Rainwater Harvesting at Macdonald Campus

Design III Final Project Report

Presented to Dr. Clark
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Executive Summary

Human population is on the rise; consequently the demand for freshwater is also drastically increasing. Rainwater is an abundant source of fresh water that can be harnessed and used for several daily functions such as laundry, toilet-flushing, or irrigation in the case of Macdonald Campus that has plentiful crop growth. The design proposed herein for such harnessing consists of two systems: a roof rainwater catchment on the Ecoresidence buildings for irrigation of the student-run and community gardens throughout the growing season; and a fountain rainwater catchment in the meditation garden for irrigation of the herbs planted therein as well as to provide an ambience of peace and serenity. The structure and roof area of the Ecoresidence buildings were examined further to determine whether they would sufficiently provide roof runoff for irrigation needs. The storage requirements and water transportation systems were investigated further as were the technical aspects of the proposed fountain design, including the feasibility of being able to provide for the whole meditation garden with one average-sized fountain. The proposed design will serve to augment the progress of Macdonald Campus towards a more environmentally sustainable existence while reducing the energy consumption of the water treatment processes.

Introduction

Effective and intelligent management of rainwater can have far reaching benefits for society. In a world full of densely populated "concrete jungles," green space is few and far between. Consequently, heavy rainfall events within cities are becoming increasingly problematic due to the relative absence of permeable surfaces. So little rainfall is absorbed by the ground that the sewer systems get overwhelmed very easily, which can result in raw sewage spills onto the city streets and eventually into open waterways. It is estimated that these overflow events in New York City deposit 2 billion liters of sewage on average into waterways each week(Bobrow). The Environmental Protection Agency (EPA) has ordered many U.S. cities to upgrade their sewer systems to handle more storm water. The most common way to perform these upgrades is to build larger sewer pipes and install a big underground tank that can hold excess water until the sewers can handle the flow. However, this approach is extremely expensive and often ineffective. For example, Milwaukee, Wisconsin has spent approximately $4 billion over twenty years on storm water management, yet it still spills billions of gallons of sewage into Lake Michigan every year (Bobrow, 2010). Philadelphia, Pennsylvania is being forced to upgrade their sewer system as well, but is a very cash-poor city. As an alternative to installing bigger pipes and expensive storage tanks, the city has come up with what is called the "Green City, Clean Waters" plan. The plan is to heavily invest in green infrastructure, such as green roofs and street edge gardens, which are capable of preventing excess water from entering the sewers in the first place (Bobrow, 2010). The "Green City, Clean Waters" plan's projected cost is $1.6 billion over a twenty year period whereas an upgrade tank would cost the city $8 billion (Bobrow, 2010).

Smaller rain events also present an opportunity for improved management. Though the runoff in these cases is not substantial enough to flood the sewer system, it does mix with raw sewage and thus ultimately requires processing at a wastewater treatment facility. The treatment of wastewater is a costly and energy intensive process, and is unnecessary for rainwater until it mixes with waste in the sewers as rainwater has undergone the natural purification process of evaporation and condensation. One way of reducing the amount of rainwater that reaches the sewers is to harvest it from impermeable surfaces. By doing so, we can reduce the load on wastewater treatment plants, which would in turn save both energy and money. Untreated rainwater is suitable for agriculture use, which makes rainwater harvesting an attractive source of water for crop irrigation.

Objective

Using as green a design as possible, we aspire to mitigate the problem of water and energy loss due to the waste of rainfall that lands on impervious surfaces. Capturing this rainwater will help to reduce the dependence of Macdonald Campus on municipally treated water and reduce the consumed energy in water treatment processes.

Past, Present and Future

As was discussed in Design II, there are two parts to the project, both meeting the objective of harvesting rainwater and using it to irrigate gardens located on the

Macdonald Campus. The first part is the collection of rainwater from the roof of one of the Ecoresidence (EcoRez) buildings located south of the Mac Market on Macdonald Campus. This water will be used to irrigate the community garden, located to the south of the EcoRez building, and the student-run garden in the Horticulture Center, located to the east of the EcoRez building. The second part of the plan is to build a fountain within the meditation garden (located to the west of the community garden) to enhance the meditative ambience as well as to collect rainwater to irrigate the herbs planted in the raised beds.

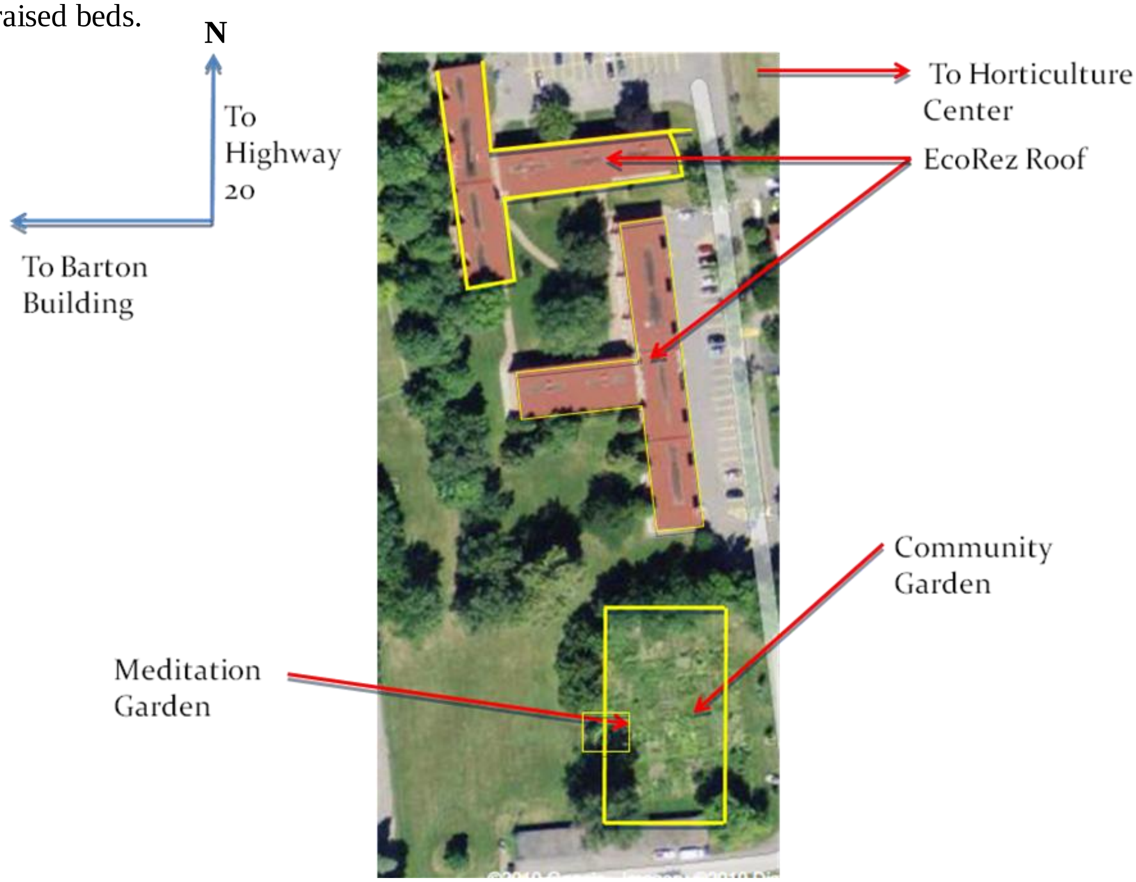


Figure 1: Plan view displaying locations of interest

In Design III, we examined the technical aspects of the proposed design. The irrigation requirements were compared to the potential amount of precipitation that can be harvested based on weather data from previous years; an optimal catchment area was determined for the roof and the fountain, the sizes of the storage tanks were also computed as were the sizes of the pipes and the pumps.

Our design promotes environmental sustainability by aiming to reduce the dependence of Macdonald Campus on municipally treated water and decrease the amount of rainwater that enters the sewage system to be treated. The materials proposed for the design will for the most part also strive to be environmentally-friendly. We are therefore considering submitting this design as a McGill Sustainability Fund Project.

Water Balance

Due to the time, weather, monetary and material constraints it was not possible to implement the systems for rainwater catchment to deliver irrigation water to the horticulture, community and meditation gardens. Therefore, to optimize the design of the system and gain some understanding of how it would work, a model of the system was developed, comprising a number of smaller models in the form of MATLAB programs and manual calculations (i.e. formal models). The model, to be discussed in further detail in the sections that follow, was constructed as such: To simulate the water flowing in from precipitation, water being stored in the tanks and water flowing out to irrigate the gardens two MATLAB programs were written, one for the EcoRez storage tank and one for the meditation garden storage tank . These programs were also used to optimize the catchment area and tank size for EcoRez and the meditation garden. Once the optimizations were completed, based on size and price, a MATLAB program was written to optimize the size of the pipes in the system. This program was also used to determine head loss in the system. Given the head loss, and the elevation values the pumps could be sized in a formal model. Additionally, given the optimization of storage tank sizes for the fountain and EcoRez storage tanks, the design and price of the tanks could be determined in a formal model. Finally, once the rest of the design was in place, sizing for the foundations of the storage tank in the horticulture center and the fountain were carried out in another formal model. The culmination of this modeling process can be read in the Results section. The sections below detail the computational and formal models employed in this design.

Analysis

In order to optimize the catchment area and storage tank sizes for the rainwater catchment system serving the horticulture center student run garden, community garden and meditation gardens, there needed to be an educated estimate as to how much water would be going into the system and how much water would be drawn from the system. In other words, to design the systems in question the water inputs and water demands needed to be estimated. The daily precipitation in Sainte Anne de Bellevue was taken as the water input in the system. The irrigation required during the growing season for the horticulture center, community and meditation gardens was taken as the water demand on the system. The values for daily precipitation in Sainte Anne de Bellevue are available from the Climate Canada website, downloadable as csv files yearly from 1969 onwards (Climate Canada, 2011). These csv files also include values for daily minimum, maximum and mean temperatures. From the Soil and Water Conservation Engineering text, as well as articles published for industry and academia it was determined that though there is no way to predict with absolute certainty how much water will be required for irrigation in a given year, the reference evapotranspiration can be estimated from the Penman Montieth equation for past years, and used to project values for the future (Fangmeier, 2006; Netafim, 2009). Irrigation requirements for a crop were calculated based on the estimated reference evapotranspiration, modified to reflect the crops in the gardens by crop coefficients, kc, and growing times taken from the FAO website. The amount of water falling on the gardens from precipitation was subtracted from the irrigation requirements. As a simplifying assumption loss of water to deep percolation and runoff was taken to be negligible. This assumption is more valid in the horticulture center than the other two gardens, as water in the student run horticulture center is provided through drip irrigation, and serves to minimize deep percolation and runoff to negligible amounts (Netafim, 2009). If careful irrigation scheduling was employed, then irrigation requirements, I = E – P, E being evapotranspiration and P being precipitation, are also more valid as excess water is not applied, a source of runoff and deep percolation (Netafim, 2009). To account for the fact that certain losses, like deep percolation and runoff are not being directly taken into account a safety factor was added to the amount of irrigation required. Therefore total irrigation requirements Isf = I*sf.

The crops grown in the community garden and the horticulture center student run garden vary for each growing season. There are however, some staple crops which recur, according to Dr. Begg and Emily McGill. In the community garden these crops are onion, cabbage, broccoli, squash, pumpkin and tomatoes. In the horticulture center student run garden these crops are tomatoes, peppers, lettuce, cucumber, spinach, squash, radish and potatoes. The crop coefficient taken to modify the reference evapotranspiration, Etref, for the horticulture garden was an average of the crop coefficients for plants growing at the time. The same technique was employed in the community garden. In the meditation garden berry shrubs and herbs are grown, in beds. There are 5 blueberry, 4 rose and 5 black and red current bushes and there are 9 herb beds. The water requirements for the meditation garden are based on the watering experiences of the student gardeners as related by Emily McGill. The berry bushes require 2 litres of water per day every five days for every shrub. The beds of herbs each require 9 litres per day. The average growing season for the meditation garden is 120 days.

To summarize, the conceptualization of the model for the horticulture center storage tank with respect to water demands involves finding the reference evapotranspiration, ETref, from weather data available at the Climate Canada website (Climate Canada, 2011). The ETref is then modified by the crop coefficients, over the growing period of that given crop, to become estimated evapotranspiration from each garden. The precipitation over the area of each garden is subtracted from the evapotranspiration value to give irrigation requirements for each garden. This irrigation requirement is then multiplied by a safety factor, to account for water losses neglected by simplifying assumptions, to give the water demand in the Water Balance model. The conceptualization of the model for the meditation garden storage tank with respect to water demands involves using empiric data from student gardeners to estimate the amount of water used to irrigate the garden on a daily basis during the growing season.

Table 1. Crop coefficients of staple crops in the horticulture and community garden (FAO).

Kccrop	Initial	Developmental	Mid	Late
Kconion	0.7	1.05	1.05	0.75
kccabbage	0.7	1.05	1.05	0.95
kcbroccoli	0.7	1.05	1.05	0.95
kcsquash	0.5	0.95	0.95	0.75
kcpumpkin	0.5	1	1	0.8
kctomatoes	0.6	1.15	1.15	0.8
kcpeppers	0.6	1.05	1.05	0.90
kclettuce	0.7	1	1	0.95
kccucumbers	0.5	1	1	0.8
kcspinach	0.7	1	1	0.95
kcradish	0.7	0.9	0.9	0.85
kcpotato	0.5	1.15	1.15	0.75

Table 2. Length of crop growth stages (time, in days) (FAO).

timecrop	Initial	Developmental	Mid	Late
timeonion	15	25	70	40
timecabbage	40	60	50	15
timebroccoli	35	35	40	15
timesquash	25	35	25	15
timepumpkin	20	30	20	30
timetomatoes	35	40	50	30
timepeppers	25	35	40	20
timelettuce	20	30	15	10
timecucumbers	20	30	40	15
timespinach	20	20	25	5
timeradish	5	10	15	5
timepotato	25	30	45	30

The water input for the Water Balance model comprises the precipitation that falls on the catchment area. In case of the horticulture center storage tank this is the area of the roof from which rainwater is drained to provide harvested rainwater to irrigate the horticulture center student run garden and the community garden. In the case of the meditation garden storage tank this is the circular area provided by the fountain catchment.

The formal model or mathematical model of the water demands on the system was based on the Penman Monteith equations, as related by Fangmeier et al. (2006).

Equations involved in formal model estimation of water demands for the horticulture center storage tank:

Tdew = minimum temperature (degrees Celsius)
Assumption for dew temperature, Tdew= minimum temperature - Ko and Ko is 0 degrees in humid and subhumid climates (ASCE, 2005) as related in Fangmeier et al (2006).

T = mean temperature (degrees Celsius)

es = 0.6108*e^(17.27*T/(T + 237.3)) saturation vapour pressure (kPa)
ea=0.6108*e^(17.27*Tdew/(Tdew+273.3)) actual vapour pressure(kPa)

slope = 2504*e^(17.27*T/(T + 273.3))/(T + 237.3)^2
Slope of the saturation vapour pressure and temperature curve

J = dm - 32 + floor((275*m)/9) + 2*floor(3/(m +1)) + floor(m/100 - rem(y,4)/4 + 0.975) day of the year
floor means that the value within the parenthesis the rounded to the next lowest integer
rem means that the value within parenthesis y, is divided by 4 and rem gives the remainder

declination = 0.409*sin((2*pi/365).*J - 1.39) solar declination (radians)
ws = acos(-tan(pi/180*45.53)*tan(declination)) sunset angle (radians)
dr = 1 + 0.033*cos(2*pi*J/365) inverse square of relative distance earth to sun
Ra=24/pi*4.92*dr*(ws*sin(pi/180*45.53)*sin(declination)+cos(pi/180*45.53)*cos(declination)*sin(ws)) extraterrestrial radiation in MJ m^-2 per day

Rso = (0.75 + (2*10^-5)*39)*Ra calculated clear-sky radiation in MJ m^-2 per day
Tmax = maximum daily temperature (degrees Celsius)
Tmin = minimum daily temperature (degrees Celsius)
Rs = 0.19*(Tmax - Tmin)^0.5*Ra; estimation of solar radiation, as per Hargreaves and Samani (1982)

Rs/Rso must be lesser than or equal to 1.

Rnl = (4.903*10^-9)*((Tmax + 273)^4 + (Tmin+ 273)^4)/2 *(0.34-0.14*(ea)^0.5)*(1.35*Rs/Rso-0.35)
Net long-wave radiation is determined from in MJ m^-2 per day

Rn = (1 - 0.23).*Rs - Rnl; net radiation in MJ m^-2 per day

Calculation of psychrometric constant
P = 101.3*(293 - 0.0065*39/293)^5.26 mean atmospheric pressure in kPa
psy = 0.000665*P psychrometric constant

The wind speed at 2 metres above the ground is estimated as 2 m/s as per the suggestion of Fangmeier (2006) due to a lack of data on wind speeds
u2 = 2

Constants for short reference crop grass as per Fangmeier et al. (2006)
Cn = 900
Cd = 0.34

Calculation of the reference evapotranspiration ETref using the short reference crop of grass
ETref = (0.408*slope*Rn + psy*(Cn/(T + 273))*(es - ea)*u2)/(slope + psy*(1 + Cd*u2))

Prototyping

The storage tank size had to be optimized, to be big enough to hold the water required to irrigate the gardens and not to be so large that it was unfeasible to build or too costly to buy. A computational model was built of the Water Balance for the EcoRez roof catchment area and another was built for the fountain catchment area. The model for the EcoRez roof catchment area was based upon the evapotranspiration equations detailed above, drawn from Fangmeier et al. (2006). The model for the fountain catchment area was based on the irrigation requirements as related by Emily McGill. The computer model for the EcoRez roof prompts users to enter the roof area to be used as catchment (each drain for rainwater drains approximately 83.6 m^2 of water, so the areas when tested, were entered in increments of this amount). It then prompts the user to enter a tank size, minimum water level in the tank (the water level can never go below 0 m^3 for example), and safety factor to allow for water loss that was not accounted for in the water balance. Similarly the fountain model prompts the user for the desired input radius in meters, the storage tank size, the minimum water volume in the tank and the safety factor to account for water losses. From this plots for each garden were generated, displaying the precipitation on the associated catchment area, irrigation and water stored in the storage tanks, in meters cubed. Examples of these plots are below. The blue lines are precipitation, the green lines are stored water and the red lines are irrigation.

