

Utilization of Rainwater as a Supplementary Water Source for Cooling Tower Makeup: A Sustainability Strategy for Potable Water Use Reduction

A Thesis Presented for the Master of Science Degree
The University of Tennessee, Knoxville

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Abstract

The use of rainwater as a supplementary water source for cooling water makeup was explored in an effort to reduce the potable water demand of the University of Tennessee's Knoxville campus. A water quality analysis involving the measurement of parameters relevant to cooling tower operation was conducted on tap water currently used for makeup supply and rainwater collected from the roof of a campus building. In anticipation of limited rainwater supplies due to issues of catchment surface area, collection efficiency, storage capacity, and climatic conditions, blends of rainwater and tap water were also analyzed. The dissolved solids concentration of the rainwater was significantly lower than in tap water, which indicated that a higher number of cycles of concentration (COC) could be achieved should rainwater be used in the makeup water source. Predicted COC values for the rainwater/tap water blends were calculated based on silica and conductivity measurements and were higher than the 4 ± 0.6 COC at which the campus towers were operating at during the investigation. A back-calculation using the blended COC values was used to determine potential makeup demand reductions. The replacement of tap water with rainwater in the makeup supply was found to contribute to the total tap water savings to a greater extent however, than increasing COC. Based on a rainwater supply estimate of 116 million gallons, it is possible that anywhere from a 20-60% blend may be utilized in each of the campus cooling towers if the average annual heat load is between 50-100%. At the current price of water and wastewater, the maximum cost savings associated with these results is about \$343,000 for the case in which a 40% blend is used for cooling towers operating at a 75% heat load.

TABLE OF CONTENTS

CHAPTER 1 – Introduction.....	1
1.1 Literature Review.....	1
1.2 Fundamentals of cooling tower operation.....	3
1.3 Cooling Tower Water Quality	6
1.3.1 Corrosion.....	7
1.3.2 Scale.....	9
1.3.3 Biological Growth.....	10
CHAPTER 2 – Materials and Methods	11
2.1 Overview of experimental approach.....	11
2.2 Quality analysis: Parameter designation and measurement.....	14
2.2.1 Sampling techniques and blend preparation for rainwater and tap water	14
2.2.2 Sampling techniques for cooling water.....	15
2.2.3 Cycles of concentration determination.....	16
2.3 Quantity analysis.....	18
2.3.1 Campus make-up demand estimate	18
2.3.2 Campus rainwater supply estimate	20
2.4 Water-savings calculation.....	20
CHAPTER 3 – Results and Discussion	21
3.1 Water quality analysis: Makeup water source comparison.....	21
3.2 Water quality analysis: Cooling water.....	24
3.3 Water quality analysis: Rainwater and tap water blends	25

3.4 COC predictions for rainwater and tap water blends.....	31
3.5 COC calculation for cooling tower with tap water as make-up water	
source	33
3.6 Tap water makeup demand predictions	36
3.7 Rainwater supply estimate	39
3.8 Tap water and cost savings	42
3.8.1 Cost analysis as a function of heat load.....	43
CHAPTER 4 – Conclusion	46
List of References.....	49
Appendices.....	53
Vita.....	75

LIST OF TABLES

Table 1 Make-up source comparison between tap water and rainwater	21
Table 2 Cooling water data	25
Table 3 Rainwater supply estimation for the campus	40
Table 4 Water chiller heat load design specifications.....	43
Table 5 100% rainwater water quality data.....	59
Table 6 Tap water quality analysis.....	60
Table 7 Cooling water data for 4/12/2012.....	61
Table 8 Cooling water data for 5/29/2012.....	61
Table 9 Cooling water data for 7/28/2012.....	62
Table 10 Cooling water data range	62
Table 11 Cooling water set-point data.....	63
Table 12 20% and 40% blend water quality data.....	64
Table 13 60% and 80% blend water quality data.....	65
Table 14 Cycles of concentration (COC) predictions.....	66
Table 15 Values for back-calculation of makeup flowrates using COC predictions.....	66
Table 16 List of campus cooling towers and circulation rates.....	67
Table 17 Surface area estimates for agricultural campus.....	68
Table 18 Surface area estimates for main campus.....	69
Table 19 Total surface area.....	71
Table 20 Rainfall data and potential collection volume for campus.....	72
Table 21 Rainwater demand estimates for each blend.....	73
Table 22 Makeup and blowdown rates as a function of heat load.....	74

Table 23 Water and wastewater savings with changing heat load.....	74
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LIST OF FIGURES

Figure 1 Adapted schematic of a cooling tower	5
Figure 2 Flow diagram of the experimental approach	12
Figure 3 pH measurements for the rainwater and tap water blends	26
Figure 4 Conductivity measurements for the rainwater and tap water blends	26
Figure 5 TDS measurements for the rainwater and tap water blends	27
Figure 6 Total hardness measurements for the rainwater and tap water blends	28
Figure 7 Calcium measurements for rainwater and tap water blends	28
Figure 8 Alkalinity measurements for the rainwater and tap water blends	29
Figure 9 Silica measurements for the rainwater and tap water blends	30
Figure 10 COC evaluation with tap water as the makeup source	31
Figure 11 COC predictions for rainwater and tap water blends	34
Figure 12 COC predictions for the 0-80% rainwater and tap water blends	35
Figure 13 Makeup flowrate comparison for increasing rainwater volume and COC	37
Figure 14 Tap water portion of predicted makeup flowrates	38
Figure 15 Comparison of the contributing factors to tap water use reduction	39
Figure 16 Rainwater demand for blend makeup flowrate predictions	41
Figure 17 Annual rainwater collection required as a function of heat load	44
Figure 18 Annual water and wastewater savings as a function of heat load	45
Figure 19 Picture of the RHS set-up	54
Figure 20 Downspout adapter	54
Figure 21 Submersible pump and check valve inside the storage tank	55
Figure 22 Float switch inside of the cooling tower's water basin	56

Figure 23	Design schematic of the RHS for cooling water makeup.....	58
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LIST OF SYMBOLS

COC Cycles of concentration

M Makeup flowrate

E Evaporation flowrate

B Blowdown flowrate

D Drift flowrate

$[S]_M$ Concentration of solids in the makeup water supply

$[S]_R$ Concentration of solids in the recirculating cooling water

R Circulation rate

ΔT Temperature range ($^{\circ}\text{F}$)

1. Introduction

1.1 Literature review

Although the United States has enjoyed nearly universal access to potable water, the increased water demand resulting from population growth and climate change imposes the challenge of developing sustainable water management strategies to adapt to these changing conditions and to mitigate the increasing competition over the decreasing water supply (Feeley III et al., 2008; Kloss, 2008; Domènech and Saurí, 2011). Successful water sustainability strategies maximize water use efficiency, which is a measure of how well the water supply volume meets the application's demand, and how well the quality of the water source matches the quality that is required for the application (Kloss 2008; Stoeglehner et al., 2011). The potable water demand, as well as any associated energy, chemical, and distribution costs, may be decreased by replacing and/or supplementing appropriate water use applications with a lesser-quality water source (Kloss, 2008; Jones and Hunt, 2010).

Cooling towers are water use applications that have been identified for non-potable water allocation (Feeley et al., 2008; Li et al., 2011; Shang et al., 2011; Choudhury et al., 2012; Liu et al., 2012). Rainwater is an available alternative to potable water, but the water quality effects during cooling tower operation have not yet been fully evaluated. Several buildings that use rainwater as cooling tower makeup have been reported by the EPA (Kloss, 2008; EPA, 2011); however, these reports are not complete with a detailed analysis on the impact of the changed water quality on cooling tower operation.

The parameter known as cycles of concentration (COC) is used to describe cooling tower operation in terms of water quality and is defined as the ratio of the concentration of solids in the recirculating cooling water to the solids concentration in the cooling tower's makeup supply

(McCoy, 1983). The San Antonio Water System has prepared a manuscript in which rainwater is suggested as a makeup supply due to its low total dissolved solids (TDS) content (Wilcut and Rios, 2005). The advantage of using rainwater, or other water sources with a low TDS content, for cooling water makeup is the higher number of COC that can be achieved during tower operation based on how COC is defined (Wilcut and Rios, 2005; Licina and Sekhar, 2012). The U.S. Department of Energy's National Energy Technology Laboratory also supports increasing the number of COC as part of its Innovations for Existing Plants Program because the effect will be the reduction of the makeup water demand (Feeley et al., 2008; San Jose, 2002). The advantage of using rainwater as cooling tower makeup water is thus twofold as a water-savings strategy in that not only does it replace potable water, but the overall makeup demand decreases by increasing the number of COC (Wilcut and Rios, 2005).

The collection of rainwater may be achieved via a rainwater harvesting system (RHS). Rainwater harvesting is an established practice for reducing the potable water demand of applications that are capable of utilizing a non-potable water supply, such as laundry, toilet flushing, vehicle washing, and irrigation (Kloss, 2008; Jones and Hunt, 2010; Ward et al., 2012). As an alternate source for cooling water however, rainwater will be utilized for a larger scale application (Zhao and Xu, 2012). A comparison between the application's demand and the quantity of rainwater that can be collected must be assessed for any RHS (Mun and Han, 2012; Ward et al., 2012). Rainfall frequency and quantity are important factors affecting the available supply, which will vary for different locations (Texas, 2005; Mun and Han, 2012). In acknowledgement of these factors, blends of rainwater and potable water (tap water), offer a solution when rainwater can only partially meet the makeup water demand.

Another factor influencing the quantity of available rainwater is the total catchment surface area used for collecting the rainwater (Texas, 2005; Mun and Han, 2012; Ward et al., 2012). Building roofs typically provide the catchment surface area component of a RHS (Texas, 2005). The total surface area of the building roofs, along with local rainfall data, can be used to estimate the available supply of rainwater (Mun and Han, 2012; Texas, 2005; Ward et al., 2012). Additionally, it is expected that the volume of rainwater obtained will be reduced due to runoff collection efficiency, and filter efficiency (Texas, 2005; Mun and Han, 2012; Ward et al., 2012). The implementation of a RHS for cooling water makeup may be feasible for a college campus due to the close proximity of the buildings to the cooling towers, which are used as part of the air-conditioning system (Li et al., 2011).

The overall goal of this study is to investigate the reduction of the tap water demand by supplementing cooling tower makeup with rainwater. The specific research objectives include: predicting the lower number of COC that can be achieved based on a water quality analysis of rainwater/tap water blends; estimating the reduced makeup water demand based on the COC predictions; and determining the potential tap water and financial savings that would result from the use of the particular rainwater/tap water blend that is predicted to be implementable based on a comparison of the reduced makeup demand and the calculated rainwater supply.

1.2 Fundamentals of cooling tower operation

Cooling towers are used to dissipate the heat generated from water-cooled refrigeration, air-conditioning, and industrial processes (ASHRAE, 2004). In air-conditioning systems, they are responsible for the final heat exchange in which heat is transferred from the recirculating cooling water to the atmospheric air (Stanford III, 2003). The cooling water absorbs heat within

the condenser unit of a water chiller before entering the cooling tower (Stanford III, 2003). The recirculation of the cooling water can therefore be referred to as the condenser loop (Stanford, 2003). The hot water from the condenser that enters the cooling tower undergoes both sensible and latent heat transfer with the atmospheric air (McCoy, 1983). Sensible heat transfer typically accounts for 20-25% of the total heat exchange, while latent heat transfer accounts for the remaining 75-80% (McCoy, 1983; Perry, 1984). However, the ratio of sensible to latent heat transfer is subject to change depending on the local dry bulb temperature and relative humidity (ASHRAE, 2004).

Latent heat transfer results in evaporative water loss which decreases the total volume of water in the cooling tower (McCoy, 1983; Perry, 1984). Another effect of the evaporation process is the increase of solids in the recirculating cooling water (McCoy, 1983; Perry, 1984). The concentration of solids in the cooling water must be limited in order to avoid scale formation and corrosion fouling in the cooling tower; therefore a maximum concentration of solids is designated (McCoy, 1983). Once this designated value is reached, a certain portion of the cooling water is discharged from the system (blowdown) to reduce the concentration of solids in the system (Perry, 1984). Makeup water is then pumped into the system to replenish the losses due to blowdown, evaporation, and drift (McCoy, 1983; Perry, 1984). Drift is another form of water loss from the cooling tower and it is composed of un-evaporated water droplets that may be swept out of the tower via wind or splashing (McCoy, 1983; ASHRAE, 2004).

The water balance on the cooling tower is written in Equation 1 (McCoy, 1983; Perry, 1984; Chien et al., 2012; Licina and Sekhar, 2012):

$$M = E + B + D \quad (1)$$

The makeup volumetric flowrate is represented by M , evaporation by E , blowdown by B , and drift by D in Equation 1. The location of each of these streams is depicted in the cooling tower design schematic in Figure 1.

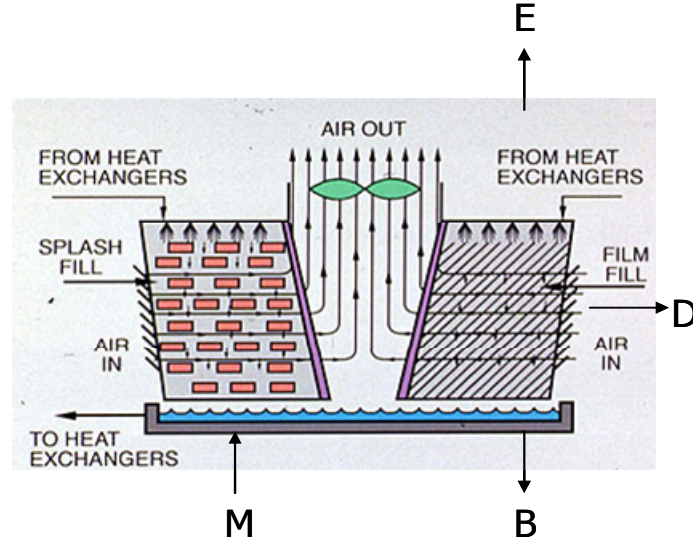


Figure 1 – Adapted schematic of a cooling tower (GE, 2012).

The ratio of the solids concentration in the recirculating cooling water to that in the makeup water is defined as the cycles of concentration (McCoy, 1983; Perry, 1984). A mass balance on the solids entering and exiting the cooling tower is used to derive the expression of the COC (McCoy, 1983).

$$[S]_M M = [S]_R (B + D) \quad (2)$$

The concentration of solids in the makeup stream is represented by $[S]_M$ and the solids concentration in the recirculating cooling water that can be removed by either blowdown and drift, is represented by $[S]_R$ (McCoy, 1983). Rearranging the terms of Equation 2, yields the expression for the COC (McCoy, 1983; Chien et al., 2012):

$$COC = \frac{[S]_R}{[S]_M} = \frac{M}{B + D} \quad (3)$$

From Equation 3, the COC can also be defined by a ratio of the volumetric flowrates, or the makeup divided by the sum of the blowdown and the drift.

Cooling towers typically operate within the range of 3-5 cycles (Perry, 1984). The number of COC that a tower completes is regulated by the maximum amount of solids that can be present in the system (McCoy, 1983). It may be inferred from Equation 3 that the number of COC may be increased by decreasing the solids concentration of the makeup stream, $[S]_M$. It follows then that the frequency of blowdown will also decrease since it will take longer for the solids to concentrate to the set maximum when the makeup supply is a less concentrated water source. The decrease in blowdown frequency means that makeup addition will also decrease; and thus, the water use reduction strategy achieved by increasing the number of COC is realized (Feeley et al., 2008). The additional advantage of using rainwater for cooling tower makeup is that not only will the number of COC increase, but a certain fraction of the reduced makeup demand will be replaced by a non-potable source (Wilcut and Rios, 2005).

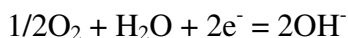
1.3 Cooling Tower Water Quality

Due to the increase in solids concentration resulting from the evaporation process, various types of fouling issues, such as scaling, corrosion, and biological growth may arise (McCoy, 1983; Stoeglehner et al., 2011). Minimizing fouling of any kind is critical to maintaining heat transfer efficiency and material preservation inside the cooling tower and inside the pipes of the condenser, through which the cooling water flows when inside the water chiller (Swart and Engelbrecht, 2004; Choudhury et al., 2012). It is imperative that the fouling potential of any water source be evaluated prior to use as cooling water.

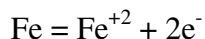
1.3.1 Corrosion

A high dissolved solids concentration increases the conductivity of cooling water, which in turn, increases the rate of corrosion (McCoy, 1983). Corrosion is defined as the oxidation of a metal by some oxidizing agent in the environment (McCoy, 1983). The reduction of the oxidizing agent, or the cathodic reaction, takes place at the cathode, while the oxidation of the metal, or the anodic reaction, takes place at the anode (McCoy, 1983). Corrosion of the metal takes place at the anode (GE, 2012). The electrochemical cell responsible for the corrosion current is completed by the difference in oxidation potential between the anodic and cathodic sites and the electron flow through the surrounding water (McCoy, 1983; GE, 2012).

The oxidizing agent in most cooling systems is oxygen and therefore, the rate of diffusion of dissolved oxygen controls the rate of the cathodic reaction, or the reduction of oxygen (McCoy, 1983; GE, 2012):



The reduction of oxygen from its diatomic form to the hydroxide ion is the predominant cathodic reaction for waters with a pH above 5 (McCoy, 1983). The anodic reaction for steel is (Stanford III, 2003; McCoy, 1983):



The electrons released from the iron oxidation initiate the electron flow, or the corrosion current, and as these electrons are accepted at the cathode, the corrosion process ensues (McCoy, 1983; Stanford III, 2003).

Factors responsible for increasing the corrosion current include increased conductivity (high TDS content), high temperature, increased aeration, and increased water velocity

(circulation rate) – responsible for providing oxygen at a faster rate to cathodic sites (McCoy, 1983). The rate of corrosion is also increased by lowering the pH (Stanford III, 2003; Choudhury et al., 2012; GE, 2012; Liu et al., 2012). The higher concentration of protons available for electron consumption enhances the oxidation of the metal at the anode (Choudhury et al., 2012). The lowest recommended pH value for wet, recirculating cooling towers is 6.5 (BAC, 2011).

