# Development of a Rainwater Harvesting Model for Broiler Farms to Estimate On-farm Storage Needs

by

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# Abstract

Access to water is critical for poultry production and rainwater harvesting (RWH) may reduce reliance on low-yield and poor water quality wells or municipal (city or county) water supplies to supplement water consumption and offset rising water costs. Current uses of RWH have been primarily focused on reducing stormwater runoff in urban areas and providing sources of potable and non-potable water. The objectives of this research were to develop a RWH model to estimate the main water consumption sources for a poultry farm; bird water consumption (BWC), evaporative cooling make-up water consumption (EWC), and maintenance water consumption (MWC) and to evaluate the performance of the model over a 25-year period for nine locations across the U.S. for varying storage capacities.

Daily BWC was estimated using industry feed intake performance data for genetic strains of broilers. NOAA weather data was used to estimate rainfall harvested (RFH) and EWC. Equations for BWC and EWC were calibrated and evaluated using data from a poultry farm in east Alabama. Model BWC was overestimated by 15% compared to farm BWC data. Model EWC was overestimated by 453 $m^3$ with a mean daily value of 8 $m^3$ compared to a farm mean daily value of 3.6 $m^3$.

Equations for BWC and EWC were used to develop a RWH model that incorporated multiple user inputs. The entire model was run over a 25-year period to evaluate the performance of a 379 $m^3$ storage capacity in Huntsville, AL and a simple economic analysis was performed for a low, medium, and high municipal water cost. The overall performance of the model was within

18.21% of total water consumption (TC) estimations for data recorded on a north Alabama farm. Economic results show that at the three municipal water costs, savings increased as water cost increased.

To evaluate the behavior of the model for various locations and storage capacities, nine locations were chosen across the U.S. that represented high poultry production areas and varying climates. Six storage capacities between 189 m$^3$ and 1,136 m$^3$ in increments of 189 m$^3$ were evaluated in each location over a 25-year period from 1990 to 2015. Values for TC were separated into municipal water usage (MU) and storage water usage (SU), where MU was water the farmer had to buy and SU was water the farmer did not have to buy (i.e. savings). A simple economic analysis was performed to estimate the savings over the 25-year period for a range of municipal water costs from \$0.79 to \$3.17 in increments of \$0.26 m$^{-3}$.

Results showed the largest reduction in MU was increasing from a storage capacity of 189 m$^3$ to 379 m$^3$. The reduction in MU was reduced with each additional increase in storage capacity. All locations experienced no savings at a municipal water costs lower than \$1.32 per m$^3$. Most locations experienced maximum savings at water costs between \$2.38 and \$3.17 using a storage capacity of 568 m$^3$. The model also showed that in locations with low amounts of annual rainfall, these locations would not benefit from installing RWH systems.

Many farmers located in high precipitation areas could potentially benefit from installing a RWH system to supplement their current water sources and offset rising water costs. This RWH model can be used as a decision tool by farmers to determine the potential benefits of installing a RWH system to meet their farm’s needs.

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# List of Abbreviations

| | |
|---|---|
| DDL | Drinker line length |
| DOA | bird day of age |
| DOP | Day of placement of first flock |
| FC | Daily feed consumption |
| FL | Flock length |
| $H_{average}$ | average house height |
| HL | House length |
| HW | House width |
| LD | Number of days between flocks |
| $lp_d$ | Daily liquid precipitation |
| $lp_h$ | Hourly liquid precipitation |
| MU | Municipal water usage |
| NB | Number of birds per house |
| NDL | Number of drinker lines |
| $NF_{DLM}$ | Number of complete flushes to clean the drinker lines |
| $NF_{EPM}$ | Number of complete flushes to clean the evaporative system storage |
| NH | Number of houses |
| NOAA | National Oceanic and Atmospheric Administration |
| pb | Barometric pressure |

| | |
|---|---|
| $p_w$ | Partial pressure of water vapor |
| $Q_{average}$ | Average house design air flow |
| SU | Storage water usage |
| TC | Total water consumption |
| $T_{db}$ | Dry bulb temperature |
| $T_{dp}$ | Dew point temperature |
| $T_{min}$ | Minimum temperature at which the evaporative cooling system begins to operate |
| $T_{pad}$ | Temperature of the air passing through the evaporative pad |
| TPL | Total evaporative pad length for one house |
| UDV | Unit drinker line volume |
| UTC | coordinated universal time |
| UTV | unit trough volume of the evaporative cooling system |
| $v$ | specific volume |
| $v_{average}$ | average house wind speed |
| W:F | Water-to-feed ratio |
| $W_{ambient}$ | Ambient humidity ratio |
| $W_s$ | Saturation humidity ratio |
| $\Delta W_{\eta_{pad}}$ | Hourly unit evaporative pad make-up water needed to refill the system |
| $\rho_{water}$ | Density of water |
| $\eta_{capture}$ | Rainfall capture efficiency |
| $\eta_{pad}$ | Evaporative cooling pad efficiency |

# Chapter 1: Introduction

Poultry farms across the U.S. rely heavily on water to ensure the well-being of broilers and can be a major cost for farmers. The three main water consumption sources for a poultry farm are bird water consumption (BWC), evaporative cooling make-up water consumption (EWC), and maintenance water consumption (MWC). To meet these consumption needs, two main water sources are available to farmers: well water and municipal (city or county) water. Some areas of the U.S. do not have access to a municipal source and must rely on well water which can have poor water quality, low yields, and maintenance issues. Farmers who do have access to municipal water have a more reliable water source. However, in some areas of the U.S., farmers are experiencing water quality issues and high water costs. Many farmers are located in high precipitation areas and could potentially benefit from installing a rainwater harvesting (RWH) system to supplement their current water sources and offset rising water costs. To investigate the effects of installing RWH systems on poultry houses, this research was separated into two studies to develop and evaluate a RWH model for poultry farms.

Study 1 highlighted the development and uses of current RWH models and systems, identifying the need for a RWH model that estimates consumption values on a daily basis specific to poultry. The objectives of this study were to:

1. Develop equations for the main water consumption sources on a poultry farm.
2. Calibrate and evaluate these water consumption estimates using water consumption data from a previous commercial farm study.

3. Develop a RWH model to incorporate multiple user inputs and evaluate the overall performance of the model.

Using the model developed in study 1, study 2 evaluated the model using test farm characteristics for six different storage capacities across nine locations in the U.S. The objectives for study 2 were to:

1. Evaluate the performance of varying storage sizes for each location.
2. Perform a simple economic analysis to estimate the potential cost savings for each storage size.

# Chapter 2: Study 1

## 2.1 Introduction

Water is a crucial component for the production of broilers across the United States and is one of the main costs for poultry farmers. The three main water consumption sources on a poultry farm are bird water consumption, evaporative cooling make-up water consumption for the cooling systems, and maintenance flushing water for drinker line and evaporative pad cleaning. Currently, the only water sources for poultry farmers are well water and municipal (city or county) water. Maintaining a reliable and clean water supply is crucial to the health of the birds and each water source has issues associated to it. In many areas across the U.S., poultry farmers do not have access to municipal water and have to rely on well water, which can have poor water quality, potentially low yields, and maintenance issues. Farmers who have access to municipal water have a more reliable water source however some areas of the U.S. have poor municipal water quality and are experiencing increases in water costs. Farmers in Cullman County, Alabama are experiencing this rising cost with water currently costing \$10.25 per 1,000 gallons (\$2.71 per m3) and expected to increase to over \$12.00 per 1,000 gallons (\$3.17 per m3) (Lawrence, 2016). In response to these rising water costs, two commercial broiler farms in northern Alabama have implemented rainwater harvesting (RWH) systems. Many poultry farms in high precipitation areas of the U.S. have the potential to benefit from installing RWH systems to supplement their current water sources and offset these rising water costs.

When developing a RWH system, one of the largest system installation cost is associated with storage (Roebuck et al., 2007). The first of the two broiler farms in north Alabama used the trial and error method to size their water storage needs; initially installing a few cubic meters (few thousand gallons) of storage and adding additional storage as needed which becomes costly overtime. The second farm, growing the same size and breed of bird, used the experience from the first farm and sized a single storage bladder with the capacity to meet 80% of their annual needs (Lawrence, 2016). It is cheaper to purchase one large storage unit rather than many small storage units. If a farmer decides to install a RWH system for a farm of differing size, smaller or larger bird size, or in a new geographic location, he or she must use the trial and error method without prior knowledge. The variability in operation and weather data associated with geographic location suggests a need for a RWH model that can accurately estimate the storage capacity for a particular farm's characteristics.

Many current RWH systems focus on urban areas where there is the potential of providing a non-potable water source for uses such as lawn irrigation, toilet flushing, and car washing to help reduce the use of potable water sources and decrease water costs (Lopes et al., 2017). Most RWH models used to estimate these storage capacities use a mass-balance approach to the system (Roebuck and Ashley, 2007). Two major parameters used in these models are average water demand assumptions (Coombes, 2007) and a wide range of rainfall estimation methods. Some estimations of rainfall include the use of average monthly rainfall (Ward et al., 2008), twelve-month historical rainfall data (Fewkes and Butler, 2000) and the creation of synthetic rainfall series using stochastic models (Lopes et al., 2017). These estimates pose an issue for estimating the appropriate storage capacity for poultry farms. Because bird consumption and evaporative cooling make-up water consumption can vary individually and in combination on a daily basis, estimating farm water demand and rainfall capture on a weekly or monthly average basis is insufficient.

The objectives of this research were to develop equations for the main poultry water consumption sources and calibrate and evaluate these estimates. Using these equations, a RWH model was developed to incorporate multiple user inputs and the overall performance of the model was evaluated.

## 2.2 Methods and Materials

### 2.2.1 Model development

A RWH model (fig. 1) was developed to operate on a daily basis; estimating rainfall harvested (RFH), bird water consumption (BWC), evaporative cooling make-up water consumption (EWC), and maintenance water consumption (MWC) given weather data for a farm's geographic location and farm characteristics.

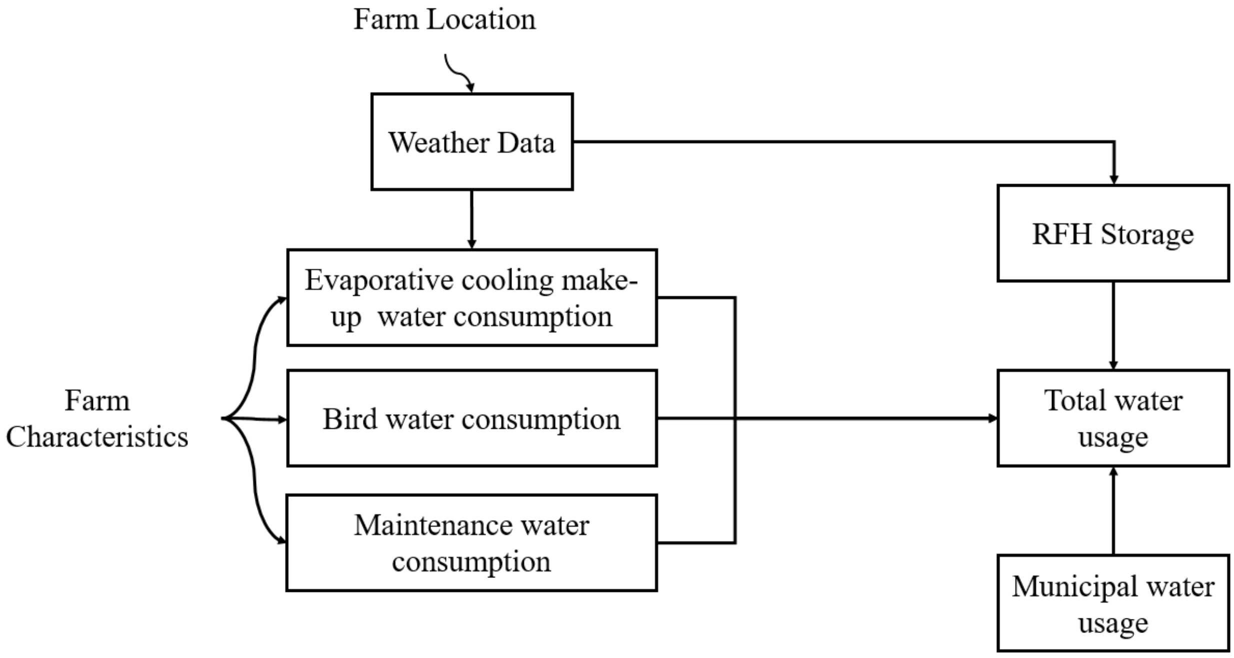

**Figure 1. Flow diagram of mass-balance of water through the system.**

From this flow diagram, the daily change in storage can be estimated by the mass-balance of water through the system as represented by the governing equation below:

$$S^{t} = S^{t-1} + (RFH^{t} - BWC^{t} - EWC^{t} - MWC^{t}) * dt \qquad (1)$$

where

$S^t$ = storage at time t ($m^3$)

$S^{t-1}$ = storage of the previous time step ($m^3$)

$RFH^t$ = rainfall harvested at time t ($m^3$)

$BWC^t$ = bird water consumption at time t ($m^3$)

$EWC^t$ = evaporative cooling make-up water consumption at time t ($m^3$)

$MWC^t$ = maintenance water consumption at time t ($m^3$)

dt = model time step (d)

The main components of this governing equation (RFH, BWC, EWC, and MWC) were estimated using user inputs and model assumptions discussed in detail below.

### 2.2.2 House characteristics

House parameters consisted of the house dimensions of length (HL) and width (HW), and number of houses (NH) on the farm. The average design airflow ($Q_{average}$) through the house during tunnel ventilation was calculated by multiplying the average house wind speed ($v_{average}$) through the house, the average house height ($H_{average}$) assumed to be 2.9 m, and HL (eqn. 1). House parameters for HL, HW, NH, and $Q_{average}$ were used in the calculation of model parameters.

$$Q_{average} = v_{average} * H_{average} * HL \qquad (1)$$

where

$Q_{average}$ = average design air flow ($m^3\ s^{-1}$)

$v_{average}$ = average house wind speed (m $s^{-1}$)

$H_{average}$ = average house height (m)

HL = house length (m)

### 2.2.3 Weather data

Hourly weather data was downloaded from the NOAA ISD-Lite data set (NOAA, 2006) and converted to appropriate units. The data was pre-processed such that any hourly entry missing one of the following parameters; dry bulb temperature ($T_{db}$), dew point temperature ($T_{dp}$), or barometric pressure (pb) and coded as -9999 was deleted. Entries for trace liquid precipitation, coded as -1, and missing liquid precipitation were set to zero. Data was recorded as coordinated universal time (UTC) and was corrected according to the time zone of the particular test location.

### 2.2.5 Estimation of rainfall harvested

The volume of RFH was estimated using equation 2. Hourly liquid precipitation ($lp_h$) values were summed for each day to get a daily precipitation ($lp_d$) value. The system capture efficiency ($\eta_{capture}$) was used to account for water loss in the first flush filter and potential spillage from the roof during a rain event.

$$RFH = (lp_d * \eta_{capture} * HL * HW) * NH \tag{2}$$

where

RFH = rainfall harvested ($m^3$)

$lp_d$ = daily liquid precipitation (m)

$\eta_{capture}$ = rainfall capture efficiency (%)

HL = house length (m)

HW = house width (m)

### 2.2.5 Estimation of bird water consumption

Daily BWC values were based on the bird day of age (DOA) and as-hatched daily feed consumption (FC) values (Appendix A) for one of three genetic strains of broilers commonly used in the industry: Ross 308 (Aviagen, 2014), Ross 708 (Aviagen, 2014), and Cobb 500 (Cobb, 2015). A water-to-feed ratio (W:F) was used to estimate daily BWC as a function of FC (Pesti et al., 1985). Given user inputs for day of placement (DOP) of the first flock, flock length (FL), number of days between flocks (LD), and length of simulation period (time span), the model created a DOA table for as many flocks as would fit within the time span. The model then used the corresponding FC value based on the DOA for the genetic strain chosen to calculate the BWC value using equation 3 given number of birds (NB), a W:F ratio, and density of water ($\rho_{water}$). For DOA values of zero (e.g. during layout days) the BWC was zero.

$$BWC_{geneticstrain} = \left[ \frac{FC * W:F * NB}{1{,}000 * \rho_{water}} \right] * NH \tag{3}$$

where

$BWC_{geneticstrain}$ = bird water consumption for type of bird grown ($m^3$)

FC = daily feed consumption (g)

W:F = water-to-feed ratio ($g\ g^{-1}$)

NB = number of birds per house

$\rho_{water}$ = density of water ($kg\ m^{-3}$)

NH = number of houses

### 2.2.6 Estimation of evaporative cooling make-up water consumption

Evaporative cooling make-up water consumption (EWC) was estimated using a program developed in MATLAB that utilizes psychrometric equations and hourly weather data to determine the change in humidity ratio of air passing through the evaporative cooling pad system. The volume of EWC was calculated on an hourly basis.

