Rainwater Irrigation Systems: Recommendations for UW Seattle

Final Report

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Table of Contents

1 Executive Summary

The goal of this study is to analyze rainwater harvesting irrigation systems in order to recommend a rainwater irrigation system for the University of Washington Seattle campus. The analysis includes different design alternatives, potential locations, as well as operation and maintenance time and budget requirements so that the system reduces potable water demand without misusing facility resources. In order to achieve this objective, the research team completed a literature review of existing rainwater irrigation research, conducted a survey of designers and operators in the Pacific Northwest who are involved with rainwater irrigation systems, gathered current market data through a trade conference, and finally analyzed the UW Seattle campus for potential rainwater irrigation systems. Based on the current cost of water and drainage in the City of Seattle, rainwater harvesting systems used solely for irrigation will not be able to have a positive return on investment during its design life. However, we – the research team – see a lot of potential in rainwater systems which use rainwater more consistently throughout the year instead of just the summer irrigation. Furthermore, as the cost of water increases annually, rainwater harvesting systems will soon be cost effective.

2 Background

Historically in arid regions of the world, communities used rainwater harvesting as a mechanism to collect water in order to irrigate corps in the dry seasons. In fact, cisterns can be traced back to the Neolithic age in southwest Asia. By the late 4,000 BC cisterns were common for dry-land farming. The Greeks in particular recognized the importance of water not only during times of drought but also during war [1]. The Romans also made extensive use of cisterns, and claim the largest cistern, Basilica Cistern, located in Athens. It is 80,000 cubic meters which could hold approximately 21 million gallons. These ancient cisterns were made with stove and covered with an impervious plaster and have lasted centuries. In the 19th and 20th centuries, concrete tanks were built at high elevation to produce water pressure in metropolitan areas.

In modern times, rainwater harvesting has become popular worldwide as a tool to mitigate development in order to create a more sustainable world [2]. Around the world, rainwater is still collected for drinking, landscapes, and agriculture [3]. Cisterns are still made out of concrete, but many new materials including plastic and fiberglass are now used [1]. From a water management perspective, rainwater harvesting has become an essential mechanism in combatting water scarcity, improving water security, and finally improving the balance between water and energy. Since rainwater is typically collected near where it will be used, the energy required to move the water is often less than what is required from a municipal source [4]–[8]. As our climate continues to change, rainwater harvesting is increasing in popularity as a mechanism to avoid or reduce the impact of extended dry periods [9], [10].

3 Literature Review

The research team conducted a literature review related to rainwater irrigation systems, excluding articles focused specifically on crop production or agriculture, water quality analysis for potable systems, groundwater recharge, and water scarcity and drought management. From the remaining articles, five article types emerged: (1) design factors or models, (2) rainwater irrigation of green roofs, (3) perspectives of rainwater harvesting, (4) return on investment and reliability, (5) water management. This report starts by presenting the findings of this literature review.

3.1 Design Factors and Modelling

Rainwater harvesting (RWH) systems are categorized into two categories: active and passive. Passive RWH systems capture water through depressions in the ground while active systems are created to collect the water for alternative uses [2]. Since the majority of systems are active RWH systems, this report will refer to active RWH as simply RWH systems from here forward. RWH systems consist of four basic components: collection, filtration, storage, and distribution as shown in the orange boxes in Figure 1 [11]. Filtration typically occurs before the water is stored and before it is distributed. While generally considered decentralized systems, RWH system often connect to an alternative supply in order to ensure there is always water available. Cross connections must be properly installed in order to avoid contamination of the municipal supply.

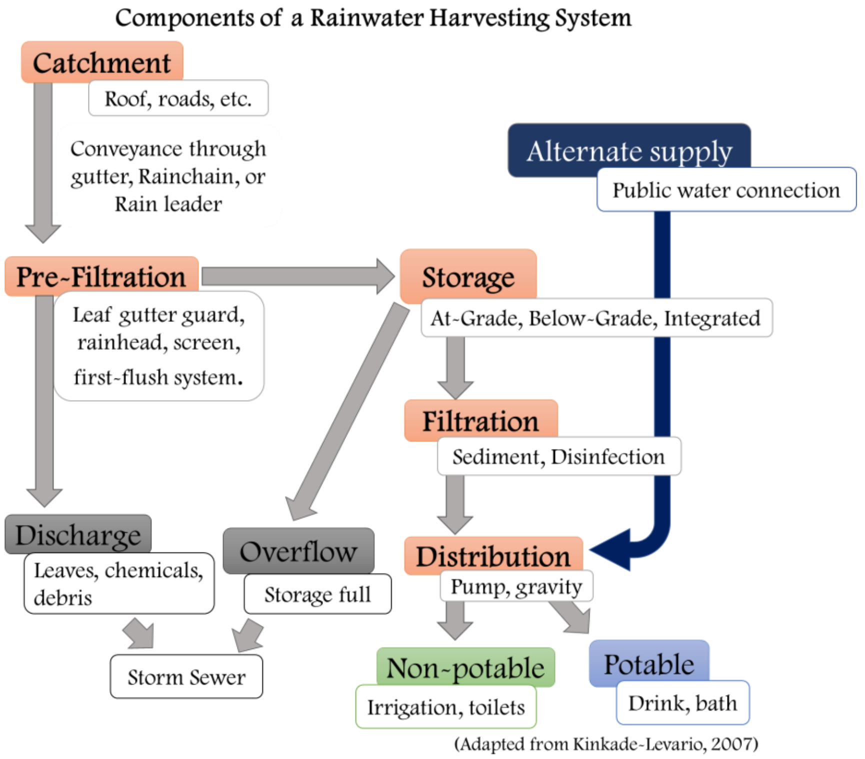

Figure 1: Rainwater Catchment Schematic

Design parameters for a RWH harvesting system are rainfall, catchment area, collection efficiency, tank volume, water demand, and filter capacity [12]. Rainfall is dependent on the climate where the RWH is installed. The design team can manipulate the remaining design parameters in order to optimize the system's performance. Throughout the following sections, we will discuss these different components. We conclude Section 3 with a discussion of how these design parameters are modelled in order to optimize performance.

3.1.1 Catchment & Collection Efficiency

Rainwater can be collected off any number of impervious aboveground surfaces; most commonly it is collected off of roofs and pavements. In Washington State, water should only be collected from roofs not built for rainwater collection unless the collector has established water rights [13]. For purposes of this study, we are also only focused on roof catchment areas. Typically, roof wills require less treatment than pavements and other catchment surfaces. However, the roof material, slope, age and surrounding vegetation will affect the water quality of the harvested rainwater. In fact, depending on the roof conditions only 75 to 95% of the water that lands on the roof will actually be collected. Potable rainwater harvesting systems should consider the roof characteristics; however, for irrigation where quality requirements are not as high, most roofs are acceptable. Prior to installing a system however, it is worth obtaining the safety information related to the roofing material, in particular determine if the roof is treated with a biocide coating which could prevent the healthy development of a biofilm in your tank. Furthermore, if possible aim to collect rainwater from a pitched roof as less debris tends to collected on pitched roofs [2].

Gutters are common way of moving the rainwater from the roof to a downspout and into the tank. Gutters typically collect water off a sloped roof and then use gravity to move water to a downspout. Flat roofs will collect rainwater in roof drains at low points in the concrete pad. Gutter screens are attached the top of the gutter to prevent debris from moving any further; however, they also require frequent maintenance in order to optimize collection efficiency. From the gutters, rainwater will enter a downspout or drain leader, which will use gravity to move the water to the tank. If a first flush diverter is included in the design, a specified amount of rainwater is diverted away from the tank to improve the quality of the water being stored in the tank. A first flush system however does not replace the prefiltration requirement for the water entering the tank which is explained in more detail in the next section [14]. While first flush diverters affect the reliability and yield of a rainwater harvesting system; the improvements in quality typically outweigh the reliability losses, particularly for potable systems [15]. In order to reduce maintenance needs, the diverted water should automatically drain.

3.1.2 Filtration

For RWH systems over 360 gallons, Standard 63 requires that filters remove all debris larger than one sixteenth of an inch [16]. There are two primary types of filters: self-cleaning and manual. Self-cleaning filters include Vortex, Cascade prefilters, and hydraulic jump filters. Vortex filters are vertical filters, which spin the water to separate the water from debris. The water is pushed to the outside of the filter while the debris falls through the center due to the spin [14]. Cascade prefilters push water through a multi-screen element while pushing debris out of the system. Cascade filters are different from Vortex filters in that the water enters through a side port and then runs over a slanted filter. Debris is pushed away with about 5% of the water, while the remaining 95% of the water goes into storage [17]. Finally, the hydraulic jump prefilters are similar to the cascade filters in that the water flows over a slanted filter; however, over time debris will gathers up below the screen. The debris “jumps” or is pushed out of the overflow when the debris reaches the overflow point [18]. For these filters, common practice is to rinse the filters quarterly or as needed once the system requirements are established.

There are two manually cleaned filters: downspout and tank-mounted filters. Downspout screen filters deflect debris away from the rainwater system; however, these filters require more maintenance as more often as debris tends to accumulate – particularly for fine screens. In addition, every downspout is required to have a filter – again creating more maintenance.

Tank mounted filters come in two forms – basket and slanted. Basket filters sit within the opening of the tank. Debris is collected on the basket filter; therefore, the filter must be above the overflow level of the tank and should be cleaned regularly. Slanted filters are usually in the systems with cone-shaped tank roofs. Water follows over the slanted filter and into the tank while debris gathers on top. If the water flow is strong enough, sometimes it will clear debris from the filter, but still should be regularly cleaned. When deciding which filter to use, it is important to consider the limits of the filter and the amount of maintenance that is reasonable for the system. For example, if the catchment area tends to accumulate debris, but the operation and maintenance budget for the system only allow annual filter cleaning, the designers should consider multiple filtration devices as well as the self-cleaning options [14].

Filtration is not the only way the water quality improves in a RWH system. Once the water enters the cistern, the microbes in the water begin to compete for resources to stay alive. Over time, the microbes will flocculate to create either masses floating at the surface or sink with the sediments to the bottom of the tank. A well-designed RWH system has pre-filtration to remove some of enough potentially toxic microbes so that healthy biofilms can develop within the tank. For example, reducing the source of containments (trees and wildlife) on the roofs greatly diminishes the amount of microbes in the collected rainwater [14]. Recent research has also shown that retention times of approximately one week allow for natural improvement of the water quality [19]. Further treatment and disinfection such as chlorination or UV is required for potable systems before consumption. In fact for pre-filtration, the first flush system has been shown to considerably reduce the amount of pollutant entering the cistern [2], [19], [20]. All together a rainwater system has a treatment train which transforms contaminated rainwater into a higher quality water for its intended purpose [14].

3.1.3 Storage

Rainwater can be stored in a number of ways. Most commonly for water reuse, rainwater collects in large containers often called cisterns, tanks, or barrels. These tanks are installed above or below ground. Above ground cisterns must be made of tinted UV resistant plastics or be protected by a shed or crawl space. Underground cisterns must have manholes that are OSHA compliant with confined space entry guidelines. The installation of these tanks should follow the manufacturer's instructions as well as those outlined in ARCSA/ASPE/ANSI 63-2014. Beyond the requirements, the tank material, location, style, and size will have large impacts of the cost and reliability of the rainwater harvesting system. The distance between the catchment area, the tank, and the designated use should be considered when placing the tank. Depending on the soil, heavy tanks might need a structural foundation [14].

A small tank will overflow too often, and a tank that is too large will be costly and never used to its full potential. Above ground tanks typically are less expensive, are easier to access, facilitate gravity or pumped distribution, moderate temperatures for surrounding plants. However, they also are more exposed to weather – wind and sunlight – and other elements such as fire. Underground tanks open up green space above ground for aesthetics, are protected from freezing and sunlight, and facilitate less bacterial growth due to the lack of sunlight. However, they are also more expensive since they must withstand more forces such as buoyancy pressures and must prevent the entrance of storm water.

Tanks are made of metal, plastic, fiberglass, polymer alloy, and concrete. Tank material is first based upon if the tank is above or below ground. Typically, galvanized and stainless steel as well as polymer alloys are only installed above ground; whereas, polyethylene, polypropylene, fiberglass, and concrete can be designed to be above or below ground. Table 1 below discusses the advantages and disadvantages of the different material options [14].