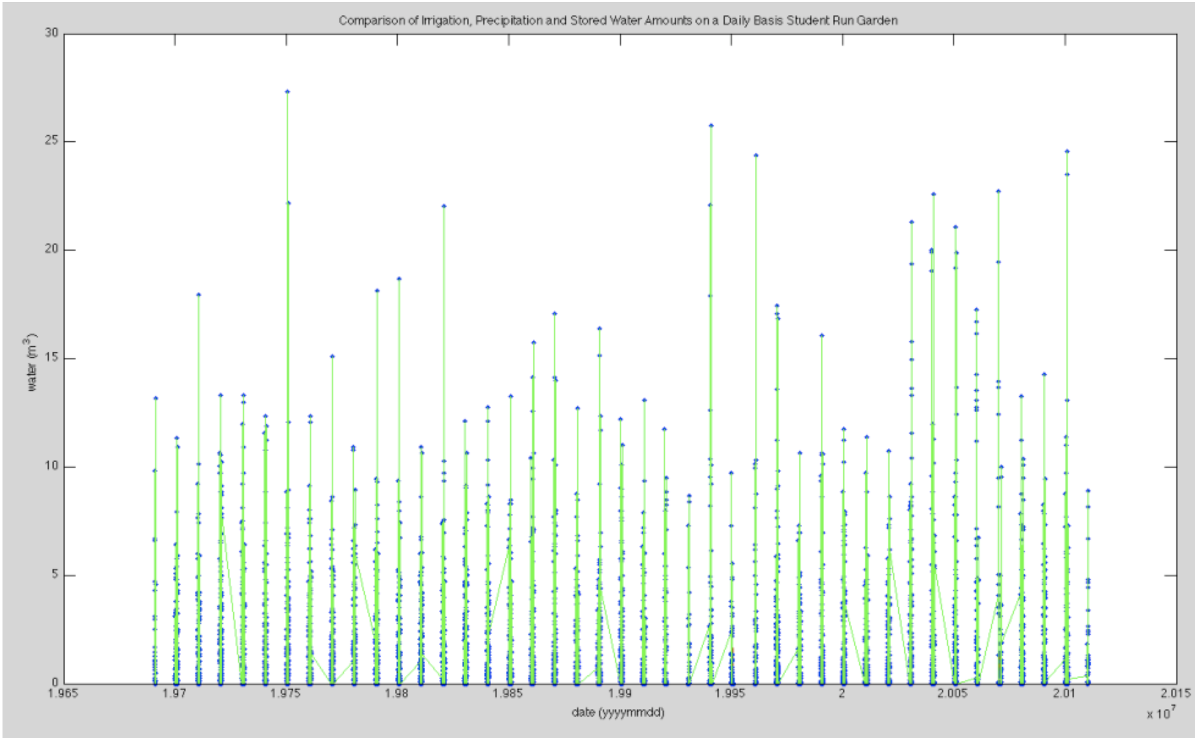


Figure 2: Example of Comparison of Irrigation, Precipitation and Stored Water Amounts on a Daily Basis Student Run Garden Horticulture Center

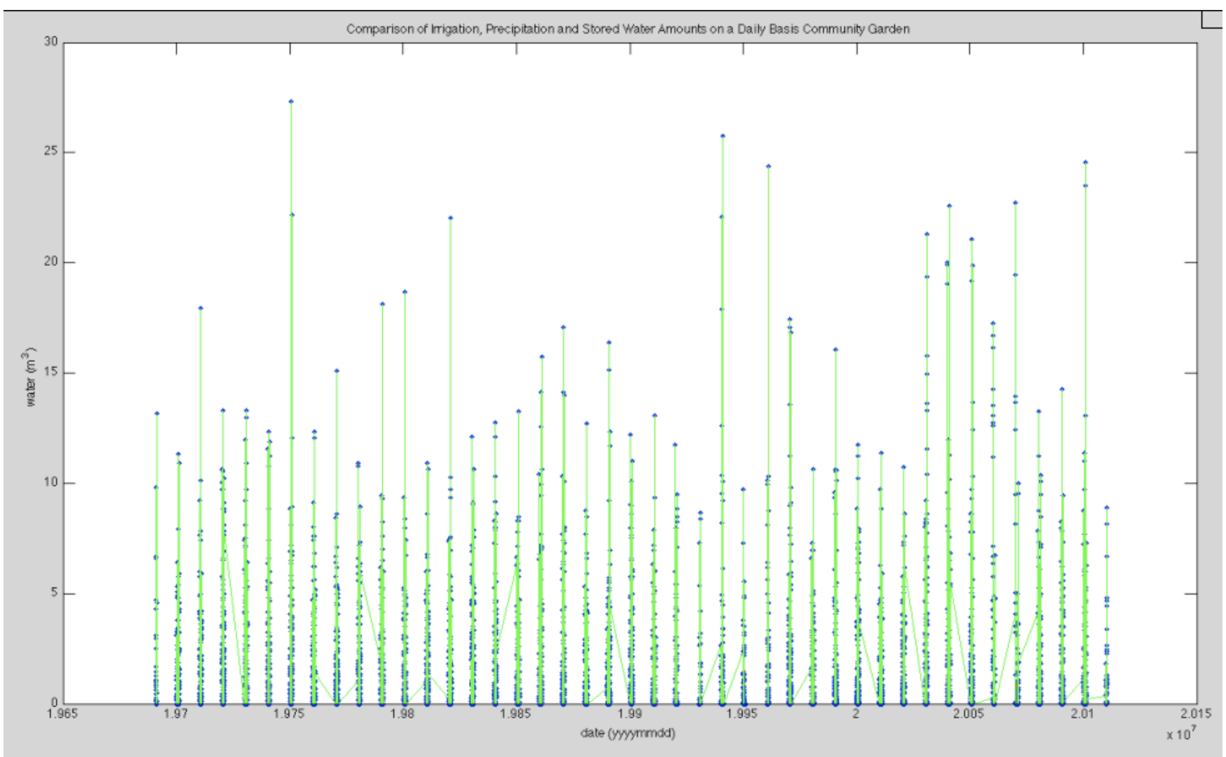


Figure 3: Example of Comparison of Irrigation, Precipitation and Stored Water Amounts on a Daily Basis in the Community Garden

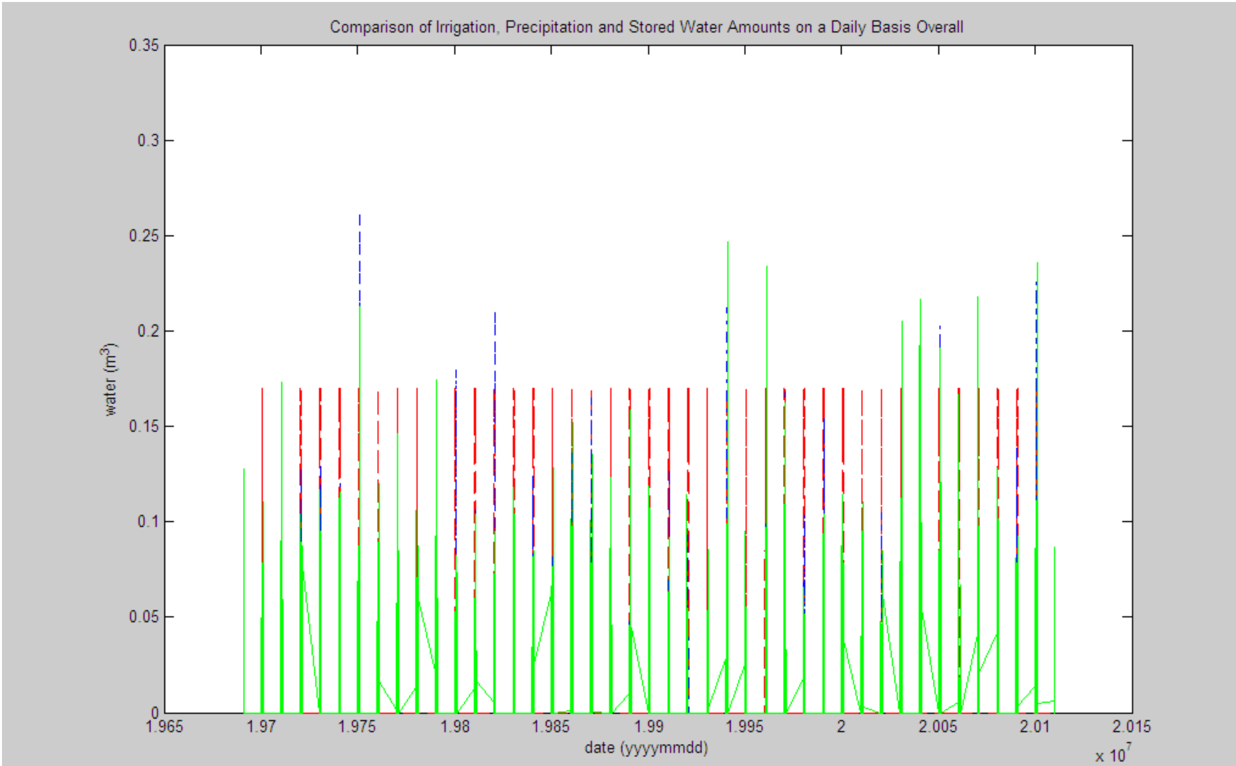


Figure 4: Example of Comparison of Irrigation, Precipitation and Stored Water Amounts on a Daily Basis Overall for the Meditation Garden

An additional plot in each MATLAB program also plotted the irrigation, precipitation and water stored in separate subplots in a single figure, along with the water deficit. These subplots consider the overall irrigation needs, or water demands, imposed on the two storage tanks (Horticulture Center storage tank and meditation garden storage tank). The water deficit is the difference between the water needed for irrigation on a daily basis and the amount of water available from the stored rainwater. The deficit is an indication of the performance of the system. If the deficit is large that means that the system as envisioned in the simulation of the model is inadequate for providing irrigation to the garden under scrutiny. Irrigation, precipitation, water stored and water deficit are plotted in separate subplots to be able to read and compare them with greater ease. Examples of these subplots, generated by the two MATLAB programs are below:

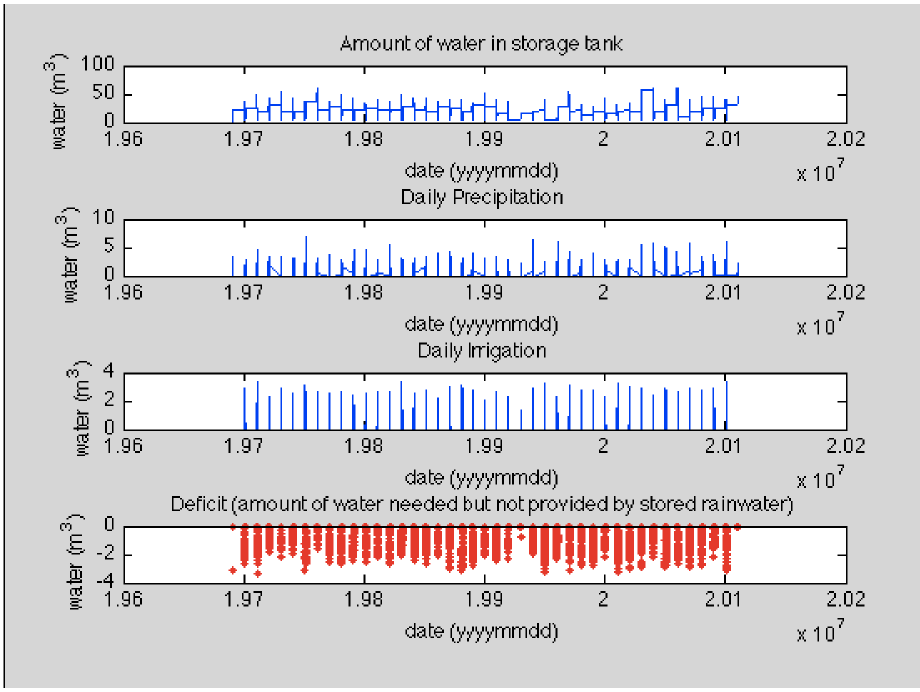


Figure 5: Example of Subplots of Stored, Precipitation, Irrigation and Deficit Water Amounts in the Horticulture Center Storage Tank System

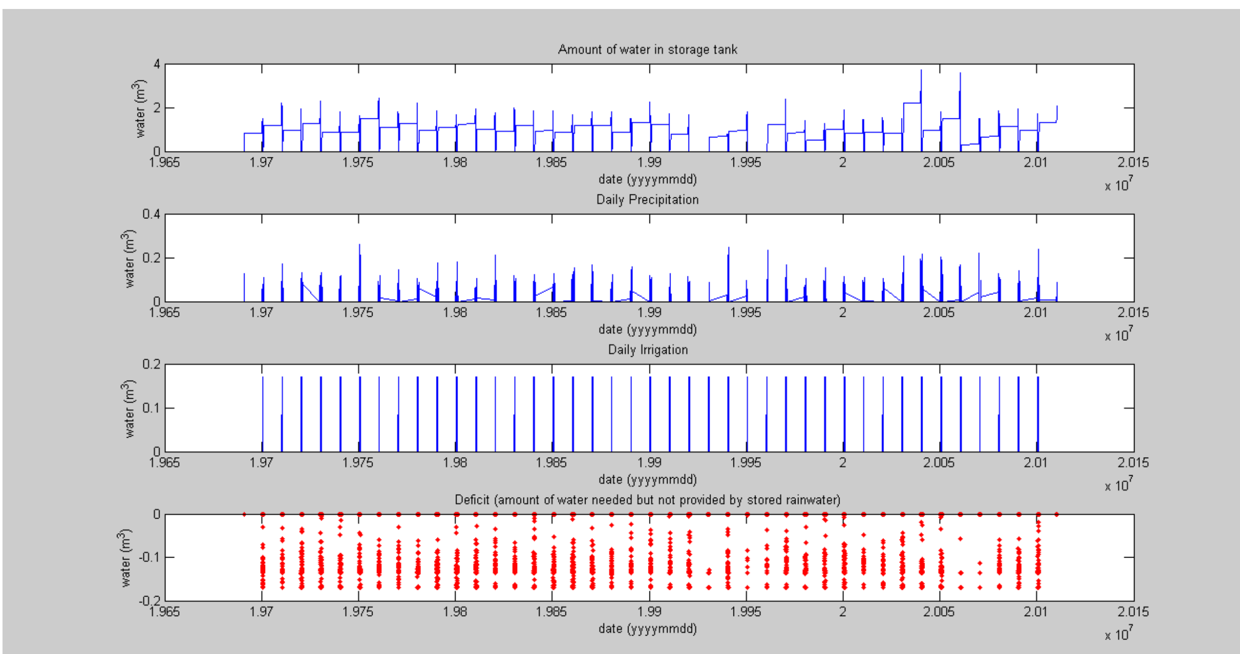


Figure 6: Example of Subplots of Stored, Precipitation, Irrigation and Deficit Water Amounts in the Meditation Garden

The plots generated and displayed above are a product of the verified code. The code had to be verified for internal consistency and mathematical accuracy, so that the numbers produced made sense in relation to the user inputs as well as physical sense with relation to the answers that the Penman Monteith equation was supposed to produce. A few errors, such as a misunderstanding of the calculation for saturated vapour pressure and the mis-coding of area of the catchment for the fountain, made the values calculated for required catchment area and tank size too large at first. The code was carefully parsed to identify and rectify the errors. Once this was done, and the values corresponded well to estimates for irrigation needed as calculated by the FAO for vegetable growth over a season, the code was ready to be used to simulate water balances for each catchment area (FAO).

Table 3: Different Vegetable Crop Irrigation Requirements As Set Out By The FAO (ranges given depend on "length of growing season and climate")

Vegetable	Irrigation requirement per growing season
Onion	350 to 550 mm
Cabbage	380 to 500 mm
Broccoli	350 to 550 mm
Squash	315 to 495 mm
Pumpkin	315 to 495 mm
Tomatoes	400 to 600 mm

Optimization

As mentioned above the user is able to input values for either area or radius, to calculate area, storage tank size, minimum water level in tank and safety factor for each catchment area model (reminder: the EcoRez roof catchment area corresponds to the Horticulture Center storage tank model and the meditation garden fountain catchment area corresponds to the fountain or meditation garden storage tank model). The safety factor was selected as 1.25, effectively adding 25% of the calculated irrigation needs onto the requirement, to cover water losses that may have been overlooked by not taking into account deep percolation, runoff or water leakage from pipes. The other three input values were, one at a time, held constant as the other two input values were changed, to find the optimal size of roof top and fountain catchment area and the optimal size of the storage tank. The minimum water level was 0 m^3 in all instances for the fountain storage tank and in some test cases for the Horticulture Center storage tank, as there cannot be negative amounts of water in reality, though the model would permit it if not told otherwise, skewing the values. In other tests of the Horticulture Center storage tank the minimum value was 3.5 or 3.0 m^3 to keep the pumps from ever running dry. When the idea of a minimum value for water level in the tank in the Horticulture Center came about, that was above 0 m^3, there was the question of how to maintain the water level above this level without employing expensive sensors. A simple solution, requiring little extra labour from the students volunteering in the gardens, was to have a small opening through which an indicator, thin and cylindrical would protrude. The indicator would end in a floating rubber ball, so that the indicator would rise and fall with the water level. The indicator would have a marking on it, visible when the water level was at the minimum level. If the water level fell below this, the indicator would provide a visual clue to the students that the water level of the tank needed to be topped up, using municipally provided water. Ideally the rainwater harvesting system would replace the municipal water supply, but due to constraints of space for the storage tanks and for the fountain, this is not possible. This is discussed further in the Results section.

Many values were tested to come to the final values for catchment area and tank sizes used in the design. Examples of the tests run, and the values that they generated are given below, along with a brief explanation of their significance. To be clear, the tank size referred to in these models is actually the amount of water that the tank can store in meters cubed. The actual tank sizes were determined once the optimization on Water Balance was complete (concrete for the Horticulture Center tank and plastic for the fountain tank).

