Passive Control of Downslope Capillary Wicking of Water in Sand-based Root Zones

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Abstract. Chronic dry spots that occur on the upper reaches of slopes on golf putting greens lead to increased frequency of irrigation to maintain a healthy turfgrass surface. To limit one cause of dry spots, the downslope wicking of water, we investigated the use of subsurface barriers to interrupt the capillary connectivity of the bottom portion of the root zone on a 3.5-m long, laboratory-simulated section of a green having a 5% slope. We evaluated the effectiveness of the barriers on a green constructed with a sand root zone over gravel drainage and on a green constructed with a sand root zone over a geotextile atop a porous plastic grid for drainage. With sand over gravel, the barriers were effective at reducing downslope wicking and the consequential loss of stored water in the root zone on the slope. In the top 0.5 m of the slope, there was 24 mm more water stored in the root zone profile of the green constructed with barriers compared with that in the green constructed without barriers. With sand over geotextile atop a plastic grid, the barriers were effective at reducing wicking of water, but only when the downslope continuity of the geotextile was broken. In that case, there was 35 mm more water stored in the root zone profile at the top of the slope in the green constructed with barriers and a discontinuous geotextile compared with the greens constructed with barriers and continuous geotextile or with sand over gravel and no barriers.

Chronic dry spots often occur on the upper reaches of slopes on golf putting greens constructed with sand-based root zones, in part because water is quickly wicked downslope through the root zone after irrigation or rainfall. Lower water contents in dry spots are associated with higher matric (capillary) water tensions that generate increased stress in the turfgrass surface, leading to increased maintenance operations and costs such as those associated with frequent hand watering. Lower water contents also provide an environment favorable for development of water repellent solids in the root zone, a condition that reinforces the tenacious nature of dry spots (Ritsema et al., 2004; Wilkinson and Miller, 1978).

Because retention of water decreases with increases in matric water tension and matric water tension generally increases with elevation from the base of the root zone, one means to maintain consistent water content in the upper portion of the root zone on slopes is to decrease the depth of the root zone with distance upslope. Although this modification can be used successfully to increase near surface water content on slopes (Frank et al., 2005; Leinauer et al., 2001), the amount of water

stored in the profile decreases with distance upslope and to an even greater degree than on slopes without modification. To maintain consistent water content in the upper portion of the root zone while at the same time maintaining an adequate amount of water stored in the profile, water-holding amendments such as calcined clay may be added and varied with position on the slope or the particle size distribution of the sand in the root zone mixture may be varied with position on the slope. Although these latter modifications are effective (Bigelow et al., 2004; Li et al., 2008; Taylor et al., 1997), varying root zone composition with position on a sloping area appreciably complicates construction and increases cost of a putting green.

Because the upper portion of the root zone is unsaturated and the ability of the root zone to transmit water drops sharply as it becomes unsaturated (Campbell, 1974), most of the water that is wicked downslope passes through the lower, saturated of the root zone (or nearly saturated portion, depending on the amount of trapped gasses). Given such, a solution to help alleviate dry spots on slopes that would not rely on altering depth or composition of the root zone might be to insert subsurface barriers that run parallel with the contour in the lower portion of the root zone so as to interrupt slopewise capillary connectivity of the root zone. In concept, these capillary barriers would consist of a strip of impermeable metal or plastic sheet such as landscape edging that would extend vertically upward from the top of the drainage material through the saturated

bottom portion of the root zone. The saturated portion of the root zone is typically the bottom half of a U.S. Golf Association (USGA)-design green and there would not likely be a net benefit for the capillary barriers to extend much nearer the surface where they might interfere with management practices such as aeration and vertical mowing. The capillary barriers would act in a strictly passive manner to control water storage. The Purr-Wick design of near half a century ago (Daniel, 1978) was developed with some of the same concepts in mind as outlined here for the subsurface capillary barriers, but it involved cumbersome subsurface management of drainage water and therefore was not widely adopted.

