Evaluation of Rainwater Harvesting on Residential Housing on Virginia Tech Campus

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Thesis submitted to the Faculty of
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Geography

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29 April 2010
Blacksburg, Virginia

Keywords
Rainwater harvesting, water-energy nexus, energy conservation, Best Management Practices, facilities infrastructure

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Abstract

Rainwater harvesting (RWH) refers to the collection of rainwater for subsequent on-site use. Rainwater is most often used for non-potable purposes including toilet flushing, laundering, landscape and commercial crop irrigation, industry, fire fighting, air-conditioning, and vehicle-washing. This study evaluates the potential impacts of RWH on residential housing on Virginia Tech campus in southwestern Virginia in regards to potable water offset, energy conservation, stormwater mitigation, carbon emission reduction, and financial savings. Potential rainwater collection was estimated from three simulations used to approximate the maximum, average, and minimum range of annual precipitation. Collected rainwater estimates were used to calculate the impacts on the areas of interest. Cumulatively, the sample buildings can collect 3.4 to 5.3 millions of gallons of rainwater – offsetting potable water use and reducing stormwater by an equivalent amount, save 320 to 1842 kWh of energy, and reduce carbon emissions by 650 to 3650 pounds annually. Cumulative savings for the nine buildings from combined water and energy offsets range between $5751 and $9005 USD, not substantial enough to serve as the sole basis of RWH implementation on campus. A significant advantage of RWH relates to the management and improvement of the Stroubles Creek watershed in which the majority of the campus sits. Additionally, RWH implementation would benefit sustainable initiatives and provide Virginia Tech additional opportunities for conservation incentives and environmental stewardship funding.

Acknowledgements

I would like to thank my committee chair and advisor, Dr. James B. Campbell for his patience, guidance, and encouragement during the research process. I would also like to thank Dr. Tamim Younos whose expertise in water resources and sustainable practices was fundamental to this study. Additionally, I would like to extend thanks to my committee members Peter Sforza and Dr. Lisa Kennedy. Mr. Sforza was instrumental in the methological foundation of this research and was tremendously helpful in both data acquisition and graphic production. Dr. Kennedy provided support and direction in the actualization of this research. I am grateful to Thomas Dickerson of the Virginia Tech Center for Geospatial Information Technology for his direction in the initial stages of research and his assistance in supporting material development.

Finally, I would like to thank my family for their love and encouragement, most especially my partner, Elizabeth Wells whose unconditional love and unwavering support kept me sane throughout this process.

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Chapter 1: Introduction

Exponential population growth, urbanization, and the consequent exploitation of water and energy resources have had severe impacts on the environment at large. Human consumption has misused natural resources to an unsustainable point, globalizing the scale of problems to levels requiring both unified and decentralized solutions. One alternative local practice commonly recommended as a Best Management Practice is rainwater harvesting (RWH), the collection of rainwater for subsequent on-site use. This research evaluates the impacts of RWH as an unconventional source of non-potable water, particularly in relation to energy conservation on a university campus.

The basic purpose of this research is two-fold: 1) the conjunctive use and conservation aspects of RWH and energy have not been fully explored by the existing literature; and 2) in relation to the human-land tradition in geographical studies, which originally focused on the influence of environment on humankind, but has since shifted to human impact on the environment. By touching upon questions relating human activity with earth transformation, this study seeks to understand the implications of RWH on the environment and whether its practice can mitigate threats to the sustainability of resource consumption and environmental integrity. The objective application of this paper is to provide of empirically based research that can assist financial decision-makers in an effort to better guide sustainable initiatives on university campuses like Virginia Polytechnic Institute and State University (Virginia Tech) in Blacksburg, Virginia.

Research Objectives

This study: 1) evaluates the potential impacts of RWH on a large, urbanized, institutional campus in southwestern Virginia with regard to potable water and stormwater mitigation; 2) examines the conjunctive use and conservation aspects of RWH and energy; 3) calculates potential carbon emission offset through RWH; and 4) translates empirical research into economic value for use by policy and financial decision-makers in an effort to better guide sustainable initiatives on university campuses like Virginia Tech, Blacksburg, Virginia.

History is full of alternatives to conventional water management practices, several of which are now being studied with the intention of resituating human culture in a more sustainable trajectory. This paper focuses on one such practice, RWH. In the course of investigating the impacts and sustainability of RWH, this paper defines RWH, delves into the significance of such a study, examines research methodologies, considers RWH systems, and analyzes the benefits and shortcomings of RWH. Throughout the review of literature the general trends in RWH studies, variations within modeling, debates over systems, gaps in research, and legal discrepancies are explored. Finally, the data analysis presents the implications of RWH on potable water and energy conservation, stormwater mitigation, carbon dioxide (CO_2) reduction, and economic savings on a university campus in southwestern Virginia.

Background and Significance

RWH refers to the storage and use of rainwater collected from various surfaces. RWH techniques are rooted in the earliest civilizations, most notably in arid regions of the Middle East, Asia, and Africa. In many of these areas, RWH continues to provide a sustainable alternative to groundwater use (Peters, 2006; Mwenge Kahinda et al., 2007). In essence, rainwater is captured as runoff from roofs and other impervious surfaces, stored until needed, and then put to beneficial use at or near the site of collection. Rainwater is most often used for non-potable purposes including toilet flushing, landscape and commercial crop irrigation, industry, fire fighting, air-conditioning, laundering and vehicle-washing. Though it is possible to use rainwater directly as potable water,

water fit for human consumption, it is generally recommended that the captured rainwater be appropriately treated prior to ingestion. The availability, practicality, and efficiency of treatment options are outside the realm of this study scope.

Conservation of potable water sources is rapidly becoming a top global priority. Gardner-Outlaw and Engleman (1997) predicted that by 2025, 48 countries will face water shortages, affecting more than 2.8 billion people—35% of the worlds projected population. However, recent studies conclude that estimate was already reached in 2005 (International Water Management Institute, 2006). Harvested rainwater for non-potable uses can drastically reduce demand on local potable water sources. Some studies in southern Brazil show that the average offset can be more than 40% of daily water demand (Ghisi, 2006; Ghisi et al., 2006). Additionally, studies in Virginia have shown possible potable water savings in both the residential and commercial sectors (Gowland and Younos, 2008; Grady and Younos, 2008).

Water use is indivisibly linked to energy consumption. In the context of water-related energy use, energy intensity is defined as "the amount of energy consumed per unit of water to perform water management related actions such as pumping, pressurizing, groundwater extraction, conveyance and treatment – for example the number of kilowatt-hours consumed per million gallons (kWh/MG) of water" (Klein, 2005, p 4). For instance, in California water-related energy consumes 19% of the state's electricity, 30% of its natural gas, and 88 billion gallons of diesel per year (Klein, 2005). Unfortunately, the water-energy nexus is symbiotic. In 1995, United States electricity production from fossil fuels and nuclear energy used 190,000 million gallons of water per day, which accounted for approximately 39% all of national freshwater withdraws (Solley et al., 1998). Based on the relationship between water and energy use, a decentralized water resource can effectively lower energy use.

As urbanization increases, so do stresses on local water sources. Large populations place a high and often unsustainable demand on available water resources. Additionally, urbanized areas are characterized by high percentages of impervious surfaces, which prevent water from infiltrating the soil and recharging the groundwater table. Unless harvested, rainwater becomes stormwater runoff, in effect changing rainwater from a beneficial resource to a harmful by-product. Stormwater runoff is detrimental to the local watershed in terms of both quantity and quality. The volume and velocity of stormwater runoff are ecologically damaging to waterways, eroding channels and degrading aquatic habitat. Runoff also carries sediments and a plethora of pollutants that negatively impact the quality of local water sources. In an urban setting, RWH can mitigate the effects of stormwater runoff and flooding and improve the health of urban waterways (Fletcher et al., 2007; Mitchell et al., 2007; Mitchell et al., 2008).

Three areas of current environmental concern –water resources, energy use, and stormwater mitigation– are impacted by RWH. Virginia Tech boasts more than 30,000 full-time students that occupy approximately 125 buildings, including residential, academic/office and miscellaneous structures, an airport and a power plant, across 2,600 acres of campus. With these dimensions, Virginia Tech functions as a microcosm of a large urban center and is therefore justified as a representative for larger urbanized areas. Thus the implications of this research can be interpolated to larger-scale urbanized areas.

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Chapter 2: Literature Review

The growing body of international literature investigating RWH can be divided into two broad categories. One branch, focusing on RWH in developing countries, mostly in arid and semi-arid regions, is largely considered in relation to agricultural irrigation (Wang et al., In press; Abdelkhaleq, 2007; Mwenge Kahinda et al., 2007; Panigrahi, 2007; Hill and Woodland, 2003; Ngigi, 2003; Ishaq and Khararjian, 1988).

Of greater relevance to this paper is a second category of research that concentrates on RWH application in developed countries, usually in urban areas, as a sustainable means of supplementing conventional water supplies, i.e. ground- and surface-water sources. A wide variety of studies have been conducted in this realm to investigate opportunities for RWH.

RWH Systems

RWH infrastructure consists of three major components: (1) a catchment area; (2) a collection device; and (3) a conveyance system. A catchment area is an impervious surface where rainfall runoff is collected. For the purposes of this study only rooftop catchments will be considered, although land catchment systems are common world-wide.

A significant body of research has focused on the quality of collected rainwater, often reaching differing conclusions. With the obvious exception of newly constructed buildings, RWH systems are designed to retrofit an existing structure. Subsequently, roofing material becomes an important factor. Rooftop runoff usually contains a high concentration of bacterium and other pollutants during the initial stages of a storm due to the washing effect of water on pollutants that accumulate on rooftop surfaces. This is commonly referred to as the "first flush" and contamination levels in captured water decrease exponentially as the rainwater collection continues.

In examining staggered liter samples of roof runoff, Yaziz et al. (1989) found that fecal coliform counts from both concrete tile and galvanized iron roofs decreased to undetectable levels by the fourth and fifth collected liter tests, showing diminution of pollutant concentration as rainfall persists. This finding correlates with stormwater runoff studies, though has inverse implications for RWH systems. Whereas stormwater retention basins are designed to collect and store first flush runoff, RWH systems are designed to divert the first flush from the storage chamber, while collecting the subsequent runoff which contains negligible levels of contaminants.

Numerous studies have been conducted on water quality from an assortment of roofing materials, with widely variable results. Forester (1999) examined the diverse results from a number of studies and found that variability in roof runoff quality was directly influenced by local pollution sources, differences in roofing material, air pollution, precipitation events characteristics, meteorology, and chemical properties of the pollutants themselves. A majority of these studies examined roof runoff for human consumption, or potable uses. While several types of filters and water treatment units are available in the market to treat rainwater for human consumption, potable uses and the treatment of potable water are outside the realm of this study, which focuses upon non-potable water uses of rainwater.

The conveyance dimension of a RWH system refers to the gutters used to direct rooftop runoff to a storage tank and then to distribute the rainwater to appropriate appliances in the building, typically toilets and laundering facilities. Few studies detail conveyance channels, as typically the major factors influencing performance of the system are thought to come from the catchment and storage components. Future research might examine what role, if any, conveyance plays in the quality of rainwater of the efficiency of a RWH system.

Storage of rainwater has received a fair amount of attention as efficient storage capacity is intricately related to overall RWH system performance. As such, extensive analyses of rainwater tank performance and capacity as well as water storage modeling have been conducted (Mitchell et al., 2008; Mitchell, 2007; Guo and Baetz, 2007; Ghisi et al., 2007; Coombes and Barry, 2007; Fewkes, 2000). Studies examining rainwater tank capacity for storage optimization use precipitation data similar to that used in water cycle models. Rainwater storage tanks typically relate to one building or a small number of buildings that will share the RWH infrastructure. Consequently, tank capacity calculations include factors such as building population; the per capita water demand; rooftop area of the collection site; and the volume of rainwater that can be captured (Ghisi et al., 2007). Some methods take into account natural processes like evaporation when developing roof runoff models, increasing the accuracy of the potential collected water measurements (Gash et al., 2008; Herrmann and Schmida, 2000). Size and performance of rainwater storage tanks are especially important because a RWH system is often evaluated by its water saving efficiency (WSE) (Villarreal and Dixon, 2005). Studies have shown that water savings efficiency is a function of rainwater tank capacity and the potable off-set demand, so potential for water saving increases as potable water demand and storage capacity increase (Gowland and Younos 2008; Ghisi et al., 2007). Also, costs of storage tanks constitute a major component of the overall rainwater harvesting system expense.