The program estimated the volume of water consumed by establishing two psychrometric state points and determining the change in humidity ratio between those state points (fig. 2). Given $T_{db}$, $T_{dp}$, and pb from the weather data, the first state point was established ($SP_1$ in fig. 2) and ambient humidity ratio ($W_{ambient}$) and specific volume (v) were calculated using equations 4 and 5, respectively. The partial pressure of water vapor ($p_w$) was calculated using equations 5 and 6 from the ASHRAE Fundamentals Handbook (ASHRAE, 2001).

$$W_{ambient} = 0.62198 * \frac{p_w}{pb - p_w} \tag{4}$$

where

$W_{ambient}$ = ambient humidity ratio ($kg_{water}\ kg_{da}^{-1}$)

$p_w$ = partial pressure of water vapor (kPa)

pb = barometric pressure (kPa)

$$v = \frac{0.2871 * (T_{db} + 273.15) * (1 + 1.6078 * W)}{pb} \tag{5}$$

where

v = specific volume ($m^3\ kg_{da}^{-1}$)

$T_{db}$ = dry bulb temperature (°C)

W = humidity ratio ($kg_{water}\ kg_{da}^{-1}$)

pb = barometric pressure (kPa)

Wet-bulb temperature ($T_{wb}$) was then calculated for $SP_1$ using an iterative process and equations 6 and 7. The iterative process involves calculating the humidity ratio (W) using an initial guess for $T_{wb}$ and comparing it to $W_{ambient}$. The correct $T_{wb}$ was determined when the condition $W = W_{ambient}$ was met.

$$W_s = 0.62198 * \frac{p_{ws}}{pb - p_{ws}} \tag{6}$$

where

$W_s$ = saturation humidity ratio ($kg_w\ kg_{da}^{-1}$)

$p_{ws}$ = saturation pressure (kPa)

pb = barometric pressure (kPa)

$$W = \frac{(2501 - 2.381 * T_{wb}) * W_s^* - 1.006 * (T_{db} - T_{wb})}{2501 + 1.805 * T_{db} - 4.186 * T_{wb}} \tag{7}$$

where

W = humidity ratio ($kg_{water}\ kg_{da}^{-1}$)

$T_{wb}$ = wet bulb temperature (°C)

$W_s^*$ = saturation humidity ratio using $T_{wb}$ ($kg_w\ kg_{da}^{-1}$)

$T_{db}$ = dry bulb temperature (°C)

Assuming the evaporative cooling process is ideal and therefore adiabatic (Gatley, 2013), the wet bulb depression (WBD in fig. 2) can be determined by following the $T_{wb}$ line to the saturation curve. Then the second state point was established with pb, $T_{wb}$, and by calculating the temperature of the air passing through the evaporative pad ($T_{pad}$) using equation 8 given a user defined pad efficiency ($\eta_{pad}$).

$$T_{pad} = T_{db} - \eta_{pad} * WBD \tag{8}$$

where

$T_{pad}$ = temperature of the air going through the evaporative pad (°C)

$T_{db}$ = dry bulb temperature (°C)

$\eta_{pad}$ = evaporative cooling pad efficiency (%)

WBD = wet bulb depression (°C)

A new humidity ratio was calculated for $SP_2$ and used to determine the change in humidity ratio ($\Delta W_{\eta_{pad}}$ in fig. 2) from $SP_1$. The calculated value for $\Delta W_{\eta_{pad}}$ represents the hourly unit evaporative pad make-up water needed to refill the system.

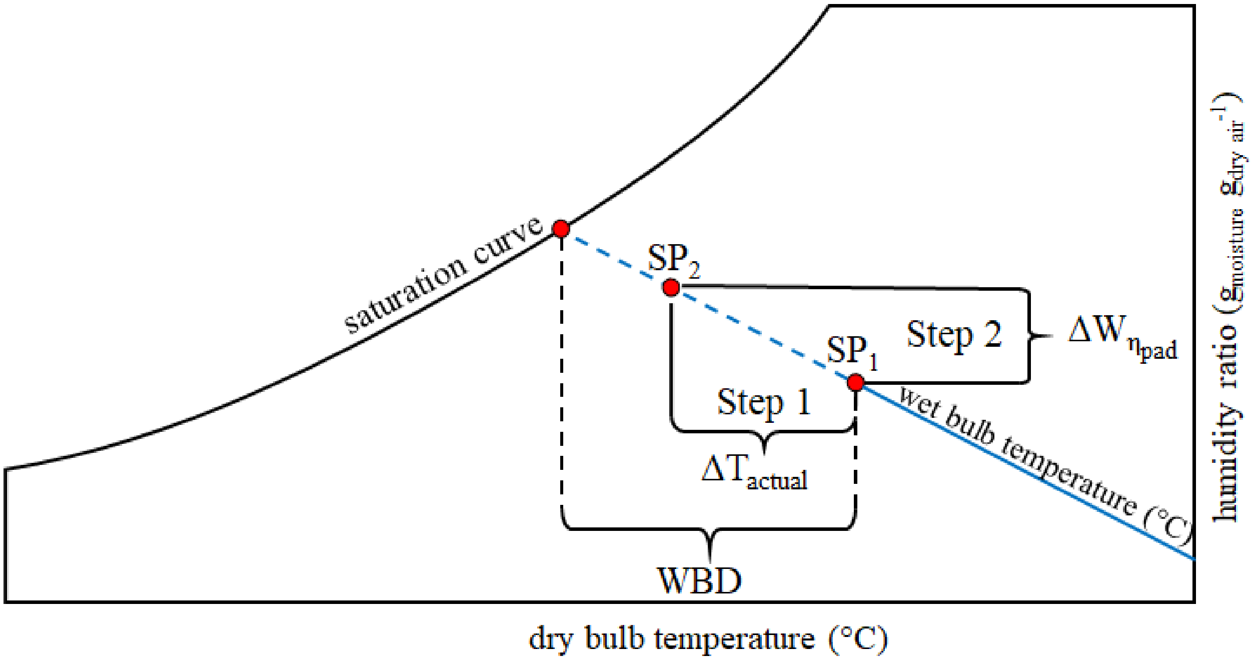

**Figure 2. Illustration of adiabatic cooling process to estimate evaporative cooling make-up water consumption through the difference in humidity ratios between state point 1 ($SP_1$) and state point 2 ($SP_2$).**

Boundary conditions were applied to hourly $\Delta W_{\eta_{pad}}$ values according to a minimum temperature threshold ($T_{min}$) and a cooling system operating time to represent the operation of the evaporative cooling system. At high temperatures, evaporative cooling is needed for birds to maintain a comfortable body temperature, therefore $\Delta W_{\eta_{pad}}$ values were zero for hourly $T_{db}$ values less than or equal to $T_{min}$. The operating time was used to avoid overuse of the cooling system and allow for evaporative cooling pads to dry. Any hourly $\Delta W_{\eta_{pad}}$ value not within the specified operating time was set to zero. Hourly $\Delta W_{\eta_{pad}}$ values meeting these conditions were summed to determine daily $\Delta W_{\eta_{pad}}$.

Multiplying the number of houses by an average design house air flow ($Q_{average}$) and the daily unit evaporative cooling make-up water ($\Delta W_{\eta_{pad}}$) and adjusting for specific volume (v) and the density of water ($\rho_{water}$), the daily EWC was calculated (eqn. 10). Evaporative cooling is typically not used during the first three weeks of a flock. Therefore, daily EWC was set to zero for DOA values less than or equal to 21 days.

$$EWC_{daily} = \left[ 3{,}600 * \frac{Q_{average} * \Delta W_{\eta_{pad}}}{v * \rho_{water}} \right] * NH \tag{10}$$

where

$EWC_{daily}$ = daily evaporative cooling make-up water consumption ($m^3$)

$\Delta W_{\eta_{pad}}$ = unit evaporative pad make-up water needed to refill the system ($kg_{water}\ kg_{da}^{-1}$)

v = specific volume ($m^3\ kg_{da}^{-1}$)

$\rho_{water}$ = density of water ($kg\ m^{-3}$)

NH = number of houses

### 2.2.7 Estimating maintenance water consumption

Maintenance water consumption (MWC) was separated into evaporative pad maintenance (EPM) and drinker line maintenance (DLM) water consumption and calculated according to user defined inputs. Evaporative pad maintenance was determined by multiplying the NH by the number of complete flushes ($NF_{EMP}$) to clean the evaporative system storage, the total evaporative pad length for one house (TPL), and the unit trough volume of the evaporative cooling system (UTV) (eqn. 10).

$$EPM = (NF_{EPM} * TPL * UTV) * NH \tag{10}$$

where

EPM = evaporative pad maintenance water consumption ($m^3$)

$NF_{EPM}$ = number of complete flushes to clean the evaporative system storage

TPL = total evaporative pad length for one house (m)

UTV = unit trough volume of the evaporative cooling system ($m^3\ m^{-1}$)

NH = number of houses

Drinker line maintenance was determined by multiplying the NH by the number of complete flushes ($NF_{DLM}$) to clean the drinker lines, number of drinker lines per house (NDL), total length per drinker line (TDL), and unit drinker volume (UDV) (eqn. 11).

$$DLM = (NF_{DLM} * NDL * TDL * UDV) * NH \tag{11}$$

where

DLM = drinker line maintenance water consumption ($m^3$)

$NF_{DLM}$ = number of complete flushes to clean the drinker lines

NDL = number of drinker lines per house

TDL = total length per drinker line (m)

UDV = unit drinker line volume ($m^3\ m^{-1}$)

NH = number of houses

### 2.2.8 East Alabama commercial farm case study

An eight house poultry farm in east Alabama near New Site, Alabama was used to evaluate the performance of BWC and EWC model parameters. In a separate study, the farm was monitored for BWC and EWC. Specific MWC events were not recorded therefore MWC model parameters were not evaluated in this study.

The nearest weather station with the most complete data values was Montgomery, AL (table 1) 56 miles from the farm. Five consecutive days of data were missing and were replaced with data from Maxwell Air Force Base (722265-13821), 19 miles from the Montgomery weather station, for the same five days. The weather data was adjusted five hours to correct for the UTC time zone.

**Table 1. Montgomery, AL weather station information.**

| Location | Station Name | USAF | WBAN | UTC Time Zone |
|---|---|---|---|---|
| Montgomery, AL | MONTGOMERY RGNL (DANNELLY FD) | 722260 | 13895 | -5 |
| Montgomery, AL | MAXWELL AFB AIRPORT | 722265 | 13821 | -5 |

House 8 was excluded from this case study because of varying flock sizes compared to houses 1 through 7. The length and width of each house was 155 m and 13 m, respectively with an estimated $Q_{average}$ value of 98 $m^3$ $s^{-1}$ to achieve a mean wind speed of 2.6 m $s^{-1}$. For the 7 houses studied, flocks had varying FL (44-48 d) and LD (8-16 d) values. To determine the accuracy of model parameters, model flock DOA was aligned with measured flock DOA rather than inputting FL and LD. Each flock consisted of 27,400 birds of the Cobb 500 genetic strain with an initial W:F of 2 g $g^{-1}$ assumed.

Values for $\eta_{pad}$ typically range from 50 to 85% (Bucklin et al., 2016; Donald et al., 2000). Evaporative pads for this farm were reasonably well maintained and a $\eta_{pad}$ of 75% was assumed. The cooling system will only run during an operating time from 9am to 7pm reflecting farm evaporative system operation and at a $T_{min}$ greater than 26.6°C. Table 2 lists the model parameters used to estimate BWC and EWC.

**Table 2. Model parameters used in the RWH model for a broiler farm in east Alabama.**

| House characteristics | |
|---|---|
| HL | 155 (m) |
| HW | 13 (m) |
| NH | 7 |
| $Q_{average}$ | 98 ($m^3 s^{-1}$) |
| **BWC parameters** | |
| NB | 27,400 |
| genetic strain | Cobb |
| W:F | 2 ($g\ g^{-1}$) |
| DOP | 1 (d) |
| FL | 44-48 (d) |
| LD | 8-16 (d) |
| time span | 396 (d) |
| $\rho_{water}$ | 983 ($kg\ m^{-3}$) |
| **EWC parameters** | |
| $\eta_{pad}$ | 75 (%) |
| $T_{min}$ | 26 (°C) |
| operating time | 9am-7pm |

Complete water consumption data for daily BWC was measured for seven complete flocks during a period between 4/18/2014 and 5/18/2015 for a time span of 396 d.

Farm BWC data for bird DOA values between 1 to 21 d showed significant spikes inconsistent with expected lower drinking patterns for small chicks. These spikes may have been DLM events or flushing events that were not specified by the farmer. Therefore, daily BWC calibration and evaluation was carried out for DOA values greater than 21 d. This calibration and evaluation of daily BWC for DOA values greater than 21 d represents the main bird water consumption period during a flock.

Farm water consumption data for daily EWC was only available for house 1 during a period between 2/13/2014 and 5/17/2015. Houses 2-8 were excluded because of inconsistent data recordings throughout flocks and during high temperature periods of the year where EWC would have been required to maintain bird well-being. Daily EWC was not calculated for bird DOA values less than or equal to 21 to match farm operation of the evaporative cooling system.

## 2.3 Results and Discussion

### 2.3.1 Calibration of bird water consumption

The seven flocks (table 3) were separated into two groups to calibrate and evaluate BWC parameters between bird DOA greater than 21 d. Flocks 2 and 6 for each house were chosen as calibration flocks for a total of 14 house/flocks evaluated. These two flocks were chosen to account for changes in temperature throughout the model time period. Flock 2 represents a warm weather flock and flock 6 represents a cold weather flock.

**Table 3. East Alabama flock start and end dates.**

| Flock | Start Date | End Date |
|---|---|---|
| 1 | 4/18/2014 | 6/3/2014 |
| 2 | 6/20/2014 | 8/5/2014 |
| 3 | 8/15/2014 | 9/30/2014 |
| 4 | 10/17/2014 | 12/1/2014 |
| 5 | 12/16/2014 | 1/28/2015 |
| 6 | 2/6/2015 | 3/24/2015 |
| 7 | 4/2/2015 | 5/18/2015 |

Calibration of BWC was carried out by evaluating the response of model BWC estimations for flocks 2 and 6 by changing the W:F ratio. A representative flock grown to 47 days is shown in figure 3 to demonstrate the response of model BWC estimations for changes in W:F ratios. The initial assumption of W:F =2.0 g $g^{-1}$ yielded a cumulative BWC overestimation of 25.67% for the 47 day period. Model BWC was 263 $m^3$ compared to farm BWC of 203 $m^3$. Using data from Williams et al. (2013), the W:F was adjusted to 1.8 g $g^{-1}$. Incorporating this W:F value reduced the model BWC estimation to 237 $m^3$ resulting in a percent difference of 15.24% compared to farm BWC.

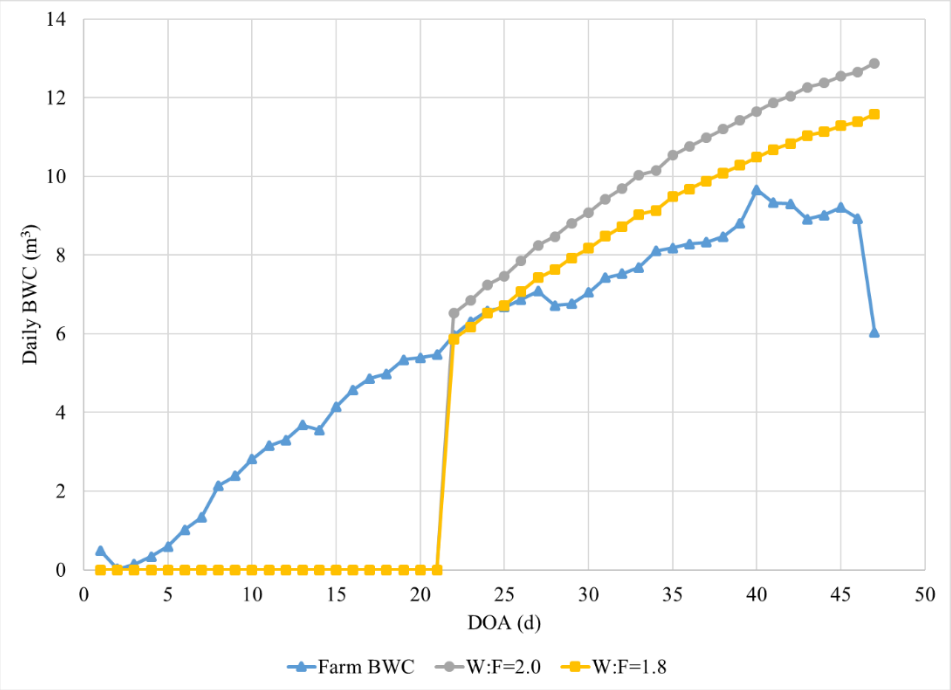

**Figure 3. Comparison between farm BWC data and model BWC estimates for DOA greater than 21 d for house 1 flock 2.**

Similar reductions in model BWC estimations were seen comparing the use of W:F values 2.0 g $g^{-1}$ and 1.8 g $g^{-1}$ across calibration flocks 2 and 6 (table 4). Using a W:F value of 1.8 g $g^{-1}$ resulted in the best estimation of BWC. The model overestimated flock 2 by 13.70% with a model BWC estimation of 1,657 $m^3$ compared to a farm BWC of 1,445 $m^3$. Flock 6 was overestimated by 19.94% with a model BWC estimation of 1,623 $m^3$ compared to a farm BWC of 1,329 $m^3$.

