

EVALUATION OF CAGE-FREE LAYER WATER USAGE PATTERNS AND PRELIMINARY
TESTING OF AN AUTOMATIC ALERT SYSTEM BASED ON HOURLY WATER USAGE

By

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(Under the Direction of Brian Fairchild)

ABSTRACT

Water usage monitoring has been a long-trusted management tool for commercial poultry production. Changes in water usage often signal the need for bird and housing inspections. This research focused on evaluating water usage in three cage-free layer houses, and identifying management alerts using hourly thresholds based on mean water usage and standard deviation. However, in the first trial, 71% of alerts lacked clear causes, potentially being false alarms. When the consistency of water usage patterns of the three laying houses was analyzed it was found that each house exhibited unique usage patterns, with consistent day-to-day trends. A new alert system based on Statistical Process Control was evaluated and detected events, yet 74% remained unexplained. These findings highlight the benefits of frequent monitoring but underscore the necessity for further research on dynamic alert thresholds.

INDEX WORDS: Water, Alert system, Usage patterns, Management, Modeling

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TABLE OF CONTENTS

Acknowledgments.....	iv
List of Tables	viii
List of Figures	x
Chapters	
1. Literature Review.....	1
a. The Function of Water in Birds	1
b. Factors that Affect Water Consumption	5
c. Modeling in Animal Agriculture	16
d. Statistical Process Control (SPC) and its Application to Animal Production Systems	19
2. Statement of Purpose	25
3. Materials and Methods.....	27
4. Results and Discussion	38
a. Trial 1.....	38
b. Trial 2.....	53
c. Trial 3.....	74
5. Conclusions.....	90

References	92
Appendix	100

LIST OF TABLES

Table 1. Photoperiods for all trials.....	28
Table 2. Feeding times for all trials.	29
Table 3. Daily Event Times ¹ for models for both farms created in Trial 2	36
Table 4. Means, standard deviations (SD), upper control limits (UCL), lower control limits (LCL), and range between thresholds (all in GPH) for Trial 1 alert model.....	41
Table 5. Number of alerts and dates, upper control limit (UCL) alerts, and lower control limit (LCL) alerts for Trial 1	43
Table 6. Means and standard errors for house normal expected usage (NEU) models created in Trial 2.....	56
Table 7. Error standard deviations for Farm A houses from the models created in Trial 2	69
Table 8. Error standard deviations for Farm B from the model created in Trial 2.....	70
Table 9. Error standard deviations for the effect of day on all Farms from the models created in Trial 2.....	71
Table 10. All Alerts from all houses during Trial 3.....	85
Table 11. Alert Categories For all houses during Trial 3.....	87
Table 12. Raw Data from December 2022 during Trial 1 on Farm A	101
Table 13. Water usage data from Farm A House 1 during Trial 2.....	103
Table 14. Water usage data from Farm A House 2 during Trial 2.....	104
Table 15. Water usage data from Farm B House 1 during Trial 2	105
Table 16. Water usage data from Farm A House 1 during Trial 3.....	106

Table 17. Water usage data from Farm A House 2 during Trial 3.....	107
Table 18. Water usage data from Farm B House 1 during Trial 3	108

LIST OF FIGURES

Figure 1. House layout sketch (not to scale), Feeders in red, drinker lines in blue, nest in grey, slats in brown, scratch area in yellow.	31
Figure 2. Flow of data of water usage from the water meter through recording and alert system used to generate abnormal usage alerts.....	34
Figure 3. Three days of typical water usage in Farm A House 1 & 2 during Trial 1	39
Figure 4. Trial 1 alert model means, upper control limits (UCL) and lower control limits (LCL)	40
Figure 5. Percentage of occurrence of consecutive alerts for both houses in Trial 1	44
Figure 6. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) during the supply issue in House 1 – Trial 1	45
Figure 7. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) during the supply issue in House 2 – Trial 1	48
Figure 8. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) in House 2 during storm event – Trial 1	51
Figure 9. Normal expected usage (NEU) model means for all houses created in Trial 2.....	55
Figure 10. Residual (observed – estimated) plot for Farm A House 1 model created in Trial 2 ..	58
Figure 11. Residual (observed – estimated) plot for Farm A House 2 model created in Trial 2...	59
Figure 12. Residual (observed – estimated) plot for Farm B House 1 model created in Trial 2 ..	60
Figure 13. Single day water usage (5-min intervals) and feeding times on Farm A House 2 – Trial 2.....	63

Figure 14. Ten days of Farm A House 2 water usage (5-min intervals), SD of residuals, and feeding times – Trial 2	64
Figure 15. Drinkers and feeders at a feeding time in Trial 2 where few birds are actively drinking	65
Figure 16. Drinkers and feeders 30 minutes after the feeding time in Trial 2 where more birds are actively drinking.	66
Figure 17. Radar plot of error standard deviation for time intervals on Farm A from the models created in Trial 2, the clockwise outward spiral shows variation increasing later in the day	72
Figure 18. Radar plot of error standard deviation for time intervals on Farm B from model created in Trial 2, the clockwise outward spiral shows variation increasing later in the day	73
Figure 19. Younger layer water usage alert model during Trial 3 Farm B House 1 on 1/18/24 (26 weeks), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)	75
Figure 20. Older layer water usage alert model during Trial 3 Farm B House 1 on 3/29/24 (36 weeks), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)	76
Figure 21. 7-Day average water usage from Farm B House 1 of 19-, 26-, and 36-week-old layers – Trial 3	78
Figure 22. Water usage alert model during system flush Farm B House 1 - Trial 3 (1/31/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)	81

Figure 23. Water usage alert model during lighting issue Farm B House 1 - Trial 3 (3/10/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD).....	82
Figure 24. Water usage alert model during feeding issue Farm B House 1 - Trial 3 (2/22/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)	84

CHAPTER 1

LITERATURE REVIEW

Water is one of the essential nutrients for poultry. Water is used for lubrication, transport of nutrients, aids in thermal regulation, and controls electrolyte balance. As a nutrient, water is often overlooked or even forgotten. Even so, it can be argued that water is the most essential nutrient as it is consumed in the highest amount. Water has many purposes in birds and has many factors that affect its consumption. The modern broiler is more efficient than 68 years ago, but less tolerant of stressors (Collins, et al. 2014). Therefore, water deprivation as a stressor may have greater consequences than before and water intake may vary more from other stressors such as heat stress (Belay and Teeter 1993) or feed changes (Viera and Lima, 2005) for the modern broiler than older lines. If the same trajectory of increasing performance and efficiency continues, the decrease of tolerance to stressors, and their effect on water consumption is also likely to continue.

THE FUNCTION OF WATER IN BIRDS

In digestion, water helps to lubricate and breakdown the solid grains that make up a majority of a chicken's diet (Scanes and Christensen, 2020). Some components of the diet are water soluble, therefore water helps with the utilization of these nutrients by increasing their absorption. Most of the grain used in bird diets has been dried from its harvest or developing states and will absorb water in its presence. (Karmas, 1973).

Water is the basis of mucus so any mucous lined tissue will be lubricated such as the respiratory tract or digestive tract (Scanen and Christensen, 2020). Water can act similar to a shock absorber, cushioning forces when they interact. This reduces friction and stress in the joints and protects vital systems from shocks. The fluid-encased systems have the energy of blows or impacts dissipated into the fluid.

Water has specific properties that are useful for biological life, such as at 37°C (98.6°F) water has its minimum specific heat, therefore less energy is used to stay at homeostasis at or around these temperatures. Temperatures around this are also considered the general optimal temperatures for mammals, birds, and pathogens. The upper biological temperature limit for mammals and birds is considered 45°C (113°F). The upper biological limit for pathogens is 60°C (140°F). An ecological borderline is considered to exist between optimal temperatures for mammals and birds (37°C) as opposed to optimal temperatures for soil microbes, insects, and warm aquatic life at 30°C (86°F). Karmas (1973) suggests that 15°C (59°F), 30°C (86°F), 45°C (113°F), and 60°C (140°F) denote possible structure transitions in water structures and why these biological limits are where they are.

Water is used in many animals for thermal regulation. Heat is typically dissipated in three ways due to heat transfer; conduction, convection, and radiation (Çengel and Ghajar, 2020). This is sensible heat transfer. Heat is also dissipated through evaporation which is referred to as latent heat transfer (Çengel and Ghajar, 2020). Unlike humans, poultry dissipate the majority of their heat through respiratory evaporation, which is their primary means of latent heat transfer, as poultry do not sweat. (Wolfensen et al, 1982; Genç and Portier, 2005). For poultry, latent heat transfer increases as temperature increases (Genç and Portier, 2005), which means more water is needed to be evaporated as temperatures increase to keep the bird's body temperature regulated.

The heat of vaporization of one gram of water is 2.26 KJ (2.14 BTUs). Thus for every gram of water evaporated from the birds respiratory system 2.26KJ (2.14 BTUs) of body heat is removed.

Osmoregulation controls water and electrolyte balance, by controlling ion concentrations in the extracellular fluid (Guyton, 1984). Birds have more organs that can affect osmoregulation than humans. Humans only use the kidney for this purpose, while birds also use their lower intestine and have salt glands for this purpose (Braun, 2015). The functional unit of the kidney is the nephron (Guyton, 1984). Bird nephrons can be of varying lengths and either looped or loopless; and the loopless type make up the majority of avian nephrons (Braun, 2015). This is different from humans as our nephrons all have these loops of Henle (Guyton, 1984). The loopless nephrons do not contribute to the countercurrent multiplier system nor aid in the formation of hyperosmotic urine (Braun, 2015). Therefore, the avian kidney does not produce as concentrated a form of filtrate as mammalian kidneys, but this fact does not have life-threatening consequences since poultry have compensating osmoregulatory organs (Braun, 2015).

Glomerular filtration rate (GFR) is the flow rate of blood filtrate through the kidneys. A Higher GFR means more filtrate is passing through each minute. A single avian nephron has a lower GFR than its mammalian counterpart, but birds usually have a higher number of nephrons than a mammal of similar body weight (Braun, 2015). The resulting total GFR is often not significantly different from mammals of a similar size (Braun, 2015). However, avian GFR is often much more variable (Braun, 2015). Birds also use their lower gastrointestinal tract for osmoregulation. In dehydrated states where water needs to be conserved they will reabsorb some water from the filtrate produced by the kidneys and increase the excreta concentration in the colon (Braun, 2015). Poultry can also use their cloaca and rectum for water reabsorption. Dicker

and Haslam (1972) observed that approximately one-fifth of the total water intake was reabsorbed in the cloaca and rectum.

Extracellular water volume is often a measure of current hydration state. Normal extracellular water volume of white leghorn pullets was 22.8% under normal environmental conditions and adequate nutrition, as opposed to 16.7% for birds stimulated with a diuretic (Harris and Koike, 1977). Stretch receptors in the body monitor this extracellular volume (Braun, 2015) and stretch receptors in the atria monitor returning blood volume (Borges et al, 2004). However, when birds are in a dehydrated state, they will decrease their GFR to conserve water, in an attempt to not affect the hematocrit level. However, Roberts and Dantzler (1989) reported a significant decrease in body weight under these conditions. Not only is water produced in several metabolic processes, but water is a main component of blood. Blood is used to transport gases, nutrients, electrolytes, and many other essential components around the body (Scanes, 2015).

The multifaceted role of water in birds extends beyond mere hydration, encompassing vital functions in digestion, lubrication, thermal regulation, and osmoregulation. Its contribution to nutrient absorption, joint and tract lubrication, shock absorption, and heat dissipation underscores its significance in maintaining avian physiological equilibrium. The unique properties of water, particularly its specific heat capacity at 37°C further emphasize its crucial role in supporting optimal biological temperatures. From respiratory evaporation for latent heat loss to osmoregulation through kidneys, and the lower intestine, water intricately regulates various aspects of avian physiology. Understanding these diverse functions of water is essential for ensuring the well-being and homeostasis of birds in different environmental conditions.

FACTORS THAT AFFECT WATER CONSUMPTION

Diet

Water consumption has a high correlation to feed consumption. The absence of water will significantly depress feed consumption relatively rapidly and vice versa (Bierer et al, 1966). The relationship between total water consumption to total feed consumption for commercial strain broilers is 1.8-2.0 times more pounds of water than pounds of feed (Czarick and Fairchild, 2006; Alqhtani, 2016). Poultry diets can have a significant effect on bird water consumption, and changes in diet composition can influence water consumption. An all-vegetarian broiler diet was observed to increase water intake versus conventional diets (approximately 13%), this was due to higher potassium levels and reduced digestibility of feed components (Viera and Lima, 2005). Changes in water intake happen with increased electrolyte and other mineral intake due to their osmotic effects (Ferket and Gernat, 2006). For example, increased dietary sodium has been shown to increase water intake in broilers. (Herrick, 1971; Marks and Washburn, 1984). Increased levels of sodium, potassium and phosphorus increase water consumption, yet increased levels of calcium had no effect on water consumption of laying hens (Smith et al, 2000). Potassium chloride supplementation also stimulates increased water consumption (Belay and Teeter, 1993), but its effects were only observed to be significant when in conjunction with cooler water temps in Beker and Teeter (1994). Diets that are higher in protein will not only increase total water consumption, therefore also increase the water to feed ratio (James and Wheeler, 1949; Marks and Pesti, 1984). This increased water consumption due to increased levels of dietary protein is theorized to be due to more water needed for the metabolization of protein (James and Wheeler, 1949). Diets that are higher in energy level can also cause an increase in the bird's water intake significantly during portions of growth periods (day 3-4)

(Marks, 1981). Diets that are higher in energy, 3170 kcal/kg vs 3445 kcal/kg, can also significantly increase the bird's water to feed ratio, 1.69 (g water/g feed) vs 1.79 (g water/g feed) respectively (Marks, 1981).

Environment

Environmental factors that affect water consumption are mostly related to increasing thermal stress. As ambient temperature increases latent heat dissipation increases (Genç and Portier, 2005) thus requiring more water for respiratory evaporation. Water consumption can double or even triple during periods of heat stress (Fairchild and Ritz, 2015). The 1994 Nutrient Requirement of Poultry (NRC) states that water consumption in broilers increases approximately 7% for each 1°F increase in temperature. Belay and Teeter (1993) again observed that heat stress not only increases water intake 78 to 133% but also increases water loss by 64%. Increased airspeed over heat stressed birds will decrease water consumption compared to birds reared with still air (May et al, 2000). May and Lott (1992a) observed that the increase in water consumption that occurs with cyclic heat stress was significantly higher during the periods of elevated temperature, and consumption decreases after the temperature decreases. The water to feed ratio itself shifts during these periods of thermal stress as seen in Xin et al (2002) where the normal water to feed ratio was 1.8-2.0 and increased to 3.0-3.4 during heat stress. Increasing stocking density can also increase thermal stress (Teo, 2018; Czarick et al, 2018) and therefore may increase water consumption. Feddes et al (2002) reported that increased stocking density increased water consumption and the water to feed ratio. However, the results of Alqhtani (2016), where pen size changed but birds per pen were constant, effectively changing stocking density, observed no difference in water usage or the water to feed ratio.

Kechil et al (1981) suggested increased water consumption can result from thermal stimulus itself not just from increased bodily water requirements due to the thermal stress and shift in heat balance. Birds in this study that were moved from a 22°C environment to a 32°C environment had significantly increased water intake in the first hour even though they only showed mild, intermittent panting. Additionally, if birds were held at a lower temperature (5°C) and then exposed to a 22°C environment, significant water intake increases were observed (Kechil et al, 1981). Infrared heat administered at 22°C also stimulated the drinking response (Kechil et al, 1981). These results may be due to the anticipatory drinking behavior theorized in Fitzsimons (1979) that will be discussed later.

The temperature of the drinking water itself can also have effects on consumption. It is considered that warm water reduces water and feed intake of laying hens (Glatz, 2001). Beker and Teeter (1994) observed increased water consumption with decreasing drinking water temperatures for broilers during heat stress. It was observed that roosters prefer cooler drinking water in the summer and winter (Degen and Kam, 1998). Leeson and Summers (1975) observed increased feed intake and rate of lay of birds provided chilled water with no difference in body weight loss or egg weight between treatment and control. Due to the correlation of feed consumption to water consumption and the water content of eggs it can be assumed that water intake of the birds provided chilled water was also increased, however that data was not provided. For layers in heat stressed environments it was seen that water cooled to 23°C (73.4°F) stimulated more feed and water consumption than birds provided 27°C (80.6°F) water (Xin et al, 2002).

Physiological Demand

The physiological demand of water is critical to poultry. For example, a loss of 20% of body water will result in death (Scanes and Christensen, 2020). However, the demand for water is beyond just sustainment of life. If physiological demands of peak performance are not met then peak performance from the birds will not be reached. Restricting water consumption of chicks to three half-hour periods daily has been reported to depress growth (Ross, 1960). Ross also reported that birds on water restriction reduced feed intake and significantly reduced body weights after 6 weeks. Significantly higher fecal moisture was observed in two of the three water restricted groups and nominally increased water to feed ratio was observed in this situation. It was suggested that because the water restricted birds tended to overdrink during watering periods and that this water restriction prevented the birds from meeting their physiological needs (Ross, 1960). This theory agrees with Sprenger et al (2009) who found that the first 30 minutes of available water after deprivation periods for broilers saw the largest water usage response. Birds consumed approximately 6.5 times more water in the first 30 minutes than was consumed in the next 90 minutes. Male broilers on water restriction showed a reduced growth response, similar to what would be seen for birds on a feed restriction program (Marks, 1986). Kirkland and Fuller (1971) showed that pullets on a water restriction program delayed sexual maturity of pullets similar to a feed restriction program, where as an ad libitum low energy diet with ad libitum water did not significantly reduce energy intake or delay sexual maturity.

Changing physiological demands change water demands in poultry. Water as a percentage of body composition consists of 57% in pullets and 78% in hens (Lopez et al, 1973). As body weight increases, water consumption increases (Marks and Pesti, 1984; Fairchild and Ritz, 2015). Maturity and reproductive status can also affect the water turnover rate. Body water

flux for hens was 2.18ml/hr/kg and in pullets it was 3.66ml/hr/kg. (Lopez et al, 1973). For day old chicks the absence of feed will depress water intake, however the absence of water will not initially depress feed intake. This is possibly due to the fact that the thirst mechanism needs to be stimulated upon first feeding (Bierer et al, 1966). Water restriction for chicks will also affect chick performance. Increasing the amount of water restriction on chicks had a linear reduction on feed intake, weight gain, and FCR (Viola et al, 2009). Water restricted birds had more aggressive behaviors, and duodenal villi height and fresh organ weight decreased with increased water restriction (Viola et al, 2009). However, Viola et al (2009) did not see the same mortality levels as Adams (1973) when birds were deprived of water. This observed performance decrease agrees with the effects of water restrictions of chicks from older broiler genetic lines as well (Kellerup et al, 1965). Bird body weight was shown to decrease 6% after 36 hours of water deprivation (Skadhauge and Schmidt-Nielson, 1967) although this disagrees with Arscott (1969) who found no body weight differences due to periods of water deprivation. Mortality increased the following week when hens experienced long periods (48-72hrs) of water deprivation, and production was reduced for multiple weeks after the deprivation period (Adams, 1973). The variability of production response is possibly due to a difference in the length of time of water deprivation.

When physiological demand is not met, reductions in performance are not always immediate, especially if there is simply a water restriction instead of full water deprivation. Hens that were placed on a water restriction program did not have a reduction in performance until 2 weeks after the restriction began (Adams, 1973). Fitzsimons (1979) theorized that there are two distinct mechanisms that drive the action of drinking. One is drinking due to a present need for water (primary drinking) and is true thirst. The other is anticipatory drinking and is driven by

oropharyngeal cues, diet, habit, and innate circadian rhythm (secondary drinking). If birds have free access to feed and water the thirst response level that stimulates primary drinking (true thirst) would not normally occur since the anticipatory (secondary) drinking behavior of the birds would illicit water intake that would satisfy these needs. Drinking behavior is not only stimulated due to the true thirst response for water need, but also oropharyngeal cues such as dry throat/mouth, habit, and innate circadian rhythm. This provides insight as to why water intake may be consistent day to day in flocks. This anticipatory drinking behavior was seen by layers in Xin et al (2002), where the hens displayed anticipatory eating and drinking behaviors 2-3 hours prior to the lights shutting off. Anticipatory feeding behaviors have also been reported in layers and because of the feed and water relationship this most likely correlated with increased water consumption (Hughes and Black, 1977). This correlation with anticipatory feeding and subsequent increased water consumption has been reported in broilers (May and Lott, 1992b)

There are several physiological mechanisms that directly elicit water intake in birds. For instance, drinking can be stimulated immediately by a dose of angiotensin II (ANG II), and when ANG II levels are elevated total water consumption increases in birds (Snapir et al, 1976). However, ANG II is not the only thirst-stimulating mechanism as drinking will still occur when the Renin-Angiotensin-System (RAS) is blocked (Fitzsimmons, 1979). Another mechanism that stimulates drinking is the osmoreceptors (Guyton, 1984). These measure general cellular dehydration and provide a thirst response to restore hydration in cells (Fitzsimmons, 1979).

Arginine vasotocin (AVT) in birds is another hormone that regulates water control in the body. AVT is produced in the posterior pituitary and is believed to be stimulated by an increase in osmotic pressure (Sykes, 1971; Arad et al, 1985). Antidiuretic Hormone (ADH) (the mammalian counterpart to AVT) causes urinary output to be reduced so that more water can be

reabsorbed. It does so by affecting the permeability to water of the walls of the distal tubules and collection ducts in the nephrons (Guyton, 1984). In the absence of ADH, these walls are almost completely impermeable to water resulting in little reabsorption and increased urinary output (Guyton, 1984). It was previously suggested that AVT does not change renal plasma flow or GFR (Skadhauge, 1964), however, newer studies report that it does decrease GFR (Arad et al, 1985). This new understanding is agreeable, because if more water is reabsorbed, less volume of filtrate would leave the nephrons. Deoxycorticosterone acetate has been reported to increase water intake and urinary output in leghorn cockerels, while cortisone acetate only caused increased urine output (Brown et al, 1958). Adrenocorticotrophic Hormone was reported to increase water intake for four out of six week but only increase urine output for one of them (Brown et al, 1958). In this Prolactin, corticosterone, and aldosterone are all thought to up-regulate osmotic transport in the intestine to increase water absorption in birds (Arad et al, 1985).