Corrosion inhibitors are typically included in the chemical treatment packages that are regularly administered to the recirculating cooling water for corrosion control (Choudhury et al., 2012). The cooling water may come in contact with different metal surfaces as it circulates through the cooling tower and the condenser. For example, the cooling water basin, located at the bottom of the cooling tower, may be made of stainless steel, whereas the pipes of the heat exchanger inside the condenser are typically made of copper (Stanford III, 2003; BAC, 2011).

Two commonly used corrosion inhibitors include phosphorus-based chemicals, polyphosphates, and tolytriazole (TTA) (Stanford III, 2003; Choudhury et al., 2012). Polyphosphates may be used for mild steel corrosion protection and are considered cathodic corrosion inhibitors for their ability to precipitate with ferrous ions and then deposit over the cathode (Choudhury et al., 2012). These deposits inhibit corrosion by forming a protective layer over the metal surface (Choudhury et al., 2012). If present in solution, calcium may play the same role as the dissolved metal cations from the metal surface, and precipitate with the inhibitor (Choudhury et al., 2012). TTA is used for copper and copper alloys, and also inhibits corrosion by forming a protective polymeric film, but through a complexation reaction between its triazole group and the copper-containing surface (Stanford III, 2003; Choudhury et al., 2012).

1.3.2 Scale

The build-up of solids due to evaporation introduces the issue of scale formation within a cooling tower (Cheremisinoff and Cheremisinoff, 1981; Stanford III, 2003; Li et al., 2011). Scaling, by definition, is the crystalline growth of an adherent layer of insoluble salt or oxide on a surface where heat is exchanged (McCoy, 1983). The major concerns with scale formation include the reduction of heat transfer efficiency within the heat exchange tubes of the condenser and the reduction or blockage of water flow within the system due to mineral precipitation on equipment surfaces (McCoy, 1983; Stanford III, Nishida et al., 2009). The scales typical of cooling systems exhibit decreasing solubility with increased temperature; hence the accumulation on the hot heat exchanging surfaces in the condenser (McCoy, 1983; Li et al., 2011). Calcium and magnesium cations are the most common potential scale forming species in water (Li et al., 2011). Types of scale include calcium carbonate, phosphate, sulfate, silicate, and magnesium phosphate and silicate (McCoy 1983; Nishida et al., 2009).

The water quality parameters that influence scale formation include the concentration of dissolved solids, alkalinity, pH, and temperature (Cheremisinoff and Cheremisinoff, 1981; Stanford III, 2003; Li et al., 2011). Concentrations of dissolved solids and temperature are important to monitor in order to avoid exceeding the solubility limits of ions in the cooling water (Cheremisinoff and Cheremisinoff, 1981; Li et al., 2011; Shang et al., 2011). Alkalinity is a measure of the concentration of ions that give a basic reaction when hydrolyzed with water, such as hydroxides, carbonates, bicarbonates, phosphates, and silicates (Cheremisinoff and Cheremisinoff, 1981). The role of these anionic species in scale formation is to precipitate out of solution with their complimentary cationic species, calcium and magnesium (Cheremisinoff and

Cheremisinoff, 1981; Li et al., 2011; Liu et al., 2012). While decreasing the alkalinity of the cooling water may seem to be a necessary measure for scale prevention, some alkalinity must be present in the cooling water as a buffer to prevent the pH from dropping and accelerating the corrosion rate (Cheremisinoff and Cheremisinoff, 1981; GE, 2012; Liu et al., 2012).

Scale prevention is achieved by administering a chemical treatment package to the cooling water (Li et al., 2011). Typical scale inhibitors, or antiscalants, include carboxylic polymers, phosphonates, and polyphosphonates (Li et al., 2011). Four mechanisms have been identified for antiscalant activity, and they are typically operating together in order to increase the effectiveness of the chemicals (Li et al., 2011). Complexation reactions with the calcium and magnesium with the antiscalant reduces the availability of these cations for scale formation (Li et al., 2012). Antiscalant chemicals may react with some of the scale forming species to essentially replace the calcium and magnesium cations (Li et al., 2011). Even if the mineral nucleus of the scale forming species has materialized, antiscalants can work by disrupting the crystallization process that follows (Li et al., 2011). Antiscalants can work to keep the mineral particulates dispersed in the cooling water so that there is lesser tendency for sedimentation or deposition (Li et al., 2011). The final mechanism relies on the adsorption of the antiscalants to metal surfaces to form a protective layer against mineral deposition (Li et al., 2011).

1.3.3 Biological growth

Another type of fouling relevant to cooling tower operation is biological growth (Cheremisinoff and Cheremisinoff, 1981; McCoy, 1983; Stanford III, 2003). An open and oxygen-rich environment facilitates the growth of microorganisms such as bacteria, fungi, algae (Stanford III, 2003). As the main source of nutrition for microorganisms, organic matter should

be limited in the cooling water (Shang et al., 2011). And since it is possible for organic substances to be washed off the roof with the collected rainwater, it is recommended that the rainwater be filtered prior to use (Helmreich and Horn, 2009). An oxidizing biocide is usually administered to the cooling water as part of the chemical treatment package (McCoy, 1983; Stanford III, 2003; Pearson, 2011). Chlorine is the typical oxidizing agent due to its effectiveness and relatively cheap cost (McCoy, 1983). Although biological fouling is a concern with regards to cooling water, the water quality parameters studied in this research specifically address corrosion and scaling. Organic content will need to be measured as a part of future work prior to implementing a RHS for cooling water make-up, but further discussion of biological fouling is outside the scope of this research.

2. Materials and Methods

2.1 *Overview of experimental approach*

Figure 4 outlines the experimental approach utilized in this investigation. The research can be divided between water quality and quantity assessments. The quality analysis included a comparison of specific water parameters that were designated for their ability to indicate the fouling potential of the rainwater and tap water samples. This comparison was used to assess the advantages and disadvantages of using the rainwater as a cooling tower makeup water source. While the dissolved solids content of the rainwater was the most prevalent water quality parameter with regards to COC calculations, it was important to characterize the rainwater to ascertain the potential for scaling or corrosion.

Silica and conductivity measurements were taken for cooling water samples, collected from a campus tower, and for tap water samples, obtained in the lab, to calculate the number of COC under current operating conditions. The other water quality parameters were also measured for the cooling water samples to verify that the samples were representative of typical operating conditions by comparing the measured values to those recommended by the manufacturer of the cooling tower.

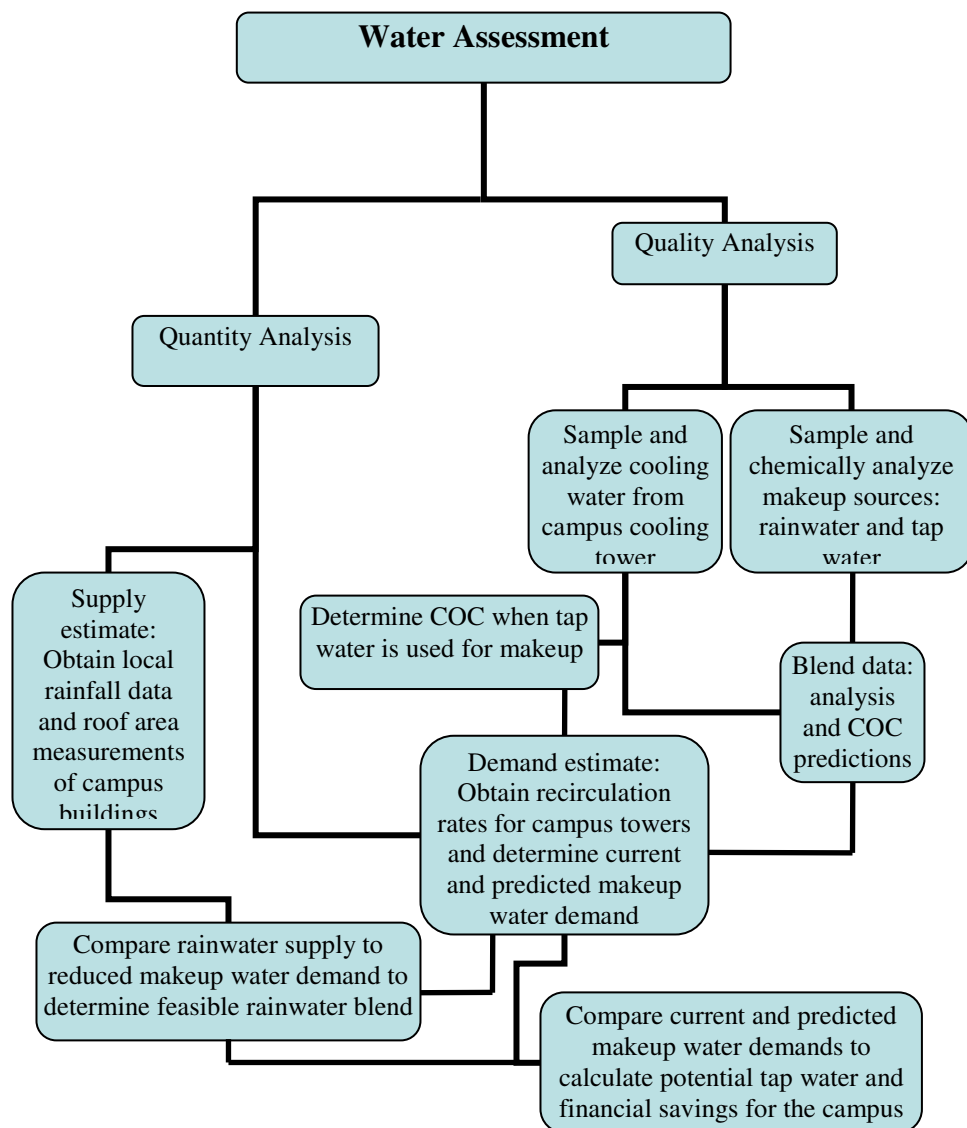


Figure 2 – Flow diagram of the experimental approach.

Since it is highly unlikely that the supply of rainwater can completely replace tap water as the makeup water source due to climate-imposed limitations, blends of rainwater and tap water were prepared and analyzed. In addition to characterizing each of the blends with the designated water quality parameters, predictions were made for the number of COC that could be achieved by consistently using a makeup water source of the same blend proportions. A back-calculation from the lab-predicted number of COC for each blend was then performed to estimate the new and reduced makeup water demand of the campus if all of the campus cooling towers were using the blended makeup water supply. The predicted makeup water demand of the campus was then compared to the current makeup water demand, using only tap water as the makeup supply, to calculate the potential tap water and financial savings of using rainwater blends.

The quantity analysis began with a supply estimate for the amount of rainwater available on the University of Tennessee's Knoxville campus that was calculated using local rainfall data and GIS programs to measure the available roof surface area. Since water meters were not already installed on the makeup lines to each campus cooling tower, the makeup water demand for the campus was estimated using information on the circulation rates for each of the cooling towers, along with the current number of COC determined from the quality analysis. The volume of rainwater that was required to obtain the estimated rainwater supply was then compared to the reduced campus makeup water demand to determine which blend or blends of rainwater could be feasible for the campus.

2.2 *Quality analysis: Parameter designation and measurement*

Water quality parameters that impact fouling of cooling towers such as: conductivity, pH, total dissolved solids (TDS), alkalinity, total hardness, and calcium hardness were chosen for analysis. Conductivity, pH, and TDS analyses were conducted using Ultrameter II meter (Myron L Company model 6PFC^E) following procedures described in the operation manual. For the alkalinity, total hardness, and calcium hardness measurements, a HACH digital titrator, model 16900, was used and methods 8203, 8213, and 8204 were followed. Additionally, silica measurements, taken specifically for the COC calculations only, were measured using a HACH Pocket Colorimeter II following HACH method 8185.

2.2.1 *Sampling techniques and blend preparation for rainwater and tap water*

A building on the University of Tennessee's Knoxville campus, Hesler Hall, was chosen to provide the rainwater catchment surface in this study. Rainwater was collected from the clay tile roof of Hesler Hall utilizing one of the multiple copper downspouts on the building. A fabricated copper sheet metal adapter was connected to the downspout and flow was redirected, through a four inch ID plastic pool hose line, to a 300 gallon polypropylene storage tank. The RHS used in this study is discussed in Appendix A. Rainwater samples were collected directly from an outlet located near the bottom of the storage tank. A first-flush diverter and/or filtration system may be installed in future work to improve the quality of the collected rainwater before it enters the storage tank (Texas, 2005; Helmreich and Horn, 2009).

Samples were taken after distinct rain events, which were defined for this research as rainfall periods flanked by dry periods of at least 24 hours. The storage tank was drained between rain events. A five gallon, high-density polyethylene (HDPE) bucket was used to

collect the rainwater and transfer it back to the lab. The bucket was thoroughly rinsed with tap water and laboratory detergent (*Sparkleen*), and then rinsed again with distilled water, before being completely hand-dried with paper towels and used for sampling. Tap water samples were taken directly from a tap in the lab. Plastic or glass beakers were used for temporary storage of the tap water while proceeding with the water quality analysis. Blends of tap water and rainwater were prepared in 2000-mL batches in the lab using the collected samples. The blends are reported as percentages, 0, 20, 40, 60, 80, and 100%, and each refers to the percentage of the total blend volume consisting of rainwater. Each blend was well-mixed prior to parameter measurement.

2.2.2 *Sampling techniques for cooling water*

One of the cooling towers used for the air-conditioning of Hesler Hall was chosen for this study. The cooling water samples were collected from the tower's water basin in 500 and/or 1000-mL HDPE bottles and transferred back to the lab. The bottles were cleaned according to the same method as described for the 5 gallon HDPE bucket used for the rainwater sampling. Cooling water samples were taken at the onset of a blowdown discharge and at pre-determined time intervals up to and including the consecutive blowdown discharge.

Blowdown is regulated by the conductivity of the circulating cooling water. As the water flows from the cooling tower's basin to the condenser unit within the water chiller, a side-stream is directed to a controller to monitor the conductivity level, as well as the oxidation reduction potential (ORP), with each pass through the condenser loop. Blowdown is discharged when the designated maximum value, or set-point, for the conductivity is reached. The set-point for each of the campus cooling towers is 1000.00 $\mu\text{S}/\text{cm}$. Parameter measurements for samples taken at

the onset of a blowdown discharge are thus referred to as the ‘set-point’ values. Samples were also collected between blowdown discharges so that a complete water quality analysis could be obtained for the cooling water as the solids concentration decreased with the influx of new makeup water, and increased due to the evaporative process.

The conductivity of the cooling water, as determined by the controller, may be accessed via an online data log. The data log was accessed before and during collection to determine when the set-point had been reached and what the typical length was between each discharge on the sampling day. The time intervals at which samples were taken between consecutive blowdown discharges were chosen based on this information. The length of time between the discharges could vary anywhere between a few minutes to an hour, depending on the evaporation rate of the cooling tower on the day of the sampling.

2.2.3 Cycles of concentration determination

Equation 3 shows how the concentration of solids measured for the recirculating cooling water and for the makeup water are used to calculate the COC. The solids concentration of the recirculating cooling water, $[S]_R$, includes the solids present in the makeup supply, as well as the solids added by the chemical treatment package used to avoid fouling issues (GE, 2012). Isolating and measuring the concentration of dissolved solids from the makeup supply in the recirculating cooling water is necessary for determining the accurate number of COC (GE, 2012). This result can be achieved by measuring a chemical that remains soluble upon concentration, and is not included as one of the treatment chemicals (Perry, 1984; Chien et al., 2012; GE, 2012). Silica was recommended for this method by a Knoxville-based cooling water treatment specialist from Water Solutions Engineering. Water Solutions Engineering is

responsible for supplying and monitoring the treatment of the cooling water at the University of Tennessee's Knoxville campus. Since silica was already present in the tap water, and was not included as part of the chemical treatment package, its concentration in the cooling water at set-point was divided by its concentration in the tap water to determine the number of COC.

Conductivity is a water quality parameter typically used to measure the solids concentration of the recirculating cooling water and thereby control the number of COC [15], (Swart and Engelbrecht, 2004; Chien et al., 2012; GE, 2012). Conductivity measurements cannot, however, differentiate between the solids of the makeup water and the solids of the treatment chemicals. Conductivity-derived COC calculations, although typically used, yield slightly higher COC values because the conductivity of the recirculating water is increased by the treatment chemicals, thereby increasing the numerator of Equation 3 (GE, 2012). Although COC calculations are more accurate when based on silica concentrations, only two rain events were used for these measurements. Conductivity-derived COC measurements were thus also calculated so that the silica-based COC results could be validated by an additional water quality parameter. Differences between the COC values determined by the two parameters were not expected to be significant.

Silica and conductivity measurements were also used to predict the number of COC that could be achieved using a rainwater/tap water blend as the makeup source. Both parameters were measured for each blend. The COC predictions were then calculated by dividing these measurements by those of the cooling water set-point samples. The predictions are based on the assumption that the current set-point, 1000.00 $\mu\text{S}/\text{cm}$, will not change. This assumption is made since tap water will be the sole makeup source during periods without rainfall and less maintenance is required by not having to readjust the set-point between wet and dry periods.

Maintaining the established set-point is also a safe assumption because lowering it would be disadvantageous from a water-savings standpoint and increasing it could be disadvantageous from a water quality standpoint.

2.3 *Quantity analysis*

2.3.1 *Campus makeup demand estimate*

The makeup water demand estimate for the campus was completed using the circulation rates for each campus cooling tower. Looking back at Equation 1, the makeup volumetric flowrate, M , is the summation of the volumetric flowrates of the blowdown, evaporation, and drift. Therefore, estimations for each of these three flowrates were made to back-calculate a value for M .

An equation for calculating the blowdown was derived using Equations 1 and 3 (McCoy, 1983). By substituting the volumetric flowrate expression for COC from Equation 3 into Equation 1, and rearranging the terms, the equation for determining the blowdown volumetric flowrate is written as (McCoy, 1983):

$$B = \frac{[E - D(COC - 1)]}{(COC - 1)} \quad (4)$$

The COC for each cooling tower on campus is the same because each tower uses the tap water supplied by the local municipality, the Knoxville Utility Board (KUB), and each tower operates according to the same conductivity set-point.

