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Stormwater Mitigation Analysis Using Roof Spray Technology

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Abstract: Stormwater mitigation has become a serious concern particularly in regions where the runoff can be costly either through runoff damage such as erosion and/or the concerns of potential hazards to human and animal life. A second and potentially more serious concern involves regions where this runoff is collected in the standard sewage treatment system resulting in the need to handle an infrequent but large flow of water that most of these systems are not equipped to handle. The consequences of these events often result in the dumping of these overflows directly into local streams including the untreated sewage, increasing the potential of health hazards.

The stormwater runoff problem has become a visible issue in many parts of the globe and particularly in the Northeastern portion of the United States. In many of these regions stormwater and raw sewage, use the same above and belowground channels. The result of this has seen hundreds of thousands of gallons of waste being dumped directly into the rivers and streams of the area, during and shortly after these heavy storms. Some of this is due to the rate and volume of the rainfall but most is due in actuality to the urbanization of the land, which covers the natural landscape with buildings and pavement. Thus, the precipitation from these storms can no longer be handled through the normal absorption of the natural landscape, which historically provided water retention and evaporation to take place in a natural setting. This paper takes a look at the analysis behind a proposed stormwater capture, filtration and reuse system using a new application of an old roof spray technology, originally used for home and office cooling. This paper focuses specifically on the region centered in Pittsburgh in the Allegheny County of Pennsylvania, USA. With record amounts of rainfall from numerous storms over the past few years, the Allegheny County Sanitation Department has often been unable to meet the runoff demands it has been tasked to handle. This system would reduce the excess water runoff created during storms that the sanitation systems cannot adequately handle. The concept for this runoff solution is provided with an analysis of the actual issues underlying these runoff problems. The results indicate that a roof cooling system that uses collected rainwater runoff can be cost effective within a ten-year time period, plus decrease the temperatures within the working environment within the buildings.

Keywords: Stormwater, Roof Spray Technology, Runoff, Wastewater, natural water cycle, evaporation

I. INTRODUCTION

In the Northeastern region of the United States, there is a growing problem in the collection and treatment of stormwater runoff. In recent years, the region has experienced record amounts of rainfall with the projections pointing to this trend continuing. The Sanitation Department in most of these areas is responsible for the collection of this stormwater, meaning that the runoff is combined with, and treated as wastewater. Most of the current water treatment systems cannot handle these increased demands during large storms and as a result there are hundreds of thousands of gallons of sewage waste dumped into the surrounding rivers and streams during and shortly after these large storms.

The US Environmental Protection Agency (EPA) is levying fines and promulgating additional regulations for these violations, so a long-term solution is needed. The proposed method of addressing some of these needs involves mimicking the natural water cycle that the region originally had prior to commercialization and urbanization. Using a more natural approach would provide for a way to collect and redistribute the water back into the environment as if the water was absorbed into the ground and then evaporated as opposed to flowing directly into the sanitation system. This study looked at a local urbanized region, Pittsburgh Pennsylvania, as a case study considering the locale and the local infrastructure, and the current and future requirements for storm water runoff mitigation.

II. THE ENVIRONMENTAL SITUATION

When land is altered from its original, natural state it upsets the way nature originally managed local and downwind atmospheric conditions including storms and rainfall occurrences. Parking lots, buildings, roads, cities, and other current infrastructure are vastly inferior in their capability to deal with excess rainwater runoff than is open ground. This inability to absorb rainfall in urbanized regions results in massive amounts of runoff entering the local waterways including in some cases the primary sewage collection system. This runoff, in addition to contributing heavily to flooding, erosion, and the destruction of the local ecosystems, can easily overload the wastewater treatment facility that supports the population centers they support.

For Allegheny County, Pennsylvania a rainfall episode as small as one tenth of an inch can be too much to treat with the current sanitation system - resulting in the dumping of whatever water cannot be processed (which includes wastewater and sewage as well as stormwater runoff) into the downstream river or body of water nearby. This pollution of water sources is damaging to the aquatic environment and can be harmful to downstream communities. This series of problems is currently being addressed by the policies of the Environmental Protection Agency in the U.S.

The EPA is also continuing to promulgate new regulations about on-site water retention for landowners. Increasing the requirements and providing increased fines and penalties for failure to enact and uphold these requirements has caused many decision-makers in these regions to rethink the problems and to seek more proactive and less expensive solutions. Their effort and those of other environment groups, however, are more directed to treatments for the symptoms, rather than proposing solutions to the problem. Our society's social and economic developments have detracted from the earth's natural ability to collect and recycle precipitation back into the atmosphere, which needs to be taken into consideration if a solution is to have a long-term and responsive outcome for everyone involved and the environment we live in.

Another aspect of this problem is that there is a lack of incentive for investment in technologies that might mitigate these types of problems. Additionally, property owners have little motivation to install technology that would reduce the rain water runoff because they are not aware of, or have seen demonstrated, a potential financial benefit to offset their cost, plus environmental benefits usually do not have enough influence on most people’s concerns or actions. Clearly, urbanization will continue thus increasing land development and the resulting increase in impermeable, non-natural surface area. Thus, the need for new technology to help mitigate some of these problems may soon be of increased interest partially due to the laws that are currently being promulgated. Effectively, while penalties do not always cause the best actions, finding solutions that either save or make money are always considered as positive.