**Table 4. Evaluation of BWC for varying W:F values for calibration flocks.**

| | Flock 2 | | | | Flock 6 | | | |
|---|---|---|---|---|---|---|---|---|
| Description | Farm BWC ($m^3$) | Model BWC ($m^3$) | Percent Difference (%) | RMSE ($m^3$ $d^{-1}$) | Farm BWC ($m^3$) | Model BWC ($m^3$) | Percent Difference (%) | RMSE ($m^3$ $d^{-1}$) |
| W:F=2.0 | 1445 | 1841 | 24.14 | 2.53 | 1329 | 1803 | 30.31 | 2.79 |
| W:F =1.8 | 1445 | 1657 | 13.70 | 1.62 | 1329 | 1623 | 19.94 | 1.82 |

Difference in farm BWC between houses also suggests other factors may affect BWC (table 5). Farm BWC for each house in flock 2 ranged from 200 $m^3$ to 222 $m^3$ whereas model BWC estimated each house BWC as 237 $m^3$. Similar results were seen for flock 6. Excluding house 7 because of a shorter FL compared to houses 1 through 6, farm BWC ranged from 183 $m^3$ to 200 $m^3$ however the model estimated BWC as 237 $m^3$ for each house. The estimation of BWC did not account for seasonal differences nor did the farmer record water consumption adjustments that may have been performed. The birds consumed less water in flock 6 compared to flock 2.

**Table 5. BWC variations between houses for calibration flocks.**

| | Flock 2 | | | | Flock 6 | | | |
|---|---|---|---|---|---|---|---|---|
| House | Farm BWC ($m^3$) | Model BWC ($m^3$) | Percent Difference (%) | RMSE ($m^3$ $d^{-1}$) | Farm BWC ($m^3$) | Model BWC ($m^3$) | Percent Difference (%) | RMSE ($m^3$ $d^{-1}$) |
| 1 | 203 | 237 | 15.24 | 1.70 | 186 | 237 | 24.16 | 2.12 |
| 2 | 200 | 237 | 17.01 | 1.88 | 183 | 237 | 25.84 | 2.17 |
| 3 | 203 | 237 | 15.12 | 1.77 | 190 | 237 | 21.86 | 1.85 |
| 4 | 203 | 237 | 15.53 | 1.74 | 200 | 237 | 16.80 | 1.51 |
| 5 | 222 | 237 | 6.26 | 0.99 | 192 | 237 | 20.61 | 1.93 |
| 6 | 205 | 237 | 14.53 | 1.53 | 189 | 237 | 22.54 | 1.93 |
| 7 | 209 | 237 | 12.59 | 1.53 | 189 | 202 | 6.92 | 0.71 |
| Total | 1445 | 1657 | 13.70 | 1.62 | 1329 | 1623 | 19.94 | 1.82 |

### 2.3.2 Evaluation of bird water consumption

Flocks 1, 3-5, and 7 were used as evaluation flocks for a total of 35 house/flocks evaluated. Results are shown in table 6 using a W:F value of 1.8 g $g^{-1}$. Model BWC was overestimated for each evaluation flock but within 17% of farm flock BWC values. Incorporating calibration and evaluation flocks for the seven houses, total model BWC was overestimated by 14.43%. Model BWC was estimated to be 11,290 $m^3$ compared to farm BWC of 9,770 $m^3$.

**Table 6. Overall BWC results for each calibrated and evaluated flock.**

| Flock | Farm BWC ($m^3$) | Model BWC ($m^3$) | Percent Difference (%) | RMSE ($m^3$ $d^{-1}$) |
|---|---|---|---|---|
| 1[b] | 1515 | 1669 | 9.65 | 1.37 |
| 2[a] | 1445 | 1657 | 13.70 | 1.62 |
| 3[b] | 1476 | 1681 | 12.96 | 1.85 |
| 4[b] | 1418 | 1611 | 12.74 | 1.31 |
| 5[b] | 1234 | 1462 | 16.96 | 1.60 |
| 6[a] | 1329 | 1623 | 19.94 | 1.82 |
| 7[b] | 1354 | 1588 | 15.85 | 1.66 |
| Total | 9770 | 11290 | 14.43 | 1.62 |

[a] calibration flock
[b] evaluation flock

### 2.3.3 Evaporative cooling make-up water consumption estimation

Houses 2-7 were not included in EWC analysis because of inconsistent data collection for farm EWC. House 1 was used to evaluate the response of model EWC estimations across eight complete flocks between 2/13/2014 and 5/17/2015 for a time span of 459 d. During this time span, the farm evaporative cooling system was operational for 82 d and not operational for 377 d. Four different scenarios were observed when comparing the number of days farm EWC was used and model EWC was simulated; farm EWC was used and the model simulated EWC use (U-S), farm EWC was used and the model did not predict EWC use (U-NS), farm EWC was not used and the model simulated EWC use (NU-S), and farm EWC was not used and the model did not predict EWC use (NU-NS) (table 7).

The model correctly simulated 91% of farm evaporative cooling events with a mean value of 8 $m^3$ $d^{-1}$ compared to a farm mean of 3.6 $m^3$ (table 8). Of the 82 d farm EWC was used, seven days were not simulated by the model. Five of those days had a lower volume of 0.28 $m^3$ compared to the mean evaporative system use of 1.5 $m^3$ $d^{-1}$. These five days could represent possible maintenance use events. The other two days not identified by the model did not meet the $T_{min}$

threshold of 26.6 °C however the farmer may have operated the system to ensure bird well-being because the particular flock was nearing its FL. For the 75 events that the model agreed with farm use, model EWC estimates were closer to measured values for bird DOA values between 41 and 47 d. During this period, the tunnel fans would be in full operation along with the use of evaporative cooling. Earlier in the flock, the grower may not have utilized the cooling pads even though the $T_{min}$ would call for the system, potentially leading to larger differences.

When farm EWC was not used, the model correctly simulated 93% of the days as no EWC use but incorrectly simulated 7% of these days as EWC use. A total of 25 days were incorrectly simulated by the model for DOA values ranging between 22 d and 48 d. These EWC events were above the $T_{min}$ value but it is not clear why the farmer did not operate the evaporative cooling system.

**Table 7. EWC observation scenarios for house 1 between 2/13/2014 and 5/17/2015.**

| Detected Evaporative Cooling Events | | | | Volume | | |
|---|---|---|---|---|---|---|
| U-S<br>no. d | U-NS<br>no. d | NU-S<br>no. d | NU-NS<br>no. d | Observed<br>$m^3$ | Simulated<br>$m^3$ | RMSE<br>($m^3$ $d^{-1}$) |
| 75 | 7 | 25 | 352 | 283 | 736 | 2.71 |

**Table 8. Max, min, and mean for farm and model EWC for U-S, U-NS, and NU-S scenarios.**

| | U-P | | U-NP | | NU-P | |
|---|---|---|---|---|---|---|
| Daily | Farm | Model | Farm | Model | Farm | Model |
| Max ($m^3$) | 11.7 | 13.5 | 5.1 | 0.0 | 0.0 | 9.1 |
| Mean ($m^3$ $d^{-1}$) | 3.6 | 8.0 | 1.5 | 0.0 | 0.0 | 5.6 |
| Min ($m^3$) | 0.0 | 1.1 | 0.0 | 0.0 | 0.0 | 0.5 |

### 2.3.4 North Alabama commercial farm case study

The full RWH model was run for a 25-year period between 1990 and 2015 to evaluate the performance of a RWH system over an extended period of time. Farm characteristics were simulated for an existing four house farm in north Alabama currently using a 379 $m^3$ RWH system. The nearest weather station with the most complete data values was Huntsville, AL; 53 miles from the farm (table 9). The data was corrected according to the UTC time zone.

**Table 9. Huntsville, AL weather station information.**

| Location | Station Name | USAF | WBAN | UTC Time Zone |
|---|---|---|---|---|
| Huntsville, AL | HUNTSVILLE INTL/C.T.JONES FIE | 723230 | 3856 | -5 |

Each house averaged 152.4 m in length and 12.5 m in width with a $Q_{average}$ value of 129 $m^3 s^{-1}$ to achieve a mean wind speed of 3.6 m $s^{-1}$. The storage capacity was 379 $m^3$ with no initial storage capacity and a $\eta_{capture}$ of 90% was assumed based on recommendations from Rainwater Resources Engineering Services (Denis Rochat, President of Rainwater Resources, personal communication, 31 January 2017). Each flock consisted of 28,000 Cobb 500 genetic strain birds with an average FL of 43 and an average LD of 18. A W:F value of 1.8 g $g^{-1}$ was used. The evaporative system operating time was assumed to be 9am to 7pm and the $T_{min}$ value was set to 26°C (table 10).

**Table 10. Model parameters used in the RWH model for a broiler farm in north Alabama over a 25-year test period.**

| **House characteristics** | |
|---|---|
| HL | 152.4 (m) |
| HW | 12.5 (m) |
| NH | 4 |
| $Q_{average}$ | 129 ($m^3 s^{-1}$) |
| **RWH parameters** | |
| storage capacity | 379 ($m^3$) |
| initial storage | 0 ($m^3$) |
| $\eta_{capture}$ | 90 (%) |
| **BWC parameters** | |
| NB | 28,000 |
| genetic strain | Cobb |
| W:F | 1.8 ($g\ g^{-1}$) |
| DOP | 1 (d) |
| FL | 43 (d) |
| LD | 18 (d) |
| time span | 9862 (d) |
| $\rho_{water}$ | 983 ($kg\ m^{-3}$) |
| **EWC parameters** | |
| $\eta_{pad}$ | 75 (%) |
| $T_{min}$ | 26.6 (°C) |
| operating time | 9am-7pm |

### 2.3.5 Model evaluation

To illustrate the performance of the simulated RWH system over the 25-year period, total water consumption (TC) was separated into municipal water usage (MU) and storage water usage (SU) for each year during the 25-year period. For each year, daily MU and SU values were calculated and were demonstrated in figure 4 during 1990. EWC was not used during the first 21 d to match farm operation of evaporative cooling systems and BWC was not simulated during the first 21 d because BWC was not calibrated or evaluated for those bird DOA values. Daily SU was illustrated as a positive consumption and MU as a negative consumption. Considerable MU consumption was seen during summer months (days 150-265). Over this year MU was 40% of

TC and SU was 60% of TC. Daily values were summed up within each year to determine annual MU and SU values.

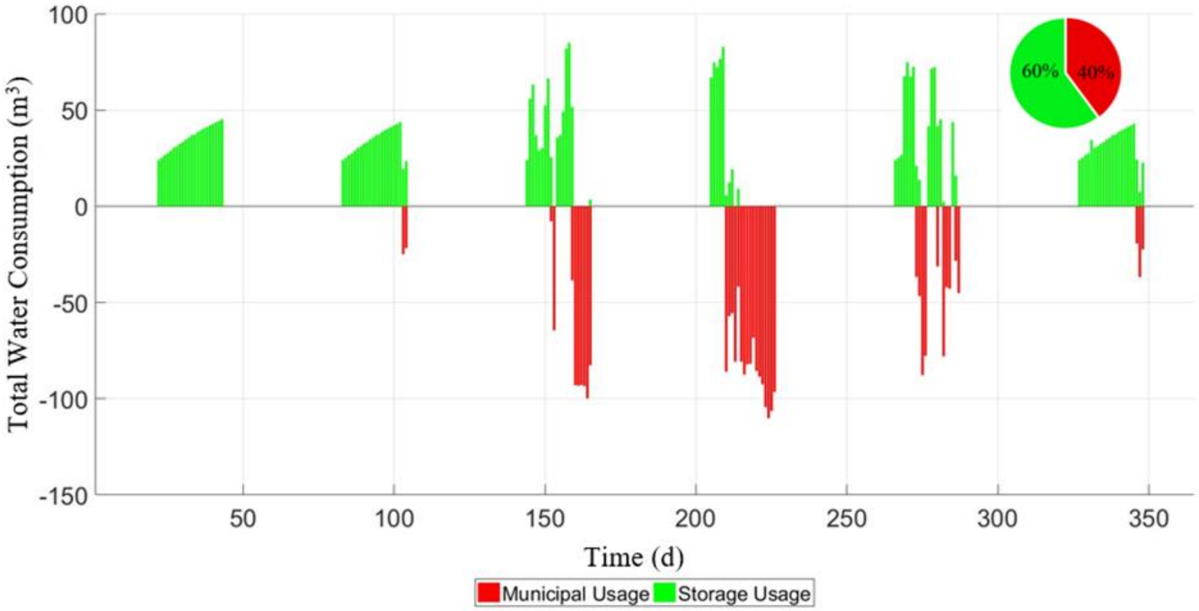

**Figure 4. Total water consumption, split into daily MU and SU, for Huntsville, AL using a 379 $m^3$ storage capacity starting January 1st and ending December 31st in 1990 with a total rainfall of 1.83 m.**

Table 11 shows the performance of the system over the 25-year period. For the storage size of 379 $m^3$, MU was required in all years. MU was higher than SU only in 2007. Increased MU consumption was demonstrated in years with low annual rainfall while SU consumption was utilized in years with high annual rainfall (fig. 5).

**Table 11. Mean annual rainfall and model water consumption estimations for 379 m$^3$ storage capacity over a 25-year period in Huntsville, AL.**

| Year | Rainfall (m) | TC (m$^3$) | MU (m$^3$) | SU (m$^3$) |
|---|---|---|---|---|
| 1990 | 1.83 | 6,813 | 2,714 | 4,099 |
| 1991 | 1.79 | 6,667 | 2,719 | 3,948 |
| 1992 | 1.42 | 5,562 | 1,302 | 4,259 |
| 1993 | 1.32 | 6,510 | 2,102 | 4,408 |
| 1994 | 1.71 | 6,075 | 1,383 | 4,691 |
| 1995 | 1.27 | 6,223 | 2,002 | 4,221 |
| 1996 | 1.42 | 5,723 | 1,763 | 3,961 |
| 1997 | 1.44 | 5,809 | 1,476 | 4,333 |
| 1998 | 1.14 | 6,668 | 2,810 | 3,858 |
| 1999 | 1.16 | 6,914 | 3,056 | 3,858 |
| 2000 | 1.09 | 6,913 | 3,040 | 3,873 |
| 2001 | 1.55 | 6,093 | 1,279 | 4,813 |
| 2002 | 1.27 | 7,082 | 3,264 | 3,818 |
| 2003 | 1.39 | 6,104 | 1,966 | 4,138 |
| 2004 | 1.50 | 6,087 | 1,923 | 4,164 |
| 2005 | 0.81 | 6,587 | 2,832 | 3,756 |
| 2006 | 0.78 | 7,360 | 3,571 | 3,789 |
| 2007 | 0.57 | 8,051 | 4,781 | 3,270 |
| 2008 | 0.95 | 7,098 | 3,283 | 3,815 |
| 2009 | 1.22 | 6,891 | 2,907 | 3,984 |
| 2010 | 0.83 | 7,390 | 3,667 | 3,723 |
| 2011 | 1.22 | 7,135 | 2,974 | 4,161 |
| 2012 | 1.14 | 7,264 | 3,517 | 3,747 |
| 2013 | 1.27 | 6,607 | 2,632 | 3,975 |
| 2014 | 1.11 | 6,738 | 2,635 | 4,103 |
| 2015 | 1.51 | 6,668 | 1,756 | 4,912 |
| Annual Mean | 1.26 | 6,655 | 2591 | 4,065 |
| SEM | ±0.06 | ±116 | ±172 | ±72 |

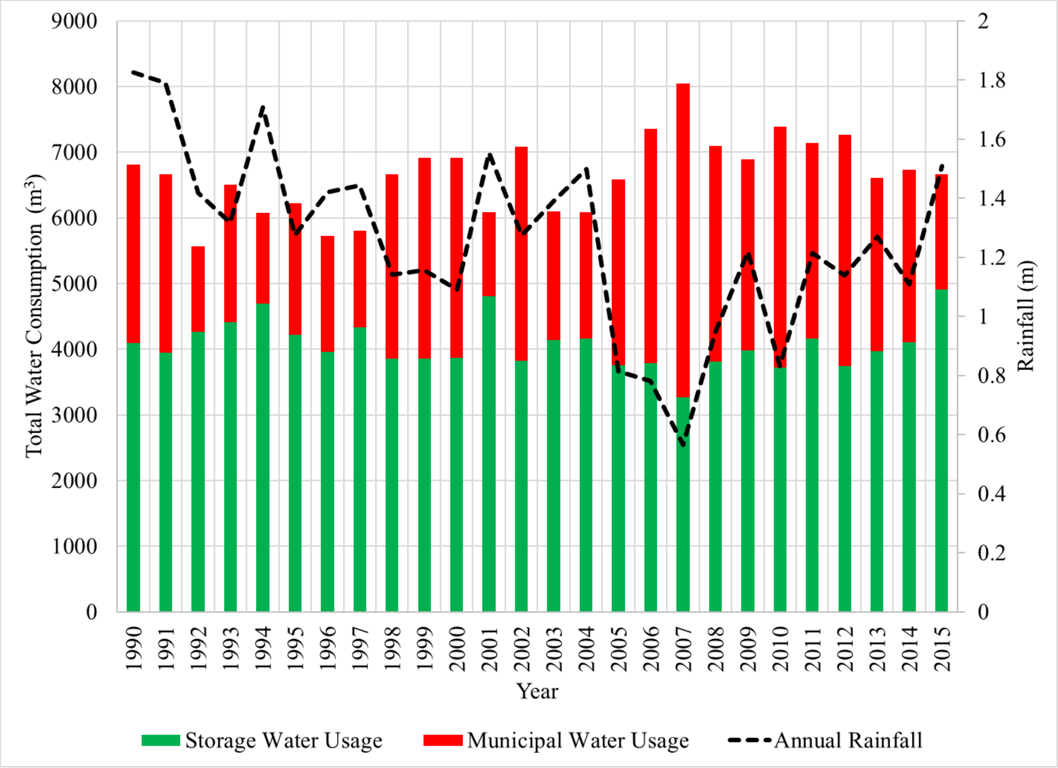

**Figure 5. Total water consumption, split into MU and SU, for a 379 m$^3$ storage capacity over a 25-year period in Huntsville, AL.**

Total water consumption data was available for the years 2011, 2012, 2014, and 2015 for the north Alabama farm. Total model water consumption estimates for these four years were within 18.21% (table 12). Excluding 2014, the model was within 5.40%.