Table 1: Comparison of Tank Materials

Material	Advantage	Disadvantage	Shape
Metal	Long life, variety of sizes, aesthetics	Internal liner, aesthetics	Cylindrical, slim line
Plastic	Low cost, variety of colors and sizes	Deteriorate in sunlight, must be shipped from factory	Cylindrical, slim line
Fiberglass	Lightweight, strong,	Must be shipped from factory as one piece, expensive	Vertical and Horizontal Cylinders
Polymer Alloys (Bladders)_	No external structure, collapsible	High freeze and puncture risk	"Pillow" custom made to fit area desired
Concrete	Can be part of structural element, connection elevations are customizable	Require reinforcing steel and engineering design	Shaped to meet site needs
Wood	Assembled on site with metal bands, connection elevations are customizable	Liner required	Cylindrical with cone shaped roof

To increase the storage capacity of a system, cisterns can be connected to each other in series or if underground, modular systems can be used. Modular systems are made up of rectangular crates, which are wrapped with a watertight liners. The crates are structurally able to withhold vehicle traffic and can be arranged in order to maximize the use of an underground space. Prior to installation, expansion projects should be discussed with the design team. Previous research has proved that consideration of a larger system prior to installation will result in more efficient system as it expands [21].

Storage systems must also have an inlet, outlet, overflow outlet, vent, and service/access port. Rainwater enters the cistern through the inlet and is distributed to its intended use through the outlet. The overflow outlet allows excess water to spill out of the tank while the vent allows air pass in and out and reduce pressure within the tank. All overflow outlets should be sized such that in a maximum rainfall event all the incoming water can be drained at the same rate. Storage should overflow twice per year in order to remove the floating debris and microbes from within the tank [22]. A vent is required in order to equalize the pressure. All openings in the storage system should protect the stored water from insects and vermin [14].

The service port is one of the most important aspects to consider when designing the storage of a rainwater harvesting system, particularly when your pump is within the storage unit. The service port should be designed not only to allow technicians to easily enter the storage container but also to allow for proper confined space safety equipment. As will be discussed in the recommendations, commonly limited or difficult access to different components of a RWH system ultimately leads to reduced maintenance and often failure.

The inlet is designed to minimize turbulence created when rainwater flows into the tank. Turbulence suspends sediments at the bottom of the tank back into the stored water causing a decrease in the outlet water quality. One method by which to reduce the turbulence is to install a calming inlet, which feeds the incoming rainwater vertically downwards until a 180 turn just above bottom of the tank where the water is released. In order to improve the outlet water quality, the outlet should float just below the surface of the water within the tank or if that is not possible at least several inches above the bottom of the tank. Outlets close to the bottom of the tank have higher concentration of sediments because over time sediments settle to the bottom of the tank [14].

Retention time and cistern design are two other ways to reduce turbidity in the water and increase the outlet water quality. The time the rainwater is held in storage is known as retention time. Long retention times allow the sediments in the rainwater to fall to the bottom. Retention time is a function of the size of the tank as well as the incoming rainwater and outgoing demand. To decrease the turbidity of the water from inlet, the distance from inlet to outlet should be increased and added depth in the water tank allows for increased separation between the bottom of the tank where settling is occurring and the top of the tank where the outlet is. Retention time however is not the only design parameter affecting the storage design. Most commonly a water mass balance is used in combination with behavioral, probabilistic or stochastic and hybrid methods to determine the storage size [23], whereas retention time, intended use, and collection area affect the layout of the RWH in order to optimize the outlet water quality. All RWH systems should consider different volumes and layouts and their effects on reliability, water quality and cost before making a final decision. For example, a rainwater irrigation system does not require high quality water; therefore, the design team can focus on the volume of the system rather than the quality of water. However, if the system can be designed to improve the water quality without or with minimal additional costs, the system will likely have a longer life with less maintenance requirements because the pump and downstream filters will be moving cleaner water. Retention times of approximately a week have been shown to considerably improve the water quality – both in terms of microbes and sediment [19]. Unfortunately currently changes in water quality over time within rainwater tanks has not been fully explained [2], [24].

3.1.4 Distribution

A distribution system takes the stored rainwater to where it needs to be. It typically includes the pipes, fitting, values, and for an active RWH system, pumps. In a passive RWH system, gravity moves the water from the cistern to the point of use. They typically do not require a certain pressure at exit, making it compatible with gravity, which typically provides lower pressures. In an active RWH system a pump will pull water from the cistern and push it through the pipes to its desired destination – for irrigation rainwater would go first to the mainlines, then to the laterals, and finally out of the sprinklers or drip line. Standard 63 requires that any pump be able to provide 15 pounds per square inch gauge (psig) at the farthest point in the distribution system and a pressure reducing value should be installed in the pump can exceed 75 psig [16].

Centrifugal pumps are the most common type of pump used in rainwater harvesting systems; they are either surface or submersible pumps. Surface pumps are positioned outside of the rainwater tank, making for easy maintenance access, while submersible pumps are placed inside the tank, reducing the overall footprint of the system. All centrifugal pumps must be designed with enough suction head to avoid cavitation. Cavitation occurs when the water inside the pump transforms from a liquid to a vapor, causing rapid pressure changes, and likely damaging the system for future use. In order to avoid cavitation, the pump must be sized properly as well positioned at ensure enough pressure from the incoming rainwater tank [14]. Pumps are sized according the pressure and flow rate required by the system. Every pump has a performance curve associated with it that shows the inverse relationship between pressure measure in pressure per square inch (psi) or feet and flow rate measured in gallons per minute (gpm) [25]. In fact, speed – which varies directly with flow rate – varies as the square root of pressure and cube root of power [26]. In order to optimize the pump efficiency, the intended use of the system must be complete. For irrigation this means the mainlines, laterals, and sprinklers must all be laid out in order to calculate the minimum flow rate and pressure needed for the entire system to operate effectively and efficiently [25]. For UW, irrigation systems are also required to have an addition 20 gpm capacity for hand-watering [27]. Most systems irrigation systems range between 40 to 45 psi [25], but at UW are traditionally designed for 75 psi [28].

In recent years, integrated water management research has focused on the water energy nexus where the goal is understand the relationship between water management and energy resources. In particular, to RWH systems, most studies have found that RWH are typically not energy efficient and in fact, many empirical studies have found that they use more energy than the existing utility water services. To this end a recent study recommended several storage and distribution considerations that could make RWH more efficient and potentially energy neutral. First using gravity will increase the energy efficiency of your system. This can be done two ways: (1) store all the harvest rainwater at a higher elevation than where it will be used or (2) install a header tank that is filled from the larger tank – usually via pump – to provide enough water based on daily demand. Second, the pumps need to be sized efficiently. In this case, it is worth considering the different demands on the system – which demands require high pressure and flow rate and how often do those occur in comparison to the average. If a RWH system is used for multiple purposes, multiple pumps can be used to optimize the pump for each purpose or a variable pumps can be used to reduce the energy consumption. While installing multiple pumps or a variable speed pump increase the capital cost of the system, the energy of savings over the long term could be more beneficial – especially if the fixed speed pumps have high start-up and standby mode energy consumption rates [29].

After exiting the pump, the rainwater flows at the desired pressure and flow rate to the intended use – in our case to the irrigation system. Therefore, the rainwater travels through a series of pipes and valves to the sprinklers in the landscape. Since this water is non-potable, one of the most important design aspects is cross-connection control. Cross-connection control prevents rainwater from mixing with potable supply. Backflow prevention is created through several valve(s): (1) reduced pressure backflow assembly, (2) double check valve, (3) pressure vacuum breakers, or (4) an anti-siphon valve. The local plumbing code details the requirements for any cross-connection and backflow prevention assemblies [25]. In Seattle, double check valves create backflow prevention; however, the city code requires a reduced pressure backflow assembly (RPBA) for a rainwater source. The different types of valves will be discussed further in the irrigation section.

3.1.5 Modelling

Rainwater harvesting system are modelled in order to understand the performance, impact and cost over time. RWH systems can be modelled over a specified period of time (critical period method) or a sequence of times (behavioral analysis). Behavioral models – a type of critical period method – and often referred to in RWH design as water mass-balance models simulate "the operation of the reservoir with respect to time by routing simulated mass flows through the algorithm that describes the operation of the reservoir" [22, p. 43]. The mass-balance transfer model is widely used and accepted as an accurate method for representing a RWH system [30]. It includes rainfall rate, catchment area, filter efficiency, storage tank size, pump efficiency, demand and more.

For RWH systems, the algorithm describes rainwater collection, transfer into a storage tank and transfer of rainwater and/or tap water based on storage and demand. Two of the most commonly algorithms are yield before storage and yield after storage. Yield before storage (YBS) includes incoming rain in the rainwater supply. Conversely, yield after spillage (YAS) does not include the incoming rainfall in the available supply; instead, rainwater supply is included after demand is taken out. YAS is often preferred for design calculations as it conservatively estimates the system performance [22], [31]. In 1987, Latham created a generic algorithm based on the YBS and YAS models, shown below as equations 1 and 2. The algorithm is largely based on YAS and YBS but adds theta as a system based parameter. Latham and Schiller showed how this general model (sometimes called the Ottawa Model) more accurately represents the data on a monthly time interval [32], [33].

$$Y_t = \min\begin{cases} D_t \\ V_t + \theta Q_t \end{cases} \tag{1}$$

$$\mathit{where}\ Y_t\ \mathit{is\ the\ amount\ taken\ from\ storage}, D_t \mathit{is\ demand\ during\ the\ time}\ (t),$$

$$V_t\ \mathit{is\ the\ volume\ in\ storage\ in\ time}, t, \theta\ \mathit{is\ storage\ operating\ parameter},$$

$$\mathit{and}\ Q_t\ \mathit{is\ the\ rainwater\ collected}$$

$$V_t = \min\begin{cases} (V_{t-1} + Q_t - \theta Y_t) - (1-\theta)Y_t \\ S - (1-\theta)Y_t \end{cases} \tag{2}$$

where S is the storage capacity.

Fewkes and Butler studied even further, how the accuracy of behavioral RWH models could be improved. They focused on the effect of the system size, the effect of demand and storage fractions on water saving efficiency, and finally the effect of the time interval has on the accuracy of the model. Based on rainfall in the UK, they determined that hourly models are most accurate for storage fractions less than 0.01. Daily models are best for storage fractions between 0.01 and 0.125, and finally, monthly models are best for storage fractions greater than 0.125. Storage fraction is the total storage (S) over the product of the catchment area (A) times the annual rainfall (R). Demand fraction is the proportion of water demand (D) to the product of the catchment area (A) times the annual rainfall (R). Water saving efficiency is calculated using equation 3. Water saving efficiency shows the proportion of tap water saved by using rainwater [22], [34].

$$E_t = \left(\sum_{t=1}^{T} Y_t \Big/ \sum_{t=1}^{T} D_t \right) X\ 100 \qquad (3)$$

The advantage of using the generalized logarithm is that is improves the accuracy of the modelling by accounting for the size of the system. Ultimately, the size of the system affects whether YAS or YBS should be used and Fewkes and Butler determined appropriate values for theta based on the storage and demand fractions [34].

Since precipitation patterns vary from year to year, the design of RWH harvesting system should be able to handle some variation in the precipitation pattern. Introducing statistical probabilities related to rainfall allows RWH system to have a defined range of reliability. Reliability for RWH systems is either the fraction of demand volume met by rainwater or of the time where rainwater fully meets demand [32]. Volumetric reliability is measured as the proportion of rainwater yielded from the system over the demand over a period of time [35]. Time-based reliability is measured as one minus the ratio of days where demand was not met over the total number of days being studied [15].

The first step is collecting historical rainfall data at daily and monthly scales and if possible at hourly intervals. This data can be used to either create synthetic rainfall series [36] or can be used to create probability density functions [37]. With either set of data, the deficit rate is calculated to show the proportion of water not met by the rainwater system over demand. The proportion of water not by the rainwater system is equal to the water bought from the mainline. Lopes and collaborators compared the deficit rate with tank size at different exceedance probabilities – percentage of time a deficit rate is equaled or exceeded [36]. They used simulated rainfall patterns for 1,000 years to estimate probabilities using a Monte Carlo and gamma probability function. They used the exceedance probabilities to show the change in deficit rates with tank size depending on the demand and roof area [36].

Su and collaborators [37] on the other hand associated normal distribution with each parameter to create probability density function. They then integrated the function to create a cumulative probability function on which they determined exceedance probabilities. However, similar to Lopes et al [36], they also created curves relating tank size to deficit rate at different exceedance probabilities [37]. Both sets of curves show that smaller tanks (less than $20m^3$) have sensitive deficit rates. Lopes et al study [36] was based on rainfall patterns in Brazil while Su et al was in Taiwan.

