Evaluation of water needs for modern commercial broiler farms and model development to estimate on-farm water needs

by

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Abstract

With global populations expected to rise, appropriation of clean water supplies for human consumption pose capacity challenges for agricultural sectors. Broiler (meat-type) chicken production consumes large amounts of water and ensuring water needs are met during a flock are crucial, particularly for farms raising large broilers in hot weather. Water needs have been commonly overlooked in the industry resulting in references to the quantity of water growers need to supply during production should be “adequate”, “sufficient”, or “plenty”. In recent years there has been increased interest by broiler industry stakeholders to better understand water consumption needs for farms. Past consumption estimates do not reflect current broiler genetic strains or housing systems therefore three studies were conducted to 1) estimate broiler drinking water consumption (BWC) needs and water-feed-ratio (WFR) for broilers grown to 63 days raised under commercially relevant conditions for three seasonal periods; winter, summer, and spring 2) develop a water consumption model to estimate BWC and evaporative cooling system water consumption (EWC) based on a farm’s characteristics and geographic location 3) estimate annual total water consumption (TWC) needs for 14 locations across the U.S. broiler belt based on 27 farm configurations.

Pen trials were conducted in a tunnel ventilated research house at the USDA Poultry Research Unit in Starkville, MS to establish BWC and WFR values for broilers finished at 63 days in study 1. Due to interruptions by the COVID-19 pandemic, only winter and summer flocks have been completed. Both flocks were raised under commercially relevant conditions following current environmental management recommendations and flock husbandry practices. Results suggest broilers grown during winter consumed 15,714 L per 1,000 birds during the 63 day growth period. Mean flock WFR was 1.82 kg water per kg feed, lower than the industry rule of thumb WFR of 2

kg water per kg feed. Summer flock consumption was 13,619 L per 1,000 birds however results were not typical likely due to a chick quality issue and high mortality.

A model was developed in MATLAB for study 2 to estimate the two main water consumption usages on a broiler farm; broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC). Governing equations were developed to estimate daily BWC and EWC values to determine an annual total water consumption (TWC) given farm inputs (e.g. house size, geographic location, broiler growth period). Estimates for BWC were based on WFR results from study 1 and primary breeder feed consumption data. Estimates for EWC were determined by calculating peak evaporative cooling (EC) system evaporation rates using outside weather conditions and psychrometric equations. EC operation boundary conditions were incorporated into the model to mimic farm EC operation. Model estimates were made for a farm in east Alabama growing a 63 day old broiler in a 13.1 x 155.5 m house. Actual farm BWC and EWC were compared to model outputs to determine the ability of the model to estimate farm water consumption. Model estimates for daily BWC overestimated consumption by 7% compared to actual farm data. Estimates for EWC were considerably higher compared to actual farm data, overestimating consumption by 140%. It should be noted the model estimates peak EWC and assumed model EC operating condition may have differed to actual EC operating. The model correctly predicted farm EC operation for 77% of the observed events over the study period.

In study 3, the model was used to estimate mean TWC for 14 locations representing high concentrations of U.S. domestic broiler production over a 30-yr period. Consumption estimates were made for a set of 27 farm configurations based on broiler age, house size, and house wind speed. The range of annual TWC for the 14 locations was approximately 1.22 to 5.73 million L per house. Variability in TWC between location was driven by EWC estimates based on local weather conditions.

As discussions within the industry become more frequent regarding farm water demand, there is a need for relevant water consumption data for today's commercial broiler farms. Both industry and the research community should update and maintain water consumption needs to provide growers and industry stake holders a better understanding of water demands.

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List of Abbreviations

BWC	broiler drinking water consumption
d	days
EC	evaporative cooling
EWC	evaporative cooling system water consumption
FC	feed consumption
ISD	Integrated Surface Dataset
NCC	National Chicken Council
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
NPTC	National Poultry Technology Center
NRC	National Research Council
TWC	total water consumption
USDA	United States Department of Agriculture
WFR	water-to-feed ratio

Chapter 1

Introduction

Today's modern commercial broiler consumes significantly more water and feed then broilers in the past. While live production research has kept pace in areas of feed diet development and establishing optimal environmental growing conditions, water needs have largely been overlooked. Water is considered an essential nutrient for broilers and annual water consumption during grow-out can be in the millions of liters per house depending on farm configuration. Broiler production in the U.S. is concentrated in an area known as the "broiler belt", spanning from Texas, through the southeast, and up the east coast to the Delmarva peninsula. Depending on the finishing age of the broiler (five to nine weeks) and geographic location, farm water needs can vary. However, water consumption research is limited in the understanding of water needs on today's commercial farms. Reported values within the literature primarily focus on one of two main water consumptions during production, broiler drinking water consumption (BWC) or evaporative cooling system water consumption (EWC). These estimates largely do not reflect consumption needs for current broiler genetics or housing systems. Discussions have become more frequent regarding farm water demand and water district capacities therefore the following outlines the research objectives of three studies aimed at providing a better understanding a broiler farm water demand.

Study 1. Determine daily broiler drinking water consumption (BWC) needs and water-to-feed ratios (WFR) for broilers grown to nine weeks using commercially relevant management practices during three seasonal periods; winter, summer, and spring.

Study 2. Develop a model to estimate daily BWC and evaporative cooling system water consumption (EWC) given a farm's size and geographic location.

Study 3. Estimate on-farm annual total water consumption (TWC) requirements over a 30-year period for 14 locations across poultry producing areas of the U.S. based on common housing configurations and broiler target weights.

Pen trials were conducted at the USDA Poultry Research Unit in Starkville, MS for study 1. Daily water and feed consumption was monitored for broilers grown to 63 days under commercial conditions. A model was then developed in study 2 to estimate daily BWC and EWC. WFR results from study 1 were used to estimate daily model BWC. Daily EWC was estimated based on calculating evaporation rates were based on psychrometric equations and ambient weather conditions. Model estimates were compared to actual farm data in east Alabama to establish the ability for the model to estimate BWC and EWC. The model was then used in study 3 to estimate TWC over a 30-year period for 14 locations across the U.S. to establish annual mean TWC for those locations.

Chapter 2

Water consumption trends for modern commercial broilers

2.1 Introduction

Water is an essential nutrient for broilers (NRC, 1994; Coon, 2002) and plays a critical role in metabolic function and body temperature maintenance. Numerous studies have been conducted to investigate factors that affect broiler bird water consumption (BWC) during the grow-out process. Increased levels of dietary protein (Patrick and Ferrise, 1962; Marks and Pesti, 1984; Alleman and Leclercq, 1997) and dietary salt (Marks, 1987) have been shown to increase water consumption. High environmental temperatures above a broiler's thermoneutral zone can significantly increase water consumption and decrease performance (Donkoh, 1989; May and Lott, 1992; North and Bell, 1990; Belay and Teeter, 1993; Alleman and Leclercq, 1997). Marks (1980) reported commercial broilers selected for fast-growth consumed significantly more water per day than broilers from a nonselected line thereby suggesting broiler genetics plays a role in water consumption. May et al. (2000) compared the effects of low (less than 15 m min^{-1}) and high (120 m min^{-1}) wind speeds for birds exposed to constant (27°C) and daily cyclic temperature (22-32-22°C) regimens. Water consumption decreased for both temperature regimens at the higher wind speed. At 120 m min^{-1} wind speed and constant temperature exposure, water consumption was significantly less by 33 to 35 days with the reduction in water consumption becoming more pronounced as bird age increased. Feddes et al. (2002) monitored water intake for broilers at four stocking densities (23.8, 17.9, 14.3, and 11.9 birds m^{-2}) and found water consumption per bird increased with increasing stocking density. There was significantly more water consumption per bird at 23.8 birds m^{-2} (5,546 mL per bird) compared to 11.9 birds m^{-2} (5,093 mL per bird). While the increase in water consumption at the higher stocking density was not fully discussed, increased heat output at the greater stocking density likely caused an increase in the bird's core temperature, resulting in increased water consumption. May et al. (1997) and Bruno et al. (2011) reported significantly higher water intake for broilers grown using bell drinkers than broilers grown using nipple drinkers. Bruno et al. (2011) also reported total water intake significantly increased with bird age. Given data from these trials and others, poultry integrators have selectively bred broilers for fast growth, formulated diets for improved growth performance, and required contract growers to follow specific environmental management practices to achieve optimal broiler performance. With regards to water, needs have being commonly ignored (Bell, 2002) and water requirements for commercial broilers have not been maintained to reflect today's broiler genetics and housing systems.

Nevertheless, daily BWC is monitored during the grow-out process and used as an indicator of flock performance (Bell, 2002; Fairchild and Ritz, 2015) and broiler welfare (Butcher et al., 1999; Manning et al., 2007a). Daily BWC is also used to estimate medication dosages during disease outbreaks (Stahl and Sunde, 1983). Bird water and feed consumption have been shown to be closely related resulting in a water-to-feed ratio (WFR) being used to estimate daily feed consumption (Czarick et al., 2001; Tabler et al., 2018). However, updated and relevant water consumption data is lacking for current broiler genetics grown to market weights of approximately 4.1 kg at nine weeks under commercial management practices.

References to water consumption requirements outlined by the National Research Council (NRC) (1994) are common in the literature, where the NRC compiled water consumption data from multiple studies conducted during the 1980s. The NRC reported for every 1°C increase above 21°C, broiler water intake increased by seven percent. Water consumption data compiled from these studies is presented by the NRC with the caveat consumption values varied depending on ambient temperature, diet, growth rate, and equipment used to conduct each study. It was noted water intake values reported apply under moderate ambient temperatures (20°C to 25°C). Reviewing the five studies referenced by the NRC shows deviations from current management practices and provides little understanding of broilers grown to nine weeks. Three of the five studies finished broilers at five to six weeks (Ross and Hurnik, 1983; Pesti et al., 1985; Miller et al., 1988) using varying diet compositions between trials and studies. Ross and Hurnik (1983) specifically noted water intake results may have been affected because 24-hr lighting at 300 lux was used for video recording to study broiler drinking behavior, representing a deviation from normal management practices. Current lighting programs suggest intensities ranging from 5 to 30 lux with periods of light and dark depending on bird age (Donald et al., 2000; Olanrewaju et al., 2006). Pesti et al. (1985) presented data for 24 broiler flocks grown from 1981 to 1983 in two commercial style houses (curtained-sided and enclosed power ventilated). It was suggested water consumption increased linearly and could be estimated by multiplying 5.28 g by the age of the broiler for broilers grown up to six weeks. Birds grown during the test period (1981 to 1983) were on performance tests therefore diet compositions varied and corrections were not made for spillage and evaporative losses for trough-type waterers used. Miller et al. (1988) observed the effects of cyclic watering (waterers were activated periodically then shut off) on performance compared to a control group provided water *ad libitum*. It should be noted cyclic watering is not a practice used in commercial broiler production where broilers are provided water *ad libitum*. The control group consumed significantly more water and feed compared to the cyclic groups however it was not clear if the NRC incorporated water intake from the cyclic groups.

Marks (1981) compared the role water plays on regulating feed intake and feed efficiency for broilers selected for fast-growth at varying levels of feed and water restriction compared to broilers of a non-selected line. Of the three trials conducted, only trials one and two consistently reported weekly mean water consumption values for the four-week test period. However, diet information and management programs were not clearly stated. While trial three did grow broilers to approximately seven weeks, only the last 12 days of water consumption were recorded providing no understanding of water intake for the first 36 days. Only Gardiner and Hunt (1984) grew broilers to nine weeks, however management practices differed from practices currently used in commercial production. Temperatures under the brooder were held at 21°C for the first seven days. Considerably lower than current recommendations of 30 to 32°C for brooding chicks (Cobb, 2017; Aviagen, 2018). It was also stated room temperature was relatively constant, however reported table values for weekly room temperature ranges show swings between 4 and 14°C.

It was unclear how water consumption data from these studies was summarized by the NRC given the variations in ambient temperature, diet, growth rate, and equipment used to conduct these studies. Feed consumption data was recorded for most of the studies allowing for the calculation of WFRs ranging from averages of 1.62 to 2.06 kg of water per kg of feed (table 2.1). Regardless, the general assumption throughout the broiler industry has been water consumption for broilers is twice the amount of feed consumption on a weight basis (i.e. 2 kg of water per kg of feed). More recent studies have suggested WFR is more varied and water intake values presented by the NRC may no longer apply to current broiler production.

Table 2.1. Summary of water-to-feed ratios (WFR) referenced by National Research Council (NRC).

Reference		Average WFR (kg of water per kg of feed)
Marks (1981)	Trial 1 – Selected-AL	2.01
	Trial 2 – Selected-AL	2.06
Gardiner and Hunt (1984)		1.62
Pesti et al. (1985)		1.77
Miller et al. (1988)	Trial 1 – Control	1.95
	Trial 2 – Control	1.78

Note: Results listed from Marks (1981) and Miller et. al (1988) refer to WFR values for trials rearing fast growing commercial broilers provided water and feed *ad libitum* (Selected-AL) and broilers provided water and feed *ad libitum* (Control), respectively.

A study conducted by Williams et al. (2013) presented data comparing water consumption and WFR for multiple flocks grown for three different test periods; 1991, 2000 to 2001, and 2010 to 2011. Average cumulative water consumption significantly increased from 5,773 L per 1,000 birds in 1991, to 6,651 L per 1,000 birds from 2000 to 2001, to 7,753 L per 1,000 birds from 2010 to 2011. Average daily water consumption during the first two weeks for flocks grown in 2010 to 2011 were similar to NRC (1994) estimates for the same weeks. However, water consumption was much greater the final four weeks compared to NRC estimates for the same period suggesting water needs of broilers has increased (table 2.2). The average WFR for flocks grown in 2010 to 2011 however was 2.02 kg of water per kg of feed, comparable to the assumed rule of thumb of 2 kg of water per kg of feed. Data presented however appeared to use average daily water consumption values over entire test periods, limiting the understanding of how changes in seasonal temperatures effect WFR. Data reported was limited to 42 days providing no understanding of water intake and WFR for larger birds.

Table 2.2. Comparison of weekly broiler bird water consumption (BWC) provided by National Research Council (NRC) (1994) and Williams et al. (2013).

Bird Age (weeks)	NRC (1994) (L per 1,000 birds)	Williams et al. (2013): 2010-2011 flock (L per 1,000 birds)
1	225	269
2	480	727
3	725	1,142
4	1,000	1,536
5	1,250	1,907
6	1,500	2,171
7	1,750	-
8	2,000	-

Note: Dashed (-) line indicates data that was not available.

McCreery (2015) presented WFR values from fifteen different broiler flocks grown from 2012 to 2014 in tunnel-ventilated commercial houses. Flock sizes ranged from 19,500 to 21,375 broilers. Values for WFR were separated and averaged into four different categories based on the season the flock was raised in; spring (1.837 kg of water per kg of feed), summer (1.838 kg of water per kg of feed), fall (1.732 kg of water per kg of feed), and winter (1.724 kg of water per kg of feed). Spring and summer WFR were both significantly different than fall and winter WFR values. Warmer weather increased the WFR by 4% over cooler seasons. Overall flock mean WFR was reported as 1.778 kg of water per kg of feed. While this data provides insight into seasonal effects on WFR and shows a decrease in WFR compared to the industry rule of thumb of 2 kg of water per kg of feed, these birds were only grown to ages ranging from 41 to 47 days. Fairchild and Ritz (2015) noted changes in WFR according to season as well. Cold, mild, and hot weather WFRs were 1.55, 1.65, and 1.75 kg of water per kg of feed respectively. Water consumption values and length of flocks were not specified.

Given a shift in the U.S. poultry industry towards producing larger birds (USDA, 2011), the largest bird averaging 4.1 kg at roughly nine weeks of age, it is important to establish a better understanding of water consumption needs for larger modern broilers to ensure adequate supplies of water are available for current housing systems and environmental conditions.

The objective of this study was to establish daily water consumption needs for current broiler genetic strains grown to nine weeks using commercially relevant management practices during three seasonal periods; winter, summer, and spring. Daily feed consumption (FC) data was collected and used to calculate daily WFR.

2.2 Methods and Materials

2.2.1 Broiler housing and pen set-up

Trials were conducted in a tunnel-ventilated research facility at the USDA Poultry Research Unit in Starkville, MS. Seasonal periods were based on meteorological seasons for the Northern Hemisphere where winter includes December, January, and February; summer includes June, July, and August; and spring includes March, April, and May. All procedures relating to the use of live birds in this study were approved by the USDA-ARS Animal Care and Use Committee at the Mississippi State location. Target weights for each trial were 4.1 kg per bird with birds grown from hatch to 63 days. Eight research pens were sized to accommodate a commercially relevant stocking density of 44 kg m^{-2} as recommended by the National Chicken Council for birds grown to more than 3.4 kg (NCC, 2020). Therefore, pen dimensions were 2.9 x 9.1 m with 15 cm of wood shavings for bedding. A total of 2,160 Ross 708 straight-run broiler chicks were obtained from a commercial hatchery and randomly distributed to each pen resulting in 270 birds per pen.

Both water and feed were provided *ad libitum* throughout the trial. Pens mimicked a commercial housing setup with a mechanical feedline system installed in the center of the pen with a water line installed on either side of the feedline. Six feed pans were installed following primary breeder recommendations of no more than 45 birds per pan for bird weights exceeding 3.5 kg

(Aviagen, 2018). All feeder pans were set to provide the maximum allowable amount of feed. Drinker lines with drip trays and 15 cm nipple spacing were installed according to manufacturer specifications (Plasson, 2017a). Nipple density followed primary breeder recommendations of 9 birds per nipple for bird weights exceeding 3 kg (Aviagen, 2018). A 37.8 L capacity water barrel was installed approximately 1.4 m above the floor of each pen, with connections made to the drinker lines (fig. 2.1). An Omron ZEN timer was used to operate a solenoid valve installed on the main water trunk line to supply water to each pen. The valve was operated each day of the trial every 3 h with a fill time of 4 min. Float values were installed on the water barrels to avoid overflow during fill times.

Figure 2.1. (left) Two water lines were installed either side of auger feed lines. (right) Water tanks with a capacity of 37.8 L were installed 1.4 m above the pen floor and supplied water to two drinker lines.

Both water line and feed pan heights were monitored daily and adjusted according to primary breeder recommendations (Aviagen, 2018). Water line pressure was monitored daily and adjusted according to manufacturer operation instructions (Plasson, 2017b).

During the brooding period (1 to 16 days), commercially available plastic migration fence was used to mimic half house brooding while still maintaining primary breeder recommendations for feeder and drinker availability. Paper was placed under both water and feedlines and cardboard feed trays were placed under chick feeders. Paper was removed on day three and chick feeders were shut off on day six. Cardboard feed trays were removed on day seven to allow chicks to consume leftover feed in trays. Birds were given access to the whole pen floor area at 16 days (Trampel et al. ,2013).

Room temperature, lighting intensity, and photoperiod followed the schedule shown in table 2.3 representing common environmental settings used in the industry. Minimum ventilation followed National Poultry Technology Center (NPTC) guidelines based on bird age (Campbell et al., 2014) (table 2.3). Round radiant brooders maintained house floor temperatures and operated off of temperature sensors connected to a controller using a prescribed temperature curve. Minimum ventilation fans were operated off a timer according to an airflow per bird requirement. Fan On/Off times were calculated by the controller and fan staging was programmed on the controller to mimic commercial housing operation. Daily room temperature and humidity were monitored and recorded.

Table 2.3. Prescribed temperature, lighting schedule, and minimum ventilation settings.

Bird Age (d)	Room Temperature (°C)	Light Intensity (lux)	Light Program (Light Hours : Dark Hours)	Minimum Ventilation (m^3/s/bird)
0	32.2	30 lux	23L:1D	0.42
4	31.1	30 lux	23L:1D	0.42
8	28.9	10 lux	20L:4D	0.42
14	26.7	10 lux	20L:4D	0.59
21	23.9	10 lux	20L:4D	0.59
28	21.1	5 lux	18L:6D	1.10
35	18.3	5 lux	18L:6D	1.10
42	18.3	5 lux	18L:6D	1.53
61	18.3	5 lux	23L:1D	1.53

Birds were provided a four-phase diet that met or exceeded NRC recommendations (NRC, 1994) consisting of a starter (1 to 16 days), grower (17 to 28 days), finisher (29 to 42 days), and withdrawal (43 to 63 days) (table 2.4).

Table 2.4. Composition of each diet (starter, grower, finisher, and withdrawal) ration on % by weight basis.