Modeling

The methodological foundation of urban RWH research has been modeling the urban hydrological cycle and its components, which involves ratio analysis between input values (potable water demand and rainfall events) and output values (stormwater runoff and wastewater). There are significant disparities in these models, however. For instance, some studies focus on sub-components of water cycle, while others examine the complete cycle. Other differences in research include the unit of analysis, which is the spatial resolution of the model depends on the scale at which a system functions, which can be studied as a unit block, cluster, or catchment. Researcher opinions differ over the significance of rainfall event variables to be included in models. Mitchell et al. (2001) rejected the importance of a hydrograph or variation in discharge of a rainfall event, stressing instead the importance of timing of rainfall. Vieux and Farajalla (1996) developed a model that likewise focused on the rate of rainfall, instead of the amount. Dunkerley (2008) advocated the inclusion of event characteristics such as discharge, but also duration and peak as fundamental to accurate simulations. In a 2007 study, Stransky et al. (2007), like Mitchell et al. (2001), included temporal qualities in his model but also considered spatial distributions of events, a variable determined crucial by other researchers (Thielen and Creutin, 1997) as well.

The resolution of temporal data is yet another difference amongst models and researchers. Some researchers focus on isolated storm events (Vivoni and Sheehan, 2001) or hourly rainfall data (Villarreal and Dixon, 2005), both of which are common units when evaluating tank size or efficiency. Other researchers use daily interval data (Farahbakhsh et al., 2009; Cheng et al., 2006; Ghisi et al., 2006; Mitchell et al., 2001), or monthly or annual averages (Li et al., 2008). The temporal period of rainfall data, like resolution of rainfall data, varies widely across studies. Zhang et al. began a 2009 study using daily rainfall data for 80 years from 1927–2006, whereas Appan (2000) used continuous readings for two hydrologic years, 1989 through 1991. In a study of a residential area in Sweden, Villarreal and Dixon (2005) used the three most recent years' records of hourly rainfall data while Ward et al. (2010) used the yearly, monthly, and daily averages from a 30 year period.

Another factor not regularly addressed is the problem of missing rainfall data. Some studies focus on areas with little precipitation data, while others are based in highly researched areas with large records of documented precipitation. Regardless of an area's weather records, complete data is rarely available. Many researchers fail to address gaps in data, while some assume missing data as zero precipitation (Cheng and Liao, 2009; Ghisi et al., 2007) and others substitute average figures or data from the next closest observation station (Kim and Yoo, 2009).

Vieux and Farajalla (1996) acknowledged that the choice of temporal scale is based on the intended purpose of the study. For instance, site design and flood prediction models utilize fine-scale data, usually in minute or hourly intervals, or even single storm events, while coarser temporal periods are more frequently used in water resource modeling. In relation to radar derived data like NEXRAD, it is vital to use an appropriate resolution. Consequently, Vieux and Farajalla (1996) advise avoiding the aggregation of precipitation data to maintain the spatial and/or temporal variability of a dataset. An example shown in their research resampled one-kilometer radial NEXRAD data into a 500-meter cell rectangular grid. Though this had no effect on the actual resolution of the data, it allowed for radial to grid conversion without the loss of temporal variability. From an antithetical perspective, Cheng and Liao (2009) used sampled point data to extrapolate rainfall zones for their studies.

Simplified artificial groundwater recharge calculations offer another facet in RWH modeling techniques. Groundwater recharge, like urban hydrological cycles, presents a vast array of methodological choices. Some estimate recharge through GIS-based techniques (Minor et al., 2007; Huesca-Dorantes, 2006) while others use non-GIS based methods, including the Monte Carlo techniques (Bekesie and McConchie, 1999). Martin (2009) proposed a probabilistic model for RWH and artificial groundwater recharge. This model uses Monte Carlo simulation that allows specified variation in uncertainty of multiple parameters, to calculate the potential volume of recharge over approximately 1000 iterations for statistical evaluation. Although the formula's simplification of traditional recharge calculations poses many limitations to this approach, its simplicity allows for site recharge computations that might otherwise be impossible.

Potable Water and Energy Conservation

In the field of RWH, a substantial amount of research relates to potable water savings through substitution of rainwater for non-potable uses, which thereby off-set the demand for potable water (Li et al., 2008; Ghisi and Mengotti de Oliveira, 2007; Ghisi, 2006; Ghisi et al., 2006). For example, Ghisi (2006) showed that in different regions of Brazil, the potential for potable water savings from RWH for non-potable uses, namely toilet flushing and clothes washing, ranged from 48-100%. In individual homes, he found the reduction to range from 33.6–35.5% (Ghisi and Mengotti de Oliveira, 2007). Additionally, studies in Virginia have shown possible potable water savings in both the residential and commercial sectors (Gowland and Younos, 2008; Grady and Younos, 2008).

In urbanized areas, RWH studies have concentrated on application at micro- and small-scale watershed levels (Fletcher et al., 2007) or focused on residential sectors (Ghisi et al., 2007), individual households (Grady and Younos, 2008) and commercial buildings (Gowland and Younos, 2007; Li et al., 2008). Thus far, only a few studies have reported on RWH and its impacts on a large university campus. Kim and Yoo (2009) used an IHACRES-based model (a catchment-scale, continuous simulation for rainfall-runoff modeling) for their hydrological analysis of three facilities, two of which were Seoul National University and Korea Institute of Construction Technology. Appan (2000) concluded an approximate reduction of 12.4% of potable water use through RWH for toilet water at Nanyang Technological University. Wittenbrink et al. (2007) developed a Comprehensive Stormwater Management Plan for Oregon Health and Science University (OHSU) on the main campus in Portland. Most research involving RWH on a university campuses focuses on water conservation and stormwater mitigation.

Implications for energy savings from decreased potable water consumption have not yet been fully studied in detail, though such reductions exist. Decreasing demand for potable water lessens inherent energy consumption used for activities including pumping, treating, and distribution of potable water; diminution in energy usage translates to economic savings. This inference has been investigated by Herrmann and Hasse (1997) in Germany, against the background of European wastewater discharge and stormwater runoff charges. In a comparative study, Grady and Younos (2008) examined differences in energy use between a RWH system and a well-water system in an individual home. Li et al. (2008) also explored energy reduction through RWH, in a car dealership.

Only a few studies have delved into energy reduction through RWH on a university campus. Schmidt (2003) studied how green roofs and rainwater harvesting could combine to reduce energy use for cooling and ventilation units at the Institute of Physics of the Humboldt University in Berlin–Adlershof, Germany. Others advocate RWH as an energy conserving technique but have not calculated any figures (Han and Park, 2007). This gap in the literature has prompted this research of the implications of RWH on water and energy conservation on a university campus, Virginia Tech, itself a microcosm of urban interaction, and how those effects can be extrapolated to larger urban areas.

RWH for Stormwater Mitigation

The reduction of stormwater runoff, commonly referred to as stormwater mitigation, is an obvious focus of RWH research because the implementation of a RWH system has immediate effects on runoff (Van Roon, 2007; Fletcher et al., 2007; Coombes et al., 2002). Stormwater runoff is simply rainwater that has not been collected and so careens off all impervious surfaces, on the fastest track to the local stream or catchment body. Impervious surface area estimates increase when considering open areas such as family lawns, parks, and sport fields. These areas tend to have turf grass cover and compacted soils that exhibit properties similar to impervious surfaces and greatly impede water infiltration to the groundwater table.

A study by Fletcher et al. (2007), found that RWH aided in decreasing runoff to more closely approximate pre-development runoff, stream flow, and water quality levels. This study also concluded that increased RWH water use results in increased storage efficiency for tanks or catchments; the more water used, the more often a tank is emptied, and the more it can be refilled, increasing overall collection efficiency. Hence, a RWH system that serves the needs of many individuals' works more efficiently than one designed to accommodate a single household (Ghisi et al. 2007; Gowland and Younos, 2008).

RWH as a means of mitigating stormwater runoff involves legal limitations as to where, and for what purposes, rainwater can be harvested in some states such as Colorado and Utah. This legal stance is taken principally because harvesting rainfall onsite removes the possibility of water use further in the cycle from ground- and surface water sources. Colorado's Division of Water Resources is responsible for protecting and enforcing water rights and argues that rainwater is assumed to ultimately contribute to stream flows and as such is deemed property (Subramanian, 2008). This is because water in Colorado and other western states is governed by the doctrine of prior appropriation, a policy dating back to the mid-1800s that essentially allocates water rights based on a "first in time, first in line" rule of thumb. The first person to intentionally utilize water for a beneficial cause has priority, with subsequent users entitled to the same rights so long as they do not interfere with the rights of the senior appropriators. To complicate matters, water rights are independent of both the land parcels on which the water originates and those on which the water is ultimately utilized. Accordingly, RWH is considered water theft unless a permit is granted by the State Engineering office. However, properties with connections to a municipal water system are mostly ineligible for a permit. While Virginia's water rights laws differ from those in western states such as Colorado and Utah, large scale RWH system planning should consider downstream appropriators of water.

Overview

This review of the literature on RWH shows common areas of research. Many studies have explored modeling techniques, subcomponents of models, and spatial model scale. In these studies, temporal resolutions of rainfall data have varied. Many studies focus on components of a RWH system, especially rainwater tanks in relation to optimal efficiency and sizing. Other research examines the effects of RWH on water conservation and stormwater mitigation. A small number of studies however, concentrate on implications of RWH on energy consumption and conservation, with even fewer analyzing these effects on a broader scale such as that of a university campus. This gap in the literature presents an opportunity to study RWH in relation to energy conservation on the campus of Virginia Tech.

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Chapter 3: Manuscript

Abstract

Rainwater harvesting (RWH) refers to the collection of rainwater for subsequent on-site use. Rainwater is most often used for non-potable purposes including toilet flushing, laundering, landscape and commercial crop irrigation, industry, fire fighting, air-conditioning, and vehicle-washing. This study evaluates the potential impacts of RWH on residential housing on Virginia Tech campus in southwestern Virginia in regards to potable water offset, energy conservation, stormwater mitigation, carbon emission reduction, and financial savings. Potential rainwater collection was estimated from three simulations used to approximate the maximum, average, and minimum range of annual precipitation. Collected rainwater estimates were used to calculate the impacts on the areas of interest. Cumulatively, the sample buildings can collect 3.4 to 5.3 millions of gallons of rainwater – offsetting potable water use and reducing stormwater by an equivalent amount, save 320 to 1842 kWh of energy, and reduce carbon emissions by 650 to 3650 pounds annually. Cumulative savings for the nine buildings from combined water and energy offsets range between $5751 and $9005 USD, not substantial enough to serve as the sole basis of RWH implementation on campus. A significant advantage of RWH relates to the management and improvement of the Stroubles Creek watershed in which the majority of the campus sits. Additionally, RWH implementation would benefit sustainable initiatives and provide Virginia Tech additional opportunities for conservation incentives and environmental stewardship funding.

