exponential	exp	2.718	2.718	2.718	
Relative Humidity	RH	58	22	67	%
Aerodynamic resistance	ra	115.37	69.22	53.25	s/m
Height of measurement	Zh	2	2	2	m
Zero plane displacement height	d0	0.08	0.08	0.08	m
Roughness length govering momentum transfer	Zom	0.01476	0.01476	0.01476	m
Roughness length govering transfer of heat and vapour	Zoh	0.001476	0.001476	0.001476	m
Von Karman's constant	k	0.41	0.41	0.41	
Extraterrestrial radiation	Ra	40.96	40.05	40.94	MJ m^-2 day^-1
Latitude (all in North direction)	La	46.88	24.71	51.86	
Solar constant	Gsc	0.082	0.082	0.082	MJ m^-2 min^-1
Invere relative distance of sun	dr	0.977	0.977	0.977	
Sunset hour angle	ω	1.949	1.731	2.027	rad
Latitude	φ	0.818	0.431	0.905	rad
Solar declination	δ	0.333	0.333	0.333	rad
Day number	J	136	136	136	day
Day light hours	N	14.89	13.22	15.48	hours
Amount of radiation absorbed on clear sky	as+bs	0.75	0.75	0.75	
Shortwave radiation	Rs	30.72	30.04	30.71	MJ m^-2 min^-1
Adjusted Rs for specific elevation	Rso	30.97	30.53	30.73	MJ m^-2 min^-1
Net shortwave radiation	Rns	23.85	23.51	23.66	MJ m^-2 min^-1
Out going net longwave radiation	Rnl	6.92	8.43	6.64	MJ m^-2 min^-1
Net radiation	Rn	16.93	15.07	17.02	MJ m^-2 min^-1
height of crop	0.12	m			
Surface resistance	70	s/m			
Albedo	0.23				
Boltman constant	5E-09	MJ K-4 m -2 day-1			

The results obtained from the calculations above are provided in Table 5.

Table 5. *Water evaporation*

	Montana	Riyadh	Gloucester	Unit
Reference evapotranspiration	4.052	8.344	4.045	mm/day
Crop Coefficient	0.4	0.4	0.4	
Crop Evapotranspiration	1.621	3.338	1.618	mm/day
Percentage of evaporation	35	35	35	%
Evaporation	0.567	1.168	0.566	mm/day

As expected, Riyadh has the highest rate of evapotranspiration with 3.3 mm/day, and due to the ratio of 0.4 constant, overall evaporation from the surface of the soil is at 1.2 mm/day. Additionally, the rate of evaporation of Gloucester and Montana are very similar. This is because both of these locations have very similar latitude of 0.82 and 0.9, therefore they have similar hours of sunshine which leads to similar net radiation. Also, where Montana may have a warmer climate, Gloucester makes up for it by being windier, which causes wind drift.

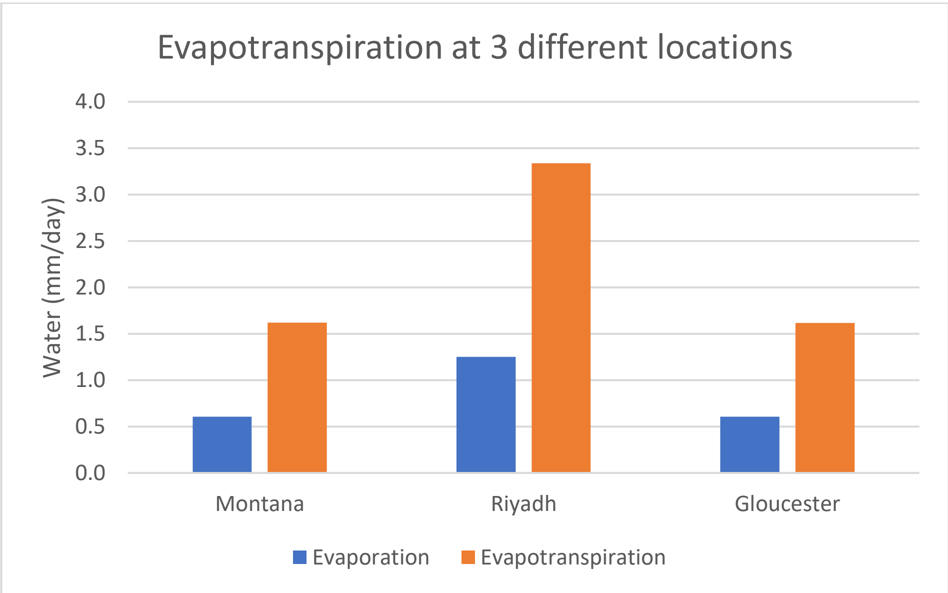

Figure 13. *Comparison graph of water evapotranspiration*

As the graph in Fig. 13 suggests, the new design should help Riyadh the most considering that this area is facing a water crisis. This is because the new design reduces evaporation, and Riyadh farmers can thus save water.

3.2 Water requirements

To calculate the total amount of water used, it is assumed that the CP is irrigating a 50 hectare (124 acres) of land, between the months of May-August (using the weather patterns for 15th of May). By selecting three different crops, sunflower, peanut and lettuce, the total water requirement is calculated. These three crops require a different amount of water each; however, it is assumed that they are all at the same height and cover the same area of land.

Moreover, by using the data provided by Singh (2010), the total water requirement can be calculated. Thus, the formula for water requirement is given by Eq. 11:

$$Total\ water = Minimum\ water\ requirement\ of\ plant + Evapotranspiration \quad Eq. 11$$

This is because evapotranspiration is a natural process and water requires additional water that is actually used for growth. Table 6 is used as guidance for the calculations.

Table 6. *Conversion table*

Acre	metres squared	Hectare
1	4046.86	0.4
124	501810.64	50

Figure 14 can be used to visualise the areas.

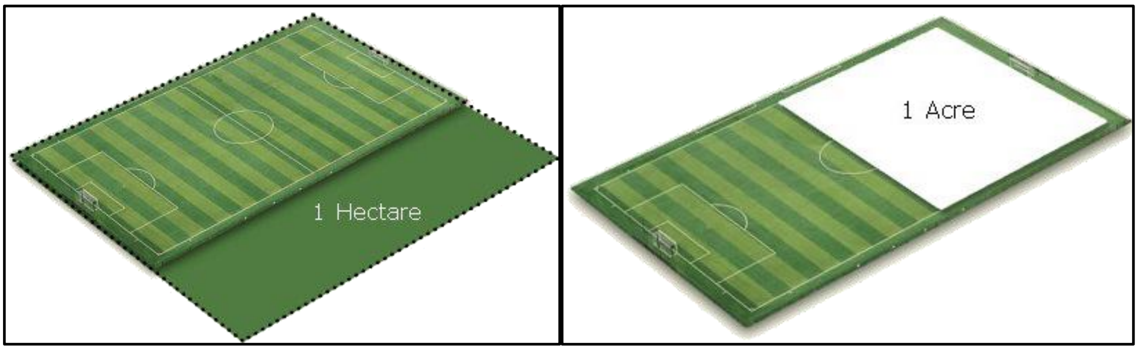

Figure 14. *Examples to visualize the land sizes (Angelfire.com, 2020)*

The calculations steps are:

1- Total water requirement per m^2= Evapotranspiration + minimum water the plant needs.
2- The water required is calculated for every metre squared, thus it's converted to acres.
3- Multiplied by 124, as this is the total irrigation area.

The water consumption is manipulated in Table 7.

Table 7. *Calculations for the amount of water required*

		Montana	Riyadh	Gloucester	Unit
Water evaporation		0.6	1.3	0.6	mm/day
Water evapotranspiration		1.6	3.3	1.6	
Sunflower	Minimum water requires	3.0	3.0	3.0	
	Total water required	4.6	6.3	4.6	
	Total water for 1 acre	18700	25647	18689	
	Total water for 124 acres	2318813	3180229	2317419	
Peanut	Minimum water requires	2	2	2	
	Total water required	3.6	5.3	3.6	
	Total water for 1 acre	14653	21600	14642	
	Total water for 124 acres	1817002	2678418	1815608	
Lettuce	Minimum water requires	1	1	1	
	Total water required	2.6	4.3	2.6	
	Total water for 1 acre	10606	17553	10595	
	Total water for 124 acres	1315191	2176607	1313798	

Moreover, using the data above, the percentage of water loss at three different locations for three different crops is calculated using Eq. 12:

$$Percentage\ of\ water\ loss = \frac{(water\ loss\ due\ to\ evaporation)}{Total\ water\ used} * 100 \qquad Eq. 12$$

For example, sunflower loses 0.6 mm/day due to evaporation and requires a total of 4.6 mm/day in Montana. Therefore;

$$Percentage\ of\ water\ loss = \frac{0.6}{4.6} = 13\% \qquad Eq. 13$$

Hence Table 8 shows the amount of water lost.

Table 8. *Percentage of water loss*

	Montana	Riyadh	Gloucester	Average
Water loss by sunflower	13.2%	19.7%	13.1%	15.3%
Water loss by peanut	16.8%	23.4%	16.8%	19.0%
Water loss by lettuce	23.2%	28.9%	23.2%	25.1%
Average water loss	17.7%	24.0%	17.7%	19.8%

As expected, water loss is extremely high at Riyadh with 28.9% being the highest. Surprisingly, CP is slightly less efficient in Gloucester than in Montana, this may be due to windier climate. Average water loss is 19.8%. Hence taking away that number from 100 gives an efficiency of 80.19 % in terms of water usage (for the months of May-August).

These results are likely accurate. Both Evans (2001) and Folvonic (2019) support this finding. Both of these evidence that the water application efficiency is 80%, using the sprinklers.

3.3 Water costs

Water costs are calculated by the following Eq. 14:

$$Water\ Cost = Water\ used\ (Litre) * Price(£\ per\ litre) \qquad Eq.\ 14$$

Table 9 is produced by taking water requirements from Table 7 and multiplying it by the costs. Southwestwater (2020) provides water for the farming industry at £ 1.4 per 1000 litres.

Table 9. *Water cost calculations*

		Montana	Riyadh	Gloucester	Unit
Cost of water for different crops at different locations per year	Sunflower	128555	176312	128478	£/year
	Peanut	100735	148491	100657	
	Lettuce	72914	120671	72837	
Average price yearly	Average factor 0.33		116628		£

Other assumptions made:

- No rainfall in these calculations was assumed for simplification of calculations
- CP system is going to put into work for 120 days throughout the year
- An average factor of 0.33 is considered to make up for the rainfall and the number of days the device is actually put into work
- The water costs are assumed to be £1.4 per 1000 Litres for all 3 different locations.

3.3.1 Water costs evaluation

As the data suggests, a relatively high amount of money is spent by the farmers on irrigation each year. A farmer in Saudi Arabia has a much higher spending at an average of £150,000, in comparison to a farmer in the UK with an average of £100,000. The new design, if applicable, should allow a reduction of costs to some degree. The water price in Saudi Arabia may be higher, hence the overall result may slightly alter for each country. The collected data in table 9 is used for discussion.

3.4 Centre Pivot Electricity Consumption

Using the calculation method of the studies by Roy et al., (2018), electricity consumption can be calculated. In this study, an average-sized CP of 400 metres long with the capability of delivering 1200 gallons of water per minute is used. With an 80.2% efficiency, the time required to go in a full cycle can be calculated using Eq. 15:

$$T = \frac{\frac{452.6\,A}{Q} * P(cp)}{E(cp)} \qquad Eq.\ 15$$

Table 10. *Input data for electricity consumption*

Symbol	Definition	Value	Unit
T	Time for a complete cycle	N/A	Hour
Q	Flow rate	1200	gpm
A	Irrigated area	124	Acre
E(cp)	Irrigation efficiency	82	%
P(cp)	Land irrigated	100	%

Hence;

$$T = \frac{\frac{452.6 * 125}{1200} * 1}{0.82} = 57.5\ hours$$

Using the same mathematical principle as Roy et al (2018), water horsepower can be calculated. Considering that CP devices are usually active for anywhere between 10-16 hours daily, these calculations have assumed an active time of 14 hours, for an average total dynamic head, H, of 300. Thus, to solve the water horsepower (WHP):

$$WHP = \frac{Q * H}{3960} = \frac{1200 * 300}{3960} = 90.9\ Watt \qquad Eq. 16$$

Pump motor used has 15HP, with a performance criterion of 0.75.

Hence the yearly pump electricity usage is given by:

$$Electricity\ consumption = \frac{WHP * Hours\ in\ use}{Pump\ motor\ HP * Perfromance\ criteria} \qquad Eq. 17$$

$$Electricity\ consumption\ per\ day = \frac{90.9 * 14}{15 * 0.75}$$

Electricity = 41531.04 kWh/year

Using an average price of 0.13 £/kWh, the sum of the electrical cost would be:

Costs = 41531.04 * 0.13 = £6229.66 *Eq. 18*

When comparing the results from this calculation to another source reported by Gasse (2017), the obtained value seems to be slightly lower. This is where Gasse (2017) estimates a value of $5,128 (£4,100), though this is because of the lower pumping rate and fewer operating hours.

Table 11. *Electricity consumption*

Irrigated land %	Pumping rate gpm	Total Head	Water horsepower WHP	Electricity usage kWh/yr	Costs @ £0.13/kWh
100	1200	300	90.9	41531.04	6230

4.0 Centre Pivot Alternative Modelling

4.1 The alternative design

As previously discussed, the new design as shown in Fig. 15 aims to reduce evaporation losses. However, it also needs to overcome some of the major drawbacks.

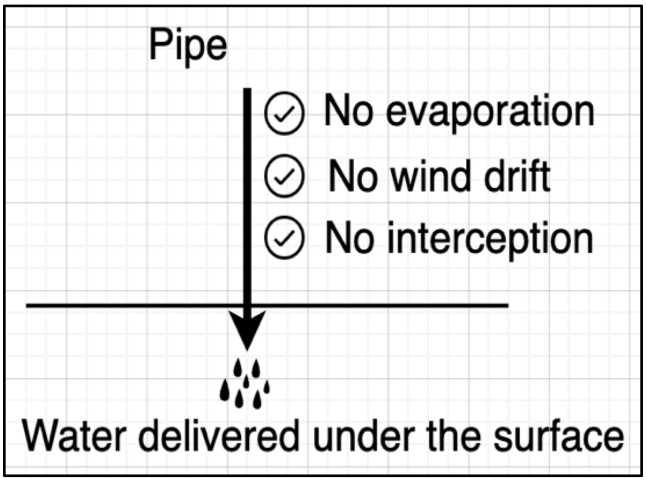

Figure 15. *Alternative design of CP (Flowchart Maker & Online Diagram Software, 2020)*

Some of the major concerns that the new design has to overcome are;

- To prove that it reduces water consumption
- Ability to penetrate the ground without damaging the soil
- Have low energy consumption
- Ability to withstand the pressure exerted by the soil upward to the pipe
- Be cost-effective
- Be environmentally friendly.