Ingredients	Stater (% by weight)	Grower (% by weight)	Finisher (% by weight)	Withdrawal (% by weight)
Corn	56.17	61.54	64.94	63.56
Soy	32.36	27.45	25.65	25.82
Poultry Fat	3.17	3.03	3.56	4.69
Poultry-by-product	5.00	5.00	2.99	3.00
Di-Cal	1.27	1.04	1.01	0.96
Lime	0.99	0.89	0.86	0.85
Salt	0.47	0.48	0.47	0.50
Methionine	0.22	0.17	0.15	0.21
Copper Sulfate	0.05	0.05	0.05	0.05
Zinc Sulfate	0.01	0.01	0.01	0.01
Vitamin Pre-mix	0.25	025	0.25	0.25
Zoamix	-	0.05	0.05	0.04
Lysine	0.03	-	-	0.01
BMD-50	-	0.05	-	-
L-Threonine	-	-	0.02	-
Choline	-	-	-	0.05

2.2.2 Water and feed data collection

Water and feed weight data were collected every minute using a datalogger (CR1000X, Campbell Scientific, Logan, UT). Water weights were measured using factory calibrated scales (Ohaus Defender® D50RQR, Ohaus, Parsippany, NJ) with a maximum capacity of 50 kg. Daily feed weights were collected by installing four, s-beam load cells (ITCM RL20000 series, Rice Lake, Rice Lake, WI) with a 226 kg weight capacity distributed along each feedline in four locations (fig. 2.2). Load cells were wired to a signal trim junction box (TuffSeal® JB4XX, Rice Lake, Rice Lake, WI) in order to output a single feed weight for each pen. Prior to bird placement, each feedline set-up was calibrated. Feed levels were monitored daily and any feed added was recorded per pen. During diet changes, any remaining feed from the previous diet was removed from the feedline, weighed back and recorded before filling feedlines with the next diet.

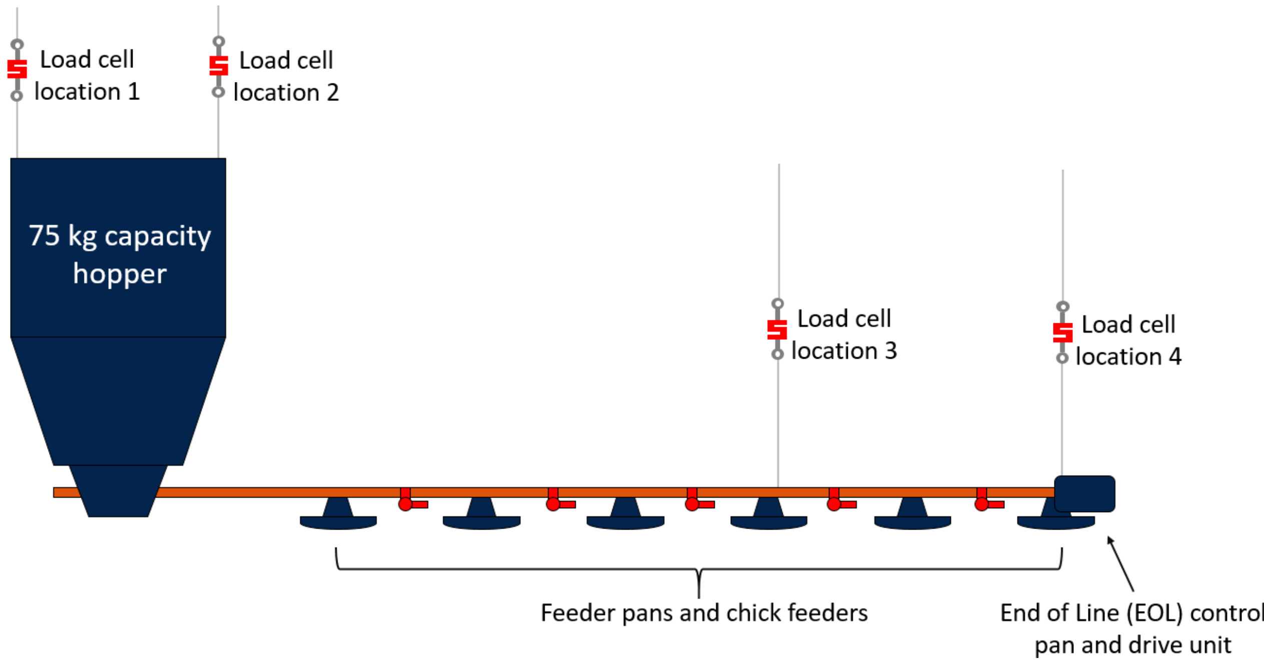

Figure 2.2. Feedline set-up with six available feeder pans and chick feeders with four load cell locations (not to scale).

Daily water and feed weight data were evaluated over a 24 h period (4:00 a.m. to 4:00 a.m.). Daily BWC was calculated by subtracting the current time step (*t*) water weight from the previous time step (*t-1*) water weight (eq. 2.1).

$$BWC(t) = Water\ Weight(t-1) - Water\ Weight(t) \quad (2.1)$$

Positive values represented water being consumed and negative values represented filling events. The sum of all positive values during the 24 h period was BWC for that day in kg. A sample of raw data over an 8-minute period is shown in table 2.5. Taking time 08:59 and 08:58 as an example and using equation 2.1, BWC at time 08:59 was 0.08 kg.

$$BWC(t) = Water\ Weight(t-1) - Water\ Weight(t)$$

$$BWC(08:59) = Water\ Weight(08:58) - Water\ Weight(08:59)$$

$$BWC(08:59) = 23.90\,kg - 23.82\,kg$$

$$BWC(08:59) = 0.08\,kg$$

Negative values representing filling events occurred from 09:00 to 09:02. Bird water consumption during this 8-minute period was 0.31 kg. Daily mortality was recorded and used to determine pen populations for each day in order to report BWC values in L per 1,000 birds ± SEM.

Table 2.5. Pen 1 raw water weight sample data from 1-Feb-2020 08:56 to 1-Feb-2020 09:04.

Date and time (DD-MMM-YYYY HH:MM)	Water weight (kg)	Water Weight(t-1) - Water Weight(t) (kg)
1-Feb-2020 08:56	24.05	-
1-Feb-2020 08:57	23.96	0.09
1-Feb-2020 08:58	23.90	0.06
1-Feb-2020 08:59	23.82	0.08
1-Feb-2020 09:00	29.72	-5.90
1-Feb-2020 09:01	35.61	-5.89
1-Feb-2020 09:02	35.63	-0.02
1-Feb-2020 09:03	35.60	0.03
1-Feb-2020 09:04	35.55	0.05
Total BWC		0.31

A different approach was taken to calculate daily feed consumption (FC) to reduce interference by birds roosting on or bumping feeder pans during light hours. Equation 2.2 was used to calculate FC in kg.

$$FC = (Initial\ Weight - Final\,Weight) + (Feed\ \ Added - Weigh\ Back) \tag{2.2}$$

Where *Initial Weight* was the feed weight recorded at the beginning of the 24 h period at 4:00 a.m., *Weigh Back* was the feed weight removed from the feedline during a diet change, *Feed Added* was the feed weight added to the hopper, and *Final Weight* was the feed weight recorded at the end of the 24 h period at 3:59 a.m. the next day. The times of 4:00 a.m. and 3:59 a.m. represent times when bird activity and feedline interference were assumed to be the least because lights were off. Lights were scheduled to turn on at 4:00 a.m. each day with a 1 min ramp time, reaching the set maximum light intensity for that day at 4:01 a.m. Using daily BWC and FC, daily WFR was calculated and reported as kg of water per kg of feed. Daily means for BWC and WFR were established by averaging results across the eight pens.

2.3 Results and Discussion

Due to delays brought on by the COVID-19 pandemic, only winter and summer trials were completed. Winter flock birds were placed 7 January 2020 and grown until 9 March 2020. Water scales were not installed until day seven because of delivery delays resulting in BWC values for days one through seven not being recorded. Most feedline systems were not completely suspended until day seven to allow chicks access to feed resulting in feed consumption not being reported during this time. Feed data for pen six on day eight and pens six and eight on day nine were excluded because feedlines were not completely suspended resulting in inaccurate feed consumption values. These three feed consumption data points were excluded from WFR calculations. Due to a power outage caused by inclement weather, BWC data for all pens was not captured on day 23 between 5:47 a.m. and 2:18 p.m. However, available BWC data for that day was used to calculate a WFR for each pen using FC data before and after the power outage.

Summer flock birds were placed on 2 August 2021 and grown until 3 October 2021. Both BWC and FC were not captured the first five days. Most feedlines were fully suspended by day six with the exception of pens four and eight which were fully suspended by day eight. Feed consumption data for these two pens was not included in WFR calculations for days six to eight.

It was expected that BWC would be greater during the summer flock when broilers were exposed to elevated temperatures (Pesti et al., 1985; Lott, 1991; NRC, 1994; Lacy, 2002; Bruno et al., 2011). However, daily mean BWC was consistently lower during the summer flock compared to the winter flock (fig. 2.3). Total mean BWC for the summer flock was 13,619±117 L per 1,000 birds and 15,714±195 L per 1,000 birds during the winter flock (table 2.6). Poor chick quality (average placement weight was 29 g per bird) and high mortality (2.3%) observed during the first two weeks of the summer flock likely explain the lower than expected BWC. This suggests results for the summer flock do not represent typical BWC for a summer flock. Therefore, discussions of results focused on the winter flock.

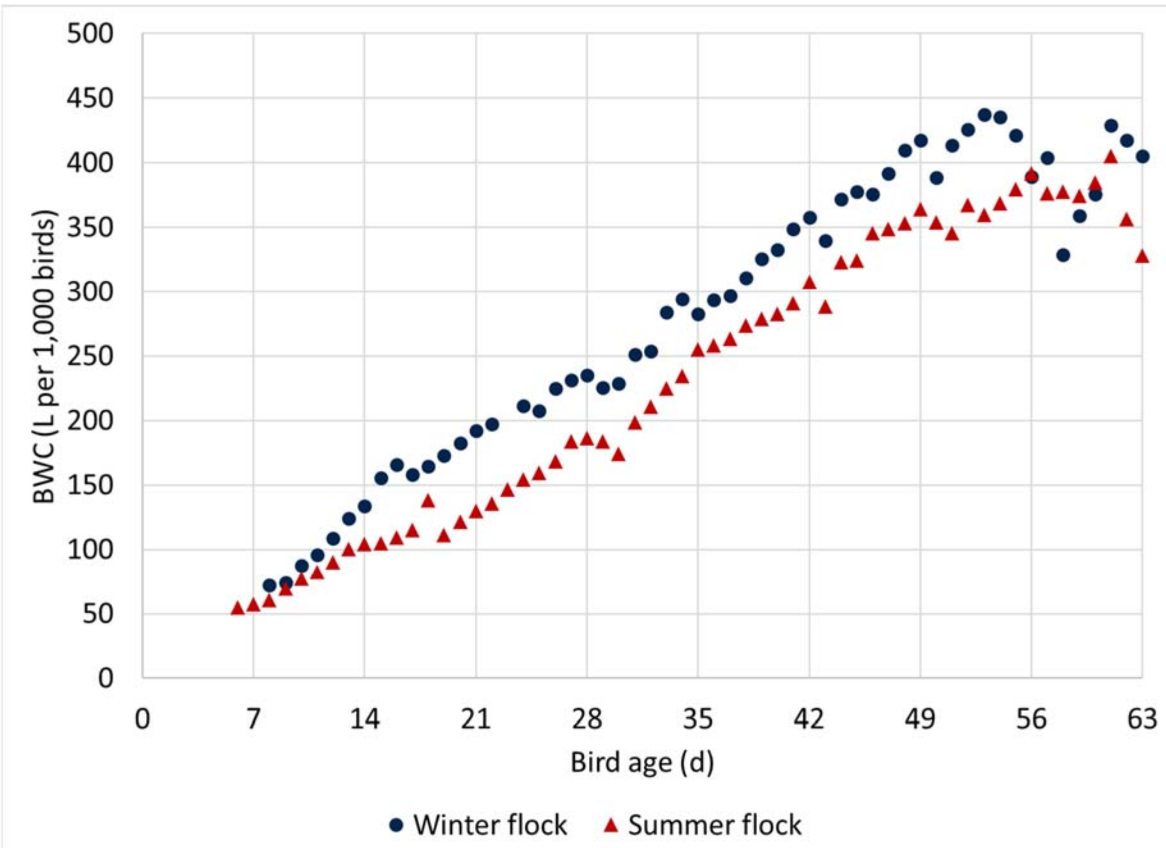

Figure 2.3. Daily mean broiler water consumption (BWC) for the winter and summer flocks

Table 2.6. Total mean, minimum, and maximum broiler water consumption (BWC) for the winter and summer flocks based on daily BWC values across the eight research pens.

Flock	Mean BWC ± SEM (L per 1,000 birds)	Min (L per 1,000 birds)	Max (L per 1,000 birds)
Winter	15,714 ± 195	14,848	16,847
Summer	13,619 ± 117	13,088	14,056

2.3.1 Broiler water consumption (BWC)

As expected, daily BWC generally increased with broiler age consistent with results reported by Pesti et al. (1985), Brake et al. (1992), Bruno et al. (2011), and Williams et al. (2013) for broilers up to 42 days. As broilers aged beyond 42 days, it was expected BWC would plateau, similar to the behavior shown in Xin et al. (1994) for birds grown to 56 days (fig. 2.4). However, a plateau in BWC was not observed during the winter flock due to a reduction in BWC between 55 and 58 days. The attending veterinarian identified a disease event based on mortality necropsy results and began a medication regimen starting day 56 until the end of the flock. This drop in BWC during the disease event was consistent with trends reported by Butcher et al. (1999) and Manning et al. (2007a). Four days after medication was given BWC begins to increase, likely signaling birds were recovering from the disease event, but did not reach values observed prior to the disease event before the end of the study.

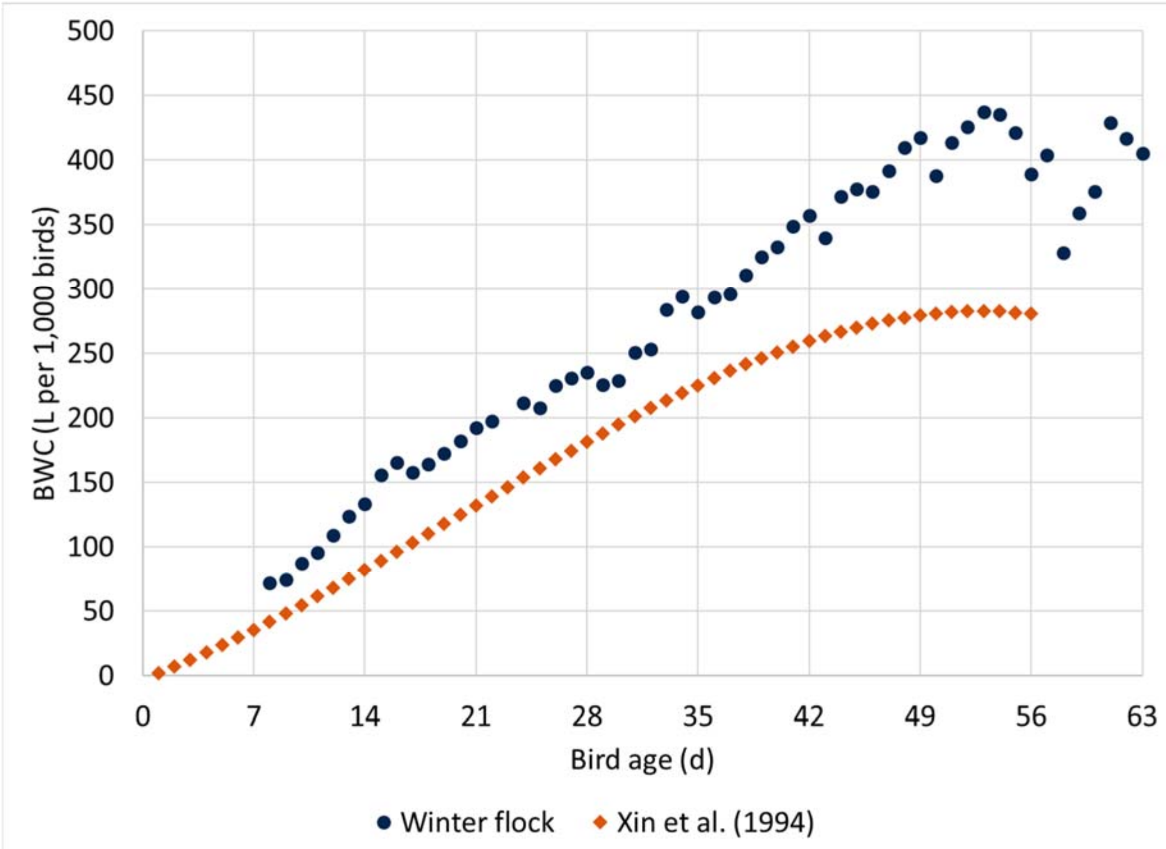

Figure 2.4. Comparison of daily mean broiler water consumption (BWC) patterns between winter flock and the regression equation for daily water use (DWU) developed by Xin et al. (1994). The regression equation was based on daily water use from averaged daily values for male flocks reared to 56 d from 1991 to 1993. No separation was made for seasonal differences.

Mean house temperature was within ±3°C of set-point temperatures and no large spikes were observed during the winter flock (fig. 2.5). While there were 16 days where mean temperature was above the house set-point (days 21, 28, 29, 30, 42, 43, 50, 55, 56, 57, 62, and 63), no large spikes in BWC were observed. This suggests that most days with elevated temperatures were still within the bird's thermal comfort zone and did not affect water consumption.

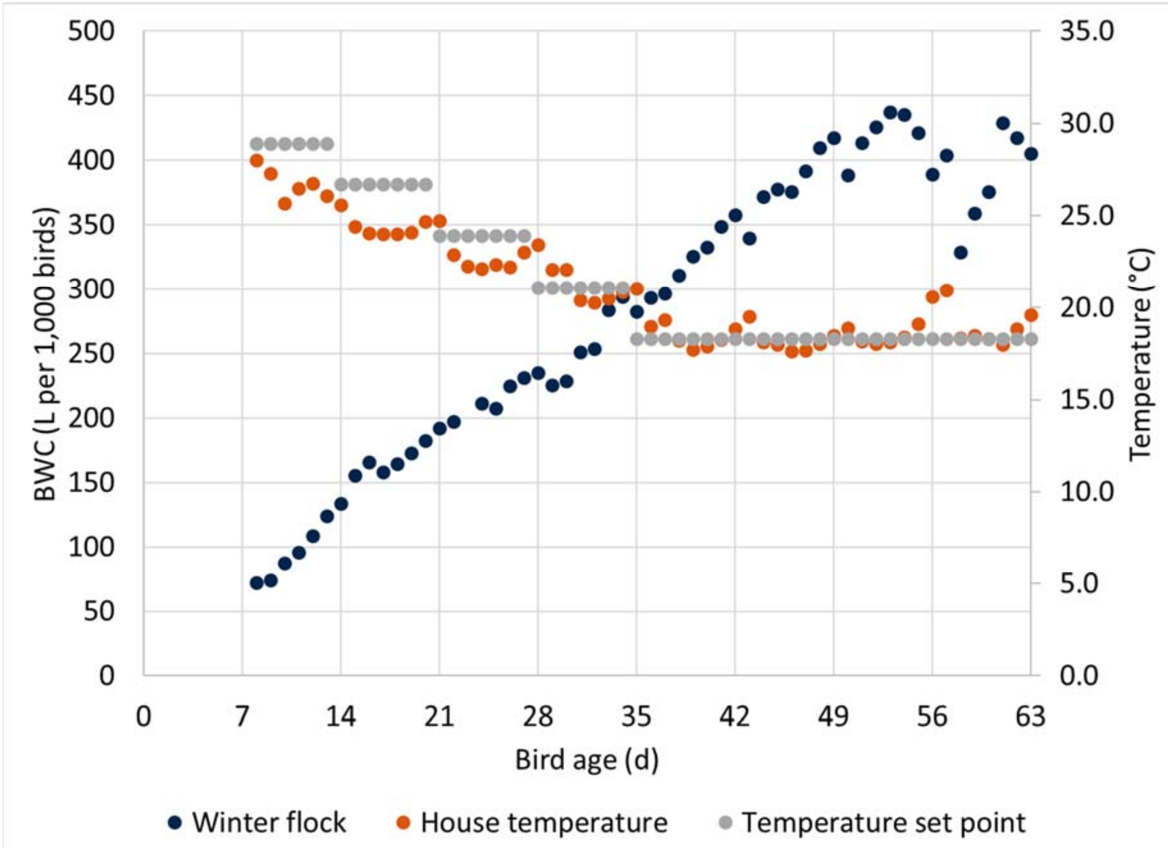

Figure 2.5. Daily mean broiler water consumption (BWC), house temperature, and temperature set point during the winter flock.

A comparison of weekly BWC reported in the literature and from this study is shown in figure 2.6. Weekly BWC was 11% to 28% higher during the winter flock compared to values reported by Pesti et al. (1985), NRC (1994), and Xin et al. (1994). Weekly values were similar for both the winter flock and those reported by Williams et al. (2013) between two to six weeks. Overall consumption during this period was 7,401 versus 7,488 L per 1,000 birds (1% decrease) for the winter flock and 2010-2011 flock, respectively. While this might suggest BWC has not changed in the past 10 years, it should be noted BWC presented by Williams et al. was averaged across ten flocks with no separation based on seasonality. Considering flocks grown during summer months are more at risk to heat stress and typically consume more water, overall consumption for today's broilers grown during spring and summer months are likely greater than estimates in Williams et al. (2013).