Introduction

Exponential population growth, urbanization and the consequent exploitation of water and energy resources have had a severe impact on the environment at large. Human consumption patterns have misused natural resources to an unsustainable level, globalizing the scale of problems to levels requiring both unified and decentralized solutions. One localized practice commonly recommended as a Best Management Practice is rainwater harvesting (RWH), the collection of rainwater for subsequent on-site use. This research evaluates the impacts of RWH as an unconventional source of non-potable water, particularly in relation to energy conservation on a university campus. This study: 1) evaluates the potential impacts of RWH on a large, urbanized, institutional campus in southwestern Virginia with regard to potable water and stormwater mitigation; 2) examines the conjunctive use and conservation aspects of RWH and energy; 3) calculates potential carbon emission offset through RWH; and 4) translates empirical research into economic value for use by policy and financial decision-makers in an effort to better guide sustainable initiatives on university campuses like Virginia Tech, Blacksburg, Virginia.

RWH refers to the storage and use of rainwater collected from various surfaces. In essence, rainwater is captured as runoff from roofs and other impervious surfaces, stored until needed, and then put to beneficial use on or near the site of collection. Rainwater is most often used for non-potable purposes including toilet flushing, laundering, landscape and commercial crop irrigation, industry, fire fighting, air-conditioning, and vehicle-washing.

RWH techniques are rooted in the earliest civilizations, most notably in arid regions of the Middle East, Asia and Africa. In many of these areas, RWH continues to provide a sustainable alternative to groundwater use through the present day (Peters, 2006; Mwenge Kahinda et al., 2007) although current research in these areas mostly consider RWH in relation to agricultural irrigation (Wang et al., In press; Abdelkhaleq, 2007; Mwenge Kahinda et al., 2007; Panigrahi, 2007; Hill and Woodland, 2003; Ngigi, 2003; Ishaq and Khararjian, 1988).

RWH systems consist of three major components: (1) a catchment area; (2) a conveyance system; and (3) a cistern or storage tank. A catchment area is an impervious surface where rainfall runoff is collected. For the purposes of this study only rooftop catchments will be considered, although land catchment systems are common world-wide. The conveyance dimension of a RWH system refers to the gutters used to direct rooftop runoff to a storage tank and then to distribute the rainwater to the appropriate appliances in the building, typically toilets and laundering facilities. Extensive analyses of rainwater tank performance and capacity as well as water storage modeling have been conducted (Mitchell et al., 2008; Mitchell, 2007; Guo and Baetz, 2007; Ghisi et al., 2007; Coombes and Barry, 2007; Fewkes, 2000), typically focused on individual households and small buildings because smaller populations often underutilize the available rainwater and cistern size is the most influential factor in RWH system cost.

Conservation of potable water sources, the primary function of RWH, is rapidly becoming a global priority. It was predicted that by 2025, 48 countries will face water shortages, affecting more than 2.8 billion people – 35% of the worlds projected population (Gardner-Outlaw and Engleman, 1997). Recent studies conclude that estimate was already reached in 2005 (International Water Management Institute, 2006). In the United States previous water shortages occurred in the west, particularly in the more arid southwest however recent water shortages have migrated to the southeast. While this trend is most notable in Georgia, states including Kentucky, Tennessee, Florida, and Virginia have experienced drought conditions in the last few years. Harvesting rainwater accesses a water resource that is otherwise unutilized. RWH studies in southern Brazil show that the average offset can be more than 40% of daily water demand (Ghisi, 2006; Ghisi et al., 2006). Appan (2000) concluded an approximate reduction of 12.4% of potable water use through RWH for toilet water at Nanyang Technological University. Local studies in southwestern Virginia have shown possible potable water savings in both the residential and commercial sectors (Gowland and Younos, 2008; Grady and Younos, 2008).

Water use is indivisibly linked to energy consumption. In 1995, the United States' electricity production from fossil fuels and nuclear energy used 190,000 million gallons of water per day, which accounted for approximately 39% all of national freshwater withdraws (Solley et al., 1998). Decreasing demand for potable water lessens inherent energy consumption used for activities including pumping, treating, and distribution of potable water – diminution in energy usage translates to economic savings. This inference has been investigated by Herrmann and Hasse (1997) in Germany against the background of European wastewater discharge and stormwater runoff tariffs. In Taiwan, Chui et al. (2009) analyzed the fiscal benefits of energy conservation in a community of over 500 buildings with mixed results. Additionally, recent RWH research from Virginia examined energy savings in a car dealership (Li et al., 2008) and compared to well-water extraction in an individual home (Grady and Younos, 2008). These studies underscore the water-energy nexus and support decentralized water resources as an effective way to lower energy use.

Large populations, as found in urbanized areas, place a high and often unsustainable demand on available water resources. Additionally, urbanized areas are characterized by high percentages of impervious surfaces, which prevent water from infiltrating the soil and recharging the groundwater table. Unless harvested, rainwater becomes stormwater runoff; in effect changing from a beneficial resource to a harmful by-product. Stormwater runoff is detrimental to the local watershed in terms of both quantity and quality. The volume and velocity of runoff are ecologically damaging to waterways, causing channel erosion and degraded aquatic life. Runoff also carries sediments and a plethora of pollutants which negatively impact the quality of local water sources. Immediate mitigation effects on stormwater runoff and flooding are shown after implementation of a RWH system (Van Roon, 2007; Fletcher, 2007; Coombes et al., 2002). A study by Fletcher et al. (2007) found that RWH aided in decreasing runoff to more closely approximate pre-development runoff, stream flow, and water quality levels.

Three major areas of urban environmental concern, water resources, energy use, and stormwater mitigation, are impacted by RWH. This study evaluates the impacts of RWH on Virginia Tech campus in relation to the aforementioned areas.

Methodology

To accomplish the goals of this study, three precipitation simulations were based on previous weather patterns to capture the range of potential rainfall in the area, using the maximum, average, and minimum amounts of annual precipitation. We used data acquired from the university to calculate the likely conservation of potable water and energy as well as the economic savings.

Study Site

Blacksburg, Virginia

This research will focus on nine buildings within the Upper Stroubles Creek Watershed on Virginia Tech campus in Blacksburg, Virginia. Blacksburg is located at 37°14' N., 80°25' W, in a temperate climate zone with an average daily temperature of 51.5°F, typically highest in July and lowest in January. Mean annual precipitation is 40.52 inches (Figure 1) with 52.6% occurring between May and October. Yearly snowfall averages 23.1 inches, usually highest in January. The average elevation is 1980 feet above sea level.

The Campus

The Virginia Tech campus is centrally located in a watershed that receives runoff from the greater portion of the Blacksburg urban center. Virginia Tech boasts more than 30,000 full-time students that occupy approximately 125 buildings—residential, academic/office and miscellaneous—including an airport and a power plant, across 2,600 acres of campus. With these dimensions, Virginia Tech functions as a microcosm of a large urban center and is therefore justified as representative of larger urbanized areas.

The Watershed

The Upper Stroubles Creek Watershed (USCW) is a sub-basin of the Upper New River Watershed. The USCW (HUC 05050001) headwaters are springs located in the northeastern part of the Town of Blacksburg, Virginia. Two major tributaries, Main Branch and Webb Branch, originating from springs, flow in a southwesterly direction through the Town and merge in the Duck Pond on the Virginia Tech Main Campus. The outflow from the Duck Pond is known as the Stroubles Creek which is a tributary of the New River. The Duck Pond currently serves as a stormwater management facility for urban runoff from the Town of Blacksburg and Virginia Tech.

The USCW comprises 6,119 acres and is largely associated with the urban areas of the Town of Blacksburg and a large portion of Virginia Tech campus. Land use in this watershed is portioned as 46% urban/residential, 28% forest, 21% pasture, and 5% cropland (Upper Stroubles Creek Watershed TMDL Implementation Plan, 2006).

Geologically, the watershed is situated in a limestone/dolomite region with karst sinkholes. Alluvium deposits of sand, clay, and silt are characteristic of the USCW with soil associations dominated by Groseclose-Poplimento-Duffield, and to a lesser extent, Berkes-Weikert, both of which are well-drained with clay and loamy soils, respectively (Upper Stroubles Creek Watershed TMDL Implementation Plan, 2006).

In 2002, the Virginia Department of Environmental Quality (VDEQ) designated a 4.98 mile portion of the Stroubles Creek as benthically impaired, citing urban runoff as one probable cause. A TMDL Implementation Plan for Stroubles Creek Benthic Impairment was released in May of 2006.

Additionally, the Stroubles Creek Watershed Initiative cited numerous problems within the watershed including, though not limited to: sewer overflows; downtown business wastewater disposal, pollutant buildup on impervious surfaces; stream channel modifications; lack of streamside forest; and erosion and sediment from construction sites (Upper Stroubles Creek Watershed TMDL Implementation Plan, 2006).

Building Data

Due to the size and nature of the institution, Virginia Tech has recorded a substantial amount of data regarding the buildings on campus which are available for research purposes. For this study, nine residence halls were chosen based on their locations within the Upper Stroubles Creek Watershed, their high occupancy rates, and the availability of complete, building-specific, long-term statistics. The nine selected buildings (Figure 2) are: Ambler Johnston Hall; Barringer Hall; Campbell Hall East; Eggleston Hall Main; Eggleston Hall West; Johnson Hall; Miles Hall; O'Shaughnessy Hall; Pritchard Hall; and Vawter Hall. Data obtained through the University's Facilities Information Systems (FIS) includes building footprint and rooftop areas; annual population; the number of bathroom, kitchen and laundry facilities; the dates of construction and the last major renovations; and water and energy usage from 2003–2009 for each of the buildings (Table 1). Water and energy use data were compiled into monthly and yearly averages whereas population was tallied only as annual averages.

Methods of Analysis

Precipitation Data Preparation

Precipitation data for the simulations used National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) station data from daily observations and rain gauge readings over a 31-year period from 1978 to 2008. The NWS station is located on Virginia Tech's campus at the Corporate Research Center, 1.27 miles from the watershed's center. Though precipitation datasets are commonly analyzed in record periods beginning on year one of a decade, i.e. 1971 to 2000, the temporal boundaries for this study were shifted to capture recent climatic patterns. Several facets of data were extracted from the dataset including: monthly and yearly averages; the years with the most and least precipitation comparatively; and the annual totals.

Annual precipitation was calculated by summing the daily observances for each year from 1978 to 2008 that is missing three or less days of data. This was deemed an acceptable margin of data loss, as the calculations work similarly to those of leap years and if excluded would create large gaps in the dataset. Any loss of data more significant caused the year to be entirely excluded, as was the case for 1989, 1994, and 1995; leaving 28 years of precipitation data as the basis of this study (Figure 3).

As it is outside of the scope of this study to attempt long-term weather prediction, this research uses observed real precipitation data to frame the range of potential rainfall. From the 28 years of precipitation records, the wettest year (the year with the maximum precipitation, 1996) and the driest year (the year with the minimum precipitation, 1991) were chosen as representative boundaries of the standard precipitation range, with an average year exemplifying the numerical mean of the total twenty-eight years of precipitation (Figure 4).

While simply averaging the years of the dataset as whole units would provide a valid working value, it would not convey the seasonal variation of precipitation. For this study, a stereotypical model year was created, an Annual Profile of Monthly Averages (APMA), compiled by averaging data by monthly units rather than by whole years. Each month was averaged separately, i.e. 30

Januarys, 30 Februaries, etc, and combined to form one whole year. This method created a 40.52 inch APMA and accurately reflects seasonal variation throughout the year.

The APMA year simulation will assume a typical precipitation scenario, avoiding drought or above average precipitation conditions, and will not consider potential rainwater loss through poor design or conveyance elements, cistern leaks or deterioration of the physical RWH system. As such, the resulting calculations assume efficient use of available collection area and optimum system functioning. Additionally, incorporation of spatial variation in these simulations is limited due to scale of the study site, the location of additional rain gauges, and data processing time constraints. This limitation is justified by spatial autocorrelation, or the notion that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970) and the resolution of available data. Finally, the El Nino/La Nina weather patterns are not included based on local NOAA scientist acknowledgment that it is difficult to correlate local weather with such phenomena (Keighton, 2009).