A few output indicators as to the efficacy of the tank were coded into the MATLAB programs and print to the screen at the end of each simulation. These are:
sumstored =The total amount of water harvested over the years, less deficiencies, to give an idea of how much water is saved over the course of the systems use (meters cubed).
maxstored = Maximum amount of water that the tank stores. If it is much less than the tank size, the tank size is too big for water input (meters cubed).
sumirrigation =The total amount of irrigation drawn from the system over the years (meters cubed).
sumprecipitation = The total amount of precipitation collected from the system over the years, minus first flush (meters cubed).
sumcountdeficit = The number of days where there is a deficit of water (meters cubed).
sumdeficit = A negative value indicating how much water is having to be supplied by municipal sources as opposed to from the rainwater harvesting system (meters cubed).
deficitaverage = The average deficit, taken as the sumdeficit/sumcountdeficit (meters cubed).
maxdeficit = The maximum water deficit (meters cubed).
maxirrigation = The maximum amount of irrigation drawn on any given day from the storage tank (meters cubed).

Horticulture Storage Tank:

Scenario 1:
Roof area drained = 83 meters squared.
Tank size = 60 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 3.0 meters cubed.

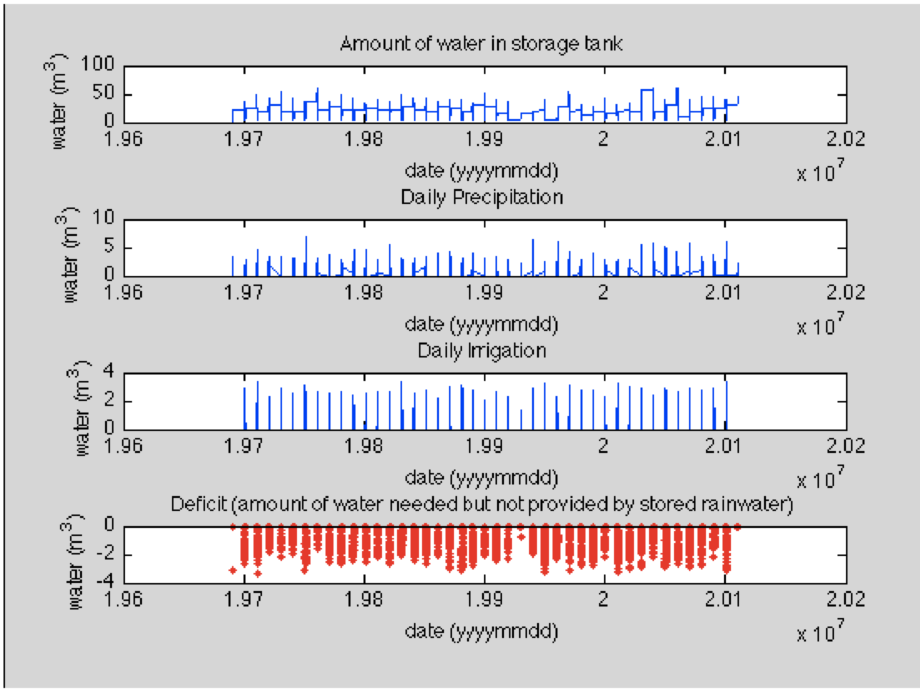


Figure 7: Scenario 1 Horticulture Center

sumstored =2.8990e+05
maxstored = 60
sumirrigation =4.8874e+03
sumprecipitation = 2.5732e+03
sumcountdeficit = 2097
sumdeficit = -2.4171e+03
deficitaverage = -1.1527
maxdeficit =-3.3840
maxirrigation = 3.3840

The total amount of irrigation is far less than the total amount or precipitation. This is an indicator right way that 83 meters squared is too small a roof area to provide the rainwater needed for harvesting. Additionally the many points on the chart for water Deficit, totaling 2097 according to sumcountdeficit, supports this.

Scenario 2:
Roof area drained = 334 meters squared.
Tank size = 35 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 3.0 meters cubed.

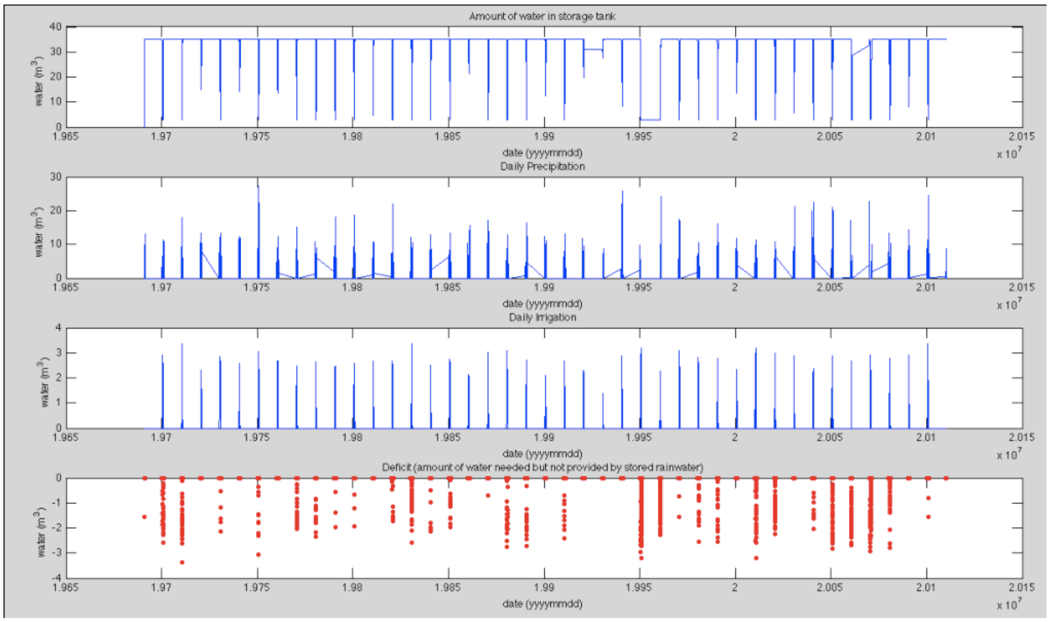


Figure 8: Scenario 2 Horticulture Center

sumstored = 4.2490e+05
maxstored = 35
sumirrigation = 4.8874e+03
sumprecipitation = 1.0293e+04
sumcountdeficit = 891
sumdeficit =-1.1151e+03
deficitaverage = -1.2515
maxdeficit = -3.384
maxirrigation =3.3840

The amount of sumprecipitation outweighs the sumirrigation, indicating that the roof area chosen supplies enough water to the garden for irrigation. The deficit count is also less than half that it was at 83 meters squared of roof area drained, indicating an improvement. The fact that there is a deficit indicates that the storage tank size is too small to hold the optimal amount of water, though with a storage tank size that is larger, the measurements begin to exceed the space available in the Horticulture Center.

Scenario 3:
Roof area drained = 334 meters squared.
Tank size = 100 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 0 meters cubed.

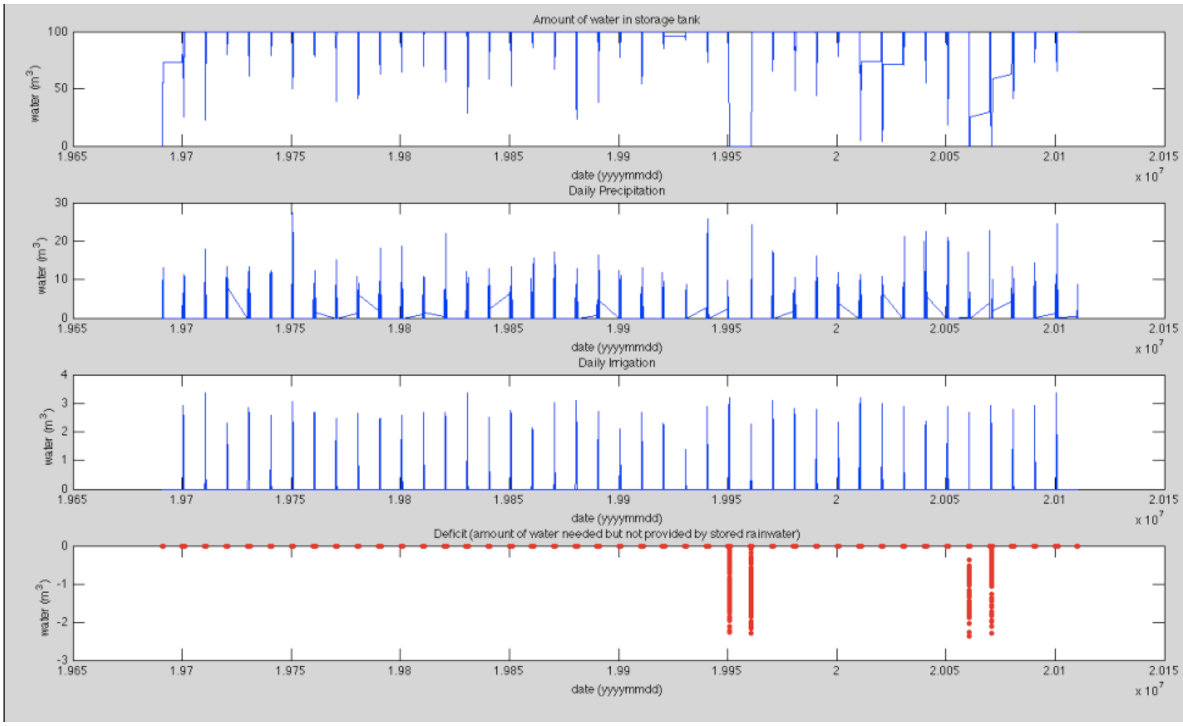


Figure 9: Scenario 3 Horticulture Center

sumstored = 1.2794e+06
maxstored =100
sumirrigation =4.8874e+03
sumprecipitation = 1.0293e+04
sumcountdeficit =307
sumdeficit = -293.4800
deficitaverage = -0.956
maxdeficit = -2.3706
maxirrigation = 3.3840

The 100 meters cubic chosen for the tank size gives only 4 years with deficits and the average of these water deficits are lower than in the previous two scenarios. A 100 meters cubed tank would be far too large however, to be considered as a realistic design alternative.

Meditation Garden Storage Tank:

Scenario 1:
Radius of fountain = 1.0 meters.
Tank size = 6.0 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 0 meters cubed.

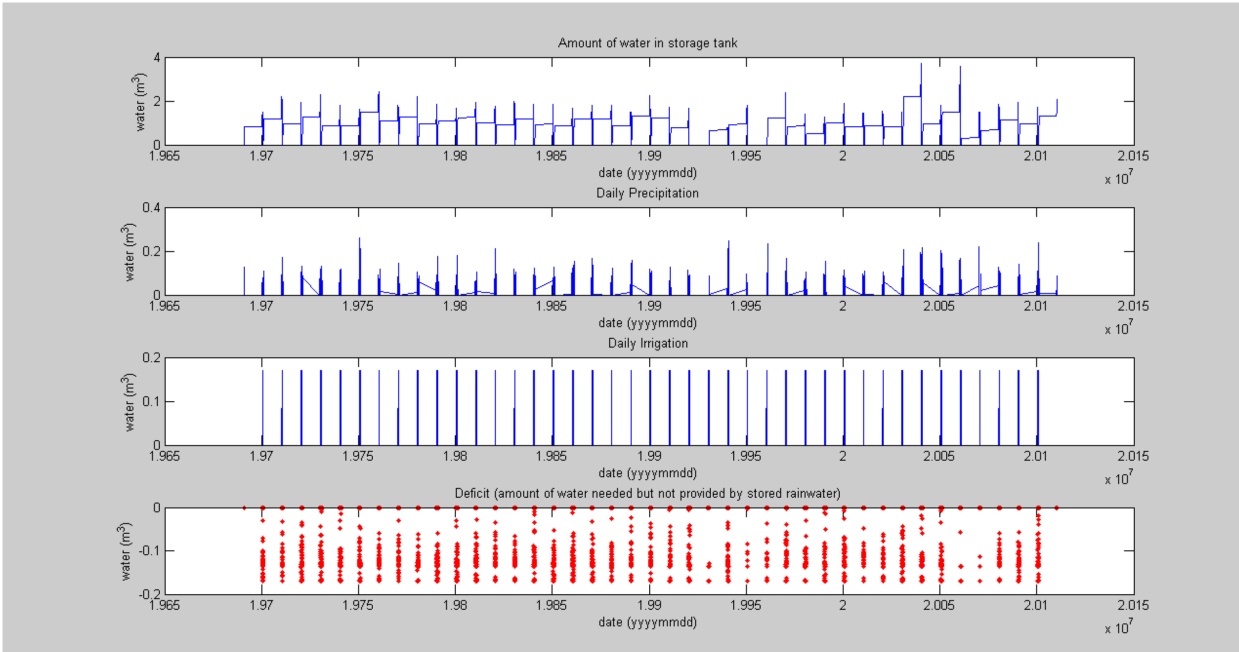


Figure 10: Scenario 1 Meditation Garden

sumstored =1.0070e+004
maxstored =3.7193
sumirrigation =705.6100
sumprecipitation = 113.4250
sumcountdeficit = 4430
maxdeficit = -0.1700

The sumprecipitation is almost a seventh of the sumirrigation and the number of days when the irrigation requirements are not met are over 4000. Therefore a 1 meter radius is inadequate for the design.

Scenario 2:
Radius of fountain = 1.5 meters.
Tank size = 4.0 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 0 meters cubed.

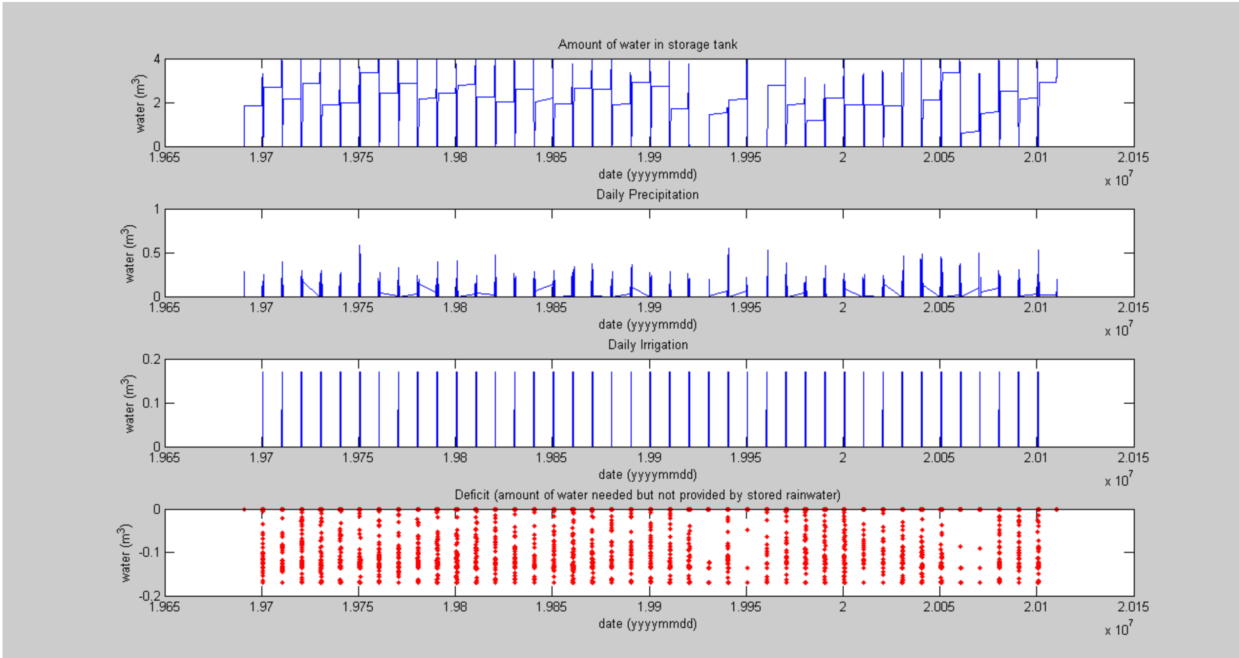


Figure 11: Scenario 2 Meditation Garden

sumstored = 2.2694e+004
maxstored = 4
sumirrigation =705.6100
sumprecipitation =255.2063
sumcountdeficit = 3675
maxdeficit =-0.1700

At 1.5 meters the fountain reached the limits of the space deemed to be appropriate by the designers (beyond a 3 meter diameter is large for a fountain). The sum of precipitation was still less than half that of irrigation, meaning that the optimal design for the fountain will not be able to supply all water for irrigation, but instead serve to diminish the dependence of the garden on municipal water supply.

Scenario 3:
Radius of fountain = 1.5 meters.
Tank size = 8.0 meters cubed.
Safety factor = 1.25.
Minimum tank storage = 0 meters cubed.