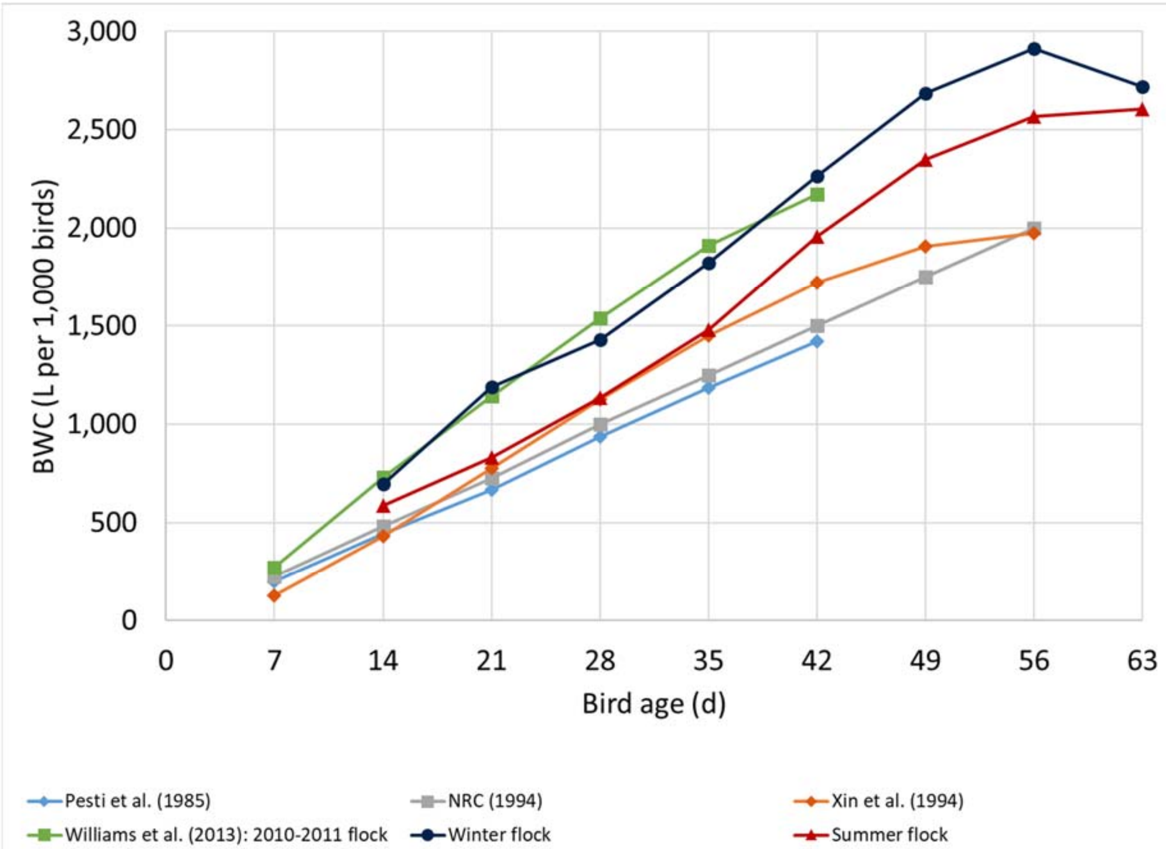

Figure 2.6. Comparisons between weekly broiler water consumption (BWC) reported in this study and weekly BWC reported in the literature.

There appears to be distinct linear patterns for BWC over the course of the flock that correspond to the diet phases (fig. 2.7). There was no distinct trend for the withdrawal phase because of the drop in BWC caused by the disease event. Fitting a trend line to the starter, grower, and finisher diet sections of BWC data shows rates of water consumption were 12.33, 7.01, and 9.72 L per 1,000 birds per day, respectively. These changes in rates were likely due to a combination of diet and age of the bird. There was also an observed decrease in BWC on days of diet change most likely due to the process of caretakers entering the pens to remove feed from the feedlines, disrupting bird drinking.

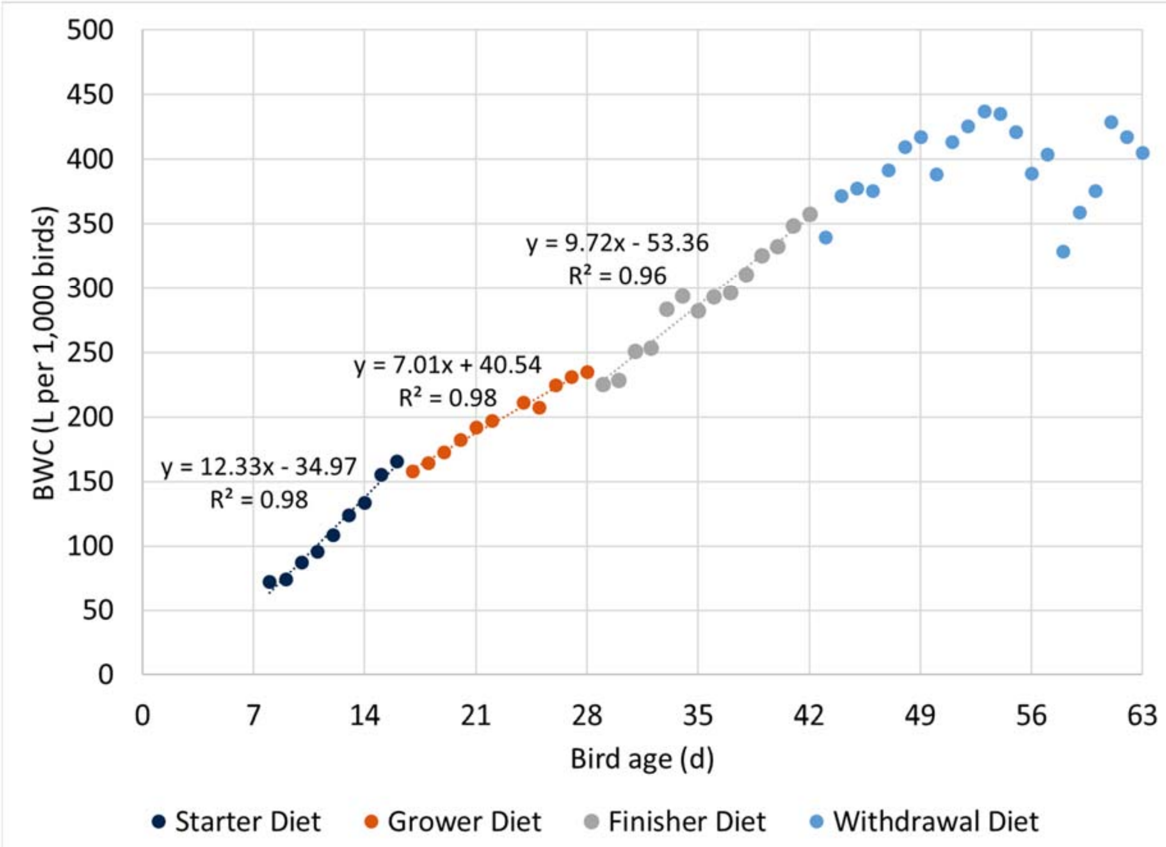

Figure 2.7. Comparison of winter flock mean broiler water consumption (BWC) for the starter, grower, and finisher diets. Trend line equations and R^2 values are included for starter, grower, and finisher diet. A trend line was not included for the withdrawal diet because of the disease event between days 56 and 60.

2.3.2 Broiler water-to-feed ratio (WFR)

Mean winter flock WFR was 1.82±0.01 kg of water per kg of feed where daily mean ranged from 2.32±0.33 to 1.57±0.03 kg of water per kg of feed on days 8 and 30, respectively (fig. 2.8). The largest daily WFR values were observed within the first two to three weeks of the flock, similar to behavior reported by Williams et al. (2013) and McCreery et al. (2013). Only days 8, 10, 14, and 15 to 17 equaled or exceeded the industry WFR rule of thumb of 2 kg of water per kg of feed. Beyond day 17, WFR remained below the industry rule of thumb. It also appears WFR decreases during a disease event. Comparing BWC and feed consumption (FC) during the disease event shows a greater drop in BWC relative to the drop in FC (fig. 2.9).

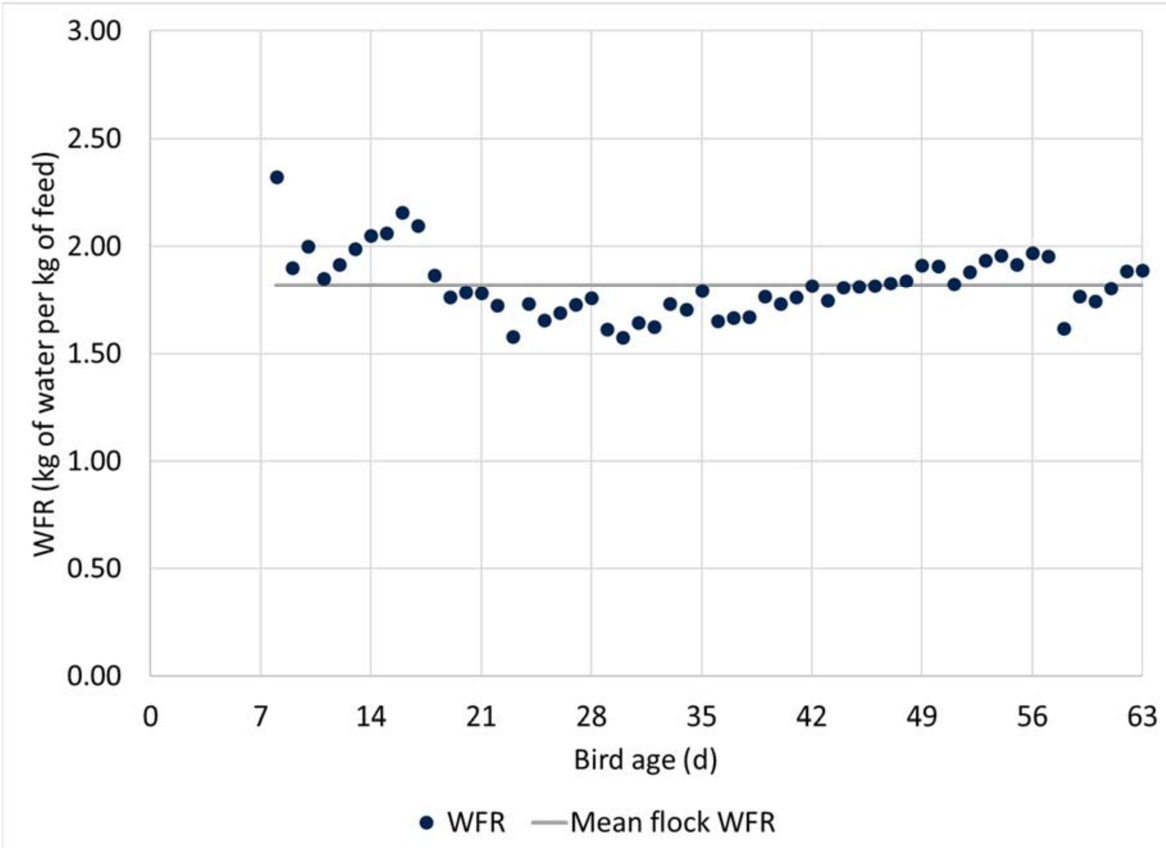

Figure 2.8. Winter flock mean daily water-to-feed ratio (WFR) and mean flock WFR of 1.82 kg water per kg feed.

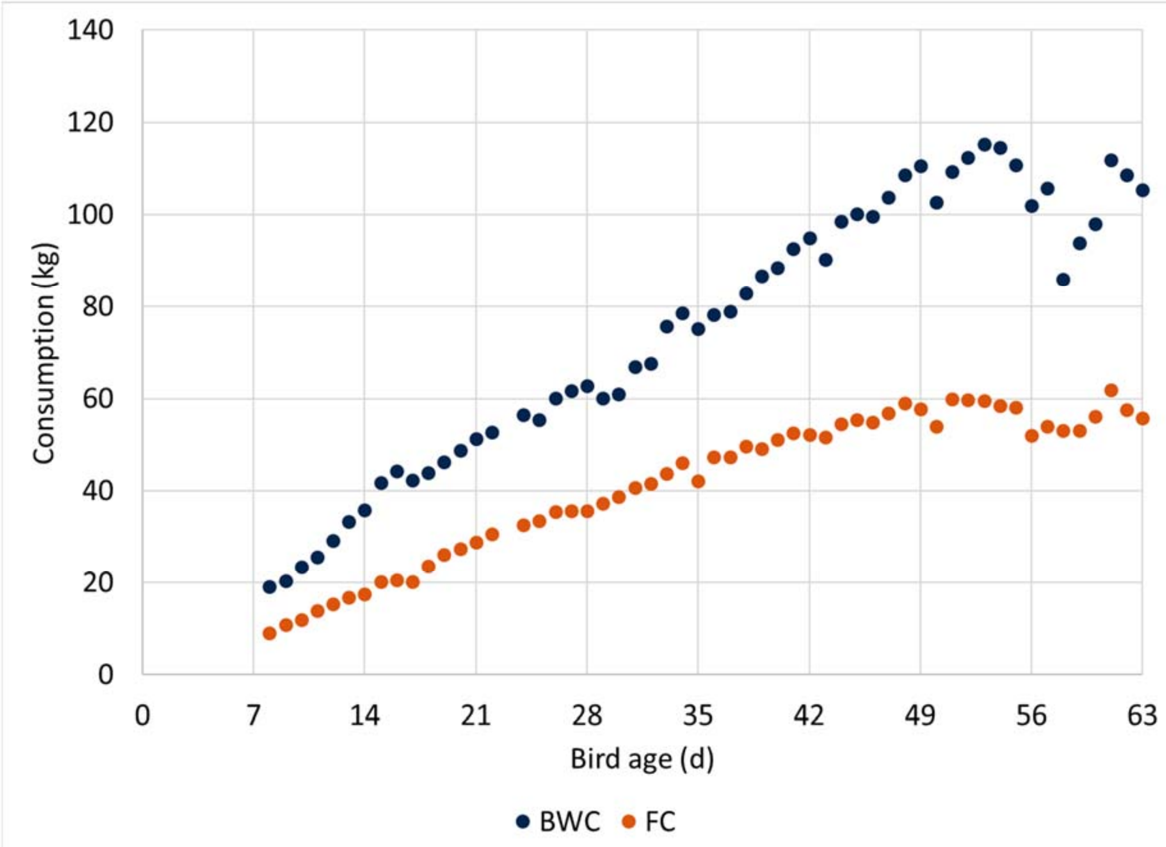

Figure 2.9. Mean daily broiler water consumption (BWC) and feed consumption (FC) for the winter flock.

Mean WFR based on diet are listed in table 2.7. The greatest mean WFR during the winter flock was 2.01 kg water per kg feed observed during the starter diet and dropped to 1.69 kg water per kg feed during the finisher diet. The differences in WFRs were likely due to bird age and diet ingredients.

Table 2.7. Comparison of mean water-to-feed ratio (WFR) by diet ration for the winter flock.

Diet	WFR (kg water per kg feed)
	Winter flock
Starter	2.01
Grower	1.80
Finisher	1.69
Withdrawal	1.85*

Note: Mean WFR for the withdrawal phase was affected by the disease event.

Mean flock WFR values reported in the literature are listed in table 2.8 and ranged from 1.55 to 2.16 kg of water per kg feed compared to 1.82 kg of water per kg of feed for the winter flock. Given these studies span 40 years, WFR has remained relatively the same. However, it is important to note a majority of these studies report WFR values lower than the industry rule of thumb of 2 kg of water per kg of feed. On a seasonal basis, this study reported a higher WFR during the winter flock compared to those reported by McCreery et al. (2013) and Fairchild and Ritz (2015). Bird genetics, age, and management practices may have contributed to these differences.

Table 2.8. Comparison of mean water-to-feed ratio (WFR) values reported in literature and WFR reported in this current study.

Reference		Broiler age (d)	Mean WFR (kg water per kg feed)
Current study	Winter Flock	63	1.82
	Summer Flock	63	1.73
Williams et al. (2013)	2010 – 2011 Flocks	42	2.02
	2000 – 2001 Flocks	42	1.98
	1991 Flocks	42	1.90
McCreery et al. (2013)	Winter	41-45	1.72
	Fall	42-47	1.73
	Spring	42-45	1.84
	Summer	42-43	1.84
Fairchild and Ritz (2015)	Cold weather	-	1.55
	Mild weather	-	1.65
	Hot weather	-	1.75
Manning et al. (2007b)	Group 1	-	1.79
	Group 2	-	1.68
Lacy (2002)		-	1.80
Xin et al. (1994)		56	1.70[a]
Brake et al. (1992)		21	2.16[a]
Miller et al. (1988)	Trial 1 - Control	42	1.95
	Trial 2 - Control	42	1.78
Pesti et al. (1985)		42	1.77
Gardiner and Hunt (1984)		63	1.62
Marks (1981)	Trial 1 - Selected	28	2.01
	Trial 2 - Selected	28	2.06

[a] Mean WFR was calculated from daily BWC and FC equations derived from the study.

Using the industry WFR rule of thumb to estimate FC based on BWC for this particular flock would result in an underestimation of total flock feed consumption. Figure 2.10 compares winter flock FC to estimated FC using the average flock WFR of 1.82 kg water per kg feed and the industry assumption of 2 kg water per kg feed. Daily feed calculations were made by dividing daily BWC by the WFR. Total mean flock FC for the winter flock was 2,289 kg compared to estimated FC of 2,270 and 2,065 kg for WFRs of 1.82 and 2 kg water per kg feed, respectively. Applying the industry assumption would underestimate total flock FC by approximately 9.8% whereas using a WFR of 1.82 underestimates actual total flock FC by approximately 0.8%.

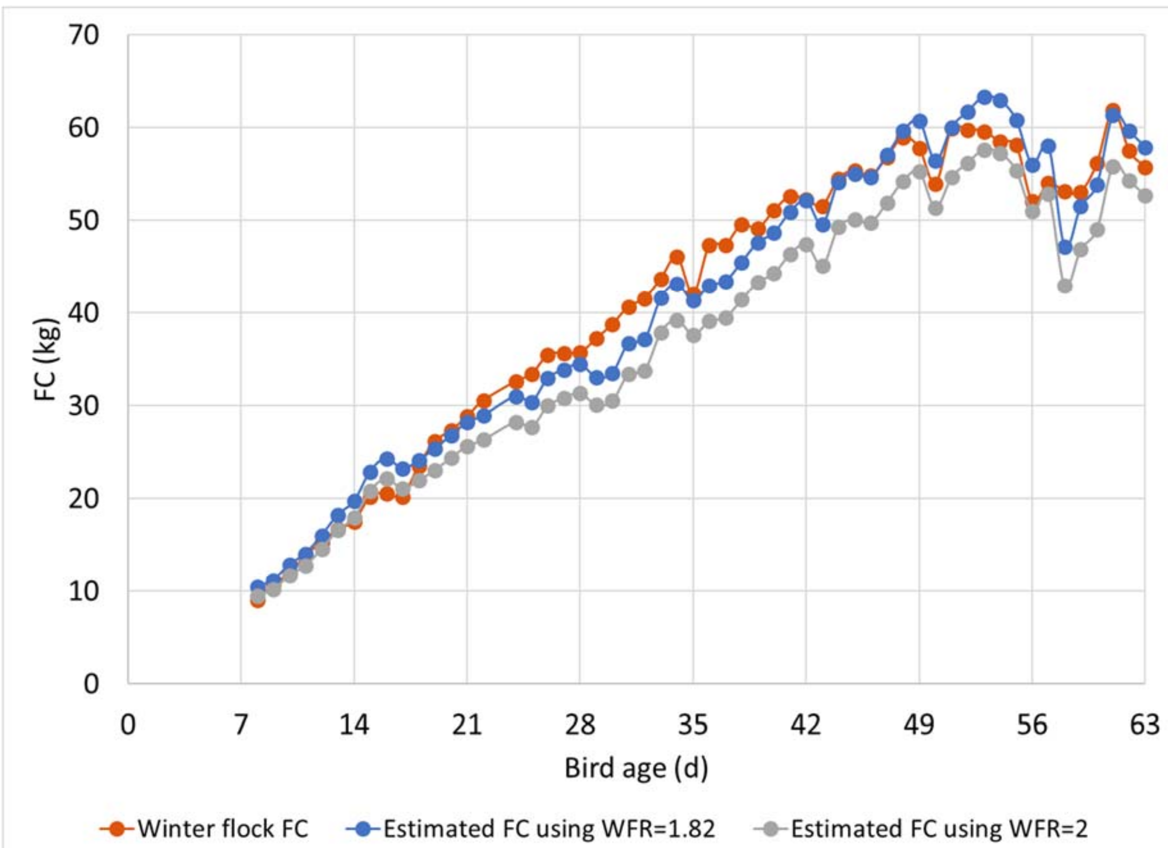

Figure 2.10. Comparison of winter flock feed consumption (FC) between estimated FC using winter flock broiler water consumption (BWC) and water-to-feed ratios (WFR) of 1.82 and 2 kg of water per kg feed. WFR of 1.82 represents the flock mean WFR for the winter flock and WFR of 2 represents the industry assumption WFR. Daily estimated FC was calculated by dividing daily BWC by WFR. Total winter flock FC was 2,289 kg and estimated FC using a WFR of 1.82 and 2 was 2,270 kg and 2,065 kg, respectively.