The overall basic idea is to replace the sprinklers, thus, Fig. 16 provides a simple outlook on the new system.

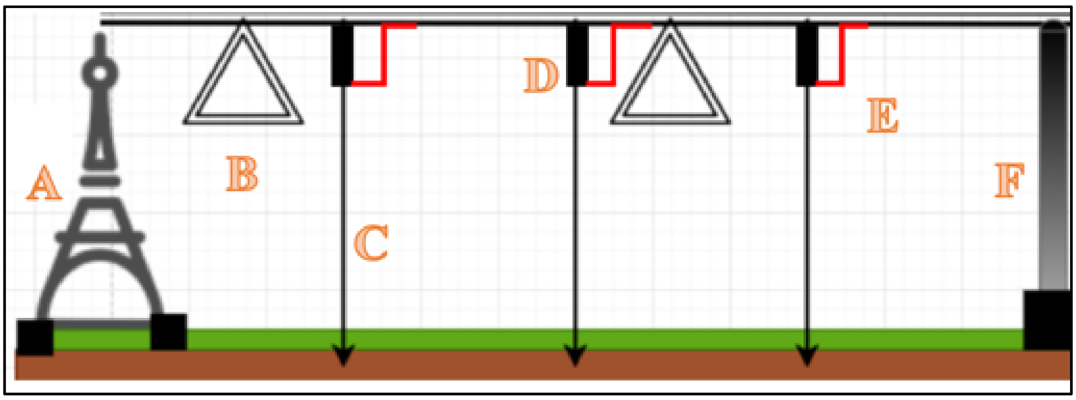

Figure 16. *Front view of Centre pivot with subsurface irrigation (Flowchart Maker & Online Diagram Software, 2020)*

The labelling is defined in Table 12.

Table 12. *Table of components for the new CP*

Letter	Components & their functionality
A	Fixed Central pivot for pumping underground water
B	Triangular structure to deal with stress build-up due to high water pressure
C	Penetrating pipe to irrigate the subsurface layer
D	Flexible pipe to allow the pipe movement
E	Actuator responsible for automation movement of the pipe
F	The wheeled tower that allows circular movement of the system

By using the simple diagram above a CAD design had been made in Fig. 17. Due to limited time and access to the Solidworks program, the labelling of the dimensions was achieved using more readily available online software (Flowchart Maker & Online Diagram Software, 2020).

Due to the vast size of the CP, Fig. 17 is only able to show the first set of pipes, until the first wheeled tower. However, the real design in this experiment is 400 metres, hence it would be ten times as large, as it would be ten of these systems (apart from the main pivot tower) connected together. It is important to notice that the pipes are actually longer than the towers. This is because the pipes are at their maximum length in this image. An isometric view is provided in Appendix B.

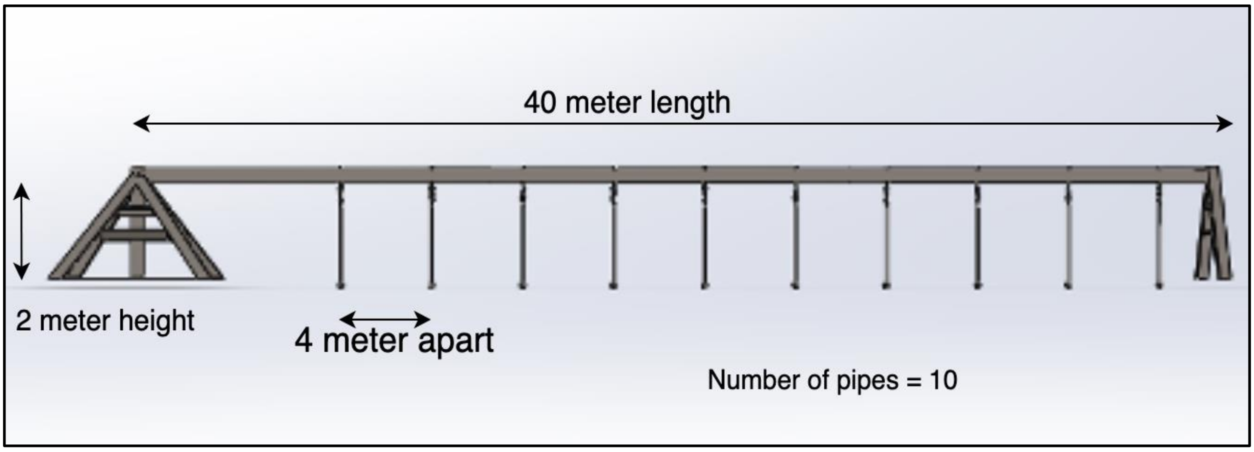

Figure 17. *Front view of CP designed on Solidworks*

4.1.1 Subsurface irrigation pipe

It was a rational decision to provide a set of pipes that connect to the main shaft. And via this pipe, water is delivered to the subsurface soil. Consequently, the new pipe must be able to penetrate the ground slow enough to not to damage the soil. Similarly, it has to be strong enough to withstand the continuous cycles of entering and leaving the ground without breaking. After series of hand drawings and examples studied, the new design was made on Solidworks, as shown in Fig. 18.

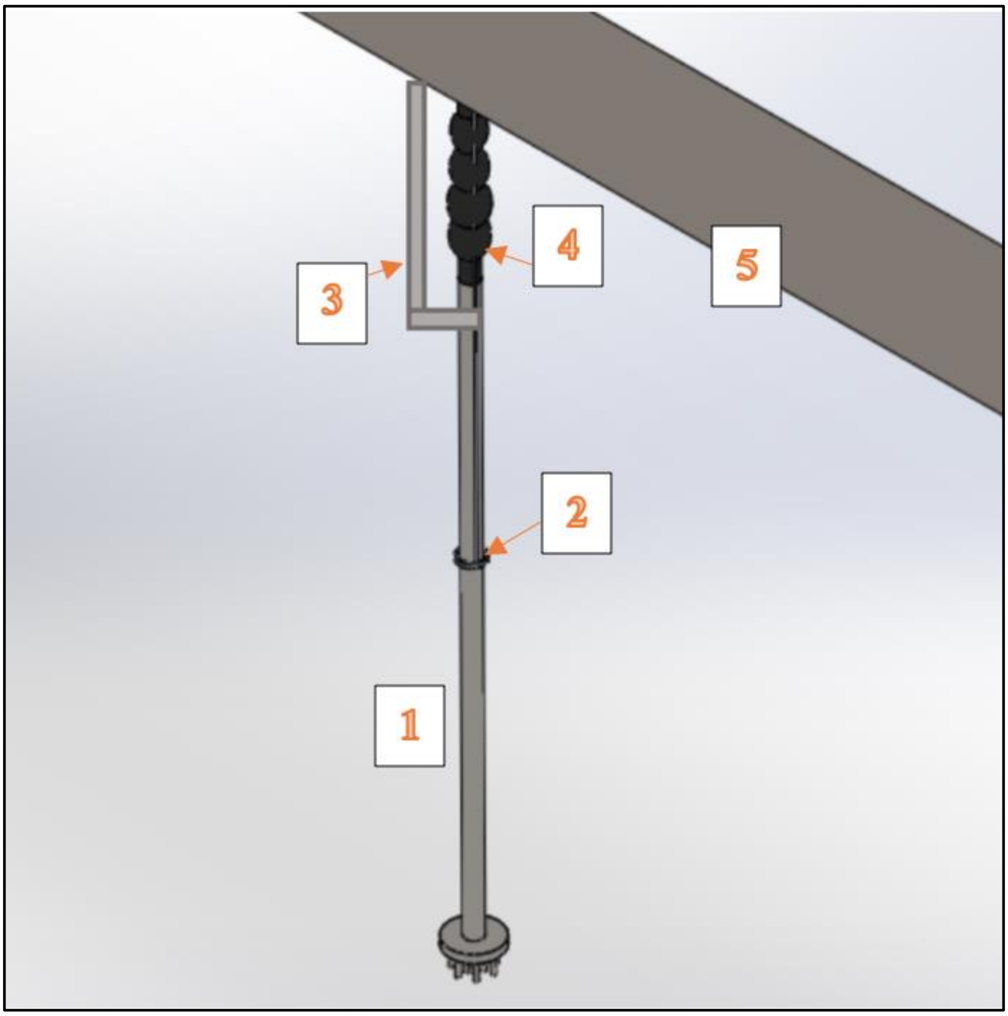

Figure 18. *Subsurface irrigation pipe*

Table 13. *Definitions and functionality of subsurface irrigation pipe*

#	Component	Function
1	Metal Pipe	Delivers water to the subsurface layer by penetrating the ground
2	Guide bar	Limits the pipe to go straight into the ground without swaying
3	Actuator	Provides electrical power for lateral movement of pipe
4	Compressible pipe	Expands and reduces to allow the movement of pipe
5	Main pipe	Water delivered from the pivot into this main pipe

Figure 18 shows a 1.7-metre metal pipe which is connected to a 30cm compressible pipe. When water is pumped from the underground source to the main pipe, it then travels via compressible pipe into the metal bar. Then, by the means of an automated actuator, the metal bar is pushed into the ground. This is only possible due to presence of the compressible pipe. Then once bottom end of the pipe enters the ground, it releases the water into the subsurface layer. Once the delivery is made, the actuator compresses the compressible pipe by 15cm, enabling the metal pipe to move up.

The system also has a guide bar. The guide bar is essentially two metal bars that are connected to each other by a loop at the end of the bars. Bars by the side are connected to the main shaft. The metal bar has to go through it; thus, it limits unnecessary movements. This results in a stable pipe.

The bottom end of the pipe, Fig. 19, is one of the critical parts of the design. The bottom surface of metal bar is made of 15 smaller tubes to ease the penetration of the soil. These mini tubes are 5cm long and have an inner diameter of 5mm. Highly pressurized water travels through these tubes at a high velocity to make sure they do not get blocked, therefore, the material of this part is critical.

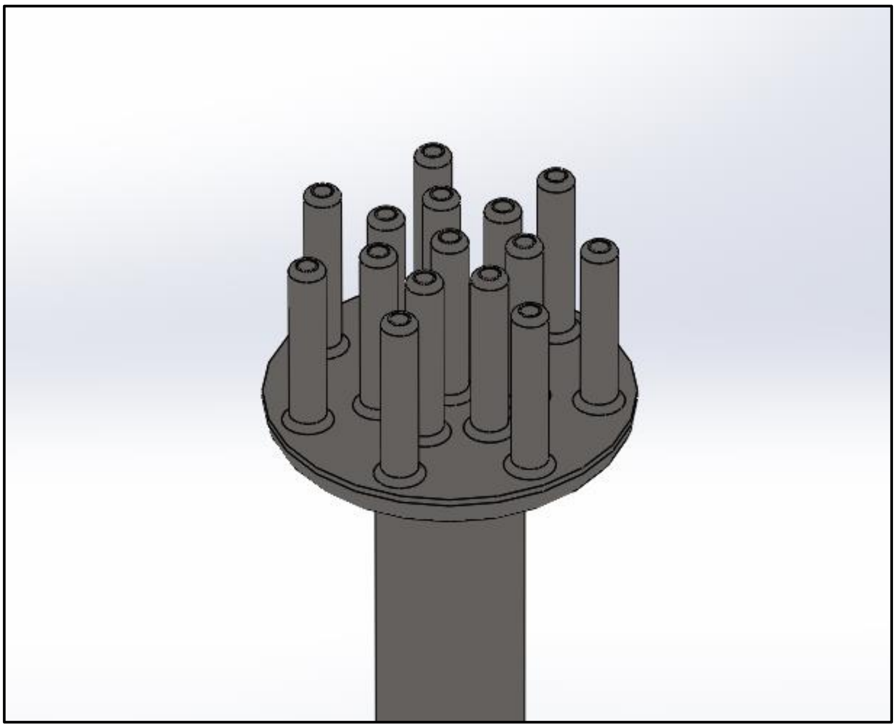

Figure 19. *Bottom surface of the pipe*

Although the model does not seem to be aesthetiacally pleasing, it is to be evaluated on its functionality. Aspects of this include:

- Structrural ability to withstand impacts from the ground
- Ability to enter the ground with minimum energy requirement
- Being cost effective and having cheap maintenance costs
- Ability to move in and out of soil without damaging the soil
- Ability to resist getting blocked by soil
- Ability to withstand harsh climates such as high humidity or high temperatures
- Be recyclable and environmentally friendly.

The overall scale of the metal pipe is provided in Fig. 20.