Drift loss is typically between 0.001 and 0.005% of the water circulation rate (ASHRAE, 2004). A value of 0.005% is used for Equation 4 to obtain a conservative estimate for the makeup demand of the cooling towers on campus. A representative from the manufacturing

company of the Hesler Hall cooling tower used for the cooling water samples also confirmed that the drift loss to that tower is calculated to be 0.005% of the circulation rate.

An estimation of the evaporation rate is determined using the following equation (Perry, 1984; Chien et al., 2012):

$$E = 0.00085(R)(\Delta T) \quad (5)$$

In Equation 5, R represents the cooling water circulation rate in gallons per hour (gph) and ΔT represents the range in degrees Fahrenheit (Perry, 1984). Using the sum of the circulation rates of each tower on campus, and using a maximum value for the range, a conservative estimate for the total evaporation can be determined for the campus. The range value of 10°F was chosen based on the “standard” design 95°F hot temperature and 85°F cold water temperature values that are typical for cooling towers used for air-conditioning (Stanford III, 2003; ASHRAE, 2004). Information obtained for the condenser of the water chiller used in conjunction with the Hesler Hall cooling tower also indicated that the 10°F was an appropriate range. When the water chiller’s condenser, and hence the cooling tower, is operating at 100% of its design heat load, the design range is 9.1°F. The range will decrease as heat load decreases (ASHRAE, 2004). Therefore, a 10°F range will yield an overestimate for the evaporation rate. This overestimation will increase the makeup demand, thereby providing a maximum demand value that the rainwater supply must meet.

With the evaporation estimate known, along with the number of COC and the drift estimate, Equation 4 may be used to determine the blowdown. Lastly, the flowrates for blowdown, evaporation, and drift may be entered into Equation 1 to calculate the total makeup water demand of the campus.

2.3.2 *Campus rainwater supply estimate*

The second aspect of the quantity analysis was the estimation of the rainwater supply. Local rainfall data and GIS programs were used together to estimate the total volume of potentially collectable rainwater. The rainfall data was provided by the City of Knoxville's Stormwater Engineering Department. The specific information extracted from this data was the number of inches received for each month from 2009 to 2011 at Tyson Park, a specific location close to the University of Tennessee's campus in Knoxville. The roof surface area was measured using The City of Knoxville's GIS program, KGIS Maps. Since the City of Knoxville's GIS program had not been updated with University's most recent layout, Google Earth was used for the roof surface area calculation of the new buildings. Google Earth was not the primary GIS program of choice due to differences in mapping tools between the two programs and the greater potential for inaccurate measurements resulting from tree coverage, elevation angles, and shadow-covered locations.

2.4 *Water-savings calculation*

The water-savings calculation followed the same format as the campus makeup water demand estimate described in section 2.3.1. The calculation began by entering the predicted number of COC for each blend, COC_{blend} , into Equation 6.

$$B_{blend} = \frac{[E - D(COC_{blend} - 1)]}{(COC_{blend} - 1)} \quad (6)$$

The same values for the evaporation and drift terms are used in Equation 6 as for the makeup water demand estimate discussed in section 2.2.1 to determine the blowdown flowrate for a blended makeup source, B_{blend} .

With the new blowdown flowrate calculated, and the evaporation and drift flowrates known, the new makeup flowrate for the blended makeup source may be determined using Equation 7.

$$M_{blend} = B_{blend} + E + D \quad (7)$$

The new and reduced makeup flowrate may then be compared to that when tap water is the sole makeup water source to determine the tap water savings and subsequent financial savings that will result from using the blended rainwater and tap water makeup supply.

3. Results and Discussion

3.1 *Water quality analysis: Makeup water source comparison*

Table 1 displays the results of the water quality analysis on the tap water and the rainwater samples.

Table 1 – Makeup source comparison between tap water and rainwater

Parameter	Tap Water (<i>Measured</i>)	# of Tests	Tap Water (<i>KUB</i>) ¹	Rainwater (<i>Measured</i>)	# of Events	Rainwater (<i>NADP/NTN</i>)
pH	7.19 ± 0.13	18	7.2 ± 0.1	6.91 ± 0.25	4	4.84 ²
TDS (ppm)	150.5 ± 24.1	18	141 ± 11	12.72 ± 6.64	4	
Conductivity (μS/cm)	230.8 ± 35.2	21	255 ± 14	20.31 ± 10.52	4	3.4 – 37.0 ²
Alkalinity (as mg/L CaCO ₃)	67.6 ± 11.7	18	66 ± 3	< 10	4	
Total hardness (as mg/L CaCO ₃)	87.8 ± 13.6	18	89 ± 6	< 10	4	0.38 ± 1.12 ^{2*}
Calcium (as mg/L CaCO ₃)	63.9 ± 9.0	18	58 ± 3	< 10	3	0.30 ± 0.30 ¹

¹ Displays the mean and standard deviation of the values reported by KUB from 2008-2010 (Keaton, 2011)

² NADP/NTN data: 2010 mean for site TN11 - Great Smoky Mountains National Park, Elkmont (NADP, 2012)

* Total hardness value calculated from the sum of measured magnesium and calcium concentrations

Additionally, tap water analysis performed by the local municipal utility (KUB) has been included for comparison (Keaton, 2011).

Conductivity and calcium differed in the study and utility analyses. When the standard deviations of both the values measured in lab and those of the values reported by KUB were considered, all of the water quality parameters measured in the lab for this research were within the expected range. This comparison was used to confirm the accuracy of the tap water lab measurements.

Four distinct rainfall events were used for the quality analysis so that the data would be representative of the rainwater typically received on the University of Tennessee's Knoxville campus. The alkalinity, total hardness, and calcium hardness tests produced results that were below the detection limit of the digital titrator, 10 mg/L as CaCO_3 . For total hardness, although the majority of tests were below the detection limit, two tests yielded results within the detection range (10-4000 mg/L as CaCO_3). The values were 10.5 and 11.9, producing a mean value and standard deviation of 11.2 ± 1.0 as mg/L CaCO_3 . These two values were obtained for the same rain event. Table 1 reports the total hardness as less than 10 mg/L as CaCO_3 (< 10) since the majority of the tests were below this limit. Calcium was not measured for the first of the four rain events due to a problem in the glassware cleaning procedure. The detergent ('*Sparkleen*') was originally used with hot water to clean the Erlenmeyer flasks and graduated cylinders used to complete the calcium tests. It was discovered between the first and second rain events that residue of the detergent in the glassware prevented the calcium from being detected. Upon this discovery, *Clorox*® bleach and hot water was used for glassware cleaning.

Values reported as the 2010 annual averages by the National Atmospheric Deposition Program (NADP)/ National Trends Network (NTN) for site TN11 in the Elkmont, Tennessee

part of the Great Smoky Mountains National Park are referenced in the “Rainwater (*NADP/NTN*)” column of Table 1. Only values for pH, conductivity, total hardness, and calcium were reported by the NADP/NTN.

The pH of the rainwater obtained in the lab was significantly higher than the value reported by the NADP/NTN, but was in the statistical range of the lab reported tap water value. It has been reported in an Australian study on rainwater harvesting that roof and collection materials contribute to the dissolved metal concentration in the rainwater from its point of catchment to the point of sampling (Mendez et al., 2011). Although this study did not specifically address pH changes, the possible impact of contact with the RHS materials may be a subject of future research. The discrepancy between the NADP/NTN and lab reported values may otherwise be a result of the location at which the rainfall was sampled.

A more basic pH than 4.84 is desirable in a cooling tower to reduce the corrosion potential (McCoy, 1983; Stanford III, 2003). A pH value closer to that of the tap water is desirable to avoid or reduce any modifications to the chemical treatment program that has been chosen based on the tap water quality that is currently used for the campus cooling towers.

A comparison of the TDS and conductivity values between the rainwater and tap water samples indicated that lower values were measured for the rainwater. The lower values would be advantageous when considering rainwater for cooling tower makeup water use because a higher number of COC would be achievable with a makeup source containing fewer solids (San Jose, 2002; Wilcut and Rios, 2005; Feeley III et al., 2008; Licina and Sekhar, 2012). The TDS and conductivity measurements would likely decrease if a first-flush diverter or filtration system had been installed as a purification step before the rainwater reached the storage tank from which it

was collected. The measurements reported here are thus considered to represent a ‘worst-case’ scenario.

The rainwater also appeared as a favorable cooling water medium due to the lower values reported for alkalinity, total hardness, and calcium hardness, compared to those measured for the tap water. Since the dissolved components measured in alkalinity and hardness are typically chemical constituents of scale, lower values for each of these parameters were the desired results (Cheremisinoff and Cheremisinoff, 1981; Li et al., 2011, Liu et al., 2012). However, some alkalinity is required in cooling water to buffer the pH to prevent corrosion; and calcium may be required in the water to bind with, and thereby activate, the corrosion inhibitor that is included as part of the cooling tower’s chemical treatment package (Cheremisinoff and Cheremisinoff, 1981; Choudhury et al., 2012). It has been suggested that the use of a more dilute water source for cooling tower makeup water will reduce the amount of chemical treatment required to control fouling inside the cooling tower (Wilcut and Rios, 2005; Licina and Sekhar, 2012). The lower limits of these parameters would therefore need to be identified for the chemical treatment package that is currently in use, and consideration of possible modifications to this package would need to be explored if rainwater was to completely replace tap water as the cooling tower’s makeup water source. The full data sets for the water quality analysis on the rainwater and tap water samples are included in Appendices B and C.

3.2 *Water quality analysis: Cooling water*

The water quality analysis for cooling water chemical constituents (minimum and maximum) are displayed in Table 2, along with the values recommended by BAC, the manufacturer of the cooling tower (BAC, 2011). The complete data sets for the cooling water

samples are included in Appendix D. Cooling water samples were collected at pre-determined time intervals between and including two consecutive blowdown discharges (set-point samples) on each of the three separate days. A minimum and maximum value was reported to reflect variations resulting from water flow dynamics within an operating cooling tower (as described in section 2.2.2). The range of each water quality parameter met the recommendations issued by BAC. These results verified that the cooling water samples were representative of those found under typical cooling tower operating conditions.

Table 2 – Cooling water data

Parameter	Min	Max	Recommended
pH	8.77	8.84	6-9
TDS (ppm)	622.8	694.2	1500 (max)
Conductivity ($\mu\text{S}/\text{cm}$)	911.8	1003	2400 (max)
Alkalinity (as mg/L CaCO_3)	204	399	500 (max)
Total hardness (as mg/L CaCO_3)	250	428	30-750
Calcium (as mg/L CaCO_3)	196	338	NA

3.3 *Water quality analysis: Rainwater and tap water blends*

Blends of collected rainwater and tap water were prepared in the lab in specific volumetric ratios. The blends were identified based on the percentage of the total sample volume that was composed of rainwater. Each of the water quality parameters were measured for the blends to observe changes with increasing amounts of rainwater. See Appendix E for data.

Figure 3 displays the results of the pH measurements for the blend analysis. The pH did not change significantly with the increasing volume of rainwater. The variation that was observed was within about a quarter of a pH unit. A significant change was not expected since

the collected rainwater and the tap water had similar pH values based on the comparison between the two water types displayed in Table 1. Since the range of pH values reported in Figure 3 fall within the range recommended by BAC (Table 2), it is unlikely that there would be an increase in fouling should any blend of rainwater be used for cooling water makeup.

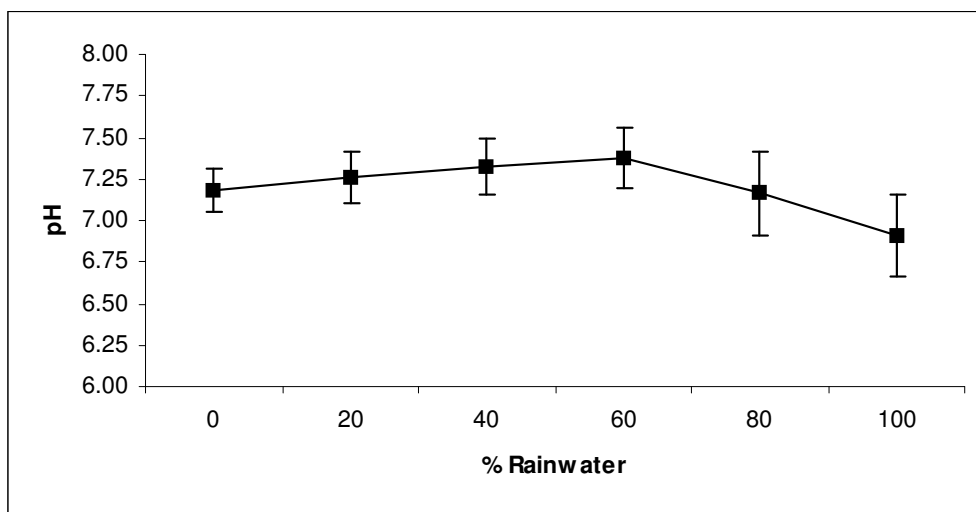


Figure 3 – pH measurements for the rainwater and tap water blends.

Figure 4 displays the conductivity measurements obtained for each blend.

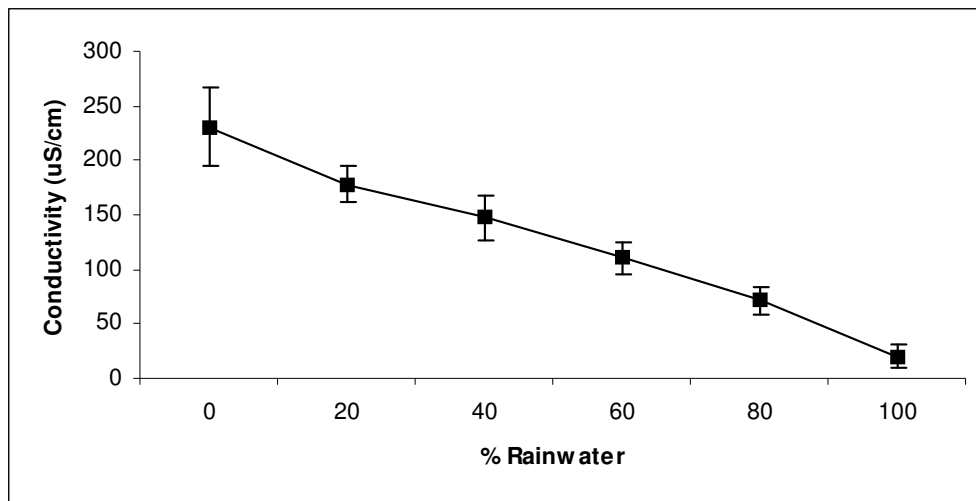


Figure 4 – Conductivity measurements for the rainwater and tap water blends.

The conductivity decreased with the increasing volume of rainwater. This result was expected since the conductivity of the collected rainwater was substantially lower than that of the tap water (see Table 1); thus the addition of rainwater diluted the tap water. Decreasing conductivity values for increasing volumes of rainwater would result in an increased number of COC.

Figure 5 displays the TDS content measured for the blends. The results were similar to those of the conductivity in that dilution of tap water occurred as the volume of rainwater increased in each blend. Again, this would increase the number of COC in the cooling tower.

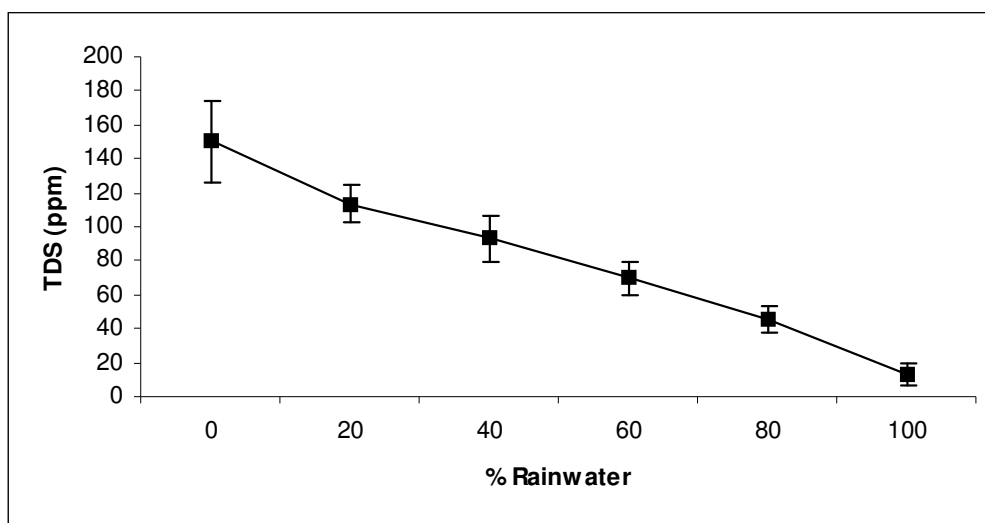


Figure 5 – TDS measurements for the rainwater and tap water blends.

Figure 6 displays the results of the total hardness measurements for the blend analysis. The total hardness results continued the dilution trend that was exhibited by the conductivity and TDS measurements. Increasing the volume of rainwater in the blends therefore diluted the magnesium and calcium concentrations, and less magnesium and calcium in the makeup source would be desirable since these are the most common scale forming species in water (Li et al., 2011). For the 100% rainwater blend, the total hardness concentration was below the detection limit of the digital titrator (10 mg/L as CaCO_3), thus no value was reported.

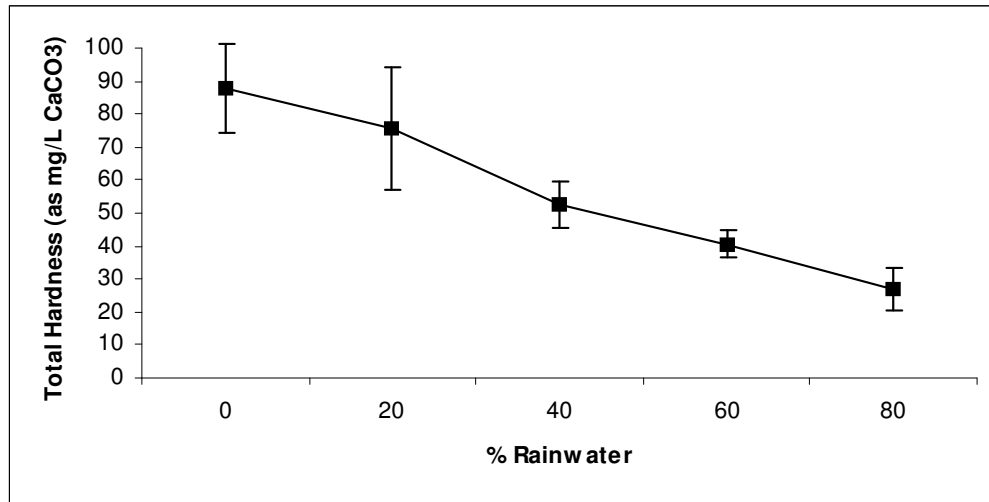


Figure 6 – Total hardness measurements for the rainwater and tap water blends.