While adding probabilistic variables complicates the design, using probabilistic variables that change with time often results in a more efficient, less expensive systems. In fact, Ward, Memon, and Bulter (2010) studied the influence of design approach on tank size by comparing three different tank-sizing methods - YAS daily simulation, storage duration, and demand requirement. They determined that the installed, simply designed systems were drastically oversized and that more sophisticated tools (i.e. YAS daily simulations) create more efficient, cost-effective systems [38].

Mun and Han (2012) evaluated the effect of the catchment area, tank volume, and water demand on the operational performance of RWH systems. They defined operational performance in terms of rainwater use efficiency, water saving efficiency, and cycle number. Rainwater use efficiency measures the rainwater used from storage divided by rainwater collected for the RWH system. Water saving efficiency is measured as defined in equation 3. Cycle number measures the amount of rainwater used per unit of tank volume. Therefore, high values of rainwater use efficiency and water saving efficiency indicate a high performing system. Cycle number is useful in understanding how long the water is stored within the tanks as well as estimating the annual rainwater consumption. In a sensitivity analysis, Mun and Han [12] determined that rainwater use efficiency and water saving efficiency are proportional to the ratio of tank volume to catchment area, but cycle number is inversely proportional. However, for all there parameters the relationships are exponential – meaning small changes in the design parameters have large effects in certain ranges, but there are also ranges where large changes will have little effect on the performance of the systems. This is particularly useful when considering how to size the storage tank [12].

Palla and collaborators [35] studied water saving efficiency, overflow ratio, and detention time with respect to demand and storage fraction. Demand fraction – annual water demand over annual inflow – was determined to have a signification relationship with water saving efficiency and overflow ratio. Water saving efficiency was calculated in the same way as Mun and Han and shown in Figure 3 [12]. The overflow ratio compliments the rainwater use efficiency in that the overflow ratio measures rainwater that cannot be capture over the total. Storage fraction – annual storage over annual inflow – affects the detention time. Thus, Mun, Hun, Palla, and collaborators [35] both show the inverse relationship between storage ratio and cycle number. Cycle numbers are inversely proportional to detention time; therefore the relationship between detention is direct. Palla et al. recommends that systems aim for a medium demand fraction and low storage fraction in order to reduce water quality degradation [35].

The Rainwater Analysis and Simulation Program (RASP) allows designers and regulators to evaluate the tradeoffs between rainwater collection as a water supply and runoff capture method. While both of these objectives are generally beneficial to the surrounding environment, rainwater systems can be adapted in order to favor one or the other. The RASP model demonstrates those tradeoffs using reliability metrics. The research team found that (1) increasing the irrigated area reduces the water supply reliability while hardly influencing the runoff capture reliability, (2) increasing the roof area has a negative effect on the runoff capture reliability, and (3) increasing storage improves both supply and capture reliability [39]. These are logical conclusions; however, more interesting, they also found that increasing the roof areas has a stronger positive effect on water supply reliability than storage. This implies that in order to increase the water supply reliability of a RWH system designers should consider increasing the roof area rather than the storage. Similarly, to increase runoff capture reliability designers should increase first storage and then indoor use [23], [39].

3.2 Return on Investment (ROI)

In order for rainwater harvesting systems to become more commonly used, they will have to create a positive benefit to the owners or operators over time. A lifecycle cost benefit analysis compares benefits to costs over the useable life of a system. Unfortunately, there are many different methods by which to create a benefit cost analysis (BCA). Luckily, many BCA models are developed using excel making them accessible to homeowners, developers, designers, and planners [40], [41]. However, each model is made with a different set of assumptions which can unfortunately drastically change the results [42]. For example, many BCA models include municipal water and wastewater charges set by the local water purveyor[39]. However in Seattle, Seattle City Light provides a wastewater credit for water that does not enter the sewer system [43]. Therefore, a BCA model for a RWH system in Seattle should not include wastewater charge reduction as a benefit of the RWH system. BCA are presented in the literature as a set of scenarios tested under certain static assumptions or as a model where by parameters can change and therefore change the result.

Four studies presented current snapshots of rainwater harvesting scenarios, a simulation of rainwater harvesting for residential irrigation in 10 different Australian cities never found a scenario with a positive benefit, even with a government rebate. The BCA included water savings for benefits and the tank, foundation, pump, filter, labor, plumbing and electrical supplies for costs over 40 years with a discount rate of 3% [44]. In the same way, a case study in Istanbul found that municipal water is still the cost effective choice because the payback period of a rainwater system is 15 years. Therefore, water efficiency improvements are more cost effective for most homeowners [45].

A recent student in Spain calculated the payback period for RWH systems in single and multi-family homes. Costs included the tank, pump, filter, maintenance, and electricity while benefits were limited to the water savings. The payback period for irrigation RWH systems was between 33 to 43 years with the higher cost of water and 0% discount rate; and more than 60 years, if a discount rate of 4% was applied. Similarly, a studying using the Economic and Environmental Analysis of Sanitation Technologies (EEAST) model found a cost payback period of 64 years due to the low cost of water; however, it also included energy and carbon emission payback periods at 12 and 9 years respectively. The research team included a tank, pump, filter, pipes, concrete foundation for tank, and energy used by pump as costs for a rainwater irrigation system [41]. In a follow-up study done by the EEAST research team, rainwater irrigation systems installed as a part of a renovation of dormitories had a more favorable cost payback period of 13 years. They attributed this to the lack of dual piping and booster pump, however, they also mentioned that the payback is still largely based on the price of water. This research is very different from the other studies in that it aims to quantify the effect of RWH systems on energy and greenhouse gas emissions. The model compares the business as usual case to a series of scenarios in terms of cost, energy, and greenhouse gas emissions. Since the beneficiary of the cost payback is the owner, and the emission reduction beneficiary is the community, the payback periods are never integrated. However, when the research team completed a life cycle assessment of the materials involved in RWH project they determined cistern is dominate both cost and emissions. They recommend that any design team optimize the financial and environmental impacts when sizing a cistern [46]. The EEAST model is available for download (http://eeast.wikispaces.com/home) and is a good tool to consider the life cycle impacts on energy and emissions for any rainwater system [41]. Furthermore, if the water is being only used outdoor, energy is saved by not treating the water to potable standards [8], [47]. Unfortunately this type of energy savings would not be seen by the owner of the rainwater system, unless they are treat their own water.

Two studies presented a BCA where the parameters changed over time. In a study done at the watershed scale in California, only small, outdoor, gravity-fed RWH system reached a positive benefit over a lifecycle of 30 years when the price of water remained constant. However, when the research team experimented with increasing the price of water beyond inflation, the majority of non-potable RHW systems from 208 liters (L) to 7571L had a positive benefit over 30 years. The BCA included the economic value of saved water and energy, the social cost of carbon as defined by 2013 Interagency Working Group, and the cost of the RWHS components (including construction and pump replacement, but not annual maintenance) [42]. Similarly, in a study using the RASP model for individual systems, RWH never reached a positive ROI when providing irrigation and fixture water in high density residential, medium density residential, low density residential, office, and commercial scenarios with a lifecycle of 50 years. The cost benefit analysis included primary benefits (direct monetary savings to the owner) and costs associated with a RWH system as well as dual plumbing for toilets fixtures indoors. However, for all land uses, if the water and wastewater rates were to double these benefits exceed the costs. Low density and medium density at current water and wastewater rates are closest to achieve positive benefits, particularly for water supply [39].

Houdesdhel et al. [48] updated the whole-life-cost model developed by the EPA, WERF, and UKWIR to include rainwater cisterns for commercial buildings with initial cost, maintenance, and lifecycle of a tank and redistribution pump. The model included the cost of installation of the tank, but did not include conveyance to the tank because it was assumed that the building conveyance system could be adapted to route rainwater into the tank at little to no cost. The redistribution pump was assumed to be used for irrigation sprinkler application with minimal filtering. The research team ran into problems finding information related to the cost of system installation and continued maintenance of a system. Therefore, the research team had to make assumptions; the cost of installation was based on a percentage of the tank cost and continued maintenance was estimated using the cost of labor, materials, and equipment from RS Means in 2008. Due to these assumptions, the research team recommends using the whole life cost tool as a template whereby the assumptions should be change for actual estimates [48]. Unfortunately this model does not cover the benefits of a RWH system in order to complete a BCA; however, it is helpful in understand the parameters which affect the cost of the system.

One noticeable gap in the current BCA models are benefits that can be gained rainwater harvesting affect on stormwater management. A rainwater harvesting system not only reduced the amount of water that is going into the storm sewer, but also can reduce the size of other stormwater management structures. Nevertheless, rainwater harvesting systems have the potential to have positive return on invests particularly in light on increasing water rates [49] and increased desire to have local water sources.

RainCycle was one of the first computer software to model RWH systems based on life cycle cost. RainCycle simulates the daily performance of a rainwater harvesting system over its usable life, focusing the system hydraulics and cost performance. It requires simulated rainfall data, demand, capital and operational cost in order to calculate long term savings and pay-back period. RainCycle uses a 3.5% discount rate, which due to the long time frame of these projects is essential to present an accurate representation of the RWH system savings [30]. RainCycle is a free software which operates through Excel.

Plugrisost is a software developed to simulate the economic and environmental impact of different rainwater and graywater systems. It uses a life cycle approach to understand the construction and operating impacts throughout the lifespan of alternative water technologies. The program uses a water balance to determine the amount of tap water that is bought, and potential environmental impacts. The potential environmental impacts are calculated based on the lifecycle of the materials used in the system, the construction activities, and the energy and replacement materials use during the system's life. Using a case study in Portugal, the research team found first that due to the low cost of tap water, only tanks less than one cubic meter had a less expensive cost of water and second that only tanks less than four cubic meters reduced the amount carbon dioxide equivalent. However, the research team does emphasize the cost of water and the amount of demand have large effects on these outcomes [50].

4 Irrigation

4.1 System Design

Irrigation is the collection, storage, and use of water for plant growth. Large scale irrigation is typically agricultural, recreational, or commercial while small scale irrigation is seen around most homes in the United States. Large fields, particularly athletic fields will have sprinkler systems, which distribute the water over them; while vineyards will have drip irrigation providing water directly to the roots, where the water is needed. Water used to irrigate crops does not have to be potable, drinking water. In fact, many farmers will use water from a nearby stream, canal, or lake while a homeowner will most likely use city drinking water. Due to changes in pressure, quality, and quantity, where the water comes from directly influences the design of irrigation system [25].

Municipal water flows from a reservoir, though a filtration and disinfection to business and homes across the area for drinking water. However, not all that water consumed by people; instead the water is used to shower, flush toilets, and irrigate lawns, golf clubs, and gardens. The utility provides that water at a defined pressure and flow rate. Since this water is already pressurized, some residential systems may not need additional pumps; however, the majority of systems will need a pump. This pump should be sized to fit the exact irrigation system being installed or that was installed. Every turn, valve, and distance that changes the pressure operating throughout the system; therefore, it is important that they system be designed [25]. The quality of the water will affect the filtration requirements throughout the system. Dirty water causes malfunctions in the solenoid valves and could clog other aspects of the system.

Irrigation systems are laid out as a function of the landscapes and components (sprinklers or drip emitters) distributing the water. Landscape designers and irrigation professionals start with the landscape and the climate, determining the water demand for each plant in combination with the evapotranspiration rate. Next, they fit a sprinkler system or a drip irrigation system to meet that demand. The manufacturers of irrigation components recommend operating pressures for certain distribution patterns. The designers now have the water demand in gallons per minute and the pressure required to make the system operate efficiently; they can now pick a pump, controller, and cross-connection setup. The pump must be able to produce the highest gallons per minute at the pressure for the farthest sprinkler/emitter. A controller can be as simple as a manual isolation valve that turns the water on and off or it can be electric (solenoid) controlled by current weather conditions and plant demands. Cross-connection, as was mentioned early, must be done correctly. Cross-connection occurs when non-potable water becomes in contact with potable water. In an irrigation system, the water distributed is considered non-potable since. At UW, a double check valve creates the cross-connection and back flow protection. The check valves will automatically close if pressure builds within the valve flowing opposite of its intended directly. The second check valve is there for redundancy and added safety. An reduced pressure backflow assembly is very similar; however, it has a drain between the two check valves that allows the black-flowing water to exit the irrigation system. Therefore, this assembly must be located above ground outside, above a floor drain inside, or adjacent to a sump pump [14], [25].