**Table 12. Farm and model total water consumption for the north Alabama farm.**

| Year | Farm Total (m$^3$) | Model Total (m$^3$) | Percent Difference % |
|---|---|---|---|
| 2011 | 7355 | 7135 | -3.03 |
| 2012 | 6882 | 7264 | 5.40 |
| 2014 | 8088 | 6738 | -18.21 |
| 2015 | 6680 | 6668 | -0.18 |

To demonstrate the benefit of operating a RWH system, a simple economic analysis was performed by calculating the annual payment for this system. Using actual costs from the 379 m$^3$ RWH system in north Alabama, the system cost was $125,000. Equation 12 was used to calculate the annual payment (A) needed for a 5% interest rate (i) loan over a 10-year period (n) for the system cost (P) of $125,000. The annual loan cost, A, of the RWH system was $16,188.

$$A = \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] P \tag{12}$$

where

A = annual loan cost ($)

i = interest rate (%)

n = loan period (y)

P = system cost ($)

Total savings for the 25-year period were estimated using a low, medium, and high water cost representative of water costs seen in Alabama. The low water cost was assumed to be $0.92 m$^{-3}$ similar to costs in south Alabama. The high water cost value was $2.77 m$^{-3}$ and represented costs seen in north Alabama. A medium range cost was assumed to be $1.85 m$^{-3}$.

At a low water cost, the system lost $64,233 over the 25-year period. For both the medium and high water costs, the system saved $33,414 and $131,062 respectively (fig. 6). After the 10-year loan period, the annual system savings for the low, medium, and high water costs were $3,700, $7,400, and $11,100 respectively. While savings were seen for the $0.92 m$^{-3}$ after the loan period, those savings did not compensate for the cost of the system.

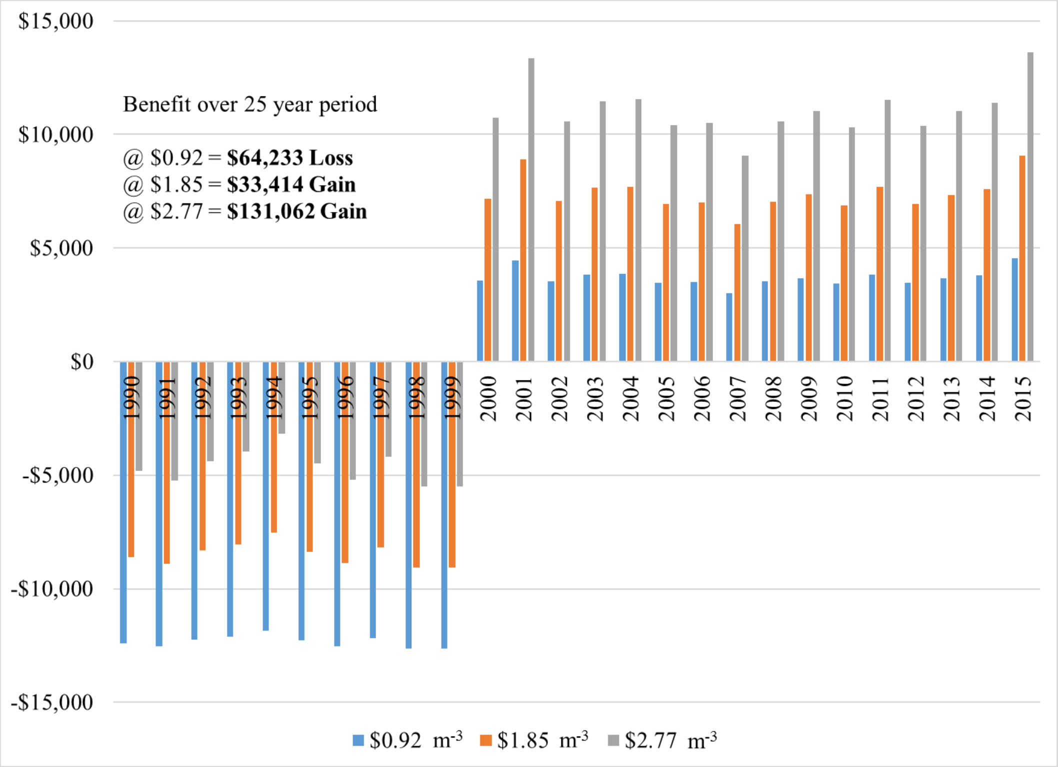

**Figure 6. Economic analysis for a system with 379 $m^3$ of storage, a total system cost of $125,000, and an interest rate of 5% over a 10-year period.**

## 2.4 Conclusions

Equations were developed to estimate the main poultry water consumption sources of BWC, EWC, and MWC. Excluding MWC because of inconsistent farm data from a previous study, BWC and EWC for bird DOA values greater than 21 d were calibrated and evaluated. Model BWC was calibrated and evaluated using a W:F value of 1.8 g $g^{-1}$ and overestimated measured BWC by 15%. Results suggest there were other environmental factors that affect BWC and further research is needed to identify and evaluate these affects to better estimate daily BWC for a flock.

Although model EWC was significantly overestimated, the model was able to predict 91% of the farm EWC events and 93% of the days farm EWC was not used. For days farm EWC was used and model EWC simulated a cooling event, model EWC had a mean of 8.0 $m^3$ $d^{-1}$ compared to a farm EWC mean of 3.6 $m^3$ $d^{-1}$. Analysis would also suggest that data discrepancies and varying farm management practices could account for the overestimation of EWC. To better estimate these values, data collection should be carried out on more houses during a longer test period to account for changes in management practices and season. Farm evaporative cooling control systems (e.g. timers operating the system) should also be monitored and incorporated into EWC estimations in order to better represent actual farm evaporative cooling system operation.

The overall performance of the model was within 18.21% of total farm estimations for TC data recorded on the north Alabama farm. Applying a simple economic analysis to evaluate a system life span of 25-years and a 10-year loan period demonstrated at increasing municipal water costs savings increased.

Incorporating better estimations for BWC and EWC into the RWH model would provide a better decision tool for farms interested in using a RWH system to supplement water sources and offset water costs.

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# Chapter 3: Study 2

## 3.1 Introduction

RWH systems have the potential to offset poultry farm water costs and reduce reliance on well or municipal water supplies. Many rural farms across the U.S. rely on well water which can be unreliable and have water quality issues. In some parts of the U.S., farms that have access to municipal water supplies are experiencing increasing water prices.

Estimating the proper storage capacity for a particular location is crucial. Using a varying dimensionless ratio for modified storage fraction which was used to relate storage capacity to average daily water demand during average dry periods, Campisano (2012) found that economic benefits decreased as modified storage fraction increased resulting in larger storage capacities becoming less effective because of the availability of rainfall. To determine the most beneficial storage size for a location, estimating rainfall and water demand is important and can be achieved using a RWH model (Su et al., 2009).

A RWH model was developed in chapter 2 to estimate the water consumption of a commercial broiler farm using hourly weather data and farm characteristics. The objectives of this research were to evaluate the performance of varying storage sizes for nine locations across the U.S. and estimate the cost savings for each storage size using a simple economic analysis.

## 3.2 Materials and Methods

### 3.2.1 Test farm

The RWH model developed in chapter 2 was evaluated using parameters for a four house commercial broiler farm (table 13) in north Alabama that currently uses a RWH system. The RWH model was used to evaluate six storage capacities across nine locations in the US. For each location, the RWH model estimated the total water consumption (TC) needs and whether that came from rainwater storage (SU) or municipal (MU) over a 25-yr period. A simple economic analysis was performed to analyze the effects of each storage capacity across geographical locations.

The farm consisted of four houses each with an average house length (HL) of 152.4 m, an average house width (HW) of 12.5 m, and an average air flow ($Q_{average}$) of 129 $m^3 s^{-1}$ to achieve a mean wind speed of 3.6 m $s^{-1}$. The Alabama farm currently uses a rainwater storage capacity of 379 $m^3$. Storage capacities of 189 $m^3$, 379 $m^3$, 568 $m^3$, 758 $m^3$, 947 $m^3$, and 1,136 $m^3$ were evaluated. The model assumed no initial water volume in storage and assumed a capture efficiency ($\eta_{capture}$) based on recommendations from Rainwater Resources Engineering Services of 90% (Denis Rochat, President of Rainwater Resources, personal communication, 31 January 2017). Each flock consisted of 28,000 Cobb 500 genetic strain birds with an average flock length (FL) of 43 and an average number of layout days (LD) of 18. A W:F of 1.8 g $g^{-1}$ was used. For calculation purposes the density of water ($\rho_{water}$) was assumed to be 983 kg $m^{-3}$. The evaporative cooling system was only run during an operating time from 9am to 7pm and at a minimum temperature ($T_{min}$) of 26.6 °C. The evaporative cooling pad efficiency ($\eta_{pad}$) was assumed to by 75%.

**Table 13. Model parameters used in the RWH model for a broiler farm in east Alabama.**

| **House characteristics** | |
|---|---|
| HL | 152.4 (m) |
| HW | 12.5 (m) |
| NH | 4 |
| Q | 129 (m$^3$ s$^{-1}$) |
| **RWH parameters** | |
| storage capacity | 189-1136 (m$^3$) |
| initial storage | 0 (m$^3$) |
| $\eta_{capture}$ | 90 (%) |
| **BWC parameters** | |
| NB | 28,000 |
| genetic strain | Cobb |
| W:F | 1.8 (g g$^{-1}$) |
| DOP | 1 (d) |
| FL | 43 (d) |
| LD | 18 (d) |
| time span | 9862 (d) |
| $\rho_{water}$ | 983 (kg m$^{-3}$) |
| **EWC parameters** | |
| $\eta_{pad}$ | 75 (%) |
| $T_{min}$ | 26 (°C) |
| operating time | 9am-7pm |

### 3.2.2 Test Locations

Nine locations (table 14) were chosen across the U.S. to evaluate the performance of the six storage capacities over a 25-year period from 1990 to 2015. These nine locations represent poultry production areas and variations in climate. Weather data for each location was downloaded from the NOAA ISD-Lite data set (NOAA, 2006) and corrected according to each location's UTC time zone.

**Table 14. Weather station information for each of nine locations.**

| Location | City | State | Station Name | USAF | WBAN | UTC Time Zone |
|---|---|---|---|---|---|---|
| 1 | Athens[a] | GA | ATHENS/BEN EPPS AIRPORT | 723110 | 13873 | -5 |
| 2 | Bakersfield[a] | CA | MEADOWS FIELD AIRPORT | 723840 | 23155 | -8 |
| 3 | Charlotte | NC | CHARLOTTE/DOUGLAS INTERNATION | 723140 | 13881 | -5 |
| 4 | Huntsville | AL | HUNTSVILLE INTL/C.T.JONES FIE | 723230 | 3856 | -5 |
| 5 | Jackson | MS | JACKSON INTERNATIONAL AIRPORT | 722350 | 3940 | -5 |
| 6 | Lancaster[a] | PA | LANCASTER AIRPORT | 725116 | 54737 | -5 |
| 7 | Lufkin[a] | TX | ANGELINA COUNTY AIRPORT | 722446 | 93987 | -6 |
| 8 | Lynchburg[a] | VA | LYNCHBURG RGNL/PRESTON GLENN | 724100 | 13733 | -5 |
| 9 | Montgomery[a] | AL | MONTGOMERY RGNL (DANNELLY FD) | 722260 | 13895 | -5 |

[a] weather data set had missing data and was modified

Weather data sets for six locations were modified due to incomplete data sets using the nearest weather station. Location 1 was missing two days, 3/27/02 and 8/01/02. Those days were replaced with Hartsfield-Jackson Atlanta International Airport data (722190-13874). Location 2 was missing one day, 11/01/02, and was replaced with data from Fresno Yosemite International Airport (723890-93193). Location 6 was missing data between 1990 and 2005. Data from Philadelphia, PA (724080-13739) was used for 1990 to 1991 and data from Harrisburg, PA (725115-14711) was used for 1992 to 2005. Two days for Harrisburg, 4/07/05 and 8/10/05, were missing and were replaced using Philadelphia data. Location 7 was missing seven days, 8/07/01, 4/22/04, 11/26/04, 9/25/05, 5/06/07, 9/14/08, and 5/04/09, and barometric pressure data between 1990 and 1999. Data from Tyler, TX (722448-13972) was used to replace missing data for location 7. Location 8 was missing one day, 8/22/14, and was replaced with data from Richmond, VA (724010-13740). Location 9 was missing six days, 6/07/14 through 6/11/14 and 9/07/15, and was replaced with data from Maxwell Air Force Base (722265-13821).

### 3.2.3 Economics

For each location, a simple economic analysis was performed to show the potential savings over the 25-year period if a RWH system were installed. Using actual system costs of the RWH system in north Alabama, fixed cost and variable storage cost were each 50% of the $125,000 total cost. Both the fixed cost and storage cost for the 379 m$^3$ system was $62,500. A unit storage cost was determined to be $165 m$^{-3}$ of storage. For each location, the fixed system cost was held at $62,500 and the storage cost was adjusted for the storage size (table 15). Total system cost was the sum of fixed and variable storage costs. Equation 13 was used to calculate the annual payment (A) needed for a 5% simple interest rate (i) loan over a 10-yr period (n) for each storage capacity and the purchase price of the system or present value (P) (table 15).

$$A = \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] P \tag{13}$$

where

A = annual loan cost ($)

i = interest rate (%)

n = loan period (y)

P = system cost ($)

**Table 15. Cost breakdown and annual loan cost for each size storage capacity.**

| Storage Size | Fixed Costs | Storage Costs | Total System Costs | Annual Loan Costs |
|---|---|---|---|---|
| 189 | $62,500 | $31,250 | $93,750 | $12,141 |
| 379 | $62,500 | $62,500 | $125,000 | $16,188 |
| 568 | $62,500 | $93,750 | $156,250 | $20,235 |
| 758 | $62,500 | $125,000 | $187,500 | $24,282 |
| 947 | $62,500 | $156,250 | $218,750 | $28,329 |
| 1136 | $62,500 | $187,500 | $250,000 | $32,376 |

## 3.3 Results and Discussion

Daily water consumption values were calculated and summed to determine an annual MU and SU estimation. Figure 7 demonstrates the daily water consumption for Montgomery, AL for the year 1995 using a 379 m$^3$ storage capacity. For this particular year MU and SU were 46% and 54% of TC respectively.

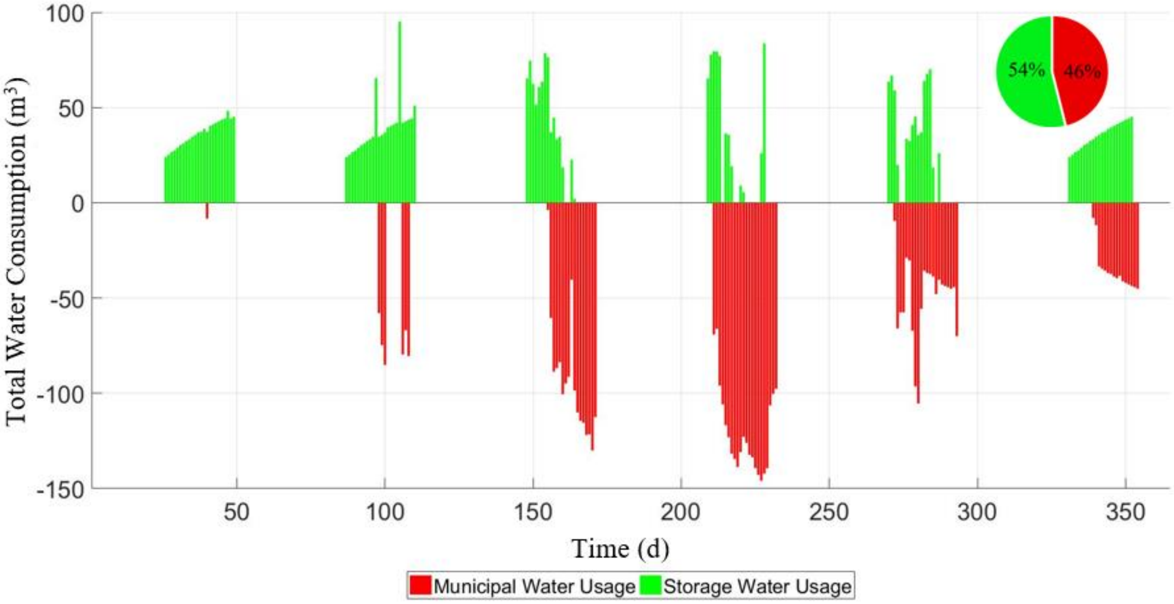

**Figure 7. Total water consumption, split into daily MU and SU, for Montgomery, AL using a 379 m$^3$ storage capacity starting January 1st and ending December 31st in 1995 with total rainfall of 1.12 m.**

Using Montgomery, AL as an example, the effect of storage size on the proportion of TC that was split between MU and SU for each of the 25 years was demonstrated (fig. 8-13). High MU values were associated with low annual rainfall values while SU values increased with higher annual rainfall and increasing storage capacities. While increased storage capacity increased the amount of rainfall captured thus decreasing MU values, there is a maximum amount of rainfall that can be captured per event. Therefore, the offset of MU decreased as storage size increased.