2.4 Conclusions

Broiler drinking water consumption (BWC) and water-to-feed ratios (WFR) were determined for 9 week old broilers grown during winter months. Total mean BWC was approximately 15,714 L per 1,000 birds and daily observations suggest BWC is still a good indicator of flock performance. Mean flock WFR was 1.82 kg water per kg feed, lower than the industry rule-of-thumb WFR of 2 kg water per kg feed suggesting the rule-of-thumb is not the best indicator for feed consumption for today's commercial broilers. Continued research is needed to established seasonal differences in both BWC and WFR.

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2.6 Appendix

Table A.2.1. Daily mean broiler water consumption (BWC) for the winter and summer flocks. Summer flock values are shown but do not reflect typical results because of chick quality issues during the flock.

Bird age (d)	BWC ± SEM (L per 1,000 birds)	
	Winter flock	Summer flock
1	-	-
2	-	-
3	-	-
4	-	-
5	-	-
6	-	55 ± 2.88
7	-	57 ± 3.50
8	72 ± 1.58	61 ± 3.99
9	74 ± 1.64	70 ± 2.16
10	87 ± 1.86	77 ± 0.92
11	96 ± 2.45	82 ± 1.55
12	109 ± 1.67	90 ± 1.49
13	124 ± 1.43	101 ± 1.58
14	134 ± 1.48	104 ± 1.46
15	156 ± 8.39	105 ± 1.77
16	166 ± 3.47	110 ± 1.96
17	158 ± 3.70	115 ± 2.12
18	164 ± 2.68	138 ± 10.42
19	173 ± 3.30	111 ± 1.89
20	182 ± 2.44	122 ± 1.94
21	192 ± 2.75	130 ± 2.63
22	197 ± 3.47	135 ± 2.70
23	121 ± 2.55	147 ± 1.81
24	212 ± 2.12	154 ± 3.98
25	208 ± 2.78	160 ± 1.24
26	225 ± 3.40	169 ± 4.07
27	231 ± 4.24	184 ± 3.72
28	235 ± 3.97	186 ± 2.21
29	226 ± 5.04	184 ± 1.91
30	229 ± 6.01	174 ± 1.57
31	251 ± 7.33	198 ± 1.55
32	254 ± 2.47	210 ± 1.57
33	284 ± 3.25	225 ± 2.21
34	295 ± 3.50	234 ± 2.80
35	282 ± 3.60	255 ± 2.39
36	294 ± 6.69	258 ± 3.12
37	297 ± 5.82	263 ± 1.95

38	311 ± 5.52	274 ± 2.80
39	325 ± 3.76	279 ± 2.59
40	333 ± 3.17	283 ± 2.99
41	349 ± 4.91	291 ± 3.26
42	357 ± 5.36	308 ± 4.02
43	340 ± 7.00	289 ± 3.12
44	372 ± 6.56	323 ± 2.91
45	378 ± 5.32	324 ± 1.83
46	376 ± 5.13	346 ± 4.04
47	392 ± 5.23	349 ± 3.81
48	410 ± 7.09	353 ± 6.25
49	417 ± 8.77	364 ± 3.31
50	388 ± 5.05	354 ± 4.73
51	414 ± 7.11	345 ± 3.62
52	426 ± 5.22	368 ± 4.13
53	437 ± 6.58	360 ± 6.80
54	436 ± 6.80	369 ± 5.92
55	421 ± 6.39	380 ± 6.05
56	389 ± 4.82	392 ± 6.28
57	404 ± 10.03	377 ± 7.13
58	329 ± 7.08	378 ± 4.79
59	359 ± 7.99	374 ± 12.33
60	376 ± 5.01	384 ± 9.97
61	429 ± 6.95	405 ± 7.61
62	417 ± 7.15	357 ± 7.69
63	405 ± 4.89	328 ± 6.95
Total	15,714 ± 195.00	13,619 ± 117.00

Chapter 3

Development of a water consumption model for commercial broiler farms in the U.S.

3.1 Introduction

A large part of the broiler industry's success has been achieved from the development of high performance broiler strains by primary breeder companies and the development of feed diets (Sherwood, 1977; Havenstein et al., 1994a; Havenstein et al., 1994b; Lacy, 2002; Zuidhof et al., 2014; Tallentire et al., 2016). The trade-off for this higher performance has meant modern broilers are less resilient to environmental changes (Lacy, 2002) prompting a transition from naturally ventilated curtain sided houses to tunnel ventilated houses. Today, new broiler house construction in the US consists of tunnel ventilation using recirculating evaporative cooling (EC) systems for cooling (Lacy and Czarick, 1992; Donald et al., 2001; Bucklin et al., 2003; MacDonald, 2008). The most common EC system used in the broiler industry uses a 15-cm cellulose pad as the cooling media (Donald, 2000; Donald et al., 2000). During system operation, the pad is wetted, outside air is pulled through the pad, cooling the airstream, and brought into the house to provide cooling. The volume of water evaporated or consumed during the evaporative cooling process is refilled with makeup water. For some growers, particularly those who grow 4.1 kg broilers, EC systems provide additional cooling when wind speed alone can no longer provide adequate cooling inside the house (Simmons and Deaton, 1989, Bucklin et al., 2003).

Today's modern commercial broilers have been selectively bred for fast growth, high meat yields, and better feed conversions. Achieving the maximum genetic potential of broilers can be realized by raising broilers in environmentally controlled housing systems, using appropriate management practices based on broiler target weights, and providing them with a nutritious diet and plenty of water. A large body of research and literature has established optimal environmental set points (e.g. lighting, ventilation, temperature, and relative humidity) based on broiler age (Trampel et al. ,2013; Olanrewaju et al., 2006; Campbell et al., 2014; Asensio, 2016), broiler management practices (NCC, 2020; Bell, 2002), and nutrient requirements for feed (NRC, 1994). Primary breeders have used information from these studies, along with internal company research, to provide both integrators and growers fairly comprehensive management guides for the live production of broilers (Aviagen,2010; Aviagen, 2018; Cobb 2021). These companies also publish updated performance objectives (Aviagen, 2019; Cobb, 2022) providing metrics such as daily body weights, feed intakes, and feed conversion ratios (FCR) for growers to gauge the performance of their own flocks. The one key component of broiler production that appears to have been overlooked is the amount of water required for broiler production.

Water is an essential nutrient for broiler metabolic function and well-being (NRC, 1994; Butcher et al., 1999; Manning et al., 2007). Growers must be able to supply water for the two main water consumption needs during the grow-out process: broiler drinking water and water for evaporative cooling systems. Research and management literature consistently stress broilers should have access to water throughout the grow-out process and any restrictions in water availability can decrease performance (Kellerup et al., 1965; Marks, 1980, Lacy, 2002; Aviagen, 2018; Cobb, 2021). Bell (2002) notes water requirements for commercial poultry can be large and should be carefully considered when planning new construction. Williams et al. (2013) also notes providing updated water consumption estimates is important for the industry particularly when sizing on-farm water systems to ensure adequate water supplies are available. While references to water requirements have been made within the literature, recommendations have been limited to certain size birds and for certain poultry producing areas of the U.S. providing little information of overall water requirements for the full range of farm sizes (e.g. house size, number of houses, flock size) within the industry. Most studies only reported either drinking water usage or EC system usage providing little information on the total amount of water needed for modern broiler farms.

Table 3.1 summarizes water usage needs for both broiler drinking water and evaporative cooling systems reported in the literature. Equations developed to estimate daily drinking water consumption for broilers raised in commercial style houses estimated mean total water consumption to be 4,768 L per 1,000 birds for broilers grown to six weeks in houses roughly 11.6 x 122 m (Pesti et al., 1985) and 9,513 L per 1,000 bird for broilers grown to eight weeks in houses measuring 12.2 x 122 m (Xin et al., 1994). Williams et al. (2013) monitored drinking water for broilers raised to six weeks in commercial houses measuring 12.2 x 122 m from 2010 to 2011, reporting mean total water consumption was 7,752 L per 1,000 birds. Results from chapter 2 reported mean total water consumption for broilers grown to nine weeks under commercial conditions during a winter and summer flock was 15,714 and 13,619 L per 1,000 birds, respectively. Mean flock WFR reported for the winter and summer flocks were from 1.73 to 1.82 kg water per kg feed, respectively. These values were lower than the assumed industry rule-of-thumb WFR of 2 kg water per kg feed. Tabler et al. (2008) reported a range of water consumption values for multiple summer flocks raised to different ages in 12.2 x 122 m commercial houses in Savoy, AR between 1995 and 2005. Broiler drinking water consumption ranged from 123,845 to 210,162 L per flock and evaporative cooling pad water consumption ranged from 8,719 to 501,126 L per flock. In Athens, GA, evaporative cooling pad consumption for a 15.2 x 171 m commercial house growing broilers to 54 days ranged from 150,320 to 169,110 L during summer flocks and 37,580 to 75,160 L during spring flocks (Czarick and Fairchild, 2009). Installed pad area for this house was 65 m^2 using 15-cm thick pads. Purswell et al. (2018) reported water supply rates for evaporative cooling systems across poultry producing areas in the U.S. ranged from 4.4 to 5.6 L/min/1,000 m^3/min and noted rates can depend on the climate and weather patterns of a specific location. Without accurate historical records of actual farm water consumption or updated water usage data matching the size and location of a farm reported in the literature, it can be difficult for growers and industry personnel to estimate broiler farm water consumption needs.

Table 3.1. Summary of broiler drinking water usage and evaporative cooling system usage reported in literature.

Reference	Broiler drinking water	Evaporative cooling system
Pesti et al. (1985)	4,768 L/1,000 birds	
Xin et al. (1994)	9,513 L/1,000 birds	
Tabler et al. (2008)	123,845 to 210,162 L/flock	8,719 to 501,126 L/flock
Czarick and Fairchild (2009)		Summer flocks: 150,320 to 169,110 L Spring flocks: 37,580 to 75,160 L
Williams et al. (2013)	7,752 L/1,000 birds	
Purswell et al. (2018)		4.4 to 5.6 L/min/1,000 m3/min
Chapter 2[a]	Winter flock: 15,714 L/1,000 birds Summer flock: 13,619 L/1,000 birds	

[a] Broiler drinking water values are from Chapter 2: Water consumption trends for modern commercial broilers.

Therefore, the objective of this research was to develop a model to estimate daily broiler water consumption and evaporative cooling water consumption given a farm's size and geographic location as user inputs. The goal of this model is to provide water usage information that can be used by industry stakeholders to better understand the water requirements of today's commercial broilers.

3.2 Methods and Materials

3.2.1 Water consumption model development

A water consumption model was developed in MATLAB (v20166b, The MathWorks, Natick, Mass.) to estimate broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) on a daily basis to establish mean total water usage over a 30-yr period. Consumption values were calculated on a per house basis according to various model inputs for farm housing and management characteristics as well as weather data given the farms geographic location. The model used current guidelines and recommendations for broiler management (e.g. conditions at which evaporative cooling systems should be operated) and flock husbandry (e.g. number of broilers in a house based on stocking density) to mimic broiler production on a farm (Trampel et al. ,2013; Aviagen, 2018; NCC, 2020; Cobb, 2021). A flow chart of model operation is shown in figure 3.1. The presence of broilers in a house was modeled over the 30-yr test period based on the flock length (e.g. 63 days) and the layout period (days during which the grower has no birds). If broilers were present, the model estimates both consumption values following user inputs and the most up-to-date management guidelines, otherwise the model estimates consumption values as zero. Total water consumption (TWC) was determined for each year of the test period and averaged to provide a mean TWC per house that a broiler farm could expect given its geographic location.

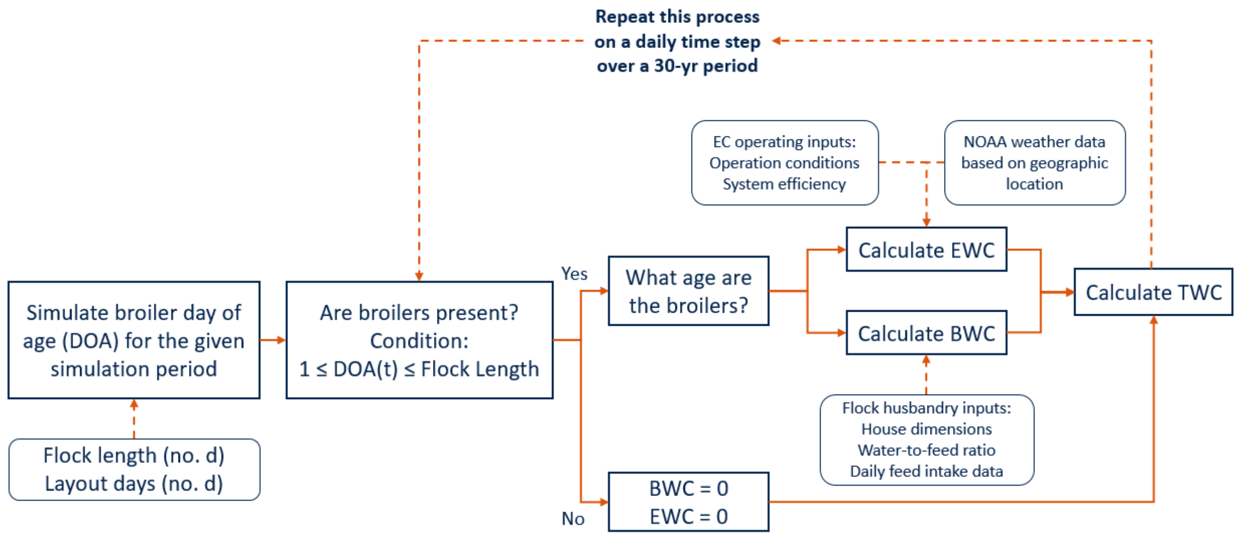

Figure 3.1. Flow chart of model operation. The model simulates broiler day age (DOA) and estimates broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) to determine the total water consumption (TWC) for a broiler farm.

3.2.2 Estimating broiler drinking water consumption (BWC)

Past studies have developed regression equations as a function of broiler day of age (DOA) (Pesti et al., 1985; Brake et al., 1992; Xin et al., 1994; Obaia, 2015) that described broiler water consumption at the time they were published. A comparison of weekly BWC values in Chapter 2, figure 2.7 suggests BWC has increased compared to the consumption estimates using equations outlined in the literature. To estimate daily broiler water consumption, this model utilizes the established understanding that broiler water and feed consumption are closely related (Czarick et al., 2001; Bell, 2002; Fairchild and Czarick, 2006; Fairchild and Lacy, 2015; Tabler et al., 2018) Therefore daily BWC was estimated using a water-to-feed ratio and feed intake data (eq. 3.1).

$$BWC(d) = WFR \times FC(d) \tag{3.1}$$

where

$BWC =$ broiler drinking water consumption (g water bird^{-1}),

$WFR =$ water-to-feed ratio (g H_2O consumed g^{-1} feed consumed),

FC = broiler feed consumption (g feed bird^{-1}),

d = daily timestep.

Historical on-farm feed consumption data would be ideal for the FC input however this data is not directly monitored. For this reason, the model used feed consumption data (g feed bird^{-1}) published by primary breeders (Aviagen, 2019; Cobb, 2018). This data is regularly updated and represents achievable performance objectives of the specific broiler strain grown up to nine weeks of age under commercially relevant conditions.

To determine the overall daily total broiler water consumption for each house, the number of birds (*NB*) present was included in equation 3.1. The initial number of birds placed (*Birds Placed*) at the beginning of a flock was calculated based on house floor area and stocking density (*SD*) recommendations by the NCC (2020) for the target weight of the broiler (eq. 3.2). A mean total flock mortality term (*Mortality*) was included to calculate daily losses expected throughout the broiler growth period (*Flock Length*). Daily mortality was calculated by dividing the product of *Birds Placed* and *Mortality* by *Flock Length*. The daily number of broilers (*NB*) present was then determined by subtracting the daily mortality from the previous day's broiler count (*NB(d-1)*) (eq. 3.3).

$$Birds\ Placed(d) = HL \times HW \times SD \quad for\ d = 1 \tag{3.2}$$

where

$Birds\ Placed$ = number of broilers initially placed (birds),

HL = average house length (m),

HW = average house width (m),

SD = broiler stocking density based on final target weight (birds m^{-2}).

$$NB(d) = NB(d-1) - \left(\frac{Birds\ Placed}{Flock\ Length} \times \frac{Mortality}{100} \right) \quad for\ 2 \leq d \leq Flock\ Length \tag{3.3}$$

where

NB(d)	=	number of broilers (birds),
NB(d-1)	=	number of broilers from the previous day (birds),
Birds Placed	=	number of broilers initially placed (birds),
Mortality	=	average flock mortality (%),
Flock Length	=	broiler growth period (d).

Incorporating the daily number of broilers within a flock into equation 3.1 provides a set of equations for calculating the daily BWC for a house of broilers (eq. 3.4 and 3.5). Daily BWC values were converted from a weight basis (g) to a volume basis (L).

$$BWC(d) = WFR \times FC(d) \times Birds\ Placed \quad for\ d = 1 \tag{3.4}$$

$$BWC(d) = WFR \times FC(d) \times NB(d) \quad for\ 2 \leq d \leq Flock\ Length \tag{3.5}$$

3.2.3 Estimating evaporative cooling system water consumption (EWC)

Daily EWC was calculated based on a peak hourly evaporation rate of water ($\dot{m}_w$) and the design airflow through the house. Purswell et al. (2018) outlines the process of calculating peak hourly $\dot{m}_w$ values using psychrometric equations and hourly weather data. Boundary conditions for ambient dry bulb temperature (T_{db}), relative humidity (*RH*), and the hour of day were incorporated to mimic the operation of evaporative cooling systems on broiler farms. Hourly $\dot{m}_w$ values were summed for each day (eq. 3.6) and multiplied by the design air flow through the house to calculate daily EWC. Based on user inputs for *HW*, average house height *HH*, and average air velocity (wind speed, *WS*), the volumetric flow rate of air (*Q*) through the house was calculated (eq. 3.7) and multiplied by $\dot{m}_w(d)$ to determine daily EWC (eq. 3.8). A day of age (DOA_{limit}) condition was applied to equation 3.8 to reflect EC systems not being operated when broilers are young (Cobb, 2021). This DOA_{limit} can be changed depending on the recommendations from primary breeder material or management guidelines from the integrator.

$$\dot{m}_w(d) = \sum \dot{m}_w(h) \quad for\ \dot{m}_w(d) > 0\ when \begin{cases} T_{db} \geq T_{limit} \\ RH < RH_{limit} \\ LOH < h \leq UOH \end{cases} \tag{3.6}$$

where

$\dot{m}_w$ = peak evaporation rate of water ($kg_{water\ vapor}\ m_{dry\ air}^{-3}$),

T_{db} = dry bulb temperature (°C),

T_{limit} = dry bulb temperature limit (°C),

RH = relative humidity (%),

RH_{limit} = relative humidity limit (%),

LOH = lower operating hour for EC system,

UOH = upper operating hour for EC system,

h = hourly timestep.

$$\dot{Q} = WS * HH * HW \tag{3.7}$$

where

$\dot{Q}$ = volumetric flowrate of air ($m^3\ s^{-1}$).

$$EWC(d) = \dot{Q} * \dot{m}_w(d) \quad for\ EWC(d) > 0\ when\ DOA_{limit} < DOA \leq Flock\ Length \tag{3.8}$$

where

EWC = evaporative water consumption (kg_{water}),

DOA = day of age,

DOA_{limit} = day of age limit.

3.2.5 East Alabama water consumption case study

Farm water consumption data from a previous study by Campbell (unpublished) on an eight house commercial broiler farm located in East Alabama was used to evaluate model BWC and EWC estimates. Houses were solid side wall, tunnel ventilated houses, measuring 13.1 x 155.5 m with an average house height of 2.9 m. Tunnel ventilation target design wind speed was 2.6 m s^{-1}. EC systems using 15-cm thick cellulose pads provided additional cooling during warm weather months and installed pad length was based on achieving a target pad face velocity of 1.8 m s^{-1}. Farm water consumption data was available for flocks grown from August 2015 to June 2019 and from April 2020 to August 2020. The genetic strain grown was a Cobb 500 broiler with target weights of 4.1 kg per bird and flock lengths ranging from 54 to 63 days. Model inputs for both BWC and EWC were based on recommendations from literature and information provided by the grower to match as closely as possible flock husbandry characteristics and EC system operation during grow-out.

Model BWC estimates were evaluated against available farm BWC data across 20 flocks for a total of 132 house by flock data sets across the eights houses (table 3.2). Some flock data was not available for a number of houses because of power loss or incomplete data records, therefore only complete flock data from placement to harvest was used. From this data, mean daily farm BWC was determined and compared to model BWC based on inputs listed in table 3.3. Stocking density was based on the farm's target weight of 4.1 kg per bird and recommendations from the NCC (2020) of 44 kg m^{-2} for target weights exceeding 3.4 kg per bird. Based on the house dimensions and SD, the initial placement of broilers modeled was approximately 21,930. Mortality data was not available for the flocks evaluated in this study, however mortality data for flocks grown prior to 2015 had an average flock mortality of 5.8%. Based on this average mortality, birds placed, and flock length of 63 days, mortality was modeled as a mean of 21 birds d^{-1}. Daily feed intake data was based on as-hatched data for the Cobb 500 broiler (Cobb, 2015). Mean WFR was assumed to be 1.82 kg water consumed per kg feed consumed based on a results from Chapter 2. It should be noted this WFR value was for a flock grown during the winter and farm BWC data includes flocks grown during other seasonal periods. However, 1.82 kg water consumed per kg feed consumed represents a WFR value for broilers grown to 63 days, whereas previous WFR values reported are for broiler grown up to 56 days (Chapter 2). Seasonal WFR input variables will be incorporated as data becomes availability to better represent BWC throughout the year.

