COMPARING CAPILLARY HYDROPONIC AND VARIABLE DEPTH ROOTZONES FOR SUSTAINABLE PUTTING GREEN MANGEMENT

By

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A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

Crop and Soil Science – Master of Science

2025

ABSTRACT

Irrigation requirements have become a focal point of golf turf management. The objective of the study was to evaluate two golf course putting green construction methods for irrigation inputs, playability, organic matter content, turfgrass quality, health and growth. The experiment was conducted in the summer 2023 and 2024 at the Michigan State University Hancock Turfgrass Research Center. Six putting greens were constructed and seeded in June 2022 with sand conforming to USGA specifications, with three constructed as Variable Depth Rootzone (VDR)and the other three as Capillary Hydroponic System (CHS), resulting in a randomized complete block design with three replications of each construction type. All greens were managed following typical maintenance practices and irrigation was provided by overhead in VDR and subsurface irrigation by CHS to maintain a volumetric water content of 8%. Volumetric water content was monitored continuously with inground soil moisture sensors and across greens surfaces at 7.62 cm weekly with a handheld moisture meter. Surface firmness and greens speed were measured twice monthly and clipping yield was collected once per month. There was no difference in surface firmness, greens speed, or clippings yield. The CHS required 59% less irrigation water than the VDR for the entirety of the trials.

To my parents, Karl and Patricia Rabe, your patience and guidance have allowed me to find my passion. You believed in me even when I was aimless and lost, giving me the support I needed to find my own way, and for that, I am forever grateful. To my brother, Bill Rabe, through you, I’ve learned the courage to step outside my comfort zone. And to my incredible wife, Anjia, your sacrifices, love, and unwavering support have made this journey possible. Through every challenge, you have stood by my side, ensuring that our growing family thrives while giving me the space to chase my dreams. I could not have done this without you.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my primary advisor Dr. Thomas A. Nikolai for shepherding me down the path of making a transition from industry to research. I would also like to thank my thesis committee, Dr. Kevin Frank, Dr. Brian Horgan, and Dr. Wei Zhang for their insight and constructive criticism during this project. Special thanks to Dr. David Gilstrap for seeing my potential and encouraging me to pursue this degree. Special thanks also to T.J. Welsh. who took a chance on me and opened my horizon to this industry. This research would not be possible without the support of time and resources from the staff at the Hancock Turfgrass Research Center especially my boss and mentor Jesse Sholl. Thanks also to the research technicians Eric Galbraith, Ryan Bearss, Evan Rogers, Kai Rensland, and Drew Ostrowski for their moral support, technical advice, and assistance in collecting data. I would also like to thank Capillary Flow and Martin Sternberg for funding the construction of the research site and providing infrastructure support, and the USGA Davis Program and Canadian Turfgrass Research Foundation for funding data collection and research on the site, and the Michigan Turfgrass Foundation for their continued support of Turfgrass research. Finally, thanks to the Robert J. Delisa Scholarship Fund, Sally Delisa and her family for their generous financial support and continued support of water research.

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INTRODUCTION

Golf courses require large volumes of water to maintain high quality turf. In 2013, the median 18-hole golf course used 45 million liters of water per year in the Northeast United States and median annual water use was approximately 130 million liters in the southwest United States (GCSAA, 2014). Advancements in technologies like soil moisture sensors, and automated irrigation systems have assisted golf course greenskeepers to reduce irrigation inputs by 25% since 2005 (Shaddox et al., 2022). Water conservation efforts are imperative because temperature increase due to climate change is expected to increase water demand and reduce availability across regions (EPA, 2017).

HISTORY

In the early 1900s, greenskeepers coming to America from overseas encountered a larger land area with more variability in soil conditions and climates than they were accustomed to managing compared to the well-established linkslands of the United Kingdom (Doak, 1998; Hunter, 1926). As long as the game of golf has been played on American soil there has been debate about proper irrigation methods (Taylor et al., 1922). A key factor greenskeepers consider when establishing a golf course is water and power availability (Beard, 2002). As America expanded westward golf courses moved to rural areas that lacked this critical infrastructure (Hurdzan, 2004). Additionally, inadequate pressure regulation and improper design and installation of irrigation systems caused a lack of irrigation uniformity (Macomber, 1916), leading to researchers and enthusiasts searching for a solution (Hurdzan, 2004).

An alternative process to overhead irrigation was subsurface irrigation, the process of supplying irrigation water directly to the rootzone of target plants (Beard & Beard, 2005). Frederick Winslow Taylor conducted many experiments searching for a superior rootzone material for establishing turf for putting greens and addressing issues of compaction. In many of his designs he included soil wicks throughout the profile that allowed for a contained water table to be brought up by capillary action (Piper and Oakley, 1917). Taylor outlined a subirrigation system for golf course putting greens consisting of an impermeable layer separating the cavity into multiple sections corresponding to the slope of the putting greens surface, and pipes beneath the surface that adjust the water table (Hurdzan, 2004). Due to technical advancements, overhead irrigation became the standard practice for many golf courses and subirrigation systems were not widely adopted. However, Taylor's work influenced the USGA and led to research and development of rootzone materials.

USGA RECOMMENDATIONS

Increased popularity in golf resulted in excess wear on golf courses and produced maintenance challenges as well as decreased quality in putting surfaces. In 1960 the USGA drafted the first recommendations for golf course putting green construction methods. These recommendations outline subgrade considerations, drainage requirements, and permeability and porosity metrics for topsoil material (USGA Green Section Staff, 1960). Modern research and innovations from the golf industry have led to five updates to these recommendations. Initial recommendations included an intermediate coarse sand layer placed between the drainage gravel and the rootzone mixture. In 1989 the USGA Green Section Staff asserted that the intermediate coarse sand layer was imperative to the design of the putting greens drainage system. However, in 1993, bridging, uniformity, and permeability factors were added to address the migration of smaller rootzone particles into the larger drainage gravel layer and the intermediate coarse sand layer was deemed optional (USGA Green Section Staff, 1993).

The most recent recommendation is for a uniform rootzone depth of 30 cm (USGA Green Section Staff, 2018). However, research suggested that varying the depth of the rootzone material by making it shallower at the peaks of an undulated surface and deeper in the lower portions of the surface would result in more uniform volumetric water content (VWC) (Frank et al., 2005). This method of construction is not included in the USGA recommendations, but it has been implemented in real world projects with perceived positive results. The USGA recommendations are predicated on water being delivered from the surface, because overhead irrigation systems continue to be the primary delivery method on golf course putting greens. However, the study and development of subirrigation methods continued.

PURRWICK

Sand based putting green construction methods recommended by the USGA rekindled ideas of water conservation. Dr. William Daniel revisited the idea of subirrigation in the mid-1960s, conducting a series of tests utilizing a subirrigation system similar to that contained in F.W. Taylor's patent known as the PURR-wick system (Hurdzan, 2004). The PURR-wick system was constructed using a plastic liner at the interface between subgrade and rootzone material. A slitted pipe was laid along the bottom of the root zone that exited the green, providing surface access by an operator. The outlet could be adjusted to control the level of the water table within the green cavity.

Daniel's tests concluded that the PURR-wick system maintained adequate water content in drought conditions (Ralston, 1970). Test plots were constructed with a flat surface; however, the PURR-wick system was implemented on golf course putting greens with an undulated surface. To achieve uniform moisture distribution the green was divided into sections corresponding to its final grade and the water table of the sections were controlled independently (Daniel, 1977). It was discovered that the matric potential gradient at the intersections of these separate sections and the force of gravity caused water to be siphoned over dividers from high areas of the green to lower points resulting in high parts of the green drying out prematurely (Roberts, 1977).

CELL SYSTEM

Another subground irrigation system known as the Cell System was designed in 1966 by James P. Izatt. The Cell System consists of a sand rootzone 40 cm in depth on top of a plastic lined subgrade. Drainage and irrigation are achieved using slitted pipes that connect to a collector pipe (Leinauer, 1998). The inlet of the collector pipe is fed by the irrigation system, and the outlet is fixed with an adjustable overflow (Leinauer, 1998). Leinauer (1998), found the cell system provided higher VMC in plots compared to plots receiving overhead irrigation when subjected to drought conditions, and cell system plots had significantly lower crop water-stress indices than overhead irrigated plots.

CAPILLARY HYDROPONIC SYSTEM

A new subirrigation system has been developed and tested in field conditions by Capillary Flow. Like previously mentioned subirrigation systems, the Capillary Hydroponic System (CHS) consists of a sand based rootzone on top of a lined subgrade. The system diverges from subirrigation systems of the past by incorporating the constant movement of water within the cavity. The cavity is divided into two equal halves that have inlet pipes tied to a control basin that is positioned adjacent to the area to be irrigated. The control basin houses compressed air lines that move the water via and airlift pump, a float valve that controls the water table depth, and overflow outlets that prevent flooding (Sternberg, 2022). The system is currently in use in a park in Sweden, and a bermudagrass golf course tee in Orlando, FL and has displayed estimated water savings of 67% in the park application and 85% in the golf course application (Sternberg, 2022).

VARIABLE DEPTH ROOTZONE

Throughout his career Dr. P.E. Rieke noticed that during construction golf courses architects would make last-minute alterations to putting greens final grade that would result in a non-uniform depth of rootzone. He noticed that where the rootzone was deposited and therefore deeper there was less black layer (P.E. Rieke, personal communication, June 1, 2022). He thought that intentionally varying the depth of rootzone dependent upon the final elevation of the surface, making the rootzone deeper in the low-lying areas of the surface and shallower at the peak of the surface, would result in more uniform moisture (P.E. Rieke, personal communication, June 1, 2022).

In 1998, Michigan State University constructed a sloped putting green at the Hancock Turfgrass Research Center to evaluate the impact of Dr. P.E. Rieke's Variable Depth Rootzone hypothesis on different soil types on volumetric water content (VWC) (Frank et al., 2005). The experiment compared uniform and Variable Depth Rootzone constructions across sand, sand/peat, and sand/soil mixes, measuring soil moisture at multiple depths and locations during repeated dry-down cycles from 2000 to 2002. Coefficient of variation data confirmed that modifying the rootzone depth from 20 cm at the summit to 40 cm at the toe slope reduced variability in VWC (Frank et al., 2005).

In 2018 the USGA mentions the promising concept of a Variable Depth Rootzone (VDR) and calls it "more art than science" (Witlark, 2018). However, the USGA does not consider greens constructed with this method to conform to USGA recommendations (Jacobs, 2024). More research is needed to verify the efficacy of this construction method.

OBJECTIVES

The objective of this research is to evaluate the VDR and CHS construction methods which utilize overhead irrigation and subirrigation deliver systems, respectively. These treatments were applied to undulated golf course putting greens to evaluate the systems under challenging conditions.

Chapter 1 focuses on quantifying the total volume of irrigation water applied to each system and evaluating how construction methods and irrigation type influence soil moisture uniformity. This chapter also considers surface organic matter content, root weight density (RWD) and soil chemical characteristics. The objective is to determine whether alternative construction types and irrigation delivery methods can reduce water used for irrigation in creeping bentgrass putting greens, as well as a uniform playing surface.

Chapter 2 expands the investigation to include turfgrass and surface performance metrics. Specifically, this chapter evaluates playability characteristics (such as surface firmness and ball roll), and key turfgrass performance indicators, including quality, health, and growth. These measurements provide an assessment of each system's ability to support sustainable, high-performing putting surfaces.