4.2 Operation and Maintenance

With all mechanical systems, there are operation and maintenance requirements; however, in irrigation this is particularly true. The entire system is exposed to the elements; sprinkler heads are often knocked off my people and animals unaware that they are there, drip irrigation lines become clogged if there is too much dirt in the system; winter temperature can cause components to freeze. At UW, the grounds crews must check the filters throughout the campus quarterly, repair any malfunctioning automatic valves, and maintain proper watering schedules through the central control system.

4.3 UW Irrigation System

The UW Seattle irrigation system uses a large network of underground piping, control systems, remote monitoring, and weather stations in order to precisely irrigate landscaped areas. Across campus, there are 17 zones; each of which has a series of sub-zones that are operated and controlled by the irrigation controller. Each of these sub-zones are designed to meet the needs of the landscape they are watering; therefore, there is a combination of drip, sprinkler, and manual (watering via hose) irrigation systems across campus as can be seen in Figure 2.

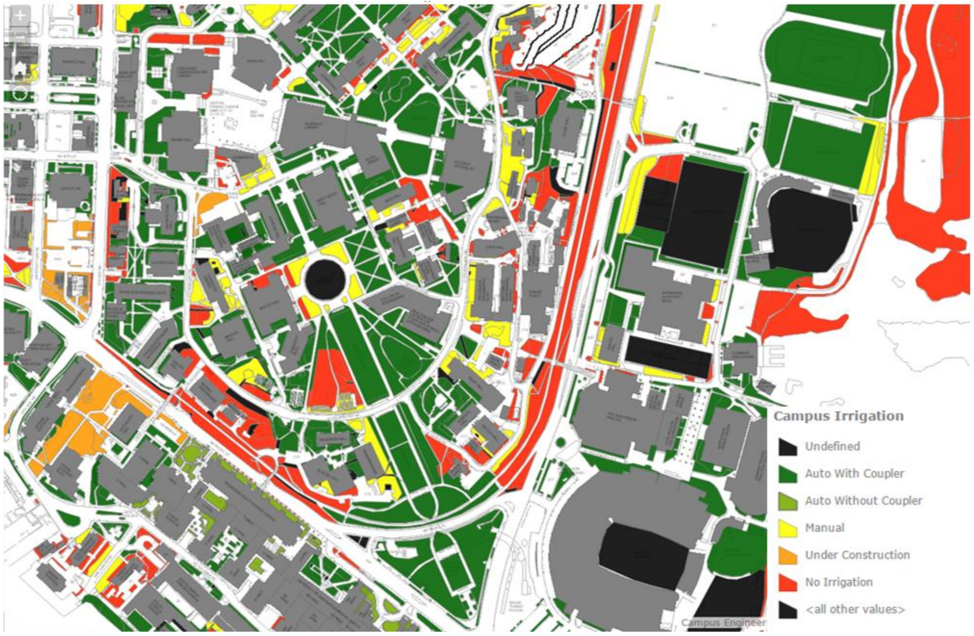

Figure 2: Irrigation Systems on UW Seattle Campus

The irrigation systems turn on during the first warm, dry days of the year – early to mid-May and then remain on until September when the rains begin again. Therefore, irrigation water is a major contributor to water usage on the UW Seattle Campus during the dry summer months, as seen by Figure 3. Since UW is determined to reduce its water consumption. UW Facilities Ground Management made significant strides in improving irrigation. Landscaped areas are irrigated through a combination of drip and sprinkler systems connected to an intricate pipe networks that is centrally controlled and supervised through an advanced system of remote monitoring. In fact, UW's water conservation efforts resulted in a 35% reduction in the number of gallons used per day [51].

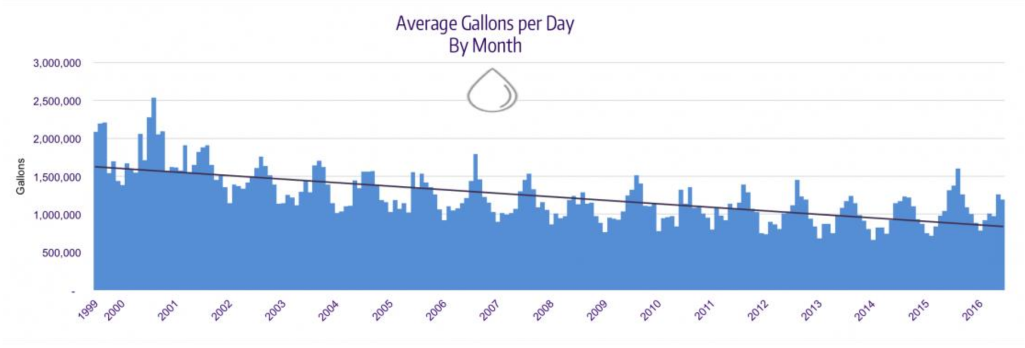

Figure 3: Water Usage at UW Seattle from 1999 to 2016 [52]

Irrigation water is purchased from Seattle Public Utilities and is primarily consumed during the SPU's peak water rates, making the water more expensive. In 1998, the irrigation shop started submetering irrigation water to assess where water was being used, identify overwatering, and ultimately reduce the wastewater charges from the University utilities bill. Today, this metering program saves UW almost $175,000 annually [51]. RWH harvesting systems can contribute to this savings by providing water for campus landscapes.

5 Market Analysis

5.1 ARCSA 2016 Conference

In the United States, the American Rainwater Collection System Association (ARCSA) is a non-profit organization, which aims to increase awareness and education about rainwater harvesting. ARCSA's mission is to "promote sustainable rainwater harvesting practices to help solve potable, nonpotable, stormwater and energy challenges throughout the world" [53]. ARCSA was the first organization, to offer an accreditation program for rainwater harvesters. Since rainwater harvesting systems can and often are designed by those with limited rainwater experience, this certification allows designers and installers learn how to improve the performance and lifecycle of rainwater systems [54]

In December 2016, ARCSA held its annual conference in Las Vegas Nevada. Rainwater professionals, designers, manufacturers, and installers gathered to share information during the two day conference and promote new products and services during the trade expo. During the conference, speakers shared about (1) the importance of rainwater being included in state water plans, particularly in light of the state of America's pipe infrastructure [55] and the increasing water rates [56], (2) the Texas legislative changes that are working to improve the integrity of the industry by implementing licensure program, (3) the systems approach to reducing water use in landscapes, (5) the evolution of tanks over time, and finally (6) the dire need for representative research about the water quality for rainwater harvesting systems. In fact, Sarah Sojka of Randolph College pointed out that there is generally a lack of academic research that is representative of what is known in the professional rainwater harvesting field (i.e. potable rainwater systems work!). Academic research tends show how rainwater systems could be designed to improve performance for demand or stormwater runoff, but few studies show how rainwater harvesting systems perform over time. Sojka aims to collect rainwater quality data from the ARCSA community in order to understand water quality trends within potable rainwater harvesting systems.

Figure 4: ARSCA 2016 Trade Expo

There were fifteen companies associated with ARCSA at the joint tradeshow with the National Groundwater and Irrigation Associations. However, only three companies offered design and consulting services; as can be seen in Figure 4, the majority of the remaining companies were manufacturers, making everything from tanks to valves. Three companies however stood out. First, Conservation Technology is a company that prides its self on system integration. They manufacture a fair number of pieces (particular anything related to green roofs) and they work with engineers and architects in order to design a system that will last 40 to 50 years. Conservation Technology offers a wide variety of cistern shapes and sizes. In particular, they specialize in thin systems, which are structurally sound to be put under porous pavement, but are also light enough to be used for storage on a roof. The advantage of these thin storage systems (shown in Figure 5) is that they are more adaptable to congested, high profile spaces. Unfortunately, Conservation Technology does not warranty their systems or components. Therefore, all installations obligations are placed first on the contractor then the building operator once construction was completed. On the other end of the spectrum

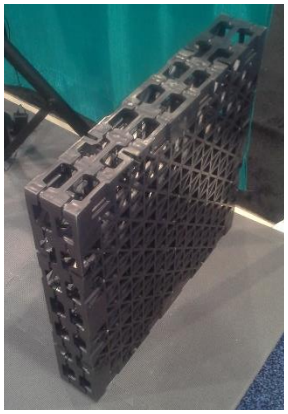

Figure 5: Thin Systems form Conservation Technology

Aquaharvest is a subdivision of larger company focused on design, construction and operation of wastewater treatment plants. While their systems are more industrialized and automated, it does come with on call service staff to help fix problems as they arrive.

Rainwater Management Solutions based out of Virginia is right in the middle. The company manufacturers, designs, and installs systems all over the world. In fact, they designed and installed the potable rainwater system in the Bullitt Center. RMS focuses on a four-step system which they believe will create the least maintenance and the most cost effective system: (1) Pre-tank filtration, (2) Smoothing inlet, (3) Floating filter, and (4) Overflow device, seen in Figure 6. This method should prevent sediment buildup in the tank and can be scaled and simplified in such a way to create a positive return on investment.

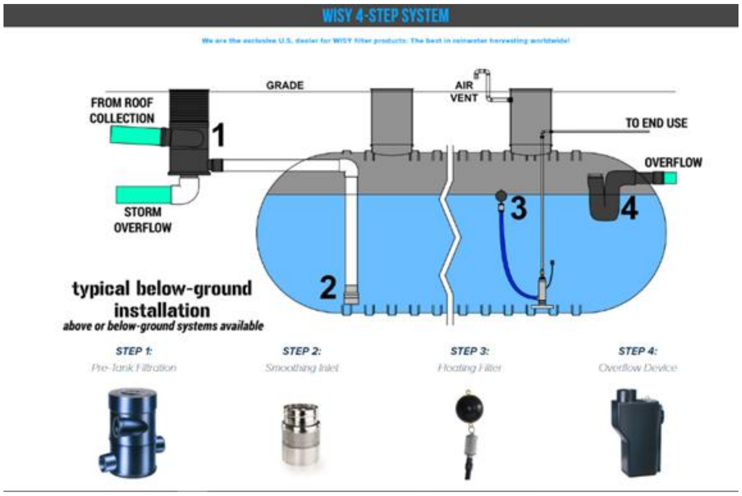

Figure 6: RMS 4-Step Rainwater Harvesting System (from www.rainwatermanagement.com)

RMS provides two questionnaires online which the research team will use to guide data collection on potential sites on the UW Seattle campus. Due to the remaining companies' pure focus on manufacturing, the research team collected information related to innovative products. For example, Blue Mountain Co., makes a leaf-eater which is designed to take the place of a first flush system, but never require maintenance, and Black Diamond makes innovative water storage bags.

5.2 Pacific Northwest Questionnaire

Since RWH systems are climate dependent, the research team conducted a survey of public universities in Washington and Oregon with RWH. Facilities, planning, capital projects, grounds, and sustainability offices from 19 different campuses including the University of Washington Seattle Campus were included in the survey. Of the 238 in the sample, seven responded during the pilot study and thirteen to the finalized survey. The responses from the pilot questionnaire helped us to clarify the questions as well as shorten the overall survey in hopes of higher response rates. Figure 7 shows the roles of the questionnaire respondents with respect to the RWH system. 50% of the respondents had working RWH systems; 30% of respondents indicated that the systems do not currently work and the remaining respondents did not know if their RWH system was operational.

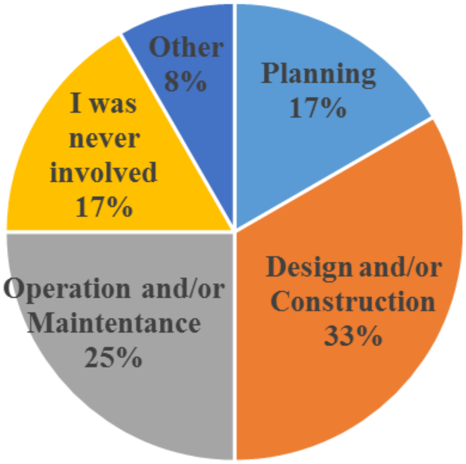

Figure 7: Survey Respondent Breakdown

The results indicated that the biggest perceived benefit of RWH systems is reduction in potable consumption (50% of respondents). Other benefits included sustainable source of water, less energy intensity, water conservation and higher quality water. As was mentioned in the literature review, Vierra et al. [29] showed that RWH can often use more energy due to the pumps not working efficiently. In fact, systems should have be designed to provide water at the optimum conditions for the pump or use gravity in order for the RWH to be more efficient than the utility system. Generally, water conservation is dependent on a highly efficient system, not the source. In our case, the irrigation systems should either be drip or set to a watering schedule which adapts for changing weather conditions. In buildings, plumbing fixtures which are low flow reduce the total amount of water consumed. Finally, RWH have positive impacts on stormwater in terms of quality and quantity. A RWH acts like a retention pond slowly releasing the water over time. As a stormwater management tool rainwater harvesting offers both an improvement to the natural environment surrounding impervious areas and a cost savings through drainage fees.