Table 16 summarizes average annual rainfall, TC, MU, and SU for each storage size in each location. Using Montgomery as an example, the largest reduction in MU for Montgomery was between 189 m$^3$ and 379 m$^3$. Adding the extra 189 m$^3$ decreased the average MU by 1,138 m$^3$. As storage size increased, reductions in MU decreased. Increasing from 379 m$^3$ to 568 m$^3$ reduced MU by 775 m$^3$, increasing from 568 m$^3$ to 758 m$^3$ reduced MU by 486 m$^3$, increasing from 758 m$^3$ to 947 m$^3$ reduced MU by 330 m$^3$, increasing from 947 m$^3$ to 1,136 m$^3$ reduced MU by 254 m$^3$.

Average annual MU and SU values for each location show similar trends of decreases in offset of MU with increasing storage size suggesting there is an optimal storage size for each location (fig. 14-22). Each location, except Bakersfield, CA, appears to experience the largest offset in MU increasing storage capacity from 189 m$^3$ to 379 m$^3$. Any additional increase in storage capacity above 379 m$^3$ reduced the offset of MU.

The economic analysis for each storage capacity and each location is summarized in table 17. For each location and storage capacity, the total savings over the 25-yr period was calculated for water costs ranging from \$0.79 to \$3.17 in \$0.26 m$^{-3}$ increments. All combinations that lost money over the 25-year period were shaded red and illustrate water costs and capacities that would not be feasible. Municipal water costs less than \$1.32 m$^{-3}$ lost money for all storage capacities and locations over the 25-year period. Model combinations that were not negative were shaded green in that there was some value to the system. However, there is a nuisance factor in that the grower may not be willing to manage the needed maintenance and cleaning activities if there was not a minimal annual savings over the 25-yr period. An annual savings of \$2,000 was chosen to illustrate the minimal savings needed (\$50,000 savings over 25 years) and these values were shaded in light green. Most system combinations would experience savings less than \$2,000 per year over the 25-year period for a water cost of \$1.85. Huntsville, AL, Jackson, MS, and Montgomery, AL experience savings less than \$2,000 per year over the 25-

year period at a lower water cost of $1.58. However, the average savings for these three locations ranged from $354 per year to $13 per year. Most locations, with the exception of Bakersfield, CA, experience large savings for municipal water costs of $2.38, $2.64, $2.90, and $3.17. For water costs between $2.38 and $3.17, most systems experienced the largest savings using a 568 $m^3$ storage capacity with slight decreases in savings as storage capacity increased.

Bakersfield, CA was identified as a particular case where the chosen storage capacities were not effective. This was demonstrated in figure 23 by determining the MU and SU values on a daily basis for a 1,136 $m^3$ storage capacity in 1998. This particular year had the most rainfall (0.33 m) of the 25-years evaluated and represented the best case scenario for this location. For the total water usage during this year, 69% (959 $m^3$) was MU and 31% (431 $m^3$) was SU. This suggests that an increase in storage size may not be suitable for areas with low rainfall without increasing the catchment area.

Locations with 1 m or greater annual rainfall experienced savings using a 568 $m^3$ storage capacity for water costs of $2.38 or greater. Of these five locations with 1 m or greater annual rainfall, Jackson, MS experienced a maximum savings using a 758 $m^3$ instead of 568 $m^3$ at a water cost of $3.17. However, by installing an extra 189 $m^3$ to increase to 758 $m^3$ of storage capacity only increased system savings $163 from $200,543 to $200,706. This savings of $163 over the 25-year period was only an annual savings of $6.52.

Locations with less than 1 m of annual rainfall, Lancaster, PA, Lufkin, TX, and Lynchburg, VA, tend to experience savings of $2,000 or greater at a water cost of $2.38 or greater, with the exception of Lancaster, PA which experienced these savings at a water cost of $2.11. At even lower annual rainfall amounts, locations such as Bakersfield, CA, farmers would not see any benefit from installing a RWH system.

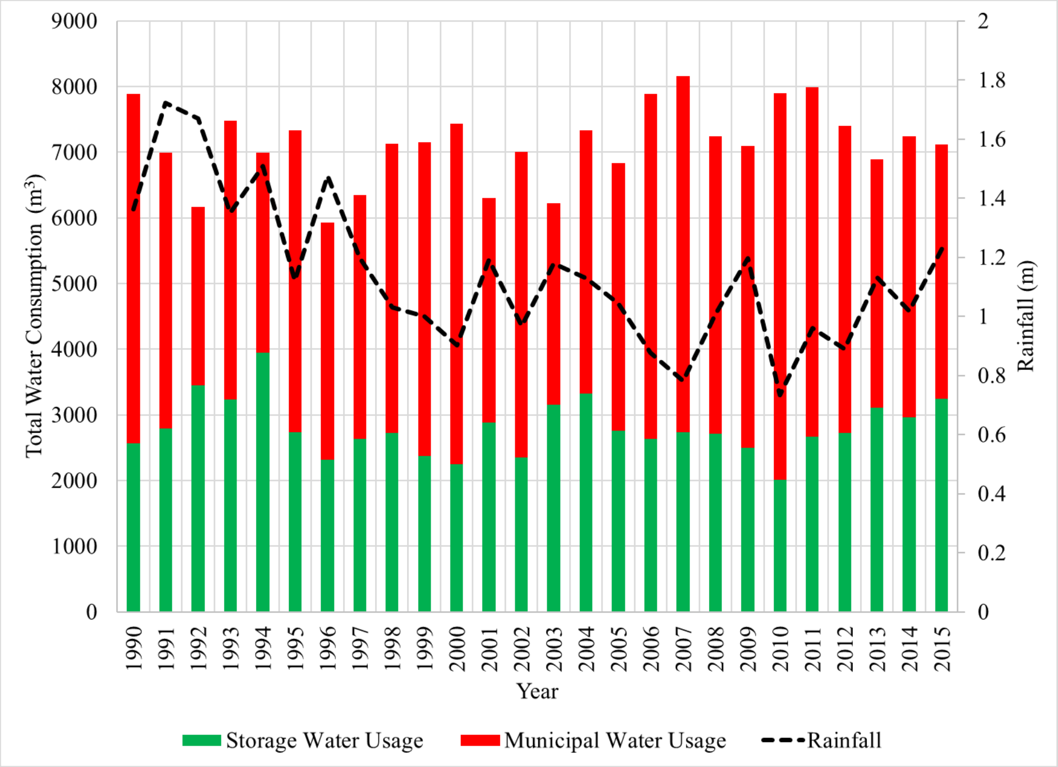

**Figure 8. Total water consumption, split into annual MU and SU, over a 25-year period for a 189 $m^3$ storage capacity in Montgomery, AL.**

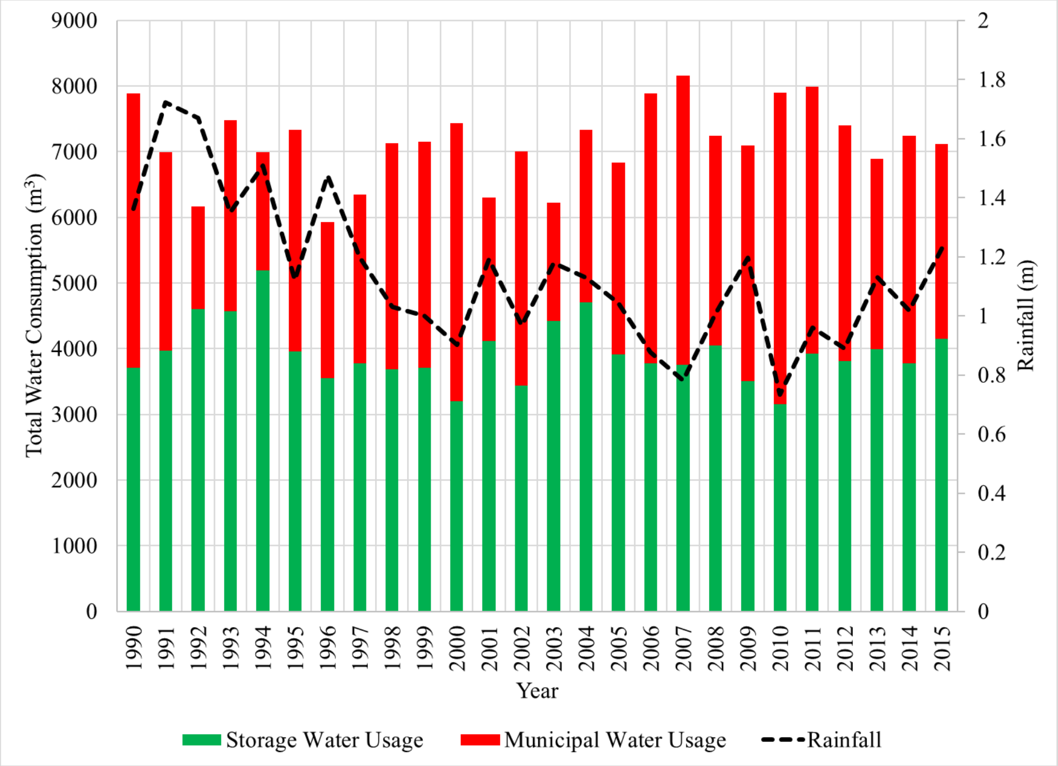

**Figure 9. Total water consumption, split into annual MU and SU, over a 25-year period for a 379 $m^3$ storage capacity in Montgomery, AL.**

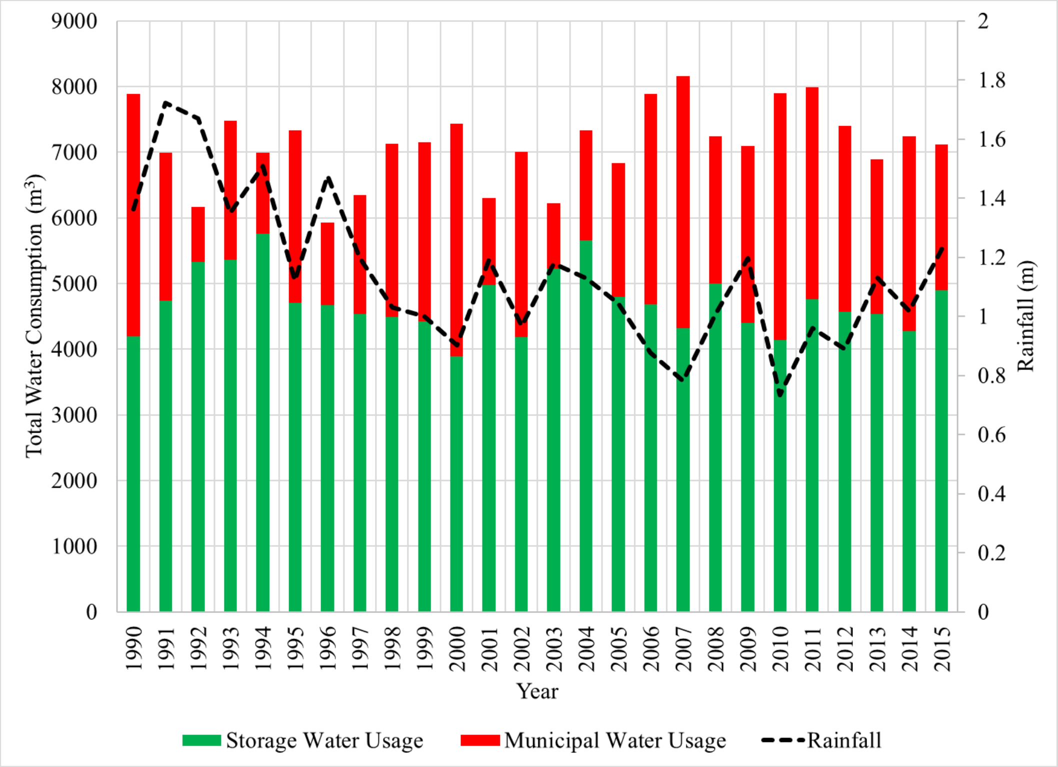

**Figure 10. Total water consumption, split into annual MU and SU, over a 25-year period for a 568 m$^3$ storage capacity in Montgomery, AL.**

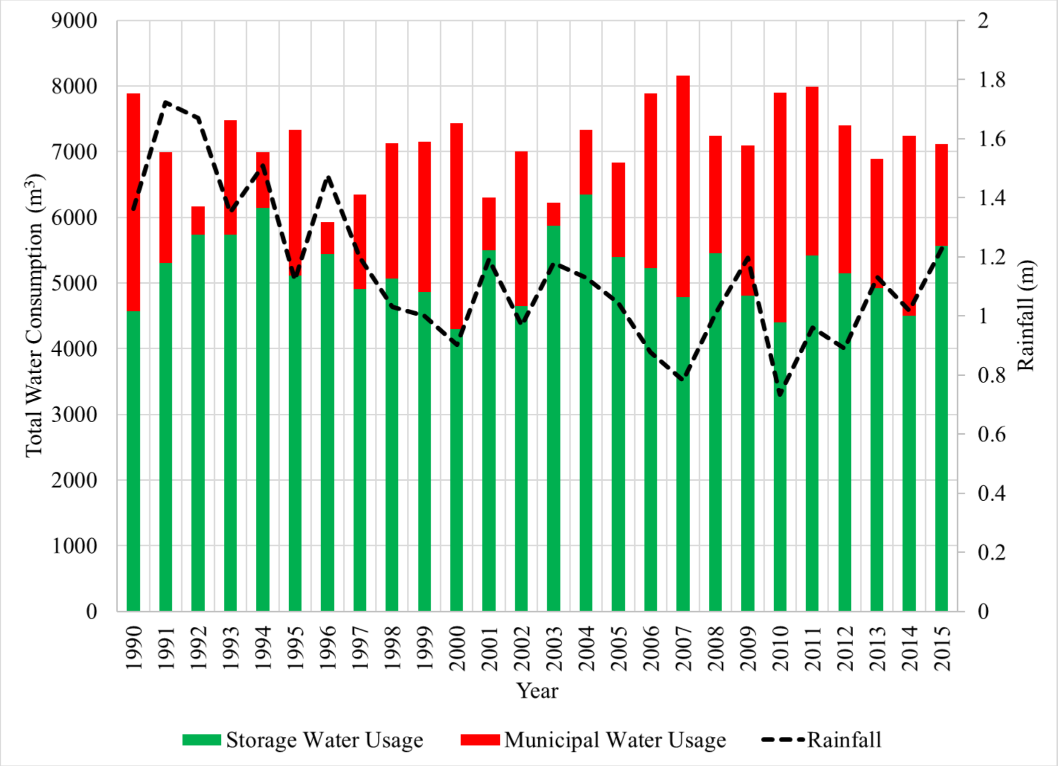

**Figure 11. Total water consumption, split into annual MU and SU, over a 25-year period for a 758 m$^3$ storage capacity in Montgomery, AL.**

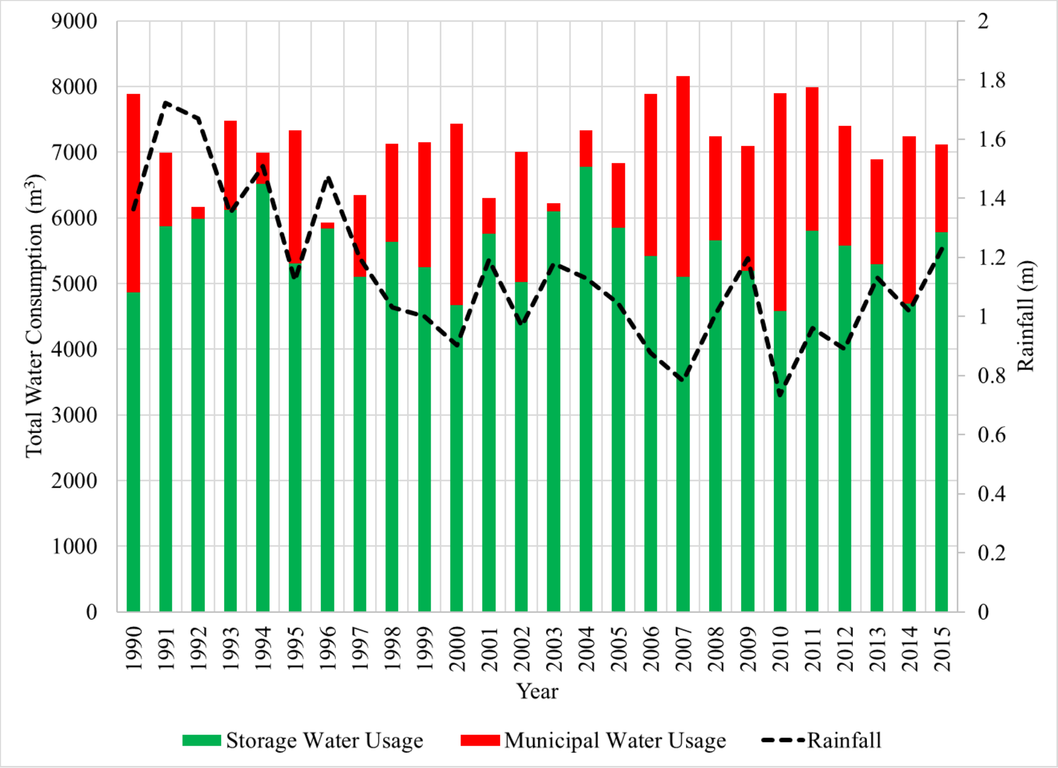

**Figure 12. Total water consumption, split into annual MU and SU, over a 25-year period for a 947 m$^3$ storage capacity in Montgomery, AL.**