Quality and Management

Water quality can influence its consumption (Saif et al, 2008). Water quality and consumption can be a key welfare indicator in poultry (Manning et al, 2007). Water quality is usually related to color, turbidity, hardness, iron, pH, total solids, nitrogen, poisonous metals, bacteria, and dissolved oxygen. The dissolved minerals that water contains can affect the palatability, and performance of the bird, as well as the maintenance of systems inside the house (Bell, 2002; Fairchild and Ritz, 2015). While not all dissolved minerals have a negative effect on bird performance, nitrates do have a negative effect on both broiler and turkey performance (Barton, 1996). There were no water consumption effects observed due to iron concentrations up to 600ppm in the water supply (Fairchild et al, 2006). However, some dissolved minerals such as phosphate and calcium can improve performance (Barton, 1996). Sanitation of drinker lines is

also important, as flushing lines and running a disinfectant or sanitizer through them is a common practice to reduce the biological load (Bell, 2002).

Bird and house management can also be a factor that affects water intake. The height of the water line affects water usage (Czarick and Fairchild, 2006). Water pressure has a significant effect on water usage for domestic birds (Czarick and Fairchild, 2006; Brown, 2016). It is important to understand there is a difference in water usage, measured by the amount of water flowing through the meter, and water consumption, the amount of water actually ingested by the birds. The difference in use and consumption is due to leakage or spillage (Ziggity, 2024). Water pressure recommendations usually increase with body weight increases. However, water discharge from the drinker also increases with rising pressure. This means it can affect water usage and litter moisture (Ziggity, 2022). This is because while a drinker with a higher rate of delivery may possibly satisfy thirst faster, there is a higher possibility that all the water delivered will not be swallowed and end up in the litter (Ziggity, 2024). Proper management of water lines such as correct height for bird age is very important as improper management can affect water usage (Czarick and Fairchild, 2006). Water lines that are adjusted too low will cause more spillage and water lines that are too high may result in birds struggling to use them. Lower nipple height has been shown to increase body weight compared to higher nipples (Lott et al, 2001), and the bird's daily water usage was higher with lower nipple heights (May et al, 1997). Preventative maintenance helps to avoid restrictions in the drinker system, such as clogged filters, low supply pressure, or airlocks. Water restrictions have been shown to be harmful to bird performance (Kellerup et al, 1965; Marks, 1981). The results of Marks (1981) suggest that water restriction has even more adverse effects on feed conversion than feed restriction.

Management of the light period will also affect water consumption as bird activity and water consumption stops during the dark period. Activity increases again after sunrise until before sunset (or with the start and end of the light period) (Xin et al, 1993). Lighting pattern changes were found to significantly affect drinking patterns more than feeding program changes (Xin et al 1993). However, this study was in broilers and the feeding program was not drastically different from the control.

There are two different types of widely used drinker systems for poultry. Bell and trough drinkers are two often used styles of open drinkers that have their water exposed to the environment. Closed drinker systems are where the water is protected from the environment by a pipe but delivers water when triggered by the bird. Historically the open systems were the most common and are often still used in backyard flocks. However, in commercial flocks now the majority of drinkers are closed systems, specifically the nipple style drinker (Michel et al, 1998). The drinker type used has been shown to affect bird performance and usage. Lott et al (2001) observed significantly higher body weight for birds reared with open style drinkers, and May et al (1997) saw significantly increased usage from open style drinkers versus nipple style drinkers. There may also be a seasonality effect to the performance differences as Wabeck et al (1994) observed that bell drinkers resulted in higher body weights compared to birds reared with nipple drinkers in the spring, summer, and fall, but not winter.

Nipple flowrate can also be a factor affecting water usage and performance. Higher nipple flowrates have been shown to result in increased body weight in pen trials (Carpenter et al, 1992), environmental chambers (Miles et al, 2004), and field trials (Dozier, 2003). However, Quilumba et al (2015) found no significant differences in weight but did agree with Carpenter et al (1992) that litter moisture under higher flow nipples was higher, resulting in a degradation of

the bird's environment. Because of the importance of litter quality, a flow rate stick was commercially developed and tested (Miles et al, 2004) as a management tool. However, testing nipple flow rates in the house with birds present can be challenging in application, as the number of birds on the line at that moment could affect the flowrate, and continuously depressing the drinker pin for 15-20 seconds may not adequately simulate the flowrate of a bird triggering the pin to drink. The number of nipples per bird, however, does not seem to be a factor affecting water consumption (Feddes et al, 2002).

Genetics, Gender, and Strain

Gender also plays a role in affecting water consumption. Marks (1985) showed that water consumption between male and female birds became significantly different by day two in Athens-Canadian random bred non-selected stocks and by day ten in commercial broiler strains. Genetics and strains affect water to feed ratios, and therefore affect water consumption relative to a pound of feed. Marks (1986) found that if male broilers were water restricted to the female intake level no sexual dimorphism occurs between the two genders. White leghorns water to feed ratio was observed as 2.53 for the first 21 days (Medway and Kare, 1959) while Rhode Island Reds chicks was observed as 1.57 over first 18 days (Barott and Pringle, 1949). Marks (1987) observed differences in water consumption response of progeny of dwarf selected lines fed two different levels of dietary sodium. There are differences even within type and gender due to genetic selection. Marks (1981) noted that higher water to feed ratios are associated with lower feed to gain ratios; water to feed ratio of 1980s Cobb male broiler was observed as 1.73 versus 1.60 for Athens-Canadian random bred non-selected males. Glatz (2001) also observed a difference in drinking response between Australian tinted commercial egg layers and European brown egg layers subjected to heat stress.

Bird Health

Keeping birds hydrated is important to bird health, again as a loss of 20% of body water will result in death (Scanes and Christensen, 2020), but bird health can also affect bird water intake. Birds in a disease state often will not drink as much water as a healthy bird. Chicks infected with coccidiosis had significantly lower water intake than uninfected birds (Williams, 1996). This depression is seen around the fourth day after coccidiosis infection (Reid and Pitois, 1965). Decreased water consumption is listed as a clinical sign of Avian Influenza, Turkey Coronavirus, *Ornithobacterium rhinotracheale* infection, *E. Coli*, and Bordetellosis (Saif et al, 2008)

Water consumption in poultry is influenced by various factors, each playing a crucial role in maintaining the well-being and performance of birds. Dietary composition, including protein, energy levels, and electrolyte content, affects water intake, impacting overall nutrient utilization and metabolism. Environmental factors, particularly temperature and heat abatement, significantly affect water needs, with heat stress leading to a substantial increase in water consumption. Physiological demand is influenced by growth stage, reproductive status, and hormones. Quality and management factors, such as water source quality, system type, and maintenance practices, also have effects on water consumption, and can consequently affect bird performance. Additionally, genetic variations, gender differences, and specific strains contribute to variability in water-to-feed ratios and intake. Finally, bird health plays a critical role, as diseases and infections can significantly alter water intake patterns.

This is why measuring and recording water usage is often done commercially by the poultry industry to monitor management and bird health throughout the flock. This can be done in the form of the grower manually recording daily water usage totals via a water meter (Scanes

and Christensen, 2020) per house or the poultry house controller doing so automatically. If a significant change in water consumption is observed from the previous day or a trend starts to emerge, this is usually an indicator suggesting that a thorough inspection of the birds and their housing should be conducted.

MODELING IN ANIMAL AGRICULTURE

Models serve as tools in animal and poultry science, enhancing the understanding of complex systems and providing insights into various aspects of production. By incorporating mathematical representations of biological processes, models enable researchers to simulate and predict the behavior of poultry under different conditions.

Broiler Growth and Feed Intake Models

Gous (2014) highlights the significance of models in portraying complex issues within poultry science, such as a tool for understanding broiler growth rate or how breeders come into sexual maturity. The Gompertz equation (Ricklefs, 1985) stands as a foundational growth model, capturing the dynamic nature of broiler growth and providing a basis for changes due to input factors. Emmans (1981) contributes models for desired feed intake and normal growth, considering variables such as protein growth, ash, water, bodily protein, and minimum lipid content. May and Lott (1992a) provide a practical application by demonstrating that models can predict changes in intake of feed and water during periods of heat stress. The model showed the increase in water intake happens before the reduction in feed intake.

Reproduction Models

Models can also serve as tools for understanding the nuanced factors influencing poultry egg type production. Lewis et al. (2004) models how extended day lengths for pullets can

delay sexual maturity. Additionally, Lewis et al. (2003) and (2007) introduce models demonstrating the influence of age at sexual maturity on total egg numbers for broiler breeders. Lewis and Morris (2004) and Lewis and Gous (2006) contribute models that describe the age at first egg based on changes in photoperiod. These models help reveal the nature of the relationships between body weight, age at sexual maturity, and lighting periods, providing a quantitative understanding of production dynamics, such as every single day of decrease to age at first egg results in a 0.75 egg per day per hen increase in total egg numbers by week 39. (Lewis and Gous, 2006).

Incubation and Hatchability Models

French (1997) models the temperatures of embryos in incubators, considering crucial inputs such as incubator temperature, embryo heat production, heat loss from water evaporation, and thermal conductivity of the egg. This model provides an understanding of not only what factors influence embryonic development during incubation, but how they influence development. Peruzzi et al. (2012) introduced a fuzzy logic modeling design as a superior alternative to traditional statistical regression, it increased accuracy in predicting hatchability in commercial hatcheries with an R^2 of 0.88 vs 0.66. This innovation in modeling techniques reflects the continual evolution of methodologies within the field. Fuzzy logic takes cases that are closer to the predicted outcome and weights them higher within the dataset, whereas with traditional regression all cases are treated equally (Vesely et al, 2016).

If models can be adequately trained to describe how input factors can affect production outcomes, and the relationship between the inputs and outcomes doesn't change, then these models can be useful in predicting normal responses. If we can accurately predict normal outcomes, then we can possibly detect abnormal responses.

Livestock monitoring systems

In the dynamic and complex area of livestock monitoring, technological innovations ranging from water monitoring systems to real-time cameras and advanced algorithms are changing the way events are detected and animals managed. Pluk et al. (2010) demonstrated the efficacy of a system monitoring water consumption in broilers, achieving an 80% success rate in detecting crucial events. Notably, however, the system's capability to identify events lacked upper threshold alert limits and was based purely on arbitrary percentages of previous daily usage, highlighting both its potential and areas for improvement. Kashina et al. (2013) implemented a real-time camera monitoring system that exhibited an 95.24% success rate in detecting management events based on transform functions of bird density. Coşkun et al. (2023) employed an algorithm capable of correctly identifying 92.3% of lame cows from thermal images of their legs. While overall sample numbers were relatively low in this study, this technological advancement showcases the potential of algorithms in animal health monitoring, emphasizing the importance of precision and accuracy in detection. The precision and accuracy of a commercial alert system are incredibly important; if the system generates a lot of false alarms the user will not trust the system and may not continue to use it. Also, if the system often misses major events then it is not a useful tool for management.

Models employed in animal and poultry science contribute tools for the exploration of intricate production systems. Spanning topics such as broiler growth and feed intake, reproductive dynamics, and incubation factors, these models not only supplement theoretical understanding but also have practical utility in understanding outcomes across diverse conditions. These models try to capture and represent nuanced biological processes, offering

predictive capabilities for important production parameters such as growth rates, egg production, and hatchability.

Furthermore, the technological innovation in livestock monitoring systems underscores a need for real-time event detection methodologies. This technological evolution, ranging from accurate and precise water usage monitoring to computer vision systems, serves as a testament to the dynamic landscape of modern animal husbandry practices. The refinement and continual expansion of modeling techniques, coupled with advancements in monitoring systems, marks advancement towards more autonomous systems that improve the management of livestock production.

STATISTICAL PROCESS CONTROL (SPC) AND ITS APPLICATION TO ANIMAL PRODUCTION SYSTEMS

Statistical Process Control (SPC) is a tool used to monitor and maintain the quality and stability of processes. Used for decades, and originally developed for manufacturing quality control, these techniques provide a systematic approach to identifying and addressing variations in production, ensuring that processes operate within desired specifications (Oakland, 2003). There are several basic techniques in SPC that are used such as process flowcharting, check sheets, histograms, graphs, pareto analysis, cause and effect analysis, scatter diagrams, and control charting.

Process flowcharting describes what is done in the process, the path, and how it is performed. Check sheets mark how often things are done. Histograms show what the variation looks like and graphs can be used to see if the variation is changing with time. Pareto analysis displays what are the major problems, and scatter plots show if there are relationships between

factors. Control charting is used to track which variations to control and how (Oakland, 2003). There are several different types of control charts, that will be discussed in detail. When SPC is implemented correctly it is a way to further process improvement without advanced statistics and provides data in a way that can be easily understood for decisions to be made.

Control Charting

Control charts are used to control processes using variable data. It is not only necessary to keep track of the accuracy (central tendency) of the process but also the precision (spread) of the data (Oakland, 2003). The term Shewhart charts is also used for these tools, the most common are mean ($\bar{x}$) and range (R) charts. These are usually used with samples from a process of at least four or more and graphed with respect to time. Limits to detect an out-of-control process are usually set with respect to the mean or goal and the standard error (SE). Upper and lower action limits are usually set $\pm 3*SE$ from the mean, warning limits are often added at $\pm 2*SE$. The chance of a normal process plotting a sample mean outside of the action limits is one in 1000 and outside the warning limits is one in 40 (Oakland, 2003). The chance of two consecutive sample means being outside the warning limits is one in 1600. Runs or trends even within the warning limits can be evidence that a process shift has occurred. Usually, seven consecutive points need to be seen to justify an action as the chance of this being a normal occurrence is approximately the same as a point outside $3*SE$ (Oakland, 2003).

However, sometimes things cannot be brought in sample batches to measure and are only presented as individuals. In these scenarios, an individual chart or i-chart and moving range chart can be used, although they are less sensitive to small changes in the process. Action limits or control limits are usually set ± 3 standard deviations (SD) away from the mean and warning limits at ± 2 SD away, and the warning trigger is two out of three consecutive points beyond a

warning limit (Oakland, 2003). Standard deviation describes how much variability there is in observations while SE evaluates the accuracy of the mean of sample data compared to population mean. There are adaptations to these charts such as zone control charts that add a limit at one SD from the mean and charted points are given a score depending on the band they fall in. Pre-control charts can also be used where the specification range is split into four sections and the middle two zones are considered the target with the outside two zones form specification limits and beyond these denoting out of control (Oakland, 2003). However, this requires the user to already know the specification range for a normal process.

There are numerous other types of control charts plotting specific characteristics and having different procedures for calculating control limits, though the representations of the charts are similar. One more important control charting system to note is moving means charting. This is used for situations where individual charting is needed but allows a form of grouping so over control is less possible. Performing a moving mean system also has a smoothing effect on the control process (Oakland, 2003). The number of observations used to form the moving (sometimes referred to as rolling) mean is arbitrarily set by the controller, however, the greater the interval is, there is more lag to the representation of process shifts. Limits are set similarly to the individual charts.

SPC in Livestock

Control charts can have practical uses in livestock management as first highlighted by Wrathall (1977). They can play a critical role in detecting problems as they arise and establishing a basis for timely action decisions. Reneau and Lukas (2006) elaborate on the concept of statistical control for livestock, reviewing uses in dairy, swine, beef, and poultry. The factors being analyzed must operate under common cause variation when in a stable state. Any

deviation from this state, termed special cause variation, is usually attributable to machine or equipment problems, operator errors, or defective raw materials. Using SPC, as a livestock management tool, helps facilitate the detection of changes as soon as possible by considering natural variation, allowing for prompt corrective actions (De Vries and Reneau, 2010).

Ravindranathan and Unni (1990), assume that shifts are due to random and assignable causes. This differentiation is critical as random variation is inherent and uncontrollable, while assignable causes can be identified and corrected. Understanding this is important when using SPC tools in livestock applications as there is often much greater random variation than in a typical manufacturing setting. SPC tools are not only for detecting problems but also for assessing the impact of planned interventions, as noted by De Vries and Reneau (2010). Since SPC's inception in the manufacturing industry in 1926 (Reneau and Lukas, 2006), SPC has become integral in maintaining and improving product quality and is used in most industrial production settings but its adoption by animal production systems has been much slower. One of the first published papers using control charts in livestock management was in 1977 (Wrathall, 1977).

Reneau and Lukas (2006) outline key considerations for what data in an animal production system is chosen to be charted, emphasizing sensitivity to change, ease of collection, cost-effectiveness, standardized measurement, simplicity, and relevance to the process level. Grouping data into rational subgroups, such as time, shifts, or pens, is essential for meaningful analysis (De Vries and Reneau, 2010). Control limits, according to Wrathall (1977), can be derived either arbitrarily or mathematically, offering flexibility in setting thresholds.

De Vries and Reneau (2010) highlight challenges in research with control charts in the livestock industry, notably the absence of real or virtual control groups. This lack of control

groups makes determining causality more challenging, impacting the ease of publication. The average run length before a signal serves as a standard measure of statistical performance must be individually decided, as there is a balancing act between setting a correct standard to serve as what is considered normal and not overcontrolling the process.

False alarms, which can be a symptom of an overcontrolled process, are an important factor to consider with livestock applications. De Vries and Reneau (2010) delve into the frequency of false alarms in control charts, noting that the general frequency of false alarms for an $\bar{x}$ chart with 3 standard deviation control limits is 1 in 370. The application of Western Electric rules, as discussed by Reneau and Lukas (2006), provides a 98% probability of correctly identifying a real change, however, just using $\pm$ three standard deviations as control limits results in a type one error rate of about 0.002.

The Western Electric Rules

The Western Electric Rules are an additional set of control rules developed by the Western Electric company. The Western Electric Statistical Quality Control Handbook (1956) suggests a set of decision rules for detecting nonrandom patterns on control charts. Specifically, it suggests concluding that the process is out of control if either one point plots outside the three σ control limits (Rule 1), two out of three consecutive points plot beyond the two σ warning limits (Rule 2), four out of five consecutive points plot at a distance of one σ or beyond from the center line (Rule 3), or eight consecutive points plot on one side of the center line (Rule 4). Reneau and Lukas (2006) present insights from monitoring dairy cattle activity using Western Electric rules. Notably that using rules two and four identified ketosis three days before a physical diagnosis, and rule one did not alert until four days after the diagnosis, demonstrating the effectiveness of these rules in early detection. De Vries and Reneau (2010) and Reneau and

Lukas (2006) also highlight the importance of time series controls, particularly when daily fluctuations or seasonality are factors. Autocorrelation, the use of residuals, and moving averages can be used for adjusting readings that change with time, providing a more accurate representation of shifts in the process.

Statistical Process Control is a useful tool for monitoring and improving processes and has applications in extending its influence from manufacturing to livestock management. The discussed control charting systems offer versatile approaches to not only see production trends but also understand the variability and quantifiably detect possible abnormal production parameters. While its adoption in the livestock industry faces challenges outlined by De Vries and Reneau (2010), the effectiveness of SPC, especially with amendments like the Western Electric Rules, is evident in early detection scenarios, as shown in dairy cattle ketosis monitoring (Reneau and Lukas, 2006). As SPC continues to be introduced into diverse fields, its role in enhancing process quality remains the driving factor behind its application. Further research in adapting SPC methodologies for livestock management may contribute to not only overcoming quality challenges and improving overall efficiency but also early event detection in animal production systems.

CHAPTER 2

STATEMENT OF PURPOSE

The previous literature review underscores the crucial role of water in poultry performance and highlights the multitude of factors influencing its consumption. Advances in poultry management methods and technologies, including bin scales, bird scales, environmental sensors, and water meters, have significantly improved industry practices. Notably, ultrasonic meters are an improvement on their mechanical predecessors in increasing accuracy and precision. This allows for a more accurate representation of water usage and can therefore allow a more frequent monitoring interval of its usage increasing the resolution of understanding the water usage patterns of poultry.

Despite its significance, water consumption remains relatively understudied compared to other aspects of nutrition or management. While commercial growers have long utilized water usage as a management tool, innovative tools using it to aid management decisions have not kept pace with technological advancements. Current practices often involve tracking daily totals, and although modern controllers can track usage more frequently, it is still mostly used as a tool to review the previous periods. There is limited research exploring more frequent monitoring intervals or evaluating water usage consistency independently of other factors such as diets and environmental stressors.

In light of these gaps, this research aims to achieve two primary objectives: firstly, to assess the viability of a management tool utilizing real-time water usage data and dynamic thresholds; and secondly, to analyze the consistency and characteristics of layer water usage patterns. By addressing these objectives, this work seeks to enhance understanding and optimize management practices in poultry production.

CHAPTER 3

MATERIALS AND METHODS

A study was conducted on two cage-free layer farms in NE Georgia, both farms were contracted with the same integrator. Two laying houses were located on one farm (Farm A) and the third house was located on a second farm (Farm B). All three 40' X 500', dropped ceiling houses were curtain-sided. The houses utilized a tunnel ventilation system during hot weather and side wall inlet system for cold and moderate weather. All houses were equipped with a Hired-Hand Evolution 4000 environmental controller (Cumberland, Shippensburg, PA, USA). Supplemental lighting was provided by high-pressure sodium lighting with an auxiliary strand of LEDs at the tunnel inlet to offset the light-filtering effect from the evaporative cooling pads installed on the side wall. The lighting times varied between flocks as well as during some of the study periods (Table 1).

The houses were equipped with wooden slats with a row of mechanical nest boxes along each side wall. There was a 12' wide scratch area with a perch system in the center of the house. Each house had two chain-style feeders, one on each slat area. Feeding times varied with flocks and time of trials (Table 2). The diets were the same for both houses and formulated by the integrator.

The study houses were equipped with a nipple drinker line on each slat area (Figure 1) with similar nipple spacing and number of nipples in each house. The drinker line height and pressure were maintained by the grower, and water was provided ad libitum. Bird water usage

Table 1. Photoperiods for all trials.

lighting times						
	Trial 1		Trial 2		Trial 3	
	Farm A	Farm B	Farm A	Farm B	Farm A	Farm B
lights on	4:00 AM	N/A	5:00 AM	5:00 AM	4:00 AM	4:00 AM
lights off	9:00 PM	N/A	10:00 PM	10:00 PM	9:00 PM	9:00 PM
lights on	N/A	N/A	N/A	N/A	12:00 AM	N/A
lights off	N/A	N/A	N/A	N/A	1:00 AM	N/A

Table 2. Feeding times for all trials.