Table 3.2. East Alabama farm flock placement information.

Date range	Number of days per grow-out (d)	Number of house
Aug. 10 – Oct. 11 2015	63	n = 8
Nov. 2, 2015– Jan. 2-3, 2016	62-63	n = 8
Jan. 26 – Mar. 21, 2016	56	n = 8
Apr. – Jun. 2016	56-58	n = 8
Jun. – Aug. 2016	59-61	n = 8
Sept. – Oct. 2016	54-55	n = 8
Dec. 2016 – Jan. 2017	54	n = 8
Feb. – Apr. 2017	58-59	n = 8
May – Jul. 2017	57-58	n = 8
Jul. – Sept. 2017	62	n = 1
Oct. – Dec. 2017	58-59	n = 4
Dec. 2017 – Feb. 2018	56-60	n = 5
Mar. – May 2018	58	n = 5
June – Aug. 2018	58-61	n = 6
Aug. – Oct. 2018	58	n = 6
Nov. 2018– Jan. 2019	54-56	n = 5
Jan. – Mar. 2019	57-58	n = 6
Apr. – June 2019	56-57	n = 6
Apr. – Jun. 2020	55	n = 8
Jun. – Aug. 2020	55-56	n = 8

Table 3.3. Flock husbandry model user inputs based on farm flock characteristics.

Flock husbandry inputs	Abbreviation	Input value
House length (m)	HL	155.5
House width (m)	HW	13.1
Stocking density (kg m^{-2})	SD	44
Number of broilers initially placed	BP	21,930
Average mortality (%)	MP	5.8
Flock length (d)	FL	63
Daily feed consumption (g $bird^{-1}$)	FC	Cobb 500
Mean water-to-feed ratio (kg water kg $feed^{-1}$)	WFR	1.82

Availability of farm EWC data was limited and only available for the five periods listed in table 3.4. The weather station at Montgomery Dannelly Field (USAF ID 722260), located 108 km south west of the farm, provided the most complete hourly weather data set nearest to the farm. Hourly dry bulb temperature (T_{db}), dew point (T_{dp}), and barometric pressure (p) for this station were downloaded from Integrated Surface Database (Smith et al., 2011) available through the National Centers for Environmental Information, ISD-Lite data set (NCEI, 2022). Barometric pressure data was missing for Sept. 7, 2015 and was replaced with data from the weather station at Maxwell AFB (USAF ID 722265), approximately 9.6 km north of Montgomery Dannelly Field. Weather data was corrected based on the number of hours from Greenwich time (Wilcox and Marion, 2008). Operation of the EC system was modeled as closely as possible to how the systems would have operated during production using the inputs listed in table 3.5. It was assumed EC systems would not be used prior to 21 days based on operation recommendations (Cobb, 2021). Beyond 21 days, EWC was only estimated during typical operation hours of 9:00 a.m. to 7:00 p.m. (Purswell et al., 2018, Cobb, 2021) and when outside dry bulb temperatures (T_{db}) were above 25.6°C and relative humidity (RH) was below 80% (Czarick and Fairchild, 2000; Donald et al., 2003). Saturation efficiency (η) was assumed to be 75% based on recommendations for 15-cm cellulose pad (Donald et al., 2000).

A total of 2,097 modeled EWC observations were compared to actual farm EWC use for the five test periods. Model estimates were compared to farm use totals and the ability of the model to predict four scenarios; farm EC was used and the model predicted EC use (U-P), farm EC was used but the model did not predict EC use (U-NP), farm EC was not used but the model predicted EC use (NU-S), and farm EC was not used and the model did not predict EC use (NU-NP).

Table 3.4. Date ranges evaluated for model evaporative cooling system water consumption (EWC).

Date range	Number of houses
Aug. 10 – Oct. 11 2015	n = 6
Apr. – Jun. 2016	n = 8
Dec. 2016 – Jan. 2017	n = 8
Jul. – Sept. 2017	n = 8
Jun. – Aug. 2020	n = 8

Table 3.5. Evaporative cooling (EC) system operation model inputs and boundary conditions to mimic east Alabama farm operation.

EC operation and boundary conditions	Abbreviations	Input value
Evaporative cooling system saturation efficiency (%)	η	75
Evaporative cooling system operating temperature limit (°C)	T_{limit}	26
Evaporative cooling system operating RH limit (%)	RH_{limit}	80
Broiler day of age limit	Broiler Age	21 days
System lower operating hour	LOH	9:00 a.m.
System upper operating hour	UOH	7:00 p.m.
Time zone correction	UTC	-6

3.3 Results and Discussion

3.3.1 Evaluating broiler water consumption (BWC) model estimates

Over the test period, the model overestimated total BWC by 6.9%, model and farm BWC were 42,764,498 L and 39,904,581 L, respectively (table 3.6). Total BWC over the 132 flocks evaluated was 302,307 L for the farm and 323,973 L for model BWC.

Table 3.6. Comparison between total farm and modeled broiler drinking water consumption (BWC).

House	Num. Flocks	Farm BWC (L)	Model BWC (L)	Percent difference (%)
1	14	4,234,664	4,568,298	7.6
2	14	4,221,870	4,589,934	8.4
3	18	5,544,841	5,790,486	4.3
4	16	4,791,548	5,163,661	7.5
5	16	4,976,185	5,140,317	3.2
6	19	5,765,761	6,166,929	6.7
7	16	4,693,767	5,152,546	9.3
8	19	5,675,945	6,192,327	8.7
Total	132	39,904,581	42,764,498	6.9
Flock mean		302,307	323,973	

A comparison between mean daily farm and model BWC is shown in figure 3.2. The model overestimated BWC between days one to six and days 21 to 63 and underestimated BWC between days seven and 20. Model overestimation between days one to six could be due to flows being below the measureable range of the positive displacement water meters installed on the farm (Johnson et al., 2022). The application of a mean daily mortality likely contributed to the over and under estimation of model BWC as well. Both Xin et al. (1994) and Tabler et al. (2004) reported mortality patterns for broilers grown from seven to eight weeks under commercial conditions. Both reported similar patterns where mortality spiked between three and seven days after placement, stabilized until day 30 to 35, and increased until harvest. Incorporating a dynamic mortality term based on age range could provide a better estimation of BWC, particularly for model BWC estimates from five to nine weeks. With an increased mortality during weeks five to nine, model BWC would decrease, moving model estimates closer to actual farm BWC. Daily farm and model BWC values are given in the appendix (table A.3.1).

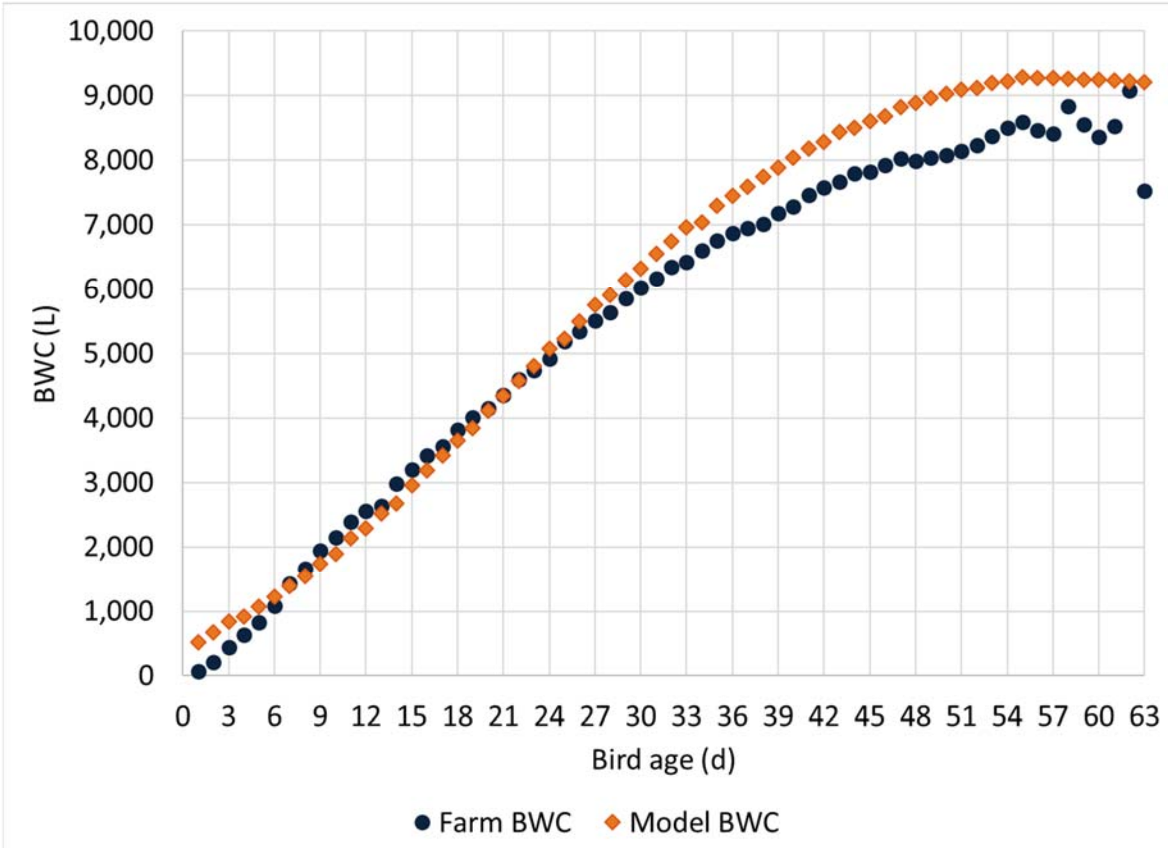

Figure 3.2. Comparison of daily mean broiler water consumption (BWC) between farm data and model estimates. Farm BWC represents mean BWC data for the 2015 to 2020 test period.

Consumption equations presented by Pesti et al. (1985), Xin et al. (1994), Brake et al. (1992), and Obaia (2015) were also compared to farm BWC reported in this study for the same age range listed in each study. Daily estimates using each study's equation are shown in figure 3.3. Estimates of daily mean BWC by the model were higher compared to previous studies and appear to mimic overall farm drinking behavoir. Pesti et al. (1985), Brake et al. (1992), and Obaia (2015) suggest a linear realationship for dialy BWC whereas farm BWC, model BWC, and Xin et al. (1994) suggests a logarithmic relationship. Equations from these previous studies underestimate total farm BWC between 12,369 and 89,936 L (table 3.7).

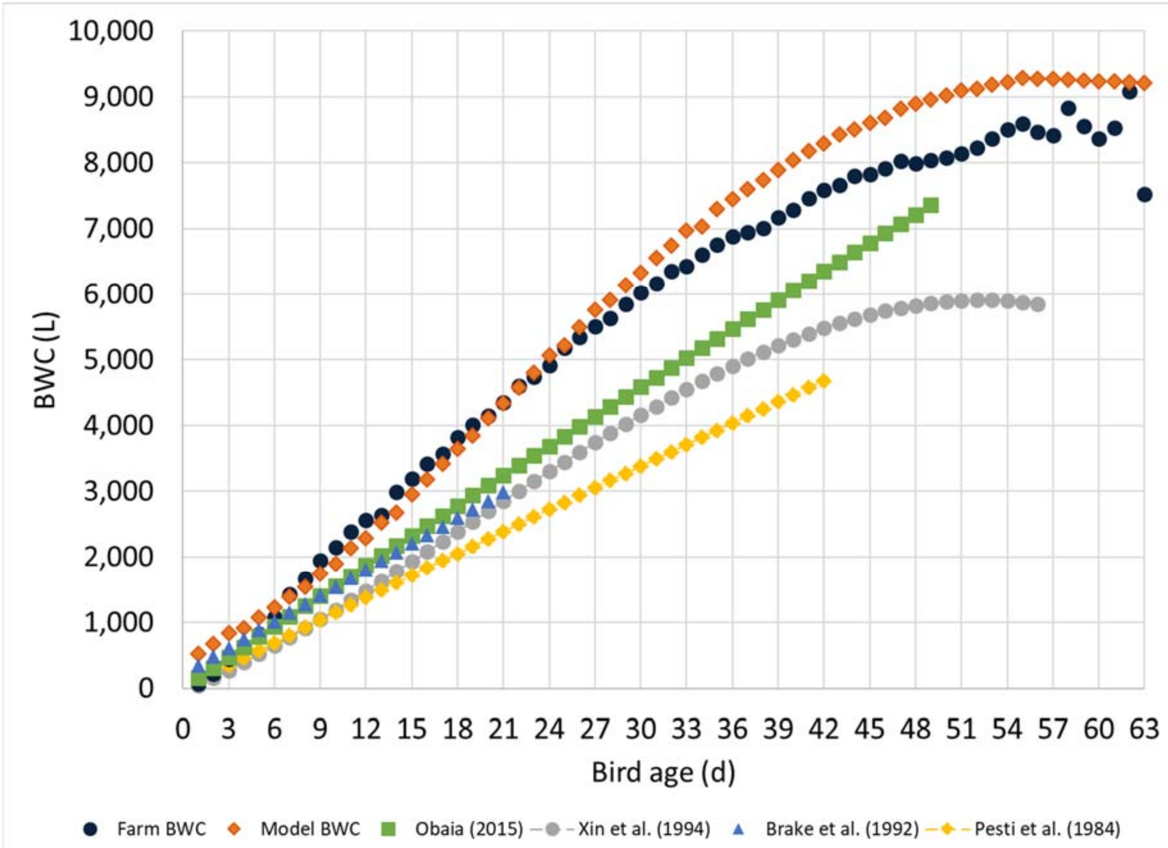

Figure 3.3. Comparison of daily mean farm and model broiler drinking water consumption (BWC) between drinking water equations presented in the literature.

Table 3.7. Comparison between estimated total broiler drinking water consumption (BWC) based on equations presented in literature and farm BWC for the same age range listed in the reference.

Reference	Age range	Estimated BWC based on reference equation and age range (L)	Farm BWC[a] (L)	Percent difference
Current study	1-63	375,825	350,960	6.8
Obaia (2015)	1-49	186,735	233,273	-22.2
Xin et al. (1994)	1-56	201,722	291,658	-36.5
Brake et al. (1992)	1-21	35,176	47,545	-29.9
Pesti et al. (1985)	1-42	101,952	178,005	-54.3

[a] Farm BWC represents BWC values for the same age range of the referenced study

3.3.2 Evaluating evaporative cooling system water consumption (EWC) model estimates

Total model EWC was overestimated by 140% compared to farm data for the five flock test period. Total model EWC was estimated over the entire test period to be 9,205,733 L compared to actual farm EWC of 2,879,309 L. The model correctly predicted EC operation for 1,608 (U-P plus NU-NP) observations out of 2,075 (77%) (table 3.8). The model predicted 843 observations of EWC compared to 1,079 observations the farm recorded EWC (U-P plus U-NP) (78%). Out of the 236 observations the farm recorded EWC, but the model did not predict EWC (U-NP), the farm recorded 151 observations of EWC between days one to 20, contrary to the model assumption EWC would not be used until 21 days and older. The farm EWC values ranged between 4 L and 2,718 L per day. While it was unclear why farm EWC was recorded, some of these events could have been from the grower running the pads for other reasons rather than cooling such as system bleed-off to maintain pads. The largest consumption values were recorded during June and July 2020 for broilers aged 19 and 20 days. Temperatures during these days were above 30°C and the grower likely chose to provide some amount of cooling through the EC system before the assumed 21 day threshold. The model correctly predicted 77% of the observations where the farm did not record EWC (765 out of 996 observations). Of the 231 observations the model incorrectly predicted EWC, 60 were during the Dec. 2016 to Jan. 2017 flock. Growers will typically "winterize" EC systems during these cold weather months to avoid damaging the systems which might explain why the grower chose not to operate the pads.

Table 3.8. Evaluation of model to determine cooling events when farm EWC was used and the model predicted EWC use (U-P), farm EWC was used but the model did not predict EWC use (U-NP), farm EWC was not used but the model predicted EWC use (NU-P), and farm EWC was not used and the model did not predict EWC use (NU-NP).

	Detected Evaporative Cooling Events			
Total number of observations No. obs.	U-P No. obs.	U-NP No. obs.	NU-P No. obs.	NU-NP No. obs.
2,075	843	236	231	765

Results suggest management assumptions made in the model for this particular farm should be modified to better represent grower operation of EC systems for both prediction of cooling events and estimating EWC. Farm data suggests in some cases cooling is needed prior to 21 days and lowering this threshold to 19 or 20 might better predict cooling events. With regards to the overestimation of EWC, the model currently estimates peak EWC values where consumption was estimated over the entire time step given hourly weather data. Growers will utilize a timer to operate EC systems in order to reduce water consumption where the system might run 2 min on and 8 min off (Czarick and Fairchild, 2018). Including a variable input for on and off times would better mimic EC operation and reduce the overestimation of EWC made by the model.

Weather station proximity would also effect the model's ability to estimate EWC quantity and cooling events. Research suggests urban areas can experience warmer temperatures compared to surrounding rural areas (Zhao et al., 2014; Filho et al., 2017). Therefore, hourly values for T_{db} could have varied between the weather station for this study, located within the city limits of Montgomery, AL, compared to T_{db} values experienced at the farm, located in a rural area of East Alabama. Using potentially elevated T_{db} would have contributed to the model simulating the EC systems being needed when in fact ambient farm T_{db} was below T_{limit}. Installing a weather station on this farm would present the ideal situation for collecting accurate and precise ambient weather conditions to estimate farm EWC.

3.3.3 Example model output for east Alabama

The model was run to estimate water consumption on a per house basis for the east Alabama farm over a 30-year period from 1990 to 2020 growing a 63 day broiler with a target weight of 4.1 kg. A total of 140 flocks were modeled over the 30-yr period (average 4.7 flocks yr^{-1}). Weather data from the Montgomery Dannelly Field weather station was used and the time zone corrected (UTC -6). Model inputs are listed in table 3.9.

Table 3.9. Flock husbandry and evaporative cooling (EC) system operation and boundary model inputs.

Flock husbandry inputs	Abbreviation	Input value
House length (m)	HL	155.5
House width (m)	HW	13.1
Flock length (d)	FL	63
Stocking density (kg m^{-2})	SD	44
Average mortality (%)	Mortality	5.8
Daily feed consumption (g $bird^{-1}$)	FC	Cobb 500
Water-to-feed ratio (kg water kg $feed^{-1}$)	WFR	1.82
EC operation and boundary inputs		
System lower operating hour	LOH	9:00 a.m.
System upper operating hour	UOH	7:00 p.m.
Mean wind speed (m s^{-1})	WS	2.6
Broiler day of age limit	DOA_{limit}	21
Evaporative cooling system operating temperature limit (°C)	T_{limit}	25.6
Evaporative cooling system operating RH limit (%)	RH_{limit}	80
Evaporative cooling system saturation efficiency (%)	η	75

Daily model output is demonstrated in figure 3.4 where estimates for BWC and EWC are shown for 13 totals flocks and one partial flock from 1990 to 1992. The primary use of EWC was modeled during mid-April through September during each year, a similar time frame noted by Purswell et al. (2018) as warm weather months when EC systems would be used. During cooler months (December through February), when growers typically "winterize" their systems, the model did estimate about 5 days of EWC when ambient temperatures were above T_{limit}.

