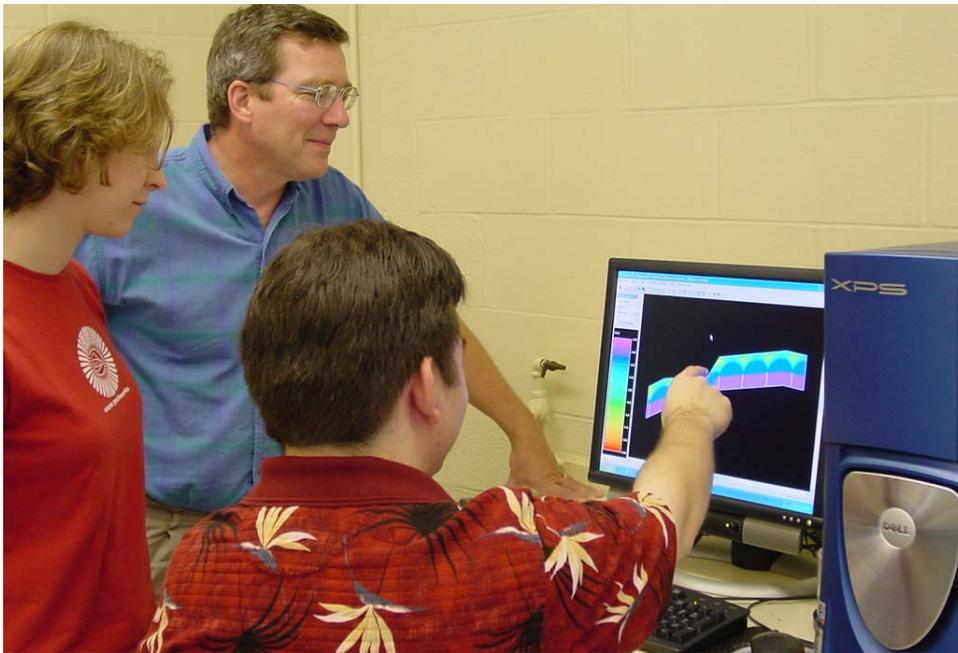




# *Turfgrass and Environmental Research Online*

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...Using Science to Benefit Golf



Scientists at The Ohio State University used computer simulations to describe water movement in putting greens constructed by three different methods: USGA recommended, California, and natural soil push-up. These simulations provide an excellent understanding of how different putting green construction methods affect water movement.

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## PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 290 projects at a cost of \$25 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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# Dynamics of Water Flow in Putting Greens via Computer Simulation

Ed McCoy and Kevin McCoy

## SUMMARY

Computer simulations of soil water flow were constructed for a USGA, California, and push-up putting green using HYDRUS-2D. The simulations generated animations of soil water content over a seven-day period for full-size greens having natural surface contours and supporting a closely mown turfgrass stand. Also generated was drainage rate and actual turfgrass evapotranspiration ( $ET_a$ ). Rainfall and evapotranspiration scenarios were selected to challenge the hydrologic response of these three putting greens and a turfgrass response protocol allowed the appraisal of water related turfgrass stress.

- The simulations demonstrate the utility of deeper rootzone, as seen in the USGA and California greens, in providing a direct connection with subsurface drainage elements and displacing perched water below turfgrass rooting.

- Alternatively, the shallow rootzone of the push-up green quickly became saturated during rain and remained nearly so for 42 hours, leading to aeration stress of the turf.

- During rain, the thickness of water perching was self-limited in the USGA green but continued to expand, forming a pattern relative to drainage spacing, in the California green.

- The simulations show that perched water can form in both USGA and California greens and, in both greens, may serve as a reservoir for subsequent water uptake by the turf. This perched water was, however, locally short-lived in both greens as down slope lateral flow removed it from the crest of steeper slopes within each green.

- The first appearance of drought stress was associated with the local absence of water perching in both the USGA and California greens, and appeared earlier in the California green due to the lesser water holding capacity of the rootzone.