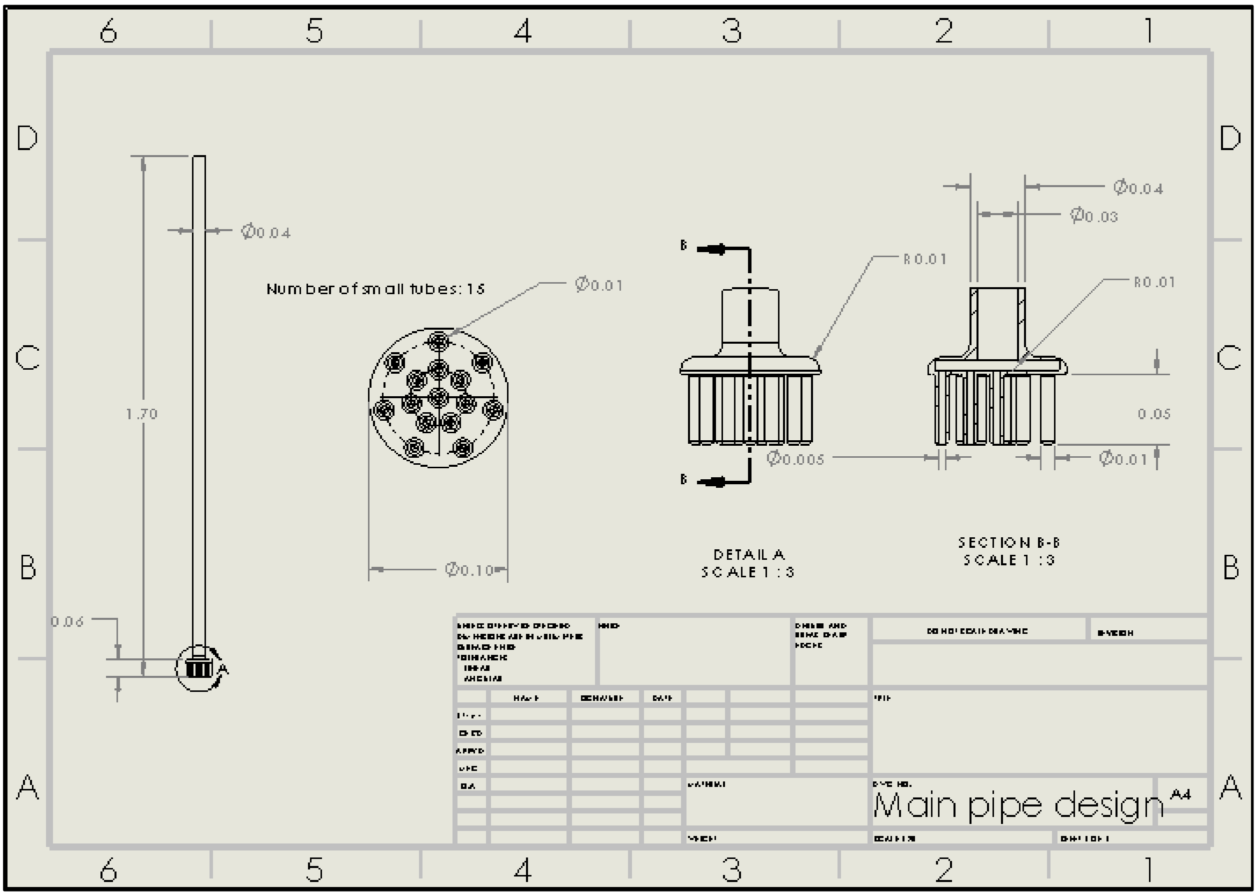

Figure 20. *Solidworks Drawing of the Metal Pipe*

The rationale behind this design is that instead of having one big pipe going into the ground, having smaller diametered mini pipes would boosts the velocity of water flowing through. This should avoid the tube becoming blocked. However, further investigations are required to know the exact velocity or pressure requirement.

4.2 FMECA Analysis

A Failure Mode, Effect and Criticality Analysis (FMECA) method helps to manage the risks in a product. A spreadsheet below illustrates how the failure mode and severity is analysed to produce a score. Thus, a failure mode is initially analysed, then mitigating factors are applied, and the risk is again analysed through thought processing, research and discussion. If there are still any unacceptable risks after mitigation, then the model needs serious reconsideration.

A risk matrix in Table 14 is used as a guideline. It indicates the risks of failure through considerations of both severity and the probability.

Table 14. *Risk matrix*

		Severity			
		Negligible	Marginal	Critical	Catastrophic
Probability		1	2	3	4
Frequent	A	Undesirable	Severe	Unacceptable	Unacceptable
Probable	B	Undesirable	Undesirable	Severe	Unacceptable
Occasional	C	Negligible	Undesirable	Severe	Severe
Remote	D	Negligible	Negligible	Undesirable	Severe
Improbable	E	Negligible	Negligible	Negligible	Undesirable

The definitions of the ratings are given in Table 15.

Table 15. *Definitions of risk matrix rantings*

Descriptor	Definition
Negligible	Acceptable, however, monitoring is required to ensure that it stays low
Undesirable	It can be tolerated if the consequence of reduction exceeds the improvements
Severe	It can be justified if no other alternatives are found
Unacceptable	The risk cannot be justified under any circumstances

Severity: Defines the possible outcomes of failure were to occur, shown in Table 16.

Table 16. *Definitions of severity*

Severity	Descriptor	Definition
1	Negligible	The overall outcome is unlikely to change
2	Marginal	Temporal severity, which can be fixed
3	Critical	Major concern with the design – requires changes
4	Catastrophic	The overall performance does not satisfy the aim

Probability: The chances of the failure occurring. Table 17 describes the definitions.

Table 17. *Probability definitions*

Probability	Descriptor	Definition
A	Frequent	It could occur in every cycle
B	Probable	It could occur more than a few times
C	Occasional	It could occur once a year
D	Remote	Very rarely, however it could still occur
E	Improbable	Unlikely to occur

FMECA analysis Table 18, was compiled for the new CP system.

Table 18. *FMECA Analysis*

Failure description			Pre-Mitigation				Post-Mitigation		
Failure mode	Failure cause	Failure effect	Severity	Probability	Risk	Mitigating Action	Severity	Probability	Risk
Buckling	Not penetrating the soil	No irrigation bending of pipe	4	C	Severe	Suitable pipe design	4	E	Undesirable
Bending	Harder soil, collision	Plastic deformation of the penetrating pipe	4	C	Severe	Correct material choice	4	E	Undesirable
High costs	Unforseen expenses	Dissatisfied client and being over the budget	3	A	Unacceptable	Careful planning	3	E	Negligible
Corrosion	Sand clogging the pipe	Performance deacrese	2	B	Undesireable	Correct material choice	2	D	Negligible
Soil damage	Fast movement of pipe	Dissatisfied customer and damaging the pipe also	3	A	Unacceptable	Steady movement of pipe, controled by actuator	3	E	Negligible
Actuator fails	Poor choice of actuator	No irrigation	3	C	Sevre	Purchase a high-qualit actuator	3	E	Negligible
Power loss	High number of actuators	No irrigation, damage the pipe	2	E	Negligible	N/A	2	E	Negligible
Missaligned pipe	Wrong fixing of pipe	Not penetrating the soil enough	3	D	Undesireable	Have a guide bar	3	E	Negligible
Cyclic failure	Loosening of the pipe	Performance deacrese non-uniform distribution of pipe	3	C	Sevre	Correct material choice	3	D	Undesirable
Structure failure	Bending stress	Imbalance of CP	3	E	Negligible	Material with high factor of safety	3	E	Negligible
Blocked Pipe	Soil blocking the pipe	No irrigation, Break the pump	3	C	Severe	Increase the prresure in the pipe, or have thin diametered pipe	3	D	Undesirable
Leakage	Poor assembly	Water distribution decreases	3	A	Unacceptable	Tightening the bolts, testing of the assembly	3	E	Negligible

FMECA analysis was carefully discussed by a group of engineering students to look for solutions. From these analyses, it is concluded that the majority of the concerns are related to either the material, the design or the cost of the system. According to the FMECA, risks of failure are manageable.

To tackle these concerns, further investigations were required in these sections. Therefore, a material investigation is needed to determine whether the pipe would buckle, as well as finding its price per unit weight.

4.3 Material Selection

Material is the most important factor for ensuring a stable, safe and sustainable pipe is made. As presented in Fig. 18, the system is made up of two pipes that are connected to each other. A main pipe which is 1.7 m, and a 30 cm flexible pipe that connects the main tube to the small pipe.

Having studied the pipes from (Ji, Edwards and Parks, 2015) and (Boldt and Stone, 2018), it was decided to compare the materials with the highest potential to be suitable for this model. The desired properties of the material were listed using the data provided by Boldt and Stone (2018). As a result, the collected data are shown in Table 19.

Table 19. *Material properties*

Material	Steel 4340	Stainless Steel	Copper	Aluminium 5052-O	FRP fibreglass	Polyester	Unit
Density	7800	7850	8960	2680	1500	1370	kg/m3
Tensile strength	400	480 - 620	210- 390	180 - 620	2000	41.4- 89.6	Mpa
Compression strength	335-1160	170- 310	45- 330	30 - 280	4000	36.3 - 44	Mpa
Hardness Vickers	160-650	152	100	60 - 160	10.8 - 21.8	9.9 - 21.5	HV
Price	0.25	0.8	1.8	1.5 - 1.63	28 - 31	2.91-3.26	£/kg
Youngs modules	210	190 - 205	121- 133	69.3	69 - 150	2.07 - 4.41	Gpa
Shear modulus	78	74 - 82	44 - 49	26	30 - 60	0.744-1.59	Gpa
Fracture toughness	100	50	94	28	0.5 - 1	0.7	MN m^03/2
Breaking strain	2.5	60	0.3	12	1.2	2	%

Although Table 19 provides valuable information, it is, however, unclear which material is the most desirable. Another table is required to rate the properties to enable a fair judgement on the selection. Thus, Table 20 below was produced. In this table, the material is judged based on the most important factors that would make it suitable in this design. They are rated from 5 being Excellent, to 1 being Poor. Moreover, some factors such as strength of a material is more important than UV resistance. To make the judgments fair, an order of importance is added to the table to correct the score. This is done by multiplying the score by their value at the end.

Table 20. *Material ratings*

Material	Steel 4340	Stainless steel	Copper	Aluminium 5052-O	FRP fibreglass	Polyester	Importance
Strength	4	4	3	2	5	1	5
Density	2	2	1	4	5	5	4
Corrosion	5	3	5	2	1	1	5
Rigidity	4	4	3	5	3	3	3
Unit cost	5	5	4	4	1	3	5
Flammability	5	5	5	5	2	2	2
UV resistance	5	5	5	5	3	2	1
Water durability	4	4	4	5	5	5	4
Machinability	4	2	2	3	2	4	3
Total score	133	117	110	115	97	92	

Based on the score from Table 20, which has been done with careful consideration, steel alloy 4340 is selected as the most suitable material with a total score of 133. Although this recyclable material may have a high density of 7800 kg/m3, it does however have a high compression strength, which means the pipe is least likely to buckle. This makes it better for long term use than aluminium or stainless steel. Additionally, using the data for steel alloy on Solidworks modelling produces a total weight of 7.8 kg.

4.4 Buckling test

A simple buckling test on the main body of the pipe can determine what is the maximum allowable force that the pipe can take. This is important as the subsurface irrigation pipe is continuously having contact with the ground. From Fig. 20, the inner and outer diameter of the pipe is provided to be 3cm and 4cm, respectively, and the length of the pipe, L, is 1.7m. Ultimately, the area moment of inertia is calculated using (Gere, 2004):

$$I = \frac{\pi}{64}(D^4 - d^4) = 8.6e^{-8}\ m^4 \qquad Eq.\ 19$$

From Table 19, $E(ym)$, the modulus of elasticity of steel is 210 Gpa. And assuming that both end of the pipe is fixed, the factor accounting for the end conditions, n, is 4 (Gere, 2004). These values can be substituted into Eq. 20 to provide the allowable load in Newtons, formula provided by Gere (2004):

$$F = \frac{(n\ \pi\ E(ym)\ I)}{L^2} = \frac{4 * \pi * 210e^9 * 8.6e^{-8}}{1.7} = 2.46\,MN \qquad Eq.\ 20$$

Therefore, the maximum force that the pipe can take just before buckling far exceeds the value of 87N, which is calculated in Eq. 24.

To support this answer, a FEA analysis was also done. To do this, an upright component was designed in Solidworks and set up for a buckling test, and the load on it is the soil's bearing capacity multiplied by the total area (15 smaller pipes). This simulation provides a real-life example of how the soil exerts force on the pipe. The factor of safety was calculated to be 5.3. This means the design is 5.3 times stronger than what the system is required to be, as shown in Fig. 21.

This indicates that in terms of material selection, a different material could've also been selected with a lower FoS. However, the benefit of having a higher FoS is that the material is capable of withstanding more cyclic loadings and consequently it will last longer.

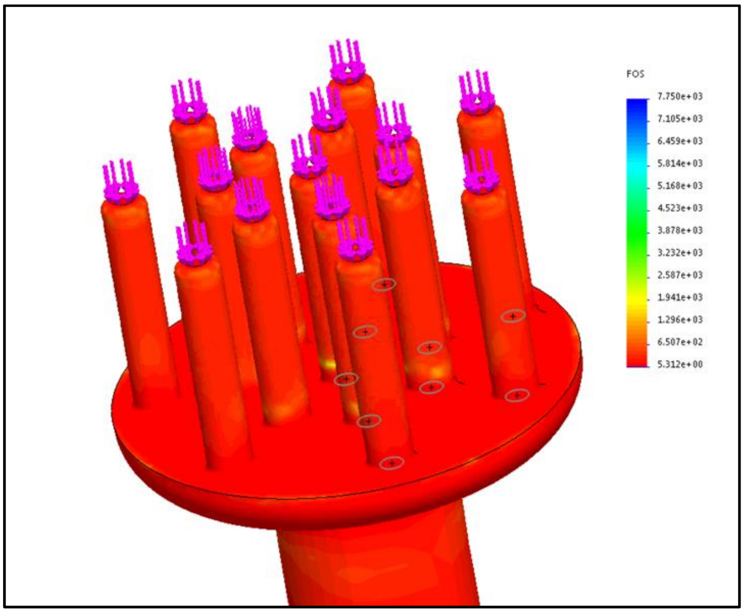

Figure 21. *FoS of the pipe represented by CAD modelling*

Figure 21 shows the result for buckling analysis that was set on the pipe. Further FEA studies of stress distribution was completed as a static simulation on Solidworks, (see Appendix C).

4.5 Electricity usage

As well as the pump electricity consumption, the new design requires another electrical power for the movement of the pipe which comes from the actuator. The breakdown of these movement is broken into 4 stages, as shown in Fig. 22. These stages help to calculate the electricity usage.