The objective of this research was to evaluate the effectiveness of subsurface capillary barriers in controlling the amount of water stored in the root zone profile of a sloping portion of a putting green. We evaluated slopes on greens constructed in line with USGA recommendations (USGA Green Section Staff, 2004) and the Airfield Systems design (Airfield Systems, Oklahoma City, OK). The Airfield Systems-design green was evaluated because the saturated portion of the root zone after irrigation or rainfall is appreciably thicker than it is in the USGA-design green given the same root zone mixture (McInnes and Thomas, 2011).

Materials and Methods

A 3.5-m long $\times$ 0.41-m tall $\times$ 0.4-m wide box made from 20-mm thick plywood was constructed to hold a simulated sloping section of a putting green. The box was sealed with a water-resistant paint and supported on a steel frame that produced a lengthwise slope of $0.05 \text{ m} \cdot \text{m}^{-1}$ (5%). A slope of $0.05 \text{ m} \cdot \text{m}^{-1}$ is on the upper end of steepness for a putting green (Lemons, 2008). The ends of the box were vertical when the box was supported on the sloping steel frame. A 0.5-mm thick polyvinyl chloride (PVC) liner was used to cover the bottom and 0.1 m up the inside walls of the box. To simulate the root zone and drainage structure in a USGA-design putting green, the box was filled with 0.3 m of silica sand atop 0.1 m of river gravel. To simulate the Airfield Systems-design green, the box was filled with 0.3 m of sand atop a spunbond polyester geotextile supported by Airfield Systems' AirDrain, a 25-mm thick porous plastic grid. The bottom of the box contained a 20-mm wide cross-slope slot every 0.5 m that allowed collection of drainage flow from each 0.5-m long slopewise portion of sand. A cross-slope strip of 6-mm stainless steel mesh was used to prevent the gravel from falling through the drainage slots. Trays to collect the water from each 0.5-m portion of the sloping root zone were placed beneath the structure.

The sand used in the studies was obtained from U.S. Silica's plant in Kosse, TX, and had a particle size distribution, as determined by dry sieve analysis, that met USGA recommendations (Fig. 1). The sand had a saturated hydraulic conductivity (ASTM, 2006) of

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44 $\mu\text{m}\cdot\text{s}^{-1}$ (63 $\text{in}\cdot\text{h}^{-1}$). The gravel used for drainage met the USGA recommendation for particle size distribution and for bridging with the sand used in the study (Fig. 1). We did not add an amendment such as peatmoss to create a root zone mixture that had a water-holding capacity to meet the USGA recommendation. The geotextile was Type 097 Lutradur (Freudenberg Nonwovens, Durham, NC), a 350- μm thick spunbond polyester having an areal density of 130 $\text{g}\cdot\text{m}^{-2}$, an apparent opening size of 198 μm , and a water flux density of 0.157 $\text{m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 50 mm head pressure.

The relationship between water content of the sand and matric water tension in the sand was measured by segmenting and gravimetrically determining the water content of 0.7-m tall $\times$ 75-mm diameter columns (3-inch Schedule 40 PVC) of the sand that had been watered to excess of holding capacity and allowed to drain for 24 h after being covered with a plastic wrap to minimize evaporation (Fig. 2). The model of van Genuchten (1980) was fit to the water content–water tension data and then the cumulative depth of water D that would be stored in a root zone profile after drainage had stopped was calculated as

$$D = \int_{z_1}^{z_2} \theta(z) dz = \int_{h_{z_1}}^{h_{z_2}} \theta(h) dh, \quad [1]$$

where $\theta(z)$ is a function describing the distribution of soil water content between vertical locations z_1 (bottom) and z_2 (top) in the root zone profile, $\theta(h)$ is the functional relationship between volumetric water content and matric water tension (here approximated by the van Genuchten model), and h_{z_1} and h_{z_2} are the matric water tensions at vertical locations z_1 and z_2 , respectively. In our case, $z_2 - z_1 = 0.3$ m.