III. REGION UNDER CONSIDERATION

In the Northeastern region of the United States, there is a growing problem in the collection and treatment of stormwater runoff. In recent years the region has experienced record amounts of rainfall with the projections pointing to this trend continuing. The Sanitation Department in most of these areas is responsible for the collection of this stormwater, meaning that the runoff is combined with, and treated as wastewater. Most of the current water treatment systems cannot handle these increased demands during large storms and as a result there are hundreds of thousands of gallons of sewage waste dumped into the surrounding rivers and streams during and shortly after these large storms.

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The focus of this project was to evaluate the Monroeville region of Allegheny County as a demonstration site for potential application of the techniques covered in this research study. Monroeville is located about 15 miles east of Pittsburgh. It is a suburban region featuring an intermingled mixture of residential and commercial developments. Monroeville’s population is currently documented at 28,386 people, with Allegheny County, as a whole, containing roughly 1,231,225 residents, making it the second most populous county in Pennsylvania, following Philadelphia [1] [2].

Allegheny County has a total area of 745 square miles; of which 730 square miles is land and 14 square miles is water [3]. The county gets a total of about 48 inches of rain per year. The region’s summer season experiences about 130 precipitation days per year coupled with an average high temperature of 85°F [4] [1]. The average low temperature during the summer months is 62°F [5] [4] [1]. The Allegheny River drains an area of roughly 11,500 mi^2in southwestern NY and western PA. Average discharge is 19.680 ft^3/s and Allegheny joins the Monongahela River to form the Ohio River.

The primary wastewater treatment facility for the Greater Pittsburgh area is the Allegheny County Sanitary Authority (ALCOSAN). This facility services 83 communities, including the City of Pittsburgh, and the subject test location in Monroeville. This 59-acre treatment plant is one of the largest wastewater treatment facilities in the Ohio River valley, processing nearly 250 million gallons of wastewater daily, and servicing a population of 900,000 [6]. Created under the Pennsylvania Municipal Authorities Act, this nonprofit agency is now funded solely by user fees with capital funds raised through the sale of sewer revenue bonds.

ALCOSAN recently completed a $400 million capital improvement program focused on odor control, treatment capacity, solids handling, and wet weather planning. Their most recent efforts are supporting one of the largest public works projects totaling $1 billion in engineering and construction projects with the intent of addressing sewer overflows [6].

IV. SITE SPECIFICATIONS AND DESCRIPTION

This evaluation will focus on the local Monroeville area, including Monroeville, McKeesport, Pittsburgh International Airport, and the Pittsburgh area, as well as focusing on the larger climate divisions to which the local area belongs. These include Pennsylvania's Southwest Plateau and the United States' Northeast climate region. The 2.102-acre test site located in Monroeville, PA, houses a flooring company and features a large warehouse, storage and fabrication area with an attached business office. This commercial property features a combination of natural vegetation, tree, and bush foliage as well as an asphalt parking lot roughly half an acre in surface area. Images of the site and diagrams of the warehouse can be seen in Figure 1.

Currently, infrastructure and asphalt paving covers roughly 40% of the total lot leaving roughly 60% natural. The 12,000sqft steel warehouse consists of a steel, corrugated roof, 150 feet long and 80 feet wide, and a height of 23 ft. with a 1/12 slope for the roof-pitch. A layer of insulation within the steel walls was assumed to be 8 in. vinyl-wrapped fiberglass. The attached 1,584sqft office is Brick and Mortar, and also has a steel roof. Flooring throughout the entire structure contains radiant heat. The stormwater systems currently in use include: 2 catch basins that feed off to the right behind the main warehouse into an off-site catch pond, 15" storm drains that connect in to the main regional sewage collection system, and a vegetative swell.

Figure 1. Aerial View of Warehouse [7]

V. RAINFALL RUNOFF

An effective impact of the roof spray system is to collect water from all surfaces that are unable to retain or inhibit the saturation of water into open earth. By categorizing a test site into permeable and impermeable surfaces, a strategy can be developed to address the needs of the varying surface types of the test site. For this specific application, three surface types have been identified that will be addressed, separately.

The three types of collection surfaces are the roof of the warehouse and office; the ground pavement of the roadways, parking lot, and sidewalks; and the undeveloped ground which accounts for the remaining area of the site. Collection of rainwater from the roof and pavement requires modification of the current roof gutter and downspout system, and the implementation of a pavement runoff collection system. Currently, water is channeled from these impenetrable surfaces to a detention basin or to the sewage system.

The amount of stormwater runoff for a given area should be determined for a 1 year and 25-year recurrence storm. For this region the 1-year storm produces 2 inches of rain over 24 hours and the 25-year storm produces 4 inches over 24 hours. The rate of rainfall is shown in Table 1 below.

Table 1. 1-and 25-year storm values.[8]

Storm type	Amount of rainfall (in)	Duration (hr)	Rate of rainfall (in/hr)
1-year	2	24	0.0833
25-year	4	24	0.1667

For this site the area of collection for the roof and the pavement, test site information and estimates were used to find the area of the individual elements and the total impenetrable area as shown in Table 2.