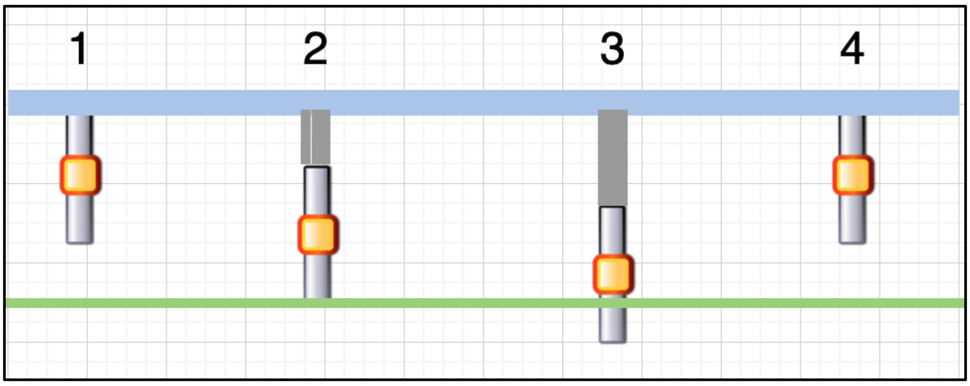

Figure 22. *Stages of pipe movement (Flowchart Maker & Online Diagram Software, 2020)*

Table 21. *Stages of pipe movement*

Stage	Process
1	Pipe is locked, hence it does not require any form of electricity.
2	When the lock releases the pipe, it moves slowly to the surface. This process does not require energy, as its assumed that the pipe moves gently by “free fall”.
3	Pipe requires a small amount of energy to enter the ground, for a 5cm distance.
4	After entering the soil, the actuator requires electrical energy to bring the pipe back up by 15 cm.

The energy calculation for this design which has 100 pipes are as followed:

$$Total\ Energy = 100 * (energy\ for\ lifting\ the\ pipe + energy\ for\ entering\ the\ ground) + Pump\ electricity$$

Eq. 21

Pump energy requirements was previously calculated.

Hence, initially calculating the lifting energy first (Lindeburg, 2013):

$$Energy\ to\ lift\ the\ pipe = Force * Displacement \qquad (or\ mgh) \qquad Eq.\ 22$$

This is where the force is product of the mass of the pipe, given through Solidworks drawing to be 7.8 kg, multiplied by gravity, 9.81 m/s2. The displacement is 15cm, (5cm for penetration + 10cm being above the ground). The answer is substituted into Eq. 21.

Energy required to calculate the force for penetrating the soil depends on few factors, including what type of soil it is, the depth and speed of penetration, the cohesion of the sand.

$$Energy = Force * time * velocity \qquad Eq.\ 23$$

To calculate the force (Lindeburg, 2013):

$$Force = Pressure\ applied * Area\ of\ the\ pipe \qquad Eq.\ 24$$

Pressure applied, as shown in Fig. 23, is equivalent to the bearing capacity of the soil, therefore;

$$Force = Qu * A \qquad Eq.\ 25$$

Yokoi (1968), provides the bearing capacity of pipe:

$$Qu = 1.3\ c\ Nc + \ \gamma\ D\ Nq + 0.3\ B\ Nr \qquad Eq.\ 26$$

Using the data provided by Catanzariti (2016), the following data are put into the equation. Derivation of the values are explained why in the Appendix D.

Table 22. *Bearing capacity symbols and definitions*

Symbol	Definition	Value
c	Cohesion of sandy loam	40 kPa
γ(w)	Bulk unit weight	15 kN/m3
D	Diameter	0.02 m
B	Width of foundation (diameter)	0.02 m
Nc	Capacity factor 1	5.7
Nq	Capacity factor 2	1
Nr	Capacity factor 3	0

Hence, Soil capacity Qu, is calculated to be 297.15 kPa. This answer is likely to be accurate as Bengtsson and Whitaker (1988) report a similar value. This number is subsequently substituted back into the main equation to produce a total of 7085 kWh/year for 1 year. Hence, the total price can be used:

$$Total\ price = Price\ per\ kwh * Energy\ used\ (in\ kwh) \qquad Eq.\ 27$$

$Total\ price = 0.15 *\ 7085$ = £1062.67 for 1 year.

Assumptions made:

- Speed of the pipe entering the soil at 1cm/s (0.036 km/hour)
- Soil type: Sandy loam, as this is the most arable type of soil
- Energy required for the water pump remain the same in both designs
- The pipe can move to the surface with no energy required, due to free fall
- Number of movements for each pipe: 209 (See Appendix E).

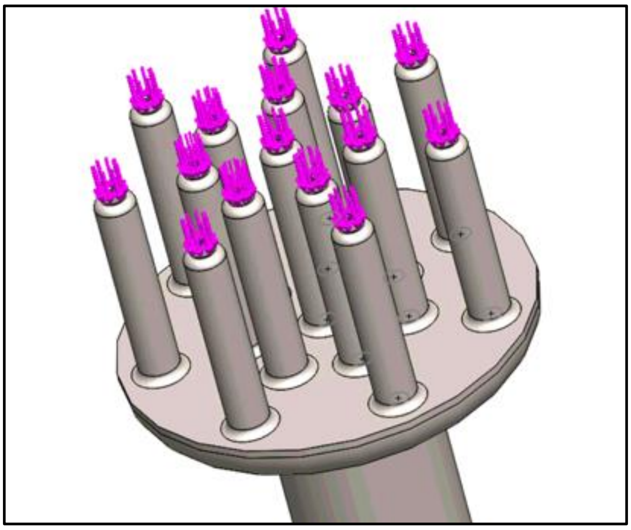

Figure 23. *Illustrates the surfaces where pressure from the soil acts on the pipe*

4.5.1 Evaluation of energy requirement

Since this is a new model, no previous studies were found. The ideal answer is therefore unknown. However, by studying soil bearing capacity papers of Bengtsson and Whitaker (1988), Yokoi (1968) and Catanzariti (2016), and combining them with known mathematical formulas in Lindeburg (2013) and Gere (2004), the energy requirement was calculated.

As seen, there were numerous but fair assumptions made. By a small change in design, the electricity consumption can easily fluctuate. For example, by arguing that the total number of pipe movements in a day is too many or too few, the electricity consumption can fluctuate. This is based on the individual's perspectives of how far they think the water can travel, and for how long. These calculations are beyond an individual's ability and requires a team of experts to be accurately measured.

Another key factor that determines energy required is the speed of the pipe entering the ground. As this model has not yet been built, one may argue that the speed is too fast, and it would damage the soil or one may argue that the speed is too slow, therefore it would use more time to irrigate the land. As a result, the issue was resolved by constant going back and forth to find what one might think is a reasonable assumption.

4.6 Water saving through subsurface irrigation

As discussed, water saved from the new design is the water evaporated from the normal CP. In previous sections, it was calculated that evaporation alone accounts for 18.5% on average. Simply by multiplying the water used in section A, and reducing it by 18.5%, the total water saved per cycle is calculated and multiplied by the same pricing as before. These calculations are provided in Table 23.

Table 23. *Water saved by subsurface irrigation*

		Montana	Riyadh	Gloucester	Unit
Total water saved in new design		284683	586179	284196	mm/day
Money saved by new design	each cycle	398.56	820.65	397.87	£/cycle
	each year	47827	98478	47745	£/year
Correction factor for different seasons		15783	32498	15756	£/year
Average Price yearly			21345		£/year

5.6.1 Evaluation of water consumption

The data show that an average amount of £21,354 can be saved. Although the amount in Riyadh which is £32498, is more than double to Gloucester or Montana. When the calculated evapotranspiration of the crop was compared to the online paper of Pereira et al. (1998), they appeared to be similar, indicating they are accurate.

However, these data are not 100% accurate, simply because of the assumptions previously discussed. The main assumption was that 100% of the evaporation becomes the saved water, which may not entirely be true. Of course, when the pipe enters or leaves the ground, some water may eventually find their way out and be lost.

Yet again, an average correction factor was included to make up for the rainfall, water runoffs and seasonal changes of other weather patterns. It is not possible to collect the data for full year to measure how much water is needed for different plants at different locations. Therefore, it is again based on an individual's perspective of how fair these assumptions are.

4.7 Cost analysis

In this section an overview of pricing the whole system will taking place. Initially, the components of the CP which are to be added to the new design with the quantity that is required for 1 device is observed. Also, the prices of sprinklers and elastic tubes that are no longer needed will be removed for the new model. Table 24 shows it in detail.

Table 24. *Manufacturing costs analysis*

Expenses	Quantity	Total require	Price
New pipe	100	180 metre	3800
Actuator	100		6000
Automation equipment	N/A		4000
Rollers	200		500
Guide bars	200	300 metre	500
Flexible hose	100	15 metre	600
Sprinkler	400		-300
Elastic tubes	400	720 metre	-1000
Total		£	14100

The obtained value of £14,000 is therefore added to the price of the new model. As previously stated, £21,345 is saved but electricity consumption is increased by £1062. Similarly, for the new design, a one-time-only (purchase) is added to Table 25. This is to make up for the purchases made in manufacturing (Table 24).

A further £10,000 is also added, this is because the new system is more valuable, thus it does make sense to add this price to the product. Maintenance costs are assumptions made based on the fact that the new design has more electrical equipment attached to it; thus, the maintenance costs are probably going to be more.

Table 25. *Costs of running CP on annual basis*

Original design	Cost £	New design	Cost £
Electricity	6230	Electricity	7292
Water	116628	Water	95282
Maintenance	450	Maintenance	3500
Additional Price (1 time only)	N/A	Excluded in the total yearly calculations	24000
Total	123307	Total	106075

By adding that One-Time-Purchase price to the first year only, Table 26 shows how the invested money starts to build up, over time.

Table 26. *Money saved over 5-year period*

	1st year	2nd year	3rd year	4th year	5th year
Net profit (£)	-6767	17233	17233	17233	17233
Total money saved (£)	-6767	10466	27698	44931	62164

As Table 26 suggests, initially, the consumer has to start with a negative figure. However, on the second year the investment starts to pay off. Finally, in the beginning of third year the money that was paid for the purchase (£24,000), is recovered, and from this point onwards any money saved is profit.

4.7.1 Evaluation on cost analysis

All of the costs were taken from Alibaba (2020). Hence, the results may differ if another individual were to make the purchases. For example, one may argue that the quality of the products is low, or that the delivery of these components is expensive. Thus, the overall costs may fluctuate from person to person.

5.0 Discussion

From this report it can be suggested that the new design can improve the water efficiency of CP and also save money over the long term. However, this is only achievable by increasing the energy consumption which is provided via electrical sources.

From the results obtained in section 4.6, all farmers could potentially save a total of 385,000 litres of water on average between the three countries. This is equivalent to £21,000 per annum. Although throughout the calculations It was necessary to make some assumptions to approximate real-life figures as much as possible. Another critical assumption was that 100% of all evaporated water is saved in the new design. In reality, it is inevitable to achieve 100% efficiency in any given system, consequently the amount of water saved is guaranteed to be lower.

It is important to note that farmers in warmer climates such as Riyadh can save more on water costs (£32,000) than cooler climates such as Gloucester (£15,000). The differences are almost double. This is simply because with lower humidity, higher temperatures and stronger net radiation, the rate of evaporation is higher in Riyadh. Also, the new CP model is more profitable during summer than in winter, as in winter the climate is cooler and also farms benefit from rainfall.

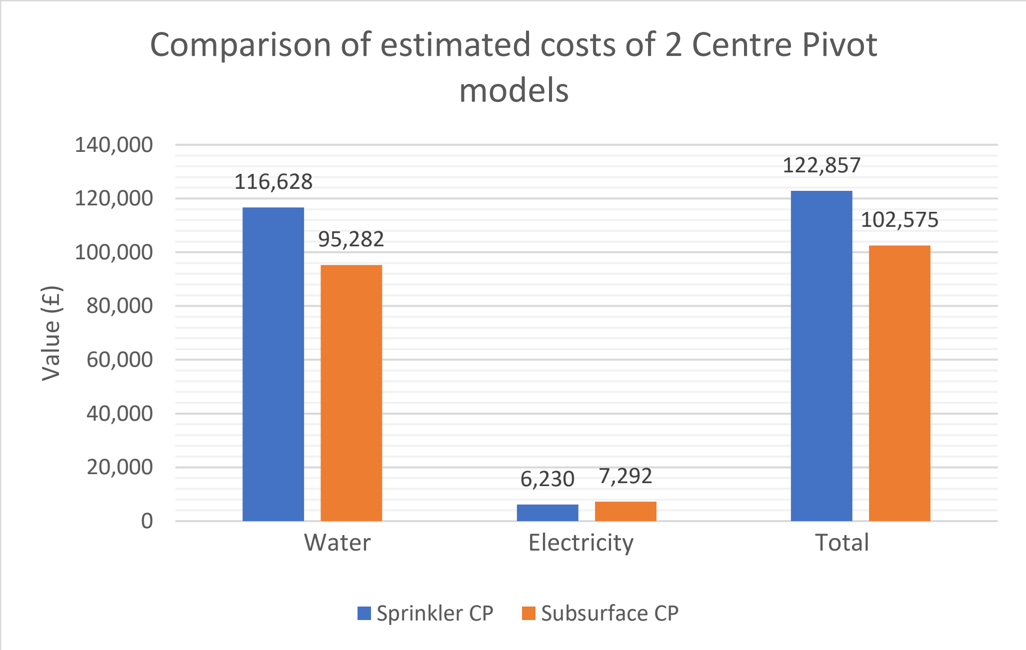

Figure 24. *Comparison graph of the costs*

As previously stated, 70% of all water consumption worldwide is used in agriculture. Hence, a small improvement on water efficiency can save billions of litres of water worldwide and thousands of pounds for an individual farmer each year. It is important to consider the new design as a potential new model. This is because the water that is used for irrigation is underground water, and are irreplaceable if over-used, making it essential to be used carefully and effectively.

Figure 24 shows that the electricity consumption of the CP design will increase using a subsurface method. Based on the calculations and assumptions made, the original CP does not require the additional actuators which account for 7,000 kWh/year. It can therefore save £1060 annually. Moreover, the new CP requires the movement of the pipe in and out of the surface which was broken down into four stages. Two stages required energy: 1) Penetration of soil Stage 2) Contraction of pipe after irrigation.

Although the water evaporation calculation was relatively accurate, the electricity consumption was highly debatable. As previously discussed, the electricity consumption may easily increase or reduce. For example, assuming that the total number of movements of pipe into the surface increases, then the consumption can easily increase, or vice-versa. However, one may argue that by using solar panels to generate electricity can reduce the costs. Therefore, calculations in this section are debatable and need further research.

Some of the key points that this model needs to overcome are: precise simulations on fluid flow, soil permeability, structural integrity and uniform water distribution. However, it is believed that the mathematical modelling developed can be used as a foundation to enhance the efficiency of CP, or it could perhaps inspire manufacturing companies to develop a similar system.