Sand was packed moist in the box to a dry bulk density of 1.58 $\text{Mg}\cdot\text{m}^{-3}$ over gravel. Then 0.3-m long, three-electrode time domain reflectometry (TDR) probes were installed vertically every 0.167 m beginning at a distance 0.11 m upslope from the lower end of the box. This arrangement of TDR probes was placed three in each of the 0.5-m contiguous portions of the slope (Fig. 3). The TDR probes were connected through coaxial multiplexers to a reflectometer (Model TDR 100; Campbell Scientific, Logan, UT). The reflectometer was connected to a data logger that was programmed to record data to allow determination of vertical-average volumetric water contents in the root zone profile along the slope. Water was applied to the sand with a handheld sprinkler until water was freely discharging from all drainage slits in the bottom of the test box. The box then was covered with a PVC sheet to minimize evaporative loss of water, and changes in the slopewise distribution of vertical-average volumetric water contents in the sand were monitored for 24 h using the TDR system. Depth of water stored in the profile was calculated as the product of vertical-average volumetric water content and the depth of the sand (0.3 m).

Fig. 1. Particle size distribution for the sand and gravel used in the study. The shaded area represents the U.S. Golf Association-recommended limits for the particle size distribution of sand for root zone mixture.

Fig. 2. Relationship between water content and matric water tension for the sand used in the study (use y-axis on the left). Error bars represent 1 sd on each side of the mean. The solid line represents a curve fit of the model of van Genuchten (1980) to the experimental data. The dashed line, derived from Eq. [1], represents the amount of water stored in 0.3 m of the sand used in the study with matric water tension at the bottom of the sand (use y-axis on the right).

Fig. 3. Schematic diagram of the top two 0.5-m sections of the U.S. Golf Association-design test box (sand over gravel) with the addition of capillary barriers.

After data were collected from the test box constructed with sand over gravel drainage, the sand was removed and then vertically oriented, 0.2-m tall, cross-slope barriers made of 3-mm thick polycarbonate sheet were placed such that the lower part of the barrier firmly

contacted the gravel. The barriers were sealed to the sides of the box with silicone caulk to prevent flow around the vertical edges. A barrier was placed just upslope of each horizontal slit in the bottom of the box (i.e., every 0.5 m), except for the slit at the low end of the

box. As was done without the barriers, moist sand was packed to a density of $1.58 \text{ Mg}\cdot\text{m}^{-3}$ in the box, TDR probes were installed, the sand was watered until water discharged from all drainage slits, the box was covered to minimize evaporative loss of water, and changes in the slopewise distribution of water storage in the sand root zone mixture system were monitored for 24 h. After monitoring and recording water storage with both treatments, the procedures were repeated twice to produce three replicates.

After completion of measurements on the sand over gravel treatments, the sand over geotextile atop AirDrain treatments were tested in the same manner and with the same number of replicates. When barriers were used, the lower part of the barrier was placed firmly in contact with the geotextile. After viewing the water storage data from the treatments having the geotextile atop AirDrain, an additional design that broke the downslope hydraulic continuity of the geotextile was investigated. In this case, segments of geotextile were installed so that they started 5 cm up the downslope sides of the barriers and stopped the same distance up the upslope side of a barrier. Installing the geotextile in this manner created short hydraulic discontinuities (gaps) in the geotextile beneath the barriers and kept the sand from washing out of those gaps.

Statistical significance of differences in the amount of water stored in the root zone profile between treatments was assessed using the Tukey honestly significant difference and *aov* statistical functions in R (R Development Core Team, 2009).

Results

Expectations. Eq. [1] can be used to predict the distribution of water storage D with position on the slope after drainage has stopped after irrigation or rainfall and the matric and gravitational water potentials are in equilibrium. For a 0.3-m deep root zone that meets the USGA recommendations for porosity and water retention, the rate of decrease in D with elevation with respect to the base of a slope (i.e., decrease in D with matric water tension) is relatively constant for the first 0.1-m change in elevation of the base of the root zone (i.e., change in matric water tension), here $-0.3 \text{ m}\cdot\text{m}^{-1}$ for the unamended sand (Fig. 2). Our observations (McInnes and Thomas, 2011) have shown that $\approx 50 \text{ mm}$ more matric water tension develops at the bottom of the root zone profile in a level USGA-design green than develops at the bottom of the root zone in a level AirField Systems-design green. Given this difference in tension and the observation that a level AirField Systems-design green develops $\approx 10 \text{ mm}$ matric water tension at the root zone geotextile interface (McInnes and Thomas, 2011), we would expect for the sand used that water storage D would be $\approx 15 \text{ mm}$ greater in the AirField Systems-design green compared with the USGA-design green at the base of the slope and that this difference would disappear by $\approx 4 \text{ m}$ up a $0.05\text{-m}\cdot\text{m}^{-1}$