Feeding Times					
Trial 1		Trial 2		Trial 3	
Farm A	Farm B	Farm A	Farm B	Farm A	Farm B
4:00 AM	N/A	5:00 AM	5:00 AM	12:00 AM	4:00 AM
5:30 AM	N/A	6:30 AM	7:00 AM	4:00 AM	7:00 AM
8:30 AM	N/A	9:30 AM	9:00 AM	6:00 AM	11:00 AM
10:30 AM	N/A	11:30 AM	12:00 PM	8:30 AM	2:00 PM
12:00 PM	N/A	1:00 PM	3:00 PM	10:30 AM	4:00 PM
3:00 PM	N/A	4:00 PM	6:00 PM	12:30 PM	6:00 PM
5:30 PM	N/A	6:30 PM		3:30 PM	
7:30 PM	N/A	8:30 PM		7:00 PM	

was measured using ARAD Sonata ultrasonic water meters (Dalia, Israel). The output from the water meters was connected to a HOBO RX 3000 data logging system (Onset Corp, Bourne, MA, USA). Ultrasonic meters were chosen for their high accuracy at low flow rates as well as providing a pulse output of $1/10^{\text{th}}$ of a gallon per pulse. Water usage data were collected at 5-minute intervals for all trials.

There were approximately 11,500 layers in each house on Farm A for Trial 1. The birds were 42 weeks old in House 1, and 46 weeks old in House 2. The same flock of birds was used for Trial 2. For Trial 2 the birds in House 1 on Farm A were 46 weeks old and 50 weeks old in House 2. Farm B was added for Trial 2 where the birds were 45 weeks old at the start of the trial. For Trial 3 all three houses had a new flock of 12,000 birds. For Trial 3 the birds at Farm A House 1 were 29 weeks old, in House 2 were 33 weeks old, and the birds at Farm B were 24 weeks old at the beginning of the trial. All birds from both flocks were of the Hy-Line Brown variety (Hy-Line International, West Des Moines, IA, USA).

Trial 1

The purpose of Trial 1 was to record the daily water usage patterns of cage-free layers to determine if the water usage pattern was consistent enough so that a dynamic real-time alert system could be created to notify the farm manager of any abnormal water usage events. Four weeks of water usage data (December 2022) were collected using the installed water meters and HOBO system and compiled and analyzed in Microsoft Excel (Redmond, WA, USA).

Due to the high level of five-minute water usage variability over the course of the day, it was decided to analyze bird water usage on an hourly basis and the standard deviation of each hour block was used to help set threshold limits. Thresholding by a percentage of the hourly

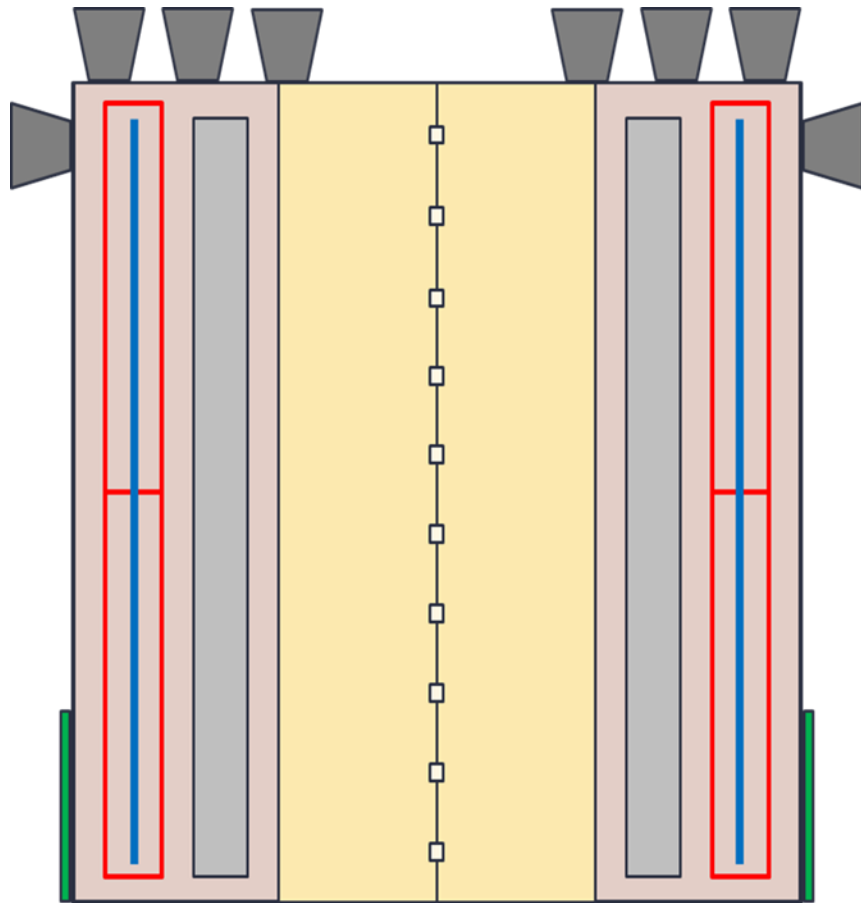


Figure 1. House layout sketch (not to scale), Feeders in red, drinker lines in blue, nest in grey, slats in brown, scratch area in yellow.

mean was considered, but it was found that the level of water usage affects these limits more than the changes in variability during the day. Static numeric water usage variation from the mean was considered but it did not factor in that usage is not static during the day and neither is normal variability.

It was decided to establish hourly alert limit thresholds based on mean usage ± 1 standard deviation (SD) from 4 am to noon, and ± 1.5 standard deviations from noon to 9 pm. This was due to water usage appearing to be more variable in the afternoon hours compared to the morning hours from the raw data, but the SD was not drastically different. Therefore, there was concern about an increased rate of false positives in the afternoon using the morning thresholding. This trend was confirmed in Trial 2. To catch any major leaks that occurred during the dark period, but not give alerts to accidental nipple triggers or other events that did not necessitate attention, hourly thresholds were set at ± 0.5 gallons, high and low respectively.

In order for water usage to be monitored autonomously, and dynamic alerts generated the hourly usage means and thresholds were programmed into MATLAB 2022a (MathWorks, Natick, MA, USA). MATLAB is a PC-based programming language that allows for external inputs to be used as part of a decision making process by the system. The PC can then be used to generate outputs such as an alert email based on the thresholds set within MATLAB and input from the meter. The water meter in House 1 (Farm A) was connected to a PC, running the MATLAB code, via a LabJack T4 (LabJack Corp., Lakewood, CO, USA) data acquisition system (DAQ). The Labjack T4 has a max stream rate of 50 ksamples/second and a command response rate of 2.2 milliseconds. A DAQ had to be used so that MATLAB could read the electronic pulse output of the water meter in real-time. Due to only having one DAQ, House 2

calculations were performed by exporting data from the installed HOBO system and analyzed in Microsoft Excel. The flow chart of data is provided in Figure 2.

Trial 2

Trial 2 (January – May 2023) utilized several months of water usage data from the three layer houses to improve the understanding of the long term consistency and repeatability of the “normal” daily water usage patterns of the layers. This was due to a high rate of false positives in Trial 1, so a better understanding of the pattern was needed. The second purpose of Trial 2 was also to develop a way of modeling and quantifying this consistency over a longer period.

Water usage data for each house were aggregated into 15-minute intervals and put into an individual linear mixed effects model using the “lme()” (Linear Mixed Effect) function in RStudio (RStudio Team, Boston, MA, USA). While several possible models were considered, a linear mixed effects model was recommended by The UGA Statistical Consulting Group (Athens, GA, USA), and allowed for fixed effects for specific time periods within a day as well as random effects for day. This gave the ability to understand consistency within specific times of the day as well as the variability overall from one day to the next. Individual models for each house were created instead of a combined model, as after looking at data from Trial 1 and other observations in preliminary model creation it was seen that even houses on the same farm under the same management had unique characteristics to their water usage patterns.

Since the goal was to evaluate the “normal” daily water usage pattern, anomalous days (days with several residuals over 5 from the first linear mixed effects model) for each house were filtered out of the data set. These filtered data were then refitted into a new linear mixed effects model for mean usage of each half-hour period and fitted with an Autoregressive Moving

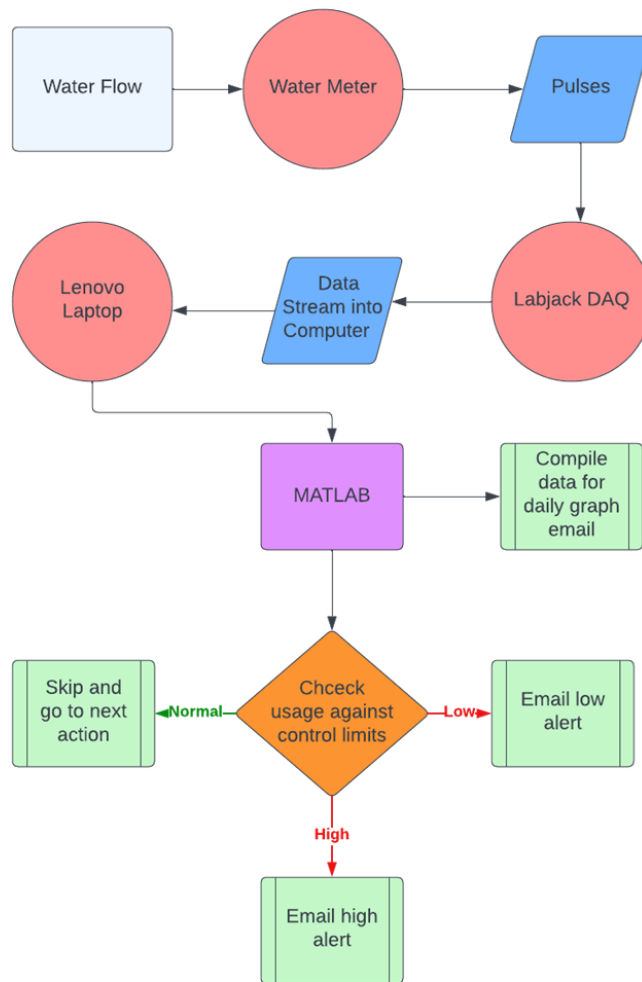


Figure 2. Flow of data of water usage from the water meter through recording and alert system used to generate abnormal usage alerts.

Average (ARMA) (1,1) correlation structure, as the errors were assumed to be serially correlated, to improve model fit.

The data were also found to be heteroscedastic with distinct variances within each of several windows of time (or variance phases) during the day. Daily Event Times (DETs) were then set based on the lighting and feeding schedule as it was considered that these events could affect water usage. The error standard deviations within the DETs and due to the random daily effect were then compared to understand and quantify the consistency/repeatability of the usage pattern. The DETs are provided in Table 3. The UGA Statistical Consulting Group was used to help make these analyses and create the model structure.

Trial 3

Trial 3 examined the effectiveness of a dynamic rule-based algorithm to establish thresholding levels automatically and update as changes during the flock occur. Each alert model was house specific due to what was learned from Trials 1 and 2. These models also used a different way of setting thresholds to attempt to decrease the high level of false positives seen in Trial 1. From January to March 2024 water usage data from all three layer houses were used to test a preliminary system of autonomously setting alert thresholds based on a rolling average design with Statistical Process Control (SPC) factors being used to set upper and lower control limits (UCLs and LCLs). This was done to try to create a dynamic alert system that could adjust over the course of the flock, while also dynamically changing the thresholding limits within the day if the pattern of usage or variation shifted.

Water usage data were aggregated hourly. A 7-day training period was initiated when the system was started. After 7 days the means and standard deviations from each hour block were

Table 3. Daily Event Times¹ for models for both farms created in Trial 2

Daily Event Times (DETs)	
Farm A	Farm B
5:00 AM	5:00 AM
6:30 AM	7:00 AM
9:30 AM	9:00 AM
11:30 AM	12:00 PM
1:00 PM	3:00 PM
4:00 PM	6:00 PM
6:30 PM	10:00 PM
8:30 PM	
10:00 PM	

¹ The event at 5:00 AM is the lights turn on and a feeding, the event at 10:00 PM is the lights turn off, and all other events are feedings.

used to set thresholding limits. These limits were created based on two of the Western Electric Rules (Western Electric Company, Manhattan, NY, USA). First, any one point ± 3 SD away from the hourly mean was an alert threshold (Rule 1). Also, 2 of 3 consecutive points 2 SD above the mean, or 2 of 3 consecutive points 2 SD below the mean, would be considered an alert condition (Rule 2). These were chosen as Rule 1 was thought to identify drastic deviations from the normal such as major restrictions or leaks quicker, while Rule 2 might identify smaller but still important deviations such as feeding issues. This way of thresholding was chosen due to a long history of SPC for controlling processes (Oakland, 2003) and some preliminary use of the Western Electric rules in thresholding for animal agriculture (Reneau and Lukas, 2006).

The entire system was a rolling design so after the 7-day training period each new day of data replaced the oldest. This allowed for the system to shift dynamically if the normal pattern changed. Additionally, minimum thresholding limits were placed so that the SD for a block could not be less than 1.67 gallons (or that 3 SDs away was 5.01 gallons). This was done to keep from overtightening the thresholds, especially during low usage periods. For instance, if for the last seven nights, no flow was detected, the mean and SD for that block would both be zero, so if even a 1/10 of a gallon of flow was detected it would trigger an alert, even though this is not something that would probably deserve attention.

These calculations were done in Microsoft Excel. Water usage from all three houses was evaluated over this timeframe and analyzed against the thresholding limits that were set. Then if alerts were detected, it was determined with the help of the growers if any discernable cause could be attributed to this change or if the cause of the alert was undefinable.

CHAPTER 4

RESULTS AND DISCUSSION

Trial 1

Three typical days of water usage from Farm A during Trial 1 are provided below, and the general water usage pattern exhibited an overall increase in usage as the day progressed, peaking a few hours before the lights were turned off (Figure 3). Peak water usage occurred between the hours of 6:00-7:00 pm, averaging 58.3 Gallons per Hour (GPH). The water usage pattern is similar to the usage pattern exhibited by layers in Xin et al (2002). The lack of a depression in the afternoon in Trial 1 compared to what was reported in Xin et al (2002) may be due to the difference in feeding regimens.

The hourly usage model with alert thresholds (± 1 standard deviation (SD) in the morning and ± 1.5 SD in the afternoon from the mean usage), is shown below in Figure 4. A table of the mean usage, SD, Upper Control Limit (UCL), Lower Control Limit (LCL), and range between UCL and LCL is shown in Table 4. The narrowest threshold limit during the lighted period was at 8:00-9:00 am with 3.7 GPH separating the upper and lower control limits. The widest threshold was at 6:00-7:00 pm with 13.2 GPH separating the upper and lower control limits.

Multiple alerts were generated by the system each day of the trial period in both houses (Table 5). Consecutive alerts that were four or more hours in length were classified as persistent alert events. Consecutive alerts that were three or fewer hours in length (including an individual

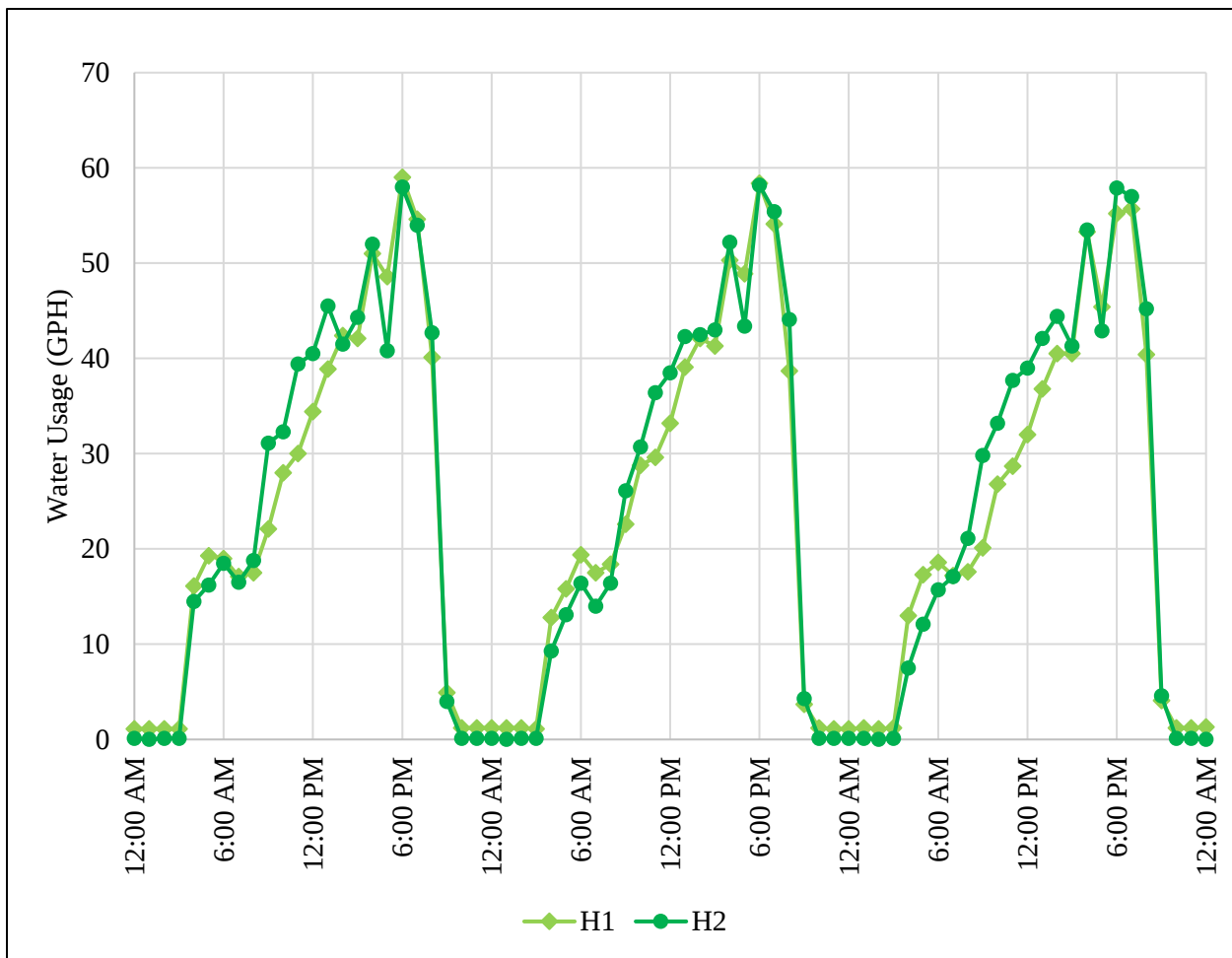


Figure 3. Three days of typical water usage in Farm A House 1 & 2 during Trial 1

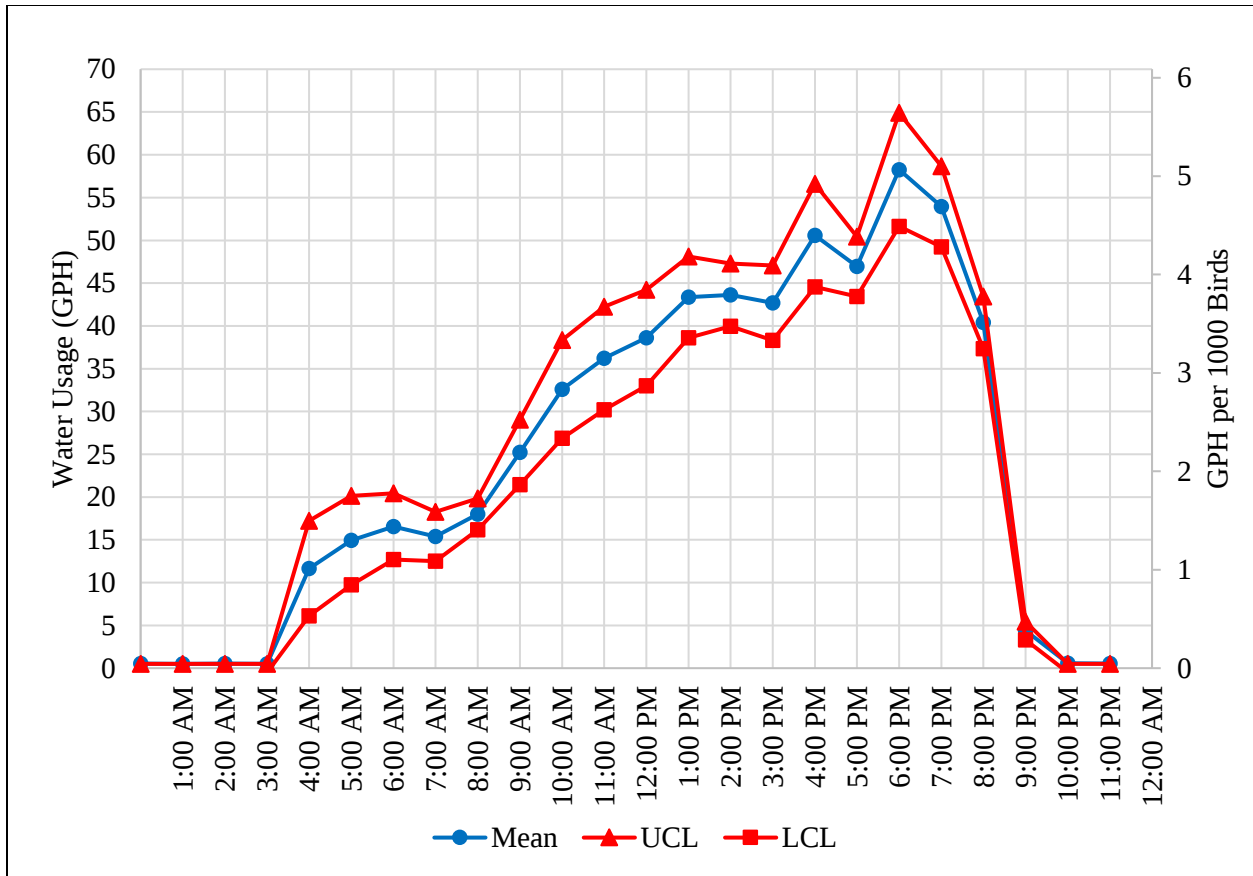


Figure 4. Trial 1 alert model means, upper control limits (UCL) and lower control limits (LCL)

Table 4. Means, standard deviations (SD), upper control limits (UCL), lower control limits (LCL), and range between thresholds (all in GPH) for Trial 1 alert model

Time	Mean	SD	UCL	LCL	Range
12:00 AM	0.5	0.3	0.5	-0.5	1.0
1:00 AM	0.5	0.3	0.5	-0.5	1.0
2:00 AM	0.5	0.3	0.5	-0.5	1.0
3:00 AM	0.5	0.3	0.5	-0.5	1.0
4:00 AM	11.7	5.6	17.2	6.1	11.1
5:00 AM	14.9	5.2	20.1	9.7	10.4
6:00 AM	16.6	3.9	20.4	12.7	7.7
7:00 AM	15.4	2.9	18.3	12.5	5.8
8:00 AM	18.0	1.8	19.8	16.2	3.7
9:00 AM	25.2	2.5	29.0	21.4	7.6
10:00 AM	32.6	3.8	38.3	26.9	11.5
11:00 AM	36.2	4.0	42.2	30.2	12.0
12:00 PM	38.6	3.7	44.2	33.0	11.2
1:00 PM	43.4	3.2	48.1	38.6	9.5
2:00 PM	43.6	2.4	47.3	40.0	7.3
3:00 PM	42.7	2.9	47.1	38.3	8.7
4:00 PM	50.6	4.0	56.6	44.6	12.0
5:00 PM	46.9	2.3	50.4	43.5	7.0
6:00 PM	58.3	4.4	64.9	51.6	13.2
7:00 PM	53.9	3.2	58.7	49.2	9.5
8:00 PM	40.4	2.0	43.4	37.3	6.1
9:00 PM	4.4	0.7	5.4	3.3	2.1
10:00 PM	0.6	0.3	0.5	-0.5	1.0
11:00 PM	0.5	0.3	0.5	-0.5	1.0

hour alert) were classified as transitory alert events. Displayed in Figure 5 is the duration of alert events as a percentage of the total alert events for each house. There were 15 alert events with attributable causes. These attributable event causes were also considered in two different categories; events due to mechanical issues or alerts due to a behavioral change in the bird's water usage. It was found after investigation and reviewing water patterns after alerts that in general events with attributable causes, such as supply issues, generated persistent alerts.