CHAPTER 1: EFFECT OF IRRIGATION TYPE ON IRRIGATION INPUTS AND SOIL CHARACTERSITICS OF CREEPING BENTGRASS PUTTING GREENS

MATERIALS AND METHODS

Construction

Six putting greens were constructed at the Hancock Turfgrass Research Center in East Lansing, MI in the summer of 2022. Three were constructed with a Variable Depth Rootzone (VDR) and three were constructed with a Capillary Hydroponic System (CHS) (Capillary Flow, Gotenberg, SE). All six greens measure 10.97 m by 10.97 m and have identical undulations with a surface elevation change of 20.3 cm and slopes of 1.5, 3.0 and 5.0 degrees. The apex of the slope is offset to the eastern third of the plots with slopes falling in all directions. Alleyways were constructed between plots 6.1 m in width east to west and 3.7 m in width north to south. The alleyways are concave to negate runoff from plot to plot and drift of irrigation treatments into adjacent plots/treatments. The grading plan (Figure 1) was drafted by golf course architect Chris Wilczynski (C.W. Golf Architecture, Saline, MI) and were constructed by Frontier Golf (Jones Mills, PA). All greens were constructed with 100% sand with particle sizes conforming to United States Golf Association recommendations (Table 1) with a block style irrigation system (Model T7, The Toro Company, Bloomington, MN) with heads placed on the corners of each green. Each irrigation block was built with a flowmeter (Model HC-200, Hunter Industries, San Marcos, CA) to measure water flow of overhead irrigation events and refilling of CHS basin. The site was seeded with creeping bentgrass (T-1, Barenbrug, Tangent, OR) on June 15th, 2022.

The VDR putting greens were constructed to USGA Recommendations (USGA Green Section Staff, 2018) with the root zone depth varying from 20.3 cm – 25.4 cm at the apex of the surface undulation to 35.6 cm – 40.6 cm in the low-lying areas of the greens surface. Once each VDR greens drainage system leaves the greens cavity it links to a solid 10.16 cm drain tile that is connected to a 30.48 cm drainage basin, allowing for collection of drainage water.

The CHS putting greens consist of a green's cavity excavated to 36 cm below initial grade with a level bottom. The cavity was divided into two equal halves by a 25.4 cm wooden wall staked into the subgrade (Figure 2). A control basin (0.61 x 0.61 x 1 m) (Capillary Flow, Gotenberg SE) was placed next to the green at the centerline (Figure 3). Two inlet pipes were installed below the subgrade and were extended from the bottom of the basin to the surface at the center of each half of the green cavity (Figure 4). A waterproof liner (30 mm, Western Liners, Tolleson, AZ) is installed in each green cavity (Figure 5) cut at the level of the initial grade and in the liner to allow inlet pipes to surface. A rubber gasket was adhered to the liner and secured around the inlet pipes (Figure 6).

A 10.5 m length of 10.16 cm perforated drainage tile was installed parallel to the dividing wall in each half with a tee connected to the inlet pipes. Pea gravel was added to a depth of 10.16 cm to encase the drainage tile (Figure 7) to allow for uniform filling. Capillary Concrete (Capillary Flow, Gotenberg SE) was added to a depth of 5.08 cm (Figure 8) to provide structure to the system. Atop the Capillary Concrete the rootzone sand was added and contoured to conform to the grade. Since the subgrade is level, the rootzone depth varies from 20.32 cm in the low-lying areas of the green to 40.64 cm at the apex of the surface undulation (Figure 9). Irrigation water was added to the subsurface system where it can be pumped back and forth between the two halves of the green's cavity.

The interior of the basin is divided equilaterally by a 0.91 m tall wall, then half of the basin is divided again by a 0.86 m tall wall creating a total of three chambers (Figure 10). At the bottom of each chamber is a spigot that allows water to flow from chambers through pipes feeding each half of the green respectively, and the third larger chamber connects to a drainage line. The small chambers also have a spigot installed at the bottom of the tall wall to allow water to pass through to the drainage section of the basin. They are connected to a 2.54 cm adjustable height pipe. A 1.9 cm pressurized feed line from the irrigation system enters the basin and is fixed with a flow meter (Model HC-075, Hunter Industries, San Marco, CA) to log subsurface irrigation events and a differential valve (Model Topaz, Jobe Valves, Matamata, NZ) that is positioned over the left small section of the basin.

The differential valve is fixed with a stop disc, float, and weight. The position of the stop disk and weight are adjustable, enabling users to set the level of the water table. Fixed to the shorter middle wall in each section are transfer pipes that extend from the bottom of the basin to over the wall. A compressed air line connected to an air lift pump is fixed approximately 2.54 cm from the bottom of the transfer pipes, allowing for the transfer of water between sections. The size of the greens cavity and water table level dictate the amount of time required to transfer the water between sections. The water in the research plots is transferred between sections every four hours.

Turfgrass plot maintenance

Plots were mowed six times per week at a height of 3.05 mm using a walk behind greens mower (Toro Flex 2100, The Toro Company, Bloomington, MN), with clippings collected and removed from all plots. Plots were rolled with a greens roller (RC50, Tru-Turf, Gold Coast, AU) a minimum of 3 times per week. Sand topdressing was applied weekly at a depth of 0.02 cm. The plots were vertical mowed in two directions in the fall of 2023 and 2024 at a depth of 3 mm with a walk behind vertical mowing unit (Model Vacu-Cutter, True Surface, Moscow Mills, MO) with clippings collected and removed. Sand topdressing was applied to dilute organic matter build up and to fill the voids left by vertical mowing.

On recommendation of the manufacturer CHS greens were treated with 20 mL of 50% (v/v) nitric acid (Ricca Chemical Company, Arlington, TX) twice monthly to prevent calcium carbonate accumulation in the porous structure of the capillary concrete. Nitric acid was added directly to the water in the basins with a syringe.

Fertilizer was applied to both CHS and VDR as a foliar spray weekly using a 24-0-8 (N-P-K) soluble granular fertilizer (The Andersons, Maumee, OH) at a rate of 9 kg ha^{-1}. Fungicides were applied to both CHS and VDR on a curative basis only (Table 2).

Irrigation Inputs

Turfgrass was established prior to the initiation of the two-year research trial. Data collection was initiated on June 21st of 2023 and 2024. In May and early June of 2023 irrigation was shut off and greens were monitored with a moisture meter (Model TDR-350, Spectrum Technologies, Bridgend, UK) at a depth of 11.43 cm and for visual cues of wilt due to excessive dryness. Wilt was visually apparent when moisture in the greens reached 7% VWC, therefore a target VMC of 8% was selected as an irrigation trigger. Next, a model base of relative potential evapotranspiration (RPET) readings from an onsite weather station (Model WxPRO, Campbell Scientific, Logan, UT) was developed to achieve 8% VMC at the 11.43-cm depth on the VDR greens.

During a period of no precipitation, soil moisture was monitored daily with a moisture meter (Model TDR-350, Spectrum Technologies, Bridgend, UK) at a depth of 11.43 cm. All daily RPET values were returned to the greens via overhead irrigation system. This resulted in

VMC values being higher than the target, so the process was repeated, lowering the percentage of daily RPET delivered until the target VMC was achieved. The model best suited to deliver the target VMC returned 80% of the daily RPET values.

For the CHS greens the water table was set to maintain a level of 10.16 cm below the lowest part of the greens surface and VMC was monitored at a depth of 11.43 cm when cycles were at their peak. This returned VMC values more than the target, so the water table was lowered until the target VMC was reached. The water table depth best suited to deliver the target VMC was 20.32 cm below the lowest part of the greens surface. For the duration of the study CHS greens did not receive overhead irrigation unless required for fungicide, fertilizer, or sand topdressing application. Irrigation water use data were collected from the flow meters utilizing a Wi-Fi enabled irrigation controller (Model: Pro-HC, Hunter Industries, San Marcos, CA).

Moisture Uniformity

Soil moisture was monitored utilizing a handheld moisture meter (Model TDR 350, Spectrum Technologies, Bridgend, UK) that logged GPS location and VWC. Readings were collected across the greens surface at a depth of 7.62 cm in a 1.83 m x 1.83 m grid in the same location weekly. Wireless in-ground moisture sensors (Model TurfGuard, The Toro Company, Bloomington, MN) were installed with probes at 7.62 cm and 19.05 cm depths in locations representing the apex of the slope, the low points of the greens surface, and an intermediate location that were identically placed in all 6 greens. Data were collected utilizing the TurfGuard interface on the Toro Lynx Irrigation Control System.

Organic matter content

To assess the percentage of total organic matter content, three cores 1.91 cm in diameter and 7.62 cm in depth were sampled from each plot in random locations at least 3.05 m apart. The verdure was not removed, and cores remained intact, and oven dried at a temperature of 105 C for 24 h (Blue M, New Columbia, PA). Samples were weighed and then ignited in a muffle furnace (Thermo Fisher Scientific, Waltham, MA) at 360 C for 2 h and weighed again. The difference in weight was divided by the total oven dry weight to achieve percent total organic matter.

Root Weight Density

Root weight density (RWD) was assessed by sampling greens at the apex of the slope as well as in low-lying areas of the green. Samples were taken at random respective of their location on each green. A core sampling tool with a diameter of 1.91 cm was used to remove a core to the sample depth of 20.32 cm. The core verdure was removed, and the core was split into three sections: 0 cm to 7.62 cm, 7.62 cm to 15.24 cm, and 15.24 cm to 20.32 cm. Roots were washed in a solution of sodium hexametaphosphate for 24 h. Excess soil was rinsed through a 0.50 mm mesh sieve then samples were oven-dried (Blue M, New Columbia, PA) for 48 h at 100 C prior to weighting the roots and reporting RWD data in g/cm^3.

Soil Tests

Nine 1.27 cm diameter cores were taken from random locations on each plot ensuring equal number taking from the apex of the slope as the low-lying areas of the green. Samples were sent to Waypoint Analytical (Champaign, IL) to undergo Mehlich 3 extraction measuring

Soil pH. Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulfur (S), Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn), Zinc (Zn), Sodium (Na), and Organic Matter.

Experimental Design and Data Analysis

The experiment was a randomized complete block design with one factor, irrigation type. which consisted of two levels, Capillary Hydroponic System (CHS) which relies on subirrigation, and Variable Depth Rootzone (VDR) which relies on overhead irrigation. When appropriate, means were separated using Fischer's least significant difference (LSD) at the 0.05 p level (SAS 9.4, Cary, NC)

RESULTS AND DISCUSSION

Irrigation Inputs

In summer of 2023, the Capillary Hydroponic System required 82.08 mm of irrigation water and the VDR required 207.62 mm of irrigation water to maintain 8% VWC (Figure 12). In the summer of 2024, the Capillary Hydroponic System required 110.99 mm of water for irrigation and the VDR required 265.45 mm of water to maintain 8% VWC (Figure 13).

Two moisture regimes were identified in each year: (1) high daily average evapotranspiration and low daily average precipitation (Figure 14, Figure 15); and (2) high daily average evapotranspiration and high daily average precipitation (Figure 14, Figure 15). During an 11-day period in 2023 when evapotranspiration was high, above 0.30 cm/day, and precipitation was low, below 0.15 cm/day, the CHS required 36.72 mm of water for irrigation and the VDR required 65.15 mm of irrigation water (Figure 15). During an 11-day period in 2024 with the same moisture regime the CHS required 22.62 mm of irrigation water and the VDR required 41.33 mm of irrigation water (Figure 16).

During an 11-day period in 2023 when evapotranspiration was high, above 0.30 cm, and daily average precipitation was high, above 0.40 cm, the CHS required 7.70 mm of water for irrigation and the VDR required 33.17 mm of irrigation water (Figure 17). During an 11-day period in 2024 with the same moisture regime the CHS required 10.19 mm of irrigation water and the VDR required 39.31 mm of irrigation water (Figure 18).

Results are consistent with previous research concluding another form of subirrigation, subsurface drip irrigation (SDI), required as much as 40% less water for irrigation (Leinauer et al., 2016; Orta et al., 2023; Serena et al., 2016).

Organic Matter

In 2023 the CHS greens had a mean surface organic matter of 1.58% by weight and the VDR greens had a mean surface organic matter of 1.58% by weight (Table 3). In 2024 the CHS greens had a mean surface organic matter of 2.40% by weight and the VDR greens had a mean surface organic matter of 2.70% by weight (Table 3). There was no significant difference in organic matter between the two systems in 2023 and 2024.