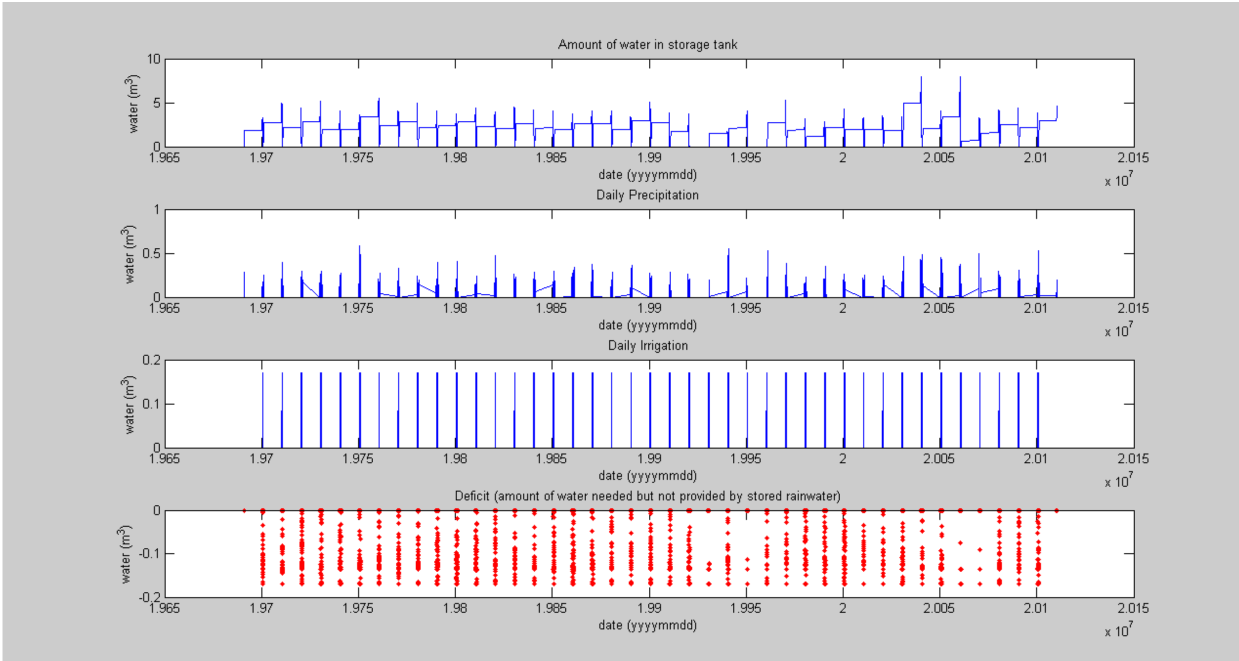


Figure 12: Scenario 3 Meditation Garden

sumstored =2.4338e+004
maxstored =8
sumirrigation = 705.6100
sumprecipitation = 255.2063
sumcountdeficit =3537
maxdeficit = -0.1700

As the water overspilled quite often in the 4 meters cubed tank (water overspills when it reaches the maximum tank storage size and then more precipitation is introduced) higher values for the storage tank capacity were tested. However, even doubling the tank size did not reduce the number of days in deficit by very much. Given the expense of buying a bigger tank, it would be better to go with the smaller tank in this case.

Results

All plots shown are for simulations run over the course of the years from 1969 until present day. Additional simulations were also run beginning at different times of the year and in different years to see how this would affect the model outputs. For simulations beginning just before or during the summer months the water deficit was introduced early in the storage tank and was greater overall for the first couple of years. This makes sense, as there is a greater water demand during the summer, but not a greater water supply. The system, for ease of construction, should be erected in the summer, but according to simulated outputs, it would be better to begin collecting precipitation in the fall and winter months before using the system for irrigation. After considering the simulated rainwater balances for both storage tanks the following catchment area and tank sizes were chosen.

For the EcoRez roof catchment area, having 4 drain pipes taking rainwater from the roof, at an area of 334 meters squared provided sufficient harvested rainwater to outweigh the sum irrigation requirements. Due to constraints of space in the Horticulture Center a 35 meter cubic tank was chosen, to be made from concrete reinforced by steel bars. This would result in Scenario 2 in the Optimization section of Water Balance. This is a high enough tank size to limit the water deficiencies to approximately 1 meter cubic on average, which can be drawn with a hose from the Horticulture Center municipal water supply. As the 35 meter cubic tank size is smaller in cubic meterage than the amount of precipitation coming in there is a significant amount of overspill. The intake inlet of the overspill pipe is located below the water opening of the pipe that transports water from the EcoRez roof to the storage tank. This will be used to recharge groundwater, by connecting the overspill pipe from within the tank to reused inverted storage barrels buried in the ground that will release the water back gradually (see Design II report for further details).

For the fountain catchment area the size became the limiting factor. The fountain was meant to create ambience as well as serving a functional purpose. As such the size could not be so large that it overwhelmed the garden. The design team judged that the maximum diameter of the fountain should not exceed 3 meters in order to achieve this. At this catchment area the irrigation requirements cannot be met by the fountain alone. Water from the municipal water supply can be used to supplement the irrigation needs, as there is a tap already attached to the municipal water supply on the East Side of the Community Garden. Overspill from the storage tank, sized as in Scenario 2 of the Optimization section for the Meditation Garden at 4 meters cubed, will be dealt with in the same manner as that in the Horticulture Center storage tank.

Given that the storage tanks and the catchment areas were sized, the design of the aforementioned were carried out as is discussed in the following sections.

EcoRez Roof Rainwater Collection

Filtration

Rainwater in itself is clean and its parameters present little health hazard physiochemically (Ward et al, 2010). However, the water collects airborne particles as well as animal excretions, leaves and fruits of trees that have fallen onto the roof. The bacterial load of roof runoff is affected greatly by weather patterns and other factors such as relative source location (Evans et al, 2006). In addition, corrosion of roof material, storage and pipe material as well as of internal and external fittings can result in high concentrations of some metals, such as copper, zinc and aluminum (Ward et al, 2010).

Kus et al (2010) performed an analysis of the quality of roof runoff during several rainfall events in a metropolitan urban residential area in Sydney. They found that the level of contaminants in the first few millimeters of roof runoff is significantly high but decreases considerably for the rest of the rainfall period. For example, as can be seen in Fig. 10, the level of suspended solids goes from being above ADWG (Australian Drinking Water Guidelines) limits in the first millimeter of rain to within the 0 – 50 mg/l range. For aluminum, ammonia and iron, the level drops under the ADWG line after 2mm of rainfall. The only two substances that do not comply are turbidity and lead. It must be noted that the type of these contaminants are dependent material of the roof used for rainwater catchment.

In terms of the water used to irrigate crops in Canada "There are few specific laws that regulate the water quality to be used in agricultural production for food safety purposes" (8). Instead there are "guidelines" which give recommended values for the level of microbes and chemicals allowed in water used for agriculture. Of these, for rainwater collected from a rooftop, the greatest concern is as listed below, derived from Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses:

"Canadian Irrigation Water Standards:

Fecal coliforms (E. coli) : <100 bacteria per 100 mL water

Total coliforms: <1,000 bacteria per 100 mL water" (8)

The accumulation of animal, particularly bird, fecal matter on rooftops, which can transfer microbes to rainwater and consequently multiply in storage, can be of concern to users of harvested rainwater for irrigation. It is thus imperative to put in some kind of system that will eliminate at least the first one millimeter of rainfall coming into the storage tank as most contaminants that could pose a potential threat are contained within this first millimeter. Only one millimeter is used because the two millimeter mark is for urban cities, so it can be assumed that the mark would be lower for a suburban area like ours). However, a physical test should be conducted to ensure that removing only one millimeter is adequate.

The first preventive measure to put in place would be a mesh that would catch all solid debris that is being washed into the pipe from the roof. This mesh would need to be place at the drain pipe entrance on the roof of EcoRez, which could be done on a day when a manual labour is required on the roof for maintenance or servicing so as to not cause more trouble to the building services.

A first flush system would also be appropriate in such a situation. A diagram of such a system is displayed in Fig. 11 where it can be seen that the initial water coming through the pipe toward the storage tank is diverted into a small T-piece tube that contains a floating ball within. The water will continue to fill this tube until the ball reaches the neck of the T-piece blocking all further entry of the water. The water then rushes through the pipe and into the storage tank. The water that has collected in the little container is the first flush – the first millimeter of roof rainwater that contains most of the contaminants. There are three options for a first flush diverter: in-line, in-ground and wall-mount (Aquabarrel, 2011). For our design, an in-ground first flush diverter will work best as the diverted rainwater pipe from EcoRez goes directly into the ground and heads towards the storage tank at the Horticulture Center. The best place to locate the first flush device would be close to the storage tank so that the possible contaminants in the length of the pipe would also be washed away so that the water entering the tank is as clean as possible. An in-ground first flush diverter is show in Fig. 12.

The water that is then stored in the tank is appropriate for irrigation use. It is important to note though that such a system may filter out most metals and debris and a substantial concentration of microbes, some microbes could pass through and propagate within reach of the crops that could pose harm to human health. Thus an advisory would have to be put in place to recommend the washing of these crops before consumption.

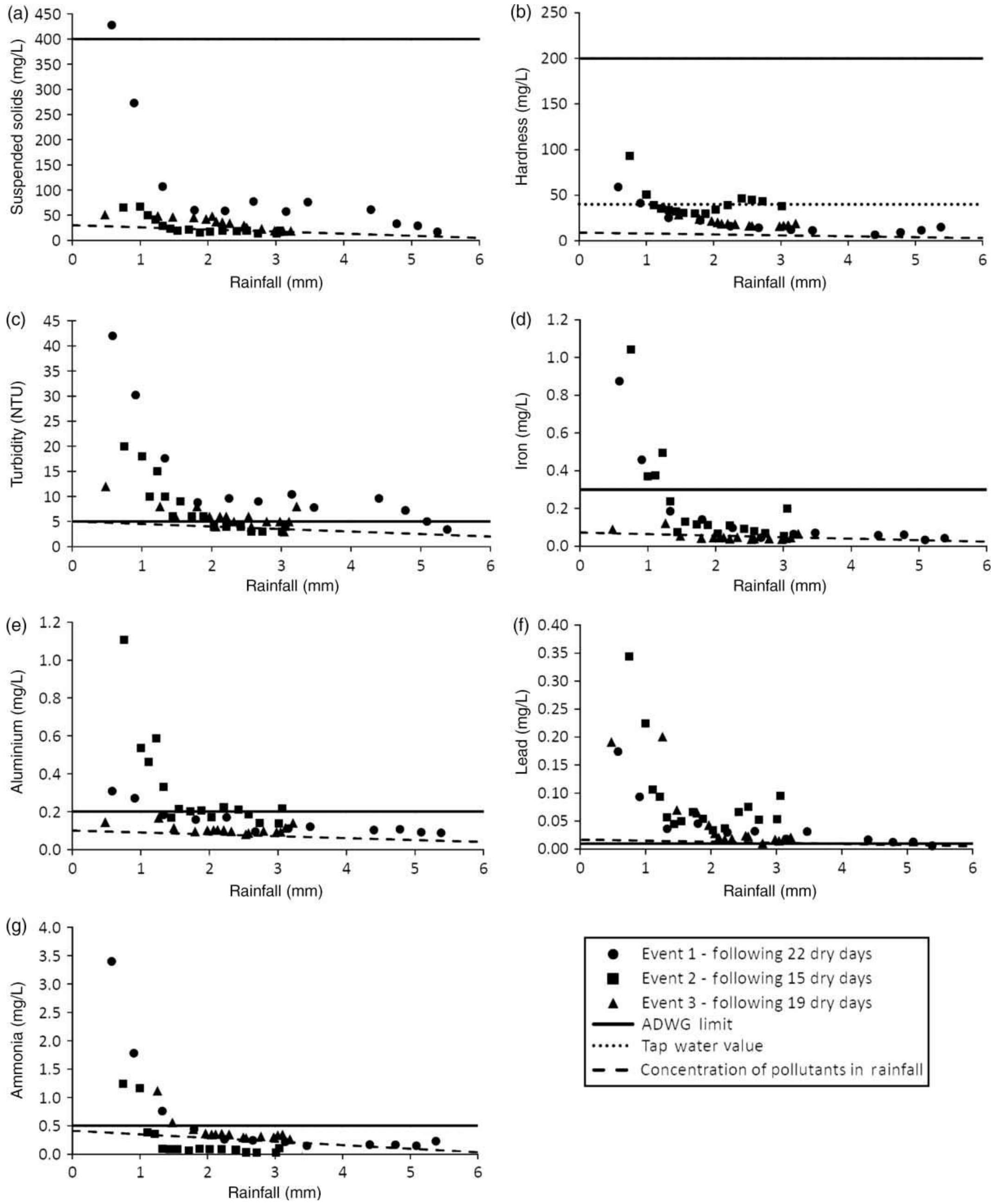


Figure 13: Constituents of roof runoff for three different rainfall events (Kus et al, 2010)

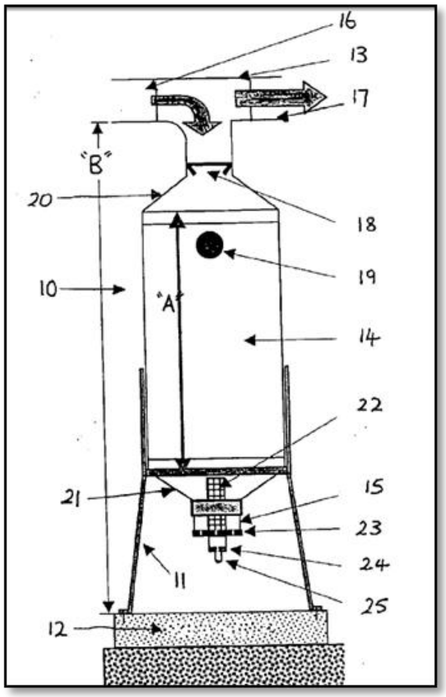


Figure 14: Design of patented T-piece first flush diverter. (Wade, 2003)

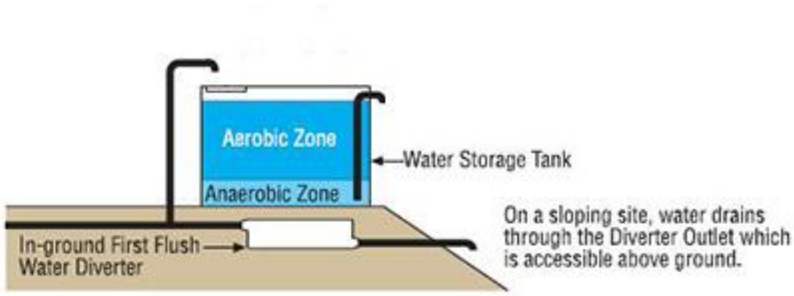


Figure 15: In-ground first flush diverter located in the vicinity of the storage tank to remove the first few millimeters of roof rainwater.

Piping Analysis

The design employs gravitational pipe flow as much as possible, eliminating the need for pumps to drive water from the catchment area to the storage tank. Google Earth was used to determine land elevations for the area surrounding EcoRez (Figure 15), the values of which were then used to optimize pipe placement such that all flows would be driven by gravity.

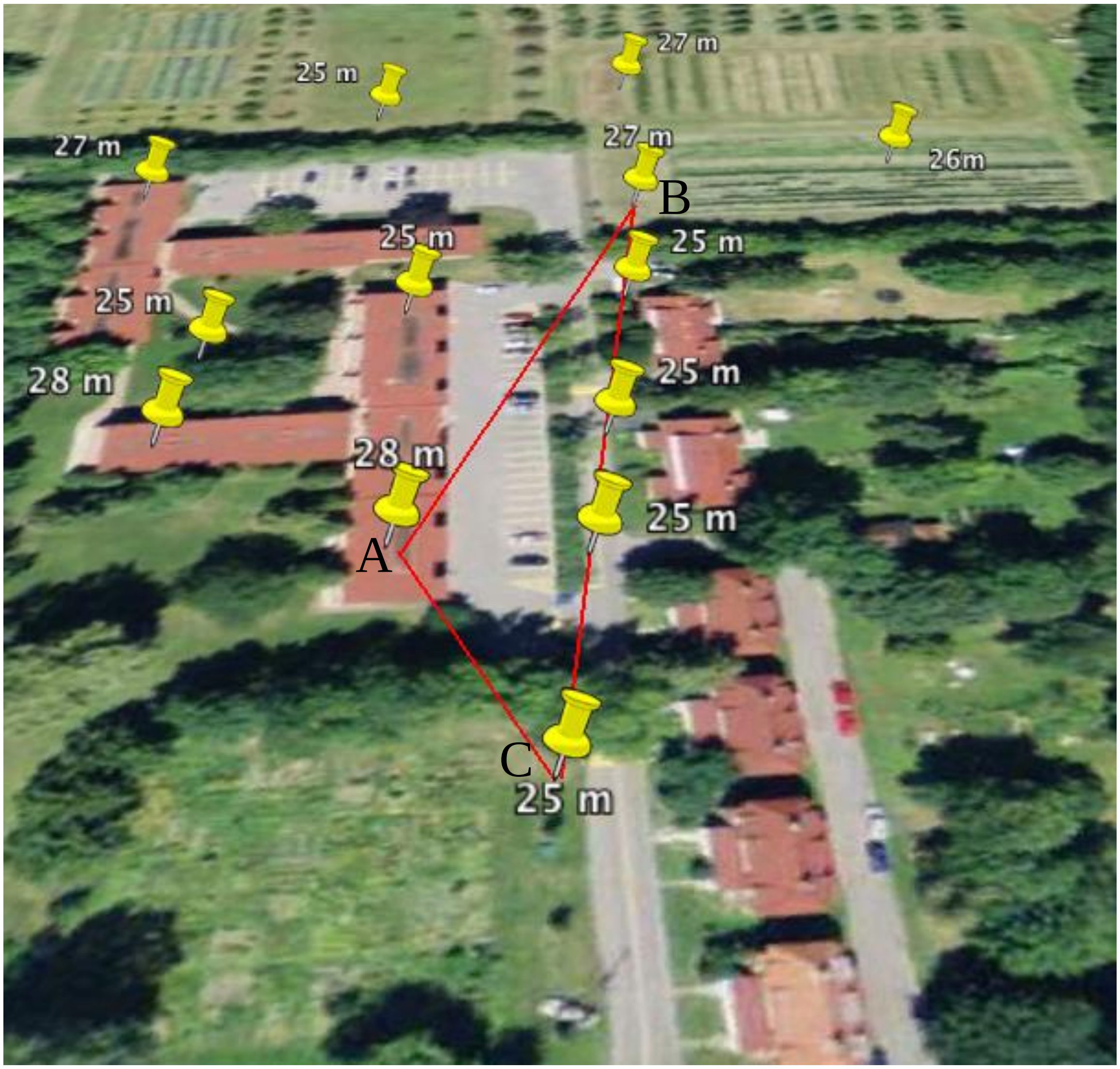


Figure 16: Google Earth Image of EcoRez, Hort. Center, and Community Garden

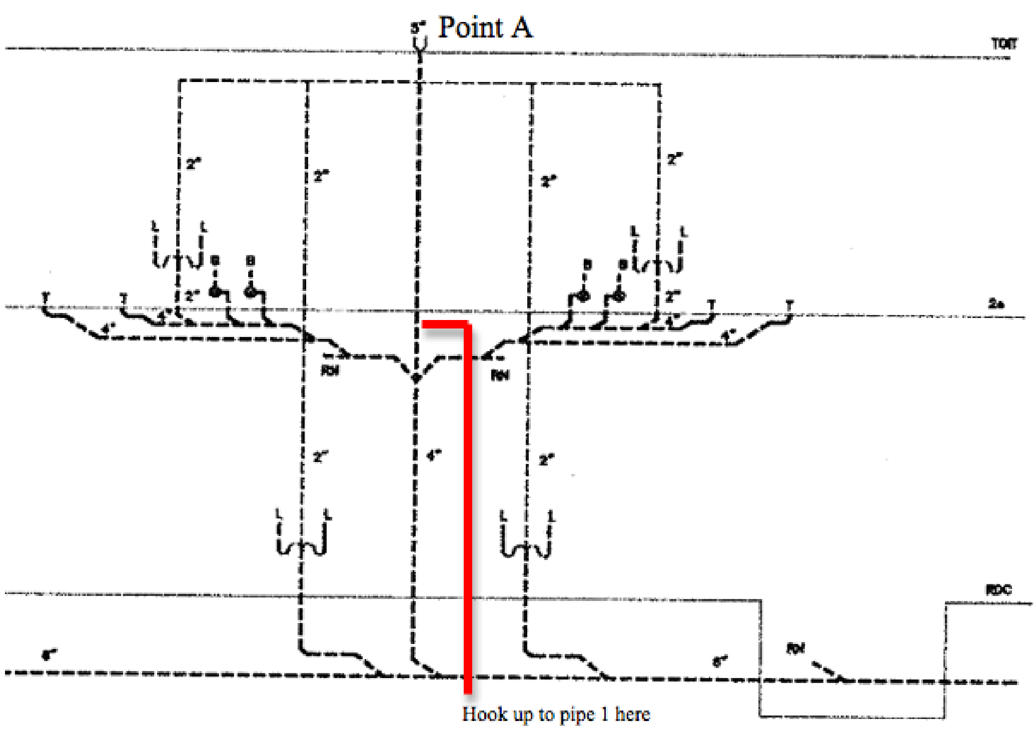
Water collected from the roof (point A) will be conveyed over a horizontal distance of approximately 101 meters to the storage tank at the horticultural center (point B). The elevation difference of 2 meters between these two points will provide enough static head to overcome head loss and fill the storage tank without utilization of a pump. The second pipe will convey the water over a horizontal distance of 138 meters from the storage tank (point B) to the community garden (point C). Again, the elevation difference of 2 meters between these two points will provide enough static head to overcome head loss and drive the water to the surface at the community garden.