House 1 Supply Issue (Mechanical alert)

On January 11th a supply issue started in House 1 (Figure 6). It was caused by sediment clogging the system and filters. This sediment was introduced from earlier pipe and well repairs. This problem was resolved with heavy flushing of the system and cleaning of the filters. It restricted the flow to the drinker lines down to 0.3 GPH at its worst point. The system generated an alert for this at 8:00 am before extremely low flow occurred, and alerts continued to be generated every hour. This event is responsible for two persistent alert events (14 and 7 consecutive alerts). These alerts were due to a mechanical issue. The water usage was reviewed at 9:00 am via the remote data collection system its update, and the severity of the issue was realized and the integrator was notified in the next hour. Unfortunately, the grower was not able to correct the problem until the next morning. As seen here, the problem was not fixed for almost 24 hours after the event started to occur. Speed in correcting these problems is crucial because long periods of water deprivation can have impacts on egg production for weeks after they occur (Adams, 1973). The issue reduced water usage enough that it may have been caught by conventional static alert thresholds in commercial controllers. However, a flow rate of zero (a common low flow alert level in compatible controllers) was never reached. The more common

Table 5. Number of alerts and dates, upper control limit (UCL) alerts, and lower control limit (LCL) alerts for Trial 1

Alerts Generated for Trial 1				
Date	House 1		House 2	
	UCL Alerts	LCL Alerts	UCL Alerts	LCL Alerts
29-Dec	4	1	4	2
30-Dec	5	4	1	7
31-Dec	6	7	2	6
1-Jan	6	5	3	3
2-Jan	8	3	1	4
3-Jan	4	1	0	6
4-Jan	4	3	1	5
5-Jan	3	1	0	5
6-Jan	3	0	1	3
7-Jan	1	5	3	0
8-Jan	1	6	1	5
9-Jan	0	5	3	8
10-Jan	1	5	3	8
11-Jan	0	14	4	9
12-Jan	3	9	5	3
13-Jan	2	7	3	3
14-Jan	1	9	4	2
Total	52	85	39	79

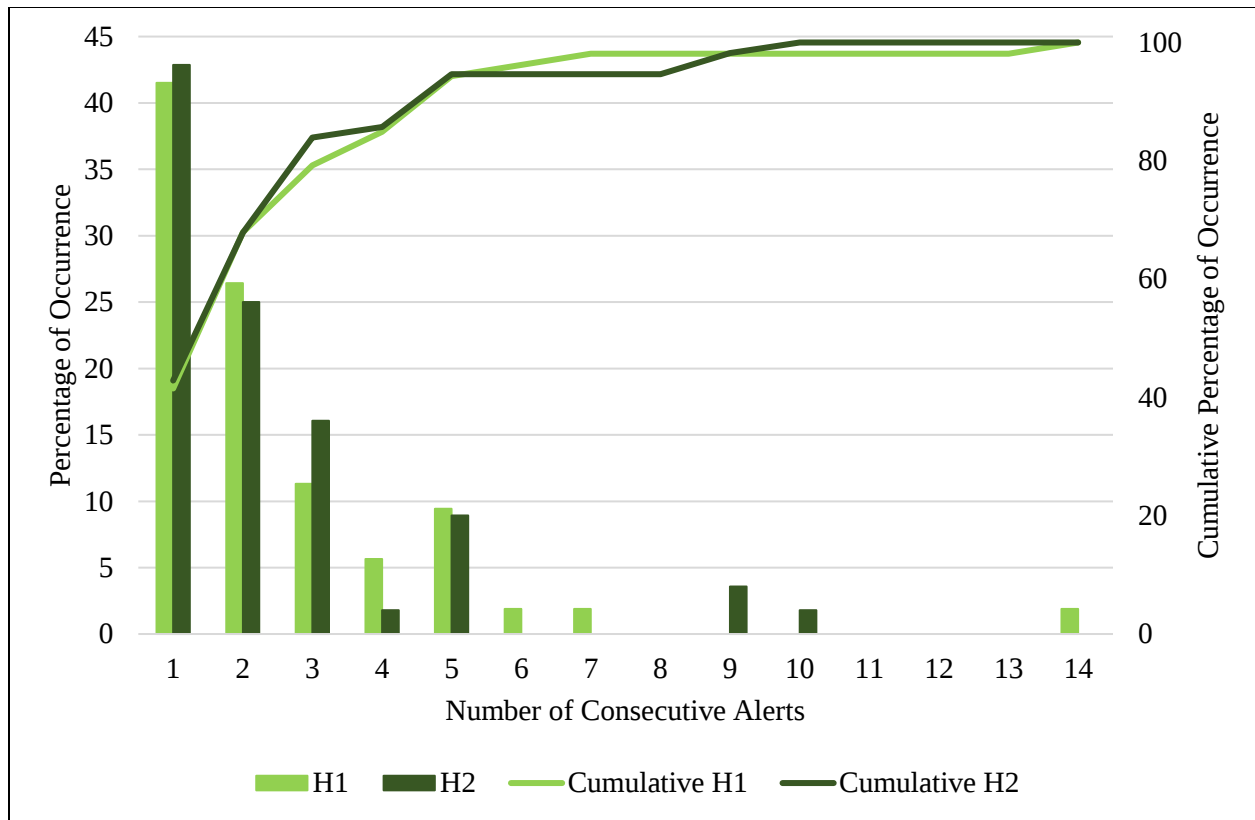


Figure 5. Percentage of occurrence of consecutive alerts for both houses in Trial 1

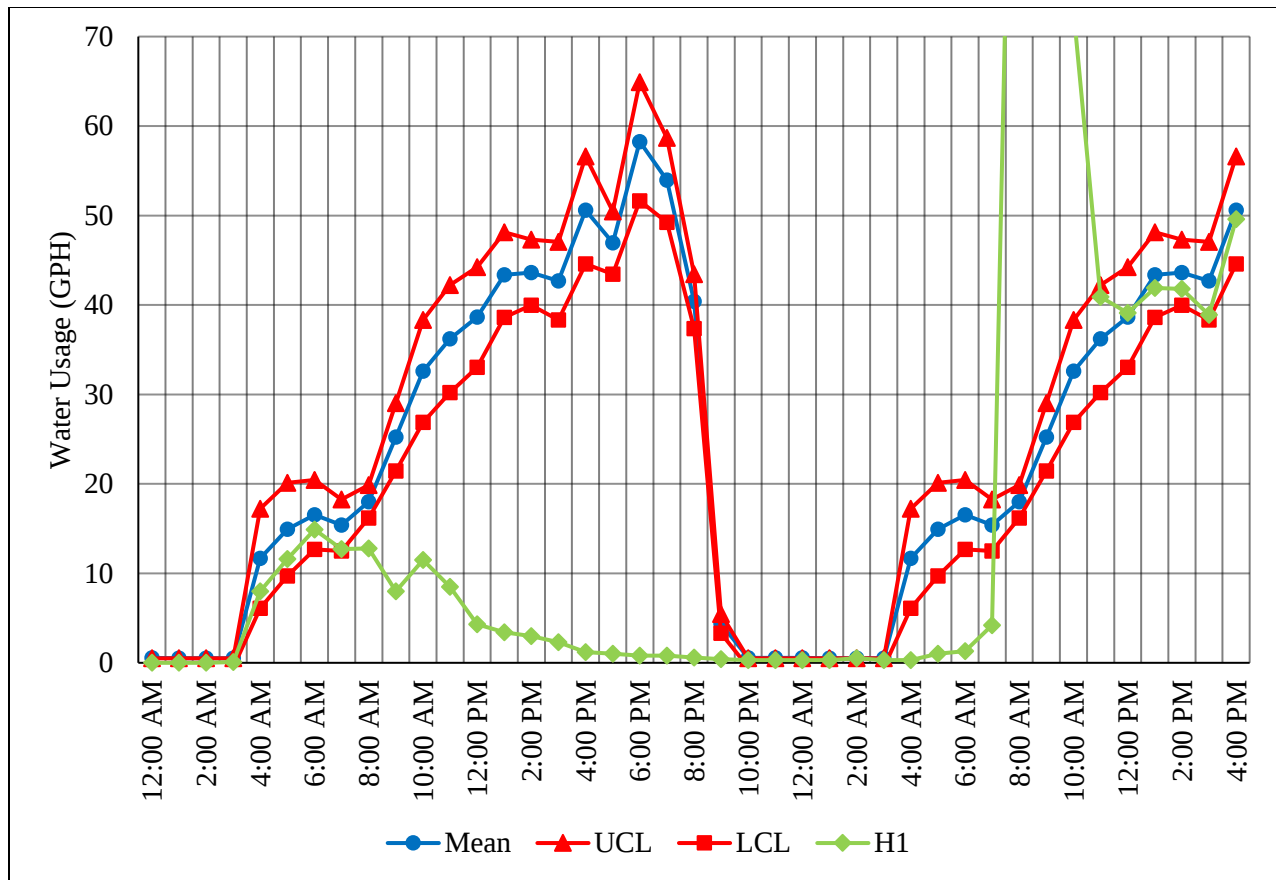


Figure 6. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) during the supply issue in House 1 – Trial 1

water alert system in houses is a water pressure sensor, however, if the restriction was after the pressure sensor, pressure may not have been affected and no alert generated.

House 2 Supply Issue (Mechanical and Behavioral alert)

A supply issue happened in House 2 and generated alerts from January 8th to the 12th (Figure 7). This supply issue is responsible for 5 persistent alert events and 4 transitory alert events. This issue was also caused by the same sediment problem as in House 1, but the restriction was less severe. Therefore, the flow was not completely restricted in this house, but was restricted to less than normal flow in the afternoon/evening, and exhibited how using a dynamic and frequent alert system is beneficial. In this case, the water flow rate was restricted to approximately 33 GPH. This flow rate was adequate for the morning hours of usage when the growers were walking the house and doing their morning checks. After talking to the growers on the farm it was found that during the morning checks: the sight tubes were filled, the water pressure was correct, and therefore it was assumed the birds were receiving an adequate supply of water. However, as their usage increased throughout the day the supply did not meet their normal usage, and it is assumed they became water-restricted. Evening water usage during this period was approximately 29% less than normal. The alerts during these times are due to a mechanical issue. After discussion with the growers, it was found that the restriction was occurring when the growers were doing other farm chores and not in the house. Therefore a pressure drop in the drinker sight tube or other indicator of an issue was not observed. As reported in Adams (1973) performance or mortality responses to water deprivation are delayed and not immediate.

This issue persisted as long as it did because the growers were inspecting the system in the morning and during these times it appeared that the supply of water was adequate. This issue required heavy flushing of the system and cleaning of the filters to correct. A static flow rate

alarm would not be able to detect this event as the lower normal morning water usage would generate an alert if it was set to this 33 GPH reduced flow rate, and if the restriction is after the water pressure sensor, a pressure alarm may not be generated either.

What is presented in Figure 7 is the third day of this water supply issue. The birds appear to be trying to compensate for the evening restriction with above average water usage in the morning hours and at 9:00 PM as the lights are shutting off. This shift in usage is most likely due to a thirst response as opposed to an anticipatory behavior of expecting the restriction. This compensatory usage increase in these hours was seen the first morning after the restriction began. An increase in water usage is seen after periods of water deprivation in broilers (Sprenger et al, 2009) and in an older, dual purpose breed (New Hampshire) (Ross, 1960). Therefore, it makes sense to observe a similar response in modern layers. The transitory alerts generated at these times would be due to a behavioral change in water usage.

The growers were using water usage as a management tool at this time, however, they were reviewing the previous day's totals the next morning, a common practice in the poultry industry. The difference in daily total water usage between the restriction was 511 gallons (restricted) versus 597 gallons (normal). This is only a 14% difference due to the increased usage at other times and did not cause alarm for the grower with their typical method of reviewing daily water totals. This problem persisted for four days and most likely would have gone on for longer had these houses not been studied and the growers notified the first day.

Additionally, because water restriction can decrease feed intake, the birds may have not consumed as much feed as normal during these times and therefore not received the expected amount of nutrients (Marks, 1986). This can be especially problematic because this event was occurring during the afternoon/evening and major eggshell development usually occurs at night

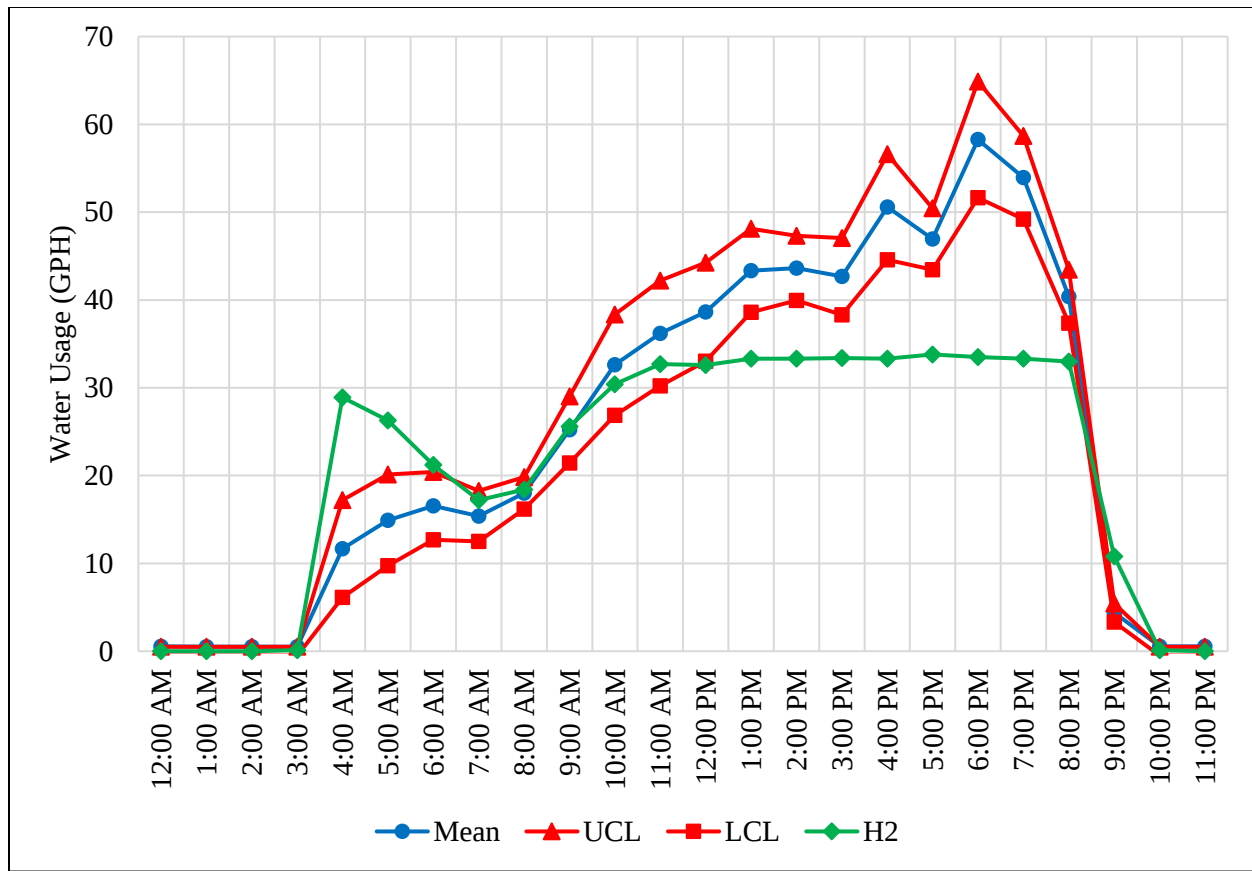


Figure 7. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) during the supply issue in House 2 – Trial 1

(Harms et al, 1996). Therefore, the nutrients that are consumed in the evening are especially important and anticipatory feeding behaviors before the dark period have been reported in broilers (May and Lott, 1992b) and in layers (Hughes and Black, 1977). These anticipatory behaviors suggest the birds can learn to expect this period of reduced activity and limited access to nutrients and therefore increase consumption because of this.

Storm (Behavioral alert)

On January 4th a severe storm moved over the farm. Water usage was seen to be depressed for 5 hours following this event in House 2 and generated one persistent alert event. The first line of storms that affected the water usage in Figure 8 arrived at the Farm just after 5:00 PM and the second line hit at approximately 6:00 PM, water usage remained below the LCL threshold for the rest of the photoperiod. While a storm is not a management issue that needs to be corrected, it is interesting to note how this event depressed water usage for the rest of the day and suggests that the drinking behavior of birds can be affected by external stressors enough to note a substantial difference in usage. This also suggests that acute issues that affect the water usage pattern can affect the water usage behavior after the event has occurred. It has been reported that other stressors such as heat stress can quickly affect water usage in broilers (May and Lott, 1992a) and in layers (Xin et al, 2002). Additionally, it has been reported that this change in usage can occur before a shift in thermal heat balance and from the thermal stimulus itself (Kechil et al, 1981).

However, this effect on water usage may not be due to a physiological stimulus but instead learned behavior. While House 1 did experience 5% less water usage during this time, the depression was not enough to generate alerts during this period. This difference is possibly due to different behavioral responses between the houses. It was theorized in Hughes and Black

(1977) that layers that were housed together and fed ad libitum adjusted their activity and feeding patterns to more closely resemble their feed restricted neighbors. Chickens can learn behaviors from their flock mates (Daisley et al, 2009) and the anticipatory behaviors that have been reported in chickens are also forms of learned behaviors (Hughes and Black, 1977; May and Lott, 1992b; Xin et al 2002). It is possible that the population in a house can learn unique behaviors and have different responses to stimuli than a similar population in a different house. It is also possible that different house conditions caused this response such as a loose curtain flapping in the wind or the lights flickering in House 2 but not in House 1.

The majority of alerts events were transitory, however, the only transitory alerts events that had an attributable cause were the increased compensatory usage during the supply issue in House 2 and the system flush in each house during the morning of January 13th and 14th after the supply issues (Table 5). Each system flush generated a single hour, transitory alert event. Of the 109 total alert events only 15 had an attributable cause, however, of the 20 persistent alert events, 7 had an attributable cause. The longest alert event without an attributable cause was 6 alerts in a row. Given this, transitory alert events began to be treated with less urgency. However, the purpose of this test was to increase the speed at which events could be identified and hopefully be addressed, and while investigation after a few hours of an event occurring is better than discovery the next morning, it leaves room for improvement.