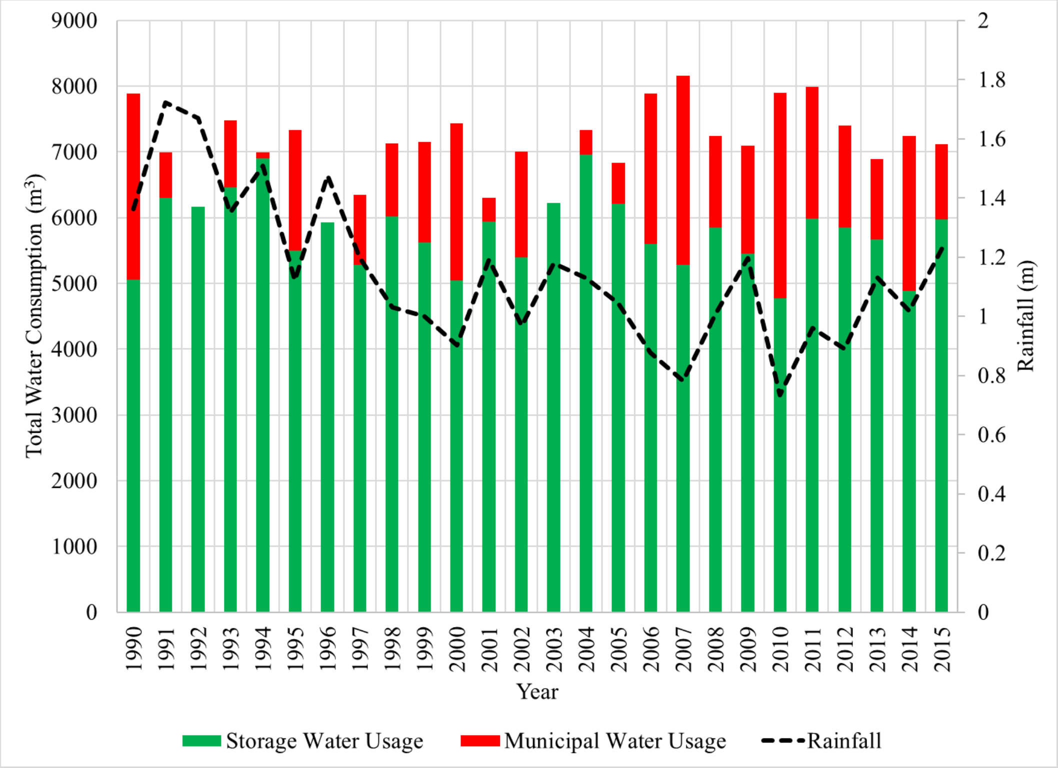

**Figure 13. Total water consumption, split into annual MU and SU, over a 25-year period for a 1,136 m$^3$ storage capacity in Montgomery, AL.**

**Table 16. Comparison of average annual MU and SU for each storage capacity in each location.**

| Location | Rainfall (m) | TC ($m^3$) | Storage Capacity ($m^3$) | MU ($m^3$) | SU ($m^3$) |
|---|---|---|---|---|---|
| Athens, GA | 1.03 ± 0.06 | 6619 ± 120 | 189 | 3821 ± 177 | 2798 ± 82 |
| | | | 379 | 2749 ± 185 | 3870 ± 91 |
| | | | 568 | 2085 ± 204 | 4534 ± 107 |
| | | | 758 | 1720 ± 219 | 4899 ± 119 |
| | | | 947 | 1468 ± 227 | 5152 ± 126 |
| | | | 1136 | 1264 ± 227 | 5355 ± 128 |
| Bakersfield, CA | 0.15 ± 0.01 | 9184 ± 154 | 189 | 8392 ± 186 | 791 ± 54 |
| | | | 379 | 8249 ± 201 | 935 ± 70 |
| | | | 568 | 8202 ± 208 | 982 ± 78 |
| | | | 758 | 8185 ± 211 | 999 ± 82 |
| | | | 947 | 8185 ± 211 | 999 ± 82 |
| | | | 1136 | 8185 ± 211 | 999 ± 82 |
| Charlotte, NC | 1.03 ± 0.04 | 6532 ± 95 | 189 | 3745 ± 148 | 2787 ± 78 |
| | | | 379 | 2610 ± 164 | 3922 ± 91 |
| | | | 568 | 1874 ± 168 | 4658 ± 91 |
| | | | 758 | 1449 ± 173 | 5083 ± 95 |
| | | | 947 | 1189 ± 178 | 5343 ± 100 |
| | | | 1136 | 996 ± 176 | 5536 ± 99 |
| Huntsville, AL | 1.26 ± 0.06 | 6655 ± 116 | 189 | 3675 ± 163 | 2980 ± 72 |
| | | | 379 | 2591 ± 172 | 4065 ± 72 |
| | | | 568 | 1867 ± 181 | 4788 ± 76 |
| | | | 758 | 1433 ± 188 | 5222 ± 85 |
| | | | 947 | 1160 ± 189 | 5495 ± 92 |
| | | | 1136 | 960 ± 183 | 5695 ± 95 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jackson, MS | 1.29 | ± | 0.05 | 7027 | ± | 101 | 189 | 4002 | ± | 143 | 3026 | ± | 64 |
| | | | | | | | 379 | 2882 | ± | 153 | 4146 | ± | 67 |
| | | | | | | | 568 | 2136 | ± | 157 | 4891 | ± | 76 |
| | | | | | | | 758 | 1643 | ± | 165 | 5385 | ± | 91 |
| | | | | | | | 947 | 1321 | ± | 163 | 5707 | ± | 95 |
| | | | | | | | 1136 | 1085 | ± | 155 | 5942 | ± | 89 |
| Lancaster, PA | 0.96 | ± | 0.03 | 5739 | ± | 67 | 189 | 2923 | ± | 115 | 2816 | ± | 82 |
| | | | | | | | 379 | 1821 | ± | 111 | 3919 | ± | 80 |
| | | | | | | | 568 | 1091 | ± | 98 | 4648 | ± | 59 |
| | | | | | | | 758 | 673 | ± | 85 | 5067 | ± | 47 |
| | | | | | | | 947 | 438 | ± | 75 | 5301 | ± | 46 |
| | | | | | | | 1136 | 316 | ± | 65 | 5423 | ± | 49 |
| Lufkin, TX | 0.95 | ± | 0.07 | 7656 | ± | 109 | 189 | 5126 | ± | 193 | 2530 | ± | 118 |
| | | | | | | | 379 | 4096 | ± | 222 | 3560 | ± | 146 |
| | | | | | | | 568 | 3458 | ± | 239 | 4198 | ± | 161 |
| | | | | | | | 758 | 3069 | ± | 257 | 4587 | ± | 179 |
| | | | | | | | 947 | 2759 | ± | 272 | 4897 | ± | 194 |
| | | | | | | | 1136 | 2522 | ± | 280 | 5134 | ± | 204 |
| Lynchburg, VA | 0.88 | ± | 0.05 | 5996 | ± | 95 | 189 | 3366 | ± | 132 | 2630 | ± | 89 |
| | | | | | | | 379 | 2333 | ± | 137 | 3662 | ± | 101 |
| | | | | | | | 568 | 1650 | ± | 137 | 4346 | ± | 119 |
| | | | | | | | 758 | 1275 | ± | 139 | 4721 | ± | 134 |
| | | | | | | | 947 | 1044 | ± | 139 | 4952 | ± | 139 |
| | | | | | | | 1136 | 883 | ± | 137 | 5113 | ± | 142 |
| Montgomery, AL | 1.14 | ± | 0.05 | 7133 | ± | 117 | 189 | 4333 | ± | 160 | 2800 | ± | 84 |
| | | | | | | | 379 | 3195 | ± | 167 | 3939 | ± | 93 |
| | | | | | | | 568 | 2420 | ± | 173 | 4713 | ± | 94 |
| | | | | | | | 758 | 1934 | ± | 184 | 5199 | ± | 106 |
| | | | | | | | 947 | 1604 | ± | 187 | 5530 | ± | 111 |
| | | | | | | | 1136 | 1350 | ± | 187 | 5783 | ± | 112 |