The similar organic matter accumulation between CHS and VDR suggests that both treatments provide adequate moisture to sustain turf growth without encouraging excessive thatch accumulation. The CHS applied significantly less water than VDR yet provided similar levels of organic matter accumulation. These finding suggest that subsurface irrigation systems can reduce irrigation inputs without compromising turfgrass quality by increasing growth or limiting decomposition.

The organic matter increased from 2023 to 2024 in both systems. However, the values remain below the 3.5% organic matter by weight threshold suggested by McCoy (1992).

Therefore, further monitoring of the surface organic matter should be continue to be a focus as these systems mature.

Moisture Uniformity

Soil moisture was more variable in the CHS than in the VDR on all dates of measurement in 2023 and 2024 (Figure 16, Figure 17). The CHS generally had a higher average VWC than the VDR. The maximum reading being 43.6% and 20.6% VWC in the CHS and VDR, respectively.

The difference in variability is understandable considering the differences in the fundamental design of the systems, most notably that CHS pumps water back and forth from subground chambers every 4 hours. Additionally, in the CHS the water table is closer to the surface of the green in the low-lying areas of the green and further away from the greens surface at the apex of the slope. The CHS relies on capillary action to deliver the rootzone leading to variations in soil moisture especially in areas adjacent to the surface.

The VDR is built the exact opposite, with less distance from the surface at the apex of the slope and more distance in the low-lying areas of the green. Putting greens built to USGA recommendations are subject to lateral flow at the interface of gravel and rootzone material leading to moisture fluctuations on sloped surfaces (Prettyman & McCoy, 2003). However, the interface of gravel and rootzone also acts as a reservoir for water because of a perched water table (E. McCoy & McCoy, 1999). Therefore, the modification of the depth of rootzone produces a more uniform VMC adjacent to the surface.

The higher uniformity in the VDR may have important implications for turf health and playability. Uniform VWC supports more consistent turf performance, root development, and nutrient availability. It may also reduce susceptibility to diseases and localized dry spot. In contrast, while CHS greens maintained adequate average moisture levels, their variability may require more precise monitoring and interventions to avoid extremes.

Root Weight Density

In 2023, there was no significant difference in RWD between the CHS and the VDR (Table 4). In 2024, the CHS had significantly less RWD at the 0 – 7.62 cm depth in the high location compared to the VDR. There was no significant difference between the CHS and VDR root density at the 7.62 – 15.24 cm or the 15.24 – 20.32 cm depths in the high location. There was also no significant difference between the CHS and VDR RWD at the 0 – 7.62 cm depth in the low location. The CHS had significantly less RWD at the depths of 7.62 – 15.24 cm and 15.23 – 20.32 cm in the low location compared to the VDR (Table 5). Generally, CHS had less RWD than the VDR.

These results differ from the findings of Serena et al., 2020 in which SDI plots generally had greater RWD than overhead irrigated plots. This is likely due to the physical position of the SDI in the rootzone. SDI differs from CHS in the sense that the irrigation emitters are installed at a consistent depth (Serena et al., 2020). This promotes consistent root proliferation around the emitters. In contrast, CHS relies on a fluctuating water table that passively rises and falls based on pumping intervals and the elevation of the putting surface. As a result, the effective depth at which roots encounter moisture varies spatially in CHS greens, especially on sloped surfaces.

The CHS plots had more take-all patch (*Gaeumannomyces graminis*) than the VDR plots and the CHS plots were impacted by take-all patch at the apex of the green more than in low lying areas. Take-all patch is known to reduce rooting in CBG (Vargas, 1994). The differences in the root weight density in the high locations may be explained by a root pathogen infection of take-all patch.

Soil Tests

There was no statistical difference in the results of Mehlich 3 extraction between the CHS and VDR in either year. In 2023, the soil had very high calcium concentrations 9359.69 ppm and 9099.67 ppm in the CHS and VDR respectively (Table 6). In 2023, the calcium concentration within the soil was less 5628 ppm and 6704 ppm in the CHS and VDR respectively. In 2024 the soil had less calcium concentrations than in 2023 but was still high at 5628 ppm and 6704 ppm in the CHS and VDR respectively (Table 7).

CONCLUSION

CHS required significantly less water for irrigation than VDR regardless of weather conditions. Soil organic matter content in the two systems were the same. The moisture content in the CHS was less uniform across the surface at a 7.62 cm depth than the VDR. CHS had significantly less RWD than VDR at the surface in the high positions of the slope and deeper in the soil in the low positions of the slope.

Data suggests CHS is a viable alternative to overhead irrigation for putting greens, and, when utilized and managed correctly, will result in an overall reduction in the amount of irrigation required. Turf managers will need to understand how to utilize the system to achieve their agronomic goals, and the system may lead to reduced control in VWC in applications where there are changes in surface elevation.

Future research should consider how weather patterns impact water usage and adjust water table levels to optimize water use. Limitations in our research trial regarding moisture uniformity was that control basins for the CHS were set to collect precipitation and therefore resulted in higher variations of moisture. Research should attempt to identify the appropriate balance between consistent VMC and reduction in amount of water required for irrigation.

TABLES AND FIGURES

Table 1. Particle size distribution of USGA recommendations and of the sand used to construct research greens.

ID	Fine Gravel	Very Coarse	Coarse	Medium	Fine	Very Fine
	Percent by Weight					
USGA	≤3	≤10	≥60		≤20	≤5
HP Sand	0	3.2	29.7	46.5	14.9	5

Table 2. Dates of application of curative fungicide treatments for the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University in 2023 and 2024.

Date	Trade Name	Active Ingredient
06-22-2023	Segway	cyazofamid
07-14-2023	Manzate ProStick T&O	mancozeb
07-25-2023	Segway	cyazofamid
08-16-2023	Manzate ProStick T&O	mancozeb
08-29-2023	Daconil Weather Stick	chlorothalonil
	Segway	cyazofamid
07-11-2024	Maxtima	mefentrifluconazole
	Provaunt	
	Segway	cyazofamid
07-12-2024	Plant Fitness Wetting Agent	
08-08-2024	Emerald	boscalid
	Heritage TL	azoxystrobin
09-05-2024	Emerald	boscalid

Table 3. The effect of irrigation type on total surface organic matter at 7.62 cm depth.

Treatment	Total Organic Matter (%)[†]	
	2023	2024
Capillary Hydroponic System	1.58 a[‡]	2.4 a
Variable Depth Rootzone	1.58 a	2.4 a

[†] Total organic matter samples taken in the fall of each year.

[‡] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 4. The effect of irrigation type on root density at 0 - 7.62 cm, 7.62 cm - 15.24 cm, and 15.24 cm - 20.32 cm depths, 2023.

	Root Density (g/cm^3)		
Sample Depth (cm)	0 - 7.62	7.62 - 15.24	15.24 - 20.32
Location [†]	High		
Capillary Hydroponic System	NS[‡]	NS	NS
Variable Depth Rootzone	NS	NS	NS
Sample Location	Low		
Capillary Hydroponic System	NS	NS	NS
Variable Depth Rootzone	NS	NS	NS

[†] Location refers to sampling location relative to the elevation to the greens surface. High being at the apex of the slope and low being in the low point of the slope.

[‡] NS = not significant (P > 0.05)

Table 5. The effect of irrigation type on root density at 0 - 7.62 cm, 7.62 cm - 15.24 cm, and 15.24 cm - 20.32 cm depths, 2024.

	Root Density (g/cm^3)		
Sample Depth (cm)	0 - 7.62	7.62 - 15.24	15.24 - 20.32
Sample Location [†]	High		
Capillary Hydroponic System	0.0311 a[‡]	NS	NS
Variable Depth Rootzone	0.0558 b	NS	NS
Sample Location	Low		
Capillary Hydroponic System	NS	0.0011 a	0.0006 a
Variable Depth Rootzone	NS	0.0016 b	0.0013 b

[†] Location refers to sampling location relative to the elevation of the greens surface. High being at the apex of the slope and low being in the low point of the slope.

[‡] Means followed by the same letter within the same column respective of sampling location are not significantly different *(P = 0.05*), NS = not significant (P > 0.05)

Table 6. Soil element concentration of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, 2023. †

	Concentration (ppm)	
Test	Capillary Hydroponic System	Variable Depth Rootzone
Phosphorus	5.67	4.33
Potassium	36.33	25.00
Calcium	9359.67	9099.67
Magnesium	163.00	159.33
Sulfur	7.00	4.00
Boron	0.20	0.10
Copper	0.10	0.10
Iron	33.00	29.00
Manganese	22.00	20.00
Zinc	1.10	0.80
Sodium	12.00	10.00

†Soil tests are taken annually in the fall season.

Table 7. Soil element concentration of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, 2024. †

	Concentration (ppm)	
Test	Capillary Hydroponic System	Variable Depth Rootzone
Phosphorus	3.33	3.67
Potassium	14.33	19.00
Calcium	5628.00	6704.00
Magnesium	99.67	101.67
Sulfur	7.00	4.00
Boron	0.20	0.10
Copper	0.10	0.10
Iron	33.00	29.00
Manganese	22.00	20.00
Zinc	1.10	0.80
Sodium	12.00	10.00

†Soil tests are taken annually in the fall season.

Figure 1. Grading plan of the research site designed by Chris Wilczynski and constructed at Hancock Turfgrass Research Center in the spring of 2022. The site includes six research plots categorized as either Capillary Hydroponic System (CHS) or Variable Depth Rootzone (VDR). Red contour lines represent elevation in inches above a baseline, blue squares indicate drains. The layout supports studies comparing irrigation requirements, moisture and turf performance across rootzone designs.