Figure 7 displays the calcium concentrations measured for each blend. The concentration of calcium was expected to decrease with an increasing volume of rainwater since it was accounted for in the total hardness measurement, which also decreased with increasing volumes of rainwater. And as with the total hardness, a makeup source with less calcium decreases the scaling potential of the water (McCoy, 1983; Nishida et al., 2009; Li et al., 2011).

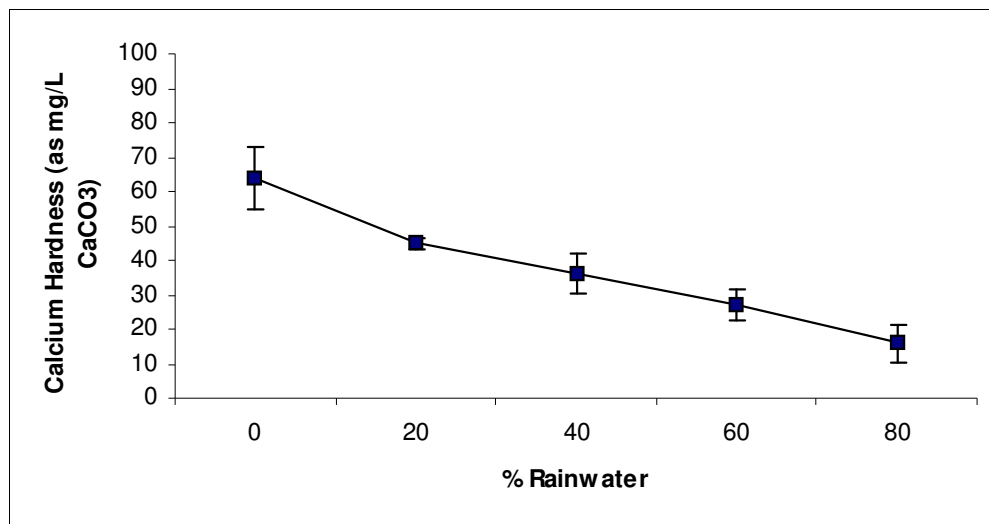


Figure 7 – Calcium measurements for rainwater and tap water blends.

The results of Figure 8 indicated the same dilution effect, as observed for the other water quality parameters. The alkalinity decreased with an increasing rainwater volume, which could potentially decrease the potential scale formation when using a rainwater blended makeup source (Li et al., 2011, Liu et al., 2012). A minimum level of alkalinity is, however, necessary to maintain the buffer capacity of the cooling water, thus minimum threshold values must be determined (Cheremisinoff and Cheremisinoff, 1981; GE, 2012).

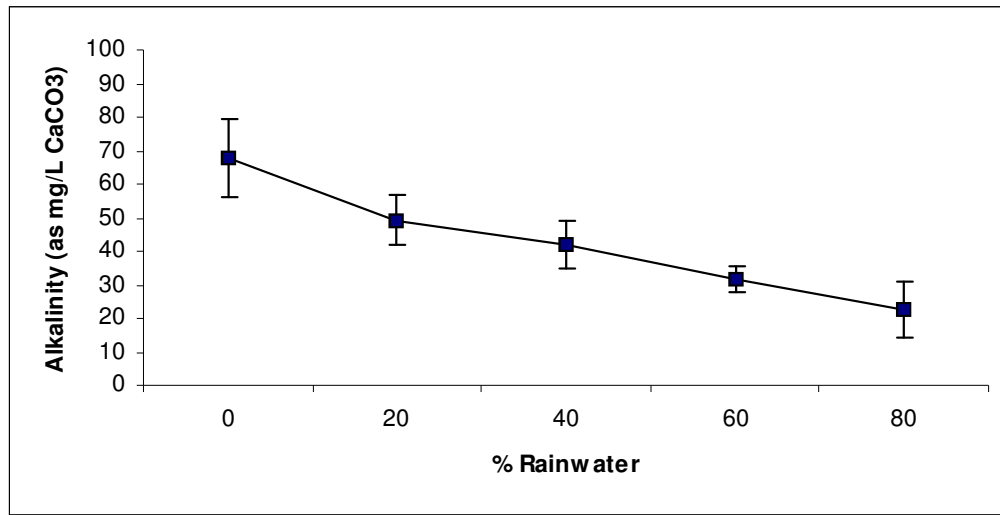


Figure 8 – Alkalinity measurements for the rainwater and tap water blends.

The results of Figures 3-8 indicate that introducing rainwater to the makeup supply with the tap water currently used in the cooling tower would not introduce any significant fouling issues with regards to the water quality parameters examined here. The low solids content of the blend was also confirmed by the conductivity and TDS data, which indicated that an increase in the number of COC from the current value could be achieved with the addition of rainwater to the makeup supply. This result was expected based on the initial makeup water source comparison in Table 1. The confirmation of the increased number of COC is displayed in the results of section 3.5.

The silica measurements were used in the COC calculations and were not used to indicate fouling issues. The measured silica concentration of the rainwater and tap water blends are shown in Figure 9. The dilution trend observed in Figures 4-9, was depicted in the silica concentration values. The plateau observed for the 60 and 80% blends was likely a result of the measurements approaching the minimum detection limit of the colorimeter (1 mg/L SiO₂). A value for the silica concentration for pure rainwater (100%) was not reported because the value was below this limit. Due to the potential inaccuracy of the silica measurements for the 60 and 80% blends, the accuracy of the subsequent COC predictions was jeopardized. For this reason, and because only two rain events were used for the silica data displayed in Figure 9, conductivity values were also used for the rainwater/tap water blend COC predictions that are reported in section 3.5.

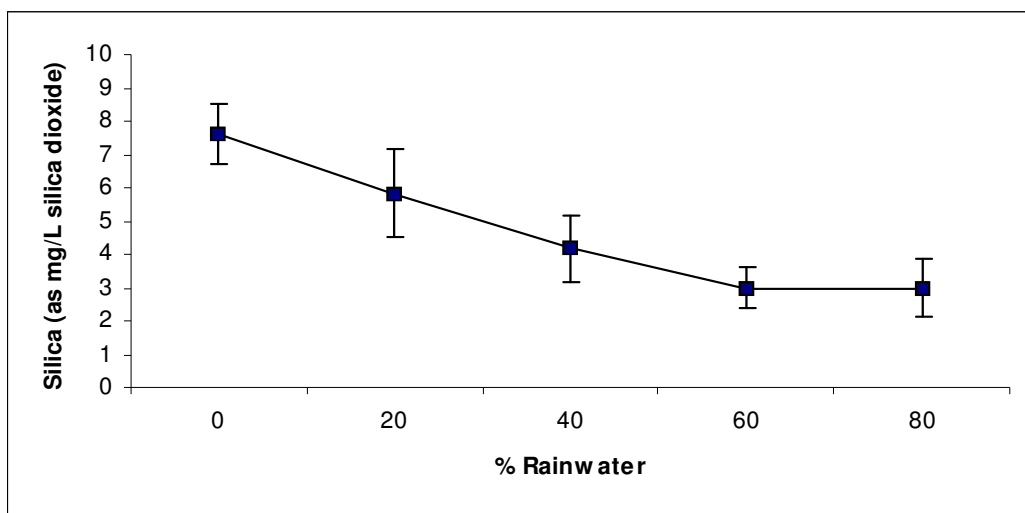


Figure 9 – Silica measurements for the rainwater and tap water blends.

3.4 COC calculation for cooling tower with tap water as makeup water source

Figure 10 displays three evaluations for the number of COC in the cooling tower when tap water was used for the makeup water supply and the chemical treatment package was being added at its designated dose. The number of COC determined using silica measurements of the tap water and cooling water samples was the most accurate because it is not influenced by the treatment chemicals. Conductivity-derived COC values were included, however, to demonstrate that the silica-based COC result was in the appropriate range. Two methods of calculation were used for the conductivity-derived COC values. One method used the controller set-point as the conductivity of the circulating cooling water, and the other, a lab-measured value.

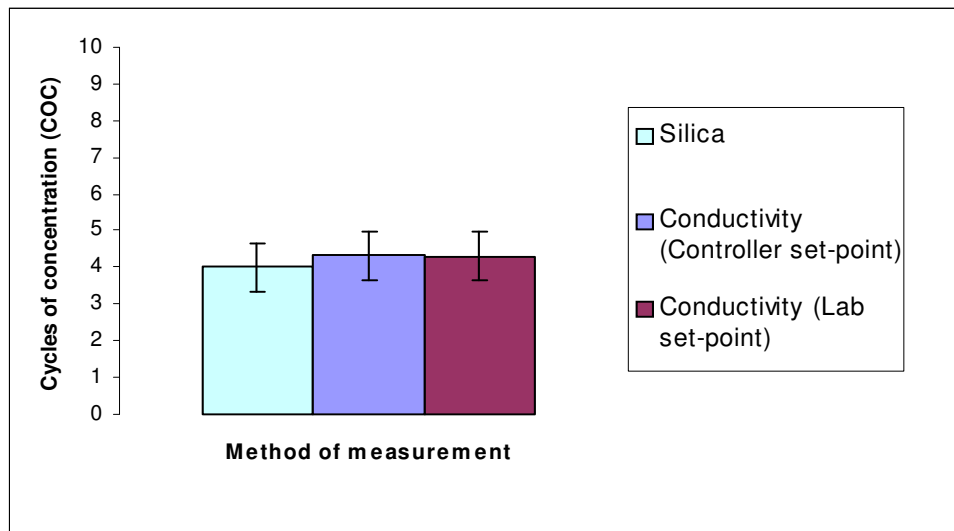


Figure 10 – COC evaluation with tap water as the makeup source.

The first column of Figure 10 was based on the silica concentrations measured in the lab for the tap and cooling water samples. The silica concentration for the tap water was measured as 7 ± 1 as mg/L SiO_2 . KUB did not report a silica concentration for its water supply and therefore a comparison could not be made with this parameter as was done with other water quality parameters in Table 1. The mean silica concentration (as mg/L SiO_2) of the set-point

cooling water samples was measured as 29 ± 2 as mg/L SiO₂. The number of COC for the cooling tower was then calculated as 4 ± 0.6 .

The second column in Figure 10 represents the number of COC that was calculated by dividing the controller set point value, 1000.00.00 μ S/cm, by the lab-measured conductivity value for the tap water, 230.8 ± 35.2 μ S/cm (see Table 1). The number of COC for this assessment was calculated to be 4.333 ± 0.661 . The third column of Figure 10 was also determined based on conductivity, except both the cooling water set-point and tap water values were measured in the lab. The number of COC was calculated as 4.303 ± 0.657 . See Appendix D for the set-point sample data.

Examining the results of Figure 10, the silica-based COC value was lower than both those calculated based on conductivity. This result was expected since the conductivity-derived number of COC accounted for the chemicals in the treatment package, whereas the silica value did not (GE, 2012). For this reason, the cooling tower was concluded to operate at the silica-derived COC value, 4 ± 0.6 cycles. It is noted however, that based on the standard deviations of the reported data, the conductivity-derived values were not significantly different.

A COC calculation based on the lab-measured conductivity value for the cooling water at set-point was included to verify that based on the controller's designated set-point. Even though the controller regulates the blowdown discharge, using lab-measured values for the conductivity of the cooling water removed any possible unknown error associated with the controller's measurement. The number of COC reported using only lab-measured values was thereby limited to measuring and sampling errors. Of the two types of error, sampling was considered to have a greater influence. The conductivity of the cooling water set-point samples was measured as 993.1 ± 6.1 μ S/cm. This value was slightly lower than the designated set-point value, 1000.00

μS/cm. The cooling water set-point samples were collected from the cooling tower's water basin. The controller, however, takes conductivity readings after the cooling water has exited the water basin and flows towards the condenser. Thus, the two conductivity values were measured at different points in the condenser loop. The difference between the values may be attributed to the exposure of the water basin to newly-cooled water flowing down over the fill. With this exposure, the solid concentration of the cooling water may still be increasing before it exits the water basin and passes through the controller. The effect on the COC calculations was marginal.

3.5 COC predictions for rainwater and tap water blends

The silica and conductivity measurements of the rainwater and tap water blends were used to predict the number of COC that would be achievable in a cooling tower that consistently used a makeup supply of a specific percentage of rainwater. These predictions were made under the assumption that the current set-point in the cooling tower would not be altered. The specific values for the COC predictions are included in Appendix F.

Although COC calculations based on the silica concentrations were likely more accurate, since the contribution of treatment chemicals to the solid concentration of the recirculating cooling water was excluded, predictions were also determined based on blended conductivity values. This approach was mainly necessary due to the inaccuracy of the silica measurements, and subsequent COC values, for the 60-100% blends resulting from low range detection issues. The inclusion of the conductivity-based COC values was also necessary since only two rain events were used for the silica blend values. The results of Figure 10 validated this approach by showing a marginal difference between the silica and conductivity COC values.

The predictions were calculated using three methods. The first method divided the conductivity set-point of the controller (1000.00 $\mu\text{S}/\text{cm}$) by the lab-measured conductivity value for each blend. The second divided the lab-measured conductivity of the controller, 993.1 ± 6.1 $\mu\text{S}/\text{cm}$, by the lab-measured conductivity of each blend. The third method was based on lab-measured silica concentrations. The silica concentration of the cooling water at set-point was determined to be 29 ± 2 mg/L as SiO_2 (see Appendix D). Figure 11 displays the COC predictions.

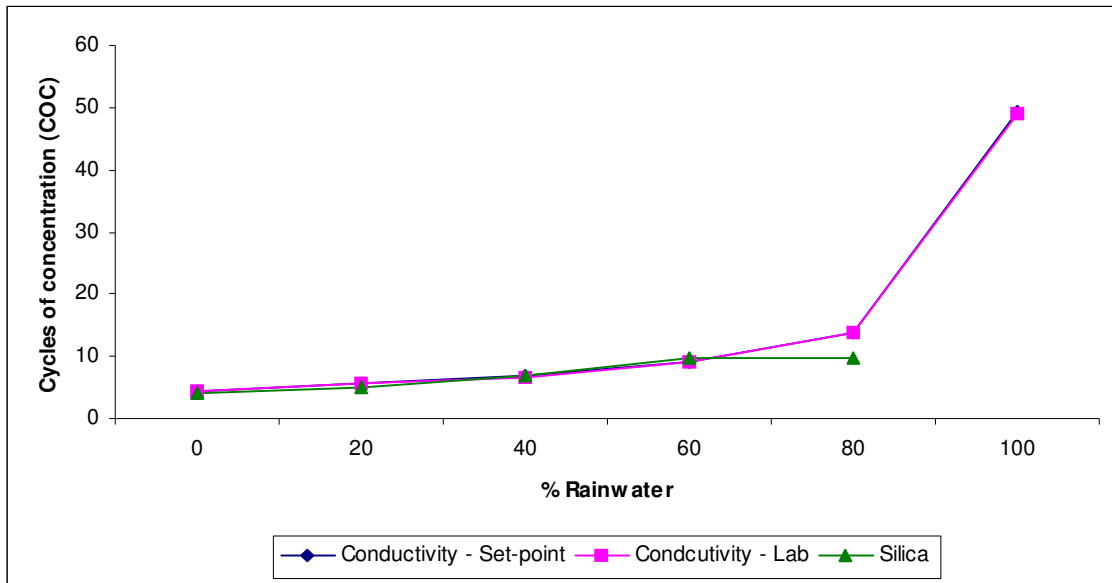


Figure 11 – COC predictions for rainwater and tap water blends.

The overall trend of the results reported in Figure 11 was that the number of predicted COC increased with an increasing volume of rainwater in the blend. A drastic increase between the predicted values occurred at the highest rainwater blend. The number of COC predicted for a 100% rainwater makeup source was calculated as 49.24 ± 25.51 cycles based on the controller set-point determination method and as 48.80 ± 25.33 cycles for the lab-measured conductivity determination method. The number of COC for a 100% rainwater makeup source based on the

lab-measured conductivity values for the cooling water and rainwater samples was 48.90 ± 25.33 . These values both have large standard deviations due to the difficulty of accurately measuring the low-range conductivity value of the pure rainwater samples. The silica concentration for the 100% rainwater samples was below the detection limit of the colorimeter thus a silica-derived COC prediction was not reported in Figure 11.

Since consistent operation of each of the campus cooling towers with a 100% rainwater makeup source is not likely due to lack of consistent supply, Figure 12 focuses on the COC predictions for the 0-80% blends. The 0% blend, or tap water data set, was included to demonstrate the increase in the number of COC when rainwater was added to the samples.