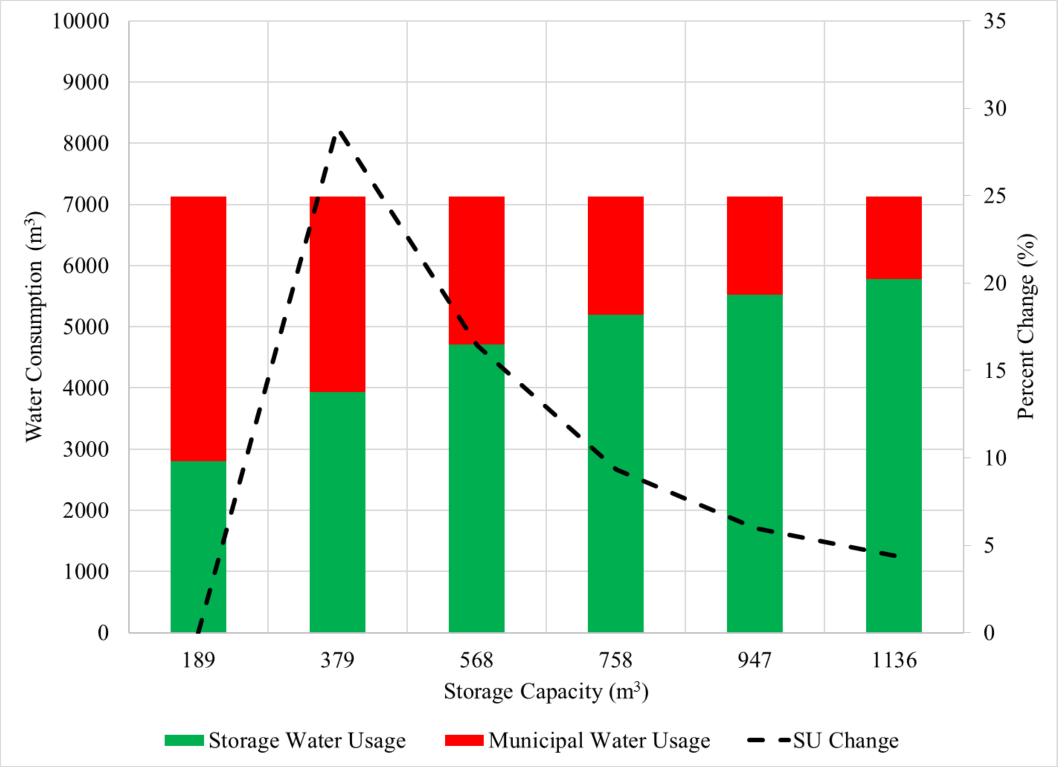

**Figure 14. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Montgomery, AL.**

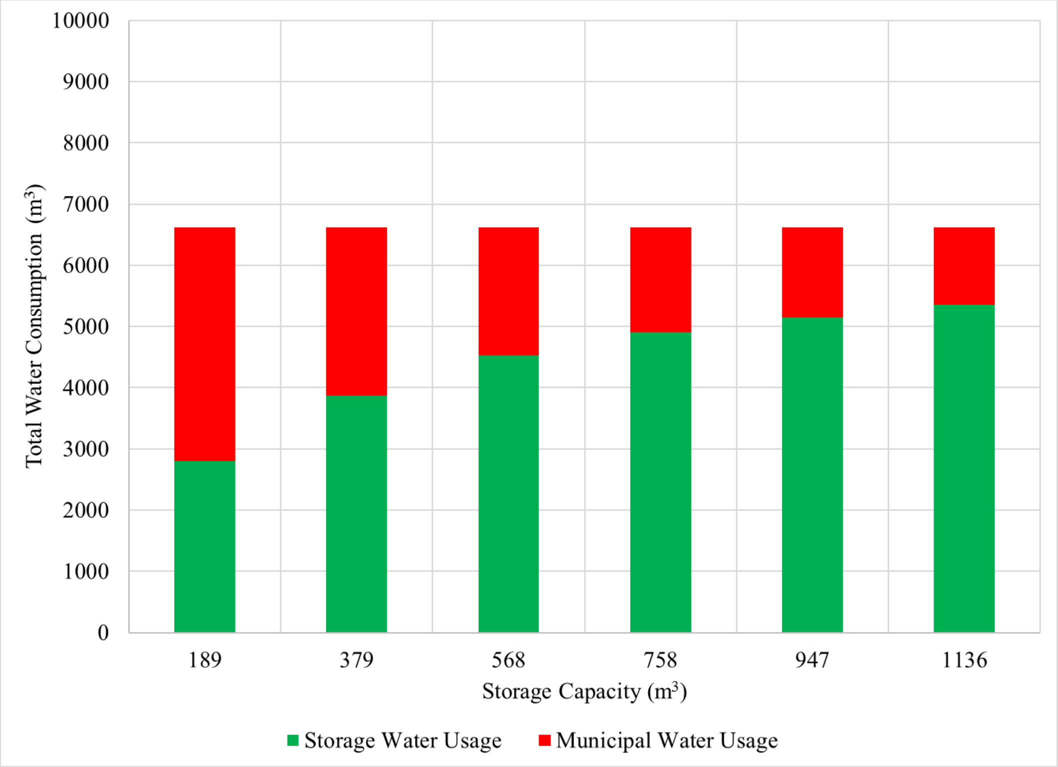

**Figure 15. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Athens, GA.**

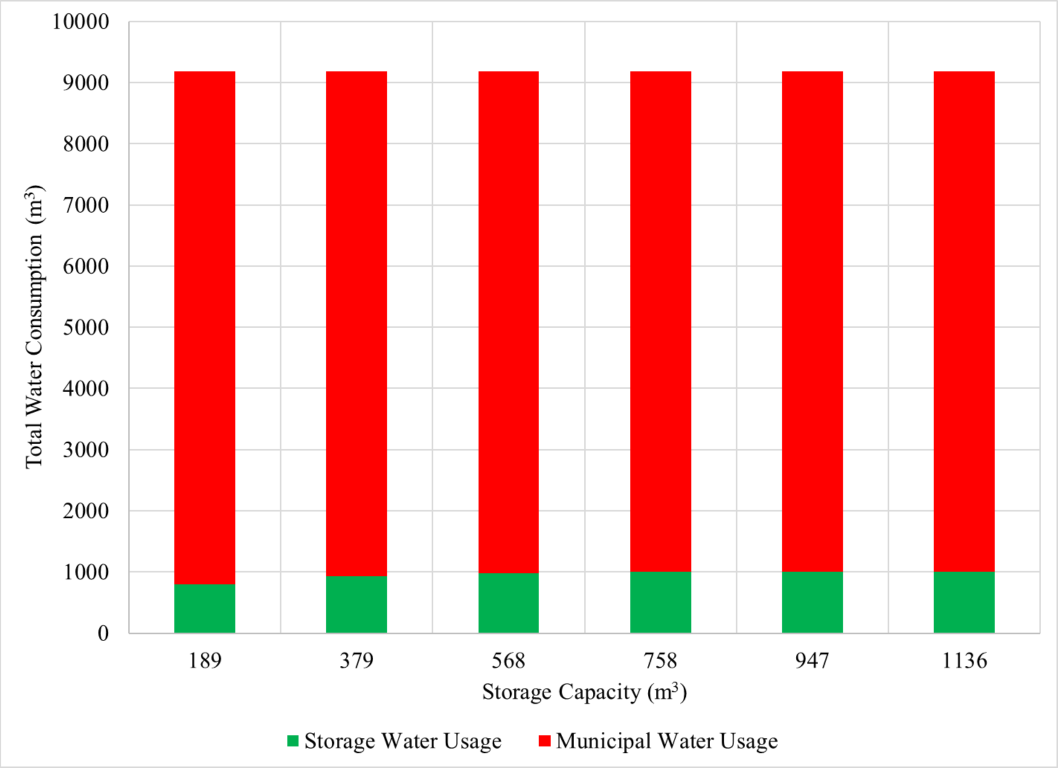

**Figure 16. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Bakersfield, CA.**

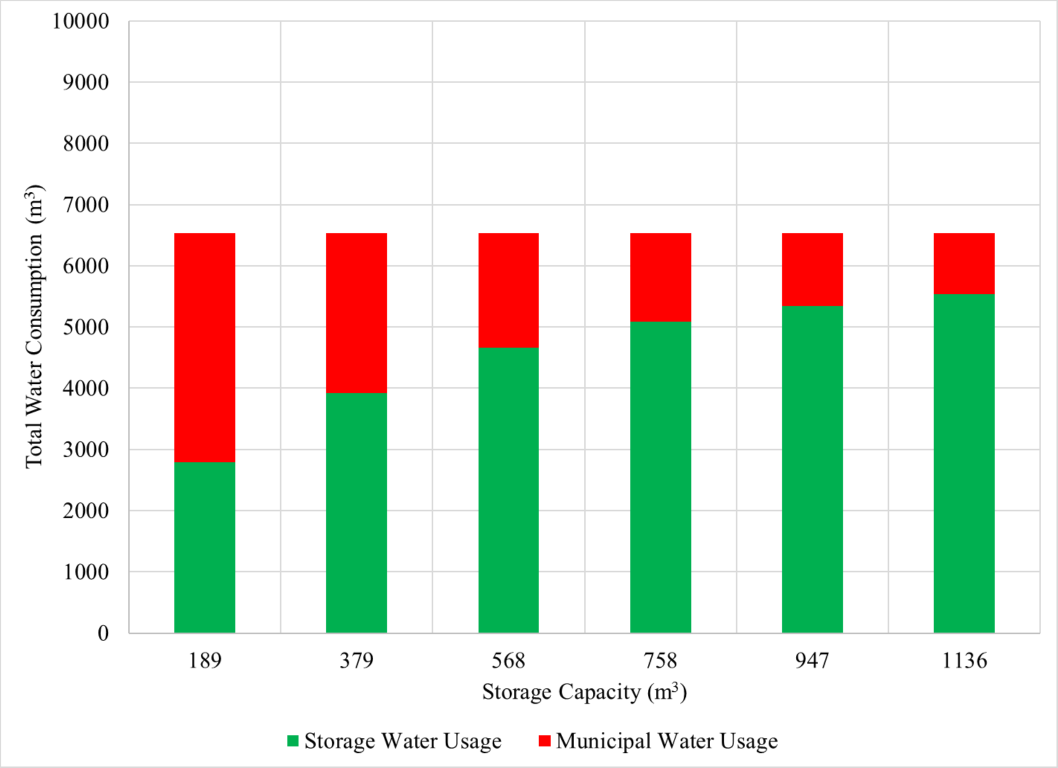

**Figure 17. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Charlotte, NC.**

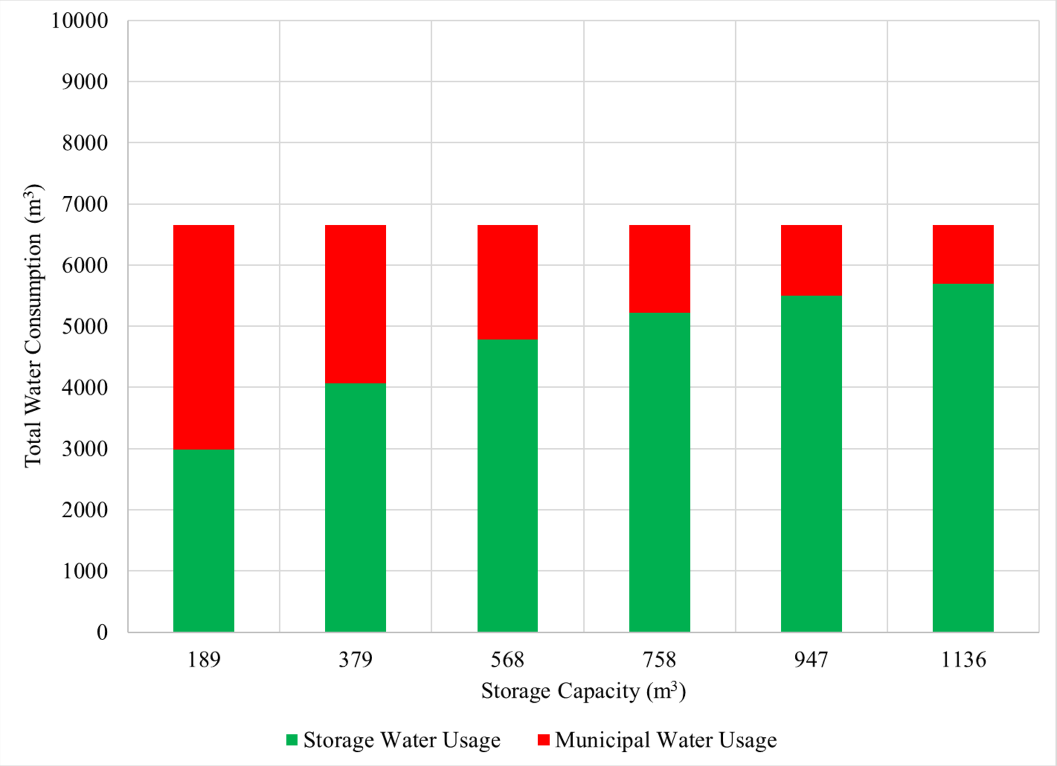

Figure 18. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Huntsville, AL.

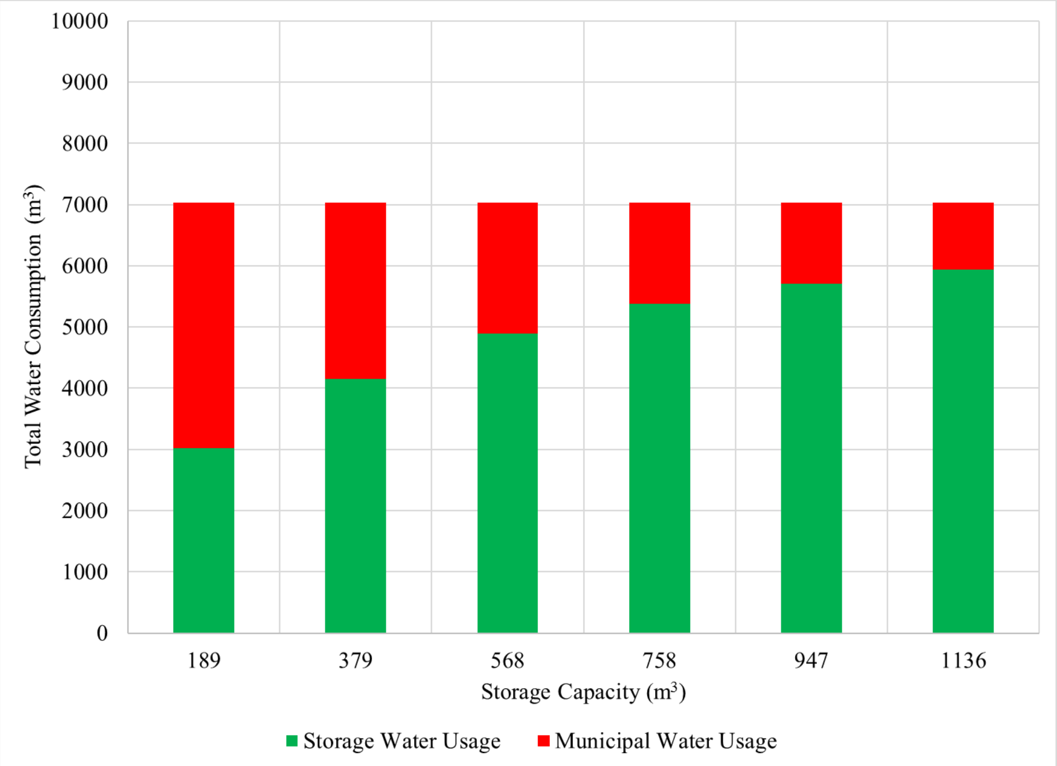

Figure 19. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Jackson, MS.

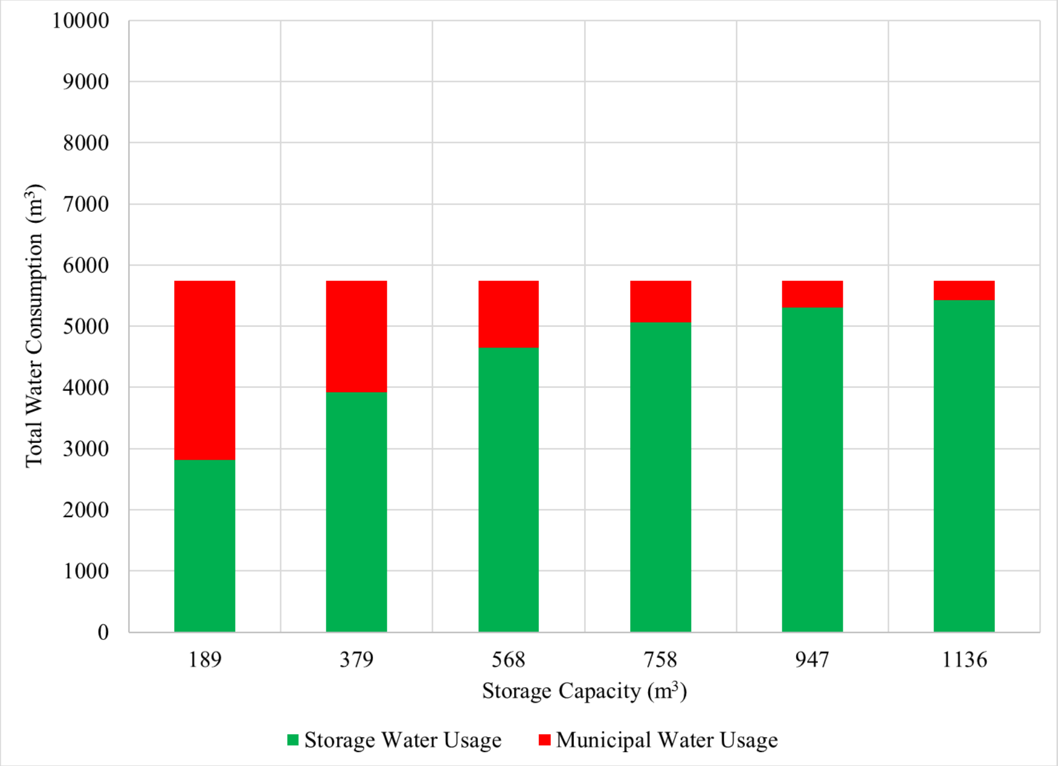

**Figure 20. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Lancaster, PA.**

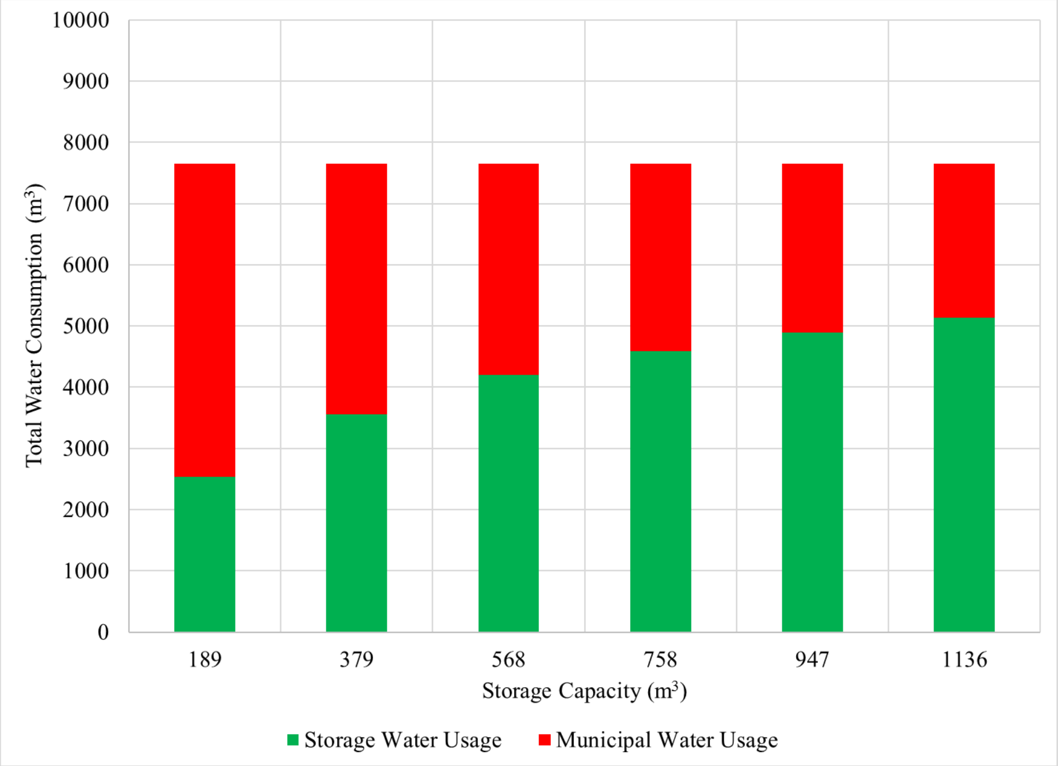

**Figure 21. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Lufkin, TX.**

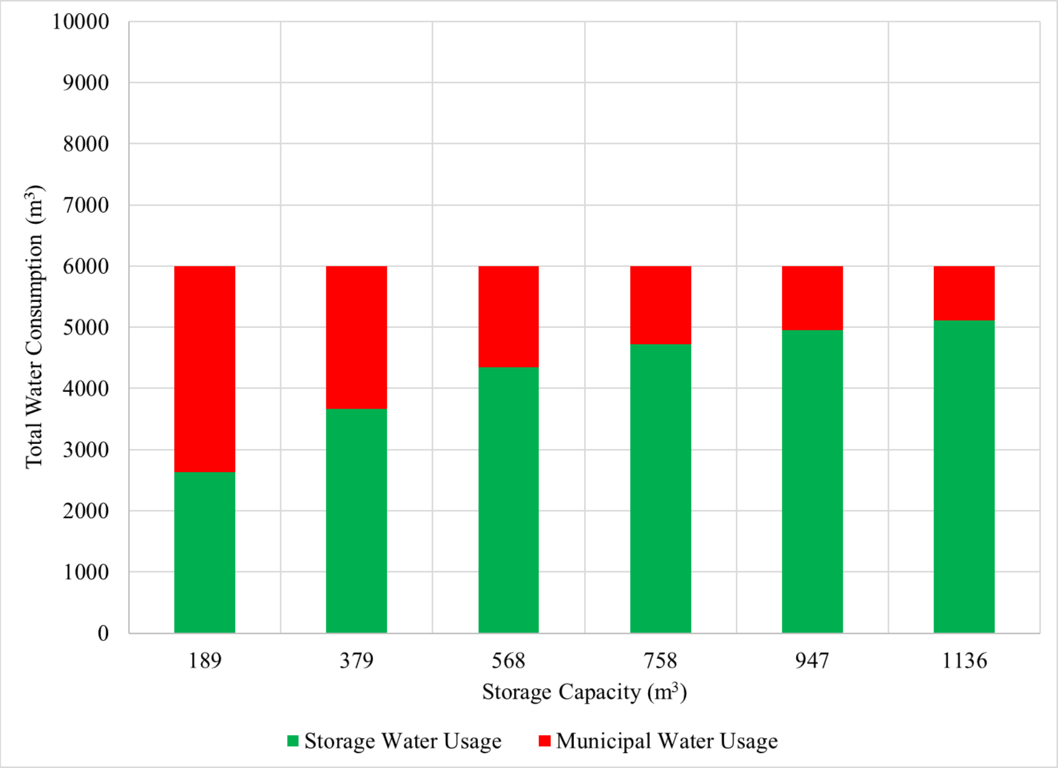

**Figure 22. Total water consumption, split into average annual SU and MU, for varying storage capacities across a 25-year period for Montgomery, AL.**

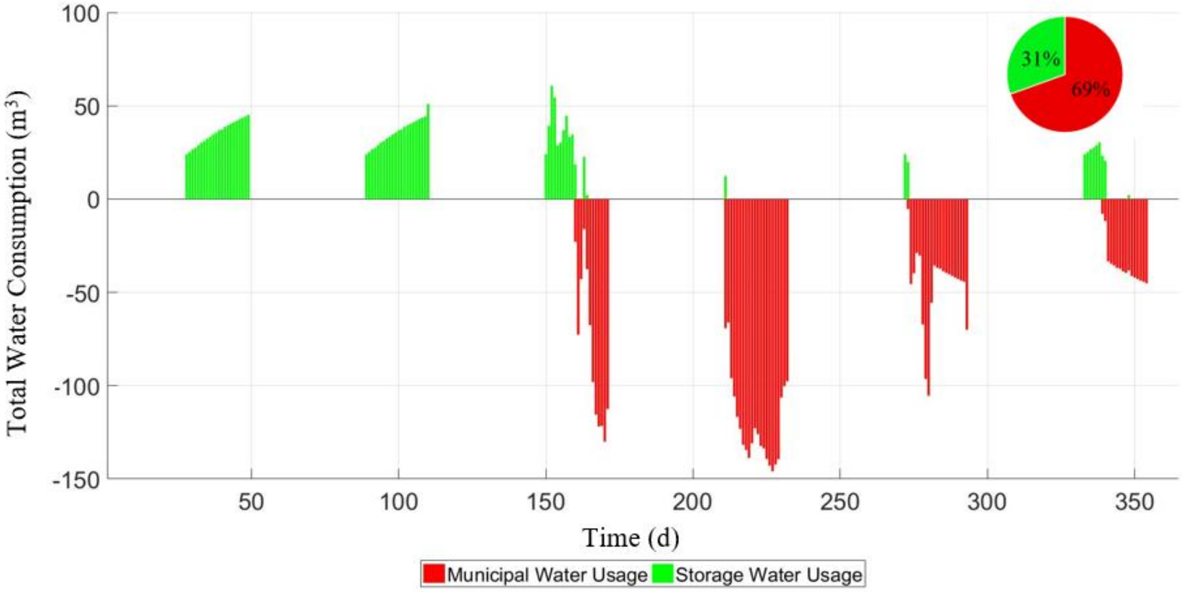

**Figure 23. Total water consumption, split into daily MU and SU, for Bakersfield, CA using a 1,136 m$^3$ storage capacity starting January 1st and ending December 31st in 1998 with total rainfall of 0.33 m.**