Putting green soil profiles are frequently classified into three general categories: USGA, California, and push-up style greens. The USGA and California profiles are purposely constructed

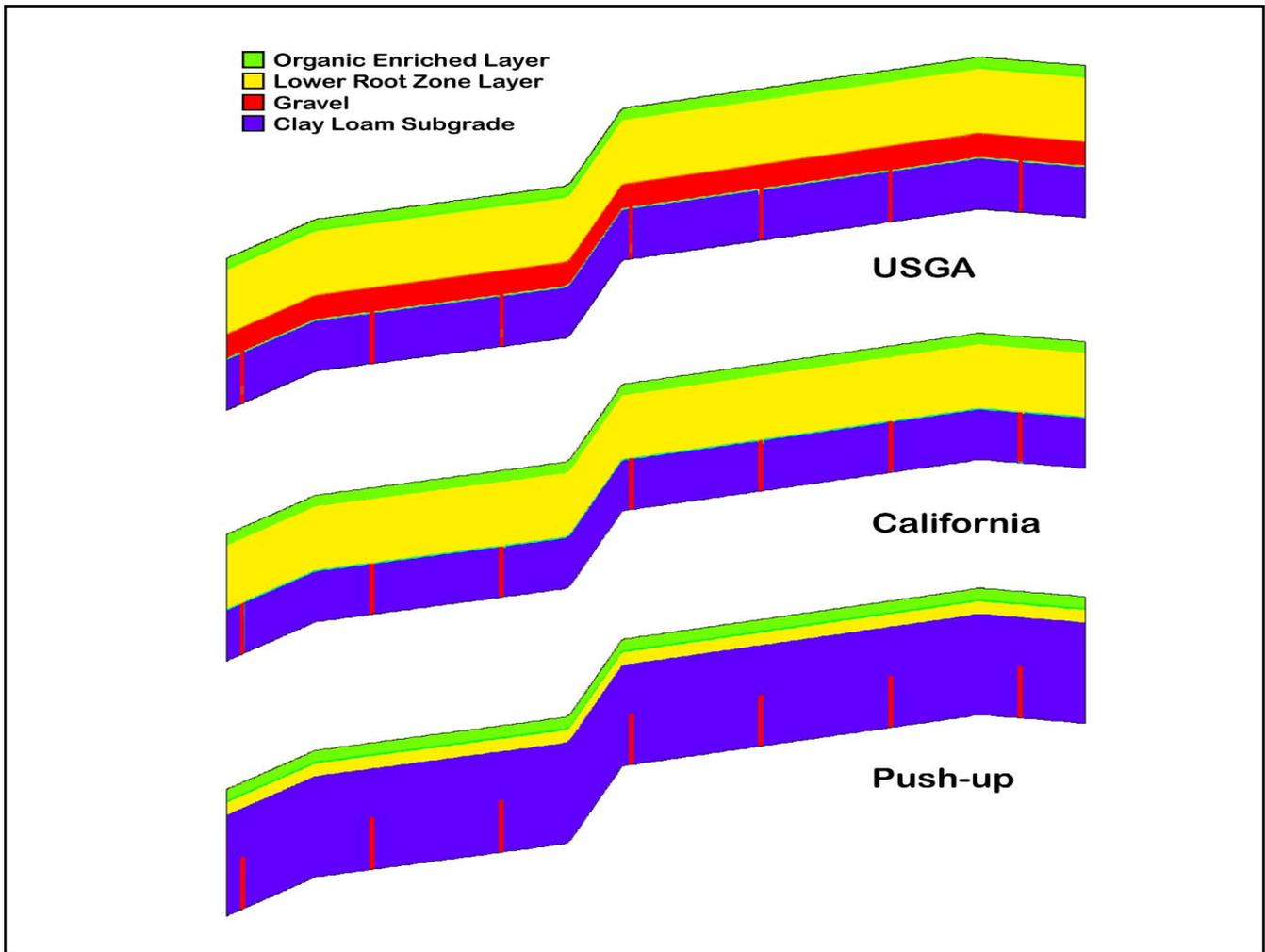
with each documented by written guidelines (2, 10). On the other hand, push-up green soil profiles have evolved from decades of sand topdressing applied to native soil. Whereas each has a sandy surface layer, or rootzone, the thickness of this layer and the type of material underlying the sandy rootzone varies for each particular construction method.