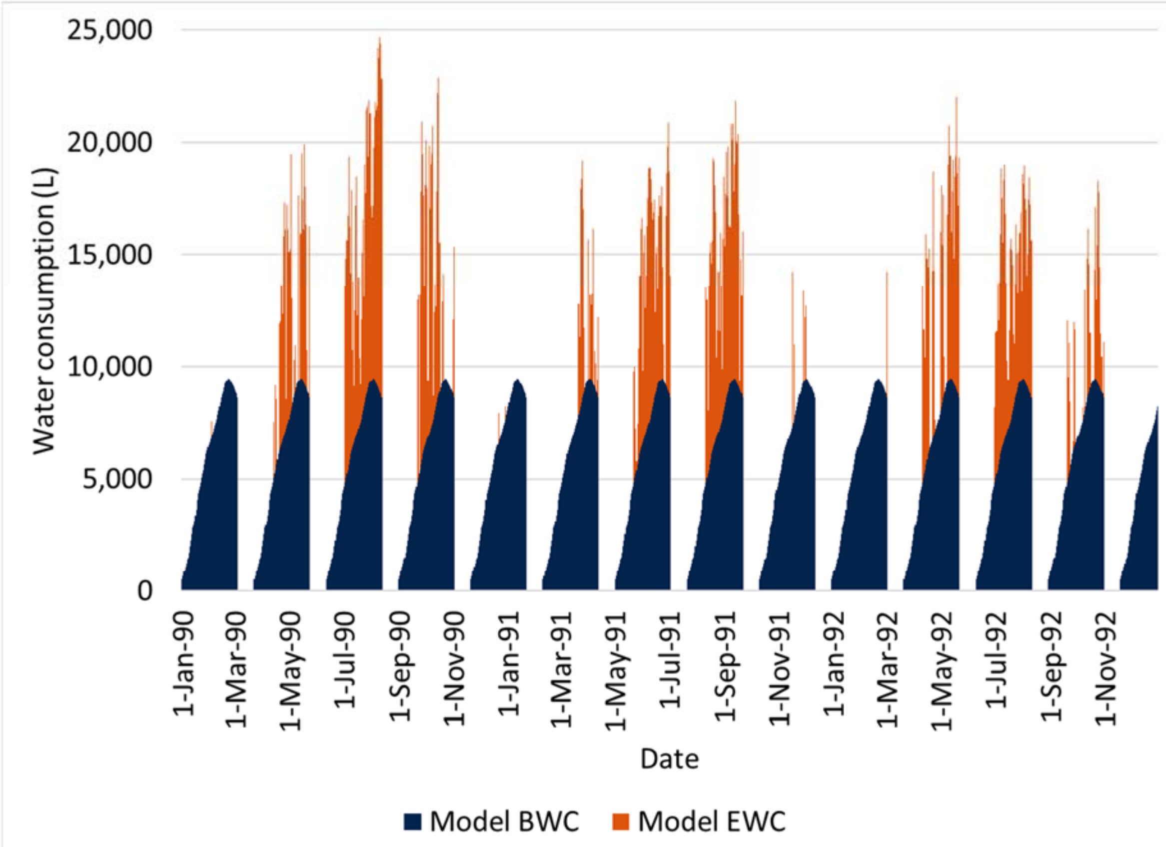

Figure 3.4. Model output for broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) from Jan. 1, 1990 to Dec. 31, 1992 for one, 13.1 x 155.5 m broiler house in east Alabama growing broilers to 63 days.

The model estimated total water consumption values for BWC and EWC on a per house basis over the 30-yr period to be 52,864,676 and 24,615,744 L, respectively (table 3.10). Mean annual estimates were 1,705,312, 794,056, and 2,499,368 L for BWC, EWC and TWC, respectively. Based on the 140 flocks modeled, mean flock BWC, EWC, and TWC would be 377,605, 175,827, and 553,432 L, respectively. It should be noted model estimates for both EWC and TWC are likely overestimations based on comparisons of model EWC to actual farm EWC data discussed previously.

Table 3.10. Model estimates for broiler drinking water consumption (BWC), evaporative cooling system water consumption (EWC), and total water consumption (TWC) for one, 13.1 x 155 m, house growing a 63 day broiler in east Alabama over a 30-yr period.

	Annual mean (L per house)	Annual min (L per house)	Annual max (L per house)	30-year Total (L per house)
BWC	1,705,312	1,574,087	1,833,002	52,864,676
EWC	794,056	524,534	1,146,527	24,615,744
TWC	2,499,368	2,165,502	2,871,826	77,480,420

3.4 Conclusions

A model was developed to estimate the two main water consumption needs on today's commercial broiler farm to provide growers, integrators, and other industry stakeholders a better understanding of how much water commercial farms require during production. Model consumption estimates were compared to data from a commercial broiler farm in East Alabama. Broiler drinking water consumption (BWC) was estimated using a water-to-feed ratio and publicly available primary breeder feed intake data to within 7% of farm data. Evaporative water consumption (EWC) was estimated based on hourly weather station data for a farms location. EWC was overestimated by approximately 6.3 mil L and correctly modelled EC operation by 77% over the five flocks evaluated. Results suggest changes to boundary conditions and modeled operation of EC systems would provide a better estimation of EWC. Overall, the model was used to estimate total water consumption for a grower in east Alabama given specific farm input variables.

The model was designed to adapt to changes the commercial broiler industry might experience in the future by incorporating multiple input variables (e.g. WFR, house size, flock length, and geographic location). Whether it is changes in management practices or broiler performance, the model aims to provide an understanding of the "current" state of water consumption for commercial broiler farms across the US. To achieve this adaptability, primary breeders and the research community should continue monitoring and updating commercial broiler performance based on best management practices. Specifically, primary breeders are encouraged to update performance data regularly and consider adding daily broiler water consumption to performance objective data. Doing so would provide growers, integrators, and researchers valuable information for growing high performance broilers.

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Table A.3.1. Comparison of daily mean farm and modeled broiler drinking water consumption (BWC) for broilers raised to 63 days in 13.1 x 155.5 m house in east Alabama.

Broiler age d	Farm BWC (L)	Model BWC (L)	Percent difference (%)	RMSE (L d^{-1})
1	69	521	153.2	457
2	217	681	103.5	492
3	447	841	61.1	495
4	636	920	36.6	453
5	824	1,079	26.9	441
6	1,082	1,238	13.5	382
7	1,427	1,392	-2.5	282
8	1,665	1,560	-6.6	301
9	1,943	1758	-10.0	349
10	2,148	1,912	-11.7	372
11	2,387	2,148	-10.5	412
12	2,565	2,305	-10.7	440
13	2,634	2,541	-3.6	341
14	2,989	2,697	-10.3	502
15	3,198	2,972	-7.3	474
16	3,414	3,206	-6.3	485
17	3,565	3,440	-3.6	468
18	3,819	3,674	-3.9	514
19	4,007	3867	-3.6	523
20	4,152	4,139	-0.3	525
21	4,357	4,371	0.3	573
22	4,600	4,603	0.0	620
23	4,742	4,834	1.9	758
24	4,919	5,104	3.7	806
25	5,185	5,255	1.3	735
26	5,340	5,524	3.4	797
27	5,505	5,792	5.1	813
28	5,641	5,943	5.2	811
29	5,854	6,170	5.2	890
30	6,030	6,359	5.3	930
31	6,169	6,587	6.5	952
32	6,347	6,775	6.5	987
33	6,429	7,001	8.5	1,036
34	6,605	7,071	6.8	1,012
35	6,758	7,338	8.2	1,086
36	6,878	7,483	8.4	1,071
37	6,944	7,630	9.4	1,178
38	7,011	7,779	10.4	1,247
39	7,176	7,926	9.9	1316
40	7,281	8,072	10.3	1,325
41	7,462	8,217	9.6	1,291
42	7,582	8,325	9.3	1,342
43	7,667	8,468	9.9	1,351
44	7,801	8,536	9.0	1,292
45	7,821	8,642	10.0	1,315
46	7,919	8,709	9.5	1,332
47	8,023	8,854	9.8	1,364
48	7,992	8,921	11.0	1,480
49	8,045	8,988	11.1	1,412
50	8,081	9,055	11.4	1,346
51	8,141	9,122	11.4	1,344

52	8,231	9,150	10.6	1,350
53	8,369	9,216	9.6	1,380
54	8,508	9,245	8.3	1,375
55	8,590	9,310	8.0	1,468
56	8,464	9,339	9.8	1,843
57	8,416	9,326	10.3	1,356
58	8,838	9,384	6.0	2,171
59	8,550	9,548	11.0	1,544
60	8,363	9,646	14.2	1,572
61	8,528	9,668	12.5	1,472
62	9,081	9,762	7.2	1,631
63	7,525	9,797	26.2	2,422

Chapter 4

Evaluating on-farm water consumption needs for commercial broiler farms in the U.S.

4.1 Introduction

U.S. broiler (meat-type chickens) production is concentrated in an area commonly referred to as the "broiler belt"; stretching from Texas, through the southeast, and up the east coast to the Delmarva peninsula. The industry has seen steady growth since 2001 and long-term projections show that growth will continue through 2031 (USDA, 2022). Like many agricultural sectors, the broiler industry is having to address challenges to meet sustainability goals and adapt to the effects that are developing from climate change. Add to this, projections that global population will increase to 9.7 billion by 2050 (UN-DESA, 2021), and competition for land, water, and energy will create further challenges for global agriculture to meet increased food production demands (FOA, 2009; Thornton, 2010).

Water in particular is a critical nutrient for broilers (NRC, 1994) and adequate supply is required during the grow-out process. This is especially true for growers raising large birds during hot weather where water consumption increases significantly with broiler age (Bruno et al., 2011) and environmental temperatures above a broiler's thermal comfort zone (Donkoh, 1989; May and Lott, 1992; North and Bell, 1990; Belay and Teeter, 1993; Alleman and Leclercq, 1997). During periods of elevated temperatures, a broiler's physiological response to heat stress is to pant, evaporating water from their respiratory tract in order to decrease their core body temperature (Julian, 2005). To avoid heat stressing birds, housing systems are designed to maintain air velocity creating a "wind chill" effect to remove heat from the house. When air velocity can no longer provide effective cooling, evaporative cooling (EC) systems are used to mitigate heat stress (Donald et al., 2000; Campbell et al., 2007; Campbell et al., 2011). Purswell et al. (2018) noted EC requirements across poultry producing areas in the U.S. varied based on climate and weather patterns of the specific location. These water demands will likely change due to climate variation and increased frequency of temperature extremes brought on by climate change (Thornton, 2010; IPCC, 2013; Rojas-Downing et al., 2017; FAO et al., 2021; Kumar et al., 2021) Heat wave frequency, duration, and intensity in broiler producing areas of the U.S. have increased significantly (USEPA, 2021) and growers will have to rely more on EC systems to provide house cooling. Considering average target weights have been shifting towards larger broilers (USDA, 2012; WATT, 2022; USDA, 2022), this will also increase BWC and the likelihood growers will rely more on EC systems to mitigate heat stress.

Chapter 3 noted while the importance of on-farm water availability has been stressed within the literature, water requirements are limited to certain farm configurations and locations in poultry producing areas of the U.S. Therefore, the objective of this research was to estimate annual total water consumption (TWC) for 27 farm configurations for 14 locations within the "broiler belt" over a 30-year period to provide a better understanding of on-farm water needs.

4.2 Methods and Materials

The water consumption model outlined in chapter 3 was used to determine annual total water consumption for 14 locations (fig. 4.1). The highlighted states accounted for 82% of U.S. domestic broiler production in 2020 (USDA, 2021) and specific cities were chosen based on high concentrations of broiler production in or near these cities. The model estimates daily broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) based on user inputs and weather data. The primary inputs to estimate BWC were feed consumption (FC) data published by primary breeders and an assumed water-to-feed ratio (WFR). Estimates for EWC were made by estimating evaporation rates using psychrometric equations and historical hourly weather data for the specific location. Weather data between 1990 and 2020 was retrieved from the National Centers for Environmental Information, ISD-Lite data set (NCEI, 2022) for each location. Weather station information is listed in the appendix (table A.4.1). Any missing data was replaced with available data from the nearest weather station.

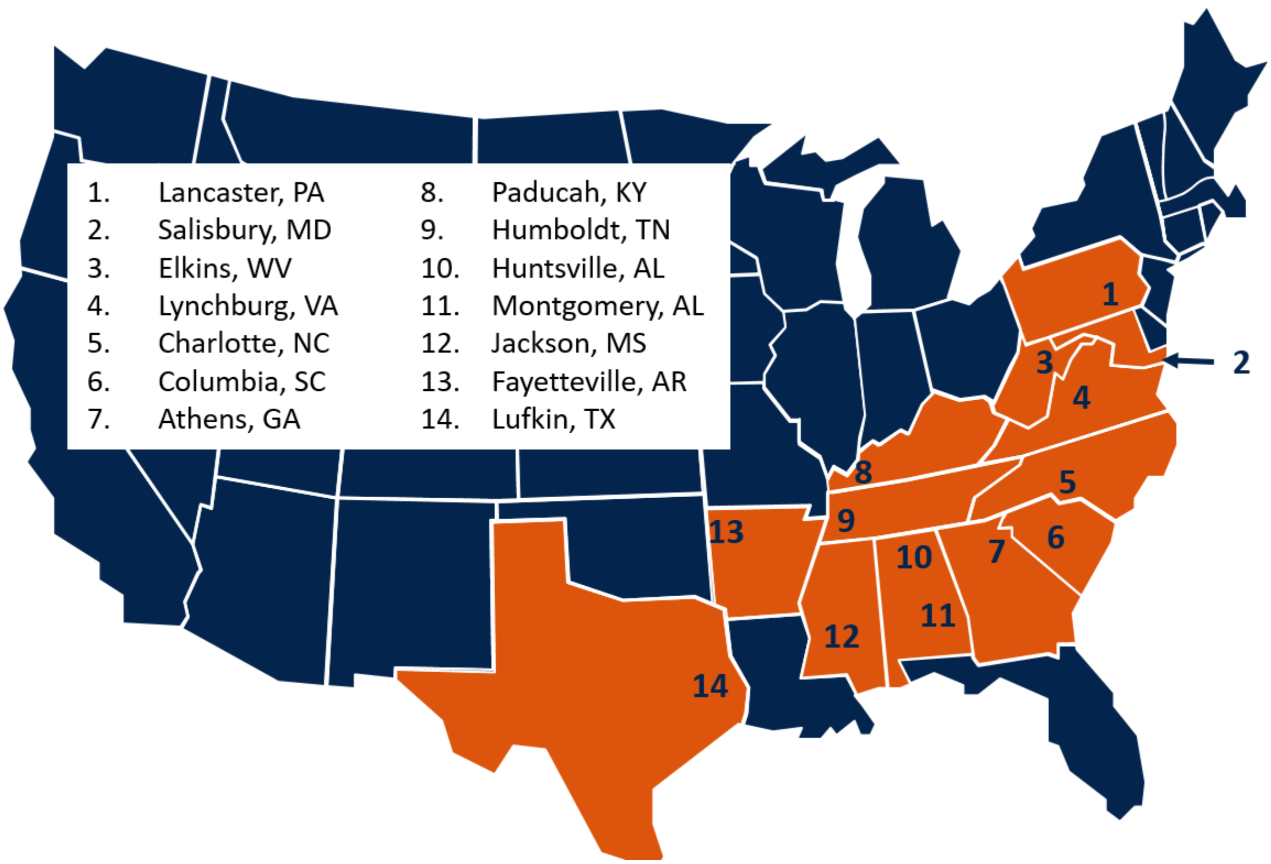

Figure 4.1. Locations representing high concentrations of U.S. broiler production in or near the cities listed in the top left corner.

A set of 27 farm configurations were chosen based on three levels of bird age, house air velocity, and house size to represent typical farming operations (table 4.1). Bird ages of 35, 42, and 63 days reflect target weights of 2.2, 2.9, and 4.1 kg bird^{-1}, respectively. Stocking density was based on

NCC (2020) recommendations for the projected target weights and were 16, 14, and 11 birds m^{-2}, for 35, 42, and 63 day old broilers, respectively. Feed consumption data was based on the genetic strain of broiler. Primary breeders have developed specific breeds to achieve certain target weights, therefore, the 35 and 42 day broilers were modeled after the Ross 308 and the 62 day broiler was modeled after the Ross 708. Feed consumption data was based on as-hatched daily values for each breed (Aviagen, 2019a; Aviagen, 2019b). The range of air velocity for the 35 day broilers was 1.78, 2.29, and 2.79 m s^{-2}, lower than the air velocity for the 42 and 63 d broilers of 2.79, 3.30, and 3.81 m s^{-2}. The lower range of air velocity would be more typical for a 35 day broiler because of the risk of chilling birds at air velocities above 2.79 m s^{-2}. House dimensions were 12.2 x 152.4, 15.2 x 152.4, and 20.1 x 183.9 m, representing three common house sizes in today's commercial broiler industry.

Table 4.1. Scenario runs representing a range of broiler farm configurations within the broiler industry.

Run	Bird age (d)	Stocking density (birds m^{-2})	Broiler strain	Air velocity (m s^{-1})	House width (m)	House length (m)
1	35	16	Ross 308	1.78	12.2	152.4
2	35	16	Ross 308	2.29	12.2	152.4
3	35	16	Ross 308	2.79	12.2	152.4
4	35	16	Ross 308	1.78	15.2	152.4
5	35	16	Ross 308	2.29	15.2	152.4
6	35	16	Ross 308	2.79	15.2	152.4
7	35	16	Ross 308	1.78	20.1	183.9
8	35	16	Ross 308	2.29	20.1	183.9
9	35	16	Ross 308	2.79	20.1	183.9
10	42	14	Ross308	2.79	12.2	152.4
11	42	14	Ross 308	3.30	12.2	152.4
12	42	14	Ross 308	3.81	12.2	152.4
13	42	14	Ross 308	2.79	15.2	152.4
14	42	14	Ross 308	3.30	15.2	152.4
15	42	14	Ross 308	3.81	15.2	152.4
16	42	14	Ross 308	2.79	20.1	183.9
17	42	14	Ross 308	3.30	20.1	183.9
18	42	14	Ross 308	3.81	20.1	183.9
19	63	11	Ross708	2.79	12.2	152.4
20	63	11	Ross 708	3.30	12.2	152.4
21	63	11	Ross 708	3.81	12.2	152.4
22	63	11	Ross 708	2.79	15.2	152.4
23	63	11	Ross 708	3.30	15.2	152.4
24	63	11	Ross 708	3.81	15.2	152.4
25	63	11	Ross 708	2.79	20.1	183.9
26	63	11	Ross708	3.30	20.1	183.9
27	63	11	Ross 708	3.81	20.1	183.9

Model inputs for flock husbandry and EC operation parameters are listed in table 4.2 and reflect similar parameters used in chapter 3. Layout period can vary based on scheduling by the integrator however the model assumed an average layout period of 18 days. Flock mortality was assumed to be 4%, within average mortality ranges (3.8% - 5%) reported by Trampel et al. (2013) and PHS (2016).

Table 4.2. Model inputs for flock husbandry and evaporative cooling (EC) system operation.

Flock husbandry inputs	**Abbreviation**	**Input value**
House length (m)	HL	*
House width (m)	HW	*
Flock length (d)	FL	*
Stocking density (kg m^{-2})	SD	*
Layout period (d)	LP	18
Average mortality (%)	Mortality	4
Daily feed consumption (g $bird^{-1}$)	FI	*
Water-to-feed ratio (kg water kg $feed^{-1}$)	WFR	1.82
EC operation and boundary inputs		
System lower operating hour	LOH	9:00 a.m.
System upper operating hour	UOH	7:00 p.m.
Mean wind speed (m s^{-1})	WS	*
Broiler day of age limit (d)	DOA_{limit}	21
Evaporative cooling system operating temperature limit (°C)	T_{limit}	25.6
Evaporative cooling system operating RH limit (%)	RH_{limit}	80
Evaporative cooling system saturation efficiency (%)	η	75

* input value varies based on scenario run

Annual model BWC and EWC were estimated values for each scenario during the test period (1990 to 2020) and summed to determine annual TWC. Results were presented as annual mean TWC, however it should be noted there is variability in water consumption from year to year based on weather conditions and what time of the year flocks are grown. Estimates presented below do not encompass the wide variability of broiler operations, rather discussions below present a snapshot of farm configurations and location to showcase the ability for the model to estimate water consumption based on user inputs.

4.3 Results and Discussion

Estimates from this study represent the maximum potential water consumption a farm might experience. This does not include water usage that might be used during maintenance of waterlines or EC systems. Estimated values for mean annual TWC for each location and scenario are given in the appendix (table A.4.2). Estimates are only applicable for the given scenario and the input variables. Observed trends for water consumption were similar for bird age, house size, and air velocity in all locations. Huntsville, AL was used as an example to demonstrate model trends and output. An increase in broiler finish size (fig. 4.2) and house size (fig. 4.3) resulted in increased BWC. The same was true for EWC. The number of cooling days was 1,353, 1,767, and 2,623 for broilers finished at 35, 42, and 63 days, respectively (table 4.3) and therefore EWC increased with increased broiler age. This suggests older broilers were more likely to experience days when EC systems were operated to provide additional cooling. As house size increased, specifically house width, the volumetric air flow increased resulting in an increase in EWC (fig. 4.3). A slight increase in EWC was also observed with increasing air velocity (fig. 4.4). Given these specific scenarios, the range of annual TWC for Huntsville, AL was between 1,329,225 and 5,553,674 L per house (fig. 4.5).