Potential Rainwater Collection

With the range of annual totals, the maximum, APMA, and minimum water conservation potential was calculated in gallons. The formula for yearly potential of rooftop rainwater collection used by Li et al. (2008) and the Rainwater Harvesting Potential and Guidelines for Texas was applied in this research.

$$\text{Roof top area } (ft^2) * \text{monthly rainfall (in)} * 0.6233 * 0.8 = \text{potential annual rain collection (gal)} \quad \text{(Eq. 1)}$$

Where: 0.6233 gallon is the yield of 1 inch of precipitation on 1 square foot of collection area

Monthly rainfall represents the highest, APMA, and lowest month totals

0.8 is the coefficient signifying the 80% assumed RWH collection efficiency

A conservative RWH system collection efficiency coefficient of 0.8 was used in the calculations to estimate rainwater collection. Collection efficiency refers to the total amount of rainwater that landed on the roof catchment and was collected and stored. Water can be lost through splashing, evaporation, system leakage, poor design or lack of maintenance. The coefficient is the ratio of the assumed amount of collection to the total amount of rainwater available to collect within the system's parameters.

Conservation Calculations

The amount of potential rainwater collected, in gallons, in the highest, APMA, and lowest precipitation years represents the water usage offset through RWH and is the foundation for several conservation and financial savings calculations.

To compute the financial savings from the water usage offset, the potential savings in gallons is multiplied by the current (2009) utility rate of $1.54 for 1000 gallons of water that the University pays the Town of Blacksburg.

$$(X/1000) * 1.54 = \textit{potential financial savings from water offset in USD} \qquad \text{(Eq. 2)}$$

Where: X is the maximum, APMA, and minimum collected rainwater in gallons

1.54 is the water tariff in USD

The amount of energy conserved through captured rainwater is calculated by a similar formula. In the Town of Blacksburg, 1.67 kilowatt hour (kWh) is used to distribute every 1000 gallons of water. Thus, for every 1000 gallons of rainwater used instead of municipal water, 1.67 kWh of energy is conserved.

$$(X/1000) * 1.67 = K \qquad \text{(Eq. 3)}$$

Where: X is the maximum, APMA, and minimum collected rainwater in gallons

1.67 is the number of kWh per every 1000 gallons of centralized water

K is the number of kWh potentially conserved through water offset

Senior Electrical Engineer Robert Dellinger of VA Tech Electric Auxiliary affirmed (2009) that the University spends $0.0772 per kWh, allowing the potential financial savings from energy conservation to be assessed.

$$K * 0.0772 = \textit{potential financial savings in USD from energy conservation through RWH offset} \qquad \text{(Eq. 4)}$$

Where: K is the potential kWh conserved through water offset

0.0772 is the utility tariff in USD

Finally, the carbon footprint of electricity for a coal-fired power plant has a coefficient of 2.249 lbs carbon dioxide (CO_2) because there are 2.249 lbs of CO_2 equivalent greenhouse gasses per kWh. In the Town of Blacksburg, Randolph et al. (2008) calculate that 88.3% of the electricity is produced by traditional coal-fired power plants while the remaining 11.7% of electricity is produced by hydro-electric and nuclear power plants which do not generate greenhouse gas emissions. Thus Blacksburg's energy coefficient is adjusted to 1.985867 lbs CO_2/kWh (Randolph et al. 2008). Using this figure, the potential amount of carbon dioxide decrease through energy conservation was determined.

$$K \text{ (in kWh)} * 1.985867 \text{(in lbs/kWh)} = \textit{reduction of } CO_2 \textit{ production through energy conservation in lbs} \qquad \text{(Eq. 5)}$$

Where: K is the number of kWh potentially conserved through water offset

1.985867 is the lbs of CO_2 per kWh generated for electricity in Blacksburg

Results and Discussion

Building Water Use

This study examined the potential for RWH of nine residential buildings on the VA Tech campus. All buildings except for Barringer Hall use more than one million gallons of water annually; Barringer Hall uses 609, 326 gallons per year on average (Figure 5). Four buildings use between one and two million gallons of water per year, while three others use approximately 2.2 to 3.65 million gallons annually. The remaining building, Ambler Johnston Hall, uses an average of 6.675 million gallons per year. It is difficult to make comparisons of water use per building without considering residential populations; however such discrepancies are not obvious from available data (Table 1).

Records show that each building uses less than 0.28% of the total space as offices, with the exception of Campbell Hall which uses 1.42% of its total square footage as office space. Additionally, all buildings in the study have laundry facilities and all but Vawter Hall have kitchen facilities. However, the lack of kitchen facilities in Vawter does not reduce its water usage. The average population of 327 students in Vawter Hall use 6,064 gallons of water per capita per year. Campbell Hall, with a slightly smaller population of 281 students, four times the number of bathrooms and kitchen facilities, uses only 4,529 gallons of water per capita per year. Johnson Hall houses the lowest number of students in the study (with six bathrooms), but uses the second highest amount of water per capita per year. Thus, the number of bathrooms seems to play no role in the water usage either. Qualitative evidence for such a large range of personal water use throughout the sample buildings' populations is inconclusive. These variations however, directly affect the efficiency of RWH systems in the sample buildings to meet the needs of the inhabitant population.

These figures are averages based on past University records; the discrepancies point not to actions of specific individuals but rather to characteristics of the buildings themselves. Records show that none of the sample buildings had been constructed or undergone major renovations since the 1960s. Aging infrastructure is prone to leaks in plumbing systems. From both economic and conservation perspectives, these buildings should be audited to ascertain the extent of possible leakage and appropriate measures should be taken to alleviate this problem.

Rainwater Harvesting

Two of the smaller Halls, O'Shaughnessy and Johnson, can collect 190,000–300,000 gal/yr; Barringer and Miles have a similar approximate range, 225,000–350,000 gal/yr; Vawter can harvest from 328,500–513,000; and Campbell can harvest 376,000–587,000 gal/yr. Of the largest three Halls, Pritchard can potentially collect 605,000–945,000 gal/yr, Eggleston 587,700–931,000 gal/yr, and Ambler Johnson 706,000–1,103,000 gal/yr. Though the potential for water savings is significant, the simulated collection amounts fall considerably shy of the total water usage in these buildings (Figure 6).

Only potable water is currently used in the buildings, therefore Figure 4 compares the total annual potable water use and the potential collection of non-potable rainwater. Because this study examines the substitution of rainwater for potable water, the potential for collected water is compared to the percentage of total use that could be replaced with non-potable rainwater. However, no literature documents institutional dormitory water end uses. Due to the lack of more relevant approximate calculations, in this study multi-story, residential building's water end use percentages were used to estimate the proportion of water utilized for a non-potable use (Mayer, 2010). Ghisi and Ferreira (2007) determined the water end use for a four-story residential complex consisting of three buildings in Brazil, allotting an average of 33.2% of all water use for toilet flushing and 4.7% for clothes washing. Assuming 38% of the annual total water is allotted for non-potable uses, the comparison between the collection potentials with only non-potable end uses shows enough rainwater can be collected to make a significant contribution towards supplying non-potable end water uses (Figure 7).

In Barringer Hall, RWH potential surpasses non-potable water use. Even in the Minimum Year simulation, Barringer Hall collects 1,171 gallons in excess of annual non-potable water usage – 231,545 gallons per year. Campbell Hall is another building capable of collecting more than enough water to supply non-potable use. In the Maximum Year simulation, Campbell Hall collects 587,743 gal/yr while the average use is only 483,593 gal/yr, a surplus of 104,150 gallons. While neither the APMA nor Minimum Year simulations collected 100% of the non-potable needs, they still collected 93% and 78% of the non-potable needs, respectively. Other halls showed varying collection potential, harvesting between 22% and 72% of non-potable needs of the remaining buildings. The results show that RWH can substantially reduce potable water use in many of the study buildings.

Stormwater Mitigation

As expected, all simulations result in large amounts of water harvested from the buildings. Cumulatively the buildings can collect 3.4–5.3 million gallons of rainwater, which would reduce stormwater runoff entering Stroubles Creek, the benthically impaired stream into which both the campus and surrounding town drain, by an equivalent amount. Benthic macroinvertebrates are commonly measured to assess the biological health of a water body. The Stroubles Creek TMDL Implementation Plan (2006), created to correct the damage, targets sediment as the primary stressor. A main source of sediment in the creek is stormwater runoff on the urbanized Virginia Tech campus and the Town of Blacksburg. RWH is not specifically suggested in the TMDL Plan, however practices that reduce the quantity and velocity of urban runoff are recommended. A study by Fletcher et al. (2007) found that RWH aided in decreasing runoff to more closely approximate pre-development runoff, stream flow, and water quality levels – which would further the goals of the TMDL Plan.

Energy Conservation

Energy saved through potable water offset ranges from 320–1842 kWh, depending on the Maximum, APMA, and Minimum simulation and the roof size (Figure 8). A kilowatt hour is an abstract measurement for many so standard comparisons are effective aids in relating the conservation potentials. For example, 1 kWh can power a laptop for 24 hours while a household refrigerator uses about 1.4 kWh per day (Wouterlood, 2010). For a broader-scale example, the average monthly consumption for a U.S. home in 2008 was 920 kWh, according to the United States Energy Information Administration. In this study, three Halls—Ambler Johnston, Pritchard, and Eggleston—can save more than enough energy annually to provide power for an average U.S. home for one month. Even the halls capable of conserving the least amount of energy in the Minimum Year simulation could still run a household refrigerator for a year on the savings.

These figures do not include energy used to for a pump to distribution rainwater within buildings. Grady and Younos (2008) deduced that a rainwater pump in a single residential home in Virginia would use 112 kWh to operate for one year. Due to the difference in building scale, this measurement is not applicable to the multi-storey residential dormitories. Though an exact figure cannot be determined with certainty, pump operation requires energy and would diminish the overall savings to some extent. Further analysis of rainwater pump energy use is integral to more accurately determine energy savings in these and other large residential buildings.

Although the overall savings are generally minute compared to the average energy use of the buildings, the reduction in energy use required no change to inhabitant behavior and minimal initial effort. The results show RWH as a passive means to effectively conserve energy.

Economic Impacts

From Potable Water Offset

The economic savings from potable water offset through RWH varies as a function of catchment area and precipitation. Overall, savings ranged from $300 to $1700 per year (Table 2). Two buildings saved less than $400 USD a year, four buildings saved between $400 and $1000 USD, and three buildings saved over $1000 USD a year, on average. Though these results demonstrate the fiscally conservative utility of RWH, the economic savings are not substantial enough to serve as the sole basis of RWH implementation on campus.

From Energy Offset

The financial savings from energy conservation through RWH in USD for the Maximum, APMA, and Minimum Year simulations for each building range between $25 and $120 annually (Table 3). Only Ambler Johnston Hall saved over $100 for two of the three simulations, with Pritchard and Eggleston Halls saving one hundred during the Maximum Year simulation. Campbell and Vawter Halls showed the potential to save $50 annually while the remaining four Halls saved less than $50 in all three simulations. Economic savings from energy conservation through RWH currently shows minimal potential.

Broader Implications

Regardless of the amount of potable water and energy conserved through RWH, the financial savings are relatively minimal. The possible combined savings range from $330 to $1850 USD per building. For a household these savings would be significant, however for an institution as large as VA Tech the savings amount to a minute fraction of costs. This differs from the conclusion of a 2009 study to optimize RWH to save energy in a hilly community with 528 buildings in Taiwan. Chiu et al. (2009) found that economic savings from water and energy conservation were not fiscally viable separately, however when combined the cost-benefit analysis for RWH became financially feasible.

The primary reason vast quantities of resources can be conserved yet fiscal savings are meager is the low tariffs for both potable water and energy at Virginia Tech. In the current context of resource use and its environmental consequences, the economic costs of these resources fail to reflect their value. The results of this research show that necessary resources are underrated in our society and such devaluation may currently prevent financial decision-makers from undertaking measures to protect and preserve our resources.