All pipelines will be placed at a minimum depth of 1.2 meters below the soil surface, which respects the frost line in Montreal.

All calculations assume steady, incompressible flow in rigid piping. A MATLAB program was created which calculated the total head loss in the pipes running from the

Ecorez roof to the storage tank and from the tank to the community garden, respectively. The head loss calculations were performed based upon a pre-determined design flow rate of based upon the maximum precipitation in the climate data downloaded. This flow rate was determined after the optimal drainage area had been established at 334 m^2. The MATLAB program generates head loss values for the following schedule 40, nominal pipe diameters: ½", ¾", 1", 1 ¼", 1 ½", 2", 2 ½", 3", 4", 5", 6", 8", 10", 12", 14", and 16". The optimal pipe size was determined to be 2 ½" from EcoRez to the storage tank in the Horticulture Center.

The plans for EcoRez show that there are currently drainage pipes running from the roof, down through the building, and into the ground. This plumbing will need to be altered so that the roof water can be diverted to our pipe network before mixing with the building wastewater (which it currently does). The following figure is a schematic of the current plumbing:



Plans drawn by Raymond Michel Cherrier, Architect. Photo courtesy of Ron Macdonald, Manager, Documentation-Facilities Operations and Development

Figure 17: The plans for diversion are illustrated in red.

Water collected from the roof (point A) will be conveyed through high-density polyethylene pipe (HDPE) over a horizontal distance of approximately 101 meters to the storage tank at the horticultural center (point B). The elevation difference of 2 meters between these two points will provide enough static head to overcome head loss and fill the storage tank without utilization of a pump. The second pipe will convey the water over a horizontal distance of 138 meters from the storage tank (point B) to the community garden (point C). Again, the elevation difference of 2 meters between these two points will provide enough static head to overcome head loss and drive the water to the surface at the community garden.

All pipelines will be placed at a minimum depth of 1.2 meters below the soil surface, which respects the frost line in Montreal.

All calculations assume steady, incompressible flow in rigid piping. A MATLAB program was created which calculated the total head loss in the pipes running from the Ecorez roof to the storage tank and from the tank to the community garden, respectively. The head loss calculations were performed based upon a pre-determined design flow rate of 0.1469 L/s. This flow rate was determined after the optimal drainage area had been established at 334 m^2 (as discussed previously). The design flow rate for the pipe connecting the tank to the community garden was assumed to be 4.5 L/min, as this is the upper range of flow rates amenable to solar power pumps for our desired pressure (Thermo Dynamics Ltd., 2011). The MATLAB program generates head loss values for the following schedule 40, nominal pipe diameters: ½", ¾", 1", 1 ¼", 1 ½", 2", 2 ½", 3", 4", 5", 6", 8", 10", 12", 14", and 16". The equations used to calculate the major and minor head losses are shown below:

$$h_{L,major} = \frac{8fL}{g\pi D^5} \cdot Q^B$$ (Munson, 2005)

$$h_{L,mior} = \frac{kV^2}{2g}$$ (Munson, 2005)

Where B=2 for steady, incompressible flow and k=1.1 for elbow bends (Munson, 2005, p. 316).

Laminar flow within the pipes is desired in order to minimize head loss. From the MATLAB program, it was determined that the flow is laminar for pipe sizes greater than or equal to 2.5" and greater than or equal to 1.25" for pipelines 1 and 2, respectively. The optimal pipe size was determined to be 2.5" for pipe 1, with a total head loss of 0.0185 m. The optimal pipe size for pipe 2 was determined to be 2", with a total head loss of 0.0121 m. Both head losses are acceptable for our design purposes.

After subtracting the head loss from the static head, the remaining head was used to determine the outlet flow pressure. The outlet flow pressure at the community garden is 18.9452 kPa.

Literature suggests that the range for water pressure in a home is from 30 to 80 psi (Ville de Montreal, 2011). This is approximately between 210 and 550 kPa. Therefore, the pressure deficit at the community garden ranges from 190 to 530 kPa. There are solar-power pumps available on the market, which are capable of satisfying this design need. It is possible to supply 4 L/min at a pressure of 210 kPa (30 psi) with a 30-Watt photovoltaic cell pump (Thermo Dynamics Ltd., 2011).

Based on this pipe size, it was determined that the dead load of the pipe, when flowing full is 4.490 kN and 21.19 kN for pipes 1 and 2, respectively. This translates to a pressure of 0.7 kPa and 1.2 kPa, respectively. The literature value for the bearing capacity of the soil type in question is around 72 kPa (Ambrose, 1981). Applying a safety factor of

3, which is standard in soil mechanics, we are left with a bearing capacity of 24 kPa. It has been shown that the pipe load on the soil is significantly less than the bearing capacity of the soil, which means our design is well within the limitations.

The decision to go with polyethylene (PE) was influenced by both cost-performance ratio and environmental impact of the material. Polyethylene pipe is leak-tight, is not susceptible to corrosion, and is capable of handling a wide range of temperatures (Oxford Plastics, Inc., 2010). In addition, PE is a much more environmentally conscious choice than PVC (Greenpeace PVC Alternatives Database, 2011).

Taking the cost of 2” PE pipe to be $0.68 per foot (BGM Supply, n.d.), the total estimated cost for pipe 2 would roughly be $265.00. We were unable to locate consistent prices for 2.5” PE pipe, and elected to make our cost estimate with the value of $0.90 per foot. This cost is approximately $460.00. Note this does not include installation costs, which were covered in the report from Design II.

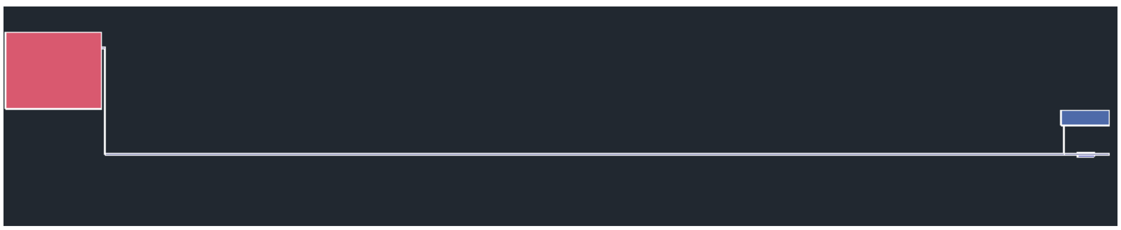


Figure 18: Side profile of the pipe conveying rainwater from EcoRez to the storage tank at the Horticulture Center

Figure 19: Top view of the pipe conveying rainwater from EcoRez to the storage tank at the Horticulture Center

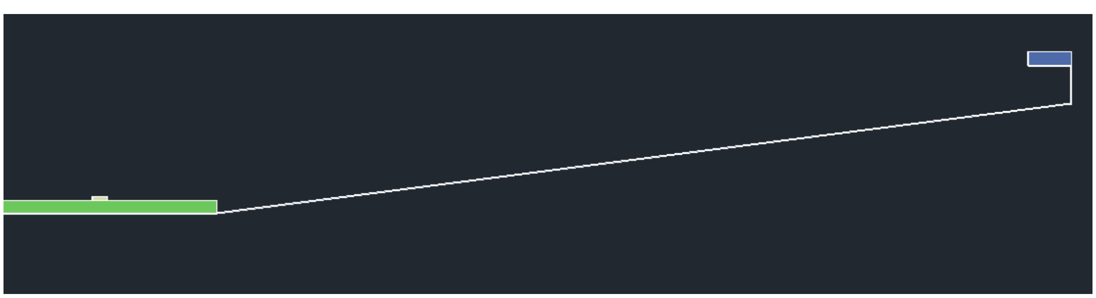


Figure 20: Side profile of the pipe conveying irrigation water from the storage tank to the Community Garden

Figure 21: Top view of the pipe conveying irrigation water from the storage tank to the Community Garden

Figure 22: Side view of the pipe conveying irrigation water from the storage tank to the Studen-run Garden at the Horticulture Center

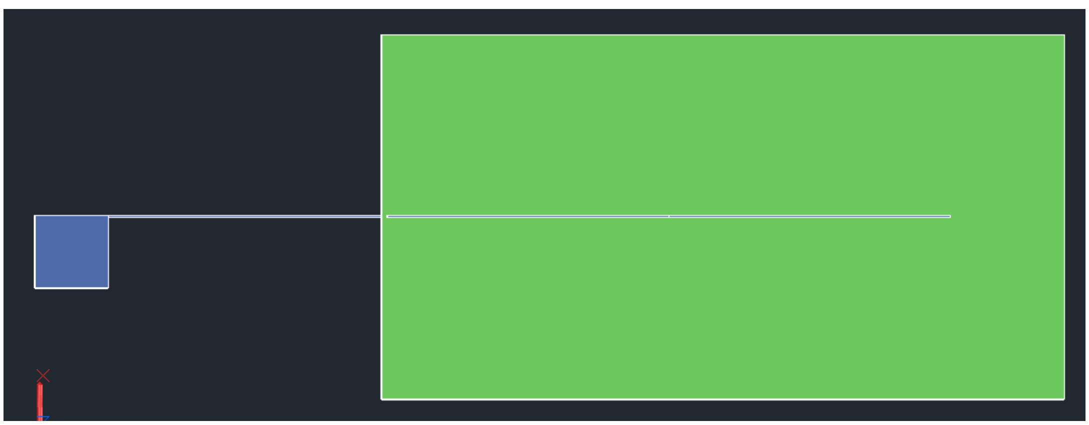
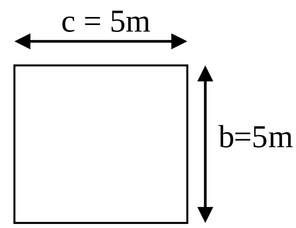


Figure 23: Top view of the pipe conveying irrigation water from the storage tank to the Studen-run Garden at the Horticulture Center

Reinforcements Calculations for Concrete Storage Tank

Design of the reinforcements in the walls of the concrete storage tank, rectangular in shape with a wall thickness of 250mm. Use a concrete compressive strength of 30MPa. The tank measures externally, 5m by 5m and is 1.5m deep. It is designed to hold water.



Calculations:

Vertical reinforcements:

We first need to calculate the moment exerted by the load in the tank, which can be determined by: $Mf = 1.5 * \frac{1}{6} * \rho * g * h^3$

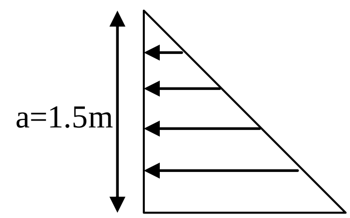
Where Mf = exerted moment of water onto the tank,

1.5 = safety factor

ρ = density of water (1000kg/m^3),

g = earth's acceleration (9.8m/s^2) and

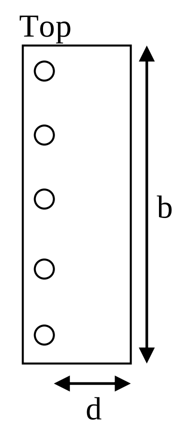
h = height of water in tank (assume same as tank height = 1.5m)



Thus Mf = 8.27kN-m

Next, we calculate the resistive moment of the tank, which is defined as:

$Mr = Kr * bt * d^2 * 10^{-6}$



Where Mr = resistive moment of the reinforced concrete walls

Kr = dependent on the compressive strength of concrete and the ductile failure (p)

$f'c$ = Concrete compressive strength = 30Mpa

$p = \frac{As}{bt*d}$, where As is the area of the bar times the number of bars

bt = length of wall, can be assumed to be 1000mm for now

d = width of wall (250mm standard) – 0.5*db – covering (dc = 50mm max)

db = diameter of steel bar

What diameter steel bar should we use?

Steel bar	db (mm)	A (mm^2)	N	p %	Kr	Mr (kN-m)
10M	11.3	100	2	0.103	N/A	N/A
10M	**11.3**	**100**	**3**	**0.154**	**0.513**	**19.38**
10M	11.3	100	4	0.206	0.687	25.95

Let's use 3 10M bars:

Mr = 19.38kN-m > Mf = 8.27kN-m, d = 194.35mm

For serviceability – to ensure ductile failure:

$N = 2 * bt * dc^2 * \left(\frac{fs}{Z}\right)^3$, want to find fs such that fs < fsmax (where fsmax = 0.6fy and fy = 400MPa for Canadian steel. So, fsmax = 240MPa) and Z = 20000N/mm for Quebec only.

⇨ $fs = \left(\frac{N}{2*bt*dc^2}\right)^{1/3} * Z = \left(\frac{3}{2*1000mm*(50mm)^2}\right)^{1/3} * 20000N/mm$ = 212MPa

$Ac = \frac{K*d}{2} = n * As * (d - K * d)$, where n = Es/Ec = 200000MPa / (4500*√(30)) = 8.11

⇨ Can solve for K: $K = sqrt(2 * p * n + (p * n)^2) - p * n$ = 0.146

$Msteel = As * fs * \left(d\left(1 - \frac{K}{3}\right)\right) = 3 * 100mm^2 * 212MPa * 194.35mm * 0.95$ = 11.74kN-m

Are we okay?

Mf = 8.27 kN-m, but safety factor is 1.5

For serviceability, safety factor = 1.0 so M = 5.51kN-m < Msteel = 11.74kN-m (good)

Therefore in a cross-section of one wall, there will be 16 vertical reinforcement bars at 322mm spacing.

Horizontal reinforcements:

Development Length: $ld = 0.45 * k1 * k2 * k3 * \frac{fy}{\sqrt{f'c}} * db$

⇨ $ld = 371.4mm * k1 * k2 * k3$ (from Table 3.1, p.3-15, CAC, Concrete Design Handbook 3rd edition)

k1 = 1.3 (for horizontal reinforcement with 300mm fresh concrete in member below development length or splice, p. 3-15, CAC)

k2 = 1.0 (no epoxy, p.3-15, CAC)

k3 = 1.0 (normal density concrete, p. 3-15, CAC)

⇨ $ld = 371.4mm * 1.3 * 1.0 * 1.0 = 483mm$ > 300mm (good)

Checking minimum Area of Steel:

$Min\ As = \frac{0.2\sqrt{f'c}}{fy} * bt * h = \frac{0.2\sqrt{30Mpa}}{400MPa} * 1000mm * 250mm = 685mm^2$

Our As = $3*100mm^2 = 300mm^2$

Our As < Min As

Need to check what kind of shear stress dealing with:

Vc = ϕc*λ*β*sqrt(fc')*bw*dv

Vc = 0.65*1.0*0.21*sqrt(30MPa)*250mm*194.35mm = 36.33 kN

Check Spacing:
S $\geq$ 1.4*db = 1.4*11.3= 15.82mm
Or S $\geq$ 1.4*a_{max} (mixture aggregate ϕ_{max} = 25mm) = 1.4*25mm = 35mm
Or S $\geq$ 30mm
So, we need S $\geq$ 35mm
Design S = 1000mm/3bars – db = 322mm $\geq$ 35mm (good)

Horizontal at in the center of the wall:

The ratio b/a = 5/1.5 = 3.33 and the ratio c/a = 3.33. We can assume the center of the walls to be more cantilever-like, thus the walls experience the same moment as that experienced by the vertical bars: $Mf = 1.5 * \frac{1}{6} * \rho * g * h^3$

Mf=1.5*1000kg/m^3*9.8m/s^2*(1.5m)^3/(1000*6)

Mf = 8.27kN-m.

Thus the same bars, 3 10M per 1000mm, can be used for the center of each of the walls that extend all the way to the corners. In the 3 meters height, there will be 9 bars at 322mm spacing on each side of the wall to balance the pressures on either side of the wall (the water on the inside and the soil on the outside).

Horizontal at in the center of the wall:

The wall no longer behaves like a cantilever at the corners (M_y increases) so horizontal bars pick up extra strain, thus may be more like a beam.
Generally, the reinforcements are doubled in the corners and an anchorage length is added so the bars don't slip in the concrete. This anchorage length is: 0.1b + ld = 0.1*5m + 0.483m = 0.983m.