There has long been an interest in how rootzone properties and soil material layering influence water flow within contoured putting greens. Measurement of this water flow is often accomplished by frequent monitoring soil water content using probes that are placed in the soil profile (4, 7, 8). By examining the time sequence of water contents following rainfall, irrigation, or turf water uptake, the rate and direction of water flow can be inferred from water content changes. These studies have directly documented how layered soils increase water retention within a sandy rootzone by the formation of perched water, the



Organic enriched layers that form within the surface of putting green rootzones have hydraulic properties much different than the lower rootzone layer.

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**Figure 1.** Soil profile layers used in the water flow simulation for a USGA, California and push-up green. In addition to layer thickness, the hydraulic properties of the organic enriched and lower rootzone layers were different for each simulation and are given in Table 1. This view shows a 10-fold exaggeration of the vertical scale.

propensity of this water to migrate down slope creating lateral non-uniform water contents, and how organic and soil amendments in the rootzone appear to modulate this response.

Experimental studies of water flow in greens, however, have limitations due to the high cost of construction, maintenance, instrumentation, and monitoring. Consequently, these studies have employed less than full-size greens with relatively few sensors that capture data over widely spaced time intervals and/or for a limited duration. The result is a somewhat incomplete picture that can miss a specific water flow process and/or generate findings that only relate to the climate at the study location. Also, experimental studies inevitably contain errors and require statistical analysis for proper interpretation of the results. Use

of statistical techniques substantially adds to experimental costs due to the need for replication and the possible inclusion of nonsensical treatments in order to isolate specific factors

Computer simulation of water flow in soils can remove many of these experimental limitations. A simulation can be built to represent a full-size putting green and capture flow events throughout the soil profile. Also, a simulation allows us to challenge the system under climatic scenarios that rarely occur at a specific location. And because simulations do not generate random errors, they need not be replicated. Yet the quality of a simulation output is solely reliant on the quality of the parameters used to describe the system. Much care must be taken in specifying the values for these parameters.

The objective of this study was to generate realistic simulations of water flow in USGA, California, and push-up style putting greens. For this we chose the software package HYDRUS-2D (9), which has been employed for a variety of applications including irrigation and drainage design, study of irrigated land salinization, transport of pesticides and toxic trace elements, and analyses of riparian systems (11). We sought to construct simulations for mature, full-size greens having natural surface contours, built according to published guidelines, and supporting a closely mown turfgrass stand. Rainfall and evapotranspiration scenarios were selected to challenge the hydrologic response of these three putting greens.

### The Putting Green Soil Profiles

The simulations were designed to describe water flow through a two-dimensional slice through the center of a typical putting green. To accomplish this, we enlisted to help of Mr. Jason Straka, ASGCA, Senior Design Associate with Hurdzan/Fry Design, Inc., who provided putting green surface elevation data along a 100-ft transect. The respective soil profiles corresponding to a USGA green, a California green, and a push-up

green were subsequently created below this surface. In each case, the putting surface consists of a 10-ft false front at 5% slope, a 30-ft lower landing area at 1.5% slope, a 6-ft terrace face at 15% slope, a 41-ft upper landing area at 1.5% slope, and a 13-ft section falling away off the back of the green at 1% slope. Smooth curve transitions also occurred between each of these surfaces and the total elevation change across the green was 2.5 ft.