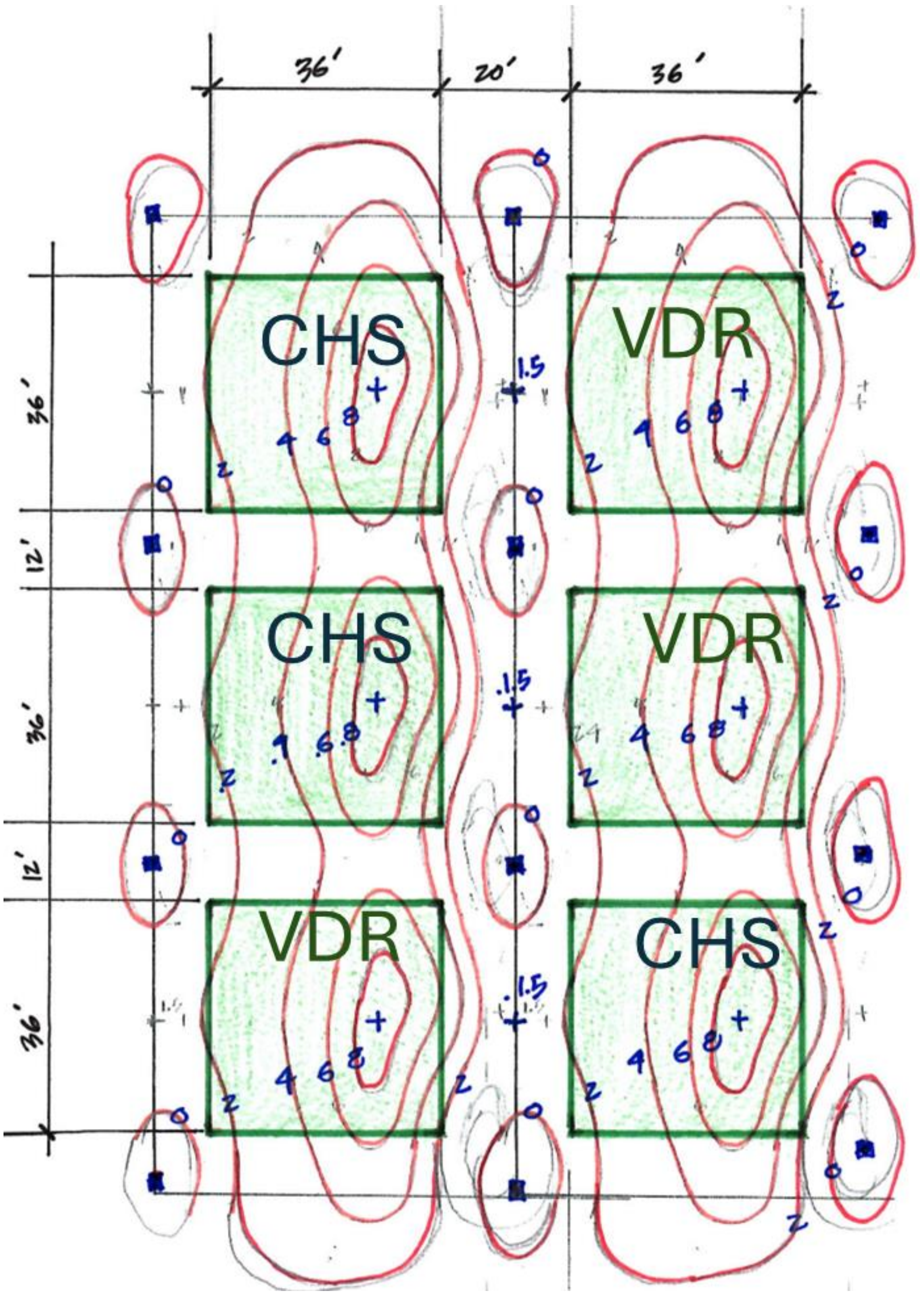


Figure 2. Workers leveling the subgrade of a Capillary Hydroponic System green at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The wooden board splits the green into two equal halves and will be covered by an impermeable liner. The control basin seen in the background to the right of the excavator will be installed adjacent to the green and house components that will move water inside the cavity back and forth between the two equal sections.

Figure 3. Control basin (foreground) installed adjacent to a Capillary Hydroponic System at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The basin is aligned with the dividing board of the green cavity, and housing components that will transfer water in the green's cavity back and forth perpetually.

Figure 4. Control basin (foreground) installed adjacent to a Capillary Hydroponic System green at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. Two inlet pipes installed below the subgrade and extend from the bottom of the basin to the surface at the center of each half of the green's cavity allow for water to flow from the cavity to the control basin.

Figure 5. A waterproof liner installed to line the Capillary Hydroponic System green cavity at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The liner creates a closed system and allows for the cavity to hold water.

Figure 6. A rubber gasket adhered to the liner that lines the cavity of the Capillary Hydroponic System at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The gasket is hose clamped around the inlet pipes to prevent water loss in the Capillary hydroponic system.

Figure 7. Pea gravel added to a depth of 10 cm to encase the drainage tile allowing uniform filling of the Capillary hydroponic system at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University.

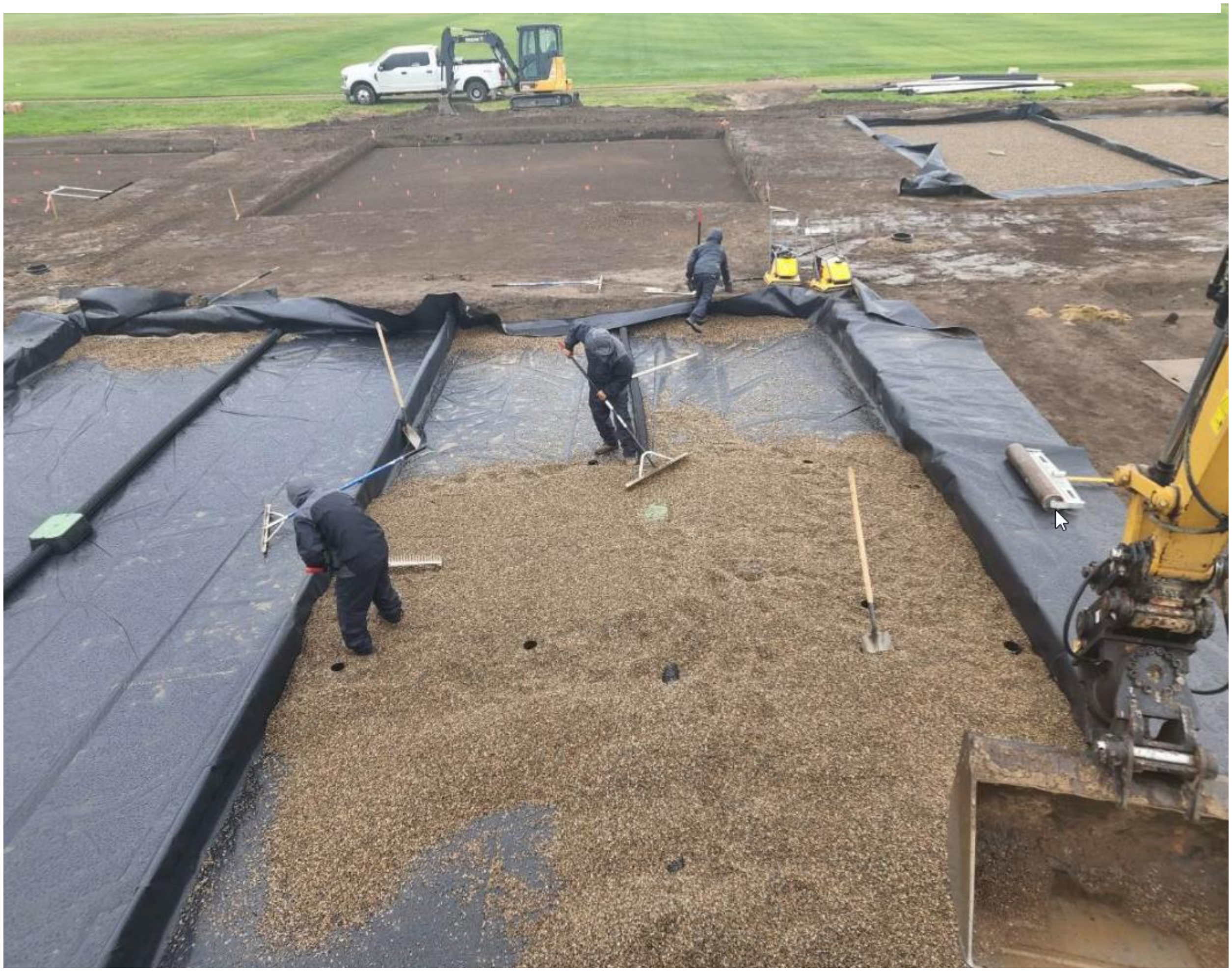


Figure 8. Capillary Concrete added to a depth of 5.08 cm, to provide a stable structure to the Capillary hydroponic system at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University

Figure 9. a cross section of the Capillary Hydroponic System as constructed at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The subgrade is level resulting in rootzone depth varying from 20.32 cm in the low-lying areas of the green to 40.64 cm at the apex of the surface undulation.

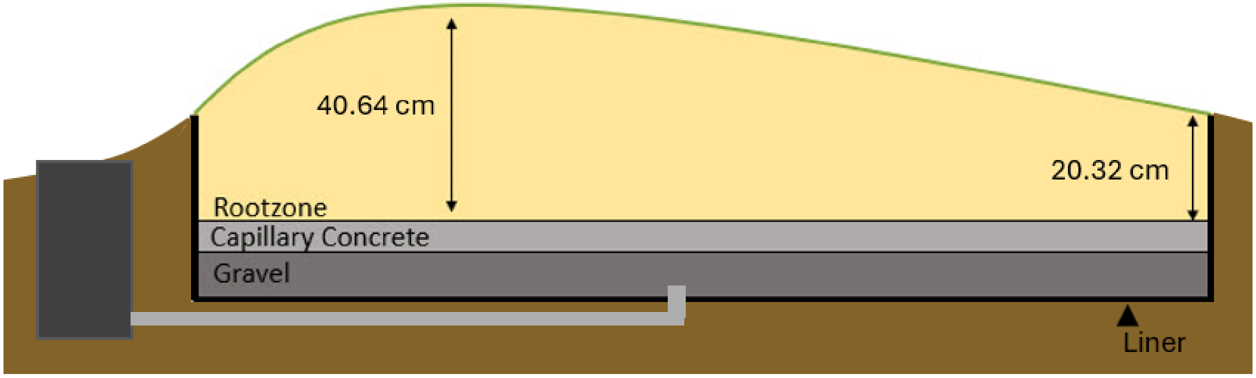
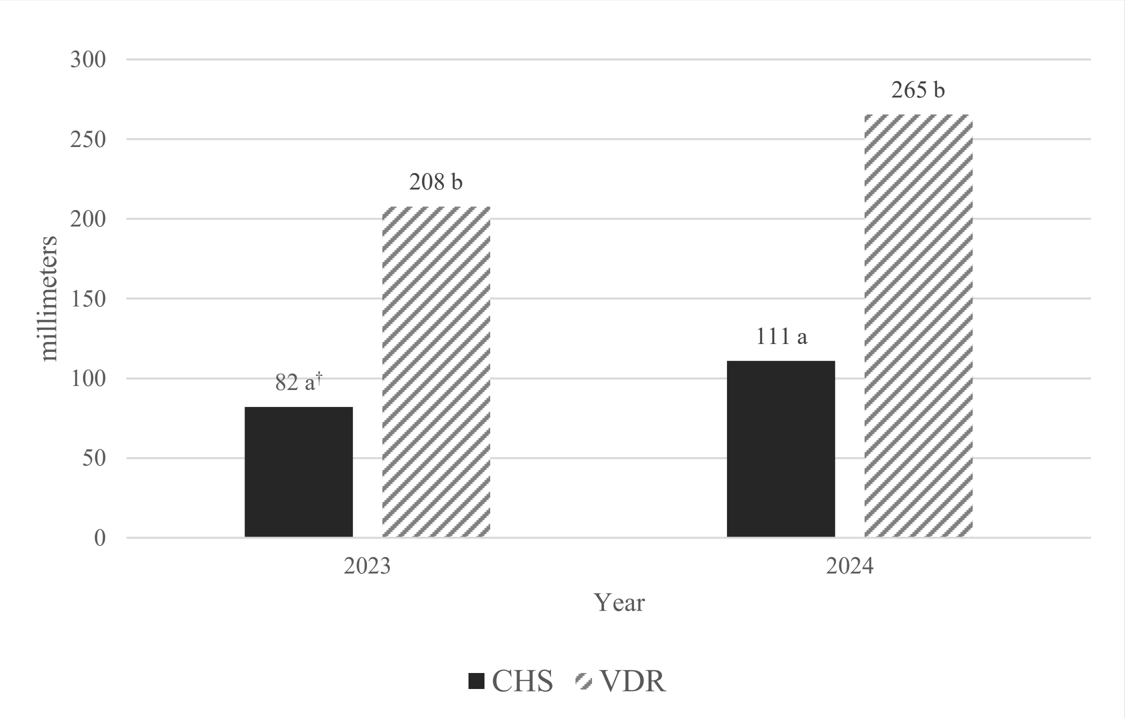