Thus the additional bars will only be added around the corners for a length of 0.983m extending in each direction. In a cross-section, there will be 9 more horizontal bars on either side of the wall at the corners of the tank. Altogether in the cross-section of a corner there would be 18 bars spaced at 161mm on either side of the wall.

Note:

It is important to note that though the calculations for the reinforcements were computed under the assumption that the tank would be full, the water will only rise to 1.4m in the tank so this 37.5m^3 tank will hold at maximum 35m^3 of water. The assumption was made to have a more conservative design in case of failure. Also note that a corrugated metal sheet will be placed on top of the tank to enclose it because of its ease of use and its functionality.

The Zen Fountain

The fountain has two functions: to provide a continuous flow of water to enhance the meditative environment of the garden and to catch rainwater that is incident upon it to provide irrigation water for the herbs planted in the neighboring raised beds. The fountain thus needs a bowl that is wide and can rest on the ground; the shape of an inverted hollow cone with a truncated top can serve this purpose. As the meditation garden is a place for people (students, staff, professors, and members of the community) to enjoy the peaceful ambience, the fountain should provide a seating area. A wall with the thickness of a standard chair, roughly 0.3 m, will surround the fountain. The mechanism that circulates the water between the storage tank and the bowl is designed in the shape of a tap to symbolize its dual function of providing irrigation water for the garden and circulating the stored water. A schematic of the meditation garden is provided below which shows the locations of the raised beds, trees and shrubs. The area with the stone circle has not yet been built and it is proposed that the fountain be constructed in that location.

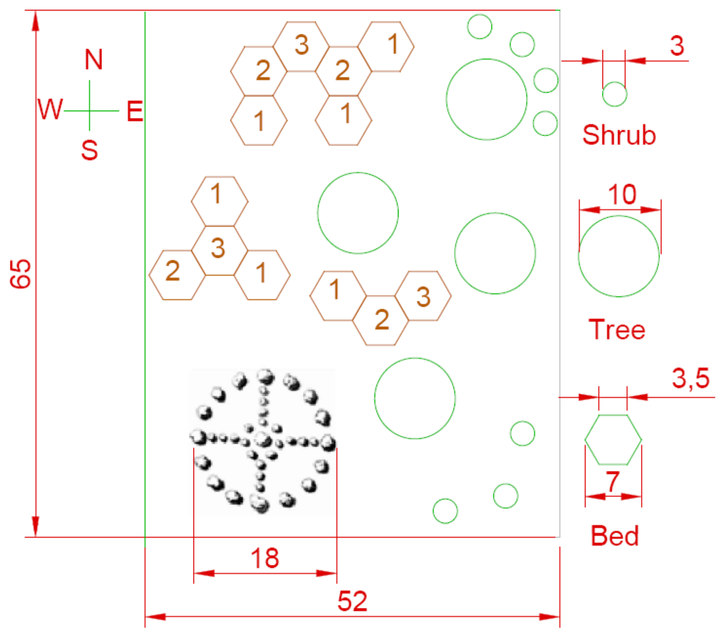


Figure 24: Schematic of the Meditation Garden. The circle of stones does not exist and that is where the fountain is planned to be located.

Fountain Bowl

Usage considerations must be made for the physical analysis of the fountain bowl. It is not a place of human occupancy, and it will not retain water. However, in the event of a storm the bowl should be able to hold the weight of water accumulating within it due to the limiting drain diameter. The bowl also needs to be constructed of a material that can withstand the climate of Montreal and that is resistant to water damage. Concrete is a suitable material; however one of its constituents, cement, is especially harmful to the environment. "The manufacturing process [for cement] depends on burning vast amounts of cheap coal to heat kilns to more than 1,500 C. It also relies on the decomposition of limestone, a chemical change which frees carbon dioxide as a byproduct" (Adam, 2007).

It has been predicted that "cement plants and factories across the world are projected to churn out almost 5 billion tons of carbon dioxide annually by 2050" (Adam, 2007). In keeping with our aspirations to make the design as green as possible, the concrete used will contain supplementary cementitious material (SCM). Examples of SCM are fly ash or ground granulated blast-furnace slag, which can replace the cement. Such eco-friendly cement is obtainable through a company by the name of Calera. Another company by the name of Concrete Creations offers a design for a fountain bowl called the "Asian Wok", the shape of which is essentially an inverted cone with a truncated top. According to their website, Concrete Creations is flexible in terms of meeting client needs and producing custom-made products. Consequently, there is real feasibility that the SCM could be incorporated in the building of the Asian Wok for the Zen Fountain.

Fountain Seating

The thick wall around the fountain bowl can be made from concrete or compressed earth blocks (CEB). The disadvantage of concrete, as discussed earlier, is the cement component. The aforementioned solution of using SCM could be employed again. However, an alternative solution would be to use packed earth or mud that could be shaped into bricks, commonly referred to as compressed earth blocks (CEB). "Most of the time, soil for CEB can be found on site or within a short distance. The reduction of transportation time, cost and attendant pollution can also make CEB more environmentally friendly than other materials" (Wayne, n.d). The site of the fountain contains soil of type CH (organic clays). It is impervious and highly compressible but has poor compacted strength and workability (McKyes, 1989). Thus, if CEB were chosen, the source material would need to be obtained and transported from another site. In addition to the environmental consideration, the choice of material for the wall depends on several other factors, namely relative cost, relative strength and the relative weight of the materials.

Fountain Spout

As mentioned before, the spout of the fountain will be in the shape of a household sink tap for aesthetic purposes. The spout will be the shell for a pipe housed within, and the pipe will transport water from the storage tank to the fountain bowl. The spout needs to be lightweight, withstand cold, and resist water damage. As its shape is much like that of a splash pad water spout, it can be made of similar material. Splash pad waterspouts are typically made of stainless steel or fiberglass reinforced plastic (FRP). FRP "does not corrode or deteriorate, it can be recycled [and the] virgin production of FRP usually has less environmental impact than even recycling alternate materials, such as steel and aluminum" (Strongwell, 2011). In addition, "FRP composite products have high resistance to rot and corrosion, a longer and more economical service life and require less frequent energy-intensive maintenance and replacement" (Strongwell, 2011). Also, as is demonstrated by splash pad water spouts, fiberglass reinforced plastics can be painted in a variety of colours. A green colour would blend well with the surrounding vegetation. It would also symbolize the eco-friendliness of the structure.

Water Transport and Storage

As rain falls into the fountain bowl, it will filter through a fine mesh placed at the opening of the drain. The fine mesh will function to catch debris such as leaves and berries. Then it will flow through a 2” pipe into the storage tank. A P118330 solar powered pump (produced by Thermodynamics Ltd) placed in the storage tank will then push the water up the spout in a 2” pipe and back into the fountain bowl, provided that there is a sufficient volume of water in the storage tank.

The storage tank, as was decided in Design II, is a barrel that will be buried horizontally, below the frost line (1.2m for Montreal). The horizontal orientation versus the vertical orientation of the barrel will reduce the excavation depth and will make for easier access for maintenance purposes. The storage tank will need to be cleaned periodically despite the mesh put in place, as small sediment will pass through the mesh and eventually build up in the tank. A manhole will be constructed directly above the tank, beside the water spout, so that the tank can be easily accessed for such purposes. The pipe leading into the spout will have a valve that will be used to turn the flow off in the winter. Also, the cylindrical shape of the fountain will make it easier to cover during the winter so that it is not exposed to the winter weather.

Plastic barrels come in various sizes and the volume of the storage tank is dependent on the area of the catchment, which is sized to supply irrigation needs (i.e. dependent on the difference between the amount of precipitation incident upon the site and the evapotranspiration). As there are multiple variables dependent upon one another, a MATLAB program was used to model the interrelations and provide an optimal output for the required catchment area. After running the code, it was determined that a radius of 1.5m would be ideal for the catchment area and a storage tank of $4m^3$ would work well with that radius.

A good design flow rate coming out of the spout would be 5L per minute as the students who water the raised herbs will be filling their watering cans at the fountain tap, thus the water needs to have a decent flow to fill up a 5L watering can without waiting for much more than a minute.

The whole fountain structure will require a foundation to support its weight. A circular foundation can be placed under the wall and bowl structure with the same diameter as that of the outside of the wall. A smaller circular foundation can be laid under the tap spout for support. The depth of each of the foundations depends on the weight of the materials used for the wall, bowl and spout structures. Foundation depth could be used as a parameter in the optimization of the type of material to be used for the wall.

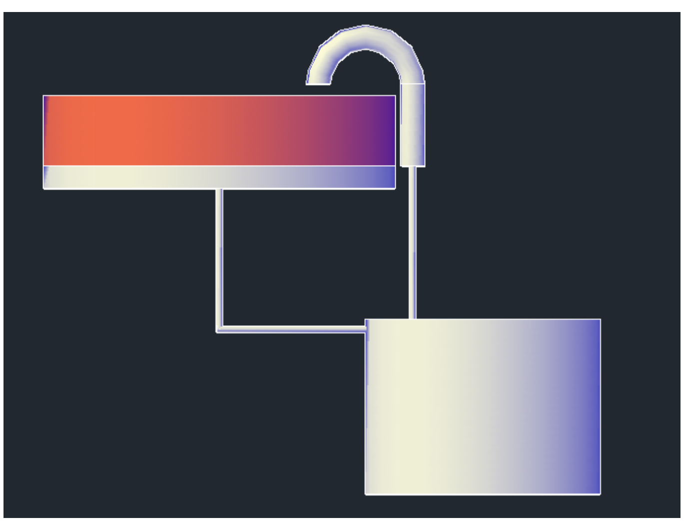


Figure 25: Side view of the fountain (AutoCAD Rendering)

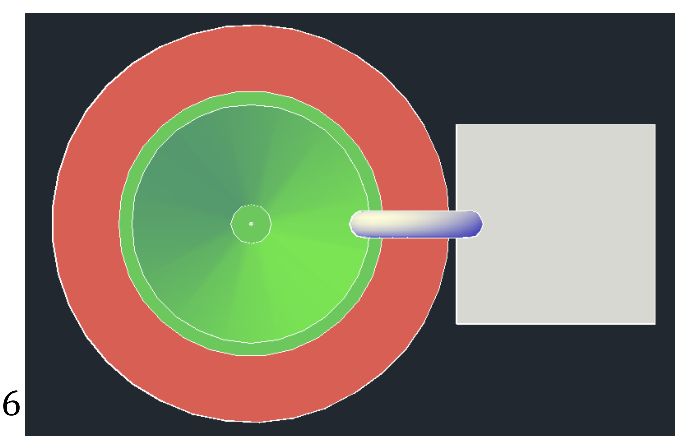


Figure 26: Top view of the fountain (AutoCAD Rendering)

Fountain Foundation Calculation

It is known that the soil type of the area is CH, which is inorganic clay of high plasticity. It is assumed that the clay in our area is soft so as to design for the worst conditions and ensure survival of the structure. Information on this particular area of expertise was provided graciously by Dr. Edward Mckyes in addition to the sources listed. It was through his suggestion that we decided on a circular slab foundation to support the fountain.

The calculations were computed by following Problem 3.5 from the Agricultural Engineering Soil Mechanics textbook. The problem states that:

$$q = qo/SF = Q/A = (Qfountain + Qfooting)/(pi*B^2/4)$$ (McKyes, 1989)

Where, Qfountain and Qfooting are total component weights of the fountain and of the foundation, respectively. The variable q is the allowable design bearing pressure which is equal to the maximum possible bearing pressure divided by the safety factor. A commonly used safety factor in these conditions is 3.0 (McKyes, 1989).

It is also stated that: Qfooting/A = yconcrete * df, where yconcrete is the specific weight of the concrete (kN/m^3) and df is the depth of the foundation.

The objective of this calculation is to determine the depth of the foundation, df, based on a given diameter, B, which will be computed by the Foundation MATLAB code upon receiving the optimal radius of the fountain catchment.

The knowns we have are:

qo = 72kPa; converted from a value of 1500 lb/cubic ft (Ambrose, 1981, p.56)

SF = 3;

B will be a known in the code, it will be equal to 2*rwo (i.e. twice the radius of the outer wall of the seating area).

yconcrete = 23.52kN/m^3; converted from a value of 2400 kg/cubic m (Hypertextbook). Also called p_con in the Foundation MATLAB code.

Qfountain = Ws in the Foundation MATLAB code that is calculated using the input radius and built in formulas for a combination of truncated cones, one inside the other, and open faced cylinders, one inside the other.

The equations can be rearranged to solve for df:

$$qo/SF = Ws/(pi*B^2/4) + yconcrete*df$$

- ⇨ $df = [qo/SF – Qfountain/(pi*B^2/4)]/yconcrete$
- ⇨ In MATLAB, it looks like: **df = (q-(Ws/(pi*rwo^2)))/p_con**

An additional item to note is that the Ws calculated in the Foundation MATLAB code is a matrix of different weights based on whether the wall around the fountain is built with concrete, lightweight concrete, packed mud or packed earth.

The results computed for the foundation depths were based on an input radius of 1.5m, which was determined to be the optimal radius for the fountain catchment area from the Water Balance MATLAB code.

df (m) =

0.8017 → normal concrete
0.8490 → lightweight concrete
0.8376 → packed mud
0.8656 → packed earth

The results show that the depth of the foundation for a wall made from normal concrete is the smallest, thus making it a better choice economically because it will require the least amount of foundation to be poured. Also, since it worked out that both wall and foundation will be made of concrete in addition to the Asian Wok fountain bowl, we can buy concrete made from supplementary cementitious material such as fly ash in bulk to save money.

Summary of Design

As the proposed design encompasses several concepts and ideas, now associated with mathematical formulation and technical data, it is necessary to provide a brief summary of the design to culminate. The first part of the design is the roof rainwater catchment wherein the rainwater line that drains water from the roof will be diverted from joining the sewage line and taken underground towards a storage tank in the horticulture center. The pipes carrying this water are 2.5” and they traverse 101m of underground at a depth of 1.2m at the shallowest end. The first one millimetres of each rainfall heading to the storage tank, which contains the most chemicals that could be complicate irrigation use, will be intercepted by the first flush mechanism. The rest will enter the storage tank and will be relatively cleaner. This water will be maintained at a height of 3m and will not be able to exceed a height of 1.4m as that is the height at which the pipe will deliver the water into the tank. An overflow system will be put into place to ensure that there is no backwash into the inflow pipe. The tank will be a 5m by 5m by 1.5m (height) reinforced concrete rectangular tank. The reinforcement bars, both horizontal and vertical, will be of 10M designation and three of them will be placed in each meter of width. The storage tank will be covered by a corrugated sheet metal to keep the tank enclosed from further debris and contamination.

The water from this storage tank has two destinations: the community garden through a 2” pipe (at a depth of 1.2m) with the help of a P118330 solar-powered pump (produced by Thermodynamics Ltd) that will a provide pressure additional to the gravitational pressure that naturally occurs from the Horticulture Center to the community garden. The pipe will attach to a tap which will attach to a hose that the users of the garden will use to water their gardens at a flow rate of 4.5L/min (the upper limits of the solar-powered pump).

The pipe going to the student-run garden at the horticulture center will need to be 1.5” to fit with the existing infrastructure and the second P118330 solar-powered pump will need to provide 45psi (310kPa). The solar-powered pump can go up to 550kPa, so we are in range. Also, the irrigation method at the student-run garden is drip-irrigation so by lowering the flow rate, the pump should have no problem reaching the required pressure.

The second part of the design consists of building a fountain in the meditation garden to enhance the meditative ambience while also catching rainwater for aesthetic purposes and for irrigation purposes. Rain will fall into a conical bowl of radius 1.5m (value optimized by Fountain’s Water Balance MATLAB code), which will have a thickness of 0.1m and a surrounding seating wall (cylindrical in shape, made of concrete) of thickness 0.3m. The fountain’s height will be 0.6m. Water will flow through a fine mesh, through a 2” pipe and into a 4m^3 storage tank. A P118330 solar-powered pump will pump water up a tap-shaped spout, made of fibreglass reinforced plastic, at a flow rate of 5L/min to either be filled by an irrigator or to run back into the fountain bowl. A manhole will be constructed close to the tap-shaped spout that will ease access to the storage for maintenance and servicing. The fountain itself will require a foundation of depth 0.8017m at a radius of 1.9m.

All concrete products will have a compressive strength 30MPa and will consist of supplementary cementitious material such as fly ash which is friendlier to the environment than regular cement as discussed before.

Cost of Project

Pump price: $767 (Thermodynamics, 2011)
Pump cost: $767 x 3 = $2301
Cost of pipe system: $265 + $460 = $725 (see Pipe Analysis)
Price of concrete: (30 MPa) $175/m^3 (Sarjeants, 2011)
Volume of concrete: Foundation + Fountain Bowl and Wall + Concrete Storage Tank = 9.1 m3 + 2.4 m^3 + 12.2 m^3 = 23.7 m^3
Cost of Concrete: $ 4147.5
Price of rebar: (Average) $5.51/1.2 m for 10M rebar (Lowes, 2011)
Total length of rebar: 892 m
Cost of rebar: $4095.87
Cost of polyethylene tank, Ace Roto Mold 1150 Gallon Cistern Tank : $917.99 (Tank Depot, 2011)
Price of Trenching : Rented Trencher, Refer to Design II = $160 per day
Estimated Trenching time: Refer to Design II = 1-2 days
Cost of Trenching: $320
Cost of First Flush System: $99.48 (Aquabarrel, 2011)
Price of FRP pipe: 8” diameter, 20’ length = $517.86 (Liteck Composites Corp., 2011)
Length of FRP Pipe: 10 m = 32’, therefore need two units of pipe
Cost of FRP Pipe = $1035.72

Total Cost of Project: $13642.56

This costing is likely an underestimation as it assumes that all labour is on a volunteer basis, it neglects shipping costs and it does not account for the cost of having to retrofit the pipe sytems that already exists within the EcoResidence. This costing does, however give an idea of the economic scale of the project and can help anyone looking to implement a rainwater harvesting system on Macdonald Campus following the guidelines laid out in this project.