Of the 255 alerts that were generated during Trial 1, only 75 had attributable causes, meaning that 71% of the alerts could not be attributed to a cause. This is too high for an alert system to be useful in a commercial setting. Most days had both high and low alerts, this suggests that the thresholds are too narrow and do not adequately account for normal water usage variation. Additionally, if the water usage data for each hour block are considered normally

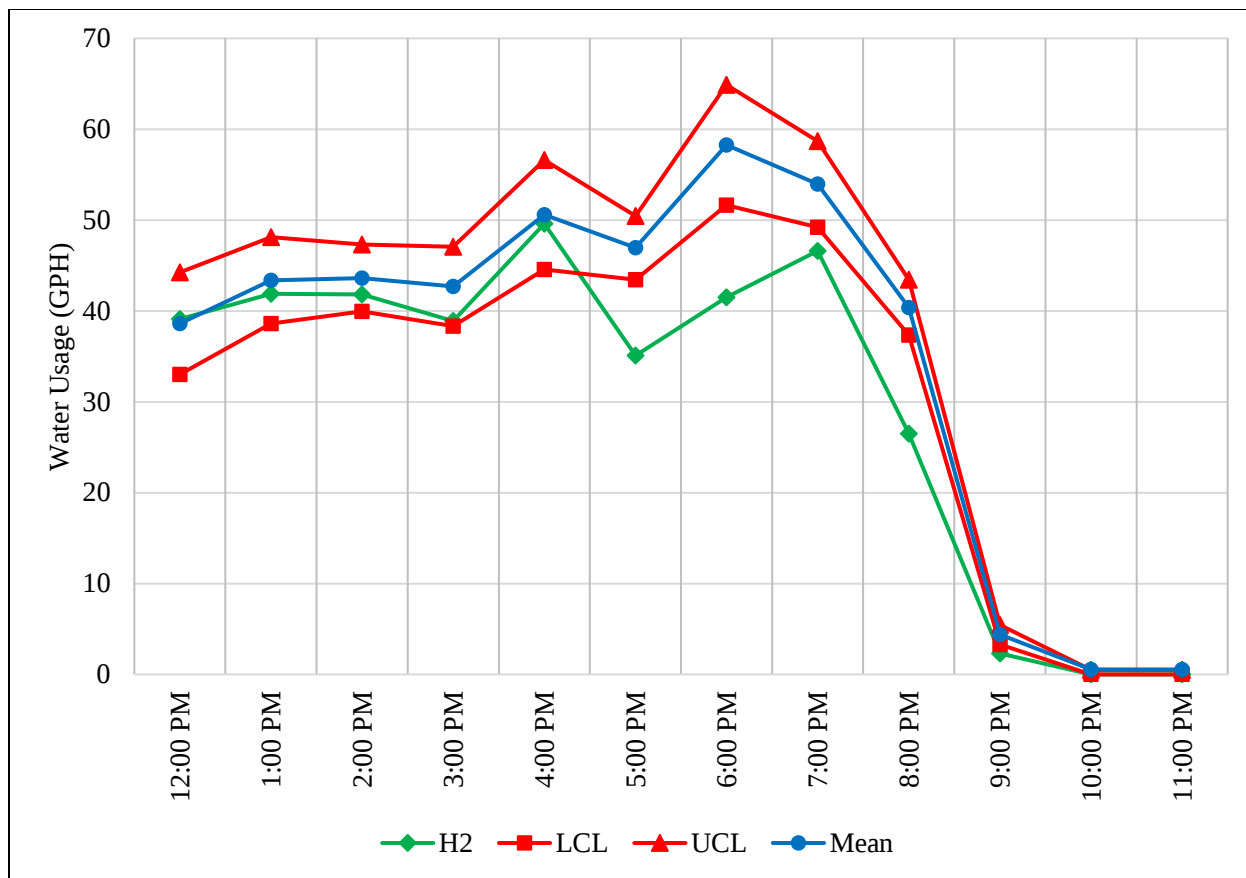


Figure 8. Water usage and alert model with upper control limits (UCL) and lower control limits (LCL) in House 2 during storm event – Trial 1

distributed then a ± 1 SD alert offset would only cover 68% of the normal data (Daniel, 2009). The chosen delineation between transitory and persistent alerts (persistent was four or more alerts in a row) was done observationally, interestingly it is similar to Rule 3 of the Western Electric Rules. Rule 3 defines an alert condition if 4 out of 5 consecutive are one or more SD away from one side of the mean (Western Electric, 1956).

Another possible reason for the high level of unexplained alerts was that the initial goal was to build a water usage model that spans this specific type of layer production (cage-free, Brown Leghorn), however even with the same feeding and lighting times the houses had small differences in trends. Therefore, aggregating the data from House 1 and House 2 into one model may have resulted in a model that was not as accurate or precise in generating alerts for either house. In the beginning it was thought that the deviations between the two houses were considered too small to matter, and it would be beneficial to aggregate together to build a cage-free layer alert model

In Trial 1, an hourly water usage model with alert thresholds, based on SD, revealed a consistent increase in water usage throughout the day that peaked in the evening. Notable events included a storm affecting House 2, a supply issue in both houses, and drinker system flushes post-issues. The storm notably affected the drinking behavior of House 2 but not House 1, possibly suggesting a difference in behavioral response between the two houses. Supply issues, particularly in House 2, highlighted the importance of dynamic alert thresholds. These issues underscored the potential impact on bird behavior and production. Investigation of alerts revealed a majority of unexplained alerts, indicating the need for considering house-specific models to improve alert accuracy and for refining threshold parameters to attempt to improve the

efficacy of the system. These topics were decided to be further investigated in Trial 2 and Trial 3.

TRIAL 2

The normal expected usage (NEU) models of these three cage-free layer houses created in Trial 2 again exhibited a gradually increasing usage during the day that peaks before the lights are turned off for the night. The results of Trial 2 indicated that though water usage patterns tends to be very similar between laying houses, each house has unique characteristics in its water usage pattern. This is an important consideration when it comes to alerting growers to changes in a house's water usage pattern, and why combined models present challenges. It was found that when trying to model mean usage, the day-to-day variability was much lower than the variability in the Daily Event Time (DET) periods. The DET periods are based around the feeding times, which are repeated and expected events that occur at the same time every day. It also showed that variability increased as the day went on showing the suspected increase in variation in the afternoon seen in Trial 1.

The NEU models of these three houses again illustrated that there is gradually increasing usage during the day that peaks prior to the lights being cut off, however, in Trial 2 the peak is later (approximately around 8:00 PM). The peak water usage for all the Houses is between 61-63 GPH (5.3-5.5 GPH/1000 birds). Figure 9 is a graph of the model means, additionally, they are provided in Table 6. Farm B House 1 had notably increased water usage compared to the Farm A houses from the hours of 8:00 AM to 12:30 PM (usage during this time averaged 30-17% higher than Farm A House 1 and House 2 respectively). There were also noticeable differences between the two houses on Farm A. House 2 had a consistent decrease in water usage leading up to the

4:00 and 6:30 PM feedings and increased usage after these feedings. Farm A House 1 did have dips in usage at these feeding times but as seen in Figure 9 and Table 6 these responses were not as dramatic as in House 2. After reviewing the model diagnostics, the UGA Statistical Consulting Group considered these well-fitting models of water usage. The residual plots displaying the difference from expected to actual water usage from Farm A House 1, Farm A House 2, and Farm B House 1 are provided in showing relatively good model accuracy (Figure 10-12).

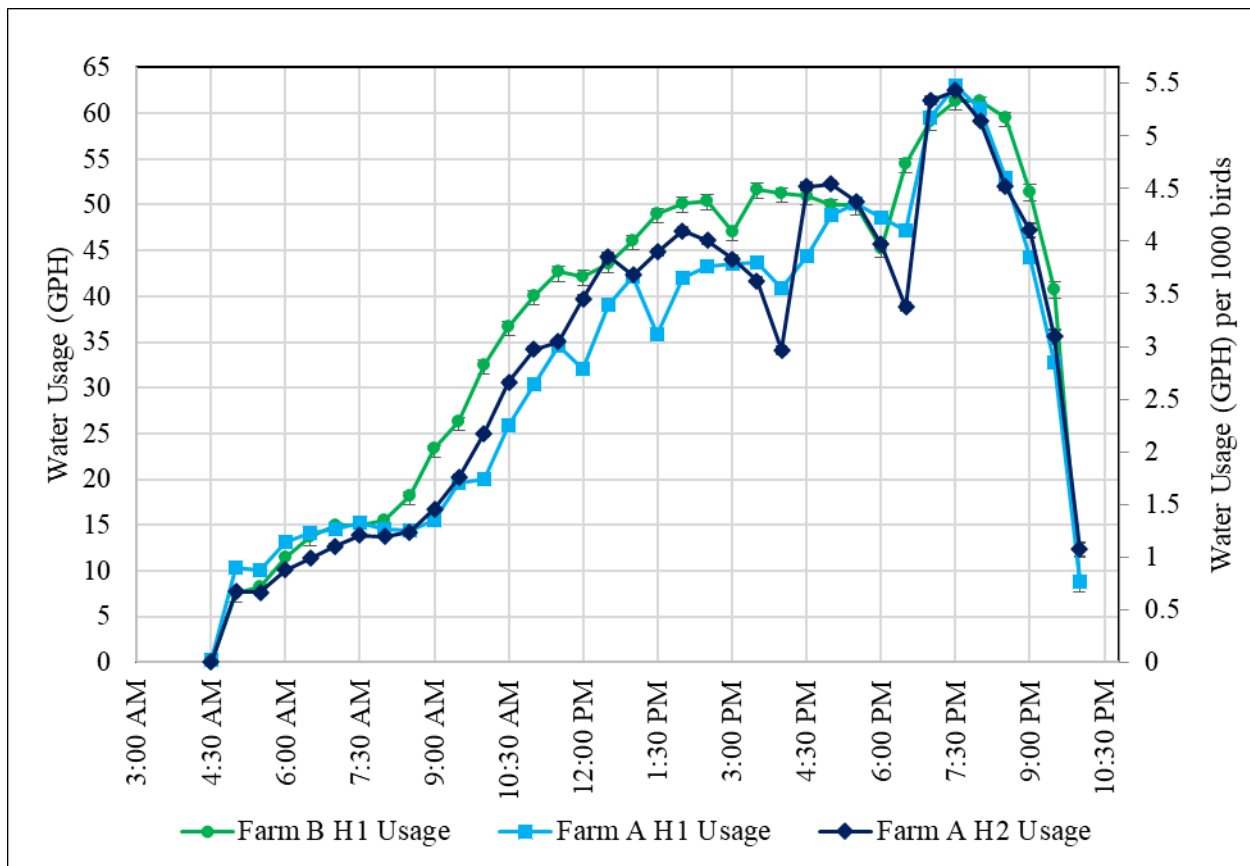


Figure 9. Normal expected usage (NEU) model means for all houses created in Trial 2

Table 6. Means and standard errors for house normal expected usage (NEU) models created in Trial 2

	Farm A H1	Farm A H2	Farm B H1
Time	Mean (GPH) $\pm$ SE	Mean (GPH) $\pm$ SE	Mean (GPH) $\pm$ SE
4:30 AM	0.31 $\pm$ 0.04	0.04 $\pm$ 0.01	0.05 $\pm$ 0.16
5:00 AM	10.34 $\pm$ 0.22	7.74 $\pm$ 0.26	7.57 $\pm$ 0.20
5:30 AM	10.06 $\pm$ 0.22	7.68 $\pm$ 0.26	8.27 $\pm$ 0.20
6:00 AM	13.20 $\pm$ 0.22	10.09 $\pm$ 0.26	11.41 $\pm$ 0.20
6:30 AM	14.11 $\pm$ 0.19	11.37 $\pm$ 0.16	13.72 $\pm$ 0.32
7:00 AM	14.60 $\pm$ 0.19	12.73 $\pm$ 0.16	14.99 $\pm$ 0.32
7:30 AM	15.20 $\pm$ 0.19	13.86 $\pm$ 0.16	14.96 $\pm$ 0.32
8:00 AM	14.51 $\pm$ 0.19	13.76 $\pm$ 0.16	15.58 $\pm$ 0.32
8:30 AM	14.42 $\pm$ 0.19	14.27 $\pm$ 0.16	18.26 $\pm$ 0.32
9:00 AM	15.57 $\pm$ 0.19	16.77 $\pm$ 0.16	23.36 $\pm$ 0.32
9:30 AM	19.65 $\pm$ 0.28	20.22 $\pm$ 0.29	26.33 $\pm$ 0.47
10:00 AM	19.97 $\pm$ 0.28	25.00 $\pm$ 0.29	32.51 $\pm$ 0.47
10:30 AM	25.85 $\pm$ 0.28	30.64 $\pm$ 0.29	36.73 $\pm$ 0.47
11:00 AM	30.33 $\pm$ 0.28	34.18 $\pm$ 0.29	40.08 $\pm$ 0.47
11:30 AM	34.53 $\pm$ 0.43	35.05 $\pm$ 0.38	42.66 $\pm$ 0.63
12:00 PM	32.08 $\pm$ 0.43	39.75 $\pm$ 0.38	42.15 $\pm$ 0.63
12:30 PM	39.13 $\pm$ 0.43	44.35 $\pm$ 0.38	43.53 $\pm$ 0.63
1:00 PM	42.09 $\pm$ 0.43	42.33 $\pm$ 0.36	46.03 $\pm$ 0.65
1:30 PM	35.85 $\pm$ 0.43	44.82 $\pm$ 0.36	48.97 $\pm$ 0.65
2:00 PM	42.04 $\pm$ 0.43	47.13 $\pm$ 0.36	50.13 $\pm$ 0.65
2:30 PM	43.28 $\pm$ 0.43	46.10 $\pm$ 0.36	50.41 $\pm$ 0.65
3:00 PM	43.55 $\pm$ 0.43	44.06 $\pm$ 0.36	47.00 $\pm$ 0.65
3:30 PM	43.73 $\pm$ 0.43	41.70 $\pm$ 0.36	51.71 $\pm$ 0.65
4:00 PM	40.84 $\pm$ 0.37	34.11 $\pm$ 0.40	51.28 $\pm$ 0.59
4:30 PM	44.40 $\pm$ 0.37	52.02 $\pm$ 0.40	51.00 $\pm$ 0.59
5:00 PM	48.83 $\pm$ 0.37	52.25 $\pm$ 0.40	49.97 $\pm$ 0.59
5:30 PM	50.19 $\pm$ 0.37	50.41 $\pm$ 0.40	49.94 $\pm$ 0.59
6:00 PM	48.63 $\pm$ 0.37	45.68 $\pm$ 0.40	45.23 $\pm$ 0.59
6:30 PM	47.17 $\pm$ 0.33	38.84 $\pm$ 0.38	54.52 $\pm$ 0.47
7:00 PM	59.47 $\pm$ 0.33	61.40 $\pm$ 0.38	59.13 $\pm$ 0.47
7:30 PM	63.07 $\pm$ 0.33	62.50 $\pm$ 0.38	61.29 $\pm$ 0.47
8:00 PM	60.48 $\pm$ 0.33	59.22 $\pm$ 0.38	61.35 $\pm$ 0.47
8:30 PM	52.87 $\pm$ 0.34	51.96 $\pm$ 0.31	59.56 $\pm$ 0.52
9:00 PM	44.29 $\pm$ 0.55	47.21 $\pm$ 0.78	51.46 $\pm$ 0.85
9:30 PM	32.79 $\pm$ 0.55	35.60 $\pm$ 0.79	40.76 $\pm$ 0.85
10:00 PM	8.86 $\pm$ 0.55	12.34 $\pm$ 0.79	8.72 $\pm$ 0.85

This underlines the importance of viewing houses independently. What is normal in one house may not be normal in another, even with many other factors being the same such as age, egg production, feeding, and management. Although the pattern is similar and overall daily water usage is only approximately 3% different between the houses on Farm A, the usage at 4:00 PM and 6:30 PM is 17% and 18% different between House 1 and House 2 on Farm A. These unique house specific trends are important to identify and consider in the development of an alert system based on water usage. If deviations from the normal are used to identify issues, then it is beneficial to be as precise as possible in defining what normal usage is. This data suggests that flocks may have learned behaviors or responses that become normal to the general population in that specific house but are not normal in the adjacent house. Therefore, a house specific approach would be beneficial in not only defining the normal water usage pattern but also in deciding the thresholds from normal to be used to detect events.

Overall, this water usage pattern portrayed by the NEU models is very similar to what was seen in Trial 1 and in Xin et al (2002). The peak water usage shift in time is partially due to a change in considering time in Daylight savings for the entirety of Trial 2. Also, it may be that increases in flock age or the changing of natural daylight hours shining on the translucent side curtains attributed to this slow and slight shift of water usage pattern through the production cycle, or as feeding times and/or diets are changed illustrates the importance that the water usage pattern is dynamic. This is important to realize when trying to evaluate normal water usage behavior.

The increased morning usage trend exhibited in Farm B House 1 may be due to multiple factors. First, they did not have as many feedings in the afternoon/evening hours as Farm A. Since they had a higher percentage of their feedings in the morning and because feed

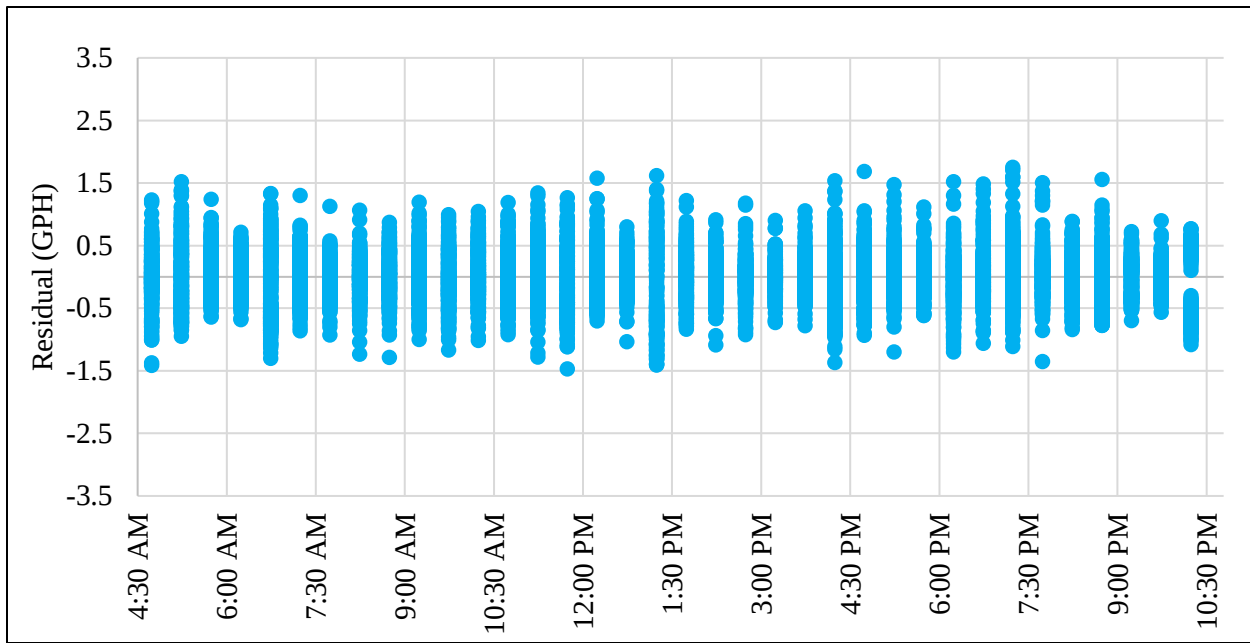


Figure 10. Residual (observed – estimated) plot for Farm A House 1 model created in Trial 2

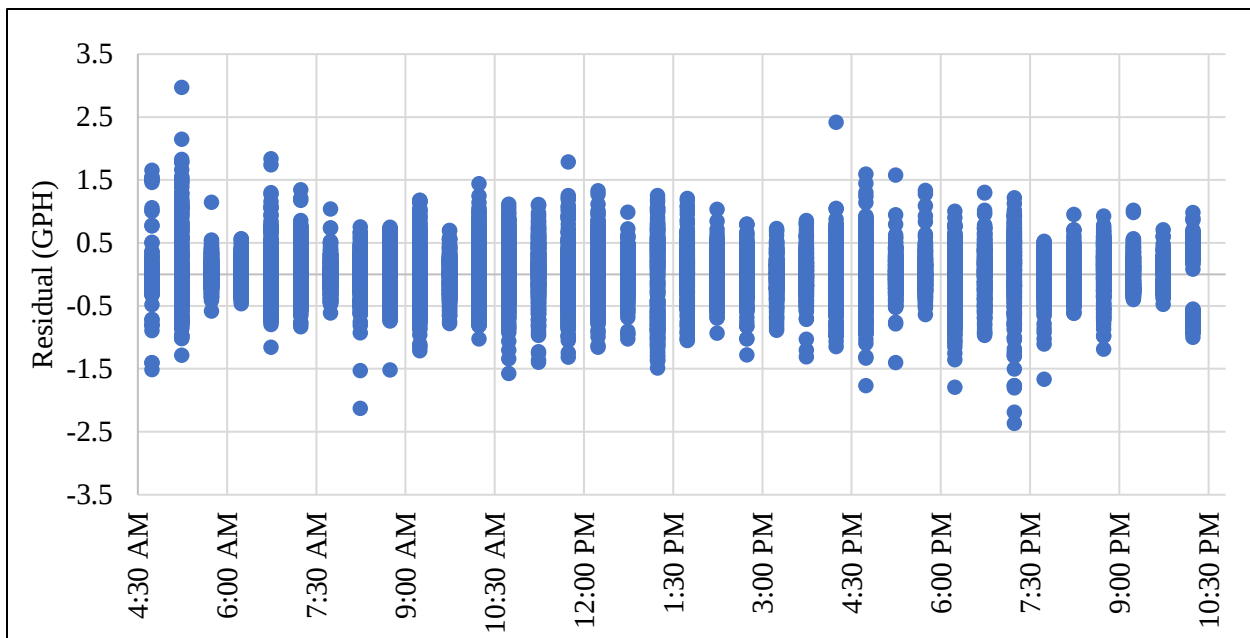


Figure 11. Residual (observed – estimated) plot for Farm A House 2 model created in Trial 2

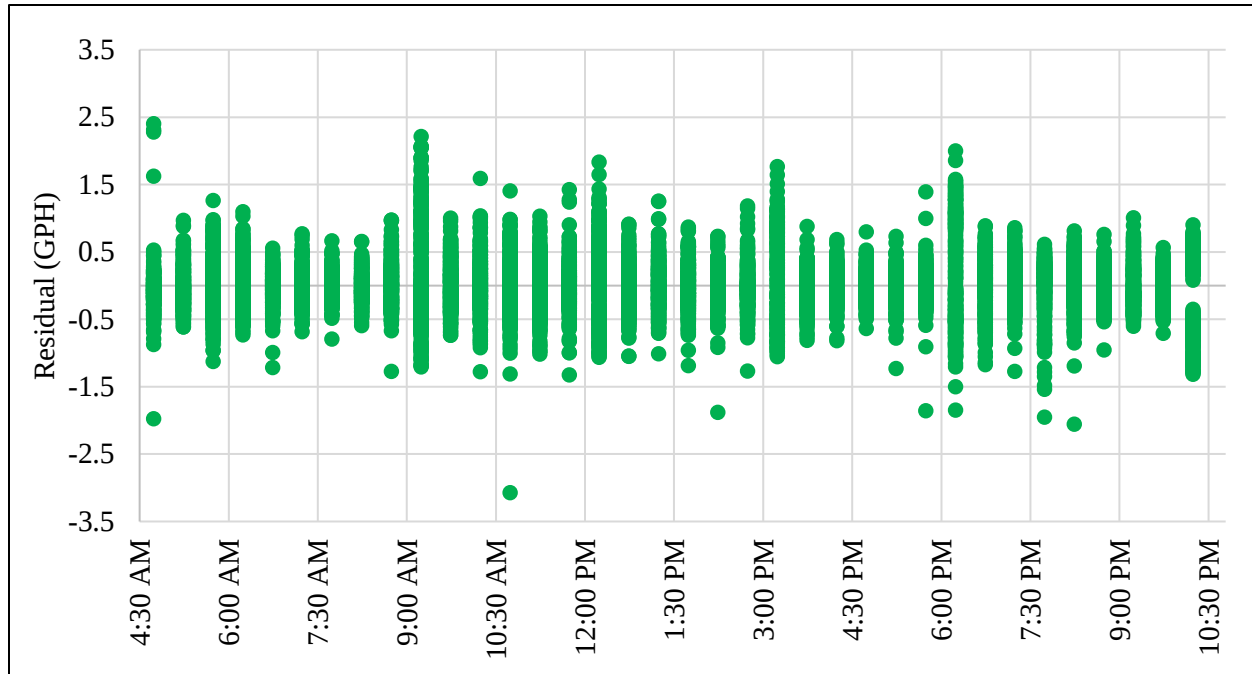


Figure 12. Residual (observed – estimated) plot for Farm B House 1 model created in Trial 2

consumption and water usage are closely related (Czarick and Fairchild, 2006) this may drive the earlier increase in usage. Changes in water usage patterns have been shown to be influenced by different feeding regimens (Xin et al, 1993). Additionally, while egg production was not modeled because only daily values were available it is important to note that Farm B had better egg production than Farm A. Farm B House 1 averaged 0.92 eggs/hen-day for the trial period while Farm A averaged 0.79 and 0.81 eggs/hen-day (House 1 and 2, respectively). The majority of egg composition is water (Réhault-Godbert et al., 2019) and therefore a higher level of egg production may be why evening usage is not decreased in Farm B House 1, although there were fewer evening feeding times. The overall feed amount each day was not drastically different for all three houses aggregated across the entire 5 month period (averaging 0.24 lbs./hen on Farm B and 0.26 lbs./hen on Farm A). This difference in number of feedings and egg production may be why slight but noticeable changes in the water usage pattern were present for Farm B.