Fig. 4. Expected relationships, derived from the data in Figure 2 and Eq. [1], between the amounts of water stored in 0.3-m deep root zones with position on a $0.05\text{-m}\cdot\text{m}^{-1}$ (5%) slope. Expected shapes of curves are shown for matric water tensions of 10 mm (representing the Airfield Systems-design green) and 60 mm (representing the U.S. Golf Association-design green) at the bottom of the root zone at the base of the slope. Also shown are expected effects of the capillary barriers on water storages.

slope (Fig. 4). The locations of the TDR probes on the extremities of the test slope we used were 0.11 m and 3.45 m measured from the base of the slope. Given the tensions that develop at the bottom of level root zones in the USGA-design and AirField Systems-design greens, the location of the TDR probes on the slope, and the $0.05\text{-m}\cdot\text{m}^{-1}$ slope, we would expect that the measured water storage in the profile to be $\approx 32 \text{ mm}$ and 44 mm less at the upper end of the slope than at the base for the USGA and AirField Systems designs, respectively. We would also expect that if capillary barriers were successful in preventing downslope wicking of water, then the difference of 15 mm stored water would persist in a sawtooth pattern with distance upslope (Fig. 4).

U.S. Golf Association design: sand over gravel. Without capillary barriers, water stopped draining from all but the slot at the base of the slope within 1 h of termination of water application to the surface. Water continued to drain from the bottom slot over the 24-h measurement period, but the rate decreased appreciably with time, and after 24 h, drops of water falling from the box were infrequent. The rapid rate and short duration of drainage were expected and were similar to those reported by Prettyman and McCoy (2002, 2003). Within the three replicates, between 37% and 50% of the water that drained from the box drained through the slot located at the base of the slope, whereas with seven equally spaced slots, 14% would have been an equal share. Obviously, the fraction of water that would drain from the base of the slope would depend on how much water was applied, but nonetheless, the large fraction found here draining from the base of the slope demonstrates how considerable downslope capillary wicking of water is to loss of stored water in upper reaches of a slope. After 24 h when drainage had nearly stopped, there was 34 mm less water stored in the profile at the upper end

of the slope compared with the base (32 mm was the expected difference). To add to the problem of reduced water storage, one also would expect from the relationship between water tension and water content (Fig. 2) that the fraction of stored water available to the turfgrass would decrease with distance upslope.

With capillary barriers in place, water drained for a longer period of time from each 0.5-m contiguous portion of root zone along the slope and the amount that drained from the base of the slope was not nearly as appreciable as without barriers. Viewing the temporal trend of water storage in the upper portion of the slope (Fig. 5), the potential for the use of the capillary barriers to prevent loss of water to downslope wicking was evident. Nearly the same amount of water was stored all along the slope (Fig. 6).

AirField Systems design; sand over geotextile atop AirDrain. Similar to the USGA-design green constructed without barriers, water stopped draining from all but the bottom cross-slope slot within 1 h of termination of water application to the surface of the AirField Systems-design green (Fig. 5). Within the three replicates, between 35% and 46% of the water that drained from the box drained through the slot located at the base of the slope. There was 44 mm less water stored in the profile at the upper end of the slope compared with the base (44 mm was the expected difference). With barriers in place and a continuous sheet of geotextile running downslope, little difference was observed in the dynamics of both drainage and water storage along the slope compared with that from the design without barriers (Fig. 5). Within the three replicates, between 33% and 38% of the water that drained from the box drained through the slot located at the base of the slope. The similarity in drainage and storage (Fig. 6) with and without the barriers was unexpected and showed that the geotextile atop AirDrain was nearly as efficient alone as it was

Fig. 5. Water stored in the root zone at the upper end of the test slope as a function of time after irrigation. Water stored is the average recorded from sensors located 3.12 and 3.28 m from the base of the slope.