Conclusion

The design proposed in this project report has potential to contribute to the progress of Macdonald Campus in the field of environmental sustainability. The EcoRez buildings, when renovated in 1998, had been redesigned to accommodate future endeavours of rainwater harvesting and/or greywater harvesting as had been mentioned in the Design II report. When this fact is combined with the existence of gardens in need of irrigation within the vicinity of the buildings, a recipe for conservation of natural resources is formed. In following this recipe, the demand on municipally treated water will be reduced significantly as will the energy consumption at the local wastewater treatment plant for not treating the rainwater that will be intercepted and redirected by this design. In addition, the materials proposed for the implementation of this design have been chosen to be as environmentally friendly as possible while keeping in mind economic constraints and physical constraints in terms of durability and strength of the materials. This design project would thus be a worthy candidate for the McGill Sustainability Fund.

Acknowledgements

This project would not have been possible without the kind help of the various resourceful people with whom we have had the pleasure of working. We would like to thank Dr. Clark for supervising the project and guiding us at each step; Dr. McKyes for unravelling the mysteries of foundations and soil mechanics; Dr. Barrington for recommending structurally sound features; Dr. Adamchuck for information on elevations and soil types; Professor Begg for enlightening us with information on the community and meditation gardens; Mike Bleho for much needed information on the student-run gardens; Professor Wees for photographs of the gardens we are targeting; John Crane and Ron Macdonald for schematics of the Ecoresidences through which we were able to deduce the current structure of the building. And last but not in the very least, we would like to acknowledge Emily McGill who has been our go-to person for little details about the three gardens as she is a part of the student body that is in charge of running the gardens.

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Appendix

MATLAB Code for EcoRez Water Balance

```
function Design_3

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Senior Design Project Model Group 5
% Rainwater Harvesting and Irrigation System
% Water harvested from Robertson EcoResidences Rooftop
% Water stored in Horticultural Center
% Water used to irrigate Community Gardens and Horticultural Center
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% In order to perform an optimization the user is asked to input area
of
% the roof that they would like to drain in order to harvest rainwater,
the
% size of the tank into which that rainwater will be stored and the
minimum
% level of water volume that will be maintained in the tank at all
times.
% Also, since some water losses are unaccounted for in the water
balance a
% safety factor, chosen by the user, is used to modify irrigation
% requirement.
A = input('Please input area of roof used in m2: ');
tank = input('Please input volume of tank in m3: ');
tankmin = input('Please input minimum amount of water in tank in m3:
');
sf = input('Please input safety factor used to modify irrigation
requirement: ');
Acg = 214; %area of community garden (12ftm x 32m)
Ahc = 234; %area of horticultural center

%% Water balance in terms of irrigation for Horticultural Center and
Community Garden
% Evapotranspiration estimates under deficient water supplies.
% Evapotranspiration is used to estimate irrigation requirement. The
% calculations carried out below are leading to the Penman Monteith
```

```
% Equation, as related by Soil and Water Conservation Engineering
% (Fangmeier et al., 2006).

% Reading the csv file which stores climate data downloaded from
Climate
% Canada for Sainte Anne de Bellevue
climate = csvread('climate.csv', 297, 0, [297, 0, 15448, 22]);
dm = climate(:,4);      % day of month
m = climate(:,3);       % month of year
y = climate(:, 2);      % year
date = climate(:,1);    % date

% Water in: Precipitation

precipitation = climate(:, 20);

% Water out: Evapotranspiration. Calculated by Penman Monteith
Equation.

mean_temp = climate(:,  10);
max_temp = climate(:, 6);
min_temp = climate(:,8);

% Net Radiation Rn = Rns - Rnl = (1-albedo)*Rs - Rnl.
% Calculations that need to be made in order to calculate net
radiation:

Tdew = min_temp;
% assumption for Tdew = min_temp - Ko and Ko is 0 degrees in humid and
subhumid climates (ASCE, 2005) as related in Fangmeier
es = 0.6108.*exp(17.27.*mean_temp./(mean_temp + 237.3));
% saturation vapour pressure in kPa
ea = 0.6108.*exp(17.27.*Tdew./(Tdew + 273.3));
% actual vapour pressure kPa
slope = 2504.*exp(17.27.*mean_temp./(mean_temp + 273.3))./(mean_temp +
237.3).^2;                % Slope of the saturation vapour pressure and
temperature curve
J = dm - 32 + floor((275.*m)/9) + 2*floor(3./(m +1)) + floor(m./100 -
rem(y,4)./4 + 0.975);       % day of the year
declination = 0.409*sin((2*pi/365).*J - 1.39) ;
% solar declination (radians)
ws = acos(-tan(pi/180*45.53)*tan(declination));
% sunset angle (radians)
dr = 1 + 0.033*cos(2*pi.*J/365);
% inverse square of relative distance earth to sun
Ra = 24/pi*4.92.*dr.*(ws.*sin(pi/180*45.53).*sin(declination) +
cos(pi/180*45.53).*cos(declination).*sin(ws));     % extraterrestrial
radiation in MJ m^-2 per day
Rso = (0.75 + (2*10^-5)*39).*Ra;
% calculated clear-sky radiation in MJ m^-2 per day
Rs = 0.19.*(max_temp - min_temp).^0.5.*Ra;
% estimation of solar radiation, as per Hargreaves and Samani (1982)

if Rs./Rso <= 1.0  % Rs/Rso must be less than or equal to 1.
```

```
Rnl = (4.903 *10^-9).*((max_temp + 273).^4 + (min_temp + 273).^4)/2 .*
(0.34 - 0.14.*(ea).^0.5).*(1.35.*Rs./Rso - 0.35);    % Net long-wave
radiation is determined from in MJ m^-2 per day

else
Rnl = (4.903 *10^-9).*((max_temp + 273).^4 + (min_temp + 273).^4)/2 .*
(0.34 - 0.14.*(ea).^0.5);
end

Rn = (1 - 0.23).*Rs - Rnl;                         % net radiation in MJ
m^-2 per day

% Calculation of psychrometric constant
P = 101.3.*(293 - 0.0065*39/293)^5.26;             % mean atmospheric
pressure in kPa
psy = 0.000665*P;                                  % psychrometric
constant

% The wind speed at 2 metres above the ground is estimated as 2 m/s as
per the suggestion of Fangmeier et al. (2006) due to a lack of data on
wind speeds
u2 = 2;

% Constants for short reference crop grass:
Cn = 900;
Cd = 0.34;

% Calculation of the reference evapotranspiration ETref using the short
reference crop of grass
ETref = (0.408.*slope.*Rn + psy.*(Cn./(mean_temp + 273)).*(es -
ea).*u2)./(slope + psy.*(1 + Cd*u2));



% Water needed: Irrigation. Crops commonly grown in the horticultural
center garden include onions, cabbage, broccoli, squash, pumpkin and
tomatoes.
% Crops commonly grown in the community garden include tomatoes,
peppers, lettuce, cucumbers, spinach, squash, radish, potato.

% Crop coefficients.
kconion = [0.7 1.05 1.05 0.75];
kccabbage = [0.7 1.05 1.05 0.95];
kcbroccoli = [0.7 1.05 1.05 0.95];
kcsquash = [0.5 0.95 0.95 0.75];
kcpumpkin = [0.5 1 1 0.8];
kctomatoes = [0.6 1.15 1.15 0.8];
kcpeppers = [0.6 1.05 1.05 0.90];
kclettuce = [0.7 1 1 0.95];
kccucumbers = [0.5 1 1 0.8];
kcspinach = [0.7 1 1 0.95];
kcradish = [0.7 0.9 0.9 0.85];
kcpotato = [0.5 1.15 1.15 0.75];

% Time of crop growth.
```

```
timeonion = [15 25 70 40];
timecabbage = [40 60 50 15];
timebroccoli = [35 35 40 15];
timesquash = [25 35 25 15];
timepumpkin = [20 30 20 30];
timetomatoes = [35 40 50 30];
timepeppers = [25 35 40 20];
timelettuce = [20 30 15 10];
timecucumbers = [20 30 40 15];
timespinach = [20 20 25 5];
timeradish = [5 10 15 5];
timepotato = [25 30 45 30];

% Websites from which crop growth times and crop coefficients were
drawn.
%
http://www.fao.org/docrep/x0490e/x0490e0b.htm#chapter%206%20%20%20etc%2
0%20%20single%20crop%20coefficient%20(kc)
% http://www.fao.org/docrep/x0490e/x0490e00.htm#Contents

%% Water balance in terms of irrigation for Community Garden

irrigation = zeros(size(precipitation),1);             % allocating
memory for irrigation matrix


for day = 1:size(precipitation)
% From the set date (day 1 of May (month == 5)) decided as the
beginning of
% growing season onward, until the time of growth of each crop is
finished
% the reference evapotranspiration calculated above will be used to
% calculate the estimated actual evapotranspiration for the given day
of
% the year. This will be stored in the irrigation matrix fro the
community
% garden and the irrigation1 matrix for the horticulture center student
run
% garden. Evapotranspiration will be different for the crop depending
on
% which stage of growth it is in (stored in the 'time' matrices as
% [1 2 3 4]) and corresponds to the kc value for that stage of growth
% (stored in the 'kc' matrices as [1 2 3 4]).

if climate(day, 4) == 1 && climate(day, 3) == 5

% In the community garden there are onions, cabbage, broccoli, squash,
% pumpkin and tomatoes.

% onion

a = day + timeonion(1);
irrigation(day:a) = ETref(day:a).*kconion(1)/6 + irrigation(day:a);
a1 = a + timeonion(2);
irrigation(a:a1) = ETref(a:a1).*kconion(2)/6 + irrigation(a:a1);
```

```
a2 = a1 + timeonion(3);
irrigation(a1:a2) = ETref(a1:a2).*kconion(3)/6 + irrigation(a1:a2);
a3 = a2 + timeonion(4);
irrigation(a2:a3) = ETref(a2:a3).*kconion(4)/6 + irrigation(a2:a3);

% cabbage

a = day + timecabbage(1);
irrigation(day:a) = ETref(day:a).*kccabbage(1)/6 + irrigation(day:a);
a1 = a + timecabbage(2);
irrigation(a:a1) = ETref(a:a1).*kccabbage(2)/6 + irrigation(a:a1);
a2 = a1 + timecabbage(3);
irrigation(a1:a2) = ETref(a1:a2).*kccabbage(3)/6 + irrigation(a1:a2);
a3 = a2 + timecabbage(4);
irrigation(a2:a3) = ETref(a2:a3).*kccabbage(4)/6 + irrigation(a2:a3);

% broccoli

a = day + timebroccoli(1);
irrigation(day:a) = ETref(day:a).*kcbroccoli(1)/6 + irrigation(day:a);
a1 = a + timebroccoli(2);
irrigation(a:a1) = ETref(a:a1).*kcbroccoli(2)/6 + irrigation(a:a1);
a2 = a1 + timebroccoli(3);
irrigation(a1:a2) = ETref(a1:a2).*kcbroccoli(3)/6+ irrigation(a1:a2);
a3 = a2 + timebroccoli(4);
irrigation(a2:a3) = ETref(a2:a3).*kcbroccoli(4)/6 + irrigation(a2:a3);

% squash

a = day + timesquash(1);
irrigation(day:a) = ETref(day:a).*kcsquash(1)/6 + irrigation(day:a);
a1 = a + timesquash(2);
irrigation(a:a1) = ETref(a:a1).*kcsquash(2)/6 + irrigation(a:a1);
a2 = a1 + timesquash(3);
irrigation(a1:a2) = ETref(a1:a2).*kcsquash(3)/6 + irrigation(a1:a2);
a3 = a2 + timesquash(4);
irrigation(a2:a3) = ETref(a2:a3).*kcsquash(4)/6 + irrigation(a2:a3);

% pumpkin

a = day + timepumpkin(1);
irrigation(day:a) = ETref(day:a).*kcpumpkin(1)/6 + irrigation(day:a);
a1 = a + timepumpkin(2);
irrigation(a:a1) = ETref(a:a1).*kcpumpkin(2)/6 + irrigation(a:a1);
a2 = a1 + timepumpkin(3);
irrigation(a1:a2) = ETref(a1:a2).*kcpumpkin(3)/6 + irrigation(a1:a2);
a3 = a2 + timepumpkin(4);
irrigation(a2:a3) = ETref(a2:a3).*kcpumpkin(4)/6 + irrigation(a2:a3);

% tomatoes

a = day + timetomatoes(1);
irrigation(day:a) = ETref(day:a).*kctomatoes(1)/6 + irrigation(day:a);
a1 = a + timetomatoes(2);
irrigation(a:a1) = ETref(a:a1).*kctomatoes(2)/6 + irrigation(a:a1);
```

```
a2 = a1 + timetomatoes(3);
irrigation(a1:a2) = ETref(a1:a2).*kctomatoes(3)/6 + irrigation(a1:a2);
a3 = a2 + timetomatoes(4);
irrigation(a2:a3) = ETref(a2:a3).*kctomatoes(4)/6 + irrigation(a2:a3);

end
end


%% Water balance in terms of irrigation for Horticulture Center

irrigation1 = zeros(size(precipitation),1);             % allocating
memory for irrigation matrix


for day = 1: size(precipitation)
% From the set date (day 1 of May (month == 5)) decided as the
beginning of
% growing season onward, until the time of growth of each crop is
finished
% the reference evapotranspiration calculated above will be used to
% calculate the estimated actual evapotranspiration for the given day
of
% the year. This will be stored in the irrigation matrix fro the
community
% garden and the irrigation1 matrix for the horticulture center student
run
% garden. Evapotranspiration will be different for the crop depending
on
% which stage of growth it is in (stored in the 'time' matrices as
% [1 2 3 4]) and corresponds to the kc value for that stage of growth
% (stored in the 'kc' matrices as [1 2 3 4]).

if climate(day, 4) == 1 && climate(day, 3) == 5

% In the student-run garden there are tomatoes, peppers, lettuce,
cucumbers,
% spinach, squash, radish, potato.

% tomatoes

a = day + timetomatoes(1);
irrigation1(day:a) = ETref(day:a).*kctomatoes(1)/8 +
irrigation1(day:a);
a1 = a + timetomatoes(2);
irrigation1(a:a1) = ETref(a:a1).*kctomatoes(2)/8 + irrigation1(a:a1);
a2 = a1 + timetomatoes(3);
irrigation1(a1:a2) = ETref(a1:a2).*kctomatoes(3)/8+ irrigation1(a1:a2);
a3 = a2 + timetomatoes(4);
irrigation1(a2:a3) = ETref(a2:a3).*kctomatoes(4)/8 +
irrigation1(a2:a3);

% peppers
```

```
a = day + timepeppers(1);
irrigation1(day:a) = ETref(day:a).*kcpeppers(1)/8 + irrigation1(day:a);
a1 = a + timepeppers(2);
irrigation1(a:a1) = ETref(a:a1).*kcpeppers(2)/8 + irrigation1(a:a1);
a2 = a1 + timepeppers(3);
irrigation1(a1:a2) = ETref(a1:a2).*kcpeppers(3)/8 + irrigation1(a1:a2);
a3 = a2 + timepeppers(4);
irrigation1(a2:a3) = ETref(a2:a3).*kcpeppers(4)/8 + irrigation1(a2:a3);

% lettuce

a = day + timelettuce(1);
irrigation1(day:a) = ETref(day:a).*kclettuce(1)/8 + irrigation1(day:a);
a1 = a + timelettuce(2);
irrigation1(a:a1) = ETref(a:a1).*kclettuce(2)/8 + irrigation1(a:a1);
a2 = a1 + timelettuce(3);
irrigation1(a1:a2) = ETref(a1:a2).*kclettuce(3)/8 + irrigation1(a1:a2);
a3 = a2 + timelettuce(4);
irrigation1(a2:a3) = ETref(a2:a3).*kclettuce(4)/8 + irrigation1(a2:a3);

% cucumbers

a = day + timecucumbers(1);
irrigation1(day:a) = ETref(day:a).*kccucumbers(1)/8 +
irrigation1(day:a);
a1 = a + timecucumbers(2);
irrigation1(a:a1) = ETref(a:a1).*kccucumbers(2)/8 + irrigation1(a:a1);
a2 = a1 + timecucumbers(3);
irrigation1(a1:a2) = ETref(a1:a2).*kccucumbers(3)/8+
irrigation1(a1:a2);
a3 = a2 + timecucumbers(4);
irrigation1(a2:a3) = ETref(a2:a3).*kccucumbers(4)/8 +
irrigation1(a2:a3);

% spinach

a = day + timespinach(1);
irrigation1(day:a) = ETref(day:a).*kcspinach(1)/8 + irrigation1(day:a);
a1 = a + timespinach(2);
irrigation1(a:a1) = ETref(a:a1).*kcspinach(2)/8 + irrigation1(a:a1);
a2 = a1 + timespinach(3);
irrigation1(a1:a2) = ETref(a1:a2).*kcspinach(3)/8+ irrigation1(a1:a2);
a3 = a2 + timespinach(4);
irrigation1(a2:a3) = ETref(a2:a3).*kcspinach(4)/8 + irrigation1(a2:a3);

% squash

a = day + timesquash(1);
irrigation1(day:a) = ETref(day:a).*kcsquash(1)/8 + irrigation1(day:a);
a1 = a + timesquash(2);
irrigation1(a:a1) = ETref(a:a1).*kcsquash(2)/8 + irrigation1(a:a1);
a2 = a1 + timesquash(3);
irrigation1(a1:a2) = ETref(a1:a2).*kcsquash(3)/8+ irrigation1(a1:a2);
a3 = a2 + timesquash(4);
irrigation1(a2:a3) = ETref(a2:a3).*kcsquash(4)/8 + irrigation1(a2:a3);
```

```
% radish

a = day + timeradish(1);
irrigation1(day:a) = ETref(day:a).*kcradish(1)/8 + irrigation1(day:a);
a1 = a + timeradish(2);
irrigation1(a:a1) = ETref(a:a1).*kcradish(2)/8 + irrigation1(a:a1);
a2 = a1 + timeradish(3);
irrigation1(a1:a2) = ETref(a1:a2).*kcradish(3)/8+ irrigation1(a1:a2);
a3 = a2 + timeradish(4);
irrigation1(a2:a3) = ETref(a2:a3).*kcradish(4)/8 + irrigation1(a2:a3);

% potato

a = day + timepotato(1);
irrigation1(day:a) = ETref(day:a).*kcpotato(1)/8 + irrigation1(day:a);
a1 = a + timepotato(2);
irrigation1(a:a1) = ETref(a:a1).*kcpotato(2)/8 + irrigation1(a:a1);
a2 = a1 + timepotato(3);
irrigation1(a1:a2) = ETref(a1:a2).*kcpotato(3)/8 + irrigation1(a1:a2);
a3 = a2 + timepotato(4);
irrigation1(a2:a3) = ETref(a2:a3).*kcpotato(4)/8 + irrigation1(a2:a3);

end

end


%% Plotting water balance
% The climate.csv file has some dates where the data was not properly
% recorded, denoted by NaN. Matlab cannot plot these so they are
counted as
% zeros, as though there was no precipitation on that day. The actual
% estimated irrigation volume required is the water needs of the
gardens,
% irrigation and irrigation1, minus the water provided by precipitation
% over the area of the garden (Acg and Ahc), modified by the safety
factor
% to take into account the water losses.

precipitation(isnan(precipitation)) = 0;
irrigation = (irrigation - precipitation)*Acg/1000*sf;
irrigation1 = (irrigation1 - precipitation)*Ahc/1000*sf;

% irrigation cannot be less than 0, and if it is NaN it is also
considered as zero for that day.
irrigation(irrigation<0) = 0;
irrigation1(irrigation1<0) = 0;
irrigation(isnan(irrigation)) = 0;
irrigation1(isnan(irrigation1)) = 0;

precipitation = precipitation*A/1000 - 1*A/1000;  % The second term is
added to account for first flush, which is 1 mm of rain per rainfall
event, taken as daily here.
precipitation(precipitation<0) = 0;
```

```
% Community garden

figure(1)

plot(date, irrigation, '--r')
hold on
plot(date, precipitation, '.-b')

stored = precipitation - irrigation;
stored(stored<0) = 0;       % cannot have negative storage

plot(date, stored, 'g');
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Community Garden')
hold off

% Student-run garden

figure(2)

plot(date, irrigation1, '--r')
hold on
plot(date, precipitation, '.-b')

stored = precipitation - irrigation1;
stored(stored<0) = 0;       % cannot have negative storage

plot(date, stored, 'g');

ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Student Run Garden')
hold off

% Overall

figure(3)

irrigation = irrigation + irrigation1;

plot(date, irrigation, '--r')
hold on
plot(date, precipitation, '-.b')

stored = precipitation - irrigation;
stored(stored<0) = 0;       % cannot have negative storage

plot(date, stored, 'g');
```

```
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Overall')
hold off

figure(4)
% Stored
stored = precipitation - irrigation;
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Amount of Water in Storage Tank')
plot(date, stored)
hold off

figure(5)
% Deficit
deficit = zeros(size(precipitation),1);
countdeficit = zeros(size(precipitation),1);

%
for nn = 2:size(precipitation)
    stored(nn) = stored(nn) + stored(nn-1);
    if stored(nn)<tankmin
        countdeficit(nn) = 1;
        if stored(nn)<tankmin
        deficit(nn) = stored(nn) - tankmin;
        end
        stored(nn) = tankmin;
    end
    if stored(nn) > tank
        stored(nn) = tank;
    end
end

%deficit = deficit - tankmin;
[irrigation precipitation stored];
subplot(4,1,1)
plot(date, stored)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Amount of water in storage tank')
subplot(4,1,2)
plot(date, precipitation)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Daily Precipitation')
subplot(4,1,3)
plot(date, irrigation)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Daily Irrigation')
subplot(4,1,4)
plot(date, deficit, '.r')
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
```

```
title('Deficit (amount of water needed but not provided by stored
rainwater)')


sumstored = sum(stored)
maxstored = max(stored)
sumirrigation = sum(irrigation)
sumprecipitation = sum(precipitation)
sumcountdeficit = sum(countdeficit)
sumdeficit = sum(deficit)
deficitaverage = sumdeficit/sumcountdeficit
maxdeficit = min(deficit)
maxirrigation = max(irrigation)
```