The biggest challenges mentioned were limited resources for maintenance, not enough rainwater supply for irrigation during the dry summer months, limited space for rainwater storage, filtering the water, compliance with regulatory agency and capital costs. Operation and maintenance is often excluded from the cost and benefit models and empirical experiments do not run past the workable life the filter. Therefore, maintenance teams often inherit systems which are not being maintained due to budget reasons and lack the information about the necessary maintenance. In fact, the questionnaire asked specifically about the operation and maintenance of these systems. The majority of the systems received O&M information through the construction submittal process, and the grounds or university team was charged with completing the necessary maintenance. Finally, water rights must be considered throughout the West Coast. Rainwater system owners should guarantee with the local authorities that collecting rainwater does not impact water rights.

The respondents were then asked if the benefits outweigh the challenges. Five people said no; three people answered yes; and finally four people said possibly. The five who responded no largely relied on the fact that operation and maintenance often outweighs the water saving cost. Those who answered yes focused on using less water from the potable system. The majority of the systems included in the survey were installed as a sign of environmental stewardship and sustainable water source.

We learned several important things from this survey. First, RWH are often installed as sustainability demonstrations while realizing that they do not have a positive return on investment. Second, the 42% of people do not believe that the benefits of RWH outweigh the challenges. Third, the challenges associated with a RWH a numerous, but are mainly a function of high maintenance demand in comparison with using domestic water. Future research should include detailed interviews to learn more the specific RWH system, its challenges, and benefits. For UW, the research team conducted those interviews for the three RWH systems currently installed on the Seattle campus. Those details as well as design details are presented in the section below.

6 Existing Installations at UW

6.1 Merrill Hall

Merrill Hall, the home for the Center for Urban Horticulture, was remodeled in 2001 after a domestic terroristic attack related to genetic modification of plants destroyed large portions of the building. It is restored to LEED Silver, costing approximately $8.1 million. The new building included a 6,000 gallon underground rainwater cistern. The rainwater irrigates a landscaped area just above the cistern through drip irrigation. The rainwater is collected from 19,000 square foot roof area and is routed through the cistern to the drip irrigation or to a bioswale for overflow. The drip irrigation system is not only efficient but also smart. The irrigation system is connected to a controller, which uses a weather station on campus to tell the system when to turn on. Figure 8 below shows the design of the system. Water is collected off the roof, stored in the underground tank, pumped into the irrigation supply line. The pump is submersible pump bolted several inches above the bottom of the tank. The overflow pipe is located three feet above the bottom of the cistern and can be manually opened with a chain from the top of the tank. In order to service the cistern, plumbers must have confined space training and must set up the proper safety equipment prior to entering. These essential steps to ensure safety are nevertheless time consuming and due to the relatively small impact rainwater cistern has, the cistern has remained empty for many years. Brain Davis and the grounds department attempted and were successful at repairing the system several years ago; however, due to the small size of the irrigated area, the system cannot be made a priority for repair.

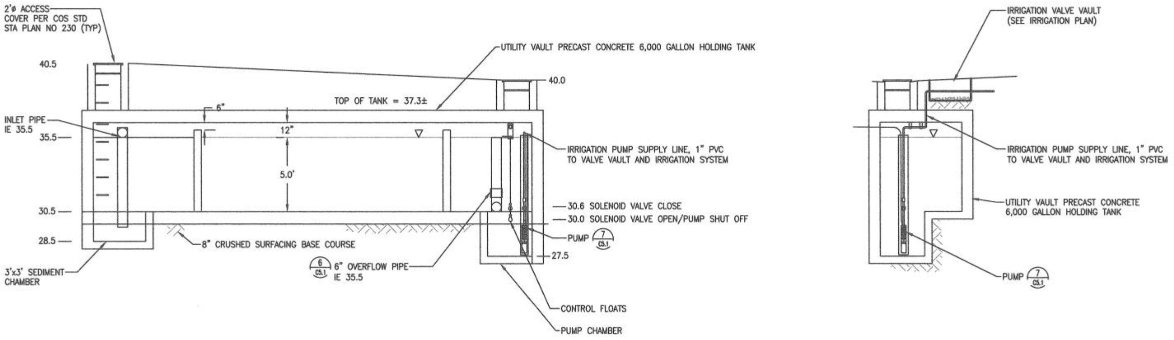

Figure 8: RWH System at Merrill Hall (Design Drawings)

6.2 Biodiversity Green Wall, Edible Green Screen, Water Harvesting Demonstration Project

Installed on Gould Hall, the green wall was installed in 2012. The system collects rainwater from the roof of Gould Hall and stores it in two thousand gallon above ground cisterns. The cisterns were installed on a concrete pad and behind a metal screen for aesthetics and security. Domestic city water is connected to supplement the cisterns if the rainwater supply is lower than demand. The overflow connects back to the rainleader within the building as is shown in Figure 9. The water irrigates the green wall. The irrigation system uses soil moisture probes to determine when the wall needed water. After several iterations of programing and drip lines, the system uses approximately five gallons of water per day. A transducer controls if the rainwater enters the cisterns as well as creates a first flush diverter. If the cisterns are full, the transducer opens for roof runoff to run directly to the storm sewer. However, when the transducer is closed, as can be seen in the figure below, the initial rainwater will collect above the transducer. Water will only start entering the cisterns once the pipe between the transducer and cistern inlet pipe is full. The first flush diverter is the only quality improvement for the collected rainwater. This system requires a considerable amount of operation and maintenance due to the sensitively of the plants. As the plants in the green wall are primarily hydroponic, irrigation is essential for their success, particularly in the dry summer months. Unfortunately, when the system was installed the operation and maintenance plan had not been established or funds designated, resulting in rework and wasted resources. To date, the pumps have been replaced twice, and as a result the plants had to be replaced.

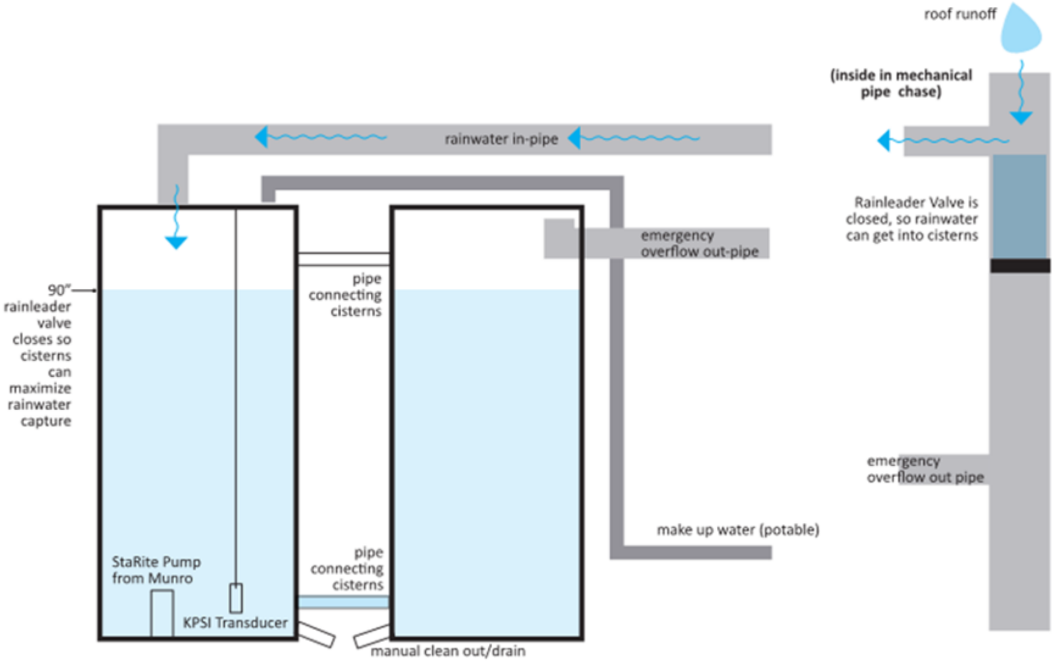

Figure 9: RWH System a Gould Hall

6.3 Mercer Court's Laundry Facility

Collecting rain from four of the five roofs in Mercer Court, the underground rainwater harvesting system is able to source approximately 90% of the daily laundry needs for the 288-

LEED Gold apartment building [57]. The rainwater harvesting system earned the design team and building five innovation credits. The water is collected from the roofs, transferred through the buildings to a central collection point outside of the cistern. As can be seen in the Figure 10, the rainwater then goes through a vortex filter and a smoothing inlet before reaching the 125,000 gallon cistern. The cistern is a concrete tank with a plastic liner. Two submersible pumps move the water from the underground cistern inside the building. It goes through a series of screen filters to day tank inside of building A. The day tank is connected to a closed-loop UV system. Water continuously pumps through the UV filter and returns to the day tank. The water from the day tank travels through a pump and into the laundry facilities. Since the rainwater is used within a building, it is clearly and frequently labelled with purple signage indicating that the water is non-potable. Domestic cold water is used by the laundry system if the demand exceeds the supply of rainwater. The system cost approximately $600,000 in 2012. The project was built as a demonstration of sustainability as well as resiliency.

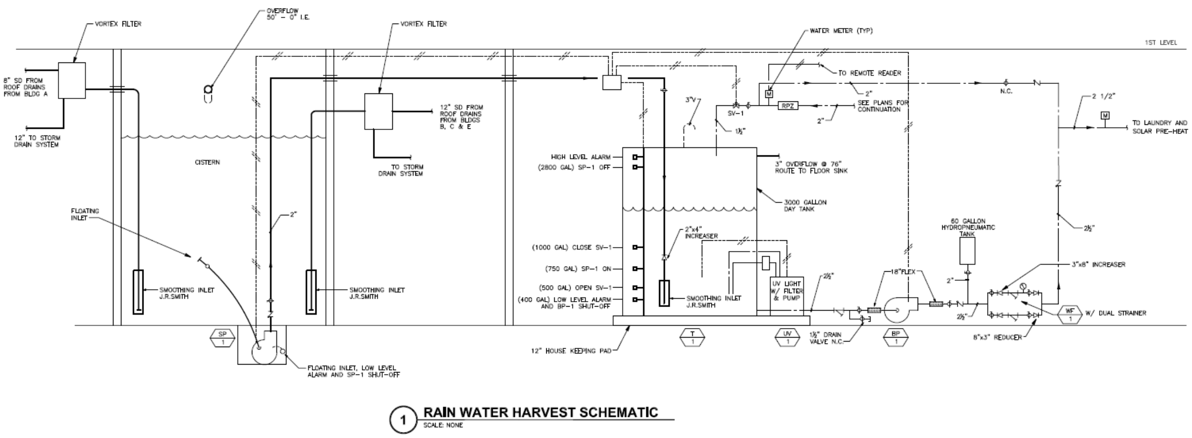

Figure 10: RWH at Mercer Court

The system has been in operation for approximately four years, and has had several reoccurring operations and maintenance issues, according to JR Fulton, Housing and Food Services' Sustainability Director. Unfortunately, during that time, the pumps have failed twice, resulting in draining the tank. While the pumps can be moved via rail to the top of the cistern for maintenance, electrical wiring and access required the tank to be drained. Initially the pump intake pulled water from the bottom of the tank. This caused an increased sediment load within the pump and eventually broke it. The replacement pumps were installed slightly higher than the original installation; however, when the pumps needed maintenance, they could not be lifted out for repair. Finally, the UV system clogs frequently causing the entire rainwater harvesting system to shut down and divert domestic water to the laundry. During construction, the project manager, Jeffery Huebler mentioned the difficulty in conveying water from four roofs to a central rainwater cistern using only gravity. Furthermore, the water service room that contains the day tank had limited space, making operation and maintenance of different components challenging. In particular, when the day tank needs replacement, it will need to be constructed within the room because the piping systems were installed around the tank due the space limitations.