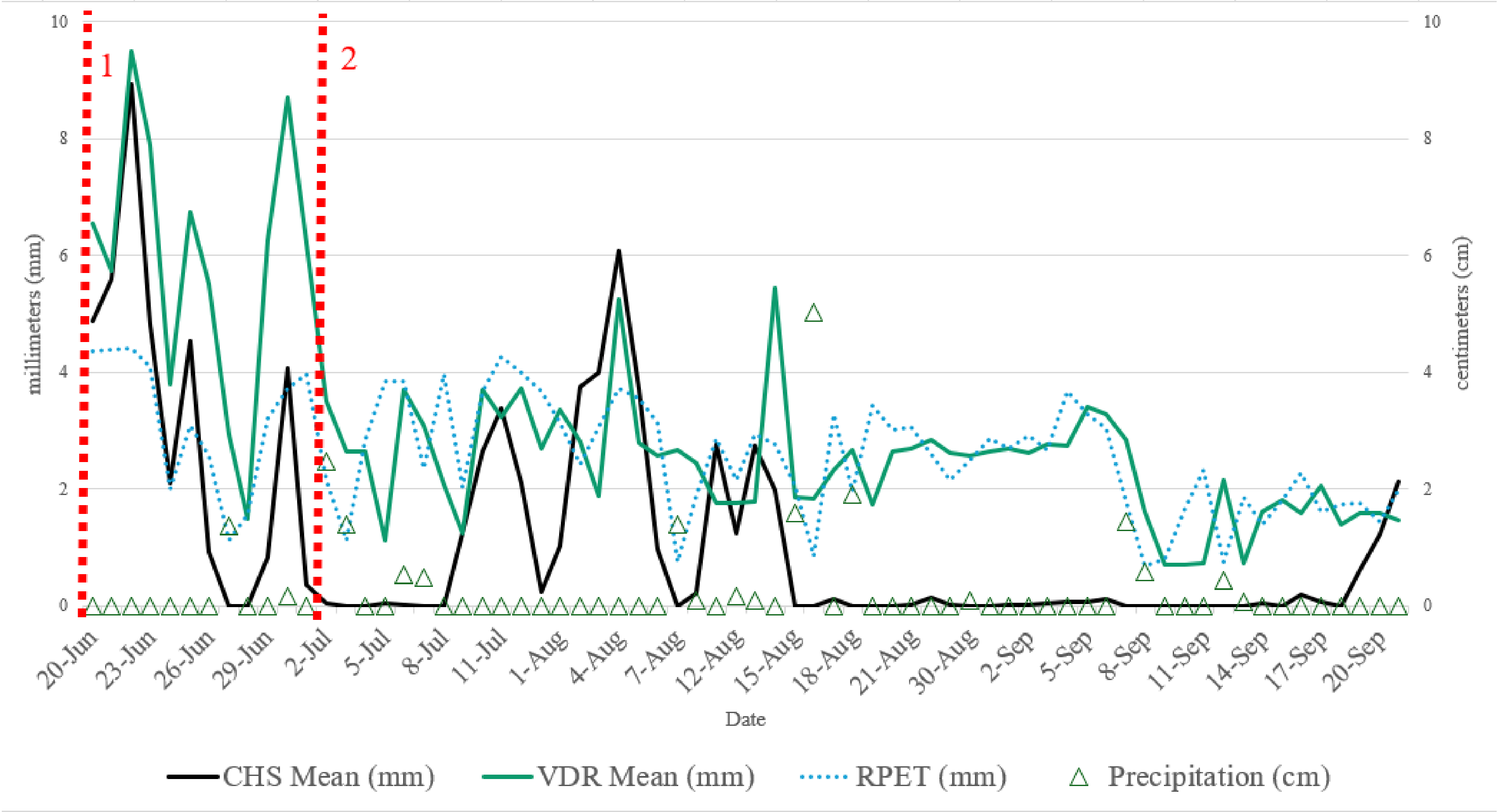
Figure 10. Interior of the Capillary hydroponic control basin prior to installation at the Capillary Hydroponic System and Variable Depth Rootzone research site at Michigan State University. The basin is divided equilaterally by a 0.91 m tall wall, then one half of the basin is divided again equilaterally by a 0.86 m tall wall resulting in a total of three chambers.

Figure 11. Total irrigation applied to the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University Jun-20 through Sept. 21, 2023, and 2024.



†Means followed by the same letter in the same year are not significantly different (α=0.05)

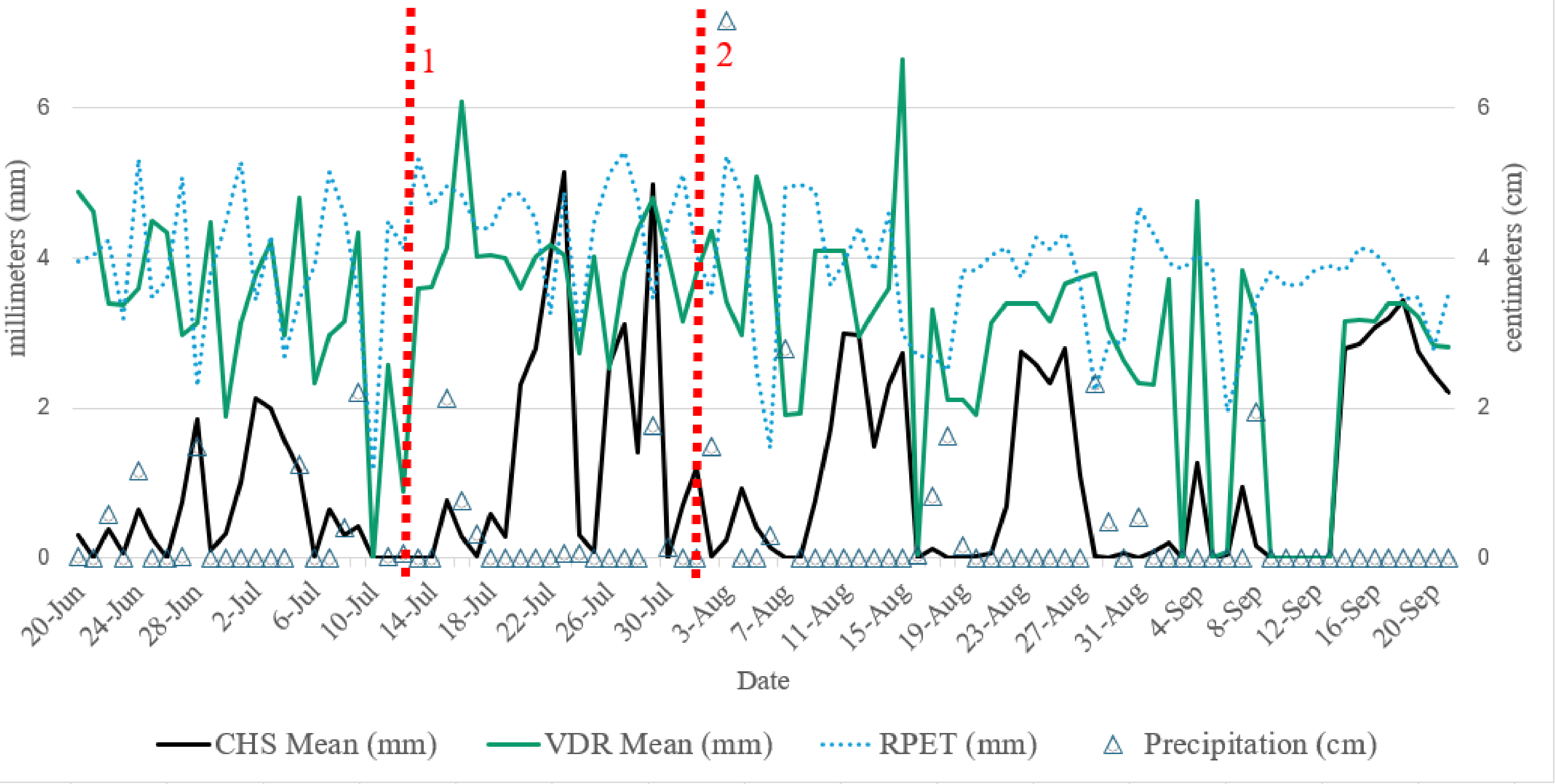
Figure 12. Daily mean irrigation, daily RPET, daily precipitation, and labeled moisture regimes, for the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University, 2023.



[1] Indicates start of 11-day interval with high RPET (daily average RPET > 0.30 cm) and low precipitation (daily average precipitation < 0.15 cm).

[2] Indicates start of 11-day interval with high RPET (daily average RPET > 0.30 cm) and high precipitation (daily average precipitation > 0.40 cm).

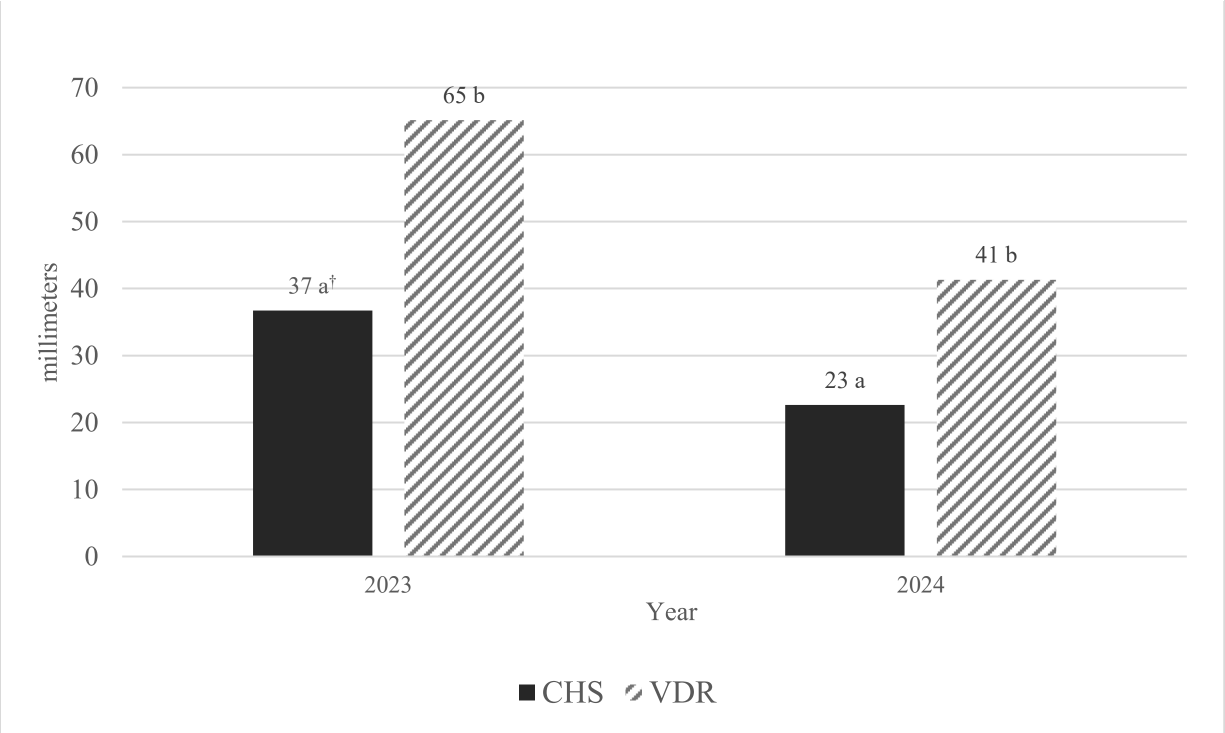
Figure 13. Daily mean irrigation, daily RPET, daily precipitation, and labeled moisture regimes, for the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University, 2024.



[1] Indicates start of 11-day interval with high RPET (daily average RPET > 0.30 cm) and low precipitation (daily average precipitation < 0.15 cm).