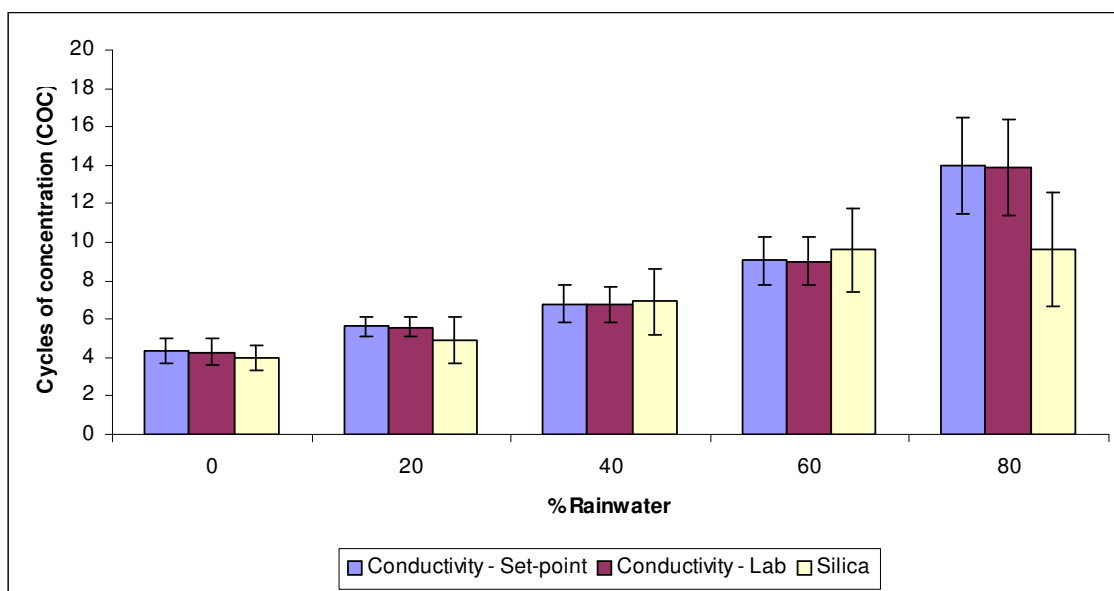


Figure 12 – COC predictions for the 0-80% rainwater and tap water blends.

The COC predictions for the two conductivity-based columns were almost equivalent for each blend. The silica-derived COC values were higher than those for the two conductivity columns in the case of the 40 and 60% blends. The silica-derived COC values were expected to be lower than those based on conductivity measurements since the conductivity of the cooling

water samples was partially attributed to the addition of treatment chemicals. However, the overlapping ranges of the standard deviations indicated that the differences between the silica and conductivity data sets were not significant; therefore this unexpected result was not considered significant. The standard deviations of the silica columns for the 40 and 60% data sets were also much larger than that of the conductivity columns, which was a reflection of the decreased accuracy as the colorimeter approached its lower detection limit for the silica concentrations of these blends. Overall, the standard deviations increased with increasing rainwater percentages due to the difficulty of low-range detection as the samples became more diluted with rainwater addition. The predicted number of COC represented by the 80% silica column was particularly affected, as this was the most dilute blend. The predicted number of COC for each of the blends was then used in the back-calculation described in section 2.4. The results of which are reported in section 3.6

3.6 *Tap water makeup demand reductions*

The COC values predicted for the rainwater and tap water blends were used in Equation 6 along with evaporation and drift rate estimates to determine the blowdown rate of a cooling tower using a makeup source of the corresponding blend. The new blowdown rates calculated for each blend were then added to the evaporation and drift estimates to obtain the value for the makeup demand according to Equation 7.

An estimate for the campus evaporation rate was determined using Equation 5 and the method of calculation was explained in section 2.3.1. The sum of the circulation rates for each of the 56 campus cooling towers was determined to be 72,926 gallons per minute (gpm) based on information on the pumps for the cooling towers that was provided by the University's Facility

Services. The list of cooling towers and circulation rates has been included in Appendix G. An estimate for the evaporation rate on campus was calculated by substituting the sum of the circulation rates, along with a 10°F range, into Equation 5. The evaporation rate was estimated as 620 gpm, or about nine hundred thousand gallons per day. The drift estimate was calculated as 0.005% of the sum of the circulation rates. The estimate used for the drift rate in Equations 6 and 7 was approximately 4 gpm.

Figure 13 displays the results of the makeup flowrates determined for each blend. The rates decreased as the volume of rainwater, and thus the number of COC, increased. The gradual decrease of the makeup water demand depicted in Figure 13 was a result of increasing the number of COC by using an increasingly dilute makeup water source. Figure 13 displays the benefit of makeup reduction by increasing the number of COC, but it does not specifically quantify the reduction of tap water use.

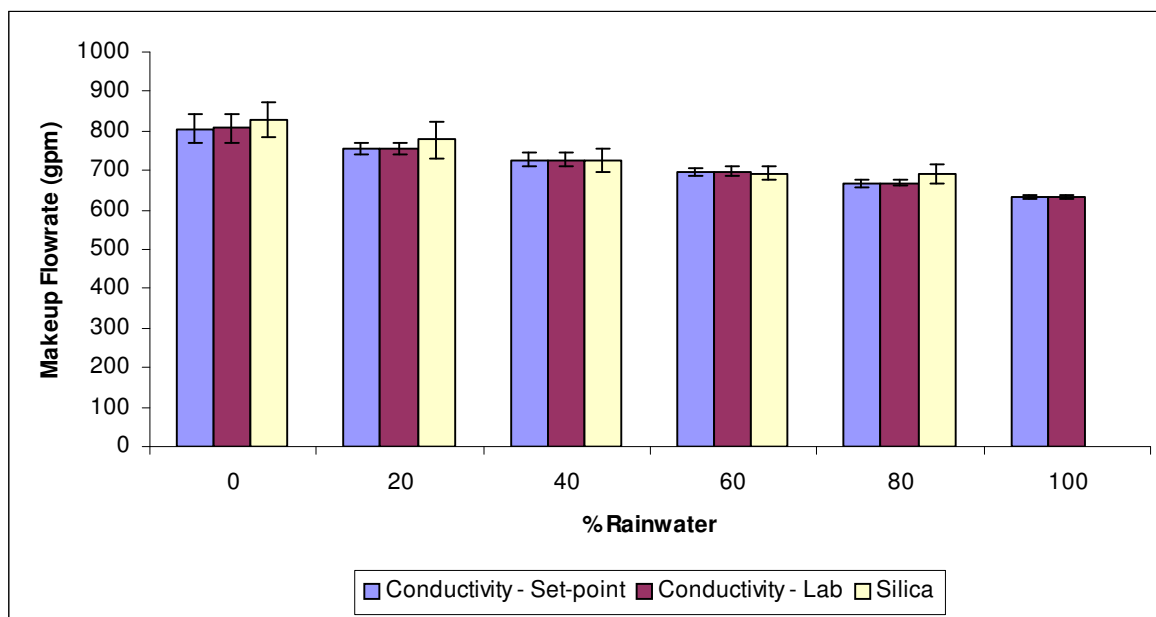


Figure 13 – Makeup flowrate comparison for increasing rainwater volume and COC.

Figure 14 portrays the reduction in tap water that would result from increasing the number of COC by operating the campus cooling towers with rainwater/tap water blends. These values were calculated by multiplying the makeup flowrates presented in Figure 13 by the fraction of tap water in the respective blends. The results of Figure 14 indicate that significant tap water savings may be gained by utilizing rainwater in the makeup supply.

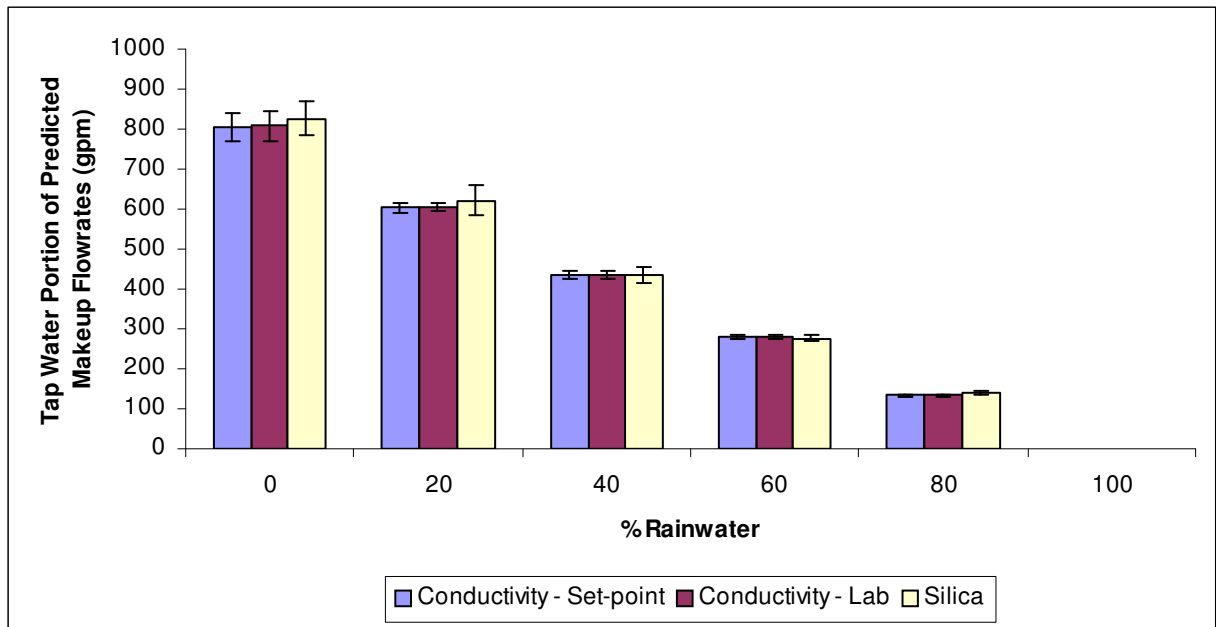


Figure 14 – Tap water portion of predicted makeup flowrates.

Figure 15 focuses on the “Conductivity – Set-point” data to isolate the respective contribution of replacement and increasing COC to the tap water makeup reduction results in Figure 14. Only one data set was chosen for this evaluation, but either the “Conductivity-Lab” or “Silica” data sets could also be used since the trends for each have been the same through the results of the blend analysis. The top line in Figure 15 represents the decreased makeup flowrate resulting strictly from increasing the number of COC in the campus cooling towers. The reported flowrates are the same as those presented in Figure 13 for the “Conductivity – Set-point” data

set. The middle line in Figure 15 represents the reduced tap water makeup demand for a hypothetical scenario in which a specific percentage (x-axis values) was replaced by rainwater without an increase in COC. This line is linear. The bottom line in Figure 15 represents the decrease in the makeup demand resulting from both increasing the number of COC and replacing the tap water with rainwater. This line is a reproduction of the “Conductivity Set-point” data set presented in Figure 14. Since the bottom line of Figure 15 is more closely fitted to the middle line, the replacement of tap water with rainwater was determined to have a greater effect on makeup water demand reduction than the increase of COC. The specific percent savings values for each data set are included in Appendix F.

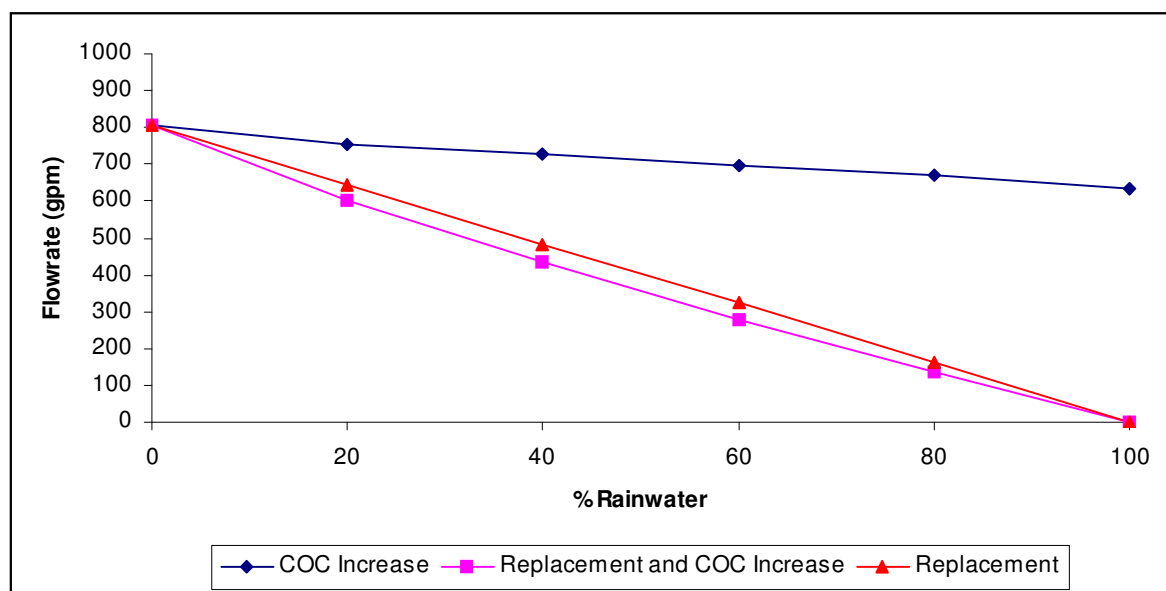


Figure 15 – Comparison of the contributing factors to tap water use reduction.

3.7 *Rainwater supply estimate*

An estimate of the rainwater supply available on the University of Tennessee’s Knoxville campus was obtained in order to determine which rainwater blend could potentially be used as

the makeup supply for each of the campus cooling towers. The number of gallons of rainwater that could potentially be collected was estimated using the local rainfall data and surface area measurements of campus buildings on the agricultural and main campus of the University of Tennessee's Knoxville campus. The surface area was estimated using a combination of two different GIS services, KGIS Maps and Google Earth. The total available surface area for rainwater catchment was estimated to be 3.4 million square feet (see Appendix H). Table 3 displays the total number of rainwater gallons that could be potentially collected from this surface area according to local rainfall data reported by the City of Knoxville's Stormwater Engineering Department from 2009-2011 (City of Knoxville, 2012). The total amount of rainfall (inches) received at the Tyson Park site, a location within about a mile of the campus, was measured and reported on a monthly basis for each year (see Appendix I).

Table 3 – Rainwater supply estimation for the campus

	<u>2009</u>	<u>2010</u>	<u>2011</u>
Rainwater supply <i>(10⁶ gallons)</i>	121	99.9	127

Using the mean of the values reported in Table 3, the University of Tennessee's Knoxville campus has the potential to collect 116 ± 14 million gallons of rainwater per year if each building roof-top on both the main and agricultural campuses were used as rainwater catchment surfaces, assuming a 100% efficient collection. This value is likely an overestimate, however, when practical and implementation considerations are considered. A retro-fitting design scheme that incorporates every building used in the supply estimate into a RHS for cooling water makeup is not likely to be implemented. Another issue that is likely to decrease the rainwater supply is collection efficiency (Texas, 2005; Mun and Han, 2012). The amount of

collected rainfall is expected to be about 75-90% of the roof area's potential rainfall (Texas, 2005).

Figure 16 displays the annual volume of rainwater required to sustain the makeup flowrates presented in Figure 13 for each blend. Based on the 100% efficient rainwater collection estimate, Figure 16 indicates that only a 20% makeup blend can be achieved on campus. The annual volume of rainwater required to operate all 56 campus cooling towers with a 20% blend makeup supply was determined to be 79.3 ± 1.5 , 79.4 ± 1.5 , and 6.96 ± 1.2 millions of gallons for the “Conductivity Set-point”, “Conductivity – Lab”, and “Silica” data sets, respectively. A 40% makeup supply for the campus required between 134-153 million gallons of rainwater per year; a demand that the rainwater supply estimate of 116 million gallons per year did not meet. The complete list of rainwater demand values for each blend is included in Appendix J.

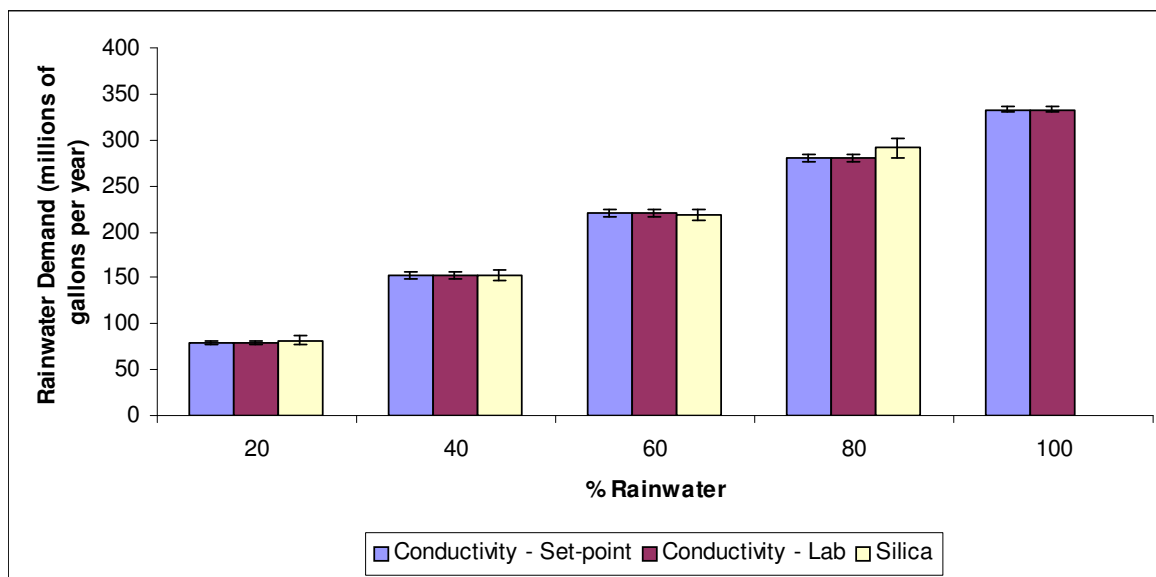


Figure 16 – Rainwater demand for blend makeup flowrate predictions.

3.8 *Tap water and cost savings*

The potential water volume and financial savings resulting from the use of a 20% rainwater/tap water blend makeup for every campus cooling tower was estimated. Only the silica data was used for these calculations since they were considered the most accurate. The first step for calculating the total number of saved tap water gallons was to multiply the makeup flowrates for the 20% blend by a factor of 0.8 to obtain the tap water fraction. This value was then subtracted from the current tap water-only makeup flowrate of the campus. The campus flowrate was estimated by the 0% silica column in Figure 13, 827 ± 44 gpm. The annual tap water savings was calculated to be 108 ± 20 million gallons. The annual financial savings were determined based on the current price of water, \$1.00 per ccf (or \$0.001 per gallon), for businesses located inside the city consuming over 5,000 ccf/month (KUB, 2012). A total of approximately \$100,000 was calculated for these potential savings.