The cause of these unique differences in water usage trends in the afternoon hours in the houses on Farm A is more difficult to determine as these houses were under the same management, feeding times, and production levels. This may be learned anticipatory behavior of the flocks within the house, similar to the reported anticipatory feeding behavior in Hughes and Black (1977). There may also be differences in feeder chain speed, light distribution or intensity, or other environmental factors that were not measured.

There was a trend at feeding times where a dip of water usage was seen in the raw data, however, much of this gets filtered (or smoothed) out with the data aggregation. This can be visualized in Figure 13, which is a single day of usage at 5-minute intervals from Farm A House 2 with feeding times marked. The NEU models were not as accurate at modeling this dip behavior. The SD of residuals around the feeding times often increases, highlighting a decrease

in the accuracy of the NEU models at this time. This means that the variability of residuals (or how far away from the expected usage the actual usage was) was increased and the model expectation of water usage is not as accurate as at other times of the day. This is most notably seen in the SD of residuals for Farm A House 2 and 10 days of House 2 water data (Figure 14). The water usage of meal fed birds may be more variable around feeding times, causing this trend. It appeared that acute small water usage changes occurred around feeding times of meal fed broilers (Xin et al, 1993) and a similar trend may be being exhibited by these layers. In time-lapse images from the layer houses the decrease in water usage during the feeding time appeared to be a result of most hens actively eating before they started to migrate to the drinker line. Two example photos are provided where Figure 15 shows the hens during a feeding time and fewer birds are at the drinker line. Figure 16 is a picture of the feeders and drinkers 30 minutes after the feeding time and shows more birds actively drinking than in Figure 15.

The error SD for the DET periods was compared to the error SD for the effect of day. This was to determine whether changes from day to day were more variable than what was occurring within time periods of the day where usage would be similar. The error SD for DET intervals are listed in Table 7 for Farm A and in Table 8 for Farm B, because of the different feeding times the DETs were different between the two farms.

In all the houses the error SD for day is lower than all intervals except the 4:30-5:00 AM period (Table 9). This period is when the lights are turned on and experienced very little usage, the usage in this period should mostly be attributed to leaky nipples or a slight difference of a few minutes in the clock between the controllers and the recording system. It creates a good basis for consistency in a period because the responses are all very similar. In all the other DET intervals error SD is much higher than the error SD for the effect of day. Therefore, the UGA

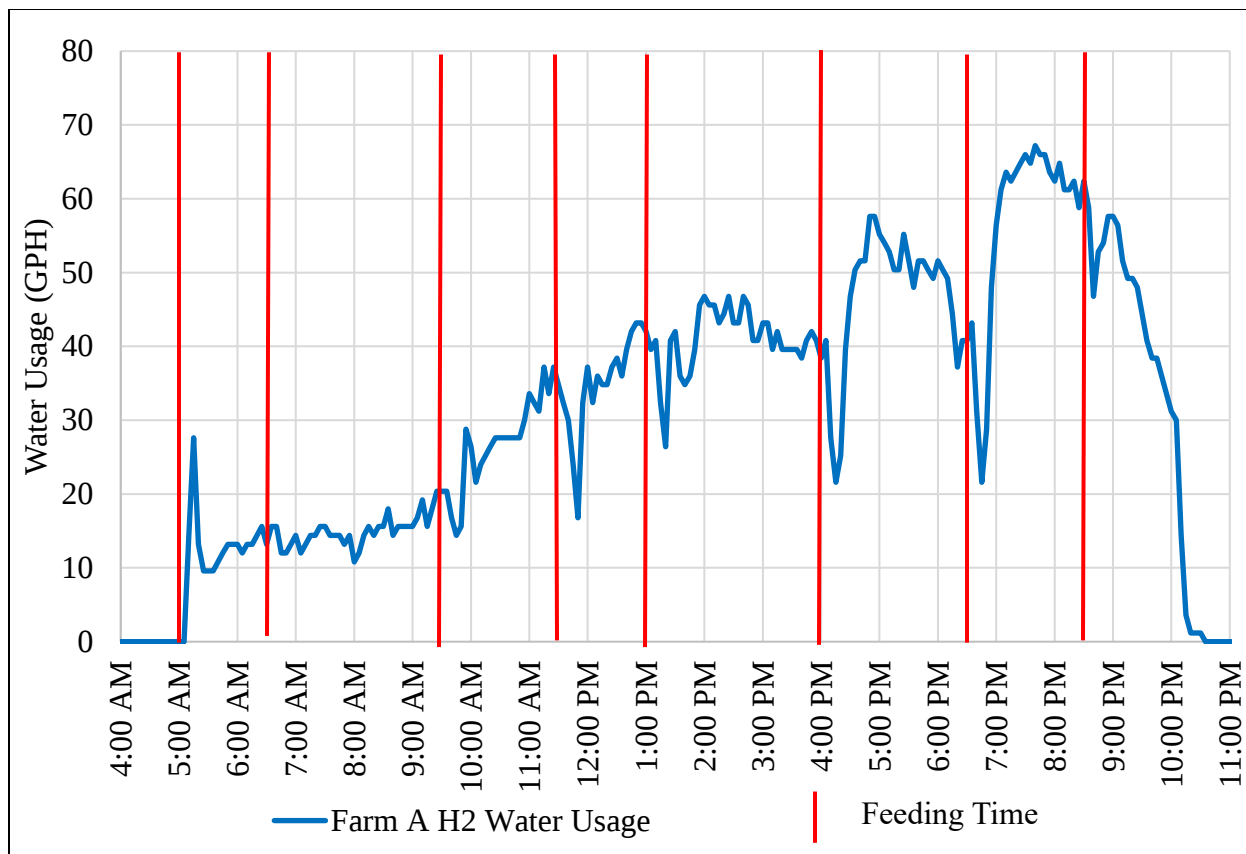


Figure 13. Single day water usage (5-min intervals) and feeding times on Farm A House 2 – Trial 2

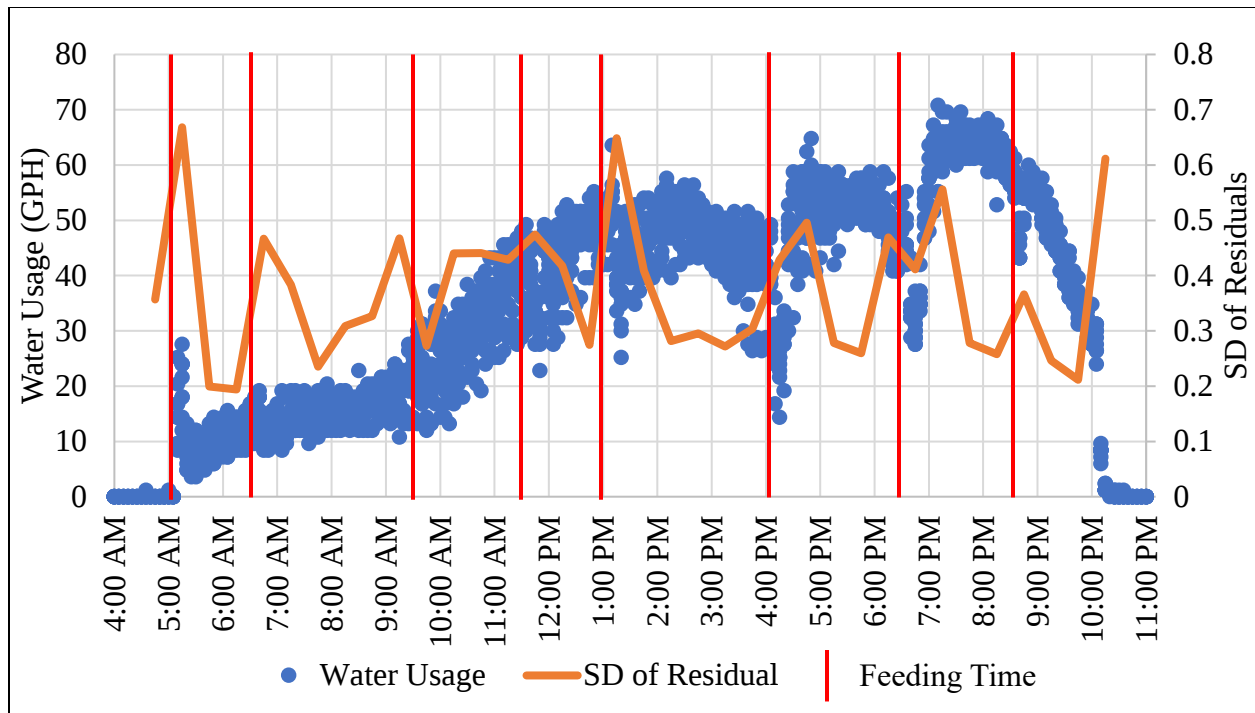


Figure 14. Ten days of Farm A House 2 water usage (5-min intervals), SD of residuals, and feeding times – Trial 2



Figure 15. Drinkers and feeders at a feeding time in Trial 2 where few birds are actively drinking



Figure 16. Drinkers and feeders 30 minutes after the feeding time in Trial 2 where more birds are actively drinking.

Statistical Consulting Group considered the days very consistent to each other within an individual house, more consistent than within periods of the day when repeated and expected events occur. If the days are very consistent with each other, then previous data may be considered a good predictor of future usage. A test for a p-value cannot be done with this type of analysis as each house has an independent model, however, this trend of day-to-day error SD being lower than error SD of the DET intervals is true across all three houses.

It is also notable that error SD for the DET intervals increased in the afternoon hours for all three houses compared to the morning hours. This trend explains what was observed in the raw data in Trial 1, and why the threshold limits were increased in the afternoon periods. Error SD is 1.5-3 times more in some periods than during the first lighted period. This means that the water usage during these times is more variable and may be more difficult to model. During the period when the lights are turned off had the highest error SD during this period for all three houses. This can be visualized with the radar plots in Figure 17 for Farm A and Figure 18 for Farm B. The error SD is increasing as the day goes on as seen by the outward spiral in Figures 17 and Figure 18.

This type of model structure could possibly be adapted to other types of poultry production, such as broiler breeders, where they are fully grown and sexually mature. This modeling structure of evaluating day-to-day error SD to error SDs of specific time periods might be useful in understanding field data where full statistical tests are not able to be performed. However, its uses in understanding broiler patterns may be limited as their high growth rate will be a factor in increasing consumption and will be difficult to understand the natural day-to-day variation from variations due to growth increases.

Trial 2 revealed insights into the water usage patterns of three different houses, despite similarities in rearing. The daily water usage pattern resembled Trial 1 with a gradual increase leading to a peak just before the end of the photoperiod, albeit with a later peak time. Farm B House 1 showed increased usage in the late morning, possibly due to different feeding regimes and higher egg production compared to Farm A. Notable differences between Farm A houses suggested house-specific behaviors. A specific trend of a dip in water usage was seen following feeding times. Error SD analysis indicated consistent day-to-day normal water usage patterns within all houses, with error SD in DET intervals showing higher variability, particularly in the afternoon. This emphasizes the importance of house-specific approaches in understanding and monitoring water usage behaviors

Table 7. Error standard deviations for Farm A houses from the models created in Trial 2

Time Interval	Farm A H1	Farm A H2
4:30-5:00 AM	0.482	0.271
5:00-6:30 AM	7.52	8.87
6:30-9:30 AM	6.47	5.44
9:30-11:30 AM	9.62	10
11:30 AM-1:00 PM	14.6	12.8
1:00-4:00 PM	14.5	12.3
4:00-6:30 PM	12.5	13.5
6:30-8:30 PM	11.1	13
8:30-9:00 PM	11.6	10.5
9:00-10:30 PM	18.7	26.6

Table 8. Error standard deviations for Farm B from the model created in Trial 2

Time Interval	Farm B H1
4:30-5:00 AM	0.219
5:00-7:00 AM	6.18
7:00-9:00 AM	10
9:00 AM-12:00PM	14.9
12:00-3:00 PM	19.8
3:00-6:00 PM	18.6
6:00-10:30 PM	21.52

Table 9. Error standard deviations for the effect of day on all Farms from the models created in Trial 2

Farm A H1	Farm A H2	Farm B H1
1.19	0.284	0.418

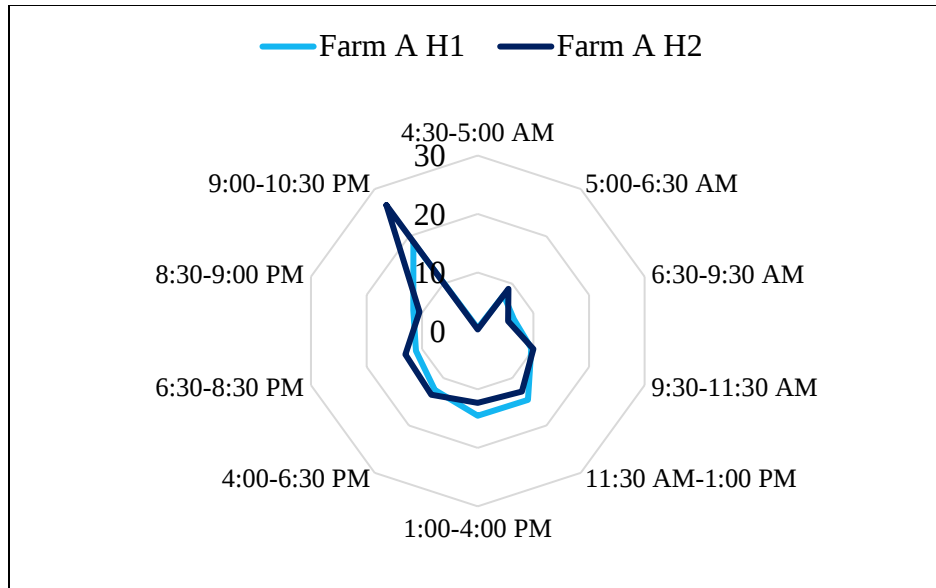


Figure 17. Radar plot of error standard deviation for time intervals on Farm A from the models created in Trial 2, the clockwise outward spiral shows variation increasing later in the day

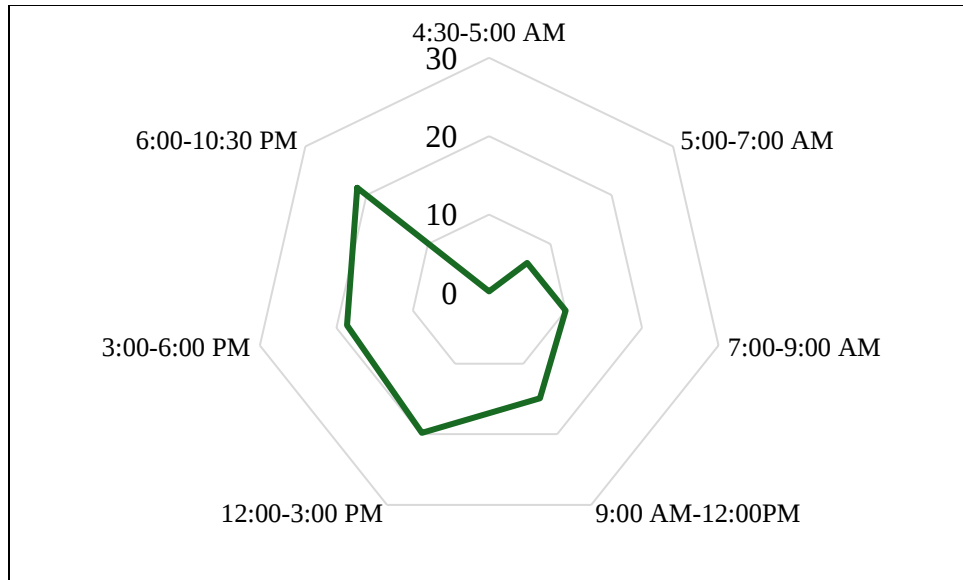


Figure 18. Radar plot of error standard deviation for time intervals on Farm B from model created in Trial 2, the clockwise outward spiral shows variation increasing later in the day

TRIAL 3

In Trial 3 layers were 29 and 33 weeks old in Houses 1 and 2 on Farm A, respectively, and 24 weeks old in House 1 on Farm B. Water usage alert systems thresholds were based on two of the Western Electric Rules. First, any one point ± 3 SD away from the hourly mean was an alert threshold. Second, two of three consecutive points 2 SD above the mean, or two of three consecutive points 2 SD below the mean, would be considered an alert condition. Since a 7-Day rolling average of hourly water usage was utilized to determine the expected water usage for a given hour. A new mean usage model and alert thresholds were created for each house every day based on the seven previous days of data.

Daily water usage profile

Although the overall shape and usage pattern of the mature layers (30 + WOA) were similar to that seen in Trials 1 and 2, it was observed that prior to the implementation of the water usage alert system that the younger layers' (less than 30 WOA) hourly water usage pattern was different in shape than that observed in older layers during the trial as well as the pattern documented in Trials 1 and 2 of older layers. The young layers exhibited peak usage in the late morning hours and then decreased throughout the day. As the layers aged, water usage peaked at mid-morning and then remained relatively constant for the remainder of the day. As their age continued to increase the water usage in the evening hours increased while the morning usage remained relatively the same, resulting in an overall increase in total daily water usage. From 19 to 36 WOA the average daily total usage increased from 418 gallons to 743 gallons respectively, after week 36 the total daily water usage stopped increasing. The difference in water usage profile can be seen by comparing Figures 19 (26 week old layers) and Figure 20 (36 week old layers).