7 Feasibility Analysis

7.1 Potential Locations

For this project, the goal was to recommend a location, design, and budget for a RWH system which would take a considerable chunk out of the irrigation demand during the summer months while being aesthetically pleasing operationally simple, and cost-effective over its lifetime. The research team identified three locations around the Seattle campus to study. We evaluated the sites for (1) proximity to a downspout, potable connection and irrigation controller, (2) availability of space for rainwater storage and access maintenance, and (3) water demand based on plants and water supply based on roof catchment area. The design goal was to provide at least ten percent of the necessary water for a landscape over the summer using rainwater. The economic goal was to have a payback period of less than ten years – a very difficult if not impossible goal according to the literature presented above. In order to accomplish those goals, we started by studying the sites and as-built record drawings. These drawings are able to identify how the building and irrigation systems connect to underground utility lines.

7.1.1 Physics-Astronomy Auditorium

On the south corner of the Physics-Astronomy Auditorium the landscaped area is being renovated after the Burke Gilman Trail was expanded. An existing irrigation supply provides easy access to the existing irrigation system and utility backup water. The roof is sloped so that rainwater is directed into six roof drains. Three of those rain leaders combine internally and then into the storm sewer underneath the building slab. Access to storm sewer is just to the east of the stairs, below the sundial. On the second floor there is a balcony that has a separate interior rain leader that would be easier to access reroute from the first floor into a cistern. Figure 11 shows schematically where the irrigated zone and catchment area are located. The orange circle represents a potential location for a rainwater cistern.

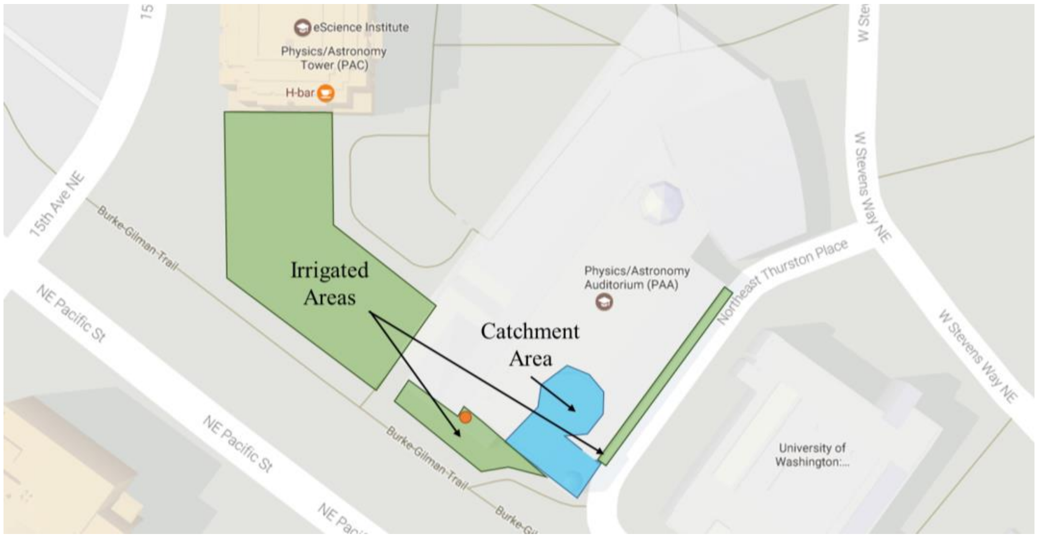

Figure 11: Physics-Astronomy Auditorium

7.1.2 Husky Union Building (HUB)

On the northwest side of the HUB, there is a small landscaped area with an irrigation control vault, making for easy access to the existing irrigation lines as well as access to electrical power. The rain leaders, like most buildings on campus, are interior making them more difficult to access. However, a RWH system could connect on the ground floor on the northwest corner of the building. This rain leader collects rain from approximately 2,500 square feet of roof. The RWH irrigation system would then connect back for the overflows to the storm sewer on the exterior of the building. The irrigation systems surrounding the HUB cover approximately 55,000 square feet as is displayed in Figure 12.

Figure 12: Husky Union Building

7.1.3 Allen Library

On the south side of Allen library is a landscape with plenty of space for a RWH irrigation system. The roof of Allen library concentrates into two rain leaders at the ground level. On the west side of the building – between the loading docks and the corner of the building the interior rain leader connects with the storm sewer. This rain leader catches approximately 8,500 square feet of roof and would be an easy diversion into a rainwater cistern. The irrigation zone surrounding Allen library is connected with Mary Gates Hall making it approximately 60,000 square feet. There is an irrigation supply vault and controller which would make integration into the existing system rather easy. In Figure 12, the small circle represents the potential location of a cistern.

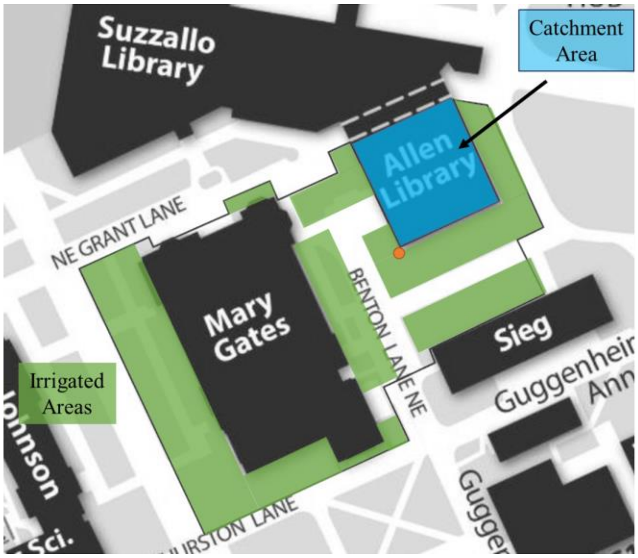

Figure 13: Potential Location near Allen Library

7.1.4 Comparison of Locations

Table 2 shows how the three chosen locations compare. The Physics Astronomy Auditorium has the smallest difference between collection area and irrigated area. Since the irrigation demand is directly correlated with the amount of landscape, RWH systems need enough roof area to catch the water demanded. For the three situations presented, the Auditorium has the best ratio; however, it also has the most constraints around the size and dimensions of the RWH tank. There is both a door limiting the width and a window which would limit the height. Both the HUB and Allen library have large irrigation areas associated with the building. However, Allen library has a larger catchment area that is accessible to a RWH catchment system, making it the most favorable of the chosen sites. For this reason throughout the rest of this report, we will use Allen library as the primary example.

Table 2: Building and Irrigation Characteristics of Selected Sites

Parameter	**Unit**	**Astro. Physics Auditorium**	**HUB**	**Allen Library**
Roof Area	Sq Ft.	2,300	2,500	8,500
Irrigated Area (approx.)	Sq Ft.	13,00	55,000	60,000
Storage Space	Sq. Ft.	50	100	650
Rain Leader Location	(Interior/ Exterior)	Interior	Interior	Interior
Controls Nearby	(Y/N)	No	Yes	Yes
Electrical Access	(Y/N)	Possible	Yes	Yes

7.2 Design Modelling for UW Seattle Campus

As was mentioned at the beginning of this section, the design of RWH typically seeks to optimize the size of the system to a certain level of demand. However, for the University of Washington campus in Seattle, we are aiming to take a dent out of the irrigation demand with rainwater but still create a system which efficient and has a reasonable return on investment. Additionally, in Washington State, rainwater must be collected from roofs built for more than just rainwater collection unless water rights are established. Thus, while all RWH systems have four primary variables (catchment area, demand, tank size, and rainfall pattern), in Washington State the roof catchment area will most likely be given or defined by the building design. For irrigation systems, the demand is a function of the weather, plants, and the amount of landscape to be watered. The following analysis presents the relationship between performance and the ratio of roof catchment areas and irrigated areas. This relationship helps clarify the optimal tank size.

After the water demand is determined, the tank size is determined using three different performance parameters: rainwater use efficiency, water saving efficiency, and deficit rate. Rainwater use efficiency is the ratio between the supply rainwater and rainwater collected from the roof. The higher the percentage of rainwater use efficiency, the more efficient the entire system. Water saving efficiency is the ratio of the rainwater supplied to the irrigation demands.

High water saving efficiency percentage implies a system which is using the water for the intended purpose. Finally, the deficit rate is the ratio of water purchased to the irrigation demand. The higher the deficit rate the more water that is bought from the local water provider. An efficiently designed RWH system will have high rainwater use and water saving efficiency, but a low deficit rate.

In order to understand those relationships for Seattle, we used daily rainfall data from the last five years [58] to model potential yield after spillage (YAS) RWH systems. For any system on campus, the three main variables to be modelled are (1) roof catchment area, (2) tank size, (3) irrigation demand. After determining those three variables, the systems return on investment or payback period can be calculated. Figure 14 below shows the relationship between catchment area (A), irrigated area (IA), tank size (S), and deficit rate for a RWH system in Seattle. As the ratio of tank storage to catchment area (S/A), also called the storage fraction, decreases, the deficit rate also decreases. Also in Figure 14, the ratio of irrigated area to catchment area, called the demand fraction, has a direct relationship with deficit rates. Therefore as the difference between the irrigated area and the catchment area gets larger the ability for the RWH to provide enough water decreases. Ideally the catchment surface will be much larger than then irrigated area. If fact, if irrigated area is half the size of the catchment area and the tank size is 20% of the catchment area, the deficit rate is zero meaning that the demand is met 100% of the time. However, that same system is going to have a rainwater use efficiency (RUE) of 10%, meaning that only about 10% of the rainwater that is collected from the roof is actually used for irrigation. This relationship is shown in Figure 15. Thus a RWH system which meets a 100% of the need but has a use efficiency of 10% has a large catchment area and tank for only a small area of landscape, making it an expensive system due to the large tank.