Table 2. Surface analysis of the test site. [8]

Location	Surface area (ft^2)
Total Lot	91563
Total Infrastructure Area	36625
Warehouse	12000
Office	1584
Parking Lot	23041
Natural Ground	54938

All of the infrastructure such as roads, parking lots, or buildings are almost completely impenetrable to rainfall. As a result, all rainfall is directly transferred to runoff [9]. Calculating the volume of rainfall for collection will be done using the area of the building or pavement times the amount of rainfall.

$$\forall_{Rainfall} = SA * h\_Rainfall \qquad \text{(Eq. 1)}$$

Considering the area of each collecting surface and the expected rainfall, the total collectable water runoff for a single rainfall can be calculated. The volume of the water runoff for each surface type is the surface area multiplied by the total rainfall. The rate volume may then be found by dividing the volume by the duration of the storm. Note that both the 1-year and 25-year storms both deliver their rainfalls in the course of 24 hours.

$$Q_{Runoff} = \forall / t \qquad \text{(Eq. 2)}$$

To express the amount of rainfall in terms for storage, the values were changed from feet cubed to gallons. Table 3 shows the maximum collectable runoff for the test site for expected heavy and severe rainfall. While these collectable volumes of water are possible, the actual collected amount will depend on the size of the storage container selected. These considerations will be expounded upon in the storage section.

Table 3. Collection amounts by area.

Collection Potential	1 Year Storm		25 Year Storm	
	Amount (Gal)	Rate (Gal/hr)	Amount (Gal)	Rate (Gal/hr)
Roof Area	16936	707	33873	1412
Pavement Area	28757	1197	57455	2394
Total Area	45663	1904	91328	3806

VI. COLLECTION SYSTEM DESIGN

The existing runoff infrastructure of the test site is equipped with a gutter system along the entire length of the warehouse as well as each edge of the office. Seven downspouts cover each corner of the warehouse and two corners of the office. The appropriate number of downspouts corresponds to a 100 to 1 ratio of square footage of the roof to square inch of the downspout [10]. Since the facility in whole has a 13,500 square foot area before accounting for the roof pitch, the area of downspout drainage must cover 135 in.^{2}[8].

Concerning runoff from the pavement, the paved lot has been designed previously to direct water towards a grassy hillside towards the center of the site. Currently, an underground channel directs water around the backside of the warehouse to the sewage system. 9 illustrates the location of the current downspouts denoted by red dots and the pavement water flow by blue arrows:

Figure 2. Downspout locations.[8]

Two collection methods are proposed to capture all runoff from the site's intended surfaces: gutter collection system, and a flow-through system.

Rain Collection From The Building Roof

First, the gutter collection systems accounts for only half of the roof's surface area. This is because the current system directs rain runoff to each corner of the roof; inevitably half the water from the roof will travel towards the storage unit and the other half in the opposite direction if the water is to be stored in a single location. While it would be ideal for all water that contacts the roof to flow to a single direction, a complete renovation of the gutter system, complete with relocated downspouts, must take place. With this in mind, several paths must be taken to collect runoff in a single location.

The roof design suggests a two route method to directing all runoff to a storage location. One path directs half the water of the warehouse to a storage tank by way of the downspouts being directly connected to the storage unit. The proper downspout size to account for half of the warehouse roof's surface area, 6000 ft^2, is a total are of 60 in^2. Two downspouts of 6in. x 5in cross-section were chosen to provide for this area. In the case of an underground storage unit, the two spouts will connect to a channeling pipe below the surface of the earth and will connect directly to the unit. This design is illustrated in 10 below:

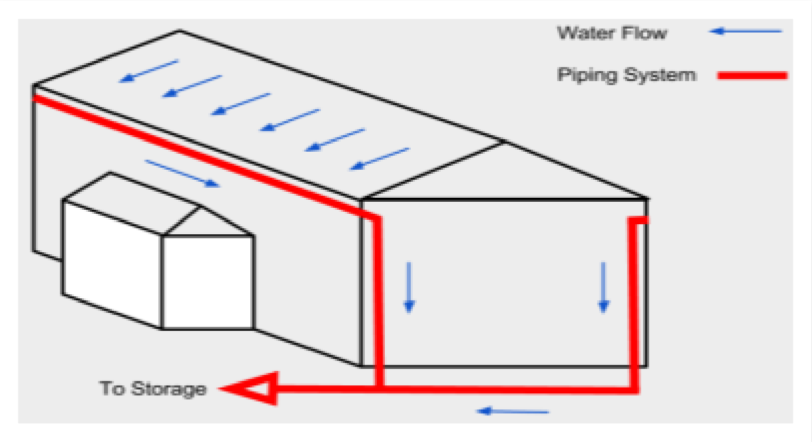

Figure 3. Roof Piping System.

This piping system will allow for all rainfall on half of the roof's area to be diverted directly to a storage unit for collection. From storage, all collected water may be drawn for the evaporative function of the proposed evaporative system.

Collection from the Parking Lot

The proposed system to collect pavement runoff is a flow-through system located above the current channel. According to the site map in 13 [8], the length of the pavement collection region is roughly 60 feet.

Figure 4. Location and Direction of the Pavement Drain.[8]

Collection from Undeveloped Land

The natural absorption ability of the ground is determined by the quality of the soil and the soil surface coverage which includes surface depressions that collect water, water taken up by vegetation, evaporation, and infiltration. Infiltration is the specific variable that is concerned with the 'Soil Conservation Service Runoff Curve Number (CN).' Other contributing factors include ground treatment, hydrologic condition, the antecedent runoff condition, and use of local drainage systems, and water retaining outlets [9].