Since increasing the number of COC decreases the frequency of blowdown, as well as makeup, a reduction in wastewater charges for the 20% blend was also calculated (Ward et al., 2012). The current wastewater rate for businesses located inside the city producing over 5,000 ccf/month is \$4.30 per ccf, or \$0.006 per gallon (KUB, 2012). The blowdown rate calculated for the 20% blend, 154 gpm, was subtracted from the estimated current blowdown rate of the campus, 203 gpm (see Appendix F). The cost savings associated with wastewater charges resulting from the utilization of rainwater in campus cooling towers was calculated to be approximately \$155,000 thousand dollars per year. Thus, the total estimated financial savings for the 20% rainwater/tap water blend was estimated to be approximately \$255,000 dollars per year.

3.8.1 Cost analysis as a function of heat load

Seasonal climatic changes will alter the heat load imposed on the campus cooling towers throughout the year (ASHRAE, 2004). The change in heat load will affect the temperature range over which the cooling water is to be cooled, and thus will also affect the evaporation rate (ASHRAE, 2004). The heat that is transferred to the cooling water as it passes through the condenser of the water chiller is that which must be transferred to the atmospheric air via the cooling tower (Stanford III, 2003). Therefore, under steady-state conditions the temperature rise of the cooling water that results from the heat absorbed from the condenser is the same range over which the water must be cooled in the cooling tower (ASHRAE, 2004). Table 4 displays the percent heat load and corresponding temperature range values that were provided by a representative from McQuay International, the manufacturer of the water chiller that operates in conjunction with the Hesler Hall cooling tower (O'Bryant, 2012). Each heat load percentage refers to a specific fraction of the water chiller's design capacity, 775.04 tons (O'Bryant, 2012).

Table 4 – Water chiller heat load design specifications

Heat Load (%)	Range (°F)
100	9.1
75	6.5
50	4.2
25	2.1

So far in this study, the campus cooling towers were assumed to be operating under a 100% heat load. Since it is highly unlikely that the campus cooling towers will be operating under a 100% heat load throughout the entire year, the makeup demand values will likely be lower than those presented in Figure 13. With a lower makeup demand, it may be possible to utilize a higher percentage of rainwater in each cooling tower. Figure 17 displays the annual rainwater requirement (in millions of gallons) for the 20, 40, and 60% blends according to the

silica data set as a function of heat load. The values of Figure 17 were calculated by using the range values shown in Table 4 in the evaporation estimate, as opposed to the 10°F that was used originally. Considering the campus rainwater supply estimate of 116 million gallons, a 60% blend may be used for the cooling towers when operating at a 50% heat load throughout the year, a 40% blend in the case of a 75% heat load, and as already discussed, a 20% blend for the 100% heat load scenario.

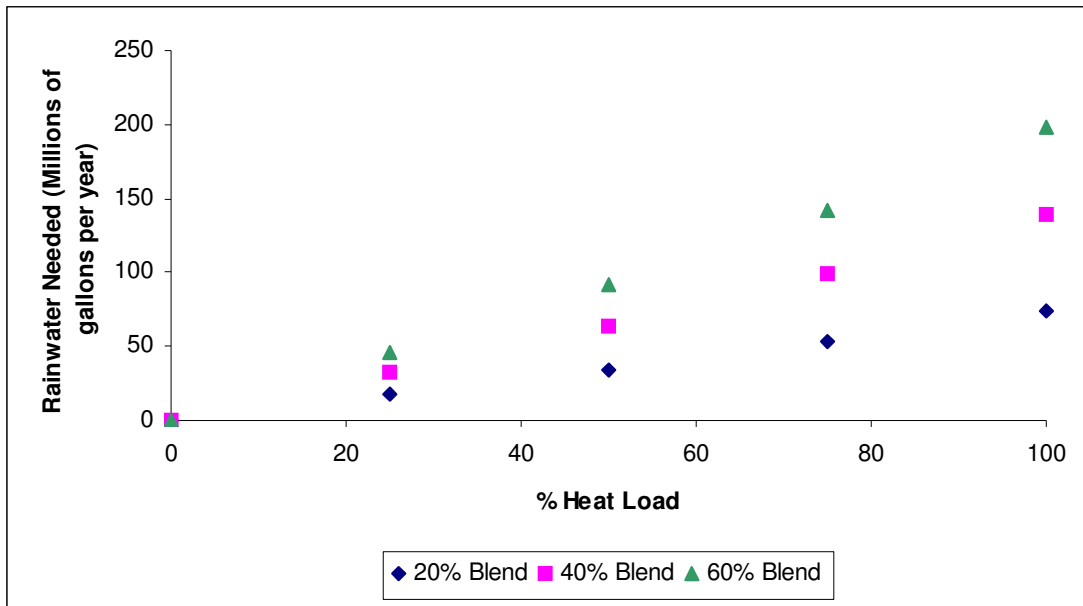


Figure 17 – Annual rainwater collection required as a function of heat load.

The corresponding water and wastewater savings for the various blends as a function of heat load are displayed in Figure 18. The values reported here are the summations of both savings. The temperature range values reported in Table 4 were used to re-calculate the evaporation rate, and the subsequent makeup and blowdown rates, for each blend. Thus, a new makeup rate was determined for the 0, 20, 40, and 60% blends for each heat load. The makeup rates were then multiplied by a specific factor corresponding to the tap water composition of each blend, e.g. a factor of 0.8 was used for the 20% blend. Next, the tap water portion of the

makeup rate for the 20, 40, and 60% blends was subtracted from that of the 0% blend to calculate the tap water savings for each heat load. The difference in tap water consumption was then multiplied by \$0.001/gal to obtain the water cost savings for each heat load. The same method of calculation was used with the blowdown rates to generate the wastewater savings, except that the charge was \$0.006/gal and a multiplication factor was not used to differentiate the tap water and rainwater portions of the blowdown. Thus, by subtracting the blowdown rate for the 20, 40, and 60% blends from that of the 0% blend, the difference could be multiplied by \$0.006/gal to obtain the wastewater cost savings. The summations of the water and wastewater savings that were determined for each heat load based on these calculations are reported in Figure 18 (see Appendix K).

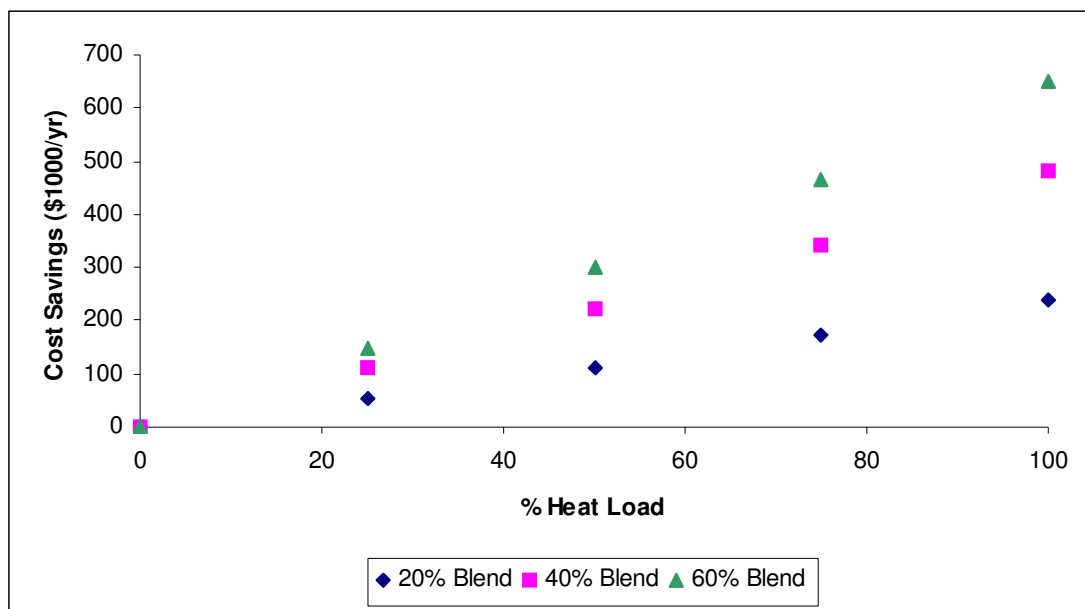


Figure 18 – Annual water and wastewater savings as a function of heat load.

Based on the rainwater supply estimate, if a 60% blend may be used for when the campus cooling towers are operating at a 50% heat load according to Figure 17, then the total cost savings would be about \$299,800 according to Figure 18. The cost savings for the 40% blend

and 75% heat load, and those for a 20% blend and 100% heat load, are about \$342,723 and \$239,238, respectively. These results indicate that the cost savings attributed to water and wastewater will thus vary depending on the heat load imposed on the cooling towers (see Appendix K).

It has been suggested that the use of a more dilute makeup source, and the subsequent reduced makeup water demand, would reduce the quantity, and therefore cost, of chemicals added to the cooling water (San Jose, 2002; Wilcut and Rios, 2005; Licina and Sekhar, 2012). Thus, further financial savings may be possible from a treatment standpoint resulting from rainwater utilization. However, the cost of constructing the harvesting systems that would be necessary to collect rainwater for cooling tower makeup would decrease the total financial savings. The energy cost associated with pump operation, as well as maintenance costs, will also decrease the total savings and increase the duration of the payback period (Ward et al., 2012). The potentially long pay-back period for implementing rainwater harvesting systems is an acknowledged drawback (Domènech and Saurí, 2011).

4. Conclusion

The water quality analysis confirmed that even after contact with the various components of the harvesting system, the collected rainwater was a more chemically dilute water source than the tap water currently used for cooling water makeup. The blended water quality analysis showed decreasing values for TDS, conductivity, alkalinity, total hardness, calcium hardness, and silica concentrations with increasing volumes of rainwater in each blend. The decreased values obtained for alkalinity, total hardness, and calcium hardness for the blends indicated that the use of rainwater in cooling towers would reduce the potential for fouling due to scaling. The

lower alkalinity may however reduce the buffering capacity of the rainwater and thus make the water source more corrosive during cooling tower operation.

The predicted increase in the number of COC that could be achieved, based on silica and conductivity measurements in rainwater/tap water blends, resulted in a reduction of the makeup water demand. While the change in water quality of the makeup supply decreased tap water demand, an additional reduction was achieved by replacing a specific fraction of the supply with rainwater. The replacement of tap water gallons with rainwater was found to have a greater contribution to the total tap water savings than increasing the number of COC.

Despite the established benefits of utilizing rainwater in the makeup supply, its availability was a limiting factor due to the large cooling water makeup demand. Based on a comparison of the rainwater supply estimate and the reduced makeup flowrates required for each of the blends, a 20% rainwater makeup supply for each of the campus cooling towers was predicted to be attainable for when the cooling towers are operating at a 100% heat load. Cooler climatic conditions throughout the year will impose smaller heat loads on the cooling towers and thus the annual makeup demand will likely be less than the estimated values presented here. A lower makeup demand means that the rainwater supply may meet a larger portion of the overall demand than 20%. Based on the estimated rainwater supply estimate of 116 million gallons, it is possible that anywhere from a 20-60% blend may be utilized in each of the campus cooling towers if the average heat load is between 50-100%. At the current price of water and wastewater, the maximum cost savings associated with these results is about \$343,000 for the case in which a 40% blend is used for cooling towers operating at a 75% heat load.

Although the challenges of retrofitting a RHS between the buildings and cooling towers on the campus, losses due to collection inefficiencies, maximizing catchment surface area and

obtaining adequate storage capacity are all aspects of this water sustainability strategy that remain to be addressed, the utilization of rainwater as cooling water makeup has proven tap water reduction benefits. The implementation of this strategy is one method of increasing water use efficiency which should be considered to meet the challenge of an increasing global water demand.

List of References

- ASHRAE, 2004. *2004 ASHRAE Handbook: HVAC Systems and Equipment*, I-P Edition, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA, pp. 36.1-36.20.
- BAC, 2011. *Common Operation & Maintenance Manual*, Baltimore Aircoil Company, Jessup, MD, pp. 19. [Online] Available: <http://www.baltimoreaircoil.com/english/resource-library/file/829>
- Cheremisinoff, N.P and Cheremisinoff, P.N., 1981. *Cooling Towers: Selection, Design, and Practice*, Ann Arbor Science Publishers, Inc., pp. 194-195.
- Chien, S.H., et al., 2012. Pilot-scale cooling tower to evaluate corrosion, scaling, and biofouling control strategies for cooling tower system makeup water, *Review of Scientific Instruments* 83, 024101-1-10.
- Choudhury, M. R., et al. Corrosion management in power plant cooling systems using tertiary-treated municipal wastewater as makeup water, *Corrosion Science* (2012), in press <http://dx.doi.org/10.1016/j.corsci.2012.04.042>
- City of Knoxville, 2012. *City of Knoxville*, Engineering Department, Stormwater Engineering Division. [Online] Available: <http://www.cityofknoxville.org/engineering/stormwater/rainfall/>
- Domènech, L. and Saurí, D., 2011. A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): social experience, drinking water savings, and economic costs, *Journal of Cleaner Production* 19, 598-608.
- EPA (2011). Strategic Sustainability Performance Plan: FY 2010-FY 2020, U.S. Environmental Protection Agency, pp. 19. <http://www.epa.gov/epahome/sspp20102020.html> (accessed 10.05.2012)
- Feeley III, T.J., et al., 2008. Water: A critical resource in the thermoelectric power industry, *Energy* 33, 1-11.
- GE, 2012. *Handbook of Industrial Water Treatment*, GE Power & Water: Water & Process Technologies, Chapter 31. [Online] Available: http://www.gewater.com/handbook/cooling_water_systems/ch_31_open.jsp
- Helmreich, B. and Horn, H., 2009. Opportunities in rainwater harvesting, *Desalination* 248, 118-124.
- Jones, M. P. and Hunt, W. F., 2010. Performance of rainwater harvesting systems in the southeastern United States, *Resources, Conservation, and Recycling* 54, 623-629.

- Keaton, K., 2011. "KUB Drinking Water Analysis Data for 2008-10," unpublished.
- Kloss, C., 2008. Managing Wet Weather with Green Infrastructure Municipal Handbook: Rainwater Harvesting Policies, Environmental Protection Agency. Low Impact Development Center, EPA-833-F-08-010, pp. 1, 11-12. <http://nepis.epa.gov> (accessed 5.09.2011)
- KUB, 2012. Business customers: water and wastewater rate schedules. [Online] Available: KUBorg, 2012 (accessed 10.05.2012)
- Li, H., et al., 2011. Control of mineral scale deposition in cooling systems using secondary-treated municipal wastewater, *Water Research* 45, 748-760.
- Licina, D. and Sekhar, C., 2012. Energy and water conservation from air handling unit condensate in hot and humid climates, *Energy and Buildings* 45, 257-263.
- Liu, W., et al. Mineral scaling mitigation in cooling systems using tertiary-treated municipal wastewater, *Water Research* (2012), in press
<http://dx.doi.org/10.1016/j.watres.2012.05.041>
- McCoy, J. W., 1983. *The Chemical Treatment of Cooling Water*, 2nd ed. New York: Chemical Publishing Co., pp. 1-4, 8-15, 21-27, 48, 82-83, 93-94.
- Mendez, C. B., et al., 2011. The effect of roofing material on the quality of harvested rainwater, *Water Research* 45 (5), 2049-2059.
- Mun, J.S. and Han, M.Y., 2012. Design and operational parameters of a rooftop rainwater harvesting system: Definition, sensitivity, and verification, *Journal of Environmental Management* 93, 147-153.
- NADP, 2012. *National Atmospheric Deposition Program/National Trends*. [Online] Available: <http://nadp.sws.uiuc.edu/ads/2010/TN11.pdf>
- Nishida, I., et al., 2009. Effect of aluminum on the deposition of silica scales in cooling systems, *Journal of Colloid and Interface Science* 335, 18-23.
- O'Bryant, M., 2012. "Data profile: Hesler Chiller Addition," unpublished.
- Pearson, W.E. (2011, February). NCDs and Biological Control in Cooling Water Systems. *CTI Journal: The Official Publication of the Cooling Technology Institute* [Online], Winter 2012, vol (1), pp, 50. Available: <http://www.cti.org/downloads/2012WinterJournalCTI.pdf>
- Perry, R.H. et al., 1984 *Perry's Chemical Engineers' Handbook*, 6th ed., McGraw-Hill, Inc., pp. 12-13 – 12-17.

- San Jose, 2002. *Guidelines for Managing Water in Cooling Systems: For Owners, Operators, and Environmental Managers*, San Jose/Santa Clara Water Pollution Control Plant and the City of San Jose Environmental Service Department. [Online] Available: <http://www.sanjoseca.gov/esd/PDFs/cooling.pdf>
- Shang, L., et al., 2011. The scale and antiscaling study of the reclaimed water re-used in industrial recycling cooling system, *Journal of Water Sustainability* 1 (2), 73-85.
- Solomon, S., et al., 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, NY, USA, 2007.
- Stanford III, H.W. 2003. *HVAC Water Chillers and Cooling Towers: Fundamentals, Application, and Operation*, New York: Marcel Dekker, Inc., pp. 1-11, 115-119, 154, 168, 191-203.
- Stoeglehner, G., et al., 2011. The water supply footprint (WSF): a strategic planning tool for sustainable regional and local water supplies, *Journal of Cleaner Production* 19, 1677-1686.
- Swart, J.S. and Engelbrecht, J.P., 2004. Pilot scale evaluation of mine water (MW) as a cooling medium. presented at 2004 Water Institute of South Africa (WISA) Biennial Conference [Online]. Available: <http://www.ajol.info/index.php/wsa/article/viewFile/5185/12722>
- Texas, 2005. *The Texas Manual on Rainwater Harvesting*, 3rd ed., Texas Water Development Board, Austin, Texas, pp. 5, 8, 29-30. http://www.twdb.state.tx.us/publications/reports/rainwaterharvestingmanual_3rdedition.pdf (accessed 10.04.2012)
- Ward, S., et al., 2012. Performance of a large building rainwater harvesting system, *Water Research* 46, 5127-5134.
- Wilcut, E. and Rios, S., 2005. Paper No. 05545: Water conservation and water reuse in cooling water systems. presented at Corrosion 2005 [Online]. Available: <http://www.onepetro.org/mslib/servlet/onepetropreview?id=NACE05545&soc=NACE&speAppNameCookie=ONEPETRO>
- Zhao, Z. and Xu, H., 2012. Study on the supplying system of cooling water of air conditioner based on the urban street rainwater, *Energy Procedia* 16, 8-13.