Reducing Carbon Footprint

Because RWH conserves energy, carbon dioxide (CO_2) emissions are reduced as well. Figure 9 shows the CO_2 savings for the Maximum, APMA, and Minimum Year simulations. For reference, one gallon of gasoline emits 19.4 pounds of CO_2 (U.S. EPA, 2010). The overall range of reduction is approximately 650–3650 pounds of CO_2, or the equivalent of the emissions from burning 33 to 186 gallons of gasoline. While the savings are comparatively minimal, it would take 7 to 43 tree saplings 10 years to sequester this amount of carbon.

RWH efficiency and scale

Focus is often placed on cistern capacity when studying efficiency improvement of RWH systems. This is because smaller populations cannot fully utilize harvested water, leaving excess water in the tank and thus reducing the rainwater that can be collected from the next precipitation event. For illustration, cistern capacity is analyzed to accommodate the needs of the inhabitants in an affordable manner such that enough water can be collected for use and emptied before the next rainfall. In this study cistern size is irrelevant because a population's water use far exceeds the full collection potential of the maximum amount of precipitation; any sized cistern would be drained before the next event could refill it. At this scale, cistern size is inconsequential as demand consistently exceeds the rainwater supply.

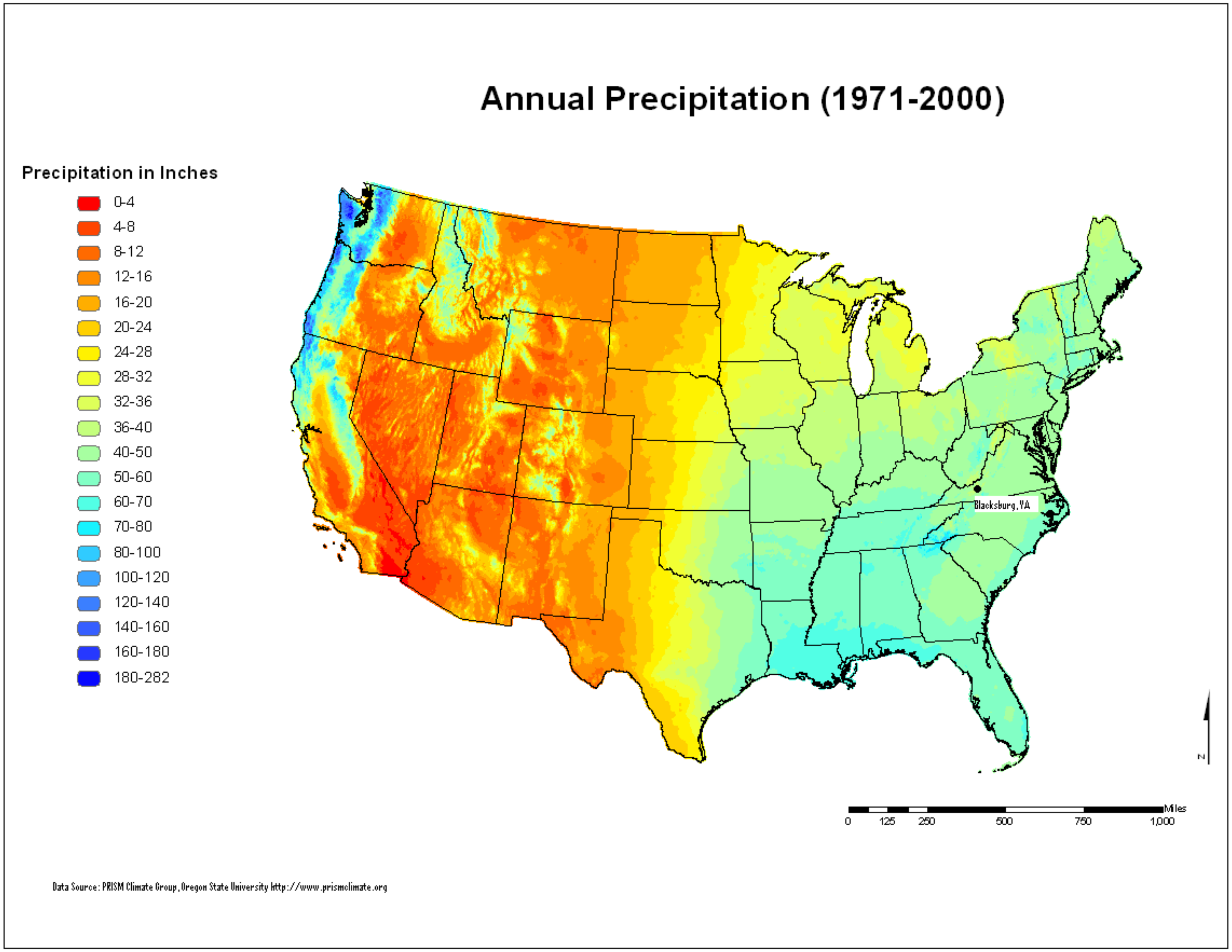
Conclusion

This study clearly conveys the conservative benefits of RWH. Cumulatively, the nine buildings could collect a staggering 3.4–5.3 million of gallons of rainwater, saving 320–1842 kWh of energy, and reducing CO_2 emissions by 650–3650 pounds annually. If these results were extrapolated to even half of the remaining 115 buildings on campus, potential savings would be immense. A decentralized water source of this magnitude could be very beneficial in times of lower water availability. Another potential application of RWH on campus involves a necessary utility: Virginia Tech uses a steam heating system. Steam heating is a completely non-potable use, but currently consumes extraordinary amounts of potable water. Further research is needed to calculate the total amount of water used by the system, the collection potential for the power plant and surrounding buildings, and the subsequent energy savings.

For this study, financial savings from RWH are minimal and not substantial enough to serve as the sole basis of RWH implementation on campus. Cumulative savings for the nine buildings from combined water and energy offsets range between $5751 and $9005 USD. Nonetheless, if RWH were to be implemented across campus for the purpose of conservation, economic savings would increase at an average approximate maximum of $1000 USD annually per building. However, further economic impacts might be seen in through credits in programs such as LEED, an internationally recognized sustainable building certification system. Continued research in sustainable design and evolving state policies is necessary and may increase potential fiscal benefits of RWH in the future.

One of the greatest advantages of implementing RWH would relate to management and improvement of the Stroubles Creek Watershed. The reduction of 3.4–5.3 million gallons of rainwater annually would diminish the sediment load and pollutants entering the watershed from urbanized areas. Stormwater mitigation through RWH would affect engineering projects in or around the Duck Pond, perhaps saving costs of future bioretention areas and infiltration trenches, as well as aid benthic improvement of the watershed.

However, when considering the full impacts of RWH, especially the combined decrease of potable water and energy use with carbon emission, the driving force behind an effort to harvest rainwater on campus would be conservation and the promotion of environmental stewardship.



Data Source: PRISM Climate Group, Oregon State University http://www.prismclimate.org

Figure 1 – National annual precipitation (1971-2000). Data source: PRISM Climate Group, Oregon State University http://www.prismclimate.org

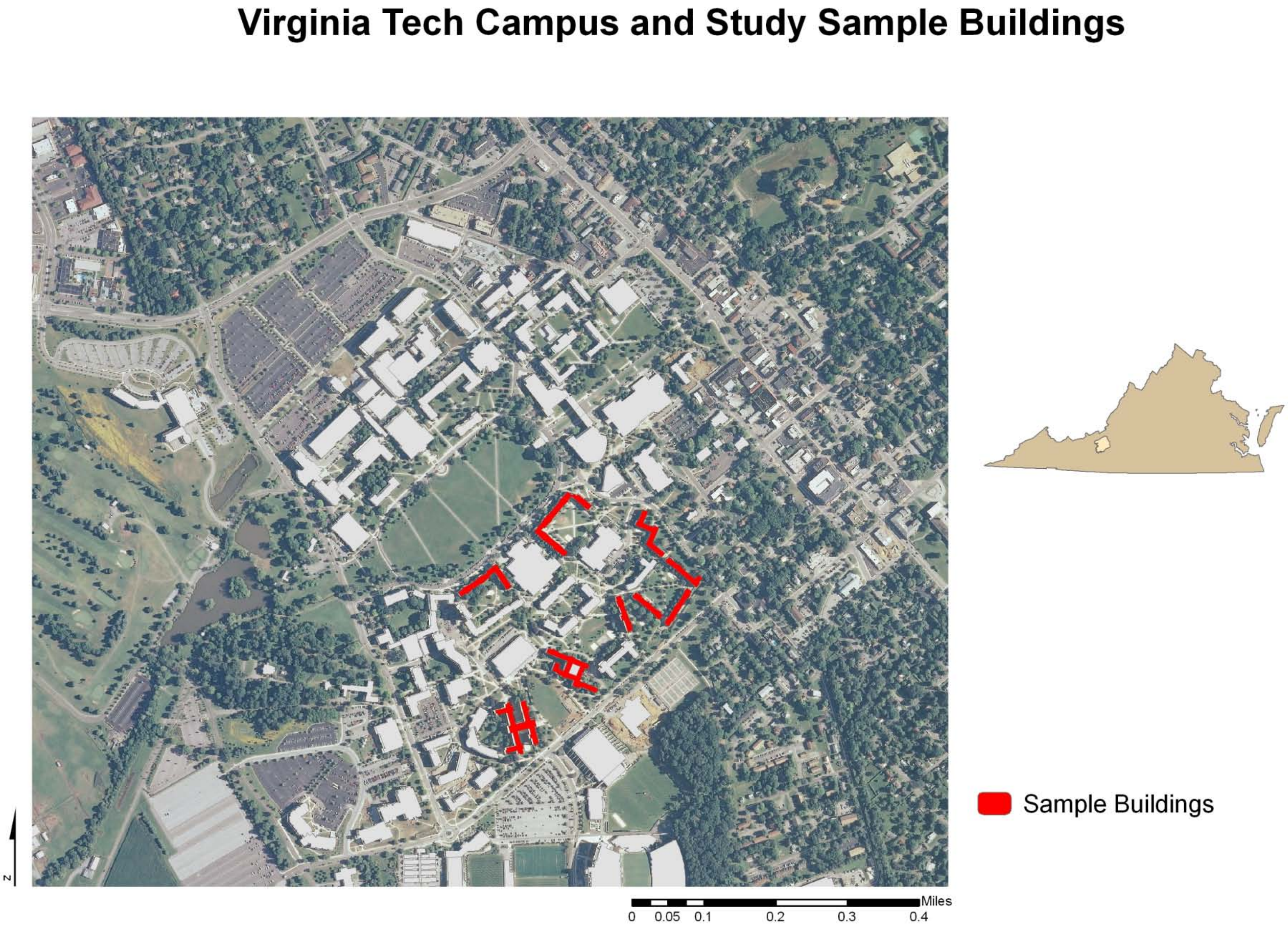


Figure 2 – Study site and sample buildings. The entire area lies within the Stroubles Creek Watershed. Imagery source: National Agriculture Imagery Program 2008