Figure 4 shows the direct runoff from a rainfall as a result of varying levels of permeable surfaces. The CN number ranges from 0-100. Depending on the surface type, permeable (0) to impermeable (100), a CN value may be attributed to that surface type. Very absorbent pasturelands ideal for taking in water have a value of about 35 while roads or sidewalks do not absorb water leading to a value upwards of 98. This method proves useful for determining many absorption types by variable rainfall[9].This analytical approach is supported by the following equations [9]:

$h_{Runoff} = \frac{[P - 0.2S]^2}{[P + 0.8S]}$	(Eq. 3)
$S = {}^{1000}/_{CN - 10}$	(Eq. 4)

Soil Absorption

An estimation method for determining the infiltration ability of the ground would be to take a soil sample of the ground to find the composition. By the use of Figure 5 below, a ground type may be selected:

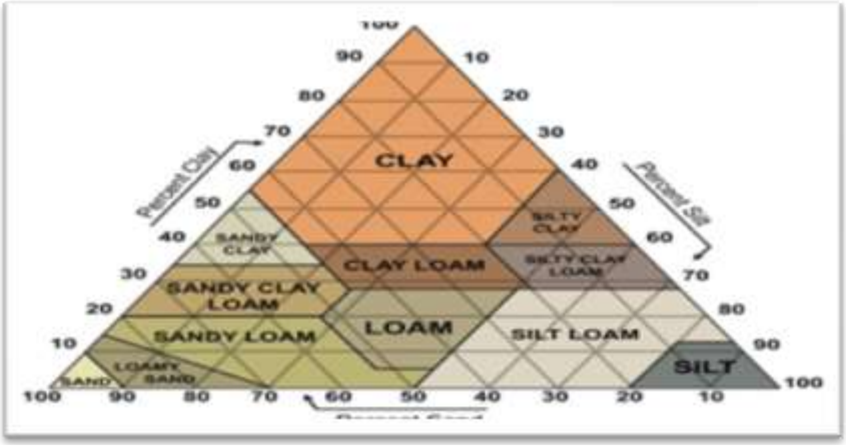

Figure 5. Soil Identification Triangle.[14]

With this estimation of infiltration, the excess rainfall on the soil type can be considered runoff. By multiplying infiltration in inches by the area of land a volumetric amount of water can be determined for the runoff water amount. By multiplying the runoff in inches by the area of land, the necessary water volume to collect can be found.

Considering the CN values above, parking lots or pavement areas have an infiltration value of close to zero. So, generally it can be assumed that all rainfall may be directly calculated as runoff. This situation proves similar for the roofs of all buildings. The completely impervious surface results in the rainfall contributed directly to runoff.

To determine how much runoff will occur due to the natural earth at the site, the infiltration capability of the soil must be known. According to the Penn State College of Agriculture, the Pittsburgh Plateau region, where Monroeville is located, most commonly has silt loam soil [15]. By knowing the slope of the area, the infiltration rate may be found. Where the surface of the ground is the system, the rainfall rate and the infiltration rate sum to a net gain or loss in the water accumulation. A net gain indicates the presence of runoff while a net loss indicates the complete absorption of the rainfall.

$\mathrm{W_{Runoff}} = \mathrm{W_{Rainfall}} - \mathrm{W_{Infiltration}}$	(Eq. 5)

Silt loam soil on a % slope of 0 to 4, where the infiltration rate of the ground is 0.5 inches per hour, which is much higher than the rainfall of the targeted storms.[5] As a result, the open ground for both the 1 and 25 year storms does not contribute to the overall rain runoff of the test property.

VII. SIMULATION AND ANALYSIS

For the analysis presented, a model of the heat transfer through the roof of the building was built, from which the rooftop temperature could be determined, based on the environmental conditions and heat drawn from the roof via evaporated water. This analysis was done in time intervals of one hour over the course of a year. The environmental information for each time interval is drawn from the Typical Meteorological Year data for Pittsburgh International Airport.

One key assumption that is fundamental to this analysis is that the thermal system for each time step is in quasi-equilibrium: although the environmental and thermal conditions are changing, they are doing so at a rate slow enough (over the course of an hour) that the system can be analyzed as if it were in equilibrium. The ambient temperature is assumed to be constant at 25 degrees Celsius (room temperature). This assumption is necessary to fix the internal conditions and to be able to solve for the rooftop temperature, which would be difficult to determine without this assumption. The constant internal ambient temperature is analogous to buildings where there is already an active air conditioning system, and means that this model is most applicable for determining energy savings for such buildings. To ease the analysis, only natural convection is considered. Also, the thermal resistance of the film of water on the rooftop surface was also assumed negligible.