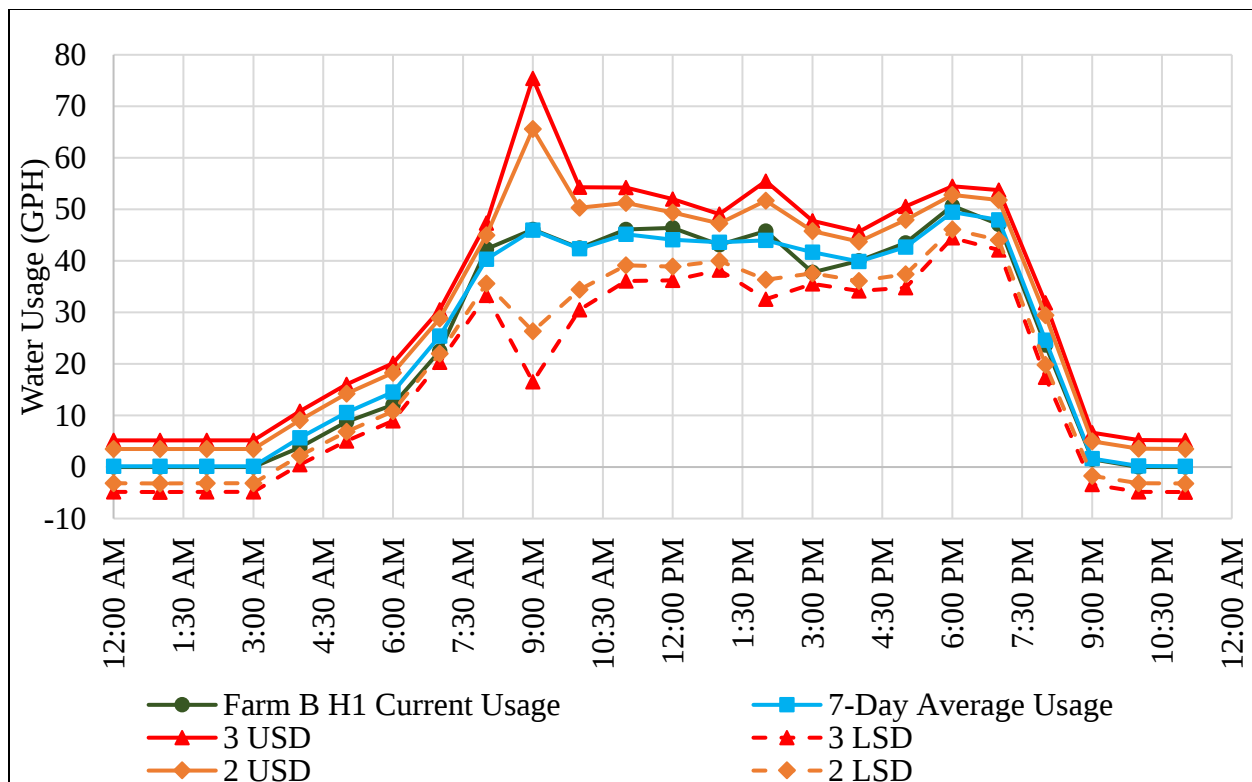


Figure 19. Younger layer water usage alert model during Trial 3 Farm B House 1 on 1/18/24 (26 weeks), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)

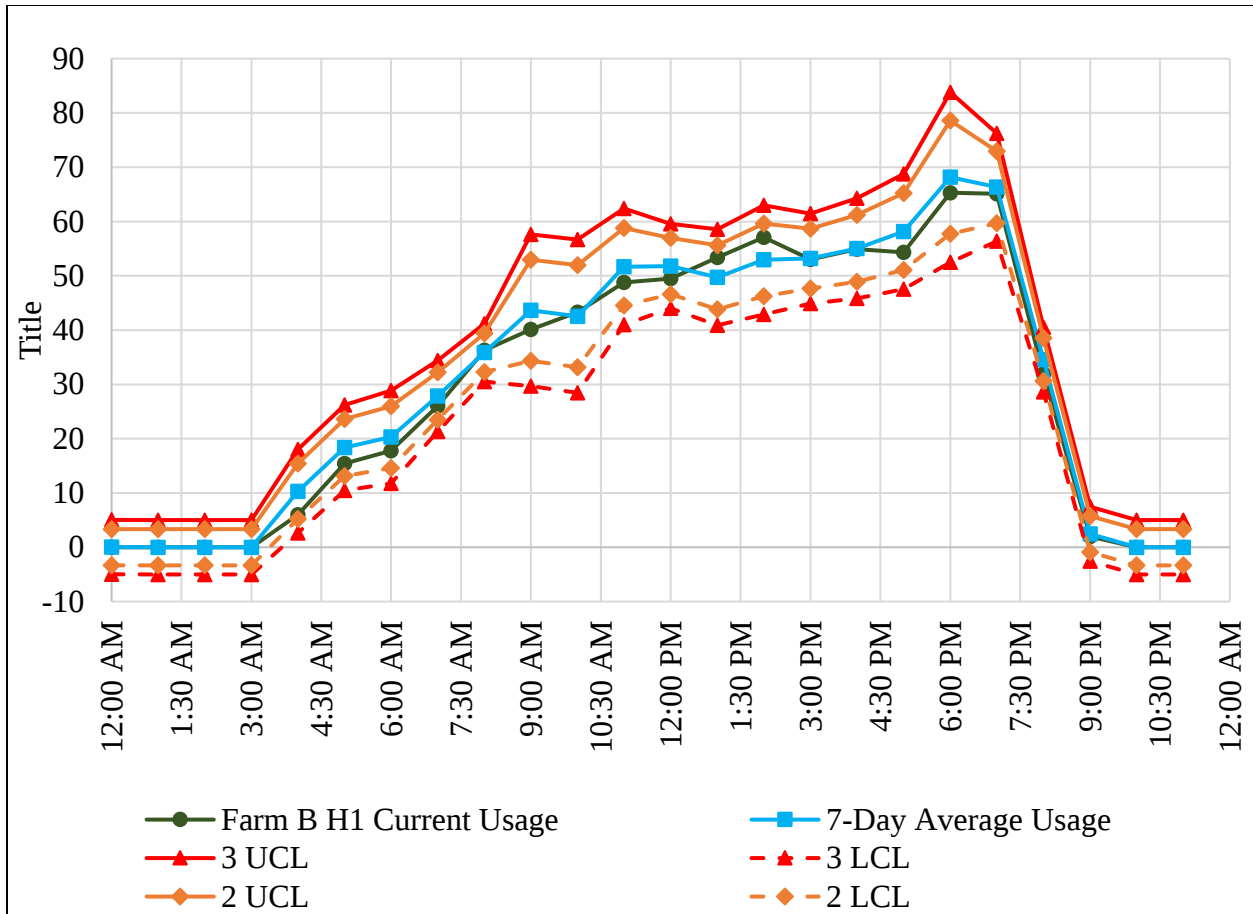


Figure 20. Older layer water usage alert model during Trial 3 Farm B House 1 on 3/29/24 (36 weeks), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)

The evolution in water usage pattern seen in Farm B House 1 (Figure 21) was also observed with the younger layers on Farm A before the alert system was initiated. However, because the birds were older (5 and 9 weeks older in Farm A House 1 and House 2, respectively) the overall shift in the daily water usage profiles during the alert system trial period was less pronounced than on Farm B House 1.

The gradual change in the water usage profile in these houses was possibly related to changes in the bird's production levels. Peak production can occur between 25 and 35 WOA (Hy-Line International, 2024) and the live production manager of this complex expects to reach peak production between weeks 28 and 35. Production peaked in week 31 on Farm B House 1. Water usage per bird is expected to increase during the build-up to peak production by 40-50% (Hy-Line International, 2024). Bodily water composition increases as a layer comes into production (57% for pullets versus 78% for layers) (Lopez et al, 1973). Therefore it is possible that changes in the drinking behavior of these layers are also affected due to egg production.

If the increase in the total daily water usage and increase in evening water usage was due to the layers increasing to peak production, then it may be related to the increased need for water in producing an egg. At this age (28 weeks), the layers will have normally achieved most of their bodily growth (Hy-Line International, 2024) and the energy needed for growth will be reduced. Due to the relationship between feed and water (Czarick and Fairchild, 2006), and the reduced need to physically grow, this means the water intake needed for growth will also be reduced. However, the body weights of the layers were not obtained. Energy and water are needed for egg production and those needs would increase as the rate of production increases. An egg is approximately 76% water, and the high rate of lay in modern commercial layers results in this being a highly demanding process (Réhault-Godbert et al., 2019). Major eggshell development

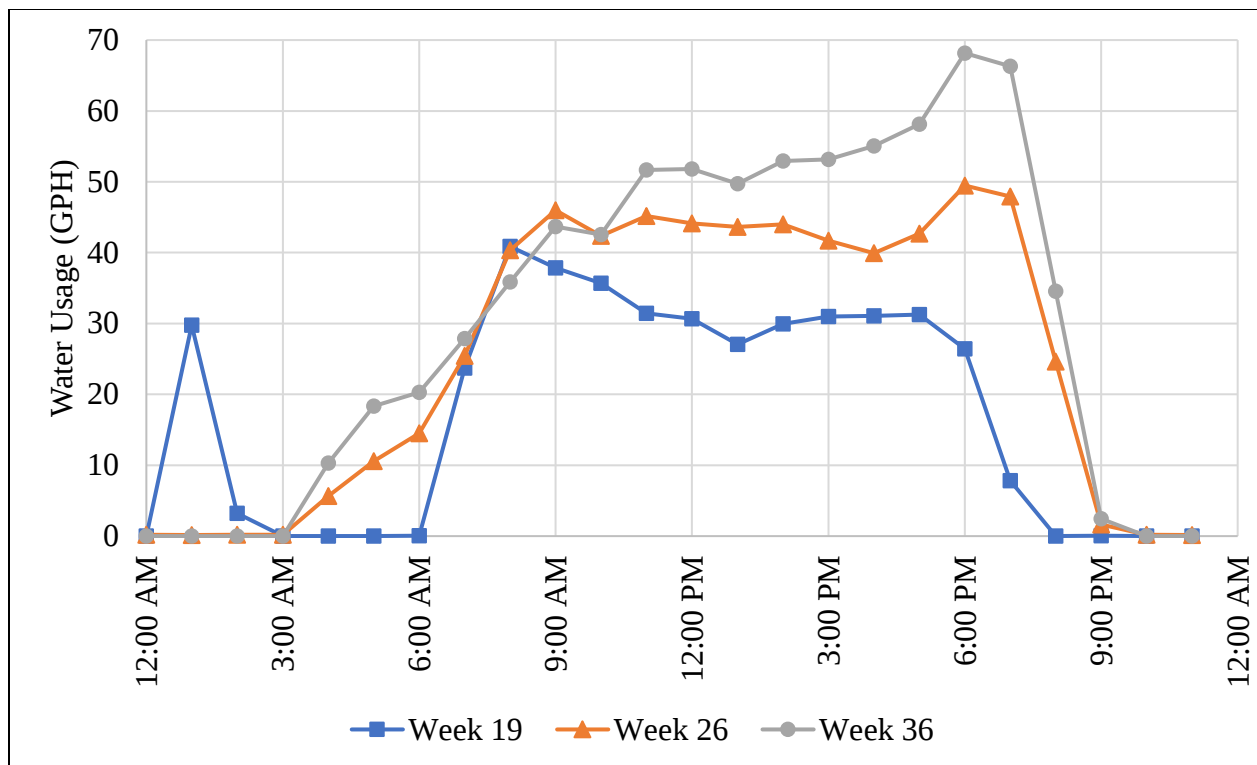


Figure 21. 7-Day average water usage from Farm B House 1 of 19-, 26-, and 36-week-old layers – Trial 3

often occurs at night (Harms et al, 1996) and is another energy and water demanding process. Therefore, this increase in evening usage may be anticipatory behavior as the birds learn the dark period is approaching (Xin et al, 1993). Anticipatory feeding behaviors before the dark period have been reported in broilers (May and Lott, 1992b) and in layers (Hughes and Black, 1977). These anticipatory behaviors suggest the birds can learn to expect this period of reduced activity and limited access to nutrients and therefore an increase in evening usage may be due to this behavior.

The continued increase in total daily water usage and evening usage past peak production in Farm B House 1 (Figure 21) was also seen in the houses on Farm A. The cause of this shift is not yet understood as egg weights were reported to not be increasing, nor was the feed amount, and production was starting to reduce. It is possible that the moisture content of the fecal material may have increased and that is where the excess water went (Ross, 1960). It is also possible that the older birds began to waste more water from the drinker line for an unknown reason and the increase in water usage is not representative of an increase in consumption. The layers studied in Xin et al (2002) that also exhibited peak usage in the evening were 29-30 weeks old and may have past peak production by this age. This data supports the idea that the water usage pattern can shift and therefore an alert system needs to not only have dynamic thresholds during the day but also needs to be able to adapt as the flock ages if the normal usage pattern shifts.

Alerts and events

There were 84 test days of the alert system in House 1 on Farms A and B and 47 test days for House 2 on Farm A (the reduced number of test days in House 2 was due to recording equipment issues) (Table 10). Test days are the number of days after the initial seven day training

period where alerts were capable of being generated. Alerts for Trial 3 fell into four categories: system flushes, lighting issues, feeding issues, and unknown causes. Alerts were generated for 52%, 39%, and 38% of the test days on Farm B House 1, Farm A House 1, and Farm A House 2 respectively (Table 10).

Water system flushing

Water system flushes resulted in sudden and greatly increased water usage that quickly returned to normal. Flushes primarily produced single 3 SD alerts (Figure 22) but could trigger a 2 SD alert if the flush occurred as the hour of the day changed during the flush. The farm manager on Farm A did not flush the water lines during Trial 3 while the manager on Farm B flushed the water lines occasionally. The increase spread in control limits during the 9:00 AM hour in Figure 19 (Farm B H1 1/18/24 data) was due to a drinking system flush that occurred during the 9:00 AM hour during the previous week. This highlights a weakness in setting alert thresholds based on previous data. Random and alert events that previously occurred are still being integrated into the rolling model. This can cause unnecessary expansion of the control limits that decreases the ability of the model to pick up on acute events at these times.

Lighting Issue

The alert occurring in House 1 – Farm B (Figure 23) was due to the farm manager adjusting the feeding time for Daylight savings but not the lighting program. As a result, the lights came on at 3:00 AM but the feed did not run until the normal 4:00 AM hour. This caused increased usage above the normal 3:00 AM level and an alert was generated since the feed was not present when the lights came on, water usage was lower than normal for the lights on/first feeding hour. Yet, when the feed ran at 4:00 AM water usage returned to normal. The absence of

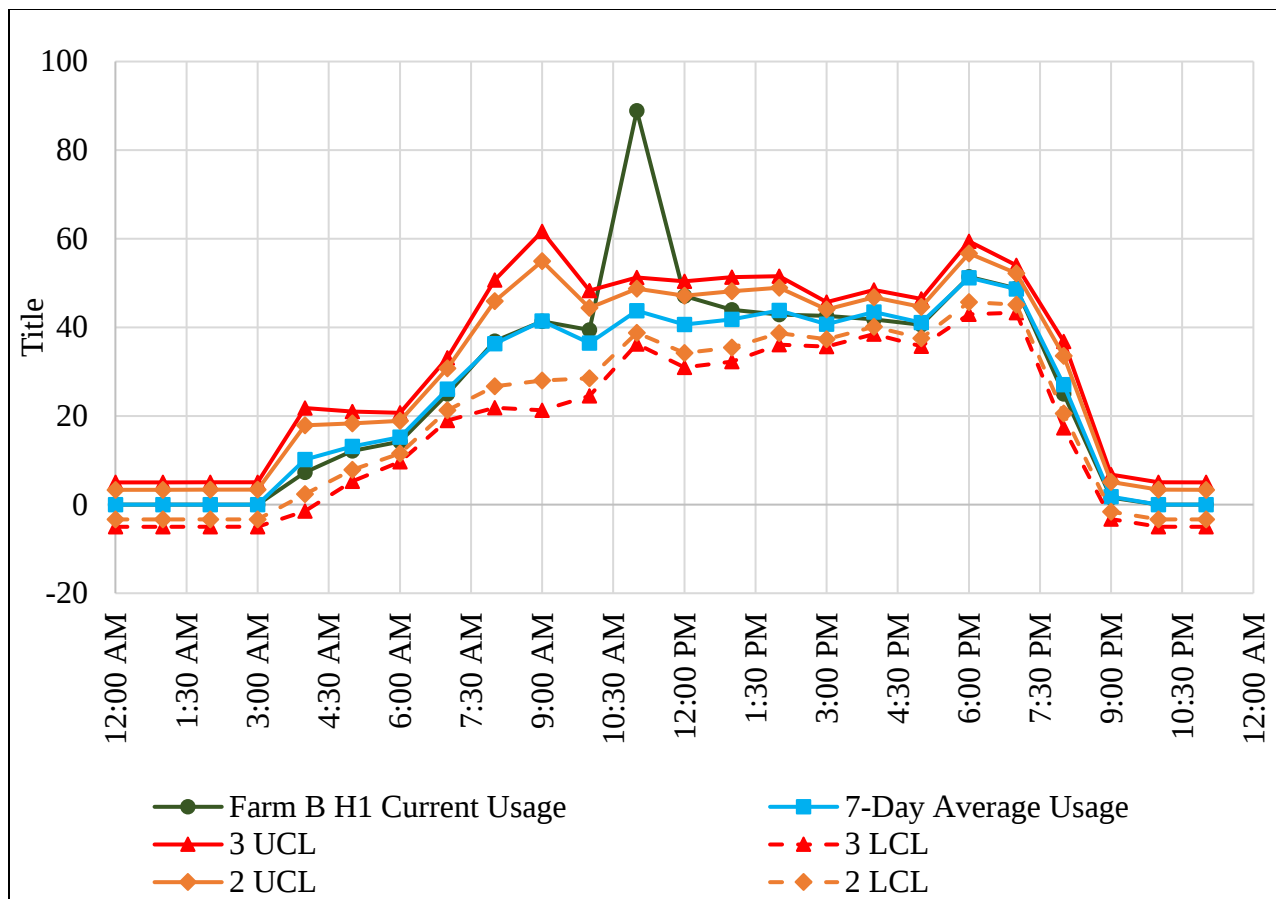


Figure 22. Water usage alert model during system flush Farm B House 1 - Trial 3 (1/31/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)

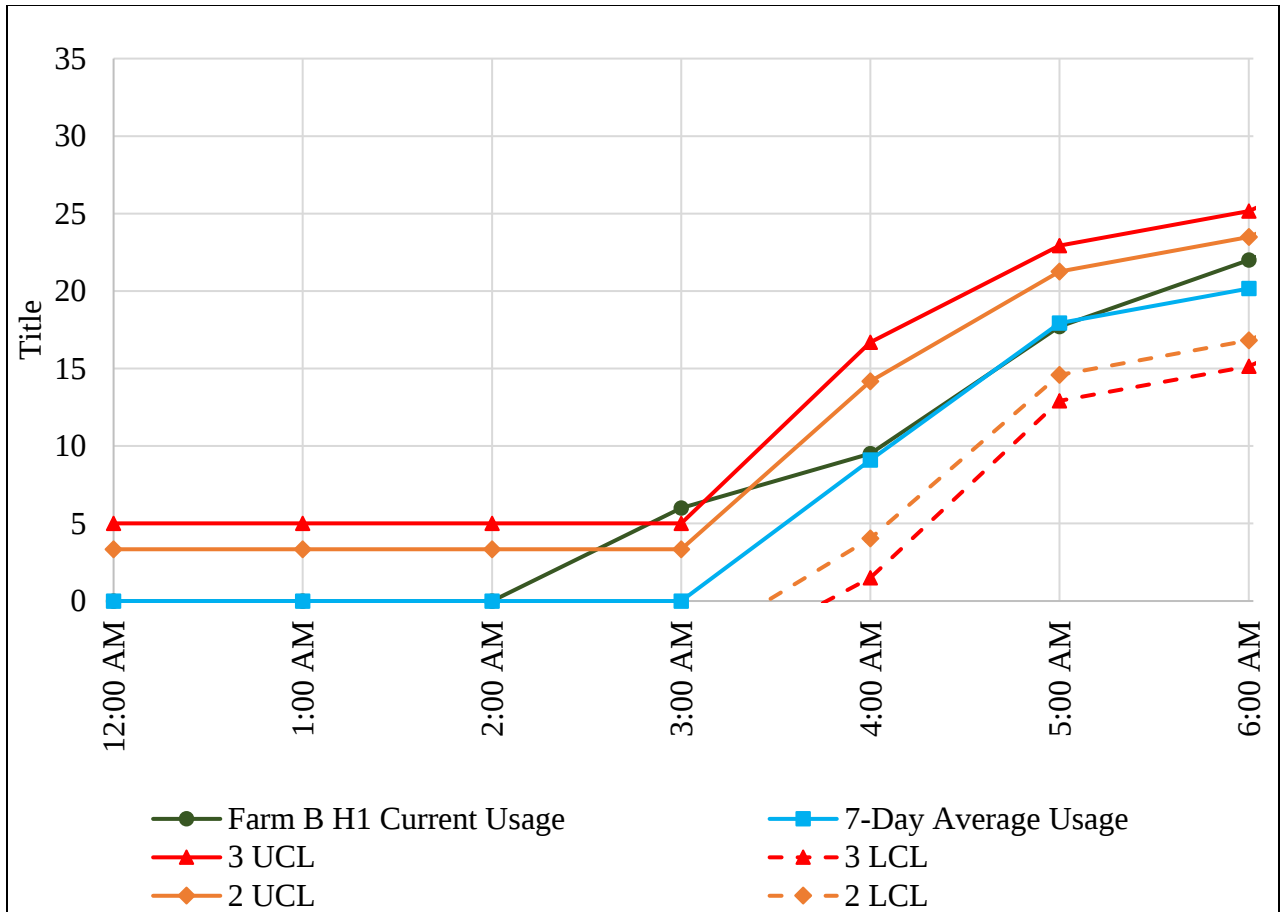


Figure 23. Water usage alert model during lighting issue Farm B House 1 - Trial 3 (3/10/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)

feed will depress water usage (Bierer et al, 1966), and the lighting periods will affect bird activity (being greater in lighted periods) and therefore water usage (Xin et al, 1993).

Feeding issues

The water usage was lower than expected on 2/22/24 on Farm B House 1 (Figure 24) due to a feed outage. When feed was returned a large spike in water usage occurred. The depression in water usage during a feed outage is expected due to the close relationship between feed and water consumption (Bierer et al, 1966; Czarick and Fairchild, 2006). The resulting spike is due to strong and rapid usage response after the reintroduction of feed. Following periods of water deprivation broilers used significantly more water immediately after it was reintroduced (Sprenger et al, 2009). Although this was only a depression of water usage not deprivation of water, a similar trend might be expressed and the feeding activity was likely increased during the reintroduction of feed. Additionally, the daily total water usage difference on this day against the 7-day average was only reduced by approximately 6%. However, during the hours of 4:00 AM to 9:00 AM, it was reduced by approximately 58% from the 7-day average, and during the hours of 10:00 AM to 1:00 PM it was increased by approximately 27% from the 7-day average. This again highlights the benefits of a dynamic alert system as the first alert was generated at 6:00 AM, but the total daily water usage is not that different from the average.