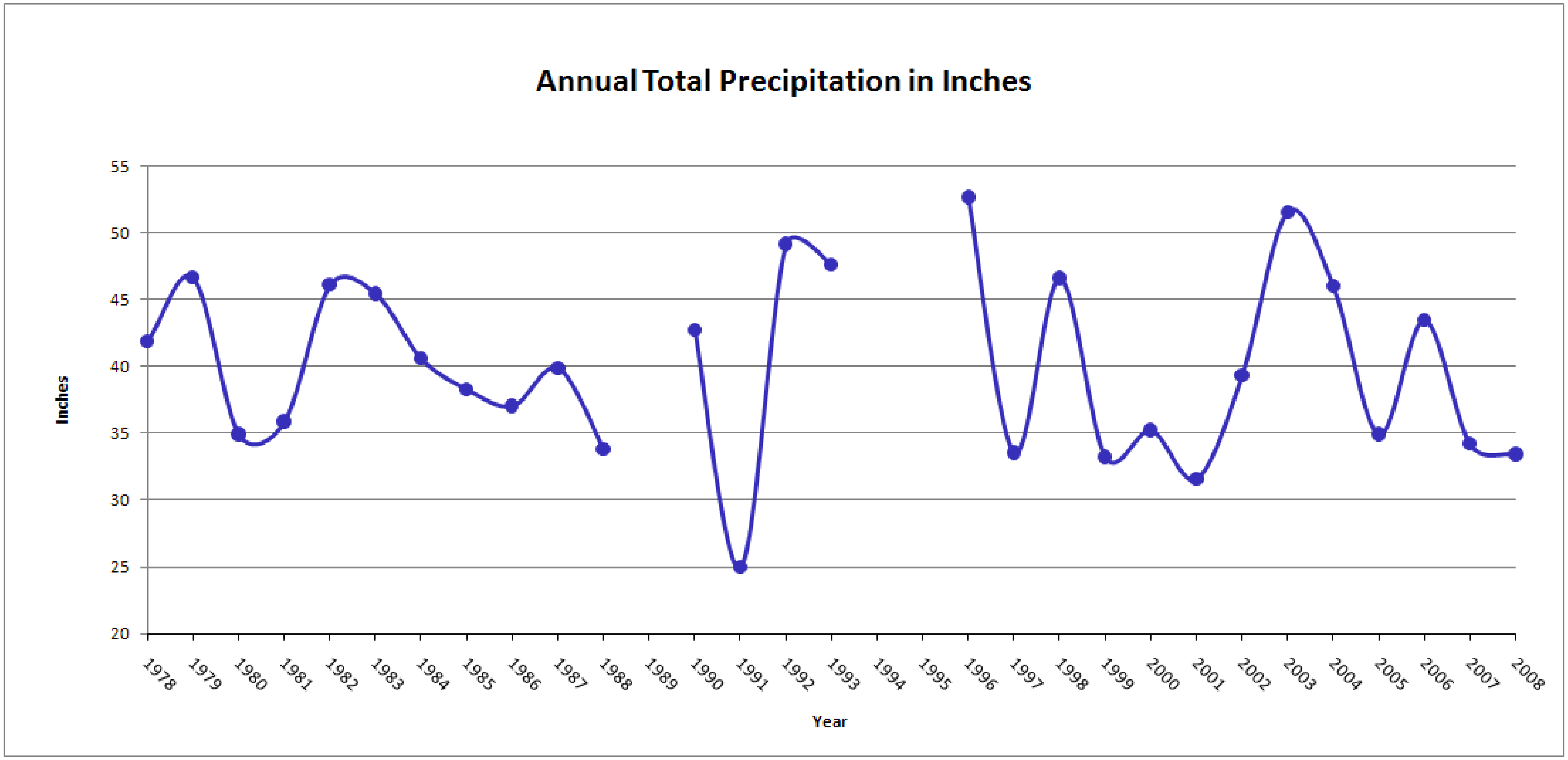
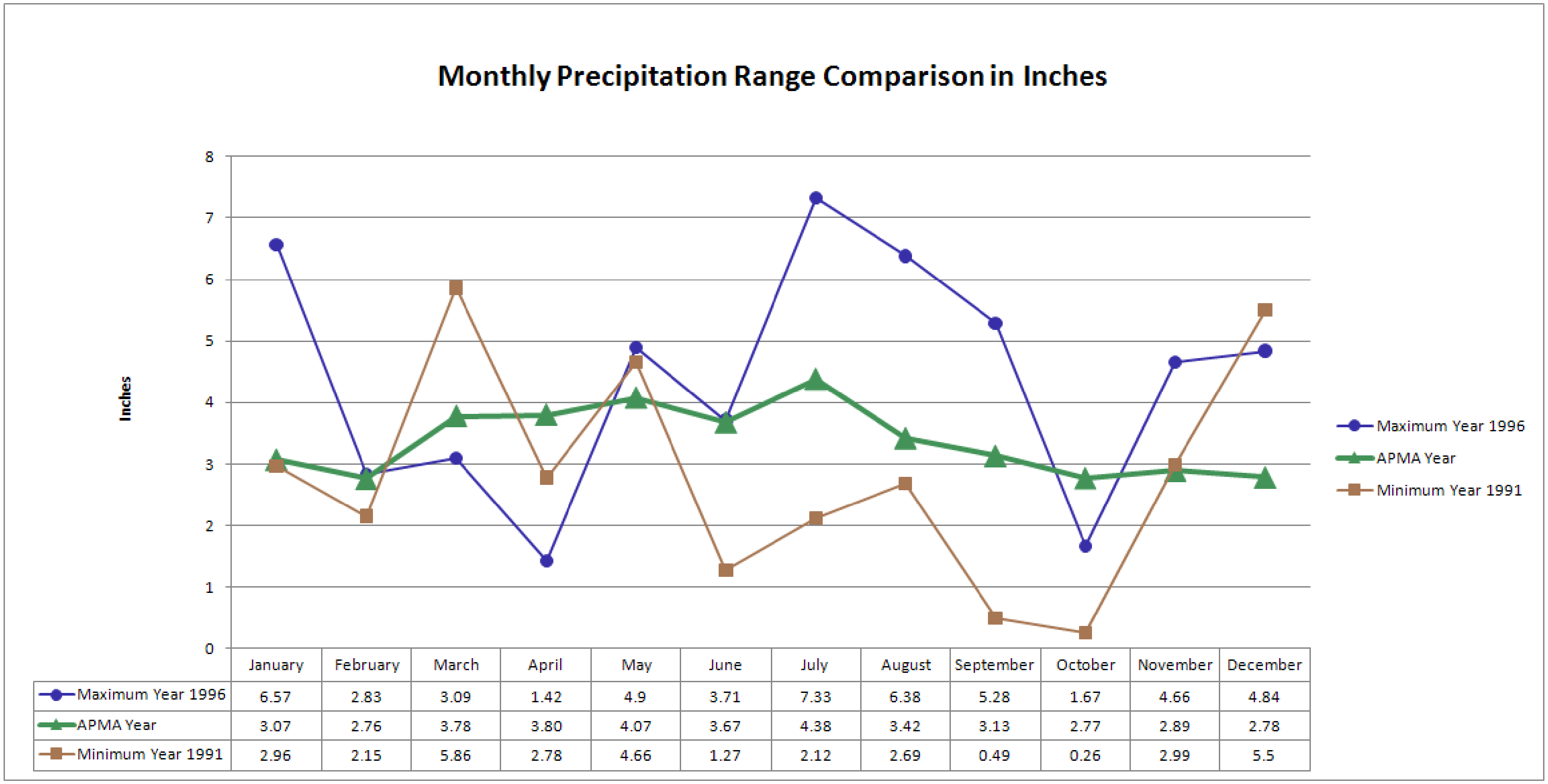


Figure 3 – Annual precipitation totals (1978-2008) from the National Weather Service (NWS) station located on Virginia Tech’s campus at the Corporate Research Center, 1.27 miles from the watershed’s center. Three years are excluded because of missing data, represented by gaps in the data line.



	January	February	March	April	May	June	July	August	September	October	November	December
Maximum Year 1996	6.57	2.83	3.09	1.42	4.9	3.71	7.33	6.38	5.28	1.67	4.66	4.84
APMA Year	3.07	2.76	3.78	3.80	4.07	3.67	4.38	3.42	3.13	2.77	2.89	2.78
Minimum Year 1991	2.96	2.15	5.86	2.78	4.66	1.27	2.12	2.69	0.49	0.26	2.99	5.5

Figure 4 – Monthly precipitation in inches for the study's three simulation years – the Maximum, APMA, and Minimum Years

Table 1 – Building characteristics used in this study

Building	Roof Area (ft^2)	Population	# Bathrm	Kitchen	Laundry	AV WUse (gal/yr)	AV WUse (gal/mo)	AV WUse/Person (gal/yr)	Year Built/ Major Renovation
O'SHAUGHNESSY HALL	11,654	343	14	Y	Y	2,326,786	193,899	6,784	1,966
MILES HALL	13,155	217	6	Y	Y	1,717,543	143,129	7,915	1,964
BARRINGER HALL	13,836	221	8	Y	Y	609,329	50,777	2,757	1,962
VAWTER HALL	19,532	327	6	N	Y	1,982,885	165,240	6,064	1,962
JOHNSON HALL	11,410	181	6	Y	Y	1,529,200	127,433	8,449	1,965
PRITCHARD HALL	35,992	1,020	26	Y	Y	3,469,657	289,138	3,402	1,967
AMBLER JOHNSTON HALL	41,986	1,298	28	Y	Y	6,675,000	556,250	5,143	1,969
CAMPBELL HALL	22,375	281	28	Y	Y	1,272,614	106,051	4,529	1930/1940/1968
EGGLESTON HALL	35,459	414	12	Y	Y	3,651,871	304,323	8,821	1935/1940