Evaporation

The evaporation model used in this analysis was built upon the following set of equations [16]:

$\mathrm{P_{ws}} = \dfrac{e^{77.345+0.0067*\mathrm{T_{atm}}-\frac{7235}{\mathrm{T_{atm}}}}}{\mathrm{T_{atm}}^{8.2}}$	(Eq. 6)
$\mathrm{P_w} = \mathrm{RH} * \mathrm{P_{ws}}$	(Eq. 7)
$\mathrm{X_s} = \dfrac{0.62389 * \mathrm{P_{ws}}}{(\mathrm{P_{atm}} - \mathrm{P_{ws}})}$	(Eq. 8)
$\mathrm{X} = \dfrac{0.62389 * \mathrm{P_w}}{(\mathrm{P_{atm}} - \mathrm{P_w})}$	(Eq. 9)
$\theta = 25 + 19 * \mathrm{S_{wind}}$	(Eq. 10)
$\mathrm{Q_{ev}} = \mathrm{h_{fg}} * \theta * \mathrm{A} * (\mathrm{X_s} - \mathrm{X})$	(Eq. 11)
$\mathrm{m_{ev}} = \theta * \mathrm{A} * (\mathrm{X_s} - \mathrm{X})$	(Eq. 12)

where T_{atm} is the dry bulb atmospheric temperature (K), RH is the atmospheric relative humidity (%), S_{wind} is the wind speed (m/s), h_{fg} is the heat of vaporization for water at the film temperature, $0.5(T_{roof} + T_{inf})$ (kJ/kg), A is the rooftop area (m^2), Q_{ev} , and m_{ev} is the mass of water evaporated (kg).

In the evaporation analysis presented, these equations were applied at every interval to determine the mass of water evaporated and heat absorbed through evaporation during that time step. One critical assumption used for this analysis was that evaporation will only occur when both the atmospheric and roof surface temperature are above freezing.

From the evaporative cooling of the rooftop surface, Q_{ev}, the amount of cooling witnessed by the interior of the building, can be calculated. This calculation was performed by transforming the thermal circuit used in the first part of the analysis into an equivalent circuit where all the thermal resistances, node temperatures, and the radiation heat transfer are the same, but Q_{ev} is removed and replaced by Q_{cool} on the inside ceiling surface of the building.

Performing this conversion yields an amount of heat transfer from the building, which is analogous to an amount of air conditioning within the building. To assign a value to this cooling, it was calculated how much running an air conditioner to remove that much heat would cost using a typical Coefficient of Performance of 1.5 [17] and an electrical energy cost of $0.08 per kW-hr.

Another goal of the code analysis was to determine how much water would be collected throughout the year, and to compare that to how much water could be evaporated from the roof. The amount of water that could be collected was determined from the area of the roof surface and the parking lot and their respective runoff coefficients. Then to determine a collection tank size, a simulation was performed that calculated the amount of water in numerous tank sizes based on the rainfall being collected and the amount evaporated for each hour through a typical summer. For the simulation, the amount of water collected for each hour was netted against the amount of water evaporated during that hour, and that net summed so it accumulated (or diminished) throughout the summer, depending on the conditions. If the volume of water in the tank is equivalent to the size of the tank, no more water could be collected and the volume of water evaporated was detracted from the volume contained. Likewise, if there was no water in the tank there is no water to be evaporated, so the volume of water collected is added to the tank. By performing this simulation with numerous tank sizes, the amount of time that the tank spends either empty or full can be determined as a time in days, or as a percentage of the total time of the simulation. Also, if the tank contains water so that evaporation can occur, the evaporative cooling and monetary value of cooling associated with it can be calculated and compared.

Tank Capacity

A critical factor in designing a system of this nature is selecting a storage tank with the appropriate capacity. Under designing the capacity of the storage tank will lead to the system not performing as desired, reducing the benefit to the environment and the business owner. Over designing the capacity can lead to both wasted space and an uneconomical investment. Two perspectives that should be considered when selecting a tank capacity include the perspective of the environmental benefit and the perspective of the financial investment. By considering both perspectives, the final tank capacity will satisfy both requirements. From an environmental standpoint, the preferred tank capacity would be able to collect all the water that falls on the site. By collecting all of the water that would otherwise flow into the stormwater drainage, the system would eliminate the sites contribution to the problem of excessive stormwater from the area. The estimated rainfall on the Monroeville site for a 1-year storm is 45,663 gallons. Unfortunately, a tank of this magnitude would be impractical to implement for the scope of this project.

To get a better idea of the demands of the system, the meteorological data from the Monroeville site was analyzed. Based on this data and the calculated evaporation potential of the roof spray technique, the amount of time a given size tank would be either full or empty was determined. When the tank is full, the system will not be able to collect additional water. On the other hand, if the tank is empty, the system will not be able to evaporate any water back into the atmosphere. Figure 6a and Figure 6b below show the projected total time in days from May to October that a given tank capacity would either be full or empty, respectively.

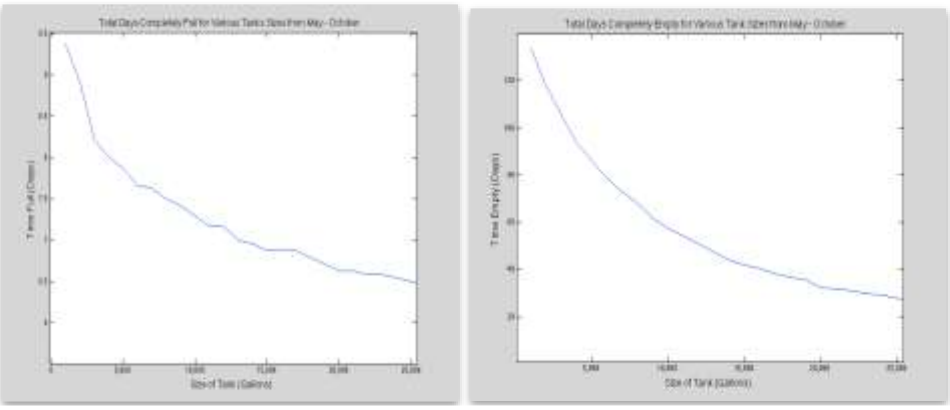

Figure 6.(a) Time a Given Tank Capacity Will be Full; (b) Time a Given Tank Capacity Will be Empty.