MATLAB Code for Fountain Water Balance

```
function Design_Project_Fountain

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Senior Design Project Model Group 5
% Rainwater Harvesting and Irrigation System
% Water harvested from Zen Fountain
% Water stored under fountain
% Water used to irrigate Meditation Garden
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% In order to perform an optimization the user is asked to input a
radius of
% the fountain that they would like to catch rain on in order to
harvest rainwater, the
% size of the tank into which that rainwater will be stored and the
minimum
% level of water volume that will be maintained in the tank at all
times.
% Also, since some water losses are unaccounted for in the water
balance a
% safety factor, chosen by the user, is used to modify irrigation
% requirement.

r = input('Radius of Fountain: ');
tank = input('Volume of tank m3: ');
tankmin = input('Minimum amount of water in tank in m3: ');
sf = input('safety factor on irrigation: ');
% on irrigation scheduling and safety factor
% http://www.netafimusa.com/files/literature/agriculture/other-
literature/crop-applications/Alfalfa-Manual.pdf
% http://www.caes.uga.edu/Publications/displayHTML.cfm?pk_id=6116
%
http://www.irnase.csic.es/users/jefer/Articulos%20en%20papel%20JE/FISIO
LOGIA%20RELACIONADA%20CON%20EL%20RIEGO/naor2006/otros/naor2006%20ocr%20
opt.pdf

%price of concrete
http://sarjeants.com/PDF/Concrete%202011%20List%20Price.pdf
%price of tanks http://www.tank-depot.com
```

```
A = pi*r^2;

%% Water balance in terms of irrigation for Meditation Garden

climate = csvread('climate.csv', 297, 0, [297, 0, 15448, 22]);  % Reads
pre-prepared csv file with climate and precipitation data
dm = climate(:,4);    % day of month
m = climate(:,3);     % month of year
y = climate(:, 2);    % year
date = climate(:,1);

% Water in: Precipitation

precipitation = climate(:, 20);

%% Water balance in terms of irrigation for Meditation Garden

irrigation = zeros(size(precipitation),1);             % allocating
memory for irrigation matrix

for day = 1:size(precipitation)
% From the set date (day 1 of May (month == 5)) decided as the
beginning of
% growing season onward, until the time of growth of each crop is
finished
% the reference evapotranspiration calculated above will be used to
% calculate the estimated actual evapotranspiration for the given day
of
% the year. This will be stored in the irrigation matrix fro the herbs
in raised
% beds and the irrigation1 matrix for the shrubs in the meditation
garden.

if climate(day, 4) == 1 && climate(day, 3) == 5

% In the meditation garden there are mint-like herbs and berry bushes.

% herbs

a = day + 120;      % Growing season is 120 days
irrigation(day:a) = 12/1000*9 + irrigation(day:a);  % herbs are watered
daily with 9L per raised bed

end
end

% berry bushes

irrigation1 = zeros(size(precipitation),1);             % allocating
memory for irrigation1 matrix

% From the set date (day 1 of May (month == 5)) decided as the
beginning of
```

```
% growing season onward, until the time of growth of each crop is
finished
% the reference evapotranspiration calculated above will be used to
% calculate the estimated actual evapotranspiration for the given day
of
% the year. This will be stored in the irrigation matrix fro the
community
% garden and the irrigation1 matrix for the horticulture center student
run
% garden.

for day = 1:size(precipitation)

if climate(day, 4) == 1 && climate(day, 3) == 5

a = day + 120;
irrigation1(day:5:a) = 2/1000*14 + irrigation1(day:5:a);    % shrubs
are watered with 2L every 5 days

end
end

%% Plotting water balance

% The climate.csv file has some dates where the data was not properly
% recorded, denoted by NaN. Matlab cannot plot these so they are
counted as
% zeros, as though there was no precipitation on that day. The actual
% estimated irrigation volume required is the water needs of the
gardens,
% irrigation and irrigation1, minus the water provided by precipitation
% over the area of the garden (Acg and Ahc), modified by the safety
factor
% to take into account the water losses.

precipitation(isnan(precipitation)) = 0;

irrigation = irrigation*sf;
irrigation1 = irrigation1*sf;

precipitation = precipitation*A/1000;

% Herbs

figure(1)

plot(date, irrigation, '--r')
hold on
plot(date, precipitation, '.-b')
hold on
stored = precipitation - irrigation;
stored(stored<0) = 0;

plot(date, stored, 'g');
```

```
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Herbs')
hold off

% Berry Bushes

figure(2)

plot(date, irrigation1, '--r')
hold on
plot(date, precipitation, '.-b')
hold on
stored = precipitation - irrigation1;
stored(stored<0) = 0;

plot(date, stored, 'g');

ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Berry Bush')
hold off

% Overall

figure(3)

irrigation = irrigation + irrigation1;

plot(date, irrigation, '--r')
hold on
plot(date, precipitation, '-.b')
hold on
stored = precipitation - irrigation;
stored(stored<0) = 0;

plot(date, stored, 'g');

ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Comparison of Irrigation, Precipitation and Stored Water Amounts
on a Daily Basis Overall')
hold off

figure(4)

stored = precipitation - irrigation;
deficit = zeros(size(precipitation),1);
countdeficit = zeros(size(precipitation),1);

for nn = 2:size(precipitation)
    stored(nn) = stored(nn) + stored(nn-1);
```

```
    if stored(nn)<tankmin
        countdeficit(nn) = 1;
        if stored(nn)<0
        deficit(nn) = stored(nn);
        end
        stored(nn) = tankmin;
    end
    if stored(nn) > tank
        stored(nn) = tank;
    end
end


subplot(4,1,1)
plot(date, stored)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Amount of water in storage tank')
subplot(4,1,2)
plot(date, precipitation)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Daily Precipitation')
subplot(4,1,3)
plot(date, irrigation)
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Daily Irrigation')
subplot(4,1,4)
plot(date, deficit, '.r')
ylabel('water (m^3)')
xlabel('date (yyyymmdd)')
title('Deficit (amount of water needed but not provided by stored
rainwater)')

sumstored = sum(stored)
maxstored = max(stored)
sumirrigation = sum(irrigation)
sumprecipitation = sum(precipitation)
sumcountdeficit = sum(countdeficit)
maxdeficit = min(deficit)
```

MATLAB Code for Fountain Foundation Depth

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Senior Design Project Model Group 5
% Rainwater Harvesting and Irrigation System
% Fountain Foundation Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The depth of foundation can be determined by the weight balance of
the structure against the foundation and the soil. We will need the
optimum radius of the catchment determined in the Water Balance Matlab
Model for the Fountain.
```

```
% 1. Weight of Structure: Bowl and Wall

% First we need to calculate the volume of both the Bowl part and the
Wall
% part

% Volume of Bowl
% The bowl is essentially one truncated cone inside another.
% Vcone = (1/3)*pi*r^2*h

rbi = 1.5;  % radius of catchment area (m)
hi = 0.6;   % height of inside cone (m)
yi = 0.1;   % height of truncated inside cone (m)
theta_i = atan(hi/rbi);   % angle for similar triangles (inside cone
and truncated cone)
xi = yi / (tan(theta_i)); % radius of truncated inside cone (m)

rbo = rbi + 0.1;  % radius of outside cone (m)
ho = 0.7;   % height of outside cone (m)
yo = 0.1;   % height of truncated outside cone (m)
theta_o = atan(ho/rbo);   % angle for similar triangles (outside cone
and truncated cone)
xo = yo / (tan(theta_o)); % radius of truncated outside cone (m)

Vbowl = (1/3)*(pi)*((rbo^2*ho - xo^2*yo) - (rbi^2*hi - xi^2*yi));   %
Volume of Bowl (cubic m)

% Volume of Wall
% The wall is essentially two open ended cylinders, one inside the
other.
% Vcylinder = pi*r^2*h

rwi = rbo;  % radius of inside cylidner
t = 0.3;    % thickness of wall
rwo = rwi + t;    % radius of outside cylinder
hw = 0.6;  % height of wall
Vwall = (pi)*(hw)*(rwo^2 - rwi^2);    % Volume of the wall (cubic m)

% Now, for the weight of the structure:
% Weight = Volume times material density times earth's gravitational
% acceleration (9.8m/s^2)

% Densities of potential materials (kg/cubic m)
p_concrete = 2400;  % density of normal concrete as per hypertextbook,
for bowl or wall
p_lconcrete = 1750; % denisty of lightweight concrete as per
hypertextbook, for wall
p_packedmud = 1906; % density of packed mud as per simetric, for wall
p_packedearth = 1522; % density of packed earth as per simetric, for
wall

% Change these densities to kN/cubic m by multiplying by earth's
% gravitational acceleration 9.8m/s^2 and dividing by 1000
p_con = (p_concrete*9.8)/1000
```

```
p_lcon = (p_lconcrete*9.8)/1000;
p_pm = (p_packedmud*9.8)/1000;
p_pe = (p_packedearth*9.8)/1000;

p = [p_con; p_lcon; p_pm,; p_pe];  % makes a vector for the densities

% http://hypertextbook.com/facts/1999/KatrinaJones.shtml
% http://www.simetric.co.uk/si_materials.htm

% Weight of structure (kN)
Ws = (Vbowl*p_con + Vwall.*p)

% 2. Weight of foundation
% The foundation is a circular slab of depth df. This is the unknown we
% will be solving for in optimization.
% Wf = p_con*pi*rwo^2*df

% 3. Weight/force of soil
% Use lowest shear strength of soil
% c = 25;        % Shear strength of soft clay soil (kPa)
% Nc = 5.14;     % factor for ultimate bearing capacity (very small
friction angle to design for worst conditions)
qo = 71.77;      % maximum bearing capacity of soil (kN/square m)
sf = 3;          % safety factor
q = qo/sf;       % factored design bearing capacity of soil
B = 2*rwo;
% Depth of foundation:
df = (q-(Ws/(pi*rwo^2)))/p_con
```

MATLAB Code for Pipe Analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Senior Design Project Model Group 5
% Rainwater Harvesting and Irrigation System
%Piping Analysis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%This program will calculate the head loss in a variety of
different pipe
%sizes (all are schedule 40). The output values can then be
used to make
%the optimal choice in pipe size for our design. The
program performs an
%analysis for both the pipeline from ecorez to the storage
tank, as well as
%the pipeline from the storage tank to the community
garden. The program
%also performs calculations to determine the water pressure
at each outlet
%and the dead load of the piping system based on each pipe
```

```
size.

clear
clc

%Definition of terms and values:

rho=1000;          %density of water [kg/m^3]
g=9.8;             %acceleration due to gravity [m/s^2]
mu=0.001308;       %kinematic viscosity of water [Pa*s]
Aroof=334          %area of roof to be drained [m^2]
ppt=38;            %average ppt event [mm] (design for worst
case)

Q=Aroof*(ppt/1000)/86400      %Flow rate [m^3/s] equals
drained roof area,
%                             multiplied by precipitation,
divided by
%                             86400 seconds in 24 hrs

D= [0.5                       %Matrix for nominal pipe
diameters (values in inches)
0.75
1
1.25
1.5
2
2.5
3
4
5
6
8
10
12
14
16];


Dactual= 0.0254*[0.622        %Actual inner diameter for
considered nominal cases, converted to meters
0.824
1.049
1.38
1.61
2.067
2.469
```

```
3.068
4.026
5.047
6.065
7.981
10.02
11.938
13.124
15];


t=  0.0254*[0.109         %Pipe thickness, converted to
meters
0.113
0.133
0.14
0.145
0.154
0.203
0.216
0.237
0.258
0.28
0.322
0.365
0.406
0.438
0.5];

Qcom=7.5*10^-5;                        %flow rate in pipe #2
based on literature values for average flow rate of hose
[m^3/s]
Apipe=pi.*Dactual.^2./4;               %cross sectional area of
pipe
u=Q./Apipe;                            %flow speed in pipe #1
ucom=Qcom./Apipe;                       %flow speed in pipe #2
Re=rho.*u.*Dactual./mu                %Reynolds number for pipe
#1
Recom=rho.*ucom.*Dactual./mu            %Reynolds number for
pipe #2
f=64./Re;                              %friction factor (for
laminar flow)
fcom=64./Recom;                         %friction factor for
pipe #2
L1=113.97;                             %pipe length from roof
to storage tank [m]
L2=141;                                %pipe length from tank
```

```
to community garden [m]
hl1=8.*f.*L1./(g*pi.*Dactual.^5).*(Q^2)
%Major head loss, pipe 1 (from ecorez to tank)
hl2=8.*f.*L2./(g*pi.*Dactual.^5).*(Qcom.^2)
%Major head loss, pipe 2 (from tank to ecorez)
k=1.1;
%constant for 90 degree bends in pipe system
hminor1=7*k.*u.^2./2*g ;
%minor head loss, assuming 7 bends in first configuration
hminor2=2*k.*ucom.^2./2*g;
%minor head loss, assuming 2 bends in second configuration
totalloss1=hl1+hminor1;
totalloss2=hl2+hminor2;                       %sum of major
and minor losses
Loss_V_Size= [totalloss1 totalloss2 D]        %matrix
displaying columns in order: head loss 1 (m), head loss 2
(m), and pipe diameter

%We must make sure that the static head is able to
compensate for head
%loss, and still get the water into the tank.



%Determining Outlet Pressure
outlet1Kpa=(1-totalloss1).*9.80665        %Outlet pressure
equals static head minus losses (m); and then converted to
kPa
outlet2Kpa=(2-totalloss2).*9.80665        %This is the more
important of the two outlet pressure calculations. It is
the
%                                         pressure
supplied at the
%                                         community
garden. We can
%                                         subtract this
value from the
%                                         needed line
pressure for
%                                         delivery, and
optimize our choice of pump size from this value.
%
%Pipe Load
Vpipe1=t*pi.*Dactual.*L1;
deadpipe1=(0.92/(1000*1*10^-6).*Vpipe1.*g);
%dead weight of pipe [N]
Vpipe2=t*pi.*Dactual.*L2;
```

```
deadpipe2=(0.92/(1000*1*10^-6).*Vpipe2.*g);

deadwater1=(pi.*Dactual.^2./4).*L1*rho*g ;
%load of water under full flow conditions [N]
deadwater2=(pi.*Dactual.^2./4).*L2*rho*g;

load1=deadpipe1+deadwater1              %load of pipe +
water = total load on soil

load2=deadpipe2+deadwater2               %same calculation
performed for second line
```