Ultimately, the original CP irrigation is still the superior design. This is simply because it has already been designed, manufactured and tested. It has also been proven to perform at the highest levels for many years. Whereas, subsurface irrigation requires more effort and investigations (which may prove costly). to be actually be put into practice. The summary comparison between the devices is provided in Table 27.

Table 27. *Comparison of two CP models*

	Sprinkler CP	Subsurface CP
More water saved		✓
Less electricity used	✓	
Money saved after 2 years	✓	
Money saved after 5 years		✓
Practically proven to work	✓	
Theoretically more efficient		✓
No expensive investigation	✓	
Environmentally friendly	✓	✓
Lower capital cost	✓	
Overall winner	✓	

6.0 Conclusion

This paper demonstrated a set of analyses on the performance of a CP with sprinklers and compared it to a theoretically developed CP with subsurface irrigation.

The comparison of the two models using mathematical modelling and computational designs cannot be regarded as a complete method of performances analysis. This is because of the number of assumptions that were made through out. For example, a slight change in crop coefficient could change the water consumption by few millimetres per day. Or, a small change in efficiency of water pump or actuators can easily fluctuate the results.

Ultimately, it can be concluded on the basis of this report that the CP water efficiency could potentially be improved by developing subsurface irrigation system. It could also reduce the overall costs of irrigation in agriculture over the long term, depending on how efficiently the system is made. However, the electricity consumption is increased because of the power requirement of actuators.

7.0 Recommendations

Further mathematical modelling recommendations

Initially the model created should be analysed to see if the pipe can deliver water without being blocked. A further mathematical model for water pressure and velocity should be created to make sure the subsurface irrigation pipe delivers water successfully. However, these steps can only be taken with more time available. Further studies on pipe flow can help to deliver results for these calculations.

Utilizing Edu-pack

Edu-pack can reduce the uncertainties on properties of the material. Access to Edu-pack was banned due the global pandemic, which led to research for material properties from different sources. The computational simulations on Solidworks can be further improved to improve the analysis accuracy.

Further study of Actuators

Actuators may not necessarily be the best option to automatically push the pipe down. Other systems such as hydraulic systems may also be considered for this design. Therefore, further research is required to ensure that the system that is responsible for this section is the most energy efficient and reliable.

8.0 Project time management

This is a complex topic which requires more time and resource to be fully understood. As previously discussed, further research may prove expensive but further mathematical modelling using fewer assumptions and more reliable datasets may shed more light on the feasibility of practical testing and research.

The current climate did not allow for this type of research. It was therefore necessary to spend additional time on desk-based mathematical modelling in order to achieve a satisfactory result. Nonetheless, the project has achieved its key aims and allowed an exploration of:

- Logbook keeping
- Project management skills
- Creative and logical thinking
- Simulations for Solidworks
- Online diagram software

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10.0 Appendices

10.1 Appendix A: Net radiation

Following the studies completed by Raes (2009), net radiation can be calculated using:

$Rn = Rns - Rnl$ $\quad Eq.\ 28$

The net radiation is proportional to the net short entering the plant surface and long wavelength leaving the surface (Raes, 2009). However, each of these are based on many other factors, that are listed in the Table 28, and they have been calculated by simply following the equations step by step and substituting the answer back to the main formula.

Table 28. *Net radiation symbols and definitions*

Symbol	Definition	Unit	Symbol	Definition	Unit
as+bs	Amount of radiation absorbed on clear sky		α	Albedo	
Rs	Shortwave radiation	MJ m^-2 min^-1	h	Crop height	M
Rso	Adjusted Rs for specific elevation	MJ m^-2 min^-1	φ	Latitude	Rad
Rns	Net shortwave radiation	MJ m^-2 min^-1	δ	Solar declination	Rad
Rnl	Outgoing net longwave radiation	MJ m^-2 min^-1	J	Day of the year	
Rn	Net radiation	MJ m^-2 min^-1	N	Day light hour	Hours
α	Albedo		n	Actual day light hour	Hours

To find the Net short-wave radiation the following steps need to be taken in order:

$Rns = (1 - \alpha)Rs$ Where albedo is a constant of 0.23. $\quad Eq.\ 29$

$Rs = \left(a_s + b_s \frac{n}{N}\right) Ra$ Where $a_s + b_s$ is a constant of 0.75. $\quad Eq.\ 30$

$N = \frac{24}{\pi} \omega s$ $\quad Eq.\ 31$

$\omega s = arcos[-\tan(\varphi)\tan(\delta)]$ $\quad Eq.\ 32$

$\delta = 0.409 \sin\left(2\pi \frac{J}{365} - 1.39\right)$ $\quad Eq.\ 33$

$dr = 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right)$ $\quad Eq.\ 34$

J is any number from 1 to 365. 135 in this case, as previously stated that all the weather patterns are from the 15th of May.

$$Ra1 = \frac{24*60}{\pi}\, Gsc\ dr\ [\omega s * sin\varphi * sin\delta + cos\varphi * cos\delta * \sin(\omega s)] \qquad Eq.\ 35$$

Where Gsc is 0.082 MJ m^-2 min^-1

And to find the Net long-wave radiation:

$$Rnl = \sigma \left[\frac{Tmax, k^4 + Tmin, k^4}{2}\right] \left(0.34 - 0.14\sqrt{ea}\right) \left(1.35\frac{Rs}{Rso} - 0.35\right) \qquad Eq.\ 36$$

Where σ, Boltzman's constant is 4.903 10-9 MJ K-4 m -2 day-1.

This calculation for different Montana, Riyadh and Gloucester were discovered, and are provided in Table 29.

Table 29. *Net radiation calculations*

	Symbol	Montana	Riyadh	Gloucester	Unit
Reference evapotranspiration	ET0	4.052	8.344	4.045	mm / day
Net radiation at crop surface	Rn	16.93	15.07	17.02	MJ m^-2 day^-1

10.2 Appendix B: Isometric view of CP designed on Solidworks.

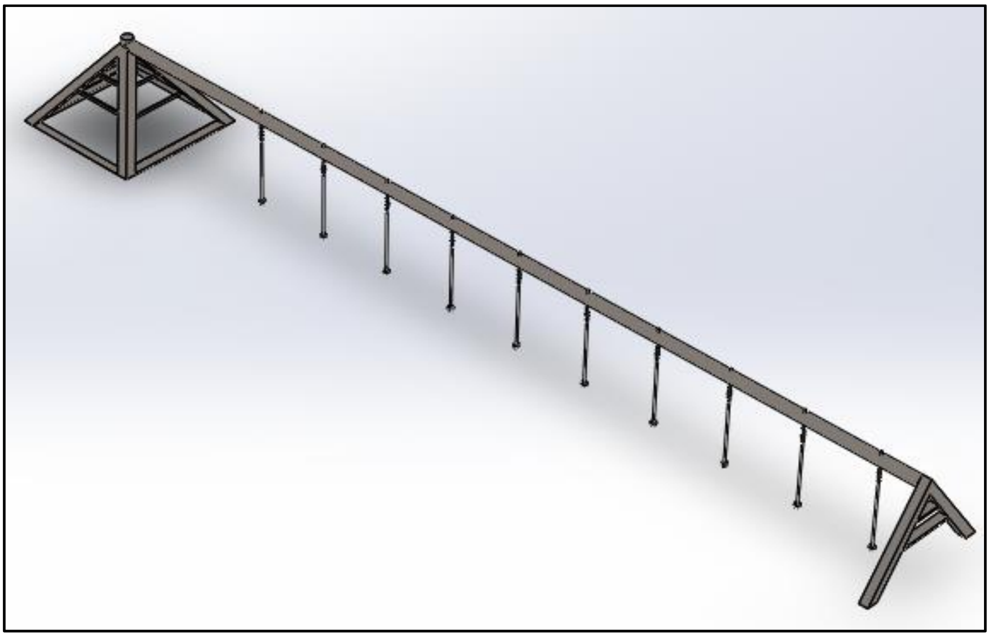

Figure 25. *Isometric view of CP model*

10.3 Appendix C: FEA Analysis

As previously stated, an upright component was designed in Solidworks and set up for a static test and the load on it is the soil's bearing capacity multiplied by the total area (15 smaller pipes). Therefore, the following results were obtained from the simulations. Figure 26 shows the stress distribution.

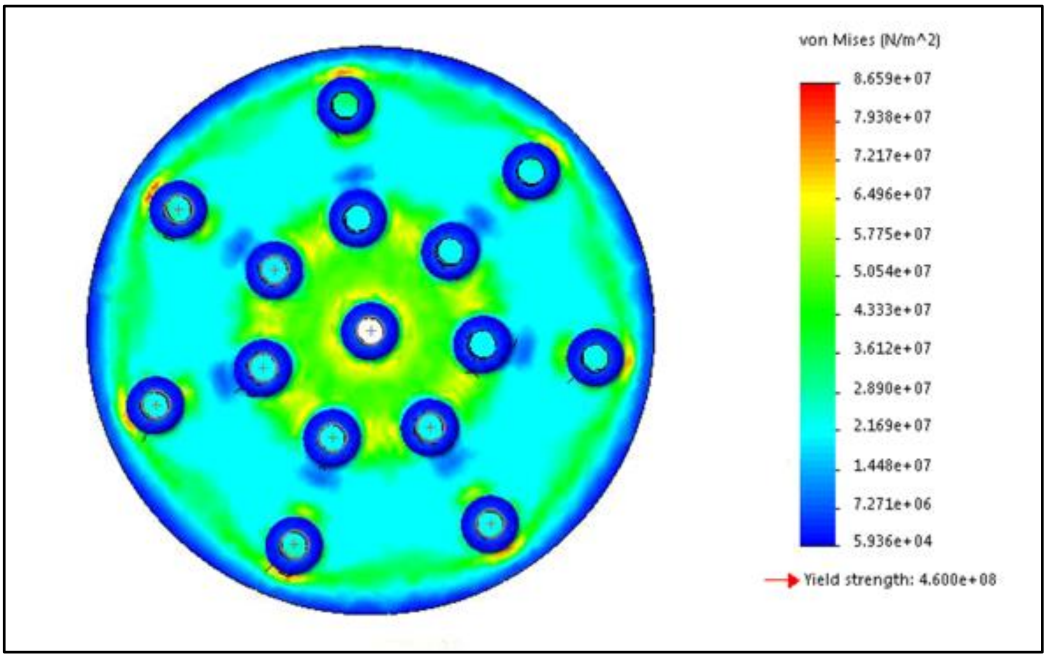

Figure 26. *Stress distribution of the bottom surface of the pipe*

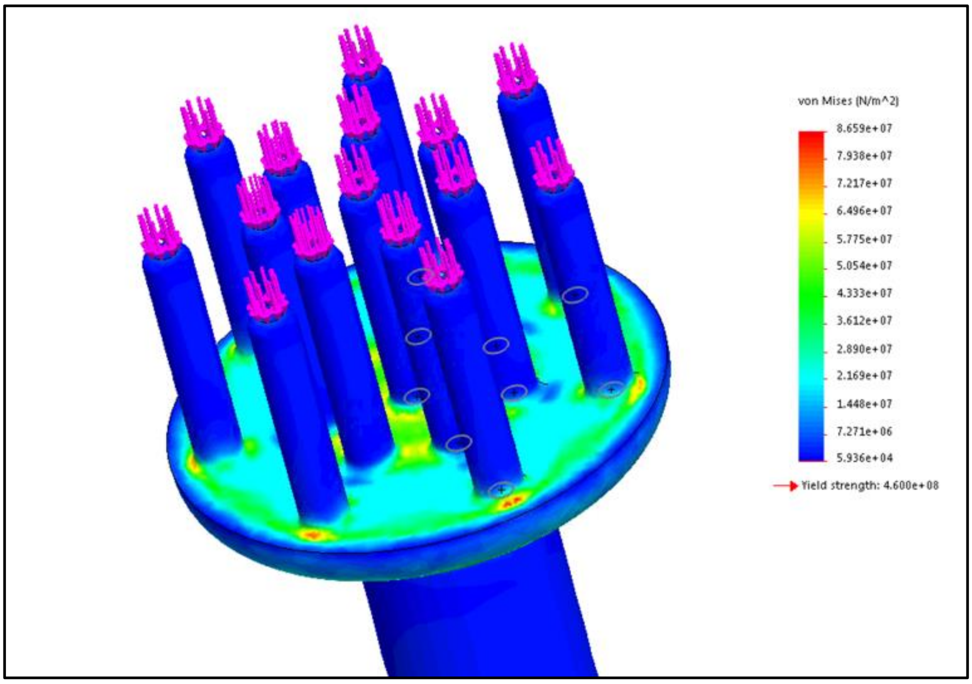

Figure 27. *Isometric view of stress distribution on the pipe*

Figure 27 shows the isometrically view of the stress distribution. From this evidence it is clear that the stress is mainly concentrated on the bottom plate where the mini pipes are attached. The maximum stress of 8.7e^7 (N/m^2) are the areas between the mini pipes and the side of the bottom “plate”. This is because they are closely located to the edge and the stress has to change its direction, therefore causing stress build up in those areas.

Another procedure to test the buckling of the pipe was done to yield another representation of how the vertical pipe would bend and fail under the force. This is shown in Fig. 28 and Fig. 29.