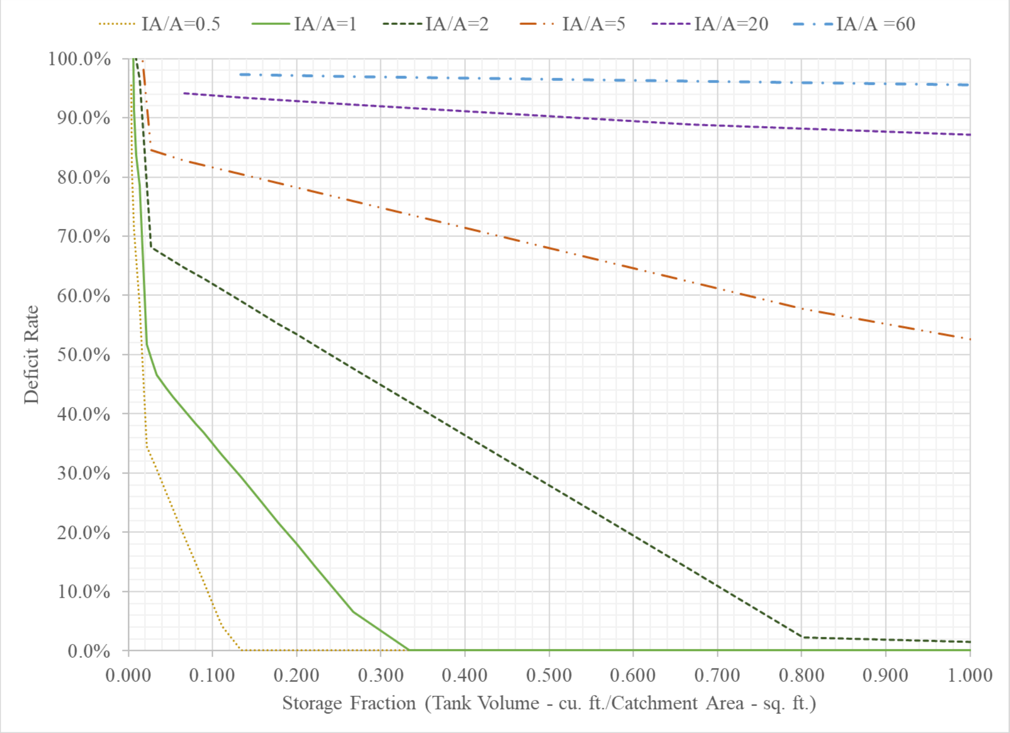

Figure 14: Storage Fraction and Deficit Rate

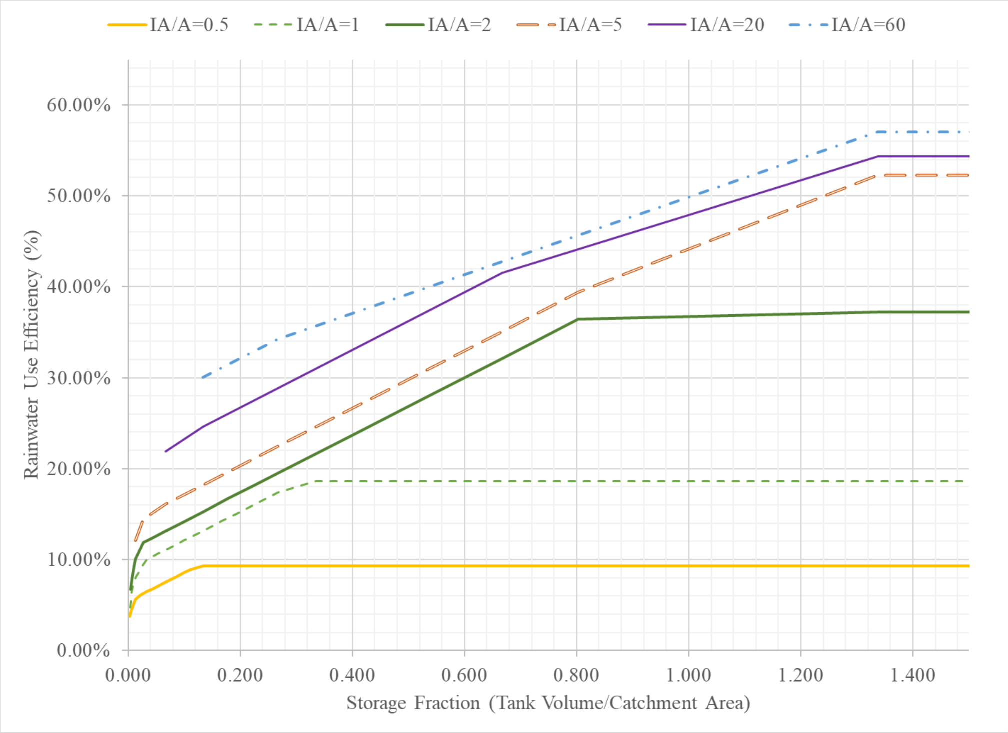

Figure 15: Storage Fraction and Rainwater Use Efficiency

For Allen Library, the roof top catchment area is 8,500 square feet; the irrigated area is approximately 60,000 square feet (the irrigation zone is in green shown in Figure 13). Then, the demand fraction is approximately 7. If we wanted to meet 10% of the irrigation needs, we would have a 90% deficiency rate. In Figure 15 at 90% DR, the IA/A = 5 slope is quite steep, implying that small changes will have large effects on the impact. However, if aim for the "elbow" – where the slope changes dramatically – the system optimizes the scenario. Since the slope changes at a storage fraction of 0.04, the system would require a tank size of 2,500 gallons. To meet 20% of the irrigation demand for the year, the storage fraction would need to be between 0.2 and 0.3. Working backwards, this system would require a 22,000 gallon tank. Now that the catchment area, demand, and tank size are determined, the annual water savings are calculated and shown in Figure 16. Therefore, a 10,000-gallon system (meeting approximately 15% of demand) at Allen Library would create between $300 and $325 in annual water savings at the current water rates.

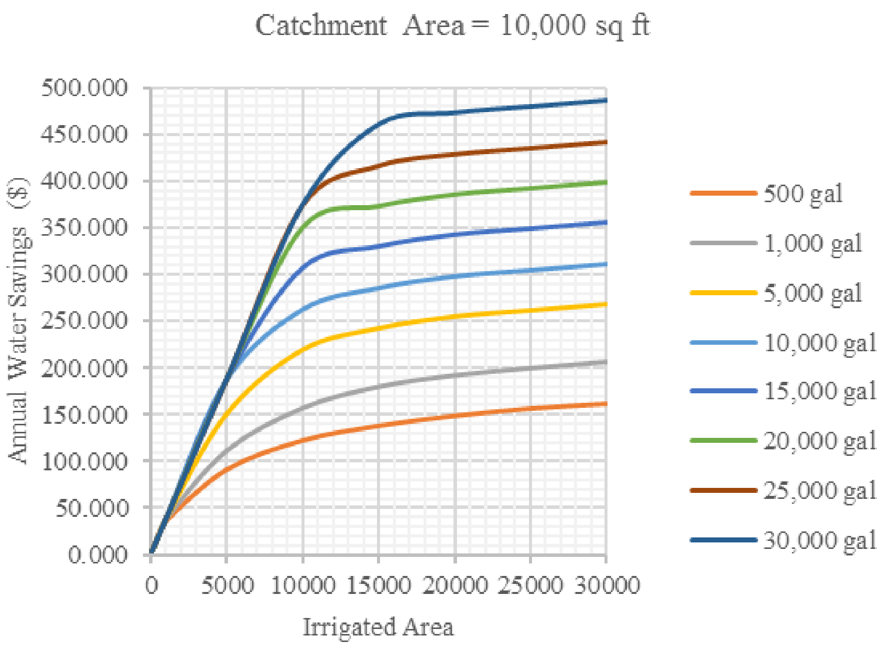

Figure 16: Annual Water Savings by Catchment Area, Irrigated Area & Tank Size

Figure 17 shows that in a fact 15% of the irrigation demand only gets solely supports rainwater though the first couple weeks of the dry season. It is important to note that we are able to achieve this percentage because the model assumes that there is some irrigation throughout the year due to dry spells and rain shadow from buildings. The RWH model presented here therefore assumes there will be some water usage between October to May. However, Seattle has ample rainfall during this time, the tank will be full and often overflowing during the winter. Another use for the rainwater from October to May would increase the efficiency and financial benefit of the system.

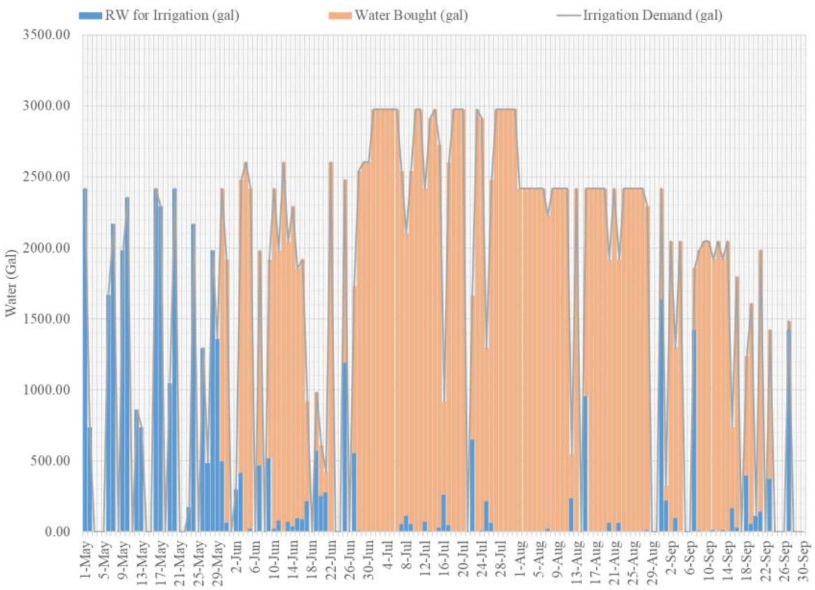

Figure 17: Rainwater Supplied for Allen Library (Meeting 20% of Demand)

7.3 Operation and Maintenance Guidelines

All RWH systems on installed on the Seattle Campus have the unfortunately similarity of problems with operation and maintenance. There are many lessons learned that have come from these systems and from installers across the world. First, it is important to design a system that is easy to maintain. The RWH system should either have components which can easily be removed for repair without entering a confined space, or there should be a permanent davit arm attached to the system to allow easier maintenance access. Both Merrill Hall and Mercer Court have struggled with equipment in the tank. There is should be enough space for trained personnel and equipment to access all areas of the systems. Furthermore, keeping these systems simple will not only reduce the capital costs, but will also create less maintenance requirements. For example, the RWH should seamlessly integrate into the central irrigation controllers with automatic control valves as well as have a manual override that allows the potable water to supply the irrigation lines.

Once the system is installed, there should be specific responsibilities assigned to members of the operation and maintenance team. During the first year of operation, the pre-filtration system, the sediment levels in the tank, and the filters within the irrigation system should be checked quarterly to determine how much is accumulating on the roof and entering the irrigation system. After the first year, a more specific maintenance schedule can be created for the system [14]. For example, the filters may only need a rinse only in the fall and spring due to the rainfall patterns because a lot of debris could build up during the summer months and be flushed through the system at first rain and in the Spring because debris accumulated due to the volume of water moving through the system.

The pump should be checked quarterly to ensure that the controller is turning the pump on and off at the right times. As was mentioned in the distribution section, pumps in low water situations can cavitate and break. Similarly, pumps which cycle on and off continuously can use a lot of power, making for an inefficient system. Annually the pump should be removed from the cistern or from its surface casings to be cleaned and checked for damages. The intake filter should also be rinsed and checked for damages. All pipes that move rainwater should be updated to make all signage clearly readable. At the end of the season, when the irrigation system is winterized could be a good time to accomplish the pump maintenance.

Rainwater tanks will accumulate sediment in the bottom of the tank over time. Every 2-3 years those sediments should be removed in order to reduce the risk of resuspension into the water column [60], [61] as well as reduce stress on the down steam filtration processes and pumps [26]. There are three ways to clean out an above ground rainwater tank. Tanks can be drained and manually cleaned using the service access; however, all persons must be trained in confined spaces and have the proper safety equipment setup prior to entering the tank. For manual, cleaning the sludge is swept or scooped out and then the interior walls are scrubbed [62]. Vacuum trucks are able to pull sludge for the bottom of the tank without emptying the cistern. This is most commonly used for underground tanks or where access is limited or unsafe. Finally, above ground systems have the ability to use a ground level valve to flush the system. In all scenarios, the system should be de-energized for safety of the people and to preserve the pump. In Australia, a country where rainwater harvesting is common for drinking water supply, TankVac (http://www.tankvac.com.au/) has created a self-cleaning system for cisterns.

RWH system can last over 50 years if well maintained; the pump will need to be replaced every ten years, but the plastic piping will last over 30 years [59]. Included within the life cycle cost should be at least one replacement pump and several valves. Table 3 below shows in more detail what a lifecycle budget for a RWH system would look like at UW.

Table 3: Example of Lifecycle Cost Budget.

	Frequency	Duration (hrs)	Responsibility	Cost per hour	Total Cost	Notes
Pre-Filter Cleaning	4 per year	1	1 Gardener	$58.84	$235.36	Note if the filter is dirty prior to each rinse and adjust the filer rinsing accordingly in year 2 and onward.
Irrigation/Sprinkler Cleaning	4 per year	1	1 Gardener	$58.84	$235.36	While these filters are already be cleaned within the UW Grounds budget, rainwater will have sediment than potable water; therefore these filters will need to be cleaned/changed more frequently.
Tank Cleaning	Every 2-3 years	8	Grounds Supervisor	$61.18	$195.78	Every 2-3 years those sediments should be removed in order to reduce the risk of resuspension into the water column.
Pump Controller	4 per year	2	Control Technician	$90.77	$726.16	Pumps are one of the more expensive components of a RWH. They continue to affect the savings and efficiency of the system throughout the rest of its life. Therefore, it is worth making sure that the control system is properly operating the tank.
Pump Check	1 per year	4	Maintenance Mechanic	$59.63	$238.52	
Replacement Valves	Every 7-8 years	NA	Grounds Supervisor	NA	$200.00	Replacement Costs
Replacement Installation	Every 7-8 years	2	Grounds Supervisor	$61.18	$122.36	
Pump replacement	Every 10 years	NA	Maintenance Mechanic	NA	$1,000.00	
Pump installation	Every 10 years	3	Maintenance Mechanic	$59.63	$178.89	

7.4 Projected Return on Investment using Benefit Cost Analysis

In order to determine the return on investment, both the costs and benefits are quantified. For a RWH harvesting project, the majority of the cost is in the capital cost for materials and the installation of the original system. Annual operation and maintenance fees were discussed in the previous section.

7.4.1 Costs

There are two different types of costs in any project: the cost to build it initially – the capital costs – and the cost to maintain it over its life. For RWH systems, the capital costs are high. Largely due to the cost of the tank and its shipping. As was mentioned in section 3.2, these capital costs often create a system which cannot pay for itself over its life. Unfortunately, the same is true for RWH irrigation systems in Seattle. The project team worked with a Rainwater Management Solutions (RMS) to determine how much it would cost to install a RWH on campus. For Allen library, a RWH would cost approximately $50,000 to install a 10,000 gallon tank with a 1 HP booster surface motor. Beyond prefiltration, the system quoted by RMS had no additional filtration, nor did it include the cost of a foundation slab. The quote is attached in Appendix A.