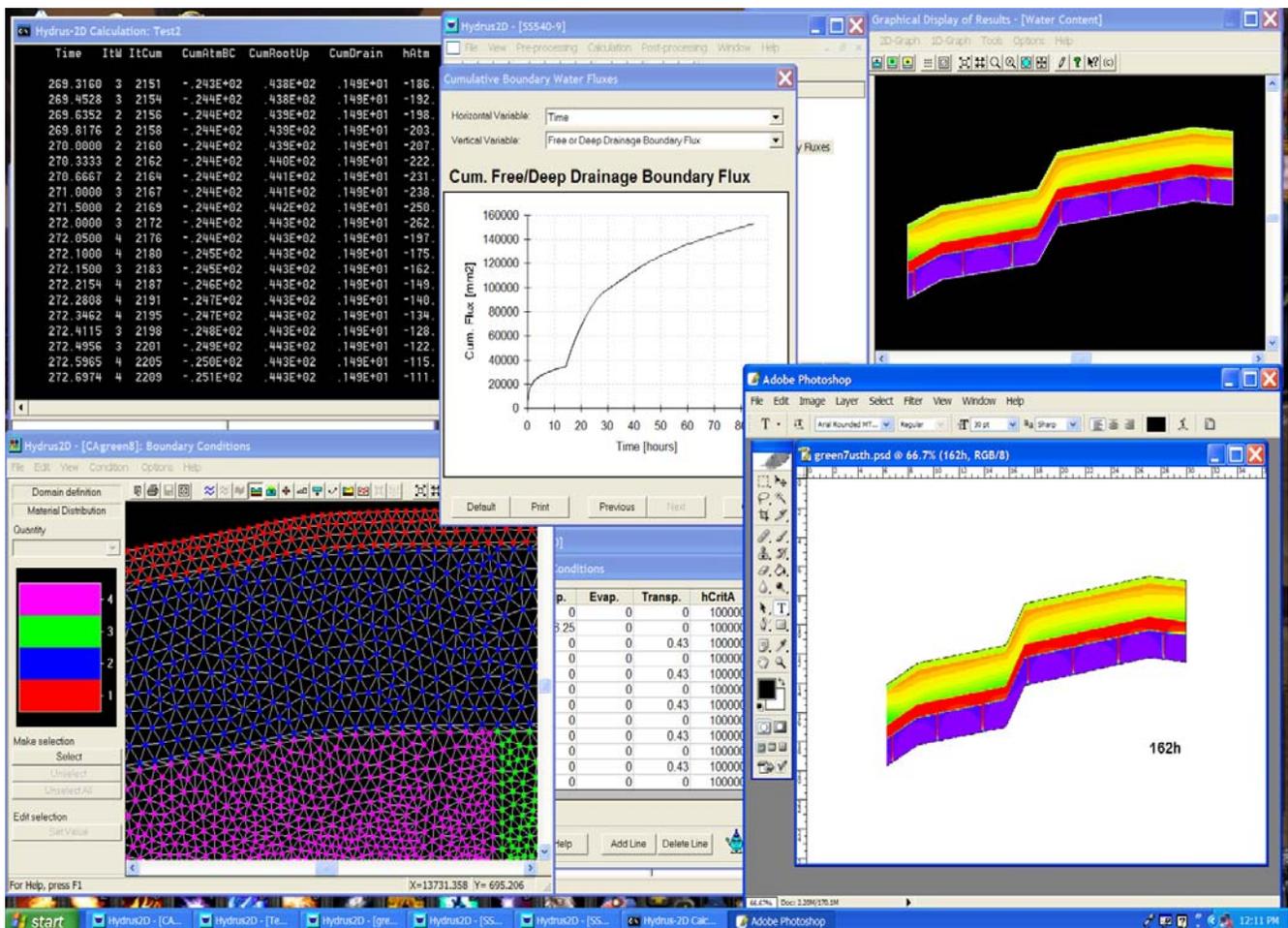
The USGA green soil profile (Figure 1) consisted of a 12-inch thick rootzone overlying a 4-inch thick gravel layer placed upon an 8-inch thick clay loam subgrade soil. Gravel-filled drainage trenches (6-inches wide by 8-inches deep) were placed in the subgrade and spaced 15 feet apart. To represent the influence of turf rooting and organic matter accumulation within the surface layer of the rootzone (1), this 12-inch layer was further subdivided into to a surface, a 2-inch thick organic enriched layer, and a 10-inch thick lower rootzone layer.