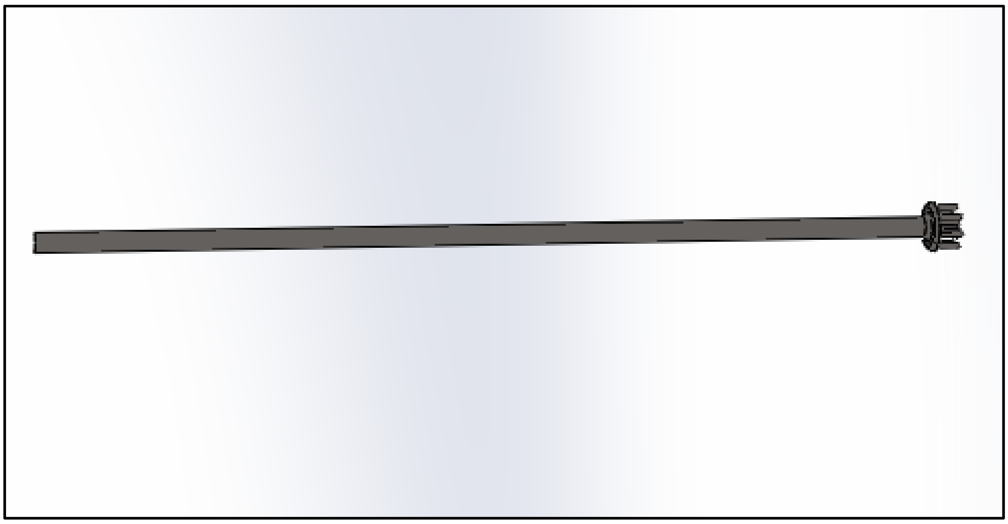

Figure 28. *Pipe design used for the buckling test*

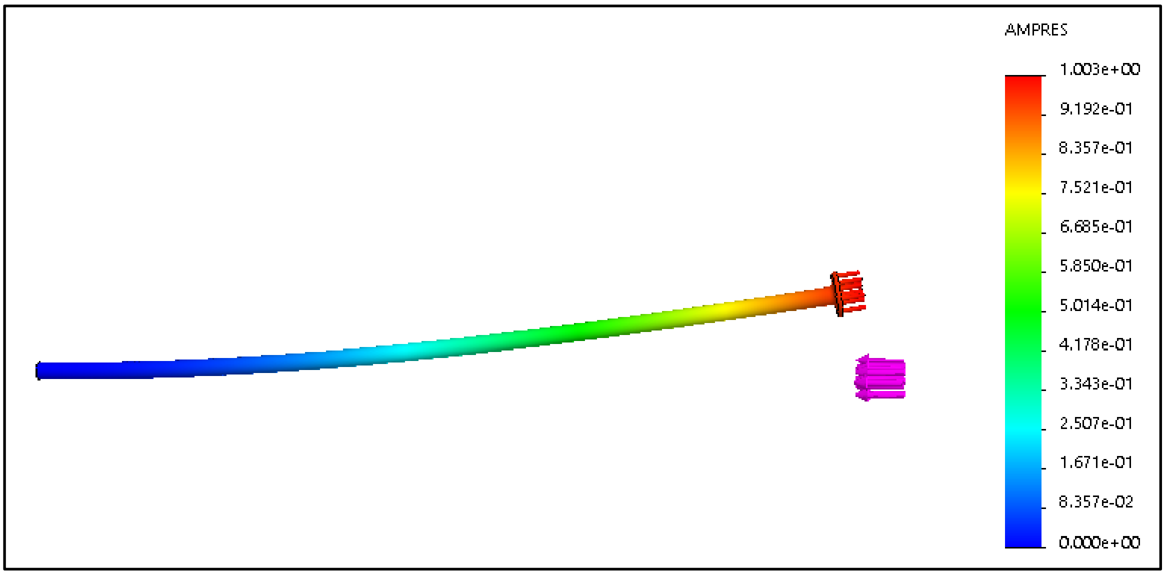

Figure 29. *Simulation of buckling test*

By observing the FEA studies of the pipe, the suitability of the model can be judged. The study provides an excellent visual representation of the stress occurring on model. It can be confirmed that the pipe is unlikely to fail. However, a sudden impact or shock on the pipe could cause a damage, of course.

Table 30. *Simulation results*

Collected Data	Value
Maximum stress (N/m2)	8.659E+7
Maximum Amplitude (AMPRES)	1.030E+0

10.3.1 Discussion of FEA

The static and buckling study identifies the areas that are most venerable. In this case, the mini pipes showed some levels of small vulnerability. However, that can be easily fixed by increasing the thickness of the pipe by an extra millimetre, thus, strengthening the structure much more. Although this is just a computer simulation, this study does confirm that the model is fit for purpose. However, an actual practice would be needed.

10.4 Appendix D: Bearing Capacity

Nc, Nq and Ny (Nr) are the bearing capacity factor in Terzaghi's equation. These numbers differ defending in the angle of shearing resistance. Ultimately, it is assumed that the pipe enters the soil directly, it means that the shearing resistance angle is zero. Anupoju (2016) provides the table of how these values may change with different angles.

Table 31. *Shear stress angles and constants*

ϕ	Nc	Nq	Ny
0	5.14	1	0
5	6.48	1.57	0.09
10	8.34	2.47	0.09
15	10.97	3.94	1.42
20	14.83	6.4	3.54

10.5 Appendix E: Number of pipe movements

The number of pipes is an important aspect of the design, as this part can easily change the amount of energy required. Previously it was discussed that the total area of land to be irrigated is 125663 m^2. Knowing that it takes almost 3 days to complete a cycle, this number is then divided by 3 to get the number in days. Also, knowing that there are 100 pipes to cover the whole area, this number is also divided by 100, which generates a number of 418.87.

At this point it was assumed that each pipe can cover a total of 2 m^2, therefore, the obtained value divided by 2 produces a value of 209 movement for a single pipe, or almost 21,000 total moves.

10.6 Appendix F: Gantt Chart

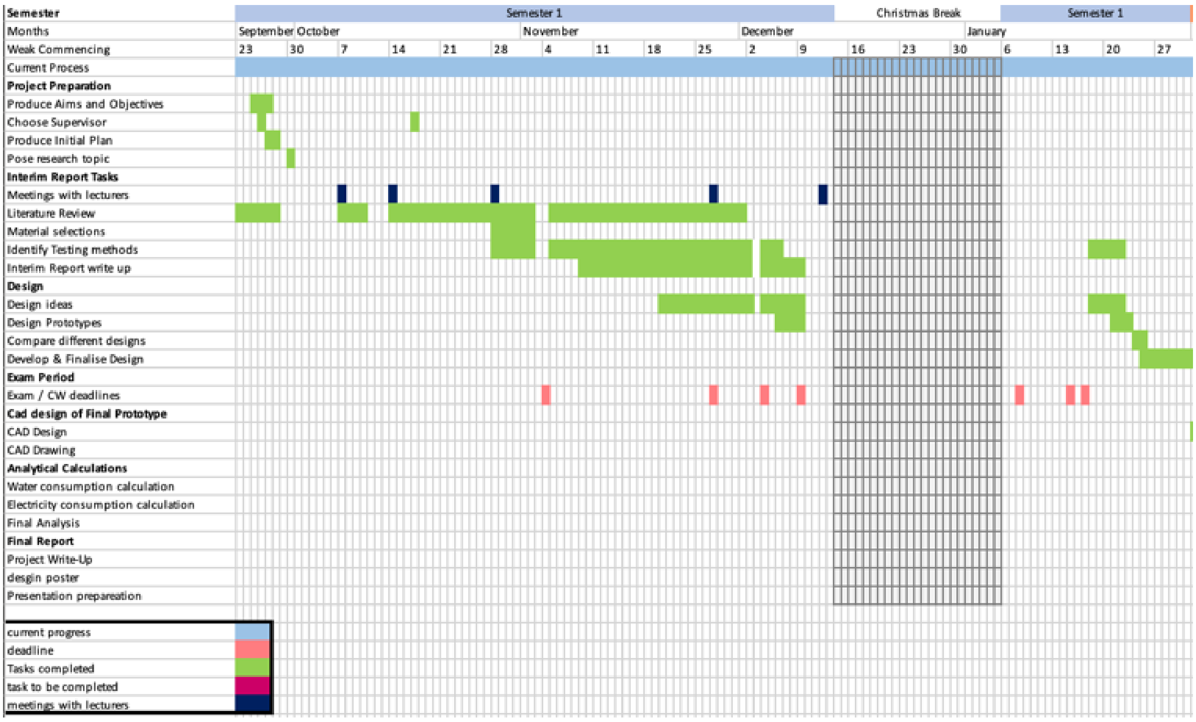

Figure 30. *Gantt Chart - Semester 1*

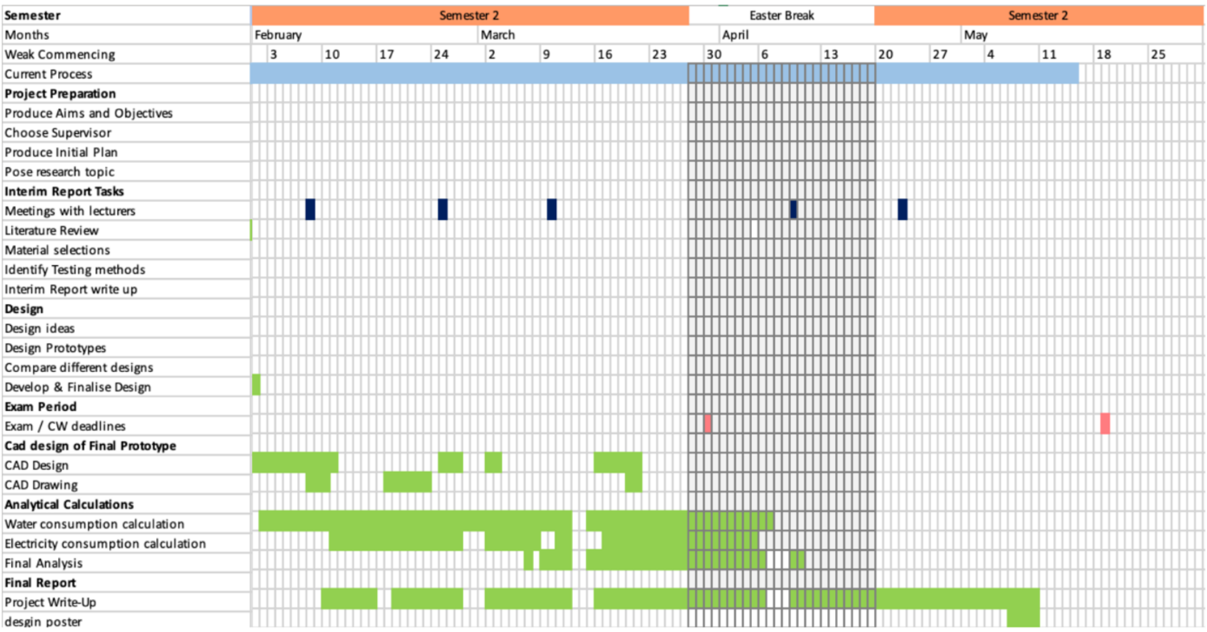

Figure 31. *Gantt Chart - Semester 2*

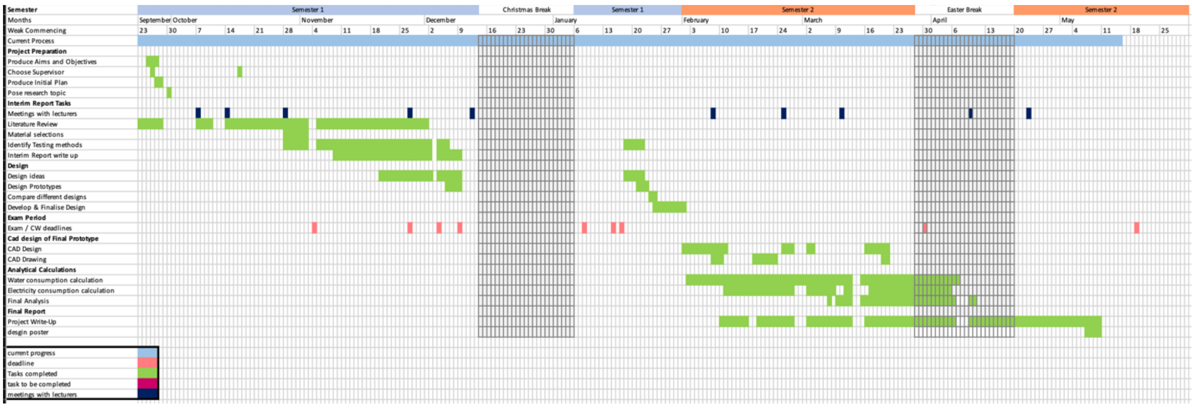

Figure32. *Gantt Chart of 2019-2020 project*

10.7 Appendix G: Interim Report

The Interim report has been screenshotted to separate it from merging with the dissertation itself.

Contents

1.0 Introduction

1.1 Global Water Crisis

Water is a scarce resource, and all lives on earth depend on this finite resource. Based on the studies of (Usgs.gov, 2019), 71% of earth's surface is covered by water, nonetheless, only 3% of all the water on the planet earth is fresh water. On the other hand, the population of the world is rapidly increasing to the heights that has never been reached before. With the rise of the population, comes the rise in demand of fresh water.

The situation gets even more critical due to the effects of global warming on freshwater. Climate change directly impacts the freshwater by increasing its temperature and changing the hydrological cycle. In their recent researches on the effect of global warming on fresh water, (Pletterbauer, Melcher and Graf, 2018) suggest that as a result of this causes, the frequency of drought increases, run-offs from snow and ice covers reduces and water quality becomes deteriorated.

Mankind has now reached a critical point in history. Humans, as the only capable and conscious species on earth, can either turn their back on this challenge, or accept this responsibility and overcome this obstacle with sustainable water management.

1.2 Water in Agriculture

Plants need water for photosynthesis and growth. They get their water and nourishment by absorbing the moisture content in soils. (Eva, 2015) Argues that at certain periods during a year, the moisture content drops because of deficient precipitation, hence farmers water their crops by irrigation by using the underground waters. However, majority of times this method leads to and poor use of water because of excessive withdrawals and mismanagements.

Globally, over 70% of freshwater is used for agriculture as shown in Figure 1, (Khokhar, 2017). According to the statistics provided by (Climate-adapt.eea.europa.eu, 2015), this figure will potentially rise to 80% in Mediterranean and 85% in Middle Eastern countries, where water is scarcer.

According to report, the moisture content of soils will continue to drop based on the current rate of climate change and the demand for water will only continue to rise in these countries. Biomass production for energy is predicted to jump up to 142 M TOE in 2030, whilst it was only a 2 M TOE demand in 2003 (Climate-adapt.eea.europa.eu, 2015).