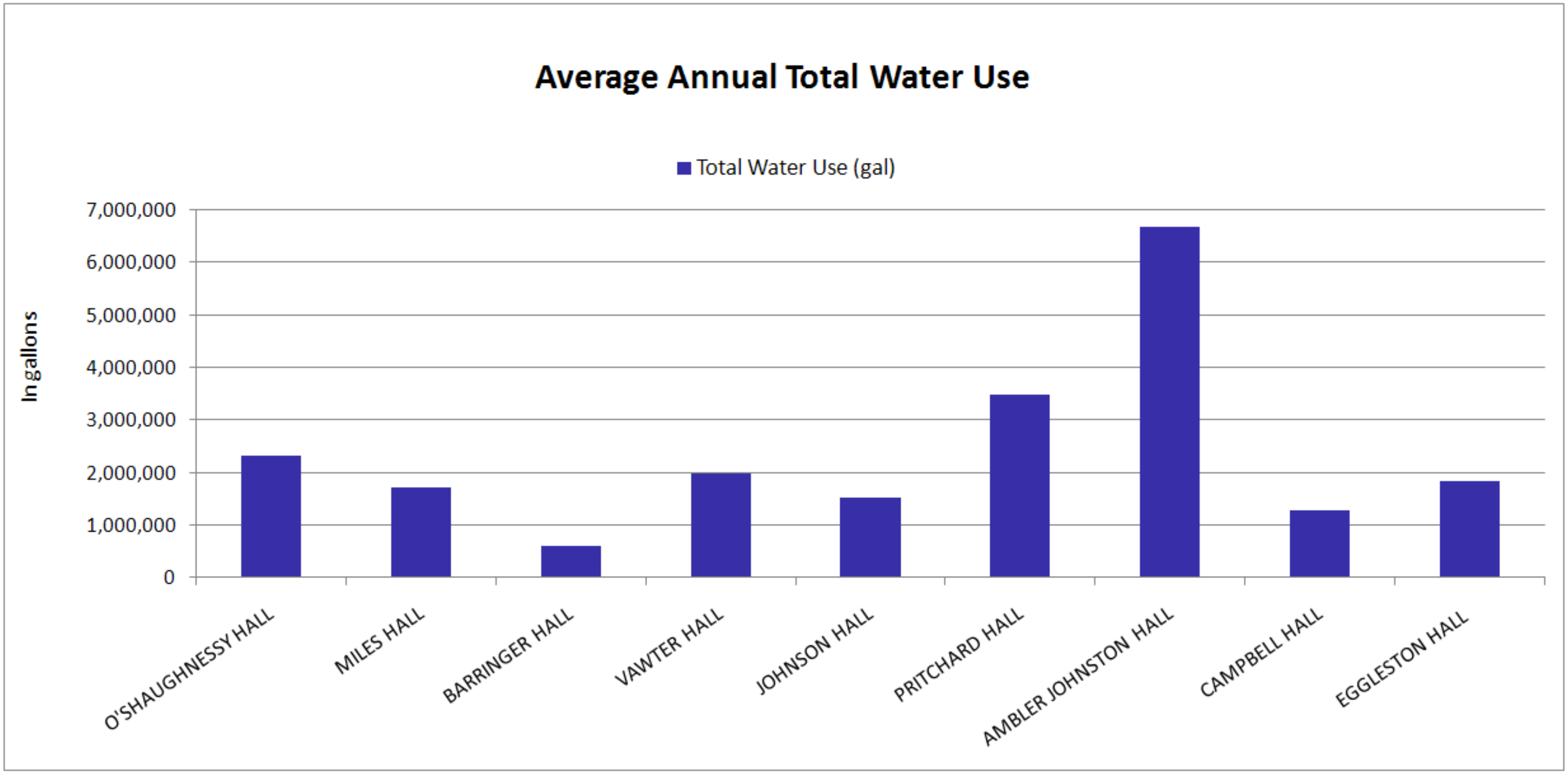
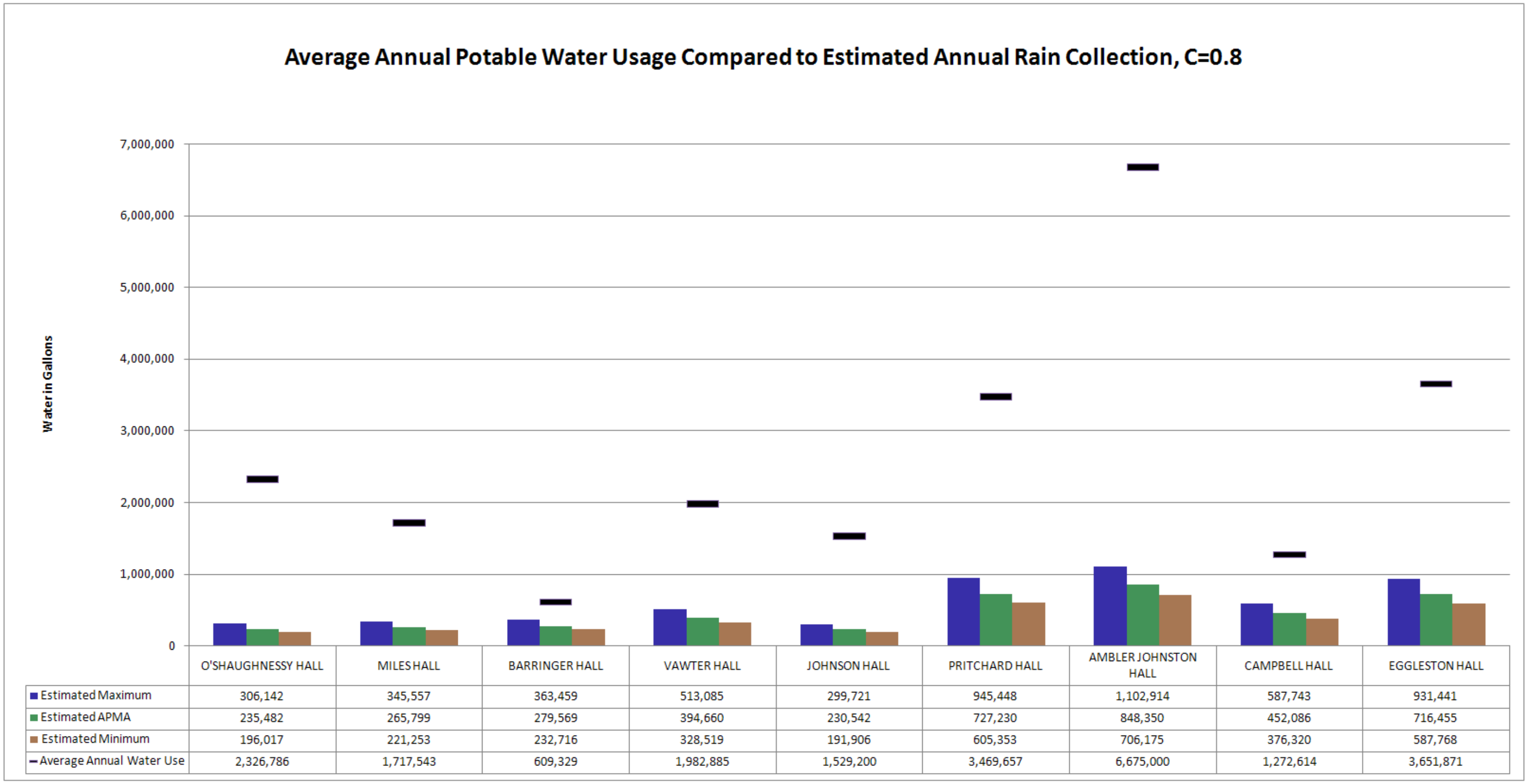
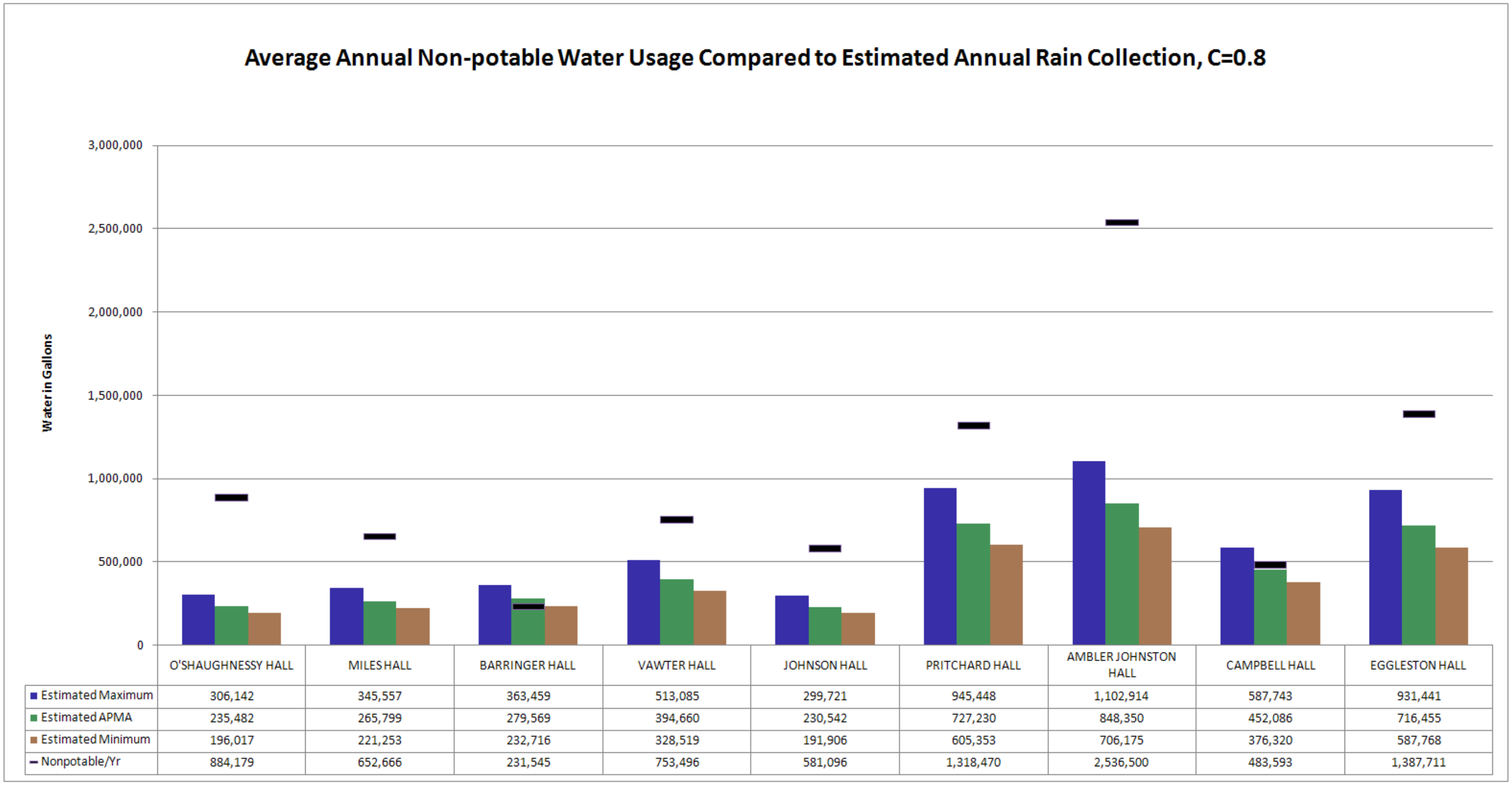


Figure 5 – Annual water use for the sample buildings, averaged from 2002-2008 university utility records.



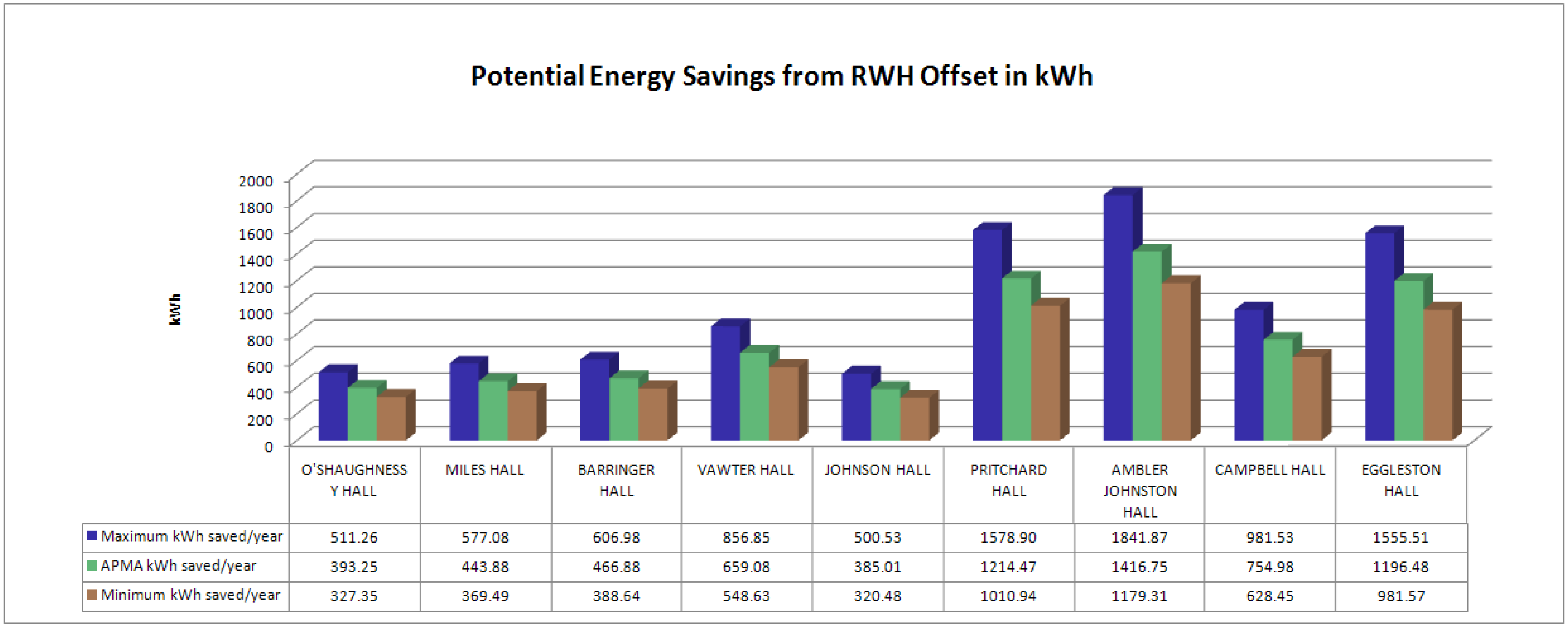
	O'SHAUGHNESSY HALL	MILES HALL	BARRINGER HALL	VAWTER HALL	JOHNSON HALL	PRITCHARD HALL	AMBLER JOHNSTON HALL	CAMPBELL HALL	EGGLESTON HALL
■ Estimated Maximum	306,142	345,557	363,459	513,085	299,721	945,448	1,102,914	587,743	931,441
■ Estimated APMA	235,482	265,799	279,569	394,660	230,542	727,230	848,350	452,086	716,455
■ Estimated Minimum	196,017	221,253	232,716	328,519	191,906	605,353	706,175	376,320	587,768
– Average Annual Water Use	2,326,786	1,717,543	609,329	1,982,885	1,529,200	3,469,657	6,675,000	1,272,614	3,651,871

Figure 6 – Average annual potable water use compared with the potential collection values for each simulation.