The California green soil profile (Figure 1) consisted of a 12-inch thick rootzone overlying an 8-inch thick clay loam subgrade soil. Gravel-filled drainage trenches (6-inches wide by 8-inches deep) were placed in the subgrade and spaced 15 feet apart. Although maximum drain spacing is

Green Construction	Layer	Total Porosity	Air-Filled † Porosity	Capillary † Porosity	$K_{sat}$
		(%)	(%)	(%)	(in $h^{-1}$ )
USGA	Organic Enriched ‡	46	20	26	6
	Lower Rootzone	40	24	16	20
California	Organic Enriched	45	22	23	12
	Lower Rootzone	39	27	11	40
Push-up	Organic Enriched	46	12	34	4
	Lower Rootzone	42	14	28	8

† Air-filled and capillary porosities are defined at 30 cm tension.  
‡ The organic enriched layer is the surface 2 inches of the soil profile.

**Table 1.** Total porosity, air-filled porosity, capillary porosity, and saturated hydraulic conductivity values of the organic enriched and lower rootzone layers of the simulated putting greens



A montage of windows is shown to illustrate the steps in the simulation and animation process. The soil profile cross section is divided into thousands of discrete nodes each of which are assigned to the appropriate soil material (lower left). Hydraulic properties are assigned to these nodes, and an environmental scenario is created (lower center). The simulation is run to create an enormous amount of numerical data (upper left). This data is assembled via a separate graphics program (upper center and right). Individual time slices of the color plots are assembled into animations by another program (lower right).

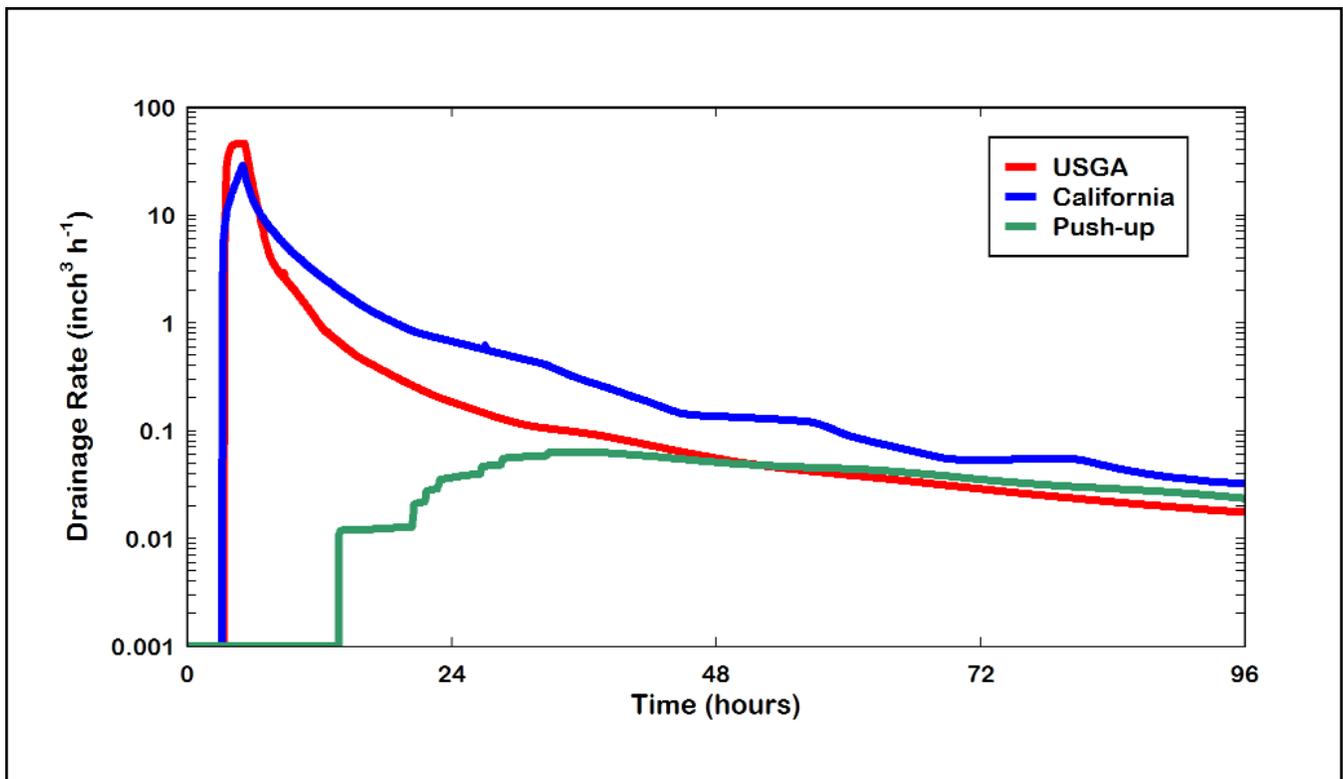
not specified for a California green, we chose this drainage system configuration to be consistent with the USGA green scenario. Also, consistent with the USGA green, the 12-inch rootzone was subdivided into to a surface, a 2-inch thick organic enriched layer, and a 10-inch thick lower rootzone layer.