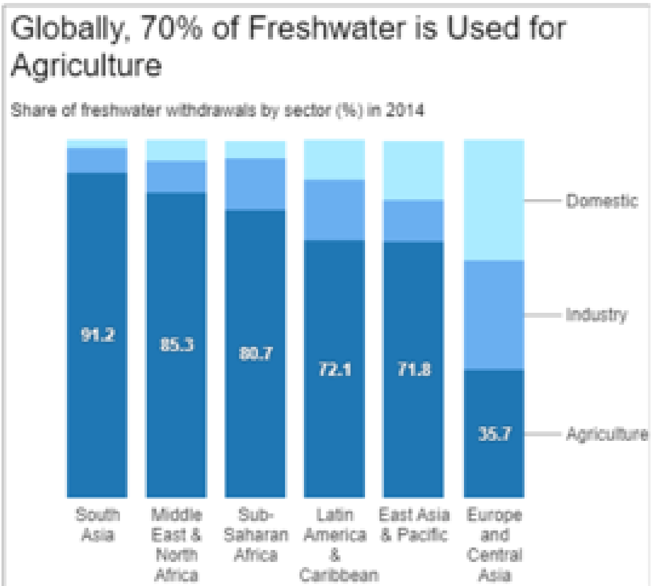

Figure 1: Percentage of freshwater used at different sectors (Source: (Khokhar, 2017

1.3 Inspiration for the project

Whilst travelling in Iran during the summer of 2017, I noticed a gardener (who worked for the council) carelessly watering a small grassland. The gardener threw a large plastic tube on a small field, whilst the water was turbulently running out of it. This made a spark in my mind. "How could a country that's

in water crisis have no efficient system of watering the lands?", I thought to myself. Whilst sat in a car, I started creating ideas in my head...
I started realizing that if I could design a system where water consumption is largely reduced:

- *Less time would be spent on the field, due to automated machine.*
- *On the long run, the energy consumption would reduce.*
- *Less water contamination and consumption would occur with effective use of water.*
- *Fertilization of land and irrigation would occur at the same time.*

2.0 Project Planning

2.1 Aim

- To introduce an irrigation equipment to reduce water consumption and analyze the implementation process of this method in the industry.

2.2 Objectives

- To compare the performance of Irrigational Sprinklers installed on Central Pivots against the performance of newly designed underground sprinklers, that are also installed to Central Pivots.
- This is done by Initially calculating the amount of water loss from the Irrigational sprinklers.
- Then, design an underground irrigation equipment that eliminates the evaporation losses completely. This equipment can be used either by attaching them to Central Pivot Irrigation system as a replacement for sprinklers and used in other forms of irrigation.

Case study: Iran

(Badawi, 2018) reports that excessive use of underground water in many developing countries, such as Iran, has paralyzed many of their environmental landscapes and lakes such as Lake Urmia in Tabriz, which is drying. This matter started to impact the economical sides, where farmers could no longer provide the required water for their crops, therefore, the agriculture exports started to drop. The Iranian government has now taken the necessary actions to refill the lost waters (Badawi, 2018). They have presented new methodologies and free irrigation equipment to the farmers at different areas. Many countries are genuinely struggling, and this project aims have an impact globally.

2.3 Project deliverables

This project aims to eliminate water losses via evaporation that is caused by irrigation in agriculture. This report aims to produce an in-depth information in regard to water crisis that's on the rise, and how new technologies are tackling this issue. In this report, a new product is introduced and analyzed to determine its capabilities in saving water. This is done by use of research papers, parametric analysis, CAD drawings and discussions.

3.0 Literature Review

(Zazueta, 2019), (Fao, 2007), (Folvonic, 2019), (Whycos, 2008), (Han and Zhou, 2013), (Netafim, 2016), (Anderson, 2018), (Agriculture.vic.gov.au, 2017) have either reviewed the Central Pivot Irrigation system or effect of irrigation sprinklers on the field.

The literature review in this report has considered implementation of Central Pivots and Irrigational Sprinklers that are either attached to Central Pivots or used individually. The analysis has been broken into smaller sections of advantages and disadvantages and an overall conclusion.

3.1 Current State of Water Management

Majority of countries are yet to take the water crisis seriously. The root of these delays is as a result of constant change in governments. This is because majority of the concerns are based on oil and rare metals. Therefore, the forthcoming issues are not taking seriously, which in effect can cause serious chaos for future generations.

Case Study: Israel

Israel have introduced modern technologies such as drip irrigation, as shown in Figure 2, and enhanced sprinklers for smaller farmlands reported by (Schuster, 2017). Other countries such as United States and Canada are developing Central Pivot Systems for bigger farms. These systems have certainly helped to reduce water and energy consumptions, and companies are looking to build up more from this point (Schuster, 2017). Water drip irrigation requires manufacturing of high number of plastic tubes, and therefore it isn't studied in this report.

Figure 2: Water Drip Irrigation in Israel (Source: (Schuster, 2017)

3.2 Initial & Recent Designs

Across the world new technologies have been developed to conserve water. Irrigation sprinklers have been used in agriculture industry for many years.

As reported by (Anderson, 2018), in 1946 whilst watching his neighbor displace large pipes that had been fitted with sprinklers on them, Frank Zybach was first inspired to invent the very first Central Pivot Irrigation (CPI) system. The very first drawing can be seen in Figure 3.

Sprinklers and Central Pivots have been developed with many different shape and sizes throughout recent history and are still relevant today. However, the sprinklers on CP are inefficient and cause water loss, and in next chapters, discussions are made to improve this system, and bring a more advanced new irrigation system.

Other types of irrigation such as drip or surface irrigation are being used and they have their own pros and cons. However, in this report, studies are based on normal sprinklers and underground irrigations, and how they can be used on Central Pivot systems.

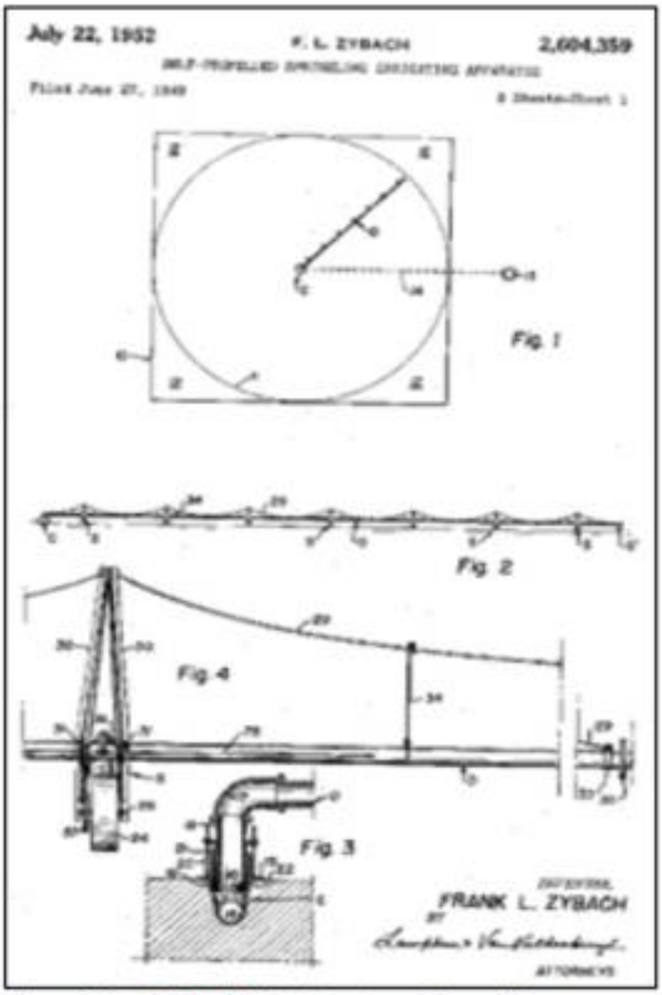

Figure 3- Frank Zybach's First Drawing of Central Pivot (Source: Anderson, 2018)

3.2.1 Central pivot Irrigation

As (Folvonic, 2019) simply describes it, the Central Pivot is a large automated machine that moves slowly in circular pattern whilst irrigating the land. It is made of a long pipe with large diameter, connected to a central tower known as the pivot. The pivot is usually anchored to a fixed point where water is pumped from this source into the pipe and then sprayed on the land. The new design can be installed on the pipes as a replacement for sprinklers. Figure 4 present an example of Central Pivot.

Center pivot provides uniformity of applied water

Figure 4- Central Pivot Irrigation System

Central Pivot Parameters

The main pipe is supported above the ground by series of "A" shaped beams as It can be seen in Figure 4, which are known as wheeled towers. With the help of wheels that are attached to these towers, the system moves slowly in a circular pattern, whilst at the same time distributing water with sprinklers (Agriculture.vic.goFv.au, 2017). The sprinklers are attached along the main pipe. Centre Pivots are mainly used on to larger lands that are between 3.5 to 200 ha as reported by (Agriculture.vic.gov.au, 2017). These systems can also be linear, this is where the system can move straight forward if there is a water source running parallel to the direction of the field.

Information provided by (Fao, 2007) shows that the diameter of the main irrigation pipeline is between 140-250mm, with 200mm being the most common. The length of the pipe used to be from 50 to 750 meters. However, they are increased to 800 meters in some cases as proven by the Shepparton Irrigation Region (Agriculture.vic.gov.au, 2017). The wheeled towers are typically 3 meters high, and 40 meters apart. Truss rod arches are sometimes added to maintain uniform weight distribution between towers. (Clearance from the ground is 2.75 meters) The spans are equipped with flexible joints, allowing pipeline to articulate, hence minimize stress on the pipes.

Water emitters are usually 3 meters apart as previously stated, but they can be altered depending on the amount of water needed (Fao, 2007). The discharge rate from sprinklers varies such that lower discharge rates being closer to the pivo, and higher discharge rates away from the pivot. Even with these measures, over wetting of areas still occur. Nelson rotators and Senninger wobblers are the most preferred sprinkler.

Materials

The main pipe and wheeled beams are made of high tensile galvanized light steel or aluminum pipes, (Fao, 2007). These materials are corrosive resistant, and they can withstand the systems operational pressures. Sprinklers on the system come in variety of sizes, and to ensure uniform distribution of water, smaller sprinklers are used at the mouth and larger sprinklers at the tail of the pipeline. And at the end side of the pivot, the "tail", another larger sprinkler is installed to increase the area of land covered.

Drive System

Both (Fao, 2007) and (Agriculture.vic.gov.au, 2017) state that the Central Pivot has a drive system. This system consists of a single power unit on each wheeled tower and controls the movement mechanism of the system, and Figure 5 demonstrates a front view of this movement. CP has a smart alignment system, where the pipelines always remain straight as a result of the neighboring tower's movement. The span furthest away usually travels at a 3 ms^-1. In the appendix A, a plan view is provided to demonstrate the movement of central pivot.

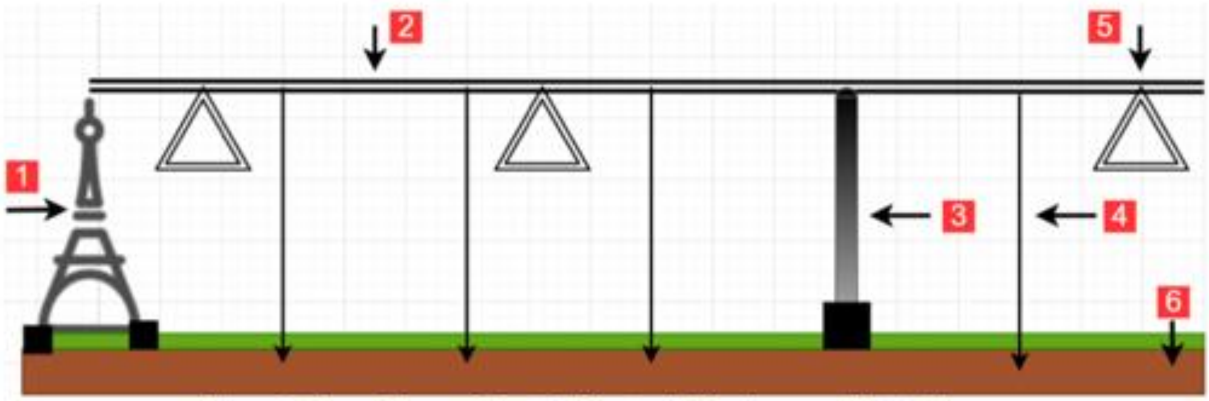

Figure 5- Front View of Central Pivot with Underground Sprinklers

1	Fixed central pivot, where underground water is pumped into initially.
2	Main water pipe, transporting water to sprinklers.
3	Wheeled tower works as drive unit by a geared motor.
4	Underground sprinkler that would penetrate the ground and squirt water.
5	Structure to support the span due to high pressures
6	Soil being irrigated in a circular pattern

3.2.2 Central Pivot Advantages and disadvantages

The results are based on research papers and articles from (Fao, 2007), (Folvonic, 2019), (Anderson, 2018) and (Agriculture.vic.gov.au, 2017).

Advantages

- Efficient use of water.
- No labor required.
- Uniform application of water.
- Able to set a timer for automatic daily operation, therefore saving time.
- Proven in the industry.

Disadvantages

- Uneven water application in windy weather.
- High initial capital and maintenance costs.
- Water evaporation due to sprinklers.
- Clogging of sprinklers because of debris.

- Requires flat surface.
- Frictional and head losses increase the energy demand.

3.3 Irrigation Sprinklers

Irrigation distribute water by spraying it through the air. (Zazueta, 2019) explains that the sprinklers are designed in a manner where the sprinklers detectors break up the water stream and by deflection into the air, the soil is irrigated. However, due to the friction between air and the sprinklers, the water droplet breaks up even further forming a vapour, where a rain-like irrigation takes place. (Zazueta, 2019) continues to explain that the breakup of water makes it vulnerable to the sunlight, which causes it to evaporate before reaching the ground. Sprinklers can be used either individually or on Central Pivots.

3.3.1 Irrigation Sprinklers Advantages

(Rivo, 2018), (Zazueta, 2019) and other sources that were previously referenced in Central Pivot, provided the advantages of sprinklers. When it comes to irrigation sprinklers are most commonly used and they have many advantages, and they include:

- Suitable for all soil types.
- Adaptation to any landscapes.
- Low labor costs.
- High water efficiency.
- Addition of fertilizer and pesticides.
- High application frequency.
- Easy automation and mechanization.

3.3.2 Disadvantages of Irrigation Sprinklers

An in-depth analysis on disadvantages of irrigational sprinklers has been broken into smaller sections; Increased time taken, Increased surface area, Transportation of water vapor, Wind drift and Interception. These effects are as a result of sprinklers and discussed.

. *Increased time taken*

The aim of the sprinkler is to distribute the water evenly, therefore, the higher the water travels from the nozzle, the more water particles break apart. However, (Zazueta, 2019) argues that sprinklers also increase the time taken for the evaporation to take place, assuming same diameter of water outlet and constant pressure from the sprinkler. On the other hand, the wind speed increases as the height from the ground increases. Therefore, the time taken combines with wind, to further increase the water loss.