Based on the trends of Figure 6a and Figure 6b, it can be seen that increasing the tank capacity initially results in a significant reduction in the days the tank is either full or empty. Once a certain tank capacity is reached, however, increasing the tank capacity diminishes the time that the tank would be either full or empty.

When selecting the appropriate tank capacity, the decision should also take into account the financial investment. When a business owner is deciding to implement this system, he or she will certainly want to know which tank capacity is the best investment. By considering the upfront investment of the different capacity tanks and the potential for savings in the form of air conditioning energy, a financial investment analysis can be performed to see which tank size provides the business owner with the best investment. Assuming a life of fifteen years and a minimum acceptable rate of return of 2.5%, the Annual Worth Method was used to calculate the best investment.

The financial investment analysis suggests that a capacity of 10,000 gallons would be the best investment for a period of fifteen years and a MARR of 2.5%. Taking a look back to Figure 6a and Figure

6bthat illustrate the projected amount of time a given capacity tank would be either full or empty, it can be seen that a 10,000-gallon tank would reduce these times significantly while not being excessively large.

Filtration

The long-term storage of harvested water is dependent on the ability to filter out dangerous toxins and debris in order to prolong the life and usefulness of the water and the collection and distribution system. The desired quality of water for this application is called "greywater". There are no quantitative standards to define greywater; however, greywater can roughly be defined as lightly contaminated water that has not come in contact with feces or other harmful intoxicants. "Greywater may contain traces of dirt, food, grease, hair, and certain household cleaning products. While greywater may look "dirty," it is safe [19]." This lightly soiled water will not spread dangerous germs or bacteria and can safely be sprayed onto a roof and evaporated. With large quantities of debris and bacteria, this degradation from greywater to blackwater can occur in as little as 24 hours. However, if proper steps of filtration are taken, the life of the water can be preserved for weeks to months [20].

Proper filtration methods should be administered in order from the least to most fine particle size. In filtration systems, the fineness can be measured in microns, and the final quality of filtration needed can be determined on a case by case basis. This should take into account the environment that is being collected from. Properties containing more organic material such as trees, plants, animals, etc. will require finer filtration to remove bacterial and decomposable matter. Systems will also be size dependent, requiring a larger system for bigger collection areas.

The filtration system chosen for the warehouse in question will be completely in-ground and will filter all debris and sediment down to 254 microns which should be suitable for this application. The level of filtration chosen will remove any large debris material from entering the tank and disrupting the pump and spraying system. Organic material will be removed in order to prevent decomposition and degradation of the water.

After being collected, water will enter an in-ground filtration system. The system will feature an industrial grade mesh filter. The filter must be suitable for at least a 1-year recurrence storm. It must be capable of handling the average flow rate of water collected during such a storm. In Monroeville, the rainfall of a 1-year recurrence storm over a 24-hour period is 2 inches [21]. Taking into consideration the area of the buildings and pavement on the site, it is calculated that the average flow rate of a one-year recurrence storm is 0.53 gallons per second. The filter chosen is able to handle up to 10.7 gallons per second of water according to manufacturer specifications [22]. This is more than enough to accommodate the site for the average one-year storm.

Table 4. Filter Specifications.

Price	Max Flow Rate	Connections	Weight	Filtration	Installation Depth
$1579.95	10.7 Gal/Sec	6" or 8"	80 lb	0.01 in (254 micron)	31 – 59 in

The filters chosen can be easily accessed via a lid above ground for easy maintenance and are self-cleaning [22]. The system is also designed to have two overflow points. There will be an overflow between filter and tank. This will allow the system to overflow to the sewer when the tank is full. There will be another overflow before the filter. This will allow the system to overflow to the sewer when the flow rate of collection exceeds that of the filter.

Piping Design

For the Monroeville Site, the area of the roof is 12,000 square feet [23]. This area is not the exact area of the roof because the layout of the roof is corrugated. An example of this type of roof is shown below in Figure 7, and it should be noted that the roof of the Monroeville site does not have these dimensions. Due to the layout of the roof, when the water is released from the spray system, the water will flow on the elevated points of the roof and eventually flow down into the basins of the roof. This could be problematic for evaporation due to a smaller usable surface area for evaporation because of its corrugated layout.

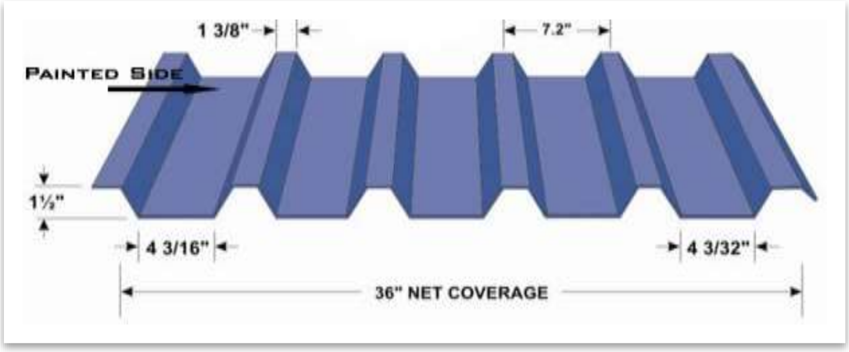

Figure 7. Corrugated Roof Dimensions Example.