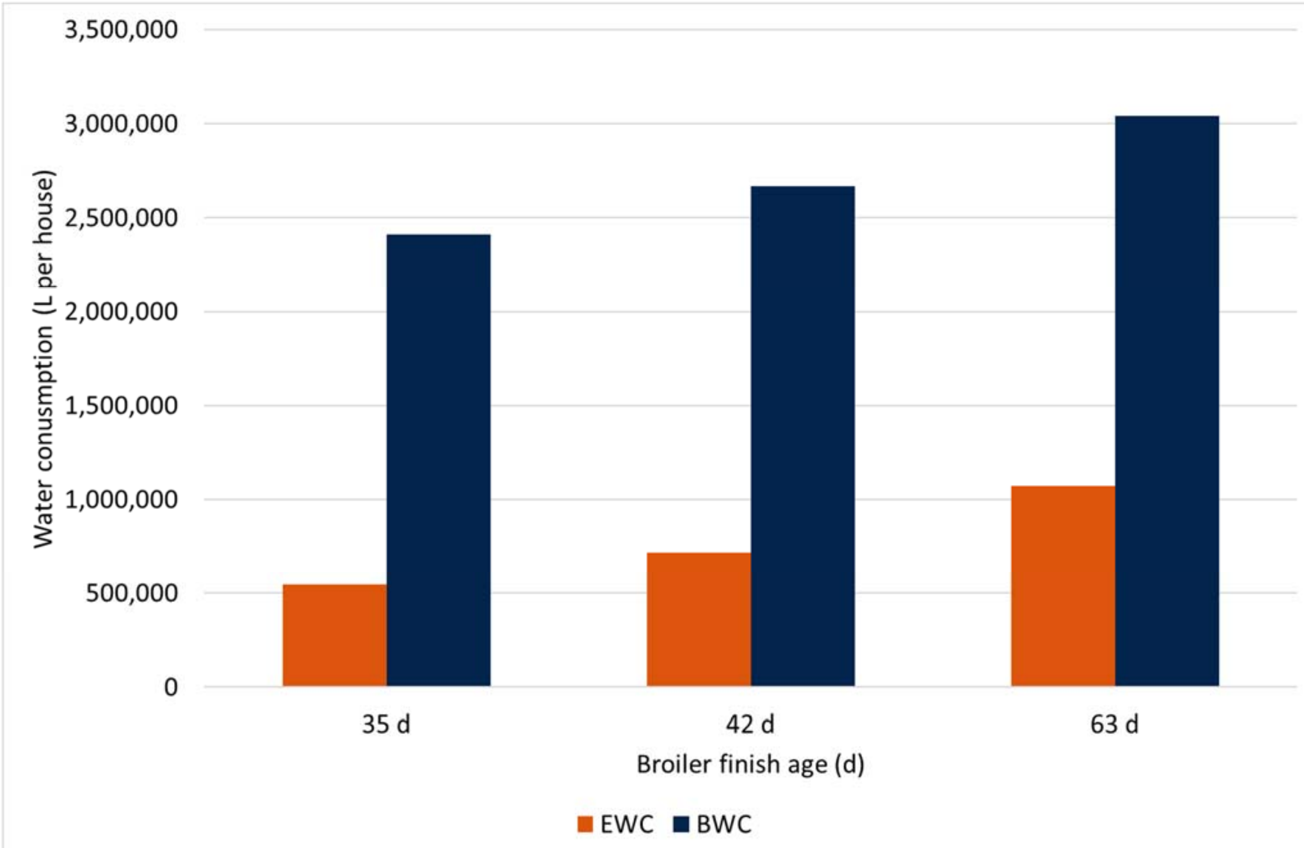

Figure 4.2. A comparison of mean annual evaporative cooling system water consumption (EWC) and broiler drinking water consumption (BWC) based on broiler age modeled for Huntsville, AL. House size and average air velocity were the same for each broiler age; 20.1 x 183.9 m and 2.79 m s^{-1}, respectively.

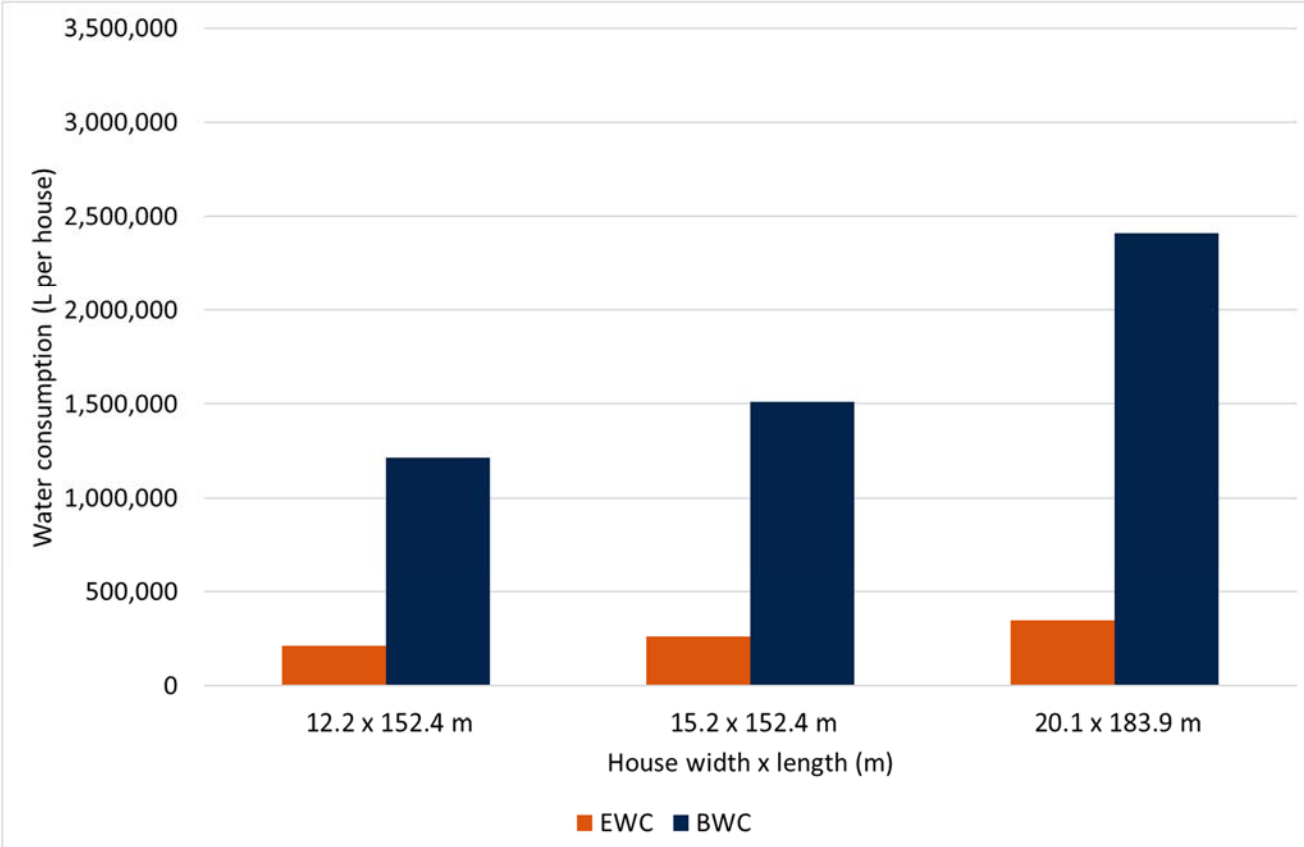

Figure 4.3. A comparison of mean annual evaporative cooling system water consumption (EWC) and broiler drinking water consumption (BWC) based on house size modeled for Huntsville, AL. Broiler age and average house air velocity were the same for each house size; 35 days and 1.78 m s^{-1}, respectively.

Table 4.3. Number of days the model estimated broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) for broilers finished at 35, 42 and 63 days during the test period in Huntsville, AL.

Broiler age (d)	Broiler drinking days (no. d)	Cooling days (no. d)
35	7,275	1,353
42	7,749	1,767
63	8,680	2,623

Note: total number of days during the test period was 11,323 (includes layout periods)

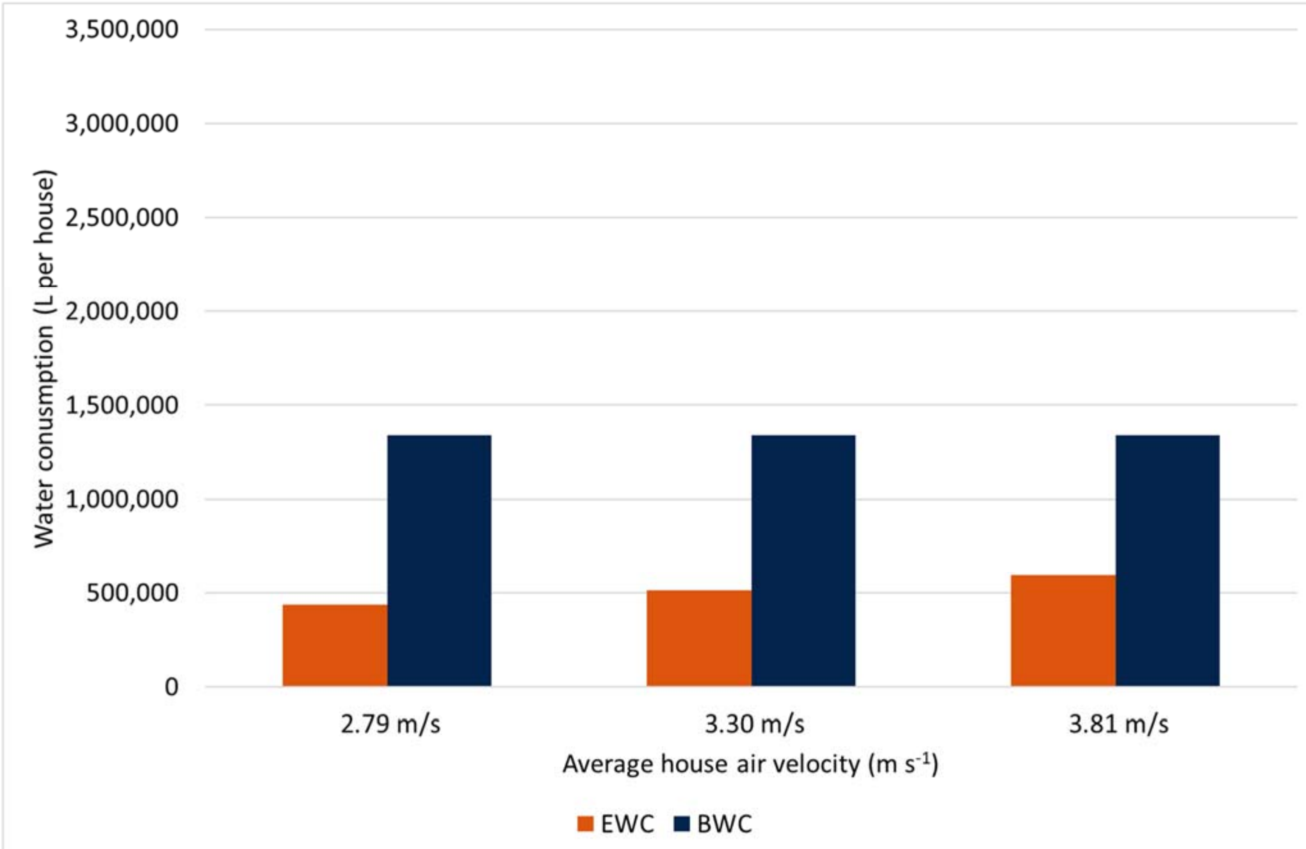

Figure 4.4. A comparison of mean annual evaporative cooling system water consumption (EWC) and broiler drinking water consumption (BWC) based on average house air velocity modeled for Huntsville, AL. Broiler age and house size were the same for each run; 42 days and 12.2 x 152.4 m, respectively.

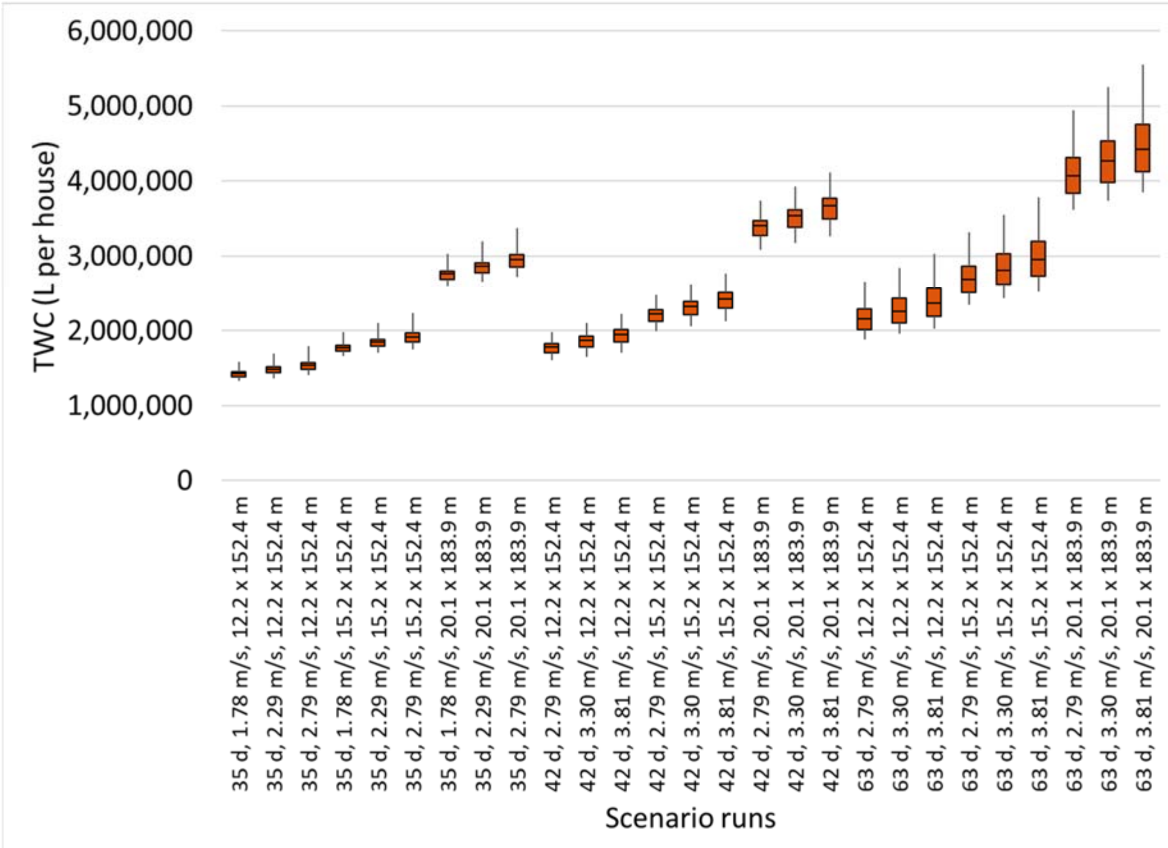

Figure 4.5. Mean annual broiler drinking water consumption (BWC) and evaporative cooling system water consumption (EWC) per house given bird age, average house air velocity, and house size for broilers grown in Huntsville, AL.

There are a few ways growers and integrators can utilize the model outputs to determine water consumption needs per house for their specific farm and geographic location. In some situations, growers might by changing from a small bird to a large bird operation and the model can provide an estimate of the new water needs for the farm. As an example, if a grower near Jackson, MS switched from growing a 35 day broiler to 63 day broiler in four 12.2 x 152.4 m houses running 2.79 m s^{-1}, mean annual TWC would increase from 1,597,050 L to 2,275,875 L per house, respectively (table A.4.2). The grower would need to ensure both their water supply and infrastructure could meet the additional 678,825 L per house annual demand switching to a larger bird program. Additionally, this grower might be interested in expanding their operation by adding two additional houses along with switching to growing larger birds. Doing so would increase mean annual farm water usage from 6,388,201 L for four houses finishing 35 day broilers to 13,655,252 L for six houses finishing 63 day broilers. The grower could use the model to determine the feasibility of building new houses based on well or municipal water capacity. In the case of growers relying on well-water, an additional well may need to be added to meet increased demand.

A second example would be the expansion or development of a new complex. An integrator looking to start a new 250 house complex in Humboldt, TN could use the model to estimate estimates the water load on the local water district. If the integrator wanted to finish 63 day broilers in 20.1 x 183.9 m houses running 3.81 m s^{-1}, mean annual TWC would be 4,338,588 L per house (table A.4.2). With the construction of 250 houses, total annual water demand for this complex would be 1.08 billion L. If the local water district does not have the capacity to meet this water demand, the integrator may have to scale down the number of house or find a more suitable location. Model outputs can also be used to demonstrate to growers, integrators, and water districts the variability in water needs based on farm configuration. This variability is demonstrated in figure 4.6 where box plots for each scenario are shown for Humboldt, TN. Each box plot represents the mean, min, and max annual TWC over the test period. Again using the example of an integrator or grower finishing 63 day broilers in a 20.1 x 183.9 m house running 3.81 m s^{-1} in Humboldt, TN, mean annual TWC was 4,338,588 L per house however annual TWC ranged between 3,769,881 and 5,261,947 L per house. Comparing across broiler ages suggest variability in annual TWC was greater as broiler age increased.

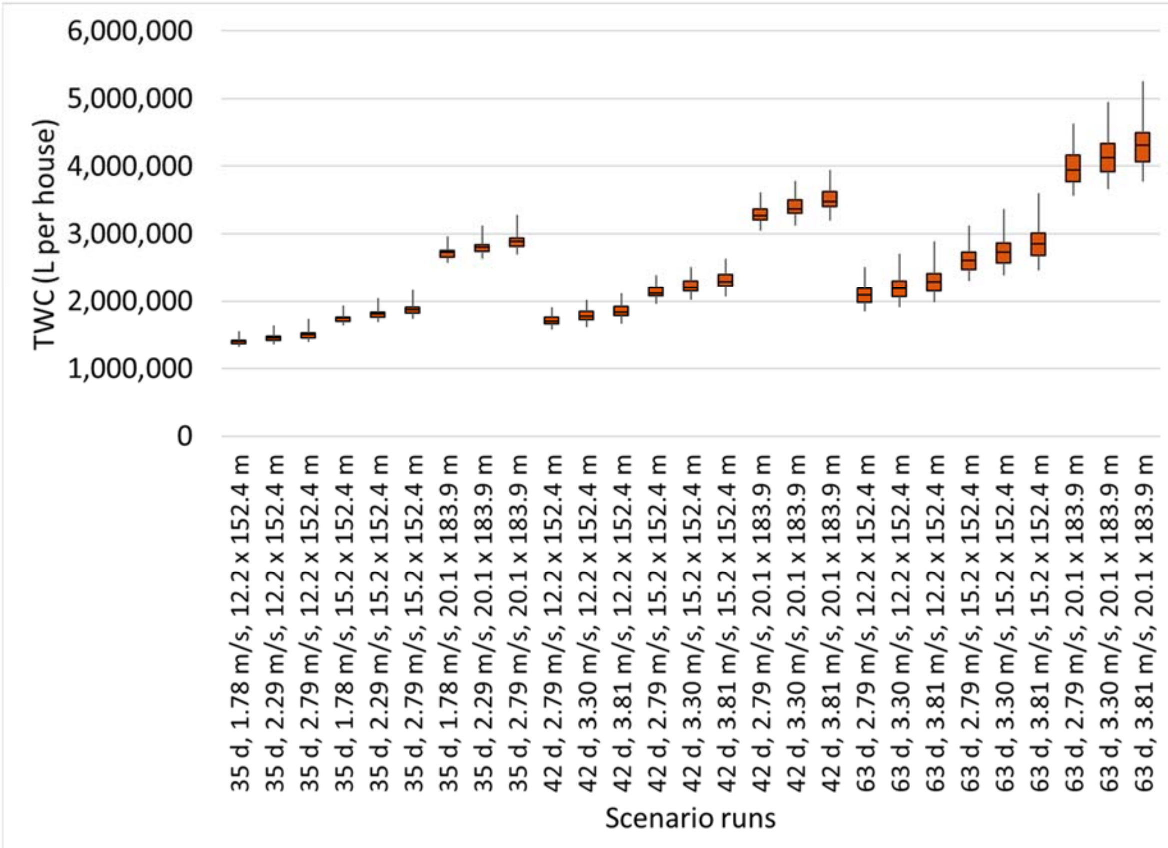

Figure 4.6. Mean annual broiler drinking water consumption (BWC) and evaporative water consumption (EWC) per house given bird age, average house air velocity, and house size for broilers grown in Humboldt, TN.

Figures 4.7 and 4.8 show the variability in annual TWC and EWC for each location, respectively. Box plots represent annual estimates for all 27 scenarios over the test period in each location. For example, based on the 27 scenarios used, consumption needs for Lancaster, PA ranged from 1,232,991 (scenario 35 d, 1.78 m s^{-1}, 12.2 x 152.4 m) to 4,674,188 (scenario 63 d, 3.81 m s^{-1}, 20.1 x 189.9 m) L per house (fig. 4.7). The range of annual TWC values across the 14 locations was between 1,218,614 and 5,727,258 L per house. The largest consumption scenario for all locations was estimated growing a 63 day broiler in a 20.1 x 183.9 m house with 3.81 m s^{-1} air velocity. Estimates for BWC ranged between 1,182,228 and 3,277,044 L per house while EWC ranged between 29,220 and 2,867,782 L per house for the 14 locations. Annual EWC varied between locations based on weather conditions in agreement with Purswell et al. (2018) (fig. 4.8) and was the driver for variability in TWC between locations. Further analysis would be needed to compare the robustness of hourly weather data sets to rule out error due to missing data. It should be noted that most locations will likely experience an increase in heat wave frequency and duration which will result in higher maximum potential water consumption values than those reported in this study.