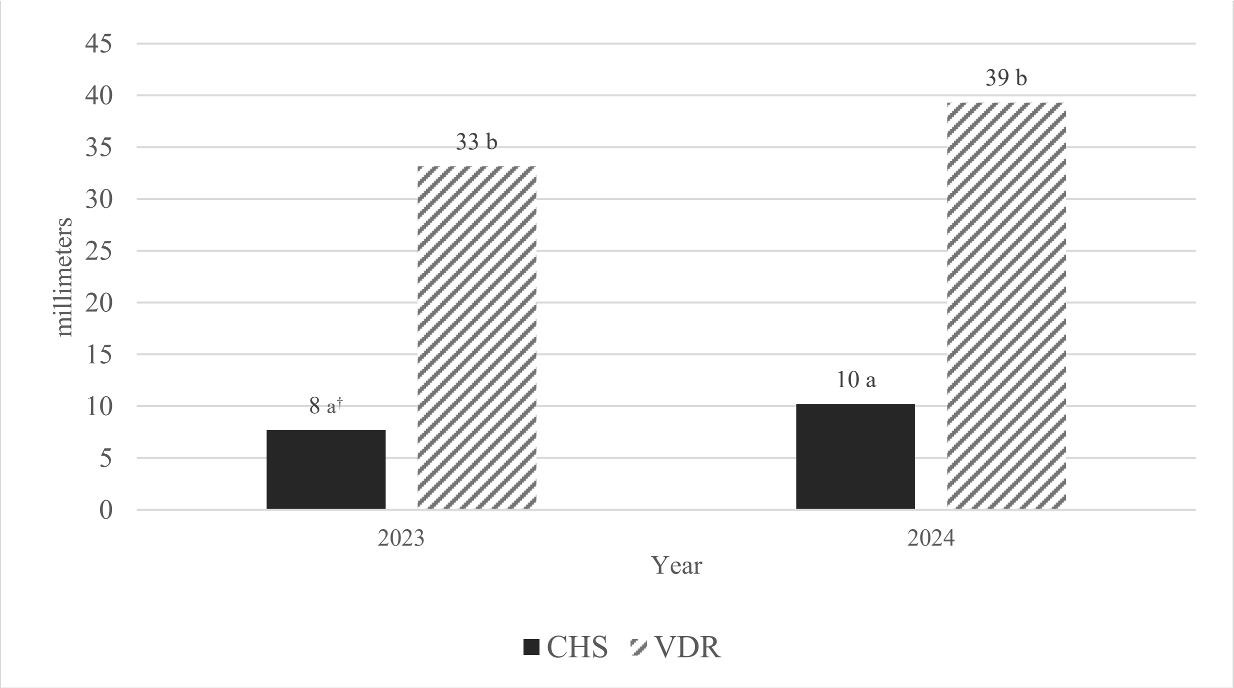
[2] Indicates start of 11-day interval with high RPET (daily average RPET > 0.30 cm) and high precipitation (daily average precipitation > 0.40 cm).

Figure 14. Total irrigation between treatments during weather regime with high evapotranspiration and low precipitation at the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University, 2023, and 2024.



†Means followed by the same letter in the same year are not significantly different (α=0.05)

Figure 15. Total irrigation between treatments during weather regime with high evapotranspiration and high precipitation at the Capillary Hydroponic System (CHS) and Variable Depth Rootzone (VDR) research site at Michigan State University, 2023, and 2024.



†Means followed by the same letter in the same year are not significantly different (α=0.05)

Figure 16. Treatment mean soil VMC measurements across plot surfaces at 7.62 cm, depth 2023 as measured with a Spectrum TDR-350.

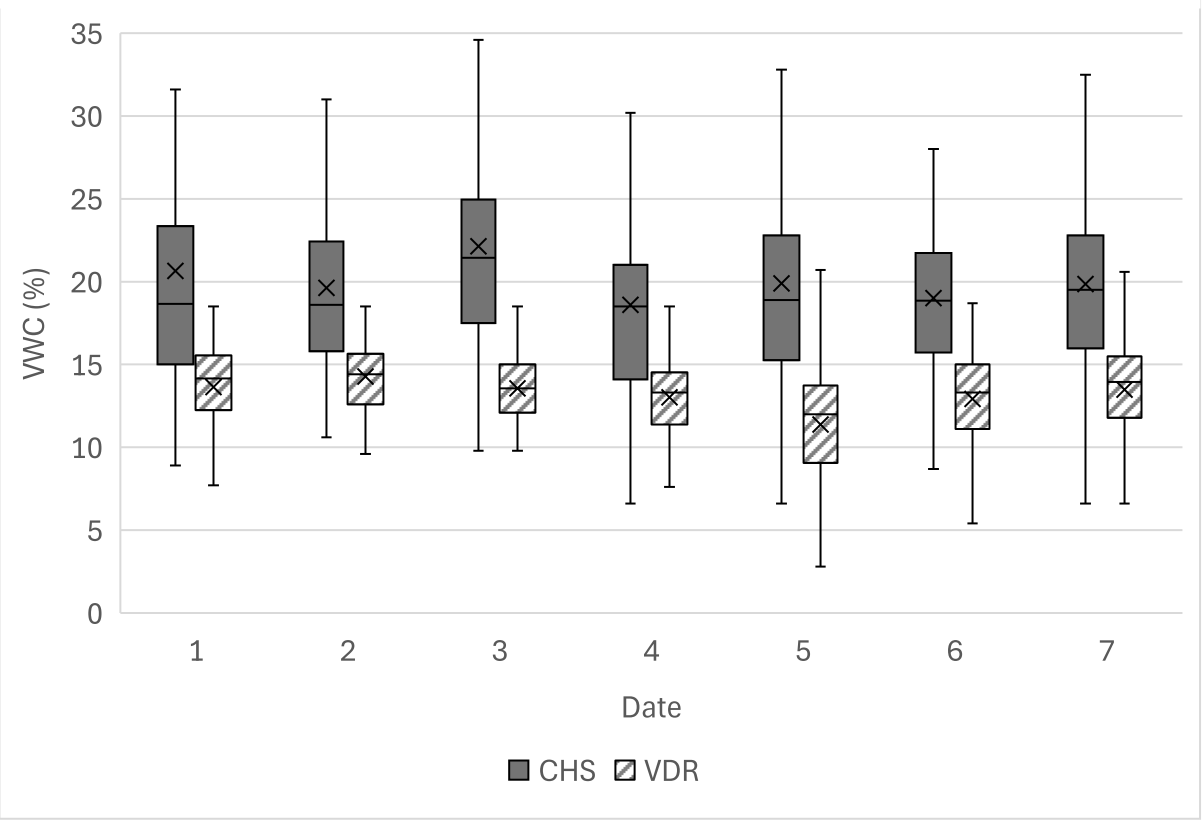
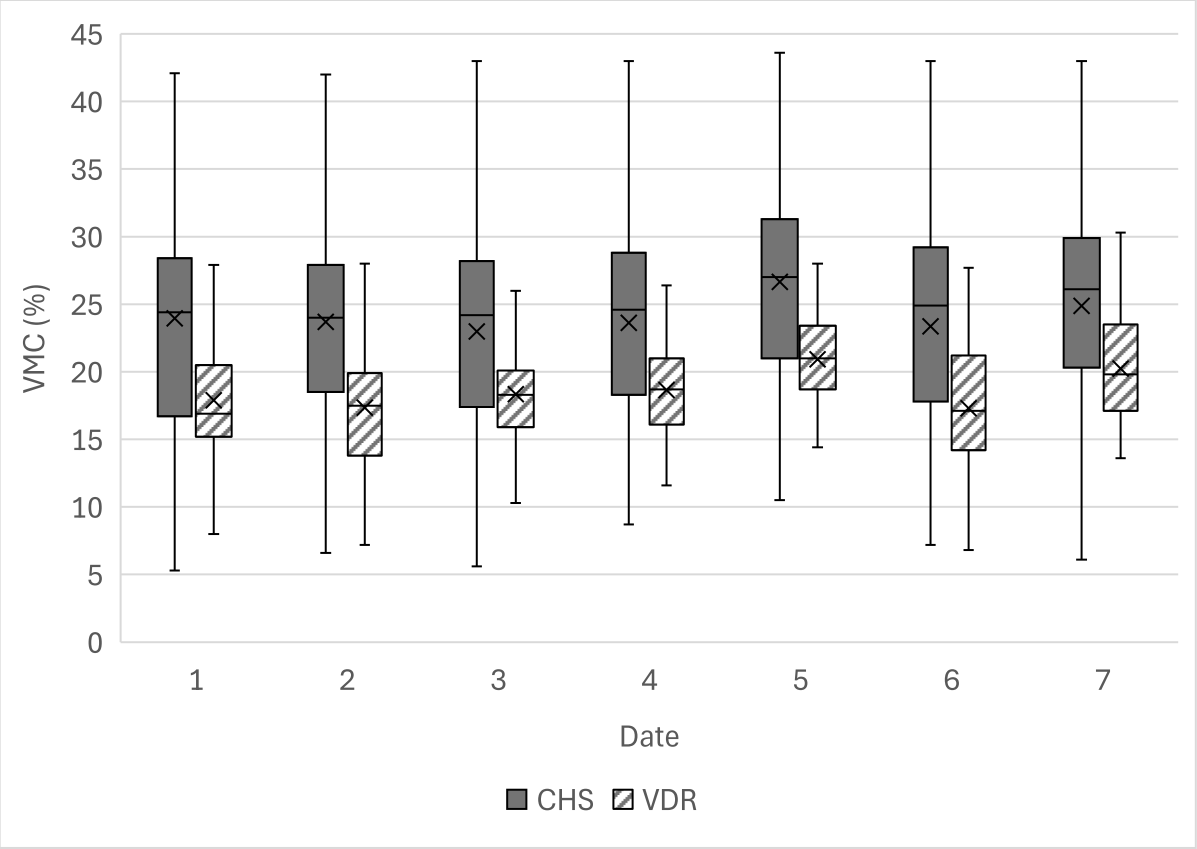


Figure 17. Treatment mean soil VMC measurements across plot surfaces at 7.62 cm, depth 2024 as measured with a Spectrum TDR-350.



CHAPTER 2: EFFECT OF IRRIGATION TYPE ON PLAYABILITY, AND TURFGRASS QUALITY, HEALTH, AND GROWTH OF CREEPING BENTGRASS PUTTING GREENS

MATERIALS AND METHODS

Construction

Six putting greens were constructed at the Hancock Turfgrass Research Center in East Lansing, MI in the summer of 2022. Three were constructed with a Variable Depth Rootzone (VDR) and three were constructed with a Capillary Hydroponic System (CHS) (Capillary Flow, Gotenberg, SE). For further details of the construction and design of the site and systems please refer to the materials and methods of Chapter 1 under the section of Construction.

Turfgrass plot maintenance

Plots were mowed six times per week at a height of 3.05 mm using a walk behind greens mower (Toro Flex 2100, The Toro Company, Bloomington, MN), with clippings collected and removed from all plots. Plots were rolled with a ride on greens roller (RC50, Tru-Turf, Gold Coast, AU) at least 3 times per week. Sand topdressing was applied weekly at a depth of 0.02 cm. The plots were vertical mowed in two directions at a depth of 3 mm with a walk behind vertical mowing unit (Model Vacu-Cutter, True Surface, Moscow Mills, MO) with clippings collected and removed in the fall of 2023 and 2024. Sand topdressing was applied to fill the voids left by vertical mowing to dilute organic matter build up.

On recommendation of the manufacturer CHS greens were treated with 20 mL of 50% (v/v) nitric acid (Ricca Chemical Company, Arlington, TX) twice monthly to prevent calcium carbonate accumulation in the porous structure of the capillary concrete.

Fertilizer was applied as a foliar spray weekly using a 24-0-8 (N-P-K) soluble granular fertilizer (The Andersons, Maumee, OH) at a rate of 9 kg ha^{-1}. Fungicides were applied on a curative basis only.

Clippings yield

Prior to clipping collection, a single perimeter pass was made with clippings discarded prior to yield data collection, and dew was removed from the sample area with a backpack blower (Model BR 700, Stihl, Waiblingen, DE). Afterward a single pass was made in the east to west direction 3.65 m from the south edge of the plots. Clippings were collected with a walk behind greens mower (Model Flex 2100, The Toro Company, Bloomington, MN). Clippings were dried in an OVEN at 105 C prior to recording clipping yield.