In order to know how much water is need to be released onto the roof each day for optimum evaporation, the maximum thickness of that water covering the roof must be calculated. To find out the thickness of the water that is able to evaporate, a calculation with dimensional analysis was used.

$$\frac{100 \text{ gallons of } H_2O}{1000 \text{ ft}^2} \text{x} \frac{1 \text{ ft}^3}{7.48 \text{ gallons of } H_2O} \text{x} \frac{12 \text{ inches}}{1 \text{ foot}} = 0.16 \text{ inches}$$	(Eq. 13)

Assuming that on average 100 gallons of water can be evaporated on a 1000 square feet area in one day [24], a thickness of 0.16 inches is found. This is confirmed through the Matlab code developed for theoretical purposes. That thickness allows for the assumed rate of evaporation, on the area specified. In order to get that thickness, a piping system at the peak of the roof will allow water to flow in an intermittent stream to ensure that the water does not go above this calculated thickness and disrupt the time of evaporation in order to provide optimum evaporation. An intermittent stream also allows the roof to dry out in order to prevent growth of bacteria and other potential issues that could weaken the structural integrity of the roof or require 12 in three sections: the first section will be 1" pipe, the next will be ¾" pipe and the last will be ½" pipe. This will increase the pressure in the pipe the farther down that the water needs to go. Each section of pipe will have 75 holes drilled into the side facing outward to spray the water down the roof. In the first two sections, the holes will have a diameter of 0.08" and to account for a pressure loss the last section will have holes with 0.06" diameter.

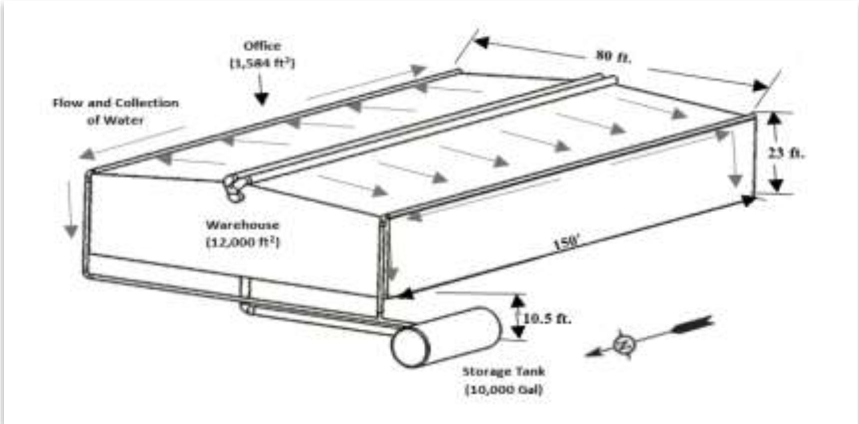

Figure 8. Isometric View of Building and Piping Design.

Using a max flow rate of 8.8366 GPM, from the code, pressure losses were able to be calculated for each section of the proposed pipe system. The maximum flow rate was calculated from the maximum volume of water that can be evaporated in a single day and converted to a rate. In the section carrying water up to the elevation of the roof, the flow rate is the same as at the outlet of the pump so a max velocity of 4 ft/s was determined. From that a head loss was determined, using the equation:

$$h_f = 8 \, \frac{\text{Length (feet)}}{100 \text{ feet}}$$	(Eq. 14)

In the first section at the peak, the flow has been separated into two so the flow rate must also be split. Using this, the same is procedure is done as before but with the new flow rate. The second section of piping at the peak, loses more flow after traveling 1/3 of the distance of the roof. Factoring this into the flow rate, the flow rate is halved and then multiplied by 2/3. The same is done for the last section of piping, but instead of multiplying by 2/3, the flow rate is multiplied by 1/3. Adding all of these head losses together, along with the head losses from each of the 90-degree pipe elbows and the pipe splitter tee, a head loss was calculated to be about 22 feet. Adding the elevation head into this, a final total head loss of 58.8 feet was calculated. The value is used along with the max flow rate to size a pump for the system proposed. From Figure 9, a proposed model of Goulds 10GS05411 Submersible Pump (10 GPM - 1/2 HP - 115 Volts - 3 Wire) is shown to meet the requirements of providing a flow rate of 8.8366 GPM and a total dynamic head of 58.8 feet and with a price of $389.00, it is cheaper than similar pumps. The yellow dot shows the value needed for the system and the blue dot shows the point which the proposed pump will be able to handle.

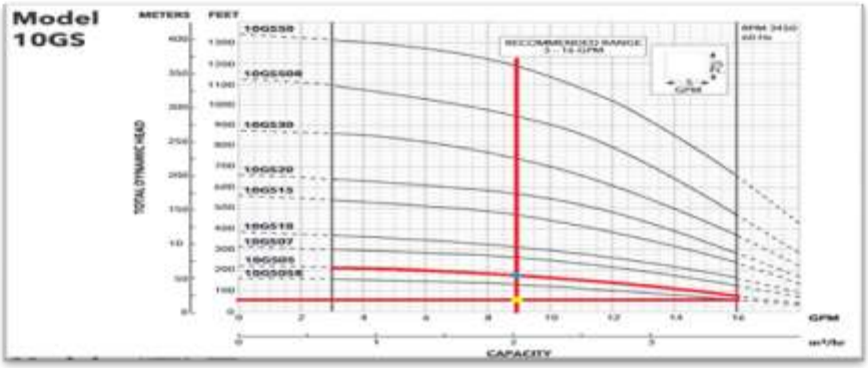

Figure 9. Total Dynamic Head versus GPM for Various Submerged Water Pumps.