Fig. 6. Water stored in the root zone 24 h after irrigation as a function of distance upslope for the five studied methods of constructing the slope of a putting green.

in combination with the sand in transporting water downslope. Because the conductance of the geotextile atop AirDrain operates in parallel with the conductance of the root zone in transmitting water downslope when capillary barriers are not present (albeit not independently), the conductance of the geotextile atop AirDrain must increase in the presence of the capillary barriers that prevent flow through the sand. This seems plausible because it is known that the conductance of a sloping geotextile increases with decreasing water tension (Stormont et al., 2001), and the barriers, if operating as expected, temporarily would cause water tension to be less at the bottom of the root zone. When the hydraulic continuity of the geotextile was broken beneath each barrier, water was not wicked downslope (Figs. 5 and 6), supporting the observation that the geotextile atop AirDrain was a hydraulically efficient capillary wick. In the small gap between sheets of geotextile, AirDrain alone was not effective at conducting water under tension.

Statistical analysis. There were no significant differences ($\alpha = 0.05$) in water storage

in the uppermost segment of the slope (3 to 3.5 m) 24 h after irrigation between the greens constructed with the following designs: USGA, AirField Systems, and AirField Systems with capillary barriers and continuous geotextile. There were significant differences ($\alpha = 0.05$) in water storage between all other combinations of the designs evaluated. In the lowest segment of the slope (0 to 0.5 m) there was a significant difference ($\alpha = 0.05$) in water storage between the AirField Systems and USGA designs, as was expected from the results of McInnes and Thomas (2011). In the standard designs, without capillary barriers, the AirField System design held 11 mm more water stored at the base of the slope than the USGA design. This difference in water storage was less than the predicted 15 mm, suggesting the difference in matric water tension at the bottom of the sand profile in the two designs was ≈ 40 mm, not 50 mm. The statistically significant difference in water storage disappeared by the top of the 3.5-m slope as predicted from the analysis summarized in Figure 4. With capillary barriers installed and the hydraulic continuity of the geotextile bro-

ken in the AirField design, the difference in water storage between the AirField Systems and USGA designs remained significant ($\alpha = 0.05$) along the slope.

Discussion

From the results of this laboratory study, it seems that subsurface barriers could effectively be used to reduce the severity of dry spots caused by downslope wicking of water. Downslope wicking of water is not the only cause of dry spots, however, and use of capillary barriers would not be a cure-all for the problem. It would be prudent to conduct small-scale tests on actual putting greens before investing in the method. With USGA-design greens, barriers could be installed in existing greens where known problems exist or they could be installed during construction of a new green as a preventive measure. With an AirField Systems-design green, barriers would need to be installed during construction of a green so that the geotextile could be installed in a manner to create capillary discontinuities in the geotextile at the barriers. Subsurface barriers also would likely be effective on slopes in a University of California-design green (Davis et al., 1990), but an answer to the question of how to allow adequate drainage of salts would have to be given adequate attention.

For the purpose of demonstrating the effectiveness of the barriers, we used an extreme golf green slope of $0.05 \text{ m}\cdot\text{m}^{-1}$ and spaced the barriers every 0.5 m. Although the barriers would be most effective on steep slopes such as we evaluated, they most likely would be effective on putting greens with much gentler slopes. For sand-based root zone mixtures that meet all USGA recommendations for physical properties, the loss in stored water in the profile with increasing matric water tension at the bottom of the root zone is usually between 0.2 and $0.3 \text{ m}\cdot\text{m}^{-1}$. On a slope of $0.02 \text{ m}\cdot\text{m}^{-1}$ (2%) for every 1-m distance upslope from the base, between 4 and 6 mm water would be lost to downslope wicking. The rate of decrease in water stored in the profile with matric water tension for the unamended sand that we used here was $-0.3 \text{ m}\cdot\text{m}^{-1}$, on the high side of what would be expected for root zones that meet all USGA recommendations. With the same sand, but that had been amended with 10% peatmoss by volume to meet USGA recommendation for water retention, McInnes and Thomas (2011) found the rate of loss to be $0.23 \text{ m}\cdot\text{m}^{-1}$. With this lower rate of decrease, a 30% longer slope would be required to produce the same decrease in stored water. Had the amended sand been used and the barriers been spaced 30% further apart, the spatial patterns in water storage likely would have been very similar. We chose to use 200-mm deep barriers, but less deep barriers likely would be effective for most root zones. Because there are infinite combinations of slopes, hydraulic properties of root zones, and environmental conditions, giving a specific recommendation on spacing and height of barrier is not

possible. The simulation model HYDRUS-2D (Simunek et al., 1999) that McCoy and McCoy (2009) used to evaluate the drainage dynamics of putting greens would seem to be an ideal tool to answer the question of spacing and depth of barrier for a particular situation.