Greens Speed

An identical location 3.65 m from the center of the east edge of each plot was selected to measure green speed with a USGA Stimpmeter. Putting green speed was determined by measuring ball roll distance according to standard procedures (USGA, 2011), which include rolling three golf balls in opposite directions along the same path and averaging the six ball roll distances on each plot.

Surface Firmness

Surface firmness ratings were taken using a turf firmness meter (Model TruFirm, Spectrum Technologies, Bridgend, UK). The firmness was tested in six random locations. When the location of the reading was sloped, the base was oriented to be pointed downhill. The plunger of the firmness meter was lifted fully and dropped so that it fell smoothly (Spectrum Technologies, n.d.).

Color and Quality

Color and quality ratings were conducted on a regular basis following Morris & Shearman, n.d. National Turfgrass Evaluation Program (NTEP) Turfgrass Evaluation Guidelines, using a 1 to 9 visual rating scale with 1 being the poorest, and 9 being the best. Ratings were conducted inside 90 cm diameter circles marked in two identical locations on each green, high and low. High designating the apex of the slope and low designating a low lying area of the research greens.

Pest Observations

Pesticides were applied on a curative basis following observation of symptoms or signs of a pest infection. Counts or ratings were conducted upon observation when possible and recorded prior to curative applications. Products were chosen to be the most selective for the treatment of specific pests. Localized dry spots and take-all patch (*Gaeumannomyces graminis*) were rated on a scale of 1-9, 1 being the least severe and 9 indicating immediate action required to prevent turf loss.

Tissue testing

Each plot was mowed in its entirety with a walk behind greens mower (Model Flex 2100, The Toro Company, Bloomington, MN) and clippings collected in a clippings basket. Clippings were then funneled into their own paper bag, for a total of 6 samples. The samples were air dried for 8 hours and sent to Waypoint Analytical to undergo plant tissue analysis.

Experimental Design and Data Analysis

The experiment was a randomized complete block design with one factor, irrigation type. Irrigation type consisted of two levels, Capillary Hydroponic System (CHS) which relies on subirrigation, and Variable Depth Rootzone (VDR) which relies on overhead irrigation. When appropriate, means were separated using Fischer's least significant difference (LSD). For surface firmness the analysis was conducted with subsamples and log transformed means were separated by conducting an F-test.

RESULTS AND DISCUSSION

Clippings Yield, Green Speed, and Surface Firmness

In 2023 and 2024 there was no significant difference in clippings yield (Table 8, Table 9). Over the six dates that green speed was measured in each year the CHS green speed was not significantly different between treatments (Table 10, Table 11). Surface firmness also did not result in significant differences in 2023 or 2024 between CHS and VDR (Table 12, Table 13).

(Krans & Johnson, 1974) found that creeping bentgrass under a fluctuating water table subirrigation system had similar clipping yield to sprinkler irrigated research plots. Our results, no significant difference between CHS (fluctuating water table subirrigation) and VDR are consistent with the previous study's findings. This suggests that subirrigation systems may support performance without reducing biomass production.

Color and Quality

Color and quality were higher and less variable in the low location on plots regardless of treatment while ratings in high location were more variable. In color ratings from August 3rd, 2023, the CHS had a statistically higher mean color rating of 6.83 in the high location while the VDR had a mean color rating of 5.16 in the same location (Table 14). The CHS also had a statistically higher mean color rating of 6.66 in the low location while the VDR had a mean color rating of 6.0 (Table 14). All other color ratings in 2023 and 2024 (Table 15) were not statistically different between treatments and all quality ratings in 2023 (Table 16) and 2024 (Table 17) were not significantly different.

Pest Observations

LDS was first observed on the research plots in August 2023. Ratings monitoring its development were taken on August 4th, August 14th, and September 5th in 2023 (Figure 17). There was no significant difference between the CHS and VDR on the August 4th and August 14th LDS ratings. On September 5th LDS ratings on the CHS were 2.33 and the rating on VDR was 6.0.

In 2024 LDS became apparent on the site with ratings taken on June 20th, July 2nd, July 5th, July 8th, July 9th, and July 29th. Ratings from June 20th, July 2nd, July 5th, July 8th, and July 9th LDS was significantly less severe on CHS compared to the VDR (Figure 19). On July 9th one of the VDR plots received a rating of 8 and it became apparent action had to be taken to prevent turf loss. Therefore, all six greens were sprayed with a wetting agent (Hydration, containing ethylene oxide-propylene oxide copolymer, Epoch Science, Chicago, IL) on July 12th, 2024. Following the application of the wetting agent, subsequent LDS ratings resulted in more severe ratings on the CHS system than on VDR (Figure 19).

LDS is a term used to characterize irregular areas of turf displaying drought stress symptoms in a soil that has an otherwise adequate VWC (Karnok & Tucker, 1989). Surfactants are used to alleviate soil water repellency and symptoms of LDS and increase infiltration rates of soils with hydrophobic properties (Aamlid & Pettersen, 2022; Kostka, 2000). Karnok & Tucker (1989) suggest that these hydrophobic properties develop from organic materials breaking down and forming organic acids that coat sand particles that could be due to consistent wetting and drying.

The LDS observed on the CHS was not similar of the LDS observed on the VDR which were small irregular patches. Instead, the LDS was observed as a large area of overall dryness. This is likely because the CHS did not receive overhead irrigation on a regular basis and therefore is not subjected to the constant wetting and drying of the soil surface. Additionally, acids from decomposing organic matter would not have a chance to enter the top 7.5 cm of the rootzone, where the surfactants are most effective (Aamlid & Pettersen, 2022), because there is no downward movement of water to carry them below the surface. The increased severity of the dryness on the CHS after the surfactant application could be due to the fact that water raising by capillary rise from below is hitting the layer of surfactant and is not able to rise as much as it was prior to application of the wetting agent.

Take-all patch (*Gaeumannomyces graminis*) was first observed on VDR plots on July 14th, 2022, two weeks after seeding. It was not observed again July 2024 at which time runner hyphae were observed in the roots of the CHS and VDR greens. The severity of the disease was greater in the CHS than in the VDR (Table 19). The take-all patch observed in the CHS was not of patches but rather a large area that was equally blighted. On the VDR there were smaller patches of take-all patch.

In CHS the wetting and drying of the rootzone via the fluctuating water table coupled with rain events in the early fall of 2023 created ideal conditions for the proliferation of take-all patch. When a rain event occurs the CHS holds the water in the reservoir and can lead to wetter conditions, then when there are periods of no rain the reservoir gets depleted and the rootzone dries to no less than our target VWC. This is consistent with known information about take all patch. Take-all patch is promoted when cool and wet conditions are followed by hot weather and drought (Penn STATE).

It is important to note that the symptoms of LDS and take-all patch can be visually similar and may overlap in the field, making definitive differentiation challenging based solely on turf appearance. While take-all patch was confirmed through root colonization and presence of runner hyphae, LDS was visually assessed. In this study, the large, uniform areas of turf decline observed on the CHS system may reflect a combination of both stressors rather than separate issues. This contributed to the difficulty in clearly distinguishing between LDS and take-all patch in the field observations, and the observed severity ratings should be interpreted with this in mind.

Dollar spot (*Clarireedia jacksonii*) was initially observed on the site in October 2023, no action was taken because of the time of year. In 2024, dollar spot was observed on the research plots on June 21st, July 10th, and August 5th (Table 17). There was no significant difference in number of colonies on June 21st, or July 10th. On August 5th there were more dollar spot colonies on the CHS than the VDR, with means of 17.33 and 5.00 colonies respectively.

The average VMC in CHS was higher than the VDR. Higher VMC in the soil surface is one of the factors that leads to higher dew formation (Jia et al., 2019). Time of leaf wetness leads to greater severity of dollar spot in creeping bentgrass (Giordano et al., 2012; Williams et al., 1996). The CHS was typically observed with more dew than the VDR. Therefore, it is possible that even though the CHS was not receiving overhead irrigation the leaf wetness was typically higher and led to increased dollar spot occurrence.

Tissue Testing

In 2023 there was no significant difference between treatments in tissue nutrient concentrations (Table 20). There were very high levels of magnesium (Mg) at 0.98% and 1.01% in the CHS and VDR respectively. Both treatments tested for extremely high levels of calcium (Ca), iron (Fe), copper (Cu), and aluminum (Al). Sodium (Na), boron (B), zinc (Zn) and manganese (Mn) tested at sufficient levels. Nitrogen (N), sulfur (S), phosphorus (P), and potassium (K) were deficient in the tissue tested.

In 2024 there was no significant difference between treatments in tissue nutrient concentrations of S, P, Mg, Na, B, Zn, or Cu (Table 21). The CHS had significantly lower levels of N and P in the plant tissue than in the tissue of the VDR. The CHS tissue tested for significantly greater levels of Ca and Mn than the tissue tested from the VDR. Finally, the CHS tested for about twice as much Fe and Al in the plant tissue as the VDR tissue.

CONCLUSION

The CHS had a greens speed and surface firmness that was not statistically significantly different from the VDR. The growth rate of the CHS and VDR were the same. Although the color of the CHS was higher on one date there were not enough differences to identify a trend. The CHS was less susceptible to LDS than the VDR and the CHS was more susceptible to dollar spot and take-all patch than the VDR. There were much higher levels of Fe and Al in the CHS than in the VDR.

There was no difference between the CHS and VDR regarding playability and visual aspects. The CHS did not display classic signs of LDS and it seemed that applying a wetting agent containing ethylene oxide and propylene oxide had a negative impact on its performance.

Future research should consider treating the root borne pathogens in the basin of CHS and compare performance of fungicides with VDR treated from the surface. Directly treating the soil from the subground through the basin of the CHS greens may lead to an effective method to control root borne pathogens. Additionally testing should be conducted in a manner that allows for measurements of contaminants and minerals through drainage water because CHS has a liner that does not allow leaching and therefore contains applied pesticides and fertilizers.

TABLES AND FIGURES

Table 8. Clippings yield of creeping bentgrass under two irrigation types, Capillary Hydroponic System, and Variable Depth Rootzone collected June, August, and September, 2023.

Treatment	Yield (g/m^2)		
	June	August	Sept.
Capillary Hydroponic System	4.15 a[†]	7.38 a	1.55 a
Variable Depth Rootzone	4.64 a	7.29 a	1.55 a

[†] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 9. Clippings yield of creeping bentgrass under two irrigation types, Capillary Hydroponic System, and Variable Depth Rootzone collected June, July, August, and September, 2024.

Treatment	Yield (g/m^2)			
	June	July	August	Sept.
Capillary Hydroponic System	1.99 a[†]	1.11 a	1.51 a	2.05 a
Variable Depth Rootzone	1.97 a	1.16 a	1.26 a	1.57 a

[†] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 10. Ball roll distance of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, as measured with a Stimpmeter[†], 2023.

Treatment	Greens Speed (m)					
	11-Jul	27-Jul	10-Aug	14-Aug	24-Aug	14-Sep
Capillary Hydroponic System	2.52 a[‡]	2.92 a	2.64 a	2.84 a	2.75 a	2.99 a
Variable Depth Rootzone	2.43 a	2.90 a	2.63 a	2.92 a	2.72 a	3.03 a

[†] Greens Speed was measured following the instructions for a USGA Stimpmeter.

[‡] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 11. Ball roll distance of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, as measured with a Stimpmeter[†], 2024.

Treatment	Greens Speed (m)					
	18-Jun	16-Jul	30-Jul	27-Aug	10-Sep	24-Sep
Capillary Hydroponic System	2.99 a[‡]	2.44 a	2.45 a	2.80 a	3.02 a	2.53 a
Variable Depth Rootzone	2.72 a	2.36 a	2.35 a	2.62 a	2.88 a	2.45 a

[†] Greens Speed was measured following the instructions for a USGA Stimpmeter.
[‡] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 12. Surface firmness of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, as measured with a Spectrum TuFirm[†], 2023.