For a RWH system at UW, Table 3 shows an recommended budget of approximately $2,000 for the annual upkeep. However, this can be reduced through detailed tracking of the system's needs. During the first year of operation, the frequency of the filter and pump inspections should be updated to match the system needs. However, at a minimum a RWH should save more money than the money that is needed to keep it running.

7.4.2 Benefits

In the City of Seattle, customers pay (1) a flat rate for connecting the water supply, a variable fee based on the amount of water they use, (2) a variable fee based on the amount of water that is going into the sewer, and (3) finally a variable fee for drainage based on the square feet or property and the amount of impervious surface to Seattle Public Utility (SPU). RWH systems can reduce these fees and are the primary method by which RWH have a reasonable return on investment. Table 4 shows the approximate fees the University of Washington pays for water annually.

Table 4: Seattle Public Utilities – Rates

Charge	Rate
Off-Peak Usage (09/16-05/15)[1]	$5.15/100 cu. ft.
Peak Usage (05/16-09/15)[1]	$6.54/100 cu. ft.
Sewer Rate[2]	$12.93/100 cu. ft.
Drainage Fee[3]	Variable (dependent on sq. ft. & impervious surfaces)

[1] Source: www.seattle.gov/util/ForBusinesses/Water/Rates/CommercialWaterRates/index.htm
[2] Source: www.seattle.gov/Util/ForBusinesses/DrainageSewerBusinesses/SewerRates/index.htm
[3] Source: www.seattle.gov/Util/ForBusinesses/DrainageSewerBusinesses/DrainageRates/RateSchedule/index.htm

Adding a RWH system will not affect the connection base charge because all the rainwater systems will still need to have the municipal bypass in case there is not enough rainwater. Furthermore, the City of Seattle offers sewer submetering to reduce sewer fees for water not going into the sanitary sewer because SPU charges customers based on the assumption that the amount of water you take from the main line eventually goes back into the sewer system. However, in the case of irrigation the water seeps into the ground. For residential customers, SPU uses the average sewer quantities from November to April (when most people are not irrigating due to the regular rainfall) for May through October sewer bills. For commercial customers, sewer submeters measure the amount of water being used in the irrigation system.

SPU then deducts the quantity of irrigation water from the amount of water being used to determine the amount of water being put in the sewer system. Therefore, adding a RWH system for irrigation will not affect the sewer rates and should therefore not be considered a benefit of the system.

As was described by Wang and Zimmerman [60], King County does have an extremely high drainage fee. Drainage fees are paid as property tax to King County annually and are calculated by the square feet of impervious surface contained within a property. In Seattle, the Stormwater Facility Credit programs allows property owners to get tax breaks for installing different low impact stormwater management designs such as biorentention and RWH systems. Property owners can receive a 10% credit on their annual drainage fee in new or remodeled commercial buildings through the Stormwater Facility Credit program [61]. The UW paid over a million dollars last year to King County in drainage fees for the approximately 20,000,000 square feet of property for the UW Seattle Campus.

As Figure 18 shows, a 10,000 gallon system at Allen Library would save UW approximately $300 dollars per year on the water bill. At that rate, the estimated $50,000 would take over 100 years to make its first return on investment – assuming no inflation or operation and maintenance costs and only water savings. With operation and maintenance costs, the system never will be able to make a return on investment as shown in Table 3. However, if UW were able to take advantage of the Stormwater Facility Credit program, a RWH harvesting system would save another $250 annually since Allen library and the associated landscape covers an area of approximately 0.01% of the Seattle campus. Even with the added annual savings, a 10,000 gallon system on Allen library would still cost more annually than it does to operate at this point in time.

7.5 Design Reflections

As design and modelling sections explained, a RWH is traditionally designed using the demand, the catchment areas, and rainfall patterns. An efficiently designed system will meet demand for the majority of the year as well as use maximize use of the storage capacity. However, in climates where there are long wet and dry periods, large storage tanks can be desirable to provide water further into the dry months. For example, irrigation is only needed in Seattle from May to September, the driest months of the year. A tank holding all the water needed for the summer would not only be large, but also would go unused during the winter when the irrigation systems are off. Therefore, design teams must strike a balance between reducing water for irrigation and the size – and expense – of the entire system.

In order to compensate for the larger systems, RWH should find additional demands in winter, as was done in Mercer Court's Laundry facility. Unlike toilets, laundry facilities are concentrated in one area of this facility, which limits the cost of dual piping, while providing a daily demand for non-potable water throughout the year. Similarly, locker rooms are a high-density of toilets, which also can use non-potable water. The two locker rooms in the basement of the IMA have not only the advantage of being underground so gravity will work for the system, but also an almost constant level of demand as gym guests are present throughout the day.

Drumheller fountain also has constant demand of non-potable water. As is being explored by several groups on campus, rainwater or groundwater are potential alternatives to potable water for filling the million-gallon pond. Since RWH systems also provide a form of storm water management through peak flow reduction, some irrigation systems are financially feasible without an alternative use.

7.6 Recommendations for UW Seattle

While the current situation is not economically ideal for a RWH irrigation system, RWH systems offer other advantages which could overcome the financial challenges. Water reliability will decrease as the climate changes and will result in an increase in the cost of water, rationing of water, etc. RWH systems offer resiliency not only in the case of a drought but also in the case of a broken water line or other infrastructure failure. RWH also mitigates peak storm water flows be detaining the water during the storm event. If the rainwater is used for irrigation, the water collected from the roof never enters the combined sewer or storm drain. Furthermore, if the system is connected to a combined sewer system, there are economics benefits in the reduction of water that needs to be treated while if the area has a separate storm system, the benefits are the improvement in quality causes by capturing and filtering the water before use for irrigation [58].

Financially, there will come a time when commercial RWH are cost effective. As the cost of water continues to increase and the storm water policies become more focused on green infrastructure, RWH will have a return on investment of less than ten years. For the Allen Library example the cost of water and drainage would need to increase five-fold in order to make the system cost effective annually. Similarly, a change in the storm water drainage fee to qualify a green roof as a previous surface would also create a more cost effective system because the RWH would save $ 0.07 per square foot per year. In June 2017, SPU released their financial forecast for 2018 through 2023. The report shows small increases over the next five years; however, those small increases in cost result in an approximately 30% increase in the cost of water by 2023 and a 60% increase in drainage fees. Therefore, the Allen library system by 2023 would save approximately $400 annually in water savings and $415 in drainage fees.

RWH systems have construction mobilization and capital costs associated with the cost of a concrete pad, shipping the tank to location, and the control panel which are relatively independent of the system size. Therefore, a future analysis should be conducted to determine the scale at which the capital costs can be paid back in less than ten years. The examples presented here are unfortunately not capable of accomplishing that. Most systems will need to have water and drainage savings of more than $6,000 annually for the system to have a reasonable return on investment of around 10 years. A third of those savings will go to operation and maintenance costs while the remaining would go towards paying back the initial construction and capital costs.

In order to design a system which saves $6,000 annually, the University will need to look for systems that use the rainwater year round. For example, the IMA facility has a larger roof area to collect water and has multiple year round uses for non-potable water. In the summer, the rainwater can be used for irrigation, and in the winter, the rainwater can be used to flush the toilets in the locker rooms. The IMA will be more cost effective than a dormitory or other academic building because the rainwater is used in one central locations – the locker rooms on the bottom floor, reducing the amount of dual piping; whereas, a dorm or academic building has restrooms throughout. Due to time constraints, we were not able to model and estimate the cost of installing a RWH at the IMA, but in future remodels or construction of new gyms on west campus, rainwater should be considered a feasible option, particularly with the increasing cost of water and drainage. If models cannot be developed based on this report, Plugrisost is a good tool to understand the lifecycle impacts and proper sizing of a RWH; however for return on investment, Plugrisost does not include operation and maintenance costs or drainage savings [62].

Figure 18 shows our schematic design recommendation for irrigation rainwater systems installed on campus. The system should use a vortex filter due to its low maintenance needs and high efficiency. The system should include a calming or smoothing inlet to reduce turbulence in the bottom of the tank. The pump should pull intake water from just below the surface of the rainwater tank; the pump should be located outside of the system so that the pump can be easily serviced. Controls between the RWH system and the existing irrigation system should be both manual and automatic (solenoid valves) in order to ensure that the irrigation system can be manually turned on if the controller is not operating correctly. The orange lines in Figure 18 represent communication with the irrigation control box. The system must have a reduced pressure backflow assembly (RPBA) where it connects with the potable water system. The cistern should also have a manual valve at the bottom to drain and flush the tank and finally a two water level sensors – the first sensor would communicate with the irrigation systems while the second would provide tank levels to those interested via a website in connection with the sustainability office.

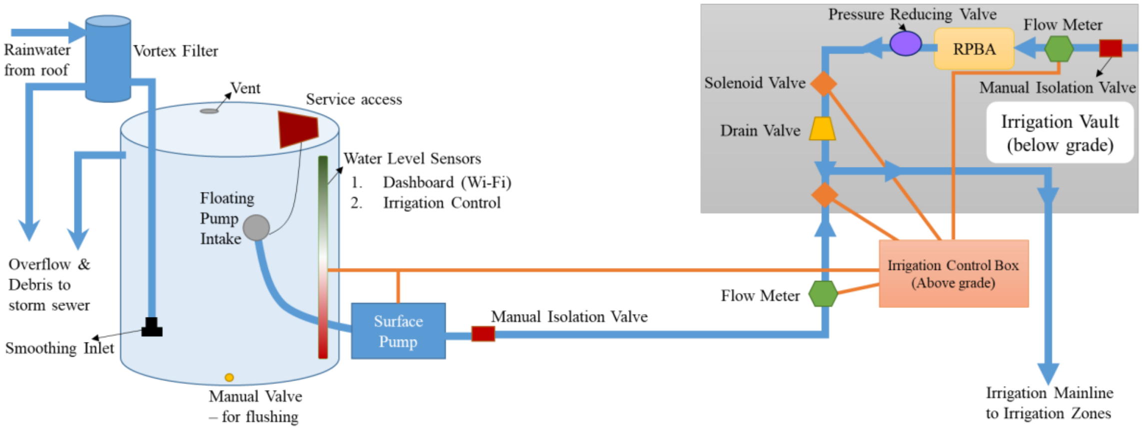

Figure 18: Schematic Layout of Recommended RWH System

8 Conclusion

The goal of this study was to understand rainwater harvesting irrigation systems in order to recommend a rainwater irrigation system for the University of Washington Seattle campus. The analysis started with a detailed literature review and market analysis. During the literature review, we described the four primary components of the rainwater harvesting system: catchment, filtration, storage, and distribution. Within each component, we discuss different design options. These different design options affect the design parameters used to model a RWH system. Modelling is used in rainwater harvesting in order to understand the performance of the system over time. Modelling a RWH system allows the owner and designer to realize the amount of water that can be used to meet demand as well as the efficiency of the system. The modelling results determine the reduction in potable water demand, effect of stormwater management, and the capital cost of the different design options. This information is used to determine the return on investment and lifecycle costs. At this point in this, the cost of domestic water makes the vast majority of RWH systems financially infeasible – particularly irrigation systems which tend to have high water demand in the summer and low in the winter. Dual purpose or more consistent demands has been shown to improve the return on investment and efficiency of the system.

From the market analysis, the research team connected with several RWH design companies. Today, the systems aim for simplicity to reduce the maintenance needs and offer innovative storage solutions for landscapes with small amounts room for water storage. Unfortunately, the majority of companies provide only different RWH system components; while a handful offer design services. From reviewing the installed RWH systems at UW, we learned that companies with RWH design experience are an essential component to reduce design flaws and high maintenance demands. The research team then focused on three potential sites on campus: Physics-Astronomy, HUB, and Allen Library. Unfortunately none of these systems were found to be cost effective due to the large irrigated area and small roof catchment. However, as was seen in the survey, universities still are installing them; therefore if UW decides to continue with the installation of more RWH system, consultation with a rainwater design firm would improve the design to reduce maintenance and improve efficiency. As the cost of water continues to increase in Seattle and across the world due to reduced water reliability, RWH still has the potential for a positive return on investment; however the system must be designed efficiently, used frequently, and maintained properly to meet that potential.

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