Appendices

Appendix A – Description of example RHS components and design schematic.

The design schematic in Figure 19 displays an example RHS for cooling tower makeup set-up. A building on the University of Tennessee's Knoxville campus, Hesler Hall, was chosen to provide the rainwater catchment surface. Rainwater was collected from the clay tile roof of Hesler Hall utilizing one of the multiple copper downspouts on the building. A fabricated copper sheet metal adapter (Figure 20) was connected to the downspout and flow was redirected, through a four inch ID plastic pool hose line, to a 300 gallon polypropylene storage tank. The rainwater moved through the pool hose as a result of gravity-induced flow.



Figure 19 – Picture of the RHS set-up.



Figure 20 – Downspout adapter. This piece was handcrafted by one of the Facility Services employees that helped with the construction of the RHS.

An Ebara Pro Drainer (EPD) stainless steel submersible pump, model EPD-5AS1 with ½ horse power, was placed inside the storage tank to pump the rainwater up into the cooling water basin of the cooling tower. The pump was chosen based on the difference between the height of the storage tank and the height of the cooling tower’s water basin. The height difference is due to the cooling tower’s location on the roof of a chiller building in close proximity to Helser Hall. A PVC pipe was attached to the top of the pump (1.5” opening) and connected to a check valve to ensure that rainwater could not flow back into the pump. Another piece of PVC pipe was used to connect the check valve to a 1” ID garden hose used as the transfer line from the storage tank to the cooling water basin. This configuration is shown in Figure 21.



Figure 21 – Submersible pump and check valve inside the storage tank.

The garden hose was supported by metal rods such that it slopes upward from the storage tank to the cooling tower basin. The slope was purposefully created to prevent rainwater from sitting in the transfer line if the pump turned off. Stagnant rainwater may result in a frozen blockage of the transfer line during winter months. Any backflow of rainwater from the garden

hose was directed back into the storage tank via a second check valve. An Advantage Controls water meter (model AW-3) was installed along the garden hose line to quantify how many gallons of rainwater were being pumped into the cooling tower.

The last piece of equipment used as part of the RHS was a float switch that was located at the end of the garden hose line, inside the cooling water basin (see Figure 22). This switch was electrically connected to the float switch responsible for triggering the pump inside the storage tank. This connection ensured that the pump only turned on when the following two conditions were met: (a) there was a large enough volume of rainwater in the storage tank, and (b) the cooling water basin required additional make up water. The electrical power for the pump and float switch was provided by an outlet located on roof of the chiller building.



Figure 22 – Float switch inside of the cooling tower's water basin.

Several notes on the RHS: (1) the system described here is a site specific design and that modifications would likely be required for other systems on the campus; (2) the system was constructed as an example but was not placed under operation since a filtration system was not

yet chosen and installed. A first-flush diverter or perhaps a more sophisticated system would need to be installed to filter roof-collected debris and organic matter to protect the pump, avoid transfer line obstruction, and prevent potential biological fouling inside the cooling tower. A schematic of the complete RHS design is shown in Figure 23.

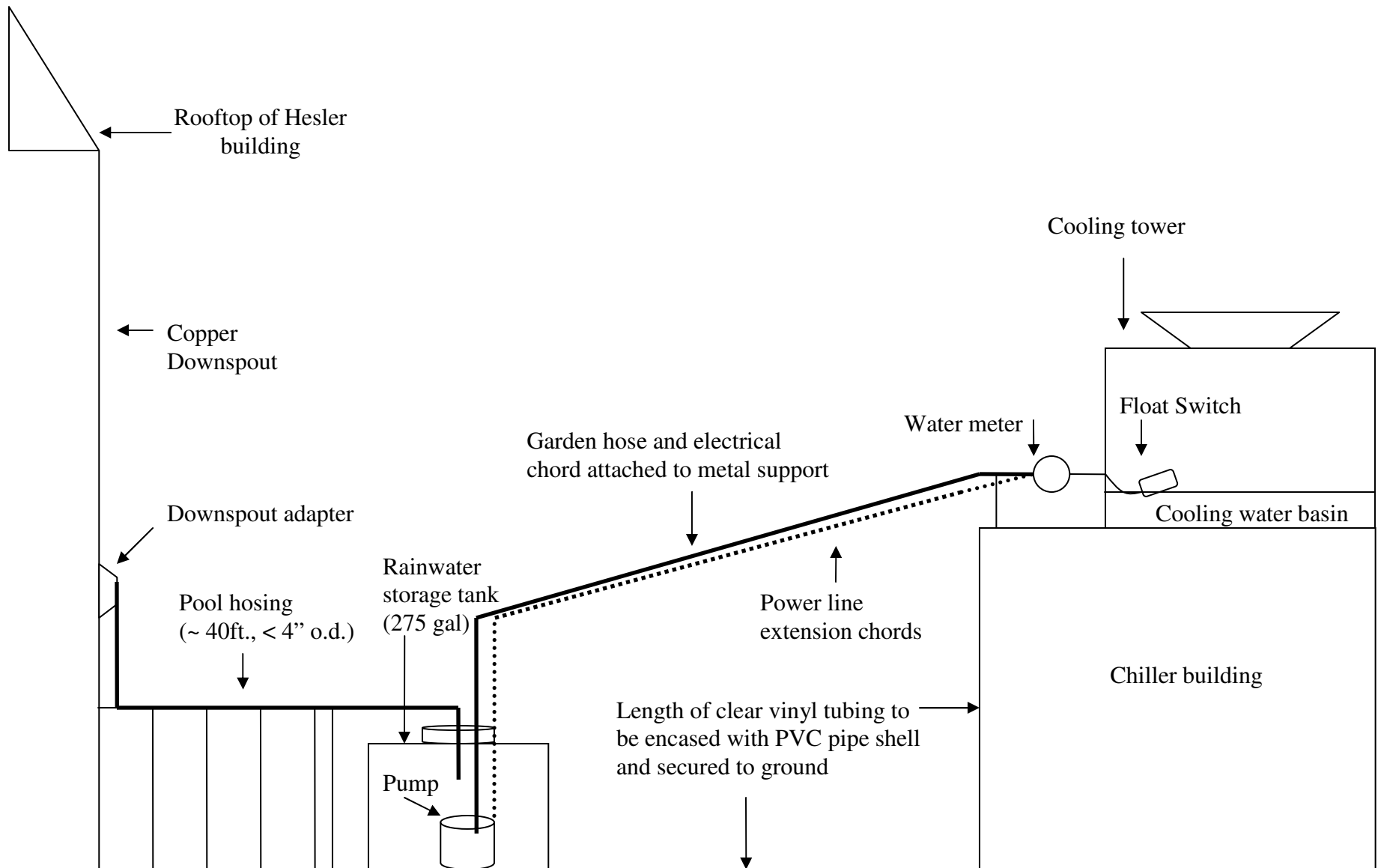


Figure 23. Design schematic of the RHS for cooling water makeup. The system is not drawn to scale. Also, the downward slope of the ground between Hesler Hall and the storage tank is not displayed.

Appendix B – Rainwater water quality data.

Table 5 – 100% Rainwater Water Quality Data

	Event 1			Event 2			Event 3			Event 4			Avg.	St. Dev.	# of Samples
pH	7.04	7.01	7.00	6.81	6.80	6.81	6.69	6.55	6.53	7.24	7.20	7.19	6.91	0.25	12
TDS (ppm)	20.66	20.68	20.79	10.08	10.07	10.06	3.87	3.83	3.88	16.21	16.24	16.21	12.72	6.64	12
Conductivity (µS/cm)	32.82	32.83	33.02	16.16	16.14	16.14	6.25	6.19	6.25	25.96	26.00	25.96	20.31	10.52	12
Alkalinity*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	NA	
Total Hardness*	BDL	BDL	BDL	BDL			BDL	BDL	BDL	11.9	10.5	BDL	11.2	1.0	2
Calcium Hardness*				BDL			BDL	BDL	BDL	BDL					
Silica [#]							1	0	0	0	1	2	1	1	6

* mg/L as CaCO₃

[#] mg/L as SiO₂

Appendix C – Water quality data for tap water samples.

Table 6 – Tap water quality analysis

	pH	TDS (ppm)	Conductivity (μ S/cm)	Alkalinity [*]	Total Hardness [*]	Calcium Hardness [*]	Silica [#]
	7.35	153.0	237.3	66.8	98.4	52.0	9
	7.38	152.6	236.6	70.8	87.2	50.0	7
	7.41	152.3	236.1	69.6	94.0	48.0	8
	7.02	117.2	184.7	48.8	68.0	56.0	7
	6.99	117.3	184.7	63.6	67.4	63.2	7
	6.98	117.1	184.6	53.6	66.0	60.8	7
	7.07	143.0	223.6	66.0	74.8	74.4	9
	7.13	141.9	221.3	64.4	77.2	80.8	6
	7.14	142.4	222.3	62.0	78.8	77.2	8
	7.31	178.3	277.4	83.2	103	63.6	7
	7.30	177.8	276.7	76.4	97.2	67.6	7
	7.33	177.7	276.6	76.8	98.8	66.4	8
	7.12	131.7	206.1	54.0	88.4	56.8	6
	7.15	130.5	205.0	52.0	84.4	68.8	6
	7.17	130.6	204.3	57.2	82.8	67.6	6
	7.16	183.4	284.7	86.0	105	62.4	
	7.16	181.3	281.8	82.0	106	67.6	
	7.16	181.1	281.5	82.8	104	66.4	
			207.3				
			207.2				
			207.1				
Avg.	7.19	150.5	230.8	67.6	87.8	63.9	7
St. Dev.	0.13	24.1	35.2	11.7	13.6	9.0	1
# of Samples	18	18	21	18	18	18	15

^{*} mg/L as CaCO₃

[#] mg/L as SiO₂

Appendix D – Water quality data for cooling water samples.

Table 7 – Cooling water data for 4/12/2012

<i>Minutes</i>	<i>0 (ON)</i>	<i>5</i>	<i>20</i>	<i>40</i>	<i>59 (ON)</i>
pH	8.79	8.80	8.79	8.80	8.80
	8.80	8.81	8.78	8.80	8.78
	8.79	8.80	8.79	8.80	8.79
TDS (ppm)	694.1	670.4	649.4	672.4	692.6
	694.2	670.3	650.1	670.5	691.8
	694.2	670	649.4	672.2	693.3
Conductivity (μ S/cm)	1003	965.3	939.2	968.3	1000
	1002	966.1	940.8	970.2	999.2
	1003	965.1	939.4	969.5	1001
Alkalinity (mg/L as CaCO ₃)	292	307	303	289	303
	298	332	399	296	312
	298	342	314	296	301
Total Hardness (mg/L as CaCO ₃)	400	383	365	386	402
	399	378	371	394	402
	393	375	378	387	403

Table 8 – Cooling water data for 5/29/2012

<i>Minutes</i>	<i>0 (ON)</i>	<i>3</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>29 (ON)</i>
pH	8.80	8.81	8.77	8.80	8.81	8.81	8.82	8.81
	8.80	8.81	8.80	8.80	8.80	8.81	8.82	8.81
	8.81	8.81	8.79	8.81	8.80	8.81	8.81	8.81
TDS (ppm)	677.3	686.3	676.8	647.2	622.8	649.4	663.7	678.7
	677.8	687.1	676.5	647.6	623.6	649.1	663.9	676
	677.5	687.3	677.2	645.6	623.7	649.1	664.2	675.4
Conductivity (μ S/cm)	988.3	1001	986.8	945.5	911.8	949.9	969.7	989.6
	989	1002	986.2	946.4	913.4	949.3	970	986.3
	988.7	1001	987.1	943.5	913.6	949.1	970.2	984.5
Alkalinity (mg/L as CaCO ₃)	258	264	270	246	238	264	288	270
	268	266	264	284	246	250	278	274
	264	270	264	276	238	248	274	272
Total Hardness (mg/L as CaCO ₃)	414	394	376	376	364	372	400	400
	400	390	390	374	364	378	378	392
	388	398	388	376	362	370	384	428
Calcium Hardness (mg/L as CaCO ₃)	298	298	280	272	290	256	318	338
	318	298	280	274	290	270	304	328
	312	286	282	274	264	290	328	326

Table 9 – Cooling water data for 7/28/2012

<i>Minutes</i>	<i>0 (ON)</i>	<i>2</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>27</i>	<i>35 (ON)</i>
pH	8.78	8.82	8.80	8.82	8.82	8.83	8.84
	8.79	8.82	8.81	8.82	8.82	8.83	8.84
	8.81	8.82	8.81	8.82	8.82	8.83	8.84
TDS (ppm)	675.3	679.8	651.2	627.8	638.7	656.4	682.9
	676.1	680.4	651.5	627.4	638.7	657.8	683.3
	676.1	680.6	651.6	627.8	639.0	657.2	683.7
Conductivity (μ S/cm)	989.7	995.2	954.4	921.9	936.1	961.1	995.1
	990.1	995.8	954.1	921.0	936.0	961.6	995.5
	990.7	996.0	954.2	921.3	936.1	960.8	995.7
Alkalinity (mg/L as CaCO ₃)	224	220	206	206	210	212	218
	222	212	208	208	210	212	228
	226	216	204	206	206	220	222
Total Hardness (mg/L as CaCO ₃)	266	278	262	250	260	278	274
	272	270	258	252	270	270	270
	278	276	262	250	262	274	282
Calcium Hardness (mg/L as CaCO ₃)	218	214	212	196	218	224	238
	216	222	210	198	210	230	234
	218	222	216	206	210	224	228
Silica (mg/L as SiO ₂)	27	29	26	28	27	28	29
	27	32	25	25	28	29	26
	28	30	27	28	27	29	34

Table 10 – Cooling water data range

	<i>Minimum</i>	<i>Maximum</i>
pH	8.77	8.84
TDS (ppm)	622.8	694.2
Conductivity (μ S/cm)	911.8	1003
Alkalinity (mg/L as CaCO ₃)	204	399
Total Hardness (mg/L as CaCO ₃)	622.8	694.2
Calcium Hardness (mg/L as CaCO ₃)	196	338
Silica (mg/L as SiO ₂)	25	34

Table 11 – Cooling water set-point data

	<i>4/12 (1)</i>	<i>4/12 (2)</i>	<i>5/29 (1)</i>	<i>5/29 (2)</i>	<i>7/28 (1)</i>	<i>7/28 (2)</i>	<i>7/30 (1)</i>	<i>Avg.</i>	<i>St. Dev.</i>	<i># of Samples</i>
Conductivity ($\mu\text{S}/\text{cm}$)	1003 1002 1003	1000 999.2 1001	988.3 989 988.7	989.6 986.3 984.5	989.7 990.1 990.7	995.1 995.5 995.7	988.3 987.6 987.7	993.1	± 6.1	21
Silica (mg/L as SiO_2)					27 27 28	29 26 34	29 29 30	29	± 2	9

Appendix E - Water quality data for the 20%, 40%, 60%, and 80% rainwater blends.

Table 12 – 20% and 40% blend water quality data

20 % Blend	Event 1			Event 2			Event 3			Event 4			Avg.	St. Dev.	# of Samples
pH	7.39	7.40	7.40	7.03	7.02	7.05	7.2	7.2	7.23	7.38	7.4	7.42	7.26	0.16	12
TDS (ppm)	124.8	125.9	125	96.82	96.8	96.82	115	114.3	114.3	116.9	116.6	116.3	113.3	10.8	12
Conductivity (µS/cm)	194.6	196.3	194.8	153.8	153.8	153.7	181	180.2	180.1	184	183.5	183.1	178.2	15.9	12
Alkalinity*	56.8	58	58.4	37.2	39.2	38.4	52.0	51.2	48	51.6	51.6	49.6	49.3	7.4	12
Total Hardness*	107	102	106	58	64	60	65.2	62	60	76.4	72	75.2	75.7	18.7	12
Calcium Hardness*				46.0	44.0	42.0	44.4	44.8	46.0	47.2	46.0	44.8	45.0	1.5	9
Silica [#]							4	5	5	7	7	7	6	1	6
40% Blend	Event 1			Event 2			Event 3			Event 4			Avg.	St. Dev.	# of Samples
pH	7.44	7.43	7.42	7.06	7.08	7.09	7.33	7.31	7.3	7.48	7.49	7.5	7.33	0.17	12
TDS (ppm)	103.1	99.55	99.12	75.38	75.39	75.56	87.99	87.57	87.54	109.2	108.5	108.4	93.11	13.25	12
Conductivity (µS/cm)	163	157.8	157.3	119.6	119.5	119.7	139.5	138.8	138.8	172.1	171.1	171.1	147.4	20.7	12
Alkalinity*	46.2	46.0	44.8	31.6	34.8	32.4	36.8	41.2	38.8	51.6	50.4	49.6	42.0	7.1	12
Total Hardness*	58.0	61.2	56.0	46.0	44.0	48.0	44.8	47.6	46.8	60.4	60.4	60.0	52.8	7.1	12
Calcium Hardness*				32.0	34.0	34.0	30.8	35.6	28.8	43.6	44.4	43.2	36.3	5.9	9
Silica [#]							3	3	4	5	5	5	4	1	6

Table 13 – 60% and 80% blend water quality data

60 % Blend	Event 1			Event 2			Event 3			Event 4			Avg.	St. Dev.	# of Samples
pH	7.34	7.37	7.37	7.11	7.1	7.11	7.46	7.43	7.41	7.62	7.59	7.56	7.37	0.18	12
TDS (ppm)	73.65	73.78	73.86	54.54	54.42	54.41	71.49	71.42	71.41	79.29	79.17	79.1	69.71	9.66	12
Conductivity (µS/cm)	116.2	116.4	116.6	86.31	86.17	86.21	113.3	113.2	113.2	125.5	125.4	125.3	110.3	15.3	12
Alkalinity*	35.2	35.2	34.4	25.6	24.8	26.8	32	29.1	31.3	33.6	33.6	37.6	31.60	4.15	12
Total Hardness*	42.0	44.0	44.4	36.0	38.0	34.0	38.9	35.6	39.6	45.2	45.6	44.8	40.68	4.18	12
Calcium Hardness*				20.0	22.0	24.0	27.6	26.8	27.2	31.2	31.6	32.4	27.0	4.4	9
Silica [#]							3	3	3	2	3	4	3	1	6
80 % Blend	Event 1			Event 2			Event 3			Event 4			Avg.	St. Dev.	# of Samples
pH	7.37	7.34	7.34	6.79	6.82	6.84	7.05	7.04	7.09	7.45	7.43	7.41	7.16	0.25	12
TDS (ppm)	48.06	48.09	48.14	32.78	32.51	33.04	55.42	52.65	51.88	46.97	46.87	46.9	45.28	7.99	12
Conductivity (µS/cm)	75.84	75.9	75.94	51.61	51.37	52.23	87.75	83.38	82.13	74.2	74.05	74.1	71.54	12.68	12
Alkalinity*	34.7	31.7	37.6	12.7	11.4	12.0	22.7	21.4	21.1	20.0	21.6	22.4	22.44	8.5	12
Total Hardness*	39.6	29.4	36.4	19.2	18.2	19.6	30.4	27.2	29.2	25.2	24.0	25.2	26.97	6.6	12
Calcium Hardness*				10.4	9.8	10.2	BDL	BDL	BDL	18.8	18.4	21.6	15.9	5.2	5

* mg/L as CaCO₃

[#] mg/L as SiO₂

Appendix F – Cycles of concentration predictions and corresponding make-up water flowrates.