**Table 17. Economic analysis for all six locations and storage sizes at varying water costs.**

| Location | Rainfall (m) | Storage Capacity ($m^3$) | Municipal Water Cost ($ $m^{-3}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $0.79 | $1.06 | $1.32 | $1.58 | $1.85 | $2.11 | $2.38 | $2.64 | $2.90 | $3.17 |
| Athens, GA | 1.03 ± 0.06 | 189 | -$63,789 | -$44,581 | -$25,374 | -$6,167 | $13,041 | $32,248 | $51,455 | $70,663 | $89,870 | $109,077 |
| | | 379 | -$82,194 | -$55,631 | -$29,069 | -$2,507 | $24,056 | $50,618 | $77,181 | $103,743 | $130,305 | $156,868 |
| | | 568 | -$108,987 | -$77,866 | -$46,745 | -$15,624 | $15,498 | $46,619 | $77,740 | $108,861 | $139,983 | $171,104 |
| | | 758 | -$141,937 | -$108,309 | -$74,680 | -$41,052 | -$7,424 | $26,204 | $59,832 | $93,460 | $127,088 | $160,717 |
| | | 947 | -$177,210 | -$141,850 | -$106,490 | -$71,129 | -$35,769 | -$409 | $34,952 | $70,312 | $105,672 | $141,033 |
| | | 1136 | -$213,487 | -$176,729 | -$139,970 | -$103,212 | -$66,454 | -$29,696 | $7,062 | $43,821 | $80,579 | $117,337 |
| Bakersfield, CA | 0.15 ± 0.01 | 189 | -$105,115 | -$99,683 | -$94,251 | -$88,819 | -$83,387 | -$77,955 | -$72,523 | -$67,092 | -$61,660 | -$56,228 |
| | | 379 | -$142,637 | -$136,223 | -$129,808 | -$123,394 | -$116,979 | -$110,565 | -$104,150 | -$97,736 | -$91,321 | -$84,907 |
| | | 568 | -$182,135 | -$175,396 | -$168,657 | -$161,919 | -$155,180 | -$148,441 | -$141,703 | -$134,964 | -$128,225 | -$121,487 |
| | | 758 | -$222,246 | -$215,388 | -$208,530 | -$201,671 | -$194,813 | -$187,955 | -$181,097 | -$174,238 | -$167,380 | -$160,522 |
| | | 947 | -$262,716 | -$255,858 | -$249,000 | -$242,142 | -$235,283 | -$228,425 | -$221,567 | -$214,709 | -$207,850 | -$200,992 |
| | | 1136 | -$303,187 | -$296,328 | -$289,470 | -$282,612 | -$275,754 | -$268,895 | -$262,037 | -$255,179 | -$248,320 | -$241,462 |
| Charlotte, NC | 1.03 ± 0.04 | 189 | -$64,029 | -$44,901 | -$25,774 | -$6,647 | $12,480 | $31,608 | $50,735 | $69,862 | $88,989 | $108,117 |
| | | 379 | -$81,123 | -$54,204 | -$27,284 | -$365 | $26,554 | $53,473 | $80,392 | $107,312 | $134,231 | $161,150 |
| | | 568 | -$106,435 | -$74,463 | -$42,491 | -$10,519 | $21,453 | $53,425 | $85,397 | $117,369 | $149,341 | $181,313 |
| | | 758 | -$138,152 | -$103,262 | -$68,372 | -$33,482 | $1,407 | $36,297 | $71,187 | $106,077 | $140,966 | $175,856 |
| | | 947 | -$173,268 | -$136,594 | -$99,920 | -$63,245 | -$26,571 | $10,104 | $46,778 | $83,452 | $120,127 | $156,801 |
| | | 1136 | -$209,765 | -$171,767 | -$133,768 | -$95,769 | -$57,771 | -$19,772 | $18,226 | $56,225 | $94,224 | $132,222 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Huntsville, AL | 1.26 | ± | 0.06 | 189 | -$60,040 | -$39,583 | -$19,126 | $1,331 | $21,788 | $42,245 | $62,702 | $83,159 | $103,616 | $124,073 |
| | | | | 379 | -$78,183 | -$50,284 | -$22,384 | $5,515 | $33,414 | $61,314 | $89,213 | $117,112 | $145,011 | $172,911 |
| | | | | 568 | -$103,759 | -$70,895 | -$38,031 | -$5,167 | $27,697 | $60,561 | $93,425 | $126,289 | $159,153 | $192,017 |
| | | | | 758 | -$135,294 | -$99,452 | -$63,610 | -$27,767 | $8,075 | $43,917 | $79,759 | $115,602 | $151,444 | $187,286 |
| | | | | 947 | -$170,136 | -$132,417 | -$94,699 | -$56,980 | -$19,262 | $18,457 | $56,175 | $93,894 | $131,612 | $169,331 |
| | | | | 1136 | -$206,492 | -$167,402 | -$128,312 | -$89,223 | -$50,133 | -$11,043 | $28,047 | $67,137 | $106,226 | $145,316 |
| Jackson, MS | 1.29 | ± | 0.05 | 189 | -$59,105 | -$38,336 | -$17,567 | $3,201 | $23,970 | $44,739 | $65,507 | $86,276 | $107,045 | $127,813 |
| | | | | 379 | -$76,515 | -$48,060 | -$19,604 | $8,851 | $37,306 | $65,761 | $94,217 | $122,672 | $151,127 | $179,582 |
| | | | | 568 | -$101,627 | -$68,053 | -$34,478 | -$904 | $32,671 | $66,245 | $99,820 | $133,394 | $166,969 | $200,543 |
| | | | | 758 | -$131,939 | -$94,979 | -$58,018 | -$21,058 | $15,903 | $52,863 | $89,824 | $126,784 | $163,745 | $200,706 |
| | | | | 947 | -$165,777 | -$126,605 | -$87,434 | -$48,262 | -$9,091 | $30,080 | $69,252 | $108,423 | $147,595 | $186,766 |
| | | | | 1136 | -$201,398 | -$160,610 | -$119,822 | -$79,035 | -$38,247 | $2,541 | $43,329 | $84,116 | $124,904 | $165,692 |
| Lancaster, PA | 0.96 | ± | 0.03 | 189 | -$63,423 | -$44,093 | -$24,764 | -$5,435 | $13,895 | $33,224 | $52,553 | $71,883 | $91,212 | $110,541 |
| | | | | 379 | -$81,186 | -$54,287 | -$27,389 | -$491 | $26,407 | $53,306 | $80,204 | $107,102 | $134,001 | $160,899 |
| | | | | 568 | -$106,638 | -$74,733 | -$42,829 | -$10,925 | $20,980 | $52,884 | $84,788 | $116,693 | $148,597 | $180,501 |
| | | | | 758 | -$138,485 | -$103,706 | -$68,927 | -$34,149 | $630 | $35,409 | $70,188 | $104,966 | $139,745 | $174,524 |
| | | | | 947 | -$174,133 | -$137,747 | -$101,361 | -$64,974 | -$28,588 | $7,798 | $44,184 | $80,570 | $116,956 | $153,342 |
| | | | | 1136 | -$212,088 | -$174,864 | -$137,639 | -$100,415 | -$63,191 | -$25,966 | $11,258 | $48,482 | $85,707 | $122,931 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lufkin, TX | 0.95 | ± | 0.07 | 189 | -$69,315 | -$51,950 | -$34,585 | -$17,220 | $145 | $17,510 | $34,876 | $52,241 | $69,606 | $86,971 |
|  |  |  |  | 379 | -$88,563 | -$64,124 | -$39,685 | -$15,246 | $9,193 | $33,632 | $58,071 | $82,511 | $106,950 | $131,389 |
|  |  |  |  | 568 | -$115,906 | -$87,090 | -$58,275 | -$29,460 | -$645 | $28,170 | $56,985 | $85,800 | $114,615 | $143,431 |
|  |  |  |  | 758 | -$148,364 | -$116,878 | -$85,392 | -$53,906 | -$22,420 | $9,065 | $40,551 | $72,037 | $103,523 | $135,009 |
|  |  |  |  | 947 | -$182,449 | -$148,835 | -$115,221 | -$81,607 | -$47,993 | -$14,379 | $19,235 | $52,849 | $86,464 | $120,078 |
|  |  |  |  | 1136 | -$218,042 | -$182,802 | -$147,563 | -$112,323 | -$77,083 | -$41,843 | -$6,604 | $28,636 | $63,876 | $99,116 |
| Lynchburg, VA | 0.88 | ± | 0.05 | 189 | -$67,251 | -$49,198 | -$31,145 | -$13,092 | $4,961 | $23,014 | $41,067 | $59,120 | $77,173 | $95,226 |
|  |  |  |  | 379 | -$86,463 | -$61,324 | -$36,185 | -$11,046 | $14,093 | $39,232 | $64,371 | $89,510 | $114,649 | $139,788 |
|  |  |  |  | 568 | -$112,858 | -$83,027 | -$53,196 | -$23,365 | $6,466 | $36,297 | $66,128 | $95,959 | $125,790 | $155,621 |
|  |  |  |  | 758 | -$145,617 | -$113,215 | -$80,813 | -$48,412 | -$16,010 | $16,391 | $48,793 | $81,194 | $113,596 | $145,997 |
|  |  |  |  | 947 | -$181,325 | -$147,336 | -$113,347 | -$79,359 | -$45,370 | -$11,381 | $22,608 | $56,596 | $90,585 | $124,574 |
|  |  |  |  | 1136 | -$218,475 | -$183,380 | -$148,284 | -$113,189 | -$78,094 | -$42,998 | -$7,903 | $27,193 | $62,288 | $97,383 |
| Montgomery, AL | 1.14 | ± | 0.05 | 189 | -$63,750 | -$44,530 | -$25,310 | -$6,090 | $13,130 | $32,350 | $51,570 | $70,790 | $90,010 | $109,230 |
|  |  |  |  | 379 | -$80,777 | -$53,743 | -$26,708 | $326 | $27,361 | $54,395 | $81,430 | $108,464 | $135,499 | $162,533 |
|  |  |  |  | 568 | -$105,291 | -$72,938 | -$40,585 | -$8,231 | $24,122 | $56,475 | $88,828 | $121,182 | $153,535 | $185,888 |
|  |  |  |  | 758 | -$135,761 | -$100,074 | -$64,388 | -$28,701 | $6,986 | $42,673 | $78,359 | $114,046 | $149,733 | $185,419 |
|  |  |  |  | 947 | -$169,427 | -$131,473 | -$93,518 | -$55,563 | -$17,608 | $20,346 | $58,301 | $96,256 | $134,210 | $172,165 |
|  |  |  |  | 1136 | -$204,670 | -$164,972 | -$125,275 | -$85,578 | -$45,880 | -$6,183 | $33,514 | $73,212 | $112,909 | $152,606 |

Red = no savings
Light green = transitional savings (less than $2,000 per year)
Green = some savings (more than $2,000 per year)
Dark green = maximum savings

### 3.4 Conclusions

A RWH model was used to investigate various storage capacities for nine locations representing poultry producing areas across the U.S. Farm characteristics were used from a poultry farm currently operating a RWH system. For each location, MU and SU were estimated over a 25-year period. The largest offset of MU for each location occurred when increasing from 189 $m^3$ to 379 $m^3$. As the amount of storage capacity increased, the reduction in MU decreased. This suggests there was an optimal storage capacity for each location and was dependent on the amount of rainfall for the specific location.

A simple economic analysis was performed to estimate the savings for the 25-year period for varying municipal water costs. Most locations achieved a maximum savings for the 25-year period for storage capacities of 568 $m^3$ with maximum savings at water costs between $2.38 and $3.17. The model also showed that areas with low amounts of rainfall such as Bakersfield, CA would not benefit from installing a RWH system.

Further research is needed to identify whether a relationship can be established between average annual rainfall and the optimal storage size for a particular location taking into account the frequency of rainfall events. Excluding Bakersfield, CA, the locations evaluated in this study had close to 1 m of average annual rainfall and generally experienced maximum savings at water costs greater than $2.38 using a storage capacity of 568 $m^3$. A wider selection of locations should be made with locations experiencing average annual rainfall values above 1.3 m and below 0.8 m to determine whether a relationship between average annual rainfall and storage capacity exists.

### 3.5 References

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# Chapter 4: Research Summary

Water is a crucial component of poultry production and many poultry farms across the U.S. in high precipitation areas have the potential to benefit from installing a RWH system. Many farms using well water or city water can experience maintenance and water quality issues which can effect production. In some areas, farmers are experiencing increasing water costs which can reduce their profitability. Installing a RWH system could provide a reliable water source and offset rising municipal water costs.

The RWH model developed in this paper was calibrated and evaluated using actual farm data from two separate commercial farm studies. Bird water consumption was overestimated by 15% and evaporative cooling water consumption was overestimated by 453 $m^3$ with a mean daily value of 8 $m^3$ compared to a farm mean daily value of 3.6 $m^3$. The model correctly simluted 91% of the days farm evaporative cooling was used and correctly simulated 93% of the days farm evaporative cooling was not used. Evalutaing the entire model using four years of total water consumption data from a separate farm study, results showed the model was within 18.21% of actual farm total water consumption values.

The model was then used to evaluate the performance of six storage capacities from 189 $m^3$ to 1,136 $m^3$ in increments of 189 $m^3$ in nine locations across the U.S. A simple economic analysis was performed to estimate the savings for municipal water costs between \$0.79 to \$3.17 in increments of \$0.26 $m^{-3}$. The largest reduction in municipal water usage for all locations was seen by increasing storage capacity from 189 $m^3$ to 379 $m^3$. All locations experienced no savings at water costs below \$1.32. Most systems experienced maximum savings between \$2.38 and

$3.17 at a storage capacity of 568 m$^3$. Areas with low annual rainfall saw no benefit in installing a RWH system.

To provide the best decision tool for farmers to evaluate the benefits of installing a RWH system in their particular location, further research is needed to better estimate the main water consumption sources on a poultry farm, in particular, evaporative cooling water consumption. Further data collection from various commercial farms across the U.S. is needed in order to evaluate the entire model for various locations. These loactions should be chosen to represent a range of average annual rainfall values and rainfall frequencies to investigate potential relationships between varying storage capacities.

# Appendix A: As-hatched industry performance data for Ross 708, Ross308, and Cobb500 genetic strain broilers

| Genetic Strain | Ross 708[a] | Ross 308[b] | Cobb 500[c] |
|---|---|---|---|
| Bird Age (d) | | Daily feed intake (g) | |
| 1 | 12 | 13 | 13 |
| 2 | 15 | 17 | 17 |
| 3 | 18 | 20 | 21 |
| 4 | 22 | 23 | 23 |
| 5 | 25 | 27 | 27 |
| 6 | 28 | 31 | 31 |
| 7 | 32 | 35 | 35 |
| 8 | 36 | 39 | 39 |
| 9 | 40 | 43 | 44 |
| 10 | 44 | 48 | 48 |
| 11 | 49 | 53 | 54 |
| 12 | 53 | 58 | 58 |
| 13 | 58 | 63 | 64 |
| 14 | 63 | 69 | 68 |
| 15 | 69 | 74 | 75 |
| 16 | 74 | 80 | 81 |
| 17 | 80 | 86 | 87 |
| 18 | 85 | 92 | 93 |
| 19 | 91 | 98 | 98 |
| 20 | 97 | 104 | 105 |
| 21 | 102 | 110 | 111 |
| 22 | 108 | 116 | 117 |
| 23 | 114 | 122 | 123 |
| 24 | 120 | 128 | 130 |
| 25 | 125 | 134 | 134 |
| 26 | 131 | 140 | 141 |
| 27 | 136 | 145 | 148 |
| 28 | 142 | 151 | 152 |
| 29 | 147 | 157 | 158 |
| 30 | 153 | 162 | 163 |
| 31 | 158 | 167 | 169 |

| | | | |
|---|---|---|---|
| 32 | 163 | 172 | 174 |
| 33 | 168 | 177 | 180 |
| 34 | 172 | 182 | 182 |
| 35 | 177 | 186 | 189 |
| 36 | 181 | 191 | 193 |
| 37 | 186 | 195 | 197 |
| 38 | 190 | 199 | 201 |
| 39 | 194 | 203 | 205 |
| 40 | 197 | 207 | 209 |
| 41 | 201 | 210 | 213 |
| 42 | 205 | 214 | 216 |
| 43 | 208 | 217 | 220 |
| 44 | 211 | 220 | 222 |
| 45 | 214 | 223 | 225 |
| 46 | 217 | 226 | 227 |
| 47 | 220 | 228 | 231 |
| 48 | 222 | 230 | 233 |
| 49 | 224 | 233 | 235 |
| 50 | 227 | 235 | 237 |
| 51 | 229 | 236 | 239 |
| 52 | 230 | 238 | 240 |
| 53 | 232 | 239 | 242 |
| 54 | 233 | 241 | 243 |
| 55 | 235 | 242 | 245 |
| 56 | 236 | 243 | 245 |
| 57 | 237 | 243 | 245 |
| 58 | 237 | 244 | 245 |
| 59 | 238 | 244 | 245 |
| 60 | 238 | 244 | 245 |
| 61 | 238 | 244 | 245 |
| 62 | 238 | 244 | 245 |
| 63 | 238 | 243 | 245 |
| 64 | 238 | 243 | - |
| 65 | 237 | 242 | - |
| 66 | 236 | 241 | - |
| 67 | 235 | 239 | - |
| 68 | 234 | 238 | - |
| 69 | 232 | 236 | - |
| 70 | 230 | 234 | - |

[a] adapted from industry performance data tables, (Cobb, 2015)

[b] adapted from industry performance data tables, (Aviagen, 2014)

[c] adapted from industry performance data tables, (Aviagen, 2014)