This time is further increased because once water reaches the ground it requires time to be absorbed by the soil. (Zazueta, 2019) continues do argue that, water evaporation requires at least 580 calories of energy to convert 1 gram of water from its liquid state into a vapor form. Although it sounds high, this energy is readily available due to sun radiation, especially in the Mediterranean and Middle Easter countries. Thus, water evaporates before reaching the plant roots, as shown in Figure 6.

. *Increased Surface Area*

"The sprinkler creates a misty environment", states (Zazueta, 2019), where water droplets get as small as they can be. As a result, the surface area of the droplets reduces. Therefore, by having other factors constant, the rate of evaporation, again, increases with reduction of the water droplet sizes.
(Khokhar, 2017) reported that in these areas the relative humidity is much lower, which means the air is dryer, hence the rate of evaporation is much higher.

. Transportation of Vapor and Wind Drifting

Wind increases the evaporation rate by transporting water vapor from area of high to low, (Rivo, 2018). The wind also takes the warm air in the surrounding areas above the irrigated area which is cooler. Therefore, the wind creates a temperature gradient, which works against the sprinklers. As (Rivo, 2018) states in its report, wind transports the vapors away and water lands on unwanted areas, and the water is unavailable to the plants. Depending on the wind speed, the effects will vary. (Zazueta, 2019) found that generally the evaporation due to wind drift is negligible for 2-4 mph.

. Interception

In general, when raining occurs, some of the falling rain land on vegetation and leaves, and they never reach the ground. Irrigation sprinklers follow the same pattern, therefore some of the water whilst is stored on vegetation covers, and these droplets evaporate before reaching the ground. Although these losses are small, they still account when calculating the efficiencies. (Zazueta, 2019) estimates that about 10 to 20 per cent of the precipitation falling during the growing season is intercepted and returned to the hydrological cycle through evaporation.

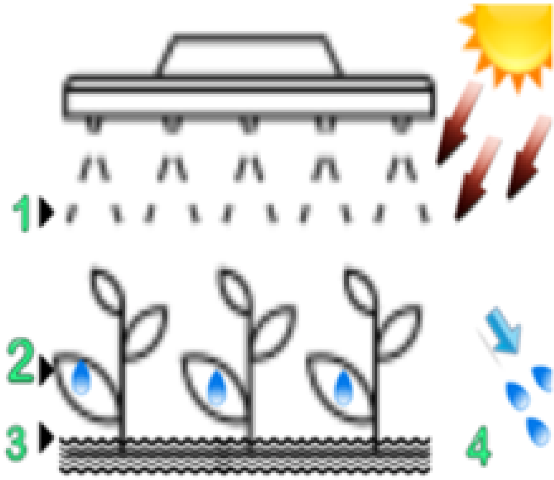

Figure 6-Sprinkler Irrigation Diagram

Figure 6 Labels: Increased time on air (1), Water Interception (2), Water evaporation on soil (3), and Wind Drift (4).

Other disadvantages

Other disadvantages reported by (Rivo, 2018), (Zazueta, 2019) and (Agriculture.vic.gov.au, 2017):

- Saline water greater than 7 millimhos/cm can cause leaf burning at hot temperatures.
- Poor efficiency under high temperatures and wind speeds.
- Constant spraying of water makes them vulnerable to diseases.
- High operating costs.
- Uniform distribution of water isn't always possible.

3.3.3 Overall view of Sprinkler Irrigation

As seen from previous designs, it's observed that no attention has been paid to water losses due to wind interaction, interception evaporation losses by sprinklers and most importantly evaporation of water from the soil surface.

4.0 Solution

The idea to solve this issue is to eliminate irrigation from the soil surface completely. Hence, to completely optimize the water use, the pumped water needs to be delivered to the soil and close to the plant's roots directly. Therefore, the aim is to design a product that maximizes the production of goods per unit of water consumed. However, application of this theory requires development and adjustments of many prototypes.

4.1 Calculation on effectiveness of the new design

The new design aims to eliminate the evaporation losses. Therefore, the losses from a normal sprinkler equals to the amount of water saved by the new design, hence simply put:

$$Total\ Water\ Loss\ of\ Sprinkler = \ Soil\ surface\ evaporation + Vegetation\ interception + Evaporation\ in\ air$$

The underground sprinkler transports water directly to the ground, and hence it doesn't have these losses, meaning:

$$Total\ Water\ Loss\ of\ Sprinkler = Total\ water\ conserced\ by\ underground\ sprinkle$$

Therefore, by simply calculating these individual losses, and adding them together, the volume of water saved and be calculated.

5.0 Progress made in semester one

Majority of the time was spent on research and finding a suitable method for calculating the effectiveness of new design in comparison to the older design. In depth research had been done to see the most relevant method of comparing irrigation methods.
Contacts were made with manufacturing companies in Canada and USA, however no reply was made.

Obstacles Identified & Plan changes

Initially, the objective was to find the rate of water evaporation from the soil. However, by studying the dynamics of soil water evaporation (Han and Zhou, 2013) and more lateral thinking, I soon realized that the evaporation from the soil is the same in every irrigation, and what actually needs to be calculated is the water evaporation from the *surface* of the soil and not the soil itself. The first objective would've led to the same results for both irrigations, and the calculations would've been irrelevant.

With more research, I discovered that I can calculate more water losses from the sprinklers. These losses include water interception on vegetations and evaporation of water whilst in the air. Therefore, more calculations are required, to precisely calculate the sprinkler performance.
I also come across a nomograph, and I had no previous knowledge on how to use it. This also required extra time to learn and how to use it effectively to assist me with the parametric calculations.

Having my supervisor leave early in the year, I often went to other lecturers to guide me. This required time to contact them and go through the rituals from the beginning. It also made me feel bad as it wasn't their responsibility to guide me, but they were very professional and supportive throughout. I then had meetings with my new supervisor to stay up to date, and good communications were made to make clearer plans.

6.0 Plans for future work

First step is to take the time during Christmas and design the underground sprinkler that is being introduced. Including the material that its being made from, the dimension and parameters, a CAD design and drawing for it.

Then calculate the amount of water that is being lost from the irrigation sprinklers, that break down into 3 steps: Evaporation of water in air, interception and evaporation from the surface of the soil. I have already broken down the steps on how I'm going to achieve this:

A: Evaporation of water in air from the sprinklers

Using the figure 7 below, and the "How to select a Sprinkler, Netafim (2016)" article, a suitable nozzle would be selected. The article would provide the parameters necessary to calculate the performance of the sprinkler.

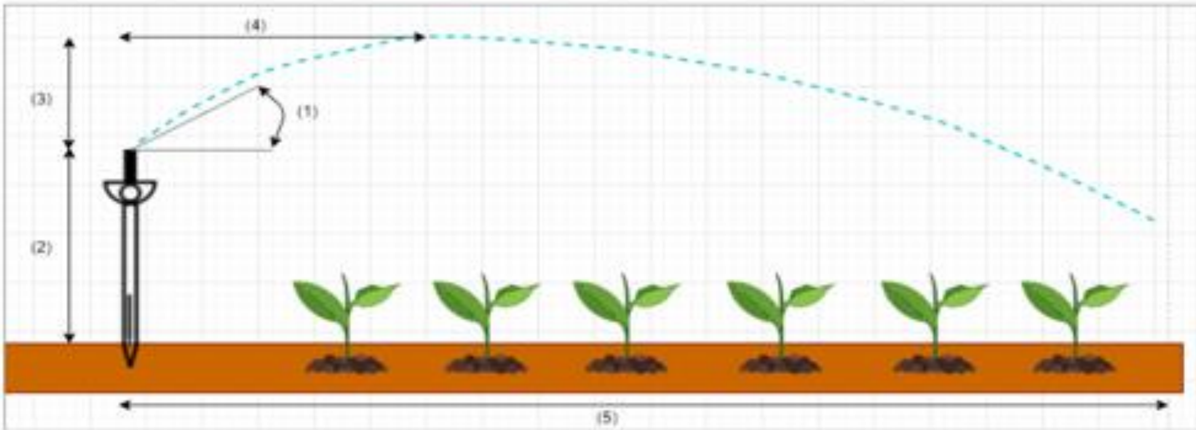

Figure 7- Sprinkler Water Trajectory

1- Sprinkler nozzle angle.
2- Elevation of sprinkler nozzle above the ground.
3- Elevation of Maximum trajectory height above sprinkler nozzle.
4- Distance of maximum trajectory height from sprinkler nozzle.
5- Maximum wetted distance

Using data from the selected sprinkler, assumed wind velocity and nozzle pressure, the percentage evaporation from the nozzle in air can be calculated from a Nomograph. A Nomograph is shown in Appendix B. Nomograph allows the user to estimate the amount of evaporation loss for different times of the day.

B: Interception Evaporation

Although this percentage loss is very small and is negligible for a wind speed under 2ms^-1, it would still require a calculation, or an assumption is needed to be made. There is no direct method of using the rate of evaporation from interception, thus this is something that needs to further literature review.

C: Soil Surface Evaporation

There are many methods to calculate the losses. They include direct methods, such as pan evaporation, or indirect methods, such as solar radiation method, (Whycos, 2008). Therefore, more literature review is required to be done on this subject.

Furthermore, more thought processing needs to be done for the design of the underground sprinkler, and design it precisely and accurately on CAD, and make a drawing out of it. Do an analysis and see the advantages and disadvantages of this project. And towards the end, I will start designing the poster and prepare the presentation, as well as finishing the write up.

7.0 Summary

- Central pivots have sprinklers attached to them.
- I have done research on Central Pivots, and how I can improve it.
- I am designing a central pivot that sprays water under the ground, instead of over.
- I will do CAD designs and drawings in next semester.
- Next, I will calculate the amount of water saved, by calculating the differences from previous and new system.
- Then I will write a conclusion and do a write up to see if my design is going to be successful or not.

7.0 Declaration

I, Arian Bahadori, declare that **no** field work throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** laboratory facilities in Marine Building work throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** student workshop throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** human or animal subjects or tissues throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** rapid prototype work throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** purchasing throughout the duration of the reported final year project will be required.

I, Arian Bahadori, declare that **no** manufacturing work throughout the duration of the reported final year project will be required.

8.0 References

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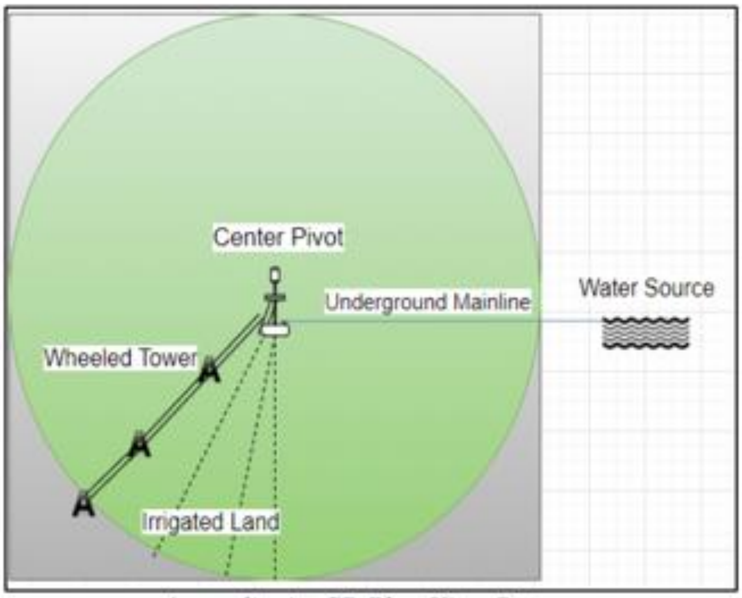
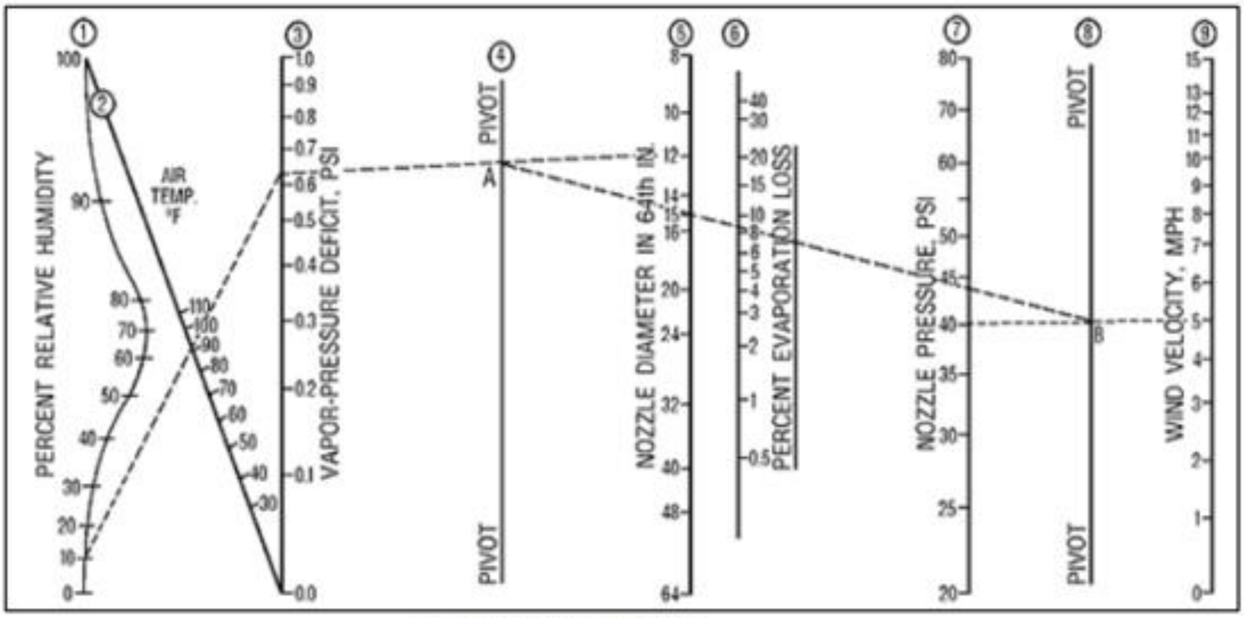
9.0 Appendix – Diagrams & Graphs



Appendix A - CP Plan View Pattern



Appendix B-Nomograph

10.0 Gantt Chart