The push-up green soil profile (Figure 1) consisted of a 4-inch thick rootzone overlying a 16-inch thick clay loam soil. For consistency with the other green designs, 6-inch wide by 8-inch deep gravel-filled drainage trenches were spaced 15 feet apart across the green with the upper surface of the drainage trench placed 10 inches below the surface of the green. As with the other scenarios, the 4-inch rootzone was subdivided into to a

surface, a 2-inch thick organic enriched layer, and a 2-inch thick lower rootzone layer.

### Rootzone Properties

In addition to soil layer thickness and orientation, the water flow simulation requires information on the hydraulic properties of each layer. Specifically, this information consists of parameters of the water retention curve and the saturated hydraulic conductivity. Our intention in this work was to simulate water flow within greens that adhered to the respective guidelines (when available) but also placed more emphasis on water transmission than on water retention. In other words, our aim was to generate hydraulic proper-



**Figure 2.** The rates of water drainage ( $\text{inch}^3 \text{h}^{-1}$ ) over the first four days of the simulation for the USGA, California, and push-up greens. Drainage resulted from a  $1 \text{ inch h}^{-1}$  rainfall rate from hours 1 to 5 for the USGA and California greens and from a  $0.25 \text{ inch h}^{-1}$  rainfall rate over the same interval for the push-up green.

ties that corresponded to a rootzone having sand particle sizes on the coarse side of the acceptable range. We did this for the lower rootzone layer of the USGA and California greens by generating hydraulic properties of a construction rootzone mix since the lower rootzone layer of a mature green is expected to have hydraulic properties similar to the rootzone mix of a newly built green (Dr. Norm Hummel and Mr. James Thomas, personal communication). The organic enriched layer for each green was intended to contain about 6% organic matter (by weight). Thus, the construction rootzone mix properties for each green were adjusted as to appropriately reflect this organic enrichment.

Finally, in order to supply the most realistic information to the simulation, we generated candidate hydraulic properties from in-house data and then provided this information to Dr. Norm Hummel (Hummel & Co. Inc.) and Mr. James Thomas (Thomas Turf Services, Inc.) for a critical review. Following their review, we adjusted the

hydraulic properties of both the organic enriched and lower rootzone layers as appropriate. Our approach to generating hydraulic properties of the push-up green rootzone was similar to that for the USGA and California greens but was more subjective because there are no published descriptions of the most prevalent rootzone characteristics.