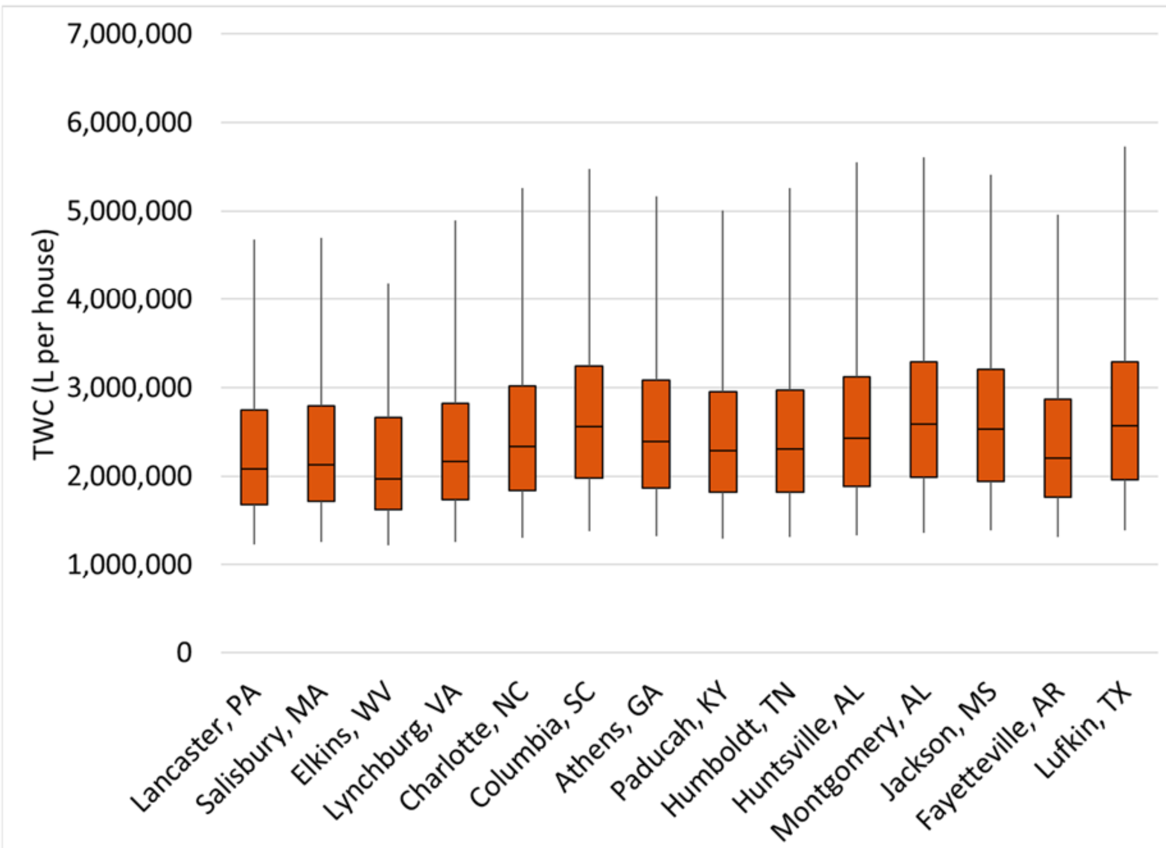

Figure 4.7. Box plot comparison of mean total water consumption (TWC) per house for each location and model scenario over the test period between 1900 to 2020.

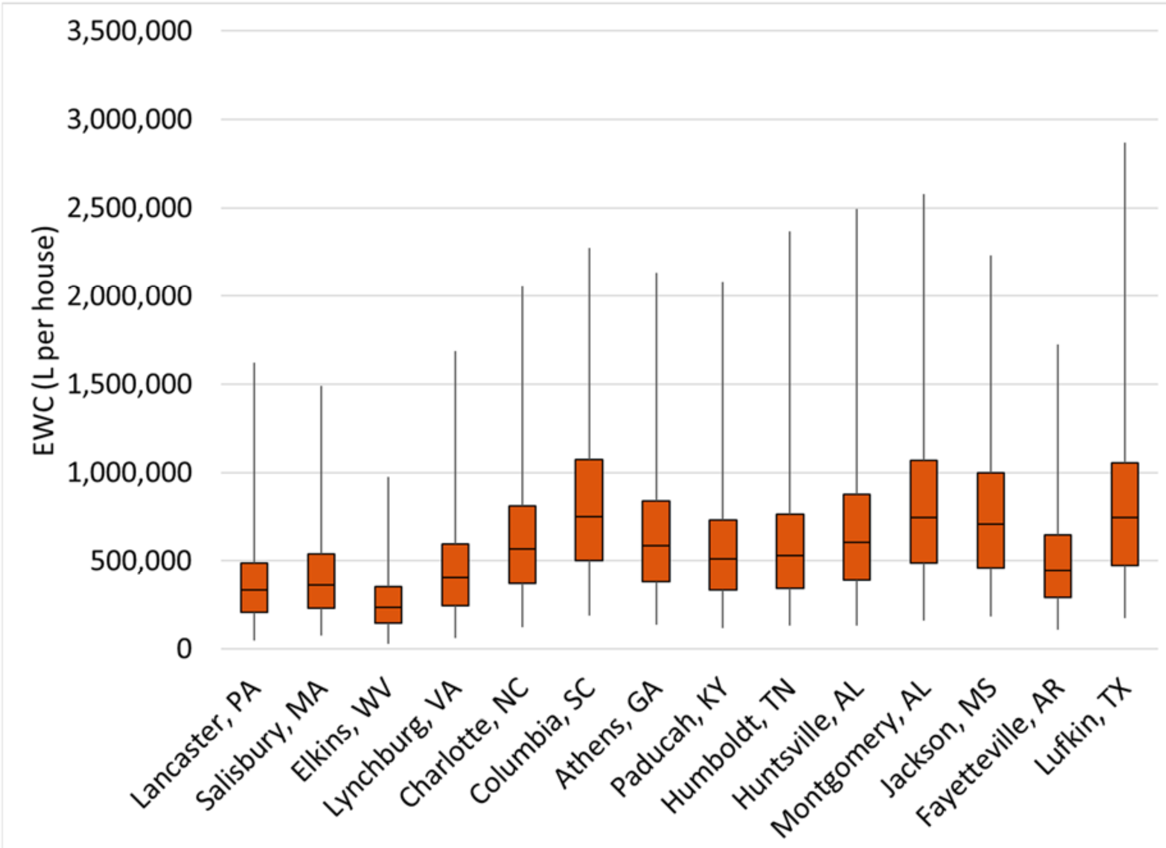

Figure 4.8. Box plot comparison of mean evaporative cooling system water consumption (EWC) per house for each location and model scenario over the test period between 1900 to 2020.

4.4 Conclusions

A water consumption model was used to estimate annual TWC per house over a 30-yr period for 14 locations across the broiler belt. Estimates were made for 27 scenarios representing typical commercial broiler farm configurations. Model results for the locations evaluated suggest the range of annual TWC for broiler production was 1.3 mil to 4.8 mil L per house. Annual BWC ranged from 1.2 million to 3.0 million L per house while EWC ranged from 86,075 L per house to 1.8 million L per house. Variability in TWC between location was driven by EWC estimates based on local weather conditions. As discussions become more frequent regarding farm water demand and water district capacities become more prevalent within the industry as well as an understanding that demand will likely increase due to effects from climate change, this model can provide growers and industry stake holders a better understanding of water demands for their specific broiler operation.

4.5 References

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4.6 Appendix

Table A.4.1. Weather station location, USAF site identifier, name, and time zone information downloaded from the National Climate Data Center (NCDC) ISD-Lite data set.

Location	USAF	Station Name	Time Zone
Lancaster, PA	725116	LANCASTER	-5
	725115	MIDDLETOWN HARRISBURG INTL AP	-5
	724080	PHILADELPHIA INTERNATIONAL AP	-5
Salisbury, MD	724045	SALISBURY WICOMICO CO AP	-5
	724040	PATUXENT RIVER NAS	-5
	745940	ANDREWS AFB	-5
Elkins, WV	724170	ELKINS ELKINS-RANDOLPH CO ARP	-5
	724177	MARTINSBURG EASTERN WV REG AP	-5
	724167	MORGANTOWN HART FIELD	-5
Lynchburg, VA	724100	LYNCHBURG REGIONAL ARPT	-5
Charlotte, NC	723140	CHARLOTTE DOUGLAS INTL ARPT	-5
Columbia, SC	723100	COLUMBIA METRO ARPT	-5
	723120	GREER GREENV'L-SPARTANBRG AP	-5
Athens, GA	723110	ATHENS BEN EPPS AP	-5
	722190	ATLANTA HARTSFIELD INTL AP	-5
Paducah KY	724350	PADUCAH BARKLEY REGIONAL AP	-6
	746716	BOWLING GREEN WARREN CO AP	-6
Humboldt. TN	723346	JACKSON MCKELLAR-SIPES REGL A	-6
	723340	MEMPHIS INTERNATIONAL AP	-6
Huntsville, AL	723230	HUNTSVILLE INTL/JONES FIELD	-6
Montgomery, AL	722260	MONTGOMERY DANNELLY FIELD	-6
	722265	MAXWELL AFB	-6
Jackson, MS	722345	JACKSON INTERNATIONAL AP	-6
Fayetteville, AR	723445	FAYETTEVILLE DRAKE FIELD	-6
	723440	FORT SMITH REGIONAL AP	-6
Lufkin, TX	722446	LUFKIN ANGELINA CO	-6
	722448	TYLER/POUNDS FLD	-6

Table A.4.2. Mean annual total water consumption (TWC) for 27 scenarios representing common broiler farm configurations.

Scenario (bird age, air velocity, house width and length)	Lancaster, PA (L yr-1)	Salisbury, MD (L yr-1)	Elkins, WV (L yr-1)	Lynchburg, VA (L yr-1)	Charlotte, NC (L yr-1)
35 d, 1.78 m s^{-1}, 12.2 x 152.4 m	1,327,454	1,341,015	1,299,395	1,351,221	1,410,003
35 d, 2.29 m s^{-1}, 12.2 x 152.4 m	1,360,154	1,377,602	1,324,057	1,390,732	1,466,356
35 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,392,214	1,413,471	1,348,235	1,429,467	1,521,604
35 d, 1.78 m s^{-1}, 15.2 x 152.4 m	1,654,259	1,671,156	1,619,301	1,683,871	1,757,108
35 d, 2.29 m s^{-1}, 15.2 x 152.4 m	1,695,001	1,716,739	1,650,028	1,733,097	1,827,318
35 d, 2.79 m s^{-1}, 15.2 x 152.4 m	1,734,944	1,761,429	1,680,151	1,781,358	1,896,151
35 d, 1.78 m s^{-1}, 20.1 x 183.9 m	2,599,855	2,622,199	2,553,629	2,639,013	2,735,860
35 d, 2.29 m s^{-1}, 20.1 x 183.9 m	2,653,732	2,682,477	2,594,260	2,704,109	2,828,703
35 d, 2.79 m s^{-1}, 20.1 x 183.9 m	2,706,551	2,741,573	2,634,095	2,767,928	2,919,726
42 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,579,374	1,604,175	1,513,336	1,632,764	1,740,651
42 d, 3.30 m s^{-1}, 12.2 x 152.4 m	1,622,903	1,652,237	1,544,794	1,686,052	1,813,661
42 d, 3.81 m s^{-1}, 12.2 x 152.4 m	1,666,432	1,700,300	1,576,252	1,739,341	1,886,671
42 d, 2.79 m s^{-1}, 15.2 x 152.4 m	1,967,968	1,998,867	1,885,692	2,034,486	2,168,904
42 d, 3.30 m s^{-1}, 15.2 x 152.4 m	2,022,201	2,058,749	1,924,885	2,100,879	2,259,867
42 d, 3.81 m s^{-1}, 15.2 x 152.4 m	2,076,434	2,118,630	1,964,078	2,167,271	2,350,830
42 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,059,809	3,100,669	2,951,009	3,147,770	3,325,519
42 d, 3.30 m s^{-1}, 20.1 x 183.9 m	3,131,525	3,179,854	3,002,837	3,235,565	3,445,806
42 d, 3.81 m s^{-1}, 20.1 x 183.9 m	3,203,241	3,259,039	3,054,665	3,323,360	3,566,093
63 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,893,903	1,924,667	1,785,362	1,962,383	2,131,234
63 d, 3.30 m s^{-1}, 12.2 x 152.4 m	1,960,549	1,996,937	1,832,168	2,041,547	2,241,263
63 d, 3.81 m s^{-1}, 12.2 x 152.4 m	2,027,196	2,069,207	1,878,974	2,120,712	2,351,293
63 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,360,212	2,398,540	2,224,981	2,445,531	2,655,903
63 d, 3.30 m s^{-1}, 15.2 x 152.4 m	2,443,247	2,488,582	2,283,297	2,544,162	2,792,989
63 d, 3.81 m s^{-1}, 15.2 x 152.4 m	2,526,282	2,578,623	2,341,612	2,642,793	2,930,075
63 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,640,575	3,691,260	3,461,750	3,753,399	4,031,588
63 d, 3.30 m s^{-1}, 20.1 x 183.9 m	3,750,378	3,810,328	3,538,865	3,883,826	4,212,866
63 d, 3.81 m s^{-1}, 20.1 x 183.9 m	3,860,181	3,929,396	3,615,980	4,014,252	4,394,144

Scenario (bird age, air velocity, house width and length)	Columbia, SC (L yr-1)	Athens, GA (L yr-1)	Paducah, KY (L yr-1)	Humboldt, TN (L yr-1)	Huntsville, AL (L yr-1)
35 d, 1.78 m s^{-1}, 12.2 x 152.4 m	1,472,723	1,419,070	1,393,108	1,397,232	1,424,739
35 d, 2.29 m s^{-1}, 12.2 x 152.4 m	1,547,047	1,478,021	1,444,620	1,449,926	1,485,314
35 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,619,913	1,535,816	1,495,122	1,501,586	1,544,701
35 d, 1.78 m s^{-1}, 15.2 x 152.4 m	1,835,251	1,768,405	1,736,058	1,741,196	1,775,467
35 d, 2.29 m s^{-1}, 15.2 x 152.4 m	1,927,851	1,841,851	1,800,237	1,806,848	1,850,938
35 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,018,634	1,913,858	1,863,157	1,871,211	1,924,928
35 d, 1.78 m s^{-1}, 20.1 x 183.9 m	2,839,194	2,750,798	2,708,024	2,714,819	2,760,137
35 d, 2.29 m s^{-1}, 20.1 x 183.9 m	2,961,644	2,847,922	2,792,892	2,801,634	2,859,937
35 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,081,694	2,943,141	2,876,096	2,886,746	2,957,780
42 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,870,255	1,758,874	1,706,809	1,718,441	1,776,344
42 d, 3.30 m s^{-1}, 12.2 x 152.4 m	1,966,956	1,835,215	1,773,632	1,787,391	1,855,879
42 d, 3.81 m s^{-1}, 12.2 x 152.4 m	2,063,657	1,911,555	1,840,456	1,856,341	1,935,413
42 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,330,377	2,191,607	2,126,739	2,141,232	2,213,374
42 d, 3.30 m s^{-1}, 15.2 x 152.4 m	2,450,857	2,286,720	2,209,995	2,227,137	2,312,466
42 d, 3.81 m s^{-1}, 15.2 x 152.4 m	2,571,337	2,381,833	2,293,250	2,313,042	2,411,558
42 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,539,047	3,355,541	3,269,762	3,288,927	3,384,325
42 d, 3.30 m s^{-1}, 20.1 x 183.9 m	3,698,365	3,481,316	3,379,857	3,402,526	3,515,361
42 d, 3.81 m s^{-1}, 20.1 x 183.9 m	3,857,684	3,607,091	3,489,951	3,516,124	3,646,398
63 d, 2.79 m s^{-1}, 12.2 x 152.4 m	2,321,046	2,156,940	2,078,350	2,106,540	2,178,737
63 d, 3.30 m s^{-1}, 12.2 x 152.4 m	2,465,773	2,271,668	2,178,713	2,212,056	2,297,450
63 d, 3.81 m s^{-1}, 12.2 x 152.4 m	2,610,499	2,386,397	2,279,076	2,317,572	2,416,164
63 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,892,390	2,687,930	2,590,015	2,625,137	2,715,087
63 d, 3.30 m s^{-1}, 15.2 x 152.4 m	3,072,706	2,830,870	2,715,057	2,756,600	2,862,992
63 d, 3.81 m s^{-1}, 15.2 x 152.4 m	3,253,021	2,973,811	2,840,099	2,888,062	3,010,897
63 d, 2.79 m s^{-1}, 20.1 x 183.9 m	4,344,312	4,073,939	3,944,460	3,990,904	4,109,852
63 d, 3.30 m s^{-1}, 20.1 x 183.9 m	4,582,755	4,262,959	4,109,812	4,164,746	4,305,436
63 d, 3.81 m s^{-1}, 20.1 x 183.9 m	4,821,197	4,451,979	4,275,163	4,338,588	4,501,021

Scenario (bird age, air velocity, house width and length)	Montgomery, AL (L yr-1)	Jackson, MS (L yr-1)	Fayetteville, AR (L yr-1)	Lufkin, TX (L yr-1)
35 d, 1.78 m s^{-1}, 12.2 x 152.4 m	1,471,162	1,458,137	1,371,197	1,466,966
35 d, 2.29 m s^{-1}, 12.2 x 152.4 m	1,545,038	1,528,282	1,416,432	1,539,640
35 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,617,466	1,597,050	1,460,779	1,610,888
35 d, 1.78 m s^{-1}, 15.2 x 152.4 m	1,833,306	1,817,078	1,708,760	1,828,078
35 d, 2.29 m s^{-1}, 15.2 x 152.4 m	1,925,348	1,904,471	1,765,117	1,918,622
35 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,015,586	1,990,150	1,820,370	2,007,391
35 d, 1.78 m s^{-1}, 20.1 x 183.9 m	2,836,622	2,815,163	2,671,925	2,829,708
35 d, 2.29 m s^{-1}, 20.1 x 183.9 m	2,958,336	2,930,728	2,746,451	2,949,441
35 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,077,663	3,044,027	2,819,515	3,066,826
42 d, 2.79 m s^{-1}, 12.2 x 152.4 m	1,873,566	1,838,904	1,664,674	1,874,927
42 d, 3.30 m s^{-1}, 12.2 x 152.4 m	1,970,872	1,929,874	1,723,796	1,972,482
42 d, 3.81 m s^{-1}, 12.2 x 152.4 m	2,068,178	2,020,844	1,782,917	2,070,037
42 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,334,502	2,291,317	2,074,244	2,336,198
42 d, 3.30 m s^{-1}, 15.2 x 152.4 m	2,455,736	2,404,657	2,147,903	2,457,742
42 d, 3.81 m s^{-1}, 15.2 x 152.4 m	2,576,970	2,517,997	2,221,563	2,579,285
42 d, 2.79 m s^{-1}, 20.1 x 183.9 m	3,544,501	3,487,395	3,200,344	3,546,744
42 d, 3.30 m s^{-1}, 20.1 x 183.9 m	3,704,817	3,637,272	3,297,749	3,707,470
42 d, 3.81 m s^{-1}, 20.1 x 183.9 m	3,865,133	3,787,149	3,395,155	3,868,195
63 d, 2.79 m s^{-1}, 12.2 x 152.4 m	2,322,850	2,275,875	2,004,535	2,316,913
63 d, 3.30 m s^{-1}, 12.2 x 152.4 m	2,467,906	2,412,345	2,091,405	2,460,884
63 d, 3.81 m s^{-1}, 12.2 x 152.4 m	2,612,963	2,548,814	2,178,275	2,604,855
63 d, 2.79 m s^{-1}, 15.2 x 152.4 m	2,894,638	2,836,112	2,498,049	2,887,241
63 d, 3.30 m s^{-1}, 15.2 x 152.4 m	3,075,364	3,006,140	2,606,280	3,066,615
63 d, 3.81 m s^{-1}, 15.2 x 152.4 m	3,256,090	3,176,167	2,714,511	3,245,989
63 d, 2.79 m s^{-1}, 20.1 x 183.9 m	4,347,284	4,269,891	3,822,847	4,337,502
63 d, 3.30 m s^{-1}, 20.1 x 183.9 m	4,586,270	4,494,730	3,965,968	4,574,701
63 d, 3.81 m s^{-1}, 20.1 x 183.9 m	4,825,256	4,719,569	4,109,090	4,811,899

Chapter 5

Conclusions and further work

These studies aimed to provide growers and industry stakeholders a better understanding of water needs based on farm characteristics and geographic location. Results suggest that WFR values for broilers grown during winter conditions are below the industry assumption of 2 kg of water per kg feed and this assumption does not reflect WFRs for modern broilers. However, further work is needed to establish the variability in BWC and WFR based on seasonal differences for broilers raised under summer and spring conditions. Doing so would provide seasonal WFR model inputs to better reflect actual BWC throughout the year. Further development of the model is also needed to better estimate daily EWC. This can likely be achieved by modifying EC operation conditions, however a comparison between model EWC output and actual farm EWC data would be needed. Given water is critical to broiler live production, water consumption needs for broilers cannot be overlooked within the research and industry communities. Primary breeders should consider providing daily water consumption data along with feed intake data in performance objective literature. Doing so would provide both growers and researchers a consistent update on drinking water needs for broilers. These values could then be used within the water consumption model to provide accurate estimates of current water needs for growers.