Unknown causes

The majority of alerts did not have a defined cause (Table 11). 68% of 3SD alerts (Western Electric Rule 1) and 78% of 2SD alerts (Western Electric Rule 2) did not have explained causes. The number of unattributable alerts varied between the houses with 93% of

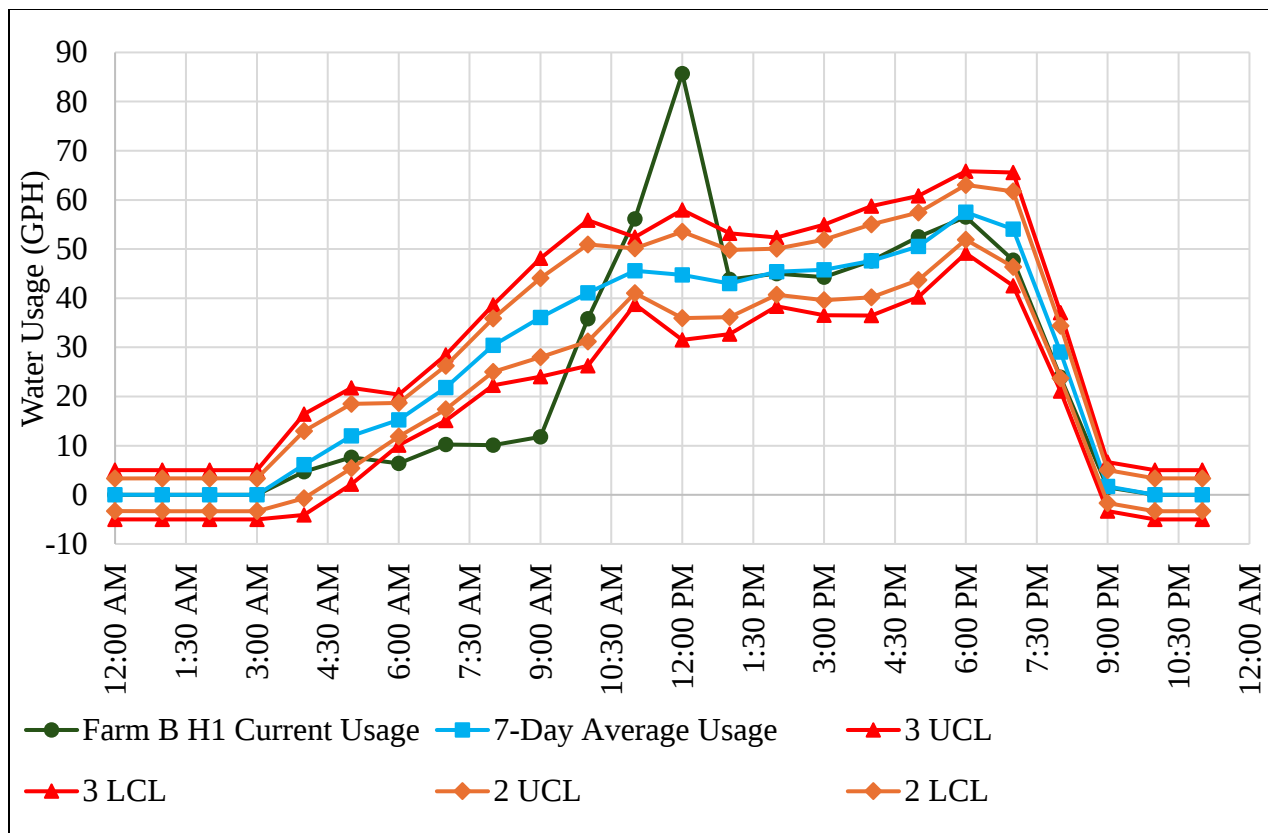


Figure 24. Water usage alert model during feeding issue Farm B House 1 - Trial 3 (2/22/24), with upper and lower three standard deviation offsets (3 USD and 3 LSD) and upper and lower two standard deviation offsets (2 USD and 2 LSD)

Table 10. All Alerts from all houses during Trial 3

	Farm B H1	Farm A H1	Farm A H2
Total test days	84	84	47
Total test days with alerts	44	33	18
Percent of test days with alerts	52 %	39 %	38 %

Farm A House 1's, 56% of Farm A House 2's, and 69% of Farm B House 1's alerts being undefined (Table 11). While the percentage of events where a cause could not be determined across all three houses was similar to Trial 1 (74%) it is important to note that all of the days in Trial 1 had at least three alerts generated, only 52%, 39%, and 38% of the total test days generated one or more alerts in Trial 3 (Farm B House 1, Farm A House 1 and Farm A House 2, respectively) (Table 10).

Some of the unexplained alerts may have been due to feed changes as the houses on Farm A had two feed changes during Trial 3 and the house on Farm B had one feed change. There were unexplained alerts generated around feed change days however, they were not consistent nor occurred each day and therefore these generated alerts may not have been due to feed changes and were counted as unexplained. There may also be events unknown to the growers or not recorded by the growers that add to this undefined alert number. Additionally, the causes found in this trial could all be considered mechanical in nature and any behavior changes in patterns may not have been noticed by the growers. Possible causes that could affect water usage behavior include the grower walking the house at different times of the day, varying sunlight through the translucent sidewall curtains, sudden lights and sounds, heat stress (Xin et al, 2002), and storms. There were also possible management-based factors that could affect water usage such as products run through the medicator that affects the palatability of the water (Fairchild and Ritz, 2015), as well as fan operation and evaporative cooling strategies (Czarick and Fairchild, 2017). Many of these factors would not have been known or recorded by the growers and would have been unwanted events to receive alerts about.

It also possible that these thresholds still do not adequately represent the natural variation in the water usage patterns. Farm B was considered a more well-managed farm than Farm A, but

Table 11. Alert Categories For all houses during Trial 3

	Farm B H1		Farm A H1		Farm A H2	
	2SD Alerts¹	3SD Alerts²	2SD Alerts¹	3SD Alerts²	2SD Alerts¹	3SD Alerts²
Total Alerts	60	61	40	33	20	25
Flushes	5	15	0	0	0	0
%	8	25	0	0	0	0
Feed Issues	10	7	2	3	9	11
%	17	11	5	9	45	44
Lighting Program	0	1	0	0	0	0
%	0	2	0	0	0	0
Undefined Alerts	45	38	38	30	11	14
%	75	62	95	91	55	56
Total % of Undefined Alerts						
% 2SD alerts (of Total 2SD)			% 3SD alerts (of Total 3SD)		% Total (of all Alerts)	
78			69		74	

¹ 2SD alerts are generated from the second Western Electric Rule (2 out of 3 consecutive points 2 standard deviations above or below the mean)

² 3SD alerts are alerts generated from the first Western Electric Rule (one point 3 standard deviations away from the mean)

it also had a high number of undefined alerts, which may suggest that this thresholding protocol does not account for the normal variation in the bird's water usage. The number of houses being observed in these trials is limited and the variability of water usage pattern consistency between houses is not yet fully understood. Statistical Process Control (SPC) operates under the assumption that the process is normally "in control" or that the correct understanding of what an "in control" process has been obtained (Oakland, 2003). Hourly layer water usage may not be consistent enough to use ordinary control limits from industrial applications. Also, the rolling charting system used in this trial may have not aggregated enough data to give an accurate representation of the pattern, it is possible that longer ranges such as 14 days or a month of data would better represent the pattern and variation. The lower percentage of days with an alert in Trial 3 compared to Trial 1, suggests an improvement towards a viable alert system, as multiple alerts every day would not be expected. However, the percentage of unknown alerts was similar between the two trials (74% of unattributable alerts in Trial 3 versus 71% in Trial 1) and suggests there are still improvements needed in lowering the number of unknown alerts. The previously mentioned behavioral and management factors that affect water usage may have introduced enough variation in the water usage that they generated some of these unknown alerts and if so, this suggests the thresholds are not adequately set. The lower number of alert days may also be due to events being less common in this trial than in Trial 1. It is possible that a more dynamic system than a rule-based algorithm is needed to accurately account for natural variations in usage and limit unattributable alerts to be a useful tool commercially.

Trial 3 introduced a new flock across all three houses, and a new moving average and thresholding alert system. The water usage patterns of mature layers in Trial 3 were similar to those of previous trials, gradually increasing throughout the day until nighttime. However,

observations revealed a potential difference in the water usage pattern of younger layers, with a shift of the usage pattern occurring as they matured. Despite the alert system's ability to detect events, a considerable portion remained without an attributable cause. The ability of the system to detect events with attributable causes varied between the houses. Analysis of attributable events revealed system flushes, lighting issues, and feeding issues as primary causes.

Furthermore, limitations in setting alert thresholds in this way were apparent, particularly in response to previous anomalies. The high number of unattributable alerts highlights the need for more sophisticated alert systems capable of adapting to evolving usage patterns and with a better understanding of the natural variation in the water usage pattern. This underscores the challenges in implementing effective alert systems in live production poultry settings and the necessity for further research into more dynamic and accurate monitoring approaches.

CHAPTER 5

CONCLUSIONS

The objective of this research was to first assess the viability of using real-time water usage data with dynamic thresholds as a management to identify events deserving attention, and second to analyze layer water usage patterns to better understand its consistency and characteristics. The results found that;

- Daily water usage profiles of cage-free layers can change over the course of the flock and therefore, an alert system should be able to adapt if the profile shifts over time.
- The variation within the daily water usage profile of cage-free layers can change during the course of the day, therefore, alert thresholds should be dynamic and able to adjust for different periods of the day.
- While rule-based thresholds did successfully detect management events needing attention, over 70% of the generated alerts were unexplained, and most likely inconsequential.
- Due to the multitude of factors that affect water usage, the Western Electric Rules 1 and 2 thresholds do not adequately account for the natural variation in hourly water usage.

These trials illustrated that more frequent water usage monitoring can detect management events earlier than reviewing the previous day's total water usage. These results also suggest that it may be beneficial to take a house specific alert system approach because houses can have small unique trends in their daily water usage profiles while having overall similar usage and

shape. However, the high number of unexplained alerts suggests that the thresholding protocols used in these trials are likely not acceptable for commercial use. It is possible that pattern recognition utilizing artificial intelligence or other algorithms would better understand the normal variation of the daily water usage profile than traditional thresholding techniques and thus reduce the number of unexplained and inconsequential alerts.

Identifying alert conditions for a flock with one input factor is unfortunately extremely difficult. While it is useful to monitor water usage due to all the factors that can affect it, the numbers of factors that can affect it inherently increase its variation in commercial settings. Another difficulty in creating alert models for live production poultry settings is that the faster the response time an alert system is created for, the harder it will be to limit unexplained alerts but at the same time the longer from the start of management events are alerts generated, a decrease response time occurs. It may be that only generating alerts if a condition satisfies multiple of the Western Electric Rules at once would limit unexplained alerts, but it would also inherently increase the time for detection of events. Future research should focus on adding other input factors along with water usage and may also utilize alternative ways to set alert thresholds to limit unexplained alerts.

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APPENDIX

Included in this appendix is water usage data from all trials aggregated hourly for average flowrate in gallons per hour (GPH), the standard deviation (SD) of the flowrate of each hour, maximum and minimum flowrates, and the number of days observed (Tables 12, 13, 14, 15, 16, 17, and 18).

Table 12. Raw Data from December 2022 during Trial 1 on Farm A

Time	Avg GPH H1¹	Avg GPH H2¹	SD H1²	SD H2²	Max GPH H1³	Max GPH H2³	Min GPH H1⁴	Min GPH H2⁴	N H1⁵	N H2⁵
12:00 AM	1.3	8.3	0.1	41.6	1.5	212.3	0.9	0.0	28	28
1:00 AM	1.2	7.5	0.2	37.8	1.5	192.7	0.8	0.0	28	28
2:00 AM	1.2	7.1	0.2	35.7	1.5	182.0	0.8	0.0	28	28
3:00 AM	1.2	8.6	0.1	43.1	1.5	220.0	1.0	0.0	28	28
4:00 AM	10.4	14.7	3.6	33.4	17.8	178.0	4.8	3.4	28	28
5:00 AM	14.3	17.0	3.6	30.2	20.9	164.4	8.6	5.6	28	28
6:00 AM	16.1	17.2	3.0	19.1	22.2	110.2	10.8	8.7	28	28
7:00 AM	14.8	13.4	2.3	3.5	20.2	18.4	11.6	0.0	28	28
8:00 AM	16.5	18.8	2.1	4.4	21.8	24.4	13.5	0.0	28	28
9:00 AM	22.2	29.3	2.1	3.7	26.8	34.6	18.6	17.5	28	28
10:00 AM	31.2	36.9	4.7	7.7	39.0	70.8	20.2	29.9	28	28
11:00 AM	33.7	40.6	5.4	3.5	42.3	46.7	20.3	34.4	28	28
12:00 PM	37.6	40.3	4.4	8.0	48.8	50.6	31.8	4.7	28	28
1:00 PM	41.9	44.6	4.1	9.5	48.3	52.4	33.4	0.0	28	28
2:00 PM	41.9	42.9	5.2	9.5	47.6	51.7	21.2	5.6	28	28
3:00 PM	41.0	46.3	4.8	7.4	47.9	77.5	22.5	32.9	28	28
4:00 PM	50.1	53.7	5.8	4.7	56.9	71.2	32.9	44.6	28	28
5:00 PM	49.7	46.2	4.2	7.0	55.8	78.4	34.8	38.9	28	28
6:00 PM	59.5	60.6	5.9	2.1	64.2	68.1	32.9	57.9	28	28
7:00 PM	53.1	56.4	4.8	1.7	56.2	58.6	31.2	51.9	28	28
8:00 PM	36.8	43.3	3.0	2.6	40.9	46.9	29.6	37.2	28	28
9:00 PM	4.7	13.2	2.4	47.5	16.3	245.9	3.5	2.5	28	28
10:00 PM	1.2	9.4	0.3	47.2	1.5	240.8	0.0	0.0	28	28
11:00 PM	1.2	9.6	0.3	48.2	1.5	245.9	0.0	0.0	28	28

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 13. Water usage data from Farm A House 1 during Trial 2

Farm A House 1					
Time	Avg GPH¹	SD²	Max GPH³	Min GPH⁴	N⁵
12:00 AM	0.3	0.4	2	0	151
1:00 AM	0.3	0.4	2	0	151
2:00 AM	0.3	0.4	1.9	0	151
3:00 AM	0.3	0.4	2	0	151
4:00 AM	0.3	0.4	1.9	0	151
5:00 AM	10.1	3.5	18.5	0.3	151
6:00 AM	13.6	3.2	21.6	1	151
7:00 AM	14.7	2.7	20.9	1.3	151
8:00 AM	15.1	7.8	93	4.2	151
9:00 AM	18.2	10.7	144.7	9.9	151
10:00 AM	23.4	10.1	139	8	151
11:00 AM	32.9	5.5	72.8	11.5	151
12:00 PM	35.8	5.3	47.9	8.5	151
1:00 PM	38.5	4.7	46.1	4.3	151
2:00 PM	42.3	5.4	53.2	3.4	151
3:00 PM	43.7	4.3	49.6	3	151
4:00 PM	42.2	4.5	52.4	2.3	151
5:00 PM	49.5	5.0	56.5	1.2	151
6:00 PM	47.8	4.8	56.5	1	151
7:00 PM	61.2	6.2	69.3	0.8	151
8:00 PM	56.5	5.9	62.1	0.8	151
9:00 PM	38.2	5.0	48.4	0.6	151
10:00 PM	4.2	1.1	6.5	0.4	151
11:00 PM	0.4	0.5	3.6	0	151

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 14. Water usage data from Farm A House 2 during Trial 2

Farm A House 2					
Time	Avg GPH¹	SD²	Max GPH³	Min GPH⁴	N⁵
12:00 AM	0.0	0.2	1.5	0	151
1:00 AM	0.0	0.2	1.5	0	151
2:00 AM	0.0	0.1	1.4	0	151
3:00 AM	0.0	0.1	1.4	0	151
4:00 AM	0.0	0.2	1.3	0	151
5:00 AM	8.5	4.9	32.4	3.1	151
6:00 AM	11.5	4.4	38.1	5.9	151
7:00 AM	13.7	3.4	37.6	8.9	151
8:00 AM	14.9	6.4	72.1	8.4	151
9:00 AM	18.6	2.4	25.3	12.4	151
10:00 AM	28.2	4.0	37.2	17.4	151
11:00 AM	35.6	4.6	46	22.8	151
12:00 PM	43.0	5.1	54.2	28.9	151
1:00 PM	43.5	4.2	54.8	32.6	151
2:00 PM	46.5	4.8	56.2	14.2	151
3:00 PM	42.9	3.4	51.2	31.1	151
4:00 PM	42.8	3.7	54.7	31.6	151
5:00 PM	51.4	4.1	59.4	33.3	151
6:00 PM	41.7	3.4	53	32.8	151
7:00 PM	61.6	6.3	70.2	33.5	151
8:00 PM	55.6	4.3	60.9	33.3	151
9:00 PM	42.9	2.8	48.7	33	151
10:00 PM	5.7	1.3	10.8	3.6	151
11:00 PM	0.0	0.2	1.4	0	151

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 15. Water usage data from Farm B House 1 during Trial 2

Farm B House 1					
Time	Avg GPH¹	SD²	Max GPH³	Min GPH⁴	N⁵
12:00 AM	0.1	0.2	1.8	0	151
1:00 AM	0.0	0.2	1.8	0	151
2:00 AM	0.0	0.2	1.7	0	151
3:00 AM	0.0	0.2	1.8	0	151
4:00 AM	0.1	0.5	5.9	0	151
5:00 AM	7.4	2.1	12.2	2.8	151
6:00 AM	12.1	2.8	18.6	4.7	151
7:00 AM	14.2	3.2	21	5.9	151
8:00 AM	16.5	7.3	95.1	6.3	151
9:00 AM	25.1	10.0	128.4	7.6	151
10:00 AM	34.6	6.6	53.5	11	151
11:00 AM	41.5	6.8	59.5	18.9	151
12:00 PM	44.1	7.5	98.2	29.8	151
1:00 PM	50.4	12.9	133.1	31.2	151
2:00 PM	52.7	12.9	144.2	36.9	151
3:00 PM	50.5	6.5	69.8	39.5	151
4:00 PM	51.8	6.3	64.2	29	151
5:00 PM	50.5	5.4	64.1	41.5	151
6:00 PM	51.3	6.5	68.9	35.6	151
7:00 PM	62.0	6.9	75.8	43.4	151
8:00 PM	62.4	7.6	79.1	43.7	151
9:00 PM	48.3	6.5	62.5	21.6	151
10:00 PM	4.6	0.8	8.2	3.1	151
11:00 PM	0.0	0.2	1.9	0	151

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 16. Water usage data from Farm A House 1 during Trial 3

Farm A House 1					
Time	Avg GPH¹	SD²	Max GPH³	Min GPH⁴	N⁵
12:00 AM	12.1	3.0	22.8	7.4	91
1:00 AM	0.0	0.0	0.1	0.0	91
2:00 AM	0.0	0.0	0.1	0.0	91
3:00 AM	0.0	0.0	0.0	0.0	91
4:00 AM	8.0	3.2	17.8	3.2	91
5:00 AM	15.6	2.9	21.9	9.8	91
6:00 AM	16.6	2.0	21.1	12.5	91
7:00 AM	15.9	1.8	20.8	12.1	91
8:00 AM	18.9	2.2	24.8	13.4	91
9:00 AM	29.6	4.6	38.7	18.5	91
10:00 AM	35.1	5.4	45.6	19.7	91
11:00 AM	42.6	5.0	52.1	32.5	91
12:00 PM	40.4	3.2	47.4	33.8	91
1:00 PM	43.6	3.2	51.5	36.4	91
2:00 PM	44.0	3.0	53.3	37.3	91
3:00 PM	43.6	2.5	49.3	36.7	91
4:00 PM	47.8	3.0	54.1	37.7	91
5:00 PM	47.6	2.2	52.7	41.0	91
6:00 PM	50.0	2.0	54.1	43.3	91
7:00 PM	46.4	2.0	52.1	40.6	91
8:00 PM	28.2	2.8	36.6	22.8	91
9:00 PM	2.6	0.8	4.6	1.3	91
10:00 PM	0.0	0.0	0.1	0.0	91
11:00 PM	0.0	0.0	0.0	0.0	91

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 17. Water usage data from Farm A House 2 during Trial 3

Farm A House 2					
Time	Avg GPH	SD	Max GPH	Min GPH	n
12:00 AM	8.4	6.9	21.6	0.0	54
1:00 AM	0.2	0.4	1.5	0.0	54
2:00 AM	0.2	0.4	1.5	0.0	54
3:00 AM	0.2	0.3	1.4	0.0	54
4:00 AM	7.8	2.6	14.9	4.2	54
5:00 AM	15.2	2.9	20.5	10.3	54
6:00 AM	16.7	2.0	21.2	13.0	54
7:00 AM	16.1	1.7	20.0	13.0	54
8:00 AM	19.5	2.9	24.0	12.8	54
9:00 AM	33.5	5.7	42.2	20.3	54
10:00 AM	40.9	5.8	48.8	27.1	54
11:00 AM	48.5	5.4	57.4	31.8	54
12:00 PM	45.0	5.0	51.5	31.4	54
1:00 PM	49.1	3.8	56.6	41.4	54
2:00 PM	48.4	3.6	55.4	40.7	54
3:00 PM	44.7	3.8	51.5	33.6	54
4:00 PM	54.0	3.4	61.4	46.7	54
5:00 PM	48.6	2.2	55.4	40.1	54
6:00 PM	48.0	2.5	54.8	42.0	54
7:00 PM	48.2	2.1	52.3	44.4	54
8:00 PM	29.3	4.0	39.0	20.5	54
9:00 PM	3.9	0.9	6.2	2.3	54
10:00 PM	0.2	0.4	1.5	0.0	54
11:00 PM	0.2	0.4	1.5	0.0	54

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days

Table 18. Water usage data from Farm B House 1 during Trial 3

Farm B House 1					
Time	Avg GPH	SD	Max GPH	Min GPH	n
12:00 AM	1.6	4.9	18.9	0.0	91
1:00 AM	0.1	0.4	1.6	0.0	91
2:00 AM	0.0	0.1	1.2	0.0	91
3:00 AM	0.1	0.6	6.0	0.0	91
4:00 AM	8.0	3.1	16.7	2.4	91
5:00 AM	13.9	3.7	21.2	6.5	91
6:00 AM	16.8	3.5	25.0	6.4	91
7:00 AM	25.3	3.4	34.2	10.2	91
8:00 AM	35.2	5.3	43.2	10.1	91
9:00 AM	39.6	9.0	100.1	11.8	91
10:00 AM	43.3	13.8	109.1	30.8	91
11:00 AM	47.6	10.1	95.0	31.6	91
12:00 PM	46.4	7.4	85.7	34.3	91
1:00 PM	44.8	5.1	61.3	35.4	91
2:00 PM	47.5	5.1	63.1	36.0	91
3:00 PM	45.5	5.7	61.6	37.4	91
4:00 PM	47.2	5.7	61.9	36.6	91
5:00 PM	48.1	6.4	62.6	38.6	91
6:00 PM	56.6	7.2	73.1	47.4	91
7:00 PM	53.1	7.8	70.6	33.1	91
8:00 PM	27.4	5.8	37.7	8.0	91
9:00 PM	1.7	0.6	3.0	0.0	91
10:00 PM	0.0	0.1	1.3	0.0	91
11:00 PM	0.0	0.1	1.1	0.0	91

¹Average flowrate in gallons per hour (GPH)

²Standard deviation (SD) of water flowrate

³Maximum flowrate in gallons per hour (GPH)

⁴Minimum flowrate in gallons per hour (GPH)

⁵Number of days