	O'SHAUGHNESSY HALL	MILES HALL	BARRINGER HALL	VAWTER HALL	JOHNSON HALL	PRITCHARD HALL	AMBLER JOHNSTON HALL	CAMPBELL HALL	EGGLESTON HALL
■ Estimated Maximum	306,142	345,557	363,459	513,085	299,721	945,448	1,102,914	587,743	931,441
■ Estimated APMA	235,482	265,799	279,569	394,660	230,542	727,230	848,350	452,086	716,455
■ Estimated Minimum	196,017	221,253	232,716	328,519	191,906	605,353	706,175	376,320	587,768
— Nonpotable/Yr	884,179	652,666	231,545	753,496	581,096	1,318,470	2,536,500	483,593	1,387,711

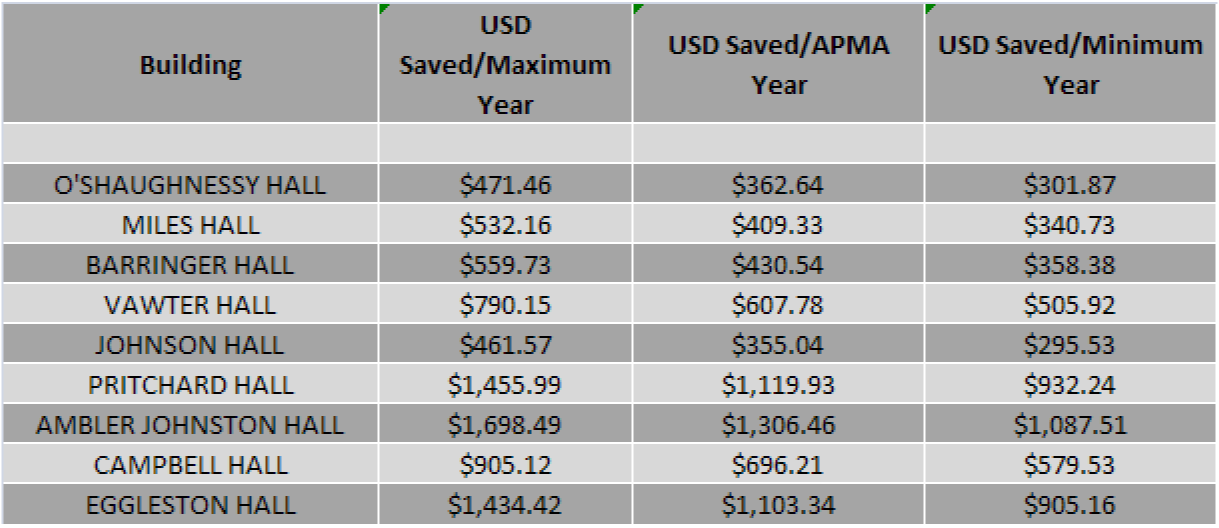
Figure 7 – Average annual non-potable water use compared with the potential collection values for each simulation.



	O'SHAUGHNESSY HALL	MILES HALL	BARRINGER HALL	VAWTER HALL	JOHNSON HALL	PRITCHARD HALL	AMBLER JOHNSTON HALL	CAMPBELL HALL	EGGLESTON HALL
■ Maximum kWh saved/year	511.26	577.08	606.98	856.85	500.53	1578.90	1841.87	981.53	1555.51
■ APMA kWh saved/year	393.25	443.88	466.88	659.08	385.01	1214.47	1416.75	754.98	1196.48
■ Minimum kWh saved/year	327.35	369.49	388.64	548.63	320.48	1010.94	1179.31	628.45	981.57

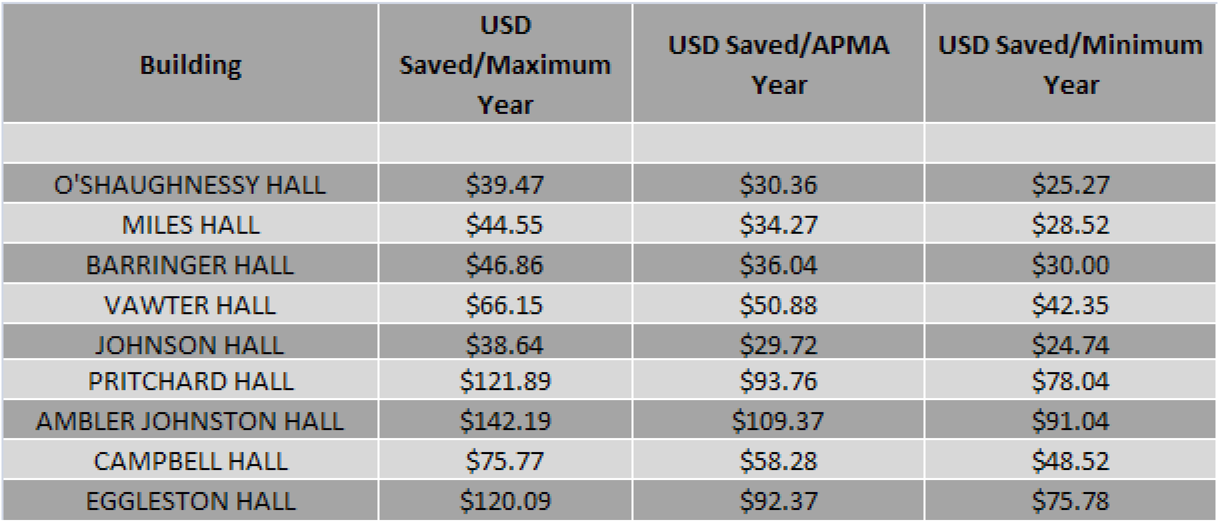
Figure 8 – Potential energy conservation in kWh through RWH implementation

Table 2 – Potential financial savings from potable water offset through RWH for each building

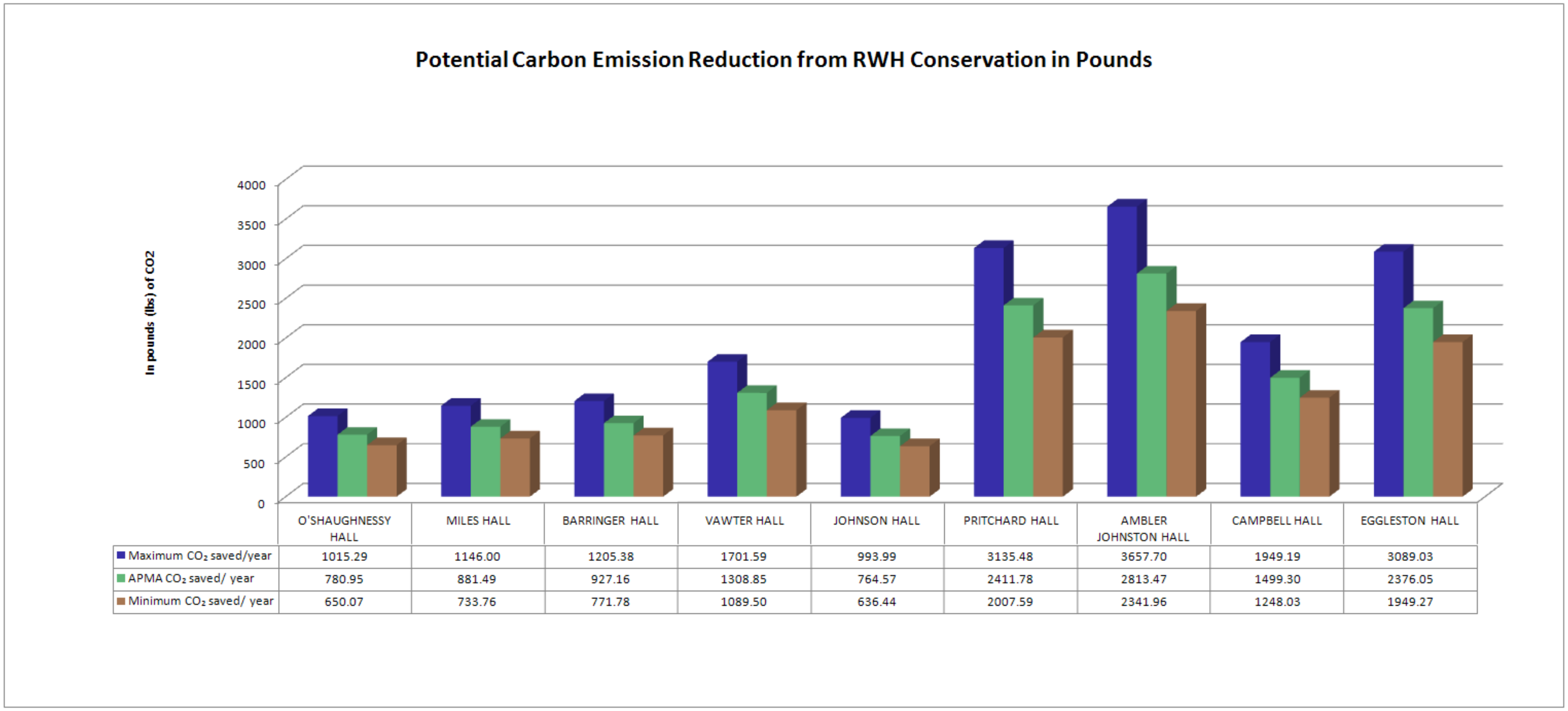


Building	USD Saved/Maximum Year	USD Saved/APMA Year	USD Saved/Minimum Year
O'SHAUGHNESSY HALL	$471.46	$362.64	$301.87
MILES HALL	$532.16	$409.33	$340.73
BARRINGER HALL	$559.73	$430.54	$358.38
VAWTER HALL	$790.15	$607.78	$505.92
JOHNSON HALL	$461.57	$355.04	$295.53
PRITCHARD HALL	$1,455.99	$1,119.93	$932.24
AMBLER JOHNSTON HALL	$1,698.49	$1,306.46	$1,087.51
CAMPBELL HALL	$905.12	$696.21	$579.53
EGGLESTON HALL	$1,434.42	$1,103.34	$905.16

Table 3 –Potential financial savings from energy conservation through RWH for each building



Building	USD Saved/Maximum Year	USD Saved/APMA Year	USD Saved/Minimum Year
O'SHAUGHNESSY HALL	$39.47	$30.36	$25.27
MILES HALL	$44.55	$34.27	$28.52
BARRINGER HALL	$46.86	$36.04	$30.00
VAWTER HALL	$66.15	$50.88	$42.35
JOHNSON HALL	$38.64	$29.72	$24.74
PRITCHARD HALL	$121.89	$93.76	$78.04
AMBLER JOHNSTON HALL	$142.19	$109.37	$91.04
CAMPBELL HALL	$75.77	$58.28	$48.52
EGGLESTON HALL	$120.09	$92.37	$75.78



	O'SHAUGHNESSY HALL	MILES HALL	BARRINGER HALL	VAWTER HALL	JOHNSON HALL	PRITCHARD HALL	AMBLER JOHNSTON HALL	CAMPBELL HALL	EGGLESTON HALL
■ Maximum CO_2 saved/year	1015.29	1146.00	1205.38	1701.59	993.99	3135.48	3657.70	1949.19	3089.03
■ APMA CO_2 saved/ year	780.95	881.49	927.16	1308.85	764.57	2411.78	2813.47	1499.30	2376.05
■ Minimum CO_2 saved/ year	650.07	733.76	771.78	1089.50	636.44	2007.59	2341.96	1248.03	1949.27

Figure 9 – Potential carbon emission reduction in pounds of CO_2 through RWH implementation

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