Treatment	Surface Firmness (cm)					
	20-Jun	27-Jun	6-Jul	25-Jul	1-Aug	30-Aug
Capillary Hydroponic System	0.90 a[‡]	01.01 a	0.72 a	0.89 a	0.75 a	0.86 a
Variable Depth Rootzone	0.91 a	1.02 a	0.70 a	0.95 a	0.72 a	0.89 a

[†] Surface Firmness was measured following the instructions for a Spectrum TruFirm meter.
[‡] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 13. Surface firmness of creeping bentgrass putting greens under two irrigation types, Capillary Hydroponic System and Variable Depth Rootzone, as measured with a Spectrum TruFirm[†], 2024.

Treatment	Surface Firmness (cm)					
	13-Jun	30-Jun	18-Jul	8-Aug	29-Aug	12-Sep
Capillary Hydroponic System	0.93 a[‡]	0.93 a	0.95 a	0.93 a	0.92 a	0.98 a
Variable Depth Rootzone	0.91 a	0.91 a	0.94 a	0.91 a	0.94 a	0.93 a

[†] Surface Firmness was measured following the instructions for a Spectrum TruFirm meter.
[‡] Means followed by the same letter within the same column are not significantly different according to Fisher's Protected LSD (α=0.05)

Table 14. The effect of irrigation type on turfgrass color in two surface locations, 2023.

	Turfgrass Color[†]					
	17-Jul	28-Jul	3-Aug	17-Aug	29-Aug	14-Sep
Sample Location[‡]	High					
Capillary Hydroponic System	6.08 a[§]	6.50 a	6.83 a	6.16 a	6.50 a	6.66 a
Variable Depth Rootzone	5.66 a	5.83 a	5.16 b	6.50 a	6.50 a	6.00 a
Sample Location	Low					
Capillary Hydroponic System	6.67 a	6.83 a	6.67 a	6.67 a	7.00 a	6.83 a
Variable Depth Rootzone	6.00 a	6.33 a	6 b	6.67 a	6.83 a	6.67 a

[†] Turfgrass color was taken on a visual scale of 1-9, 9 being the highest.

[‡] Location refers to sampling location relative to the elevation of the greens surface.

[§] Means followed by the same letter within the same column respective of sampling location are not significantly different (α = 0.05)

Table 15. The effect of irrigation type on turfgrass color in two surface locations, 2024.

	Turfgrass Color[†]					
	9-Jul	22-Jul	7-Aug	23-Aug	6-Sep	23-Sep
Sample Location[‡]	High					
Capillary Hydroponic System	5.00 a[§]	4.67 a	6.50 a	7.00 a	6.67 a	7.00 a
Variable Depth Rootzone	5.17 a	5.33 a	6.83 a	6.83 a	6.67 a	6.67 a
Sample Location	Low					
Capillary Hydroponic System	7.00 a	7.00 a	7.33 a	7.33 a	7.33 a	7.33 a
Variable Depth Rootzone	7.00 a	7.33 a	7.33 a	7.00 a	6.83 a	7.17 a

[†] Turfgrass color was taken on a visual scale of 1-9, 9 being the highest.

[‡] Location refers to sampling location relative to the elevation of the greens surface.

[§] Means followed by the same letter within the same column respective of sampling location are not significantly different (α = 0.05)

Table 16. The effect of irrigation type on turfgrass quality in two surface locations, 2023.

	Turfgrass Quality[†]					
	17-Jul	28-Jul	3-Aug	17-Aug	29-Aug	14-Sep
Sample Location[‡]	High					
Capillary Hydroponic System	6.83 a[§]	6.67 a	6.50 a	6.50 a	6.67 a	6.83 a
Variable Depth Rootzone	6.67 a	6.67 a	6.00 a	6.83 a	7.00 a	6.33 a
Sample Location	Low					
Capillary Hydroponic System	7.00 a	7.17 a	7.00 a	7.00 a	7.00 a	7.00 a
Variable Depth Rootzone	6.5 a	7.00 a	6.50 a	6.83 a	6.83 a	7.00 a

[†] Turfgrass quality was taken on a visual scale of 1-9, 9 being the highest.

[‡] Location refers to sampling location relative to the elevation of the greens surface.

[§] Means followed by the same letter within the same column respective of sampling location are not significantly different (α = 0.05)

Table 17. The effect of irrigation type on turfgrass quality in two surface locations, 2024.

	Turfgrass Quality[†]					
	9-Jul	22-Jul	7-Aug	23-Aug	6-Sep	23-Sep
Sample Location[‡]	High					
Capillary Hydroponic System	5.67 a[§]	5.33 a	7.17 a	7.00 a	6.50 a	7.00 a
Variable Depth Rootzone	6.17 a	6.33 a	6.83 a	6.50 a	6.83 a	7.00 a
Sample Location	Low					
Capillary Hydroponic System	8.00 a	8.00 a	7.00 a	7.17 a	7.17 a	7.00 a
Variable Depth Rootzone	8.00 a	8.00 a	7.00 a	7.00 a	6.83 a	7.00 a

[†] Turfgrass quality was taken on a visual scale of 1-9, 9 being the highest.

[‡] Location refers to sampling location relative to the elevation of the greens surface.

[§] Means followed by the same letter within the same column respective of sampling location are not significantly different (α = 0.05)

Table 18. Effect of irrigation type on dollar spot (*Clarireedia jacksonii*), 2024.

	Number of DS[†] Colonies		
	21-Jun	10-Jul	5-Aug
Capillary Hydroponic System	NS[‡]	NS	17.33 b
Variable Depth Rootzone	NS	NS	5.00 a

[†] DS= Dollar Spot (Clarireedia jacksonii)

[‡] NS = not significant (P > 0.05), Means followed by the same letter within the same column are not significantly different (P = 0.05)

Table 19. Effect of irrigation type on take-all patch (*Gaeumannomyces graminis*), 2024.

	Severity of take-all patch[†]		
	8-Jul	30-Jul	7-Aug
Capillary Hydroponic System	5.3 a[‡]	5.8 a	3.8 a
Variable Depth Rootzone	2.8 b	2.0 b	1.0 b

[†] Severity rated on a scale of 1-10 10 being the worst.

[‡] Means followed by the same letter within the same column are not significantly different (P = 0.05)

Table 20. Effect of irrigation type on concentration of elements in tissue testing, 2023. [†]

Test	Concentration (ppm)			
	Capillary Hydroponic System		Variable Depth Rootzone	
Nitrogen	13,200	NS[‡]	14,600	NS
Sulfur	1,400	NS	1,600	NS
Phosphorus	1,600	NS	1,900	NS
Potassium	7,000	NS	7,800	NS
Magnesium	9,800	NS	10,100	NS
Calcium	44,800	NS	44,500	NS
Sodium	200	NS	200	NS
Boron	11	NS	11	NS
Zinc	29	NS	27	NS
Manganese	193	NS	189	NS
Iron	7,252	NS	6,738	NS
Copper	116	NS	116	NS
Aluminum	2,584	NS	2,527	NS

[†] Tissue tests are taken annually in the fall season.

[‡] NS= not significant (P > 0.01)

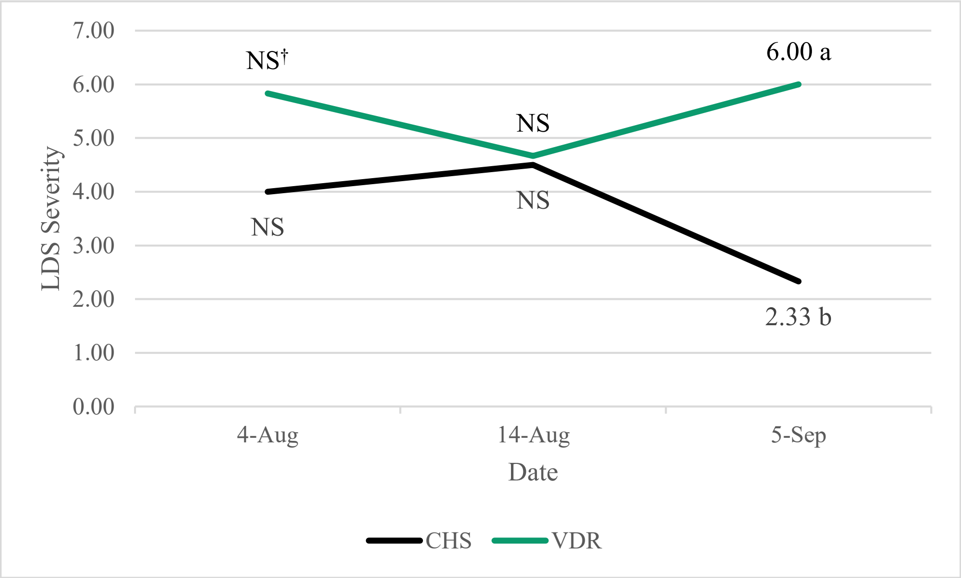
Table 21. Effect of irrigation type on concentration of elements in tissue testing, 2024. [†]

Test	Concentration (ppm)			
	Capillary Hydroponic System		Variable Depth Rootzone	
Nitrogen	32,067	b[‡]	34,433	a
Sulfur	3,100	NS	4,567	NS
Phosphorus	3,900	b	4,467	a
Potassium	18,600	NS	19,833	NS
Magnesium	2,833	NS	2,833	NS
Calcium	10,733	a	8,400	b
Sodium	233	NS	267	NS
Boron	10	NS	8	NS
Zinc	44	NS	44	NS
Manganese	93	a	68	b
Iron	1,456	a	731	b
Copper	17	NS	16	NS
Aluminum	577	a	257	b

[†] Tissue tests taken annually in the fall season.

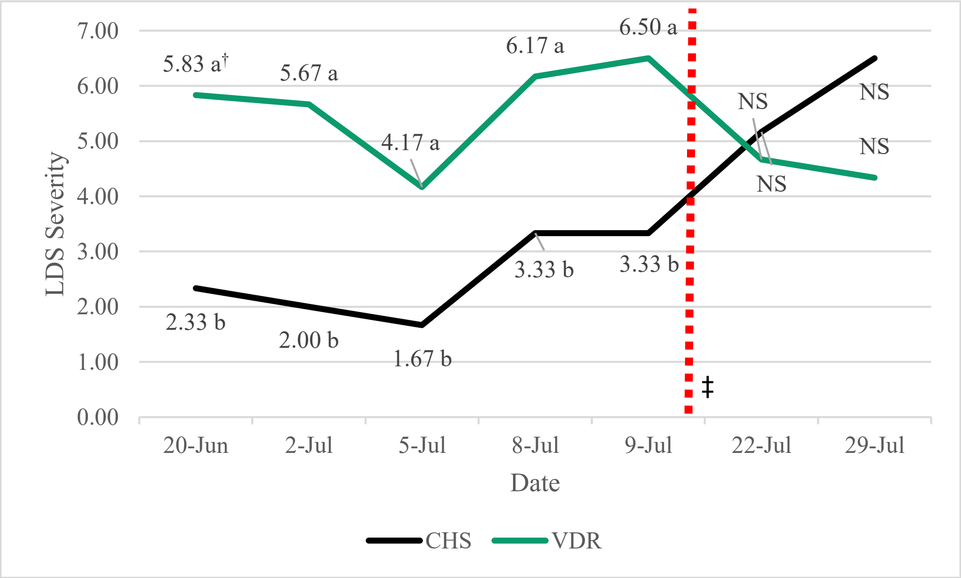
[‡] Means followed by the same letter within the same row are not significantly different (P < 0.01), NS = not significant (P > 0.01)

Figure 18. Effect of irrigation type on localized dry spot severity, 2023.



†Means followed by the same letter in the same year are not significantly different, NS= Not Significant (α=0.05)

Figure 19. Effect of irrigation type on localized dry spot severity, 2024.



†Means followed by the same letter in the same year are not significantly different, NS= Not Significant (α=0.05)
‡Indicates date of surfactant application.

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