Another factor involved in pump selection is the efficiency of the pump. The efficiency of the pump that is recommended has at worse an efficiency of 51%. Using that value and the ratings of the proposed pump, a pump shaft power in wattage of 1.20 Watts can be determined using the equation:

$$W_s = \frac{p * Q * HP}{\zeta_p} \qquad \text{(Eq. 15)}$$

where p is the pressure in lb/ft^3, Q is the Max flowrate in ft^3/s, HP is the horsepower, and ζ_p is the efficiency in feet of H_2O.

VIII. RESULTS

One technique for recycling the water collected from rain is to return it to the environment through evaporation. A major benefit to using this method is that the water draws heat from its environment. If the water evaporates from a thin film on a roof surface, heat will be absorbed by the water and the roof will be cooled (and through conduction and convection on the inside ceiling, the interior of the building). The evaporation of a fluid from a surface is a function of the atmospheric conditions including humidity, temperature, the magnitude of solar radiation, and the temperature of the roof.

This model calculates the amount of water that could be evaporated if one were to be able to supply that much water. Accordingly, for the summer period between May 1 and October 31, the total mass of water evaporated is 1.52 million kilograms. This corresponds to a volume of 402,000 gallons of water. This amount of evaporation is unlikely in reality because it would be very difficult and uneconomic for a person to be able to supply that much water- they will be limited by the amount of rainfall, and the size of a collection tank. A more realistic amount of water that one could expect to evaporate is 244,000 gallons. This amount accounts for the tank size and rainfall in a 10,000-gallon tank, and considers whether or not there is any water collected from rainfall to evaporate.

The cost is important to consider in the design and implementation of the system. The technology must be designed to provide a benefit to the user and a return on the initial investment. The cost of the investment includes the gutters, tank, filter, piping and pump.

Table 5. Investment costs.

Item	Investment
Gutters	$23.69
Filter	$1,579.95
Piping	$120.00
Pump	$389.00
Tank	$24,027.70

Total	**$26,140.34**

The tank comprises the largest percentage of the investment cost, and must be selected in order to optimize the return. Tanks between 1,000 and 30,000 gallons are considered in the selection process. A cash flow analysis is completed for each size tank. Certain assumptions must be made in order to complete this analysis. The effective tax rate used is 34 percent. This should be an acceptable approximation for the revenue of the business in question [25] [26]. The cost of electricity for an industrial property in Pennsylvania is assumed to be 7.19 cents per Kilowatt-hour [27]. The depreciation is assumed to be a 20-year recovery period in accordance with a “land improvement” based on IRS depreciation tables [28]. The present worth is then calculated for each tank as seen in Figure 10.

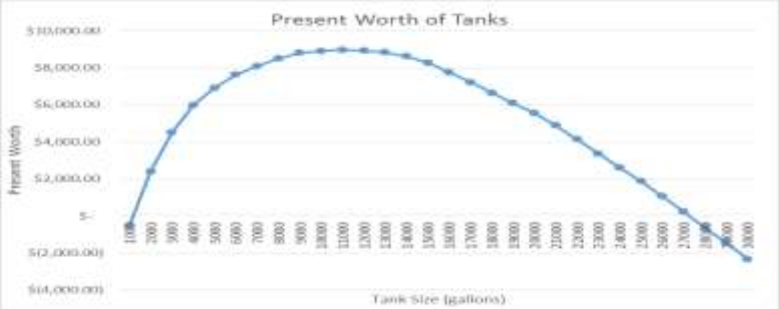

Figure 10. Present Worth Comparison.

A 10,000 gallon tank is chosen as the optimal size based on the present worth. The present worth of the system is calculated to be $8,112.50 as seen in Figure 11 [29].

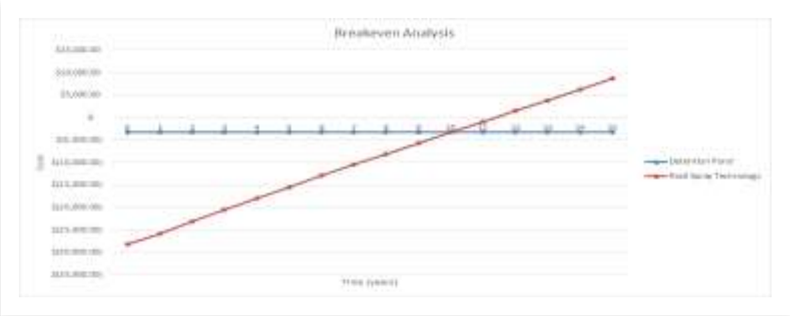

Figure 11. Breakeven Analysis.

When compared to a detention pond, it is seen that there is a breakeven point with the detention pond in approximately 10 years, and with the cost of the entire system is approximately 11.5 years, this this configuration.

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