Table 14 - Cycles of concentration (COC) predictions

	0%		20%		40%		60%		80%		100%	
	<i>Avg.</i>	<i>St. Dev.</i>	<i>Avg.</i>	<i>St. Dev.</i>	<i>Avg.</i>	<i>St. Dev.</i>	<i>Avg.</i>	<i>St. Dev.</i>	<i>Avg.</i>	<i>St. Dev.</i>	<i>Avg.</i>	<i>St. Dev.</i>
Conductivity <i>Set-point</i>	4.333	0.661	5.610	0.499	6.786	0.953	9.065	1.253	13.98	2.48	49.24	25.51
Conductivity <i>Lab</i>	4.303	0.657	5.572	0.498	6.739	0.947	9.002	1.246	13.88	2.46	48.90	25.33
Silica	4	0.6	5	1	7	2	10	2	10	3		

Table 15 - Values for back-calculation of makeup flowrates using COC predictions

Conductivity <i>Set-point</i>	0%	20%	40%	60%	80%	100%
<i>B_blend (gpm)</i>	182.4 ± 36.2	130.8 ± 14.2	103.5 ± 17.1	73.21 ± 11.39	44.12 ± 8.5	9.204 ± 5.235
<i>M_blend (gpm)</i>	805.9 ± 36.2	754.3 ± 14.2	727.0 ± 17.1	696.7 ± 11.4	667.6 ± 8.5	632.7 ± 5.2
<i>% Savings</i>	-	25.12 ± 4.84	45.87 ± 5.10	65.42 ± 5.39	83.43 ± 5.85	100.0
Conductivity <i>Lab</i>	0%	20%	40%	60%	80%	100%
<i>B_blend (gpm)</i>	184.0 ± 36.6	131.9 ± 14.4	104.4 ± 17.2	73.81 ± 11.51	44.48 ± 8.53	9.295 ± 5.281
<i>M_blend (gpm)</i>	807.6 ± 36.6	755.5 ± 14.4	727.9 ± 17.2	697.3 ± 11.5	668.0 ± 8.5	632.8 ± 5.3
<i>% Savings</i>	-	25.16 ± 4.89	45.92 ± 5.15	63.08 ± 5.45	81.65 ± 5.91	100.0
Silica	0%	20%	40%	60%	80%	100%
<i>B_blend (gpm)</i>	203 ± 44	154 ± 47	101 ± 30	68 ± 17	68 ± 24	-
<i>M_blend (gpm)</i>	827 ± 44	777 ± 47	725 ± 30	692 ± 17	692 ± 24	-
<i>% Savings</i>	-	25 ± 7	47 ± 6	64 ± 6	81 ± 7	-

Appendix G – List of campus cooling towers and their respective circulation rates obtained from the University of Tennessee’s Facility Services.

Table 16 - List of campus cooling towers and circulation rates

Location	Pump Capacity (GPM)	# of Pumps (# of towers)	Circulation Rate per tower (gpm)
Alumni Memorial	450	2	225
Andy Holt Tower	3600	2	1800
Carolyn Brown UC	2400	2	1200
Claxton Complex	3600	2	1800
Clement Hall	1200	1	1200
Conference Center	2700	2	1350
Dabney/Buehler	12000	4	3000
Gibbs Hall	600	1	600
Haslam Business Bldg	1650	2	825
Hesler Biology (Hesler Hall)	4720	2	2360
Hodges Library	3000	2	1500
Hoskins Library	915	1	915
Humanities	2500	2	1250
Joseph E. Johnson Bldg	1800	2	900
Middlebrook Pike Bldg	470	3	157
Music Bldg	1500	2	750
Neyland-Thompson	850	1	850
Plant Science Biotech	6000	3	2000
Reese Hall	4500	3	1500
Stokely Athletics	341	2	170.5
Stokely Management	1800	2	900
Student Aquatic Center	1000	1	1000
Student Recreation Bldg	1680	2	840
Taylor Law College	2700	2	1350
Thompson-Boling Arena	4950	4	1238
Veterinary Teaching Hosp.	3600	2	1800
Walter Life Sciences	2400	2	1200
Total	72926*	56	

*Campus circulation rate used for calculations

Appendix H – Surface area estimates for the agricultural and main campuses.

Table 17 – Surface area estimates for agricultural campus

Agricultural Campus Building Name	KGIS Maps Roof Surface Area (ft²)	Google Earth Roof Surface Area (ft²)	Total (ft²)
Animal Science Laboratory	1381.2		1381.2
Biosystems Eng. And Soil Science Lab	38778.4		38778.4
Biosystems Eng. And Soil Science Offices	4745.2		4745.2
Business Incubator Building	8325.1		8325.1
C.E. Brehm Animal Sciences	63548.8		63548.8
Central Greenhouse		9999.39	9999.39
Ceramics Annex	2434.1		2434.1
CRC/BEST Lab	8669.1		8669.1
CRC/MAST Lab	10095.8		10095.8
Crops Genetics Lab	1925.1		1925.1
Ellington Plant Sciences	27744		27744
Environmental and Landscape Lab	7475.1		7475.1
Food Safety and Processing	11675.1		11675.1
Food Sciences	<i>(Included in C.E. Brehm)</i>		
Hollingsworth Auditorium	<i>(Included in Ellington Plant Sciences)</i>		
McCord Hall	9485.9		9485.9
Morgan Hall	24255		24255
North Greenhouses		16664.40	16664.40
Pendergrass Library	<i>(Included in Teaching Hospital)</i>		
Plant Biotech	38461.1		38461.1
Plant Propagation	3537.3		3537.3
Plant Sciences Annex B	3932.6		3932.6
Publications and Services	10640		10640
Racheff Research Building	6049.6		6049.6
South Greenhouse	16655.9		16655.9
Tennessee Division of Forestry	2358.3		2358.3
Tickle Small Animal Hospital	<i>(Included in Teaching Hospital)</i>		
UT Gardens Support	1300.7		1300.7
Veterinary Teaching Hospital	148256.3		148256.3

Table 18 – Surface area estimates for main campus

Main Campus Building Name	KGIS Maps Roof Surface Area (ft²)	Google Earth Roof Surface Area (ft²)	Total (ft²)
Alumni Memorial Building	34577.5		34577.5
Andy Holt Tower	12356.3		12356.3
Apartment Residence Hall	26356		26356
Aquatic Center	55149.4		55149.4
Art and Architecture	66298		66298
Austin Peay	14346.2		14346.2
Auxillary Services Bldng	53072.2		53072.2
Ayres Hall	22147		22147
Bailey Education Complex	15301.2		15301.2
Berry Hall	2718.9		2718.9
Black Cultural Center	8301.1		8301.1
Blount Hall	9829.7		9829.7
Brenda Lawson Athletic Center/ Neyland Thompson Sports Center	142150.6	55569.8042	197720.4
Burchfiel Geography Building	8093		8093
Campus Parking Information Center		99.6838	99.6838
Carousel Theatre	7406.3		7406.3
Carrick Hall	21646.7		21646.7
Center for International Education	2774.1		2774.1
Ceramics Addition	<i>(Included in Art and Architecture)</i>		
Clarence Brown Theatre	25504.5		25504.5
Claxton Education Building	34084.1		34084.1
Clement Hall	19086.6		19086.6
Nursing Building	<i>(Included in the Bailey Education Complex)</i>		
Communications and Univ. Extension	65067		65067
Conference Center Building	52649.4		52649.4
Credit Union	8794.9		8794.9
Dabney/Buehler Hall	50073.7		50073.7
Dougherty Engineering	32398.1		32398.1
Early Learning Center (F4)	1884.5		1884.5
Early Learning Center (M3)	4405.3		4405.3
Earth and Planetary Sciences	9263		9263
Dunford Hall	15766		15766
East Stadium Hall	<i>(Under Neyland Stadium Seats, not included)</i>		
Engineering Annex	17543.2		17543.2
Equity and Diversity Office	2405.1		2405.1
Estabrook Hall	28165.4		28165.4
Facilities Services	29028.4		29028.4
Ferris Hall	12206		12206
Gibbs Hall	21822.9		21822.9

Main Campus Building Name	KGIS Maps Roof Surface Area (ft²)	Google Earth Roof Surface Area (ft²)	Total (ft²)
Goodfriend Tennis Center	36384		36384
Greve Hall	13802.7		13802.7
Haslam Business Building		34915.037	34915.037
Henson Hall	7868.6		7868.6
Herbarium & Nursing	6576.6		6576.6
Hesler Biology	24341.3	2542.54	26883.8
Hess Hall	42409.1		42409.1
Hodges Library	78383.7		78383.7
Hopecote	2639.2		2639.2
Hoskins Library	35349.1		35349.1
Howard H. Baker Ctr. For Public Policy	15036		15036
HPER	59370.8		59370.8
Humanities and Social Sciences	27994.4		27994.4
Humes Hall	17558.8		17558.8
International House	6948.7		6948.7
Jesse Harris Building	19649.6		19649.6
Jones Intercollegiate Aquatics Center	47754.6		47754.6
Kingston Pike Building	76012.1		76012.1
Lady Vol Crew Boathouse	7732		7732
Laurel Apartments	20177.1		20177.1
Law Library	<i>(Included with Taylor Law Center)</i>		
Lee Softball Stadium	13345.1	5110.67	18455.8
Lindsey Nelson Stadium		13271.82	13271.82
Massey Hall	15968.6		15968.6
McClung Museum	12845.9		12845.9
McClung Tower	7585.2		7585.2
Melrose Hall	5651.9		5651.9
Min Kao Building		40659.61	40659.61
Morrill Hall	12260.5		12260.5
Neyland Stadium/Shields-Watkins Field		74759.43	74759.43
Neyland Biology Annex	<i>(Included as Engineering Annex)</i>		
Neyland-Thompson Sports Center	<i>(Included as Brenda Lawson Athletic Center)</i>		
Nielsen Physics Building	16514.3		16514.3
Panhellenic Building	14481.7		14481.7
Parking and Transit Services	193257.6		193257.6
Pasqua Nuclear Engineering	7273		7273
Perkins Hall	14387.3		14387.3
Physical Education	<i>(Included as HPER)</i>		
Pratt Basketball Pavilion	28114.3		28114.3

Main Campus Building Name	KGIS Maps Roof Surface Area (ft²)	Google Earth Roof Surface Area (ft²)	Total (ft²)
Presidential Court	30087.6		30087.6
Reese Hall	17946.2		17946.2
Regal Soccer Stadium		7797.14	7797.14
Senter Hall	20497.9		20497.9
Science and Engineering Research (SERF)	36055.9		36055.9
Silverstein-Luper Building	5756.6		5756.6
Sophonria Strong Hall	30164.1		30164.1
South College	5447.6		5447.6
South Stadium Hall	<i>(Under Neyland Stadium Seats, not included)</i>		
Sports Bubble	28719.2		28719.2
Steam Plant	27205.9		27205.9
Stokely Athletic Center	131404.1		131404.1
Stokely Management Center	12883.6		12883.6
Student Health Center		40481.01	40481.01
Student Services Building	<i>(Included in Communications and Univ. Extn.)</i>		
Student Success Center-Melrose	1672.9		1672.9
TANDEC	9749.9		9749.9
Taylor Law Center	41233.3		41233.3
TN Rec. Ctr. For Students	62194.3		62194.3
Textiles Processing Laboratory	2009.3		2009.3
Thompson-Boling Assembly Ctr. & Arena	143,926.40		143,926.40
Thornton Athletics Student Life Center	12182		12182
Tom Black Track & Recreation Areas		3335.00	3335.00
Transportation Services	17931.3		17931.3
Tyson Alumni Center	6409.5		6409.5
University Center	59279.3		59279.3
University Police		350.57	350.57
University Honors	<i>(Included in Melrose Hall)</i>		
Visitors' Center	17419.6		17419.6
Volunteer Hall Residence Complex	82369.4		82369.4
Walters Life Sciences Building	44103.5		44103.5

Table 19 – Total surface area

Campus	Surface Area (ft²)
Agricultural	478393.5
Main	2945887.8
Total	3424281.3

Appendix I – Rainfall data used to estimate rainfall supply estimate along with campus roof surface area estimate.

Table 20 - Rainfall data and potential collection volume for campus

	2009			2010			2011		
	Rainfall (inches)*	Campus (10 ⁶ gallons)	Case Study [#]	Rainfall (inches)*	Campus (10 ⁶ gallons)	Case Study [#]	Rainfall (Inches)*	Campus (10 ⁶ gallons)	Case Study [#]
Jan	5.59	11.9	0.326	5.24	11.2	0.305	3.56	7.60	0.207
Feb	2.56	5.46	0.149	2.93	6.25	0.171	6.04	12.9	0.352
Mar	3.91	8.35	0.228	3.27	6.98	0.190	6.93	14.8	0.404
Apr	2.59	5.53	0.151	2.79	5.96	0.162	10.91	23.3	0.635
May	5.44	11.6	0.317	4.41	9.41	0.257	1.44	3.07	0.084
Jun	6.91	14.8	0.402	2.34	5.00	0.136	6.42	13.7	0.374
Jul	5.12	10.9	0.298	4.04	8.62	0.235	4.41	9.41	0.257
Aug	4.19	8.94	0.244	2.78	5.93	0.162	0.92	1.96	0.054
Sep	6.32	13.5	0.368	4.48	9.56	0.261	7.57	16.2	0.441
Oct	4.30	9.18	0.250	4.93	10.5	0.287	2.29	4.89	0.133
Nov	3.22	6.87	0.188	7.87	16.8	0.458	6.86	14.6	0.400
Dec	6.68	14.3	0.389	1.72	3.67	0.100	2.14	4.57	0.125
Total	56.83	121	3.31	46.8	99.9	2.73	59.49	127	3.46

*Rainfall data provided by City of Knoxville's Stormwater Engineering Dept. (Tyson Park Site) [36]

Appendix J – Rainfall demand estimates based on blend makeup flowrates.

Table 21 - Rainwater demand estimates for each blend

<i>(Millions of gallons per year)</i>					
	20%	40%	60%	80%	100%
Conductivity <i>Set-point</i>	79.3 ± 1.5	153 ± 4	220 ± 4	281 ± 4	333 ± 3
Conductivity <i>Lab</i>	79.4 ± 1.5	153 ± 4	220 ± 4	281 ± 4	333 ± 3
Silica	69.6 ± 1.2	134 ± 1	218 ± 5	291 ± 10	

Appendix K – Makeup and blowdown rates as a function of heat load, and subsequent water and wastewater savings based on the silica data set for COC predictions.

Table 22 – Makeup and blowdown rates as a function of heat load

Heat load (%)	ΔT (°F)	E (gpm)	D (gpm)	B_0% (gpm)	M_0% (gpm)	B_20% (gpm)	M_20% (gpm)	B_40% (gpm)	M_40% (gpm)	B_60% (gpm)	M_60% (gpm)
100	9.1	564	4	185	752	140	707	92	660	62	630
75	6.5	403	4	131	537	99	505	65	471	43	450
50	4.2	260	4	83	347	63	327	40	304	27	291
25	2.1	130	4	40	174	29	163	18	152	12	145

Table 23 – Water and wastewater savings with changing heat load

Heat load (%)	20%			40%			60%		
	Water (\$/yr)	Wastewater (\$/yr)	Sum (\$/yr)	Water (\$/yr)	Wastewater (\$/yr)	Sum (\$/yr)	Water (\$/yr)	Wastewater (\$/yr)	Sum (\$/yr)
100	97,924	141,314	239,238	187,405	292,408	479,813	263,016	386,548	649,567
75	69,946	100,939	170,884	133,861	208,863	342,723	187,869	276,106	463,975
50	45,196	65,222	110,418	86,495	134,957	221,452	121,392	178,407	299,800
25	22,597	32,611	55,209	43,247	67,479	110,726	60,696	89,203	149,900

Vita

Liz Costello received her undergraduate degree in Chemical Engineering, as well as a certificate in Sustainable Energy, from Princeton University in June 2010. As a graduate student at the University of Tennessee she balanced her role as an instructor for an undergraduate lab class in the Civil and Environmental Engineering Department with the completion of her coursework and thesis work in her second-to-last semester. During her time at the University of Tennessee, Liz also competed as Lady Vol on the University's track and field team. She won three individual Southeastern Conference (SEC) championships, earned her fourth All-America award (indoor 5,000m), and set school and SEC meet records in the 10,000m. As a post-collegiate athlete she also went on to lead Team USA to their first place finish at the 2012 North America, Central America, Caribbean (NACAC) Cross Country Championships held in Trinidad and Tobago, and later in the year finished 16th in the 10,000m at the 2012 U.S. Track and Field Olympic Team Trials.