The hydraulic properties of the rootzone layers for the USGA, California, and push-up greens are given in Table 1. The USGA green rootzone had hydraulic properties characteristic of minimally amended and fairly uniform medium-coarse sand. This is indicated by small total and capillary porosity values and large  $K_{\text{sat}}$  and air-filled porosity values, when compared to recommended USGA guidelines. The California green rootzone had hydraulic properties characteristic of unamended and uniform medium sand with greater  $K_{\text{sat}}$  and air-filled porosity values and smaller total and capillary porosity values than the USGA rootzone. The push-up green rootzone had



Contoured surfaces found on most putting greens are an important feature that was considered in this analysis.

hydraulic properties as would be expected from years of consistent and frequent topdressing using quality topdressing sand.

In all cases, organic enrichment resulted in an increase in total and capillary porosity values and a reduction in air-filled porosity and  $K_{sat}$  values. Finally, the clay loam subgrade had a  $K_{sat}$  value of  $0.02 \text{ in h}^{-1}$  and the gravel had a  $K_{sat}$  value of  $4700 \text{ in h}^{-1}$  characteristic of these respective materials.

### **Turfgrass Rooting and Response Protocols**

A powerful feature of HYDRUS 2D is the ability to include in the simulation a plant that is capable of responding to the soil water status. In this particular case study we included the best available information corresponding to a closely mown turfgrass species. This included specifying the distribution of turfgrass rooting and indicating at what soil water status the turf would suffer water-related stress.

The turfgrass rooting information consisted of specifying the proportion of the total root system that occurs within selected depth increments. To isolate soil profile and rootzone property responses in this work, we chose to employ an identical rooting pattern for each of the three

greens. In each case, 50% of the roots were present in the 0- to 1-inch increment, 32.5% in the 1- to 2-inch increment, 10% in the 2- to 4-inch increment, 5% in the 4- to 5-inch increment, and 2.5% in the 5- to 6-inch increment. No roots were present below 6 inches depth and this same pattern was employed across the entire green surface.

In HYDRUS, drought stress is simulated by the inability of turf roots to take up soil water when the water content surrounding the root is less than some specified value. In this work, we chose a water content of 10% (by volume) as indicating the onset of reduced root water uptake. This is consistent with our field studies (5) wherein "footprinting" on experimental greens was observed to occur at this level of soil water content. Further, as the local water content falls below 10% (by volume), root water uptake is progressively reduced.

HYDRUS is also capable of simulating soil aeration stress on the root wherein water uptake is limited via inadequate local air-filled porosity (defined as total porosity minus the local water content). Another term for aeration stress is "wet wilt" as defined by Dernoeden (3). In this study, wet wilt occurred when the local air-filled porosity was 10% (by volume) and water uptake was progressively reduced as air-filled porosity declined below this value.