Literature Cited

- ASTM. 2006. Standard test methods for saturated hydraulic conductivity, water retention, porosity, and bulk density of putting green and sports turf root zones. F1815-06. ASTM International, West Conshohocken, PA.
- Bigelow, C.A., D.C. Bowman, and D.K. Cassel. 2004. Physical properties of three sand size classes amended with inorganic materials or sphagnum peat moss for putting green root-zones. *Crop Sci.* 44:900–907.
- Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Sci.* 117:311–314.
- Daniel, W.H. 1978. PURR-WICK rootzone system for turf. *Midwest Turf News and Res. Bull.* 40:1–4.
- Davis, W.B., J.L. Paul, and D. Bowman. 1990. The sand putting green: Construction and management. Publ. 21448. Univ. of California Div. of Agric. and Nat. Resour., Davis, CA.
- Frank, K.W., B.E. Leach, J.R. Crum, P.E. Rieke, B.R. Leinauer, T.A. Nikolai, and R.N. Calhoun. 2005. The effects of a variable depth rootzone on soil moisture in a sloped USGA putting green. *Intl. Turfgrass Soc. Res. J.* 10:1060–1066.
- Leinauer, B., P. Rieke, and J. Crum. 2001. Retaining moisture in USGA putting greens. *Golf Course Mgt.* 69:65–69.
- Lemons, J. 2008. Putting green speeds, slopes, and ‘non-conforming’ hole locations. *USGA Green Section Record* (July/August):21–25.
- Li, D., D.D. Minner, and N.E. Christians. 2008. Managing isolated dry spot by topdressing inorganic amendments on a sloped golf green. *Acta Hort.* 783:341–348.
- McCoy, E.L. and K.R. McCoy. 2009. Simulation of putting-green soil water dynamics: Implications for turfgrass water use. *Agr. Water Mgt.* 96:405–414.
- McInnes, K.J. and J.C. Thomas. 2011. Water storage in putting greens constructed with United States Golf Association and Airfield Systems designs. *Crop Sci.* 51:1261–1267.
- Prettyman, G.W. and E.L. McCoy. 2002. Effect of profile layering, root zone texture, and slope on putting green drainage rates. *Agron. J.* 94:358–364.
- Prettyman, G.W. and E.L. McCoy. 2003. Profile layering, root zone permeability, and slope affect on soil water content during putting green drainage. *Crop Sci.* 43:985–994.
- R Development Core Team. 2009R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Ritsema, C.J., L.W. Dekker, J. van Dam, and K. Oostindie. 2004. Principles of flow and transport in turfgrass profiles, and consequences for management. *Acta Hort.* 661:137–144.
- Simunek, J., M. Sejna, and M.Th. van Genuchten. 1999. The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat, and multiple solutes in variably-saturated media. In: IGWMC-TPS 53, Version 2.0. International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.
- Stormont, J.C., C. Ray, and T.M. Evans. 2001. Transmissivity of a nonwoven polypropylene geotextile under suction. *Geotech. Test J.* 24: 164–171.
- Taylor, D.H., C.F. Williams, and S.D. Nelson. 1997. Water retention in root-zone soil mixtures of layered profiles used for sports turf. *HortScience* 32:82–85.
- Green Section Staff, U.S.G.A. 2004. USGA recommendations for a method of putting green construction. *USGA Green Section Record* 31: 1–3.
- van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Amer. J.* 44: 892–898.
- Wilkinson, J.F. and R.H. Miller. 1978. Investigation and treatment of localized dry spots on sand golf greens. *Agron. J.* 70:299–304.