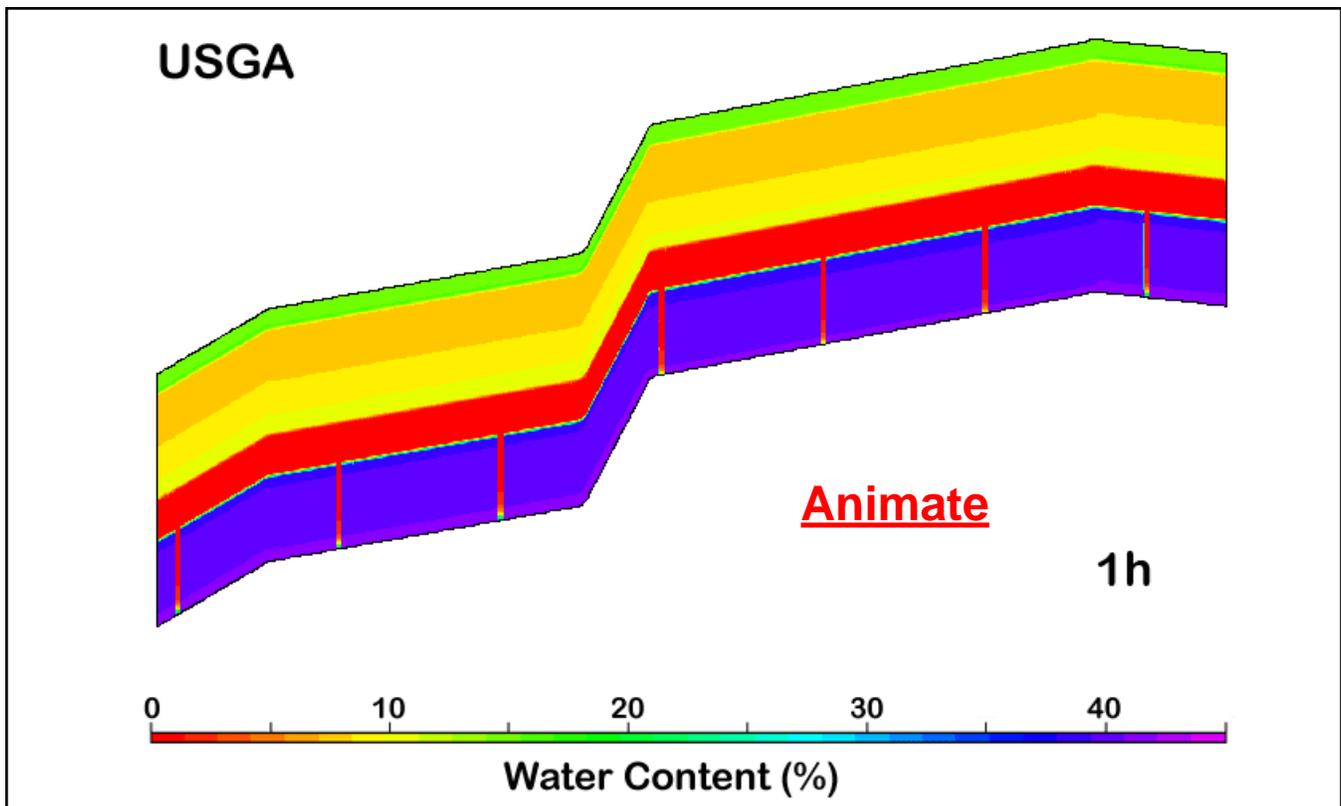
## The Simulation Scenario

The simulation runs for 168 hours, beginning at 12:00 am and continuing for seven days. Initially (at hour 0), the soil profile is moist with equilibrium water contents corresponding to the presence of a water table 0.5 inches below the drainage trenches. At hour 1 rainfall occurs across the USGA and California greens at a precipitation rate of  $1.0 \text{ inch h}^{-1}$  and continuing for four hours. This high intensity rainfall delivering four inches of rain was selected to challenge the infiltration and drainage capabilities of each green. Because the push-up green was incapable of infiltrating four inches of rain, the precipitation rate for this scenario was adjusted down to  $0.25 \text{ inch h}^{-1}$  yielding one inch of total rainfall. No additional precipitation or irrigation occurred on any of the greens after this initial event.

Subsequently, a diurnal evapotranspiration cycle was imposed on these greens and consisted of an atmospheric demand of  $0.014 \text{ inch h}^{-1}$

between the hours of 8:00 am and 8:00 pm with no water uptake during the intervening hours. This hourly ET rate over a 12-hour daylight period yielded a daily atmospheric demand (referred to as  $ET_{\text{crop}}$ ) of 0.17 inches of water.

Our choice of this value was based on the work of McCoy and McCoy (5) wherein daily  $ET_{\text{crop}}$  values corresponding to putting green turf were generated for a 20-year period at each of six locations throughout the US. Examining the distribution of the April-September daily  $ET_{\text{crop}}$  values from this previous study indicated that our selected rate of  $0.17 \text{ inch day}^{-1}$  was about one standard deviation greater than the mean for Phoenix, AZ, two standard deviations greater than the mean for Boulder, CO, and three standard deviations greater than the mean for Columbus, OH. So our selected  $ET_{\text{crop}}$  value represents a moderately above-average drying event for Phoenix, and somewhat extreme drying event for Boulder, and a severely extreme drying event for Columbus.



**Animation 1.** Water content (% by volume) within the soil profile of a USGA putting green over a period of 162 hours. Rainfall occurs from hour 1 to 5 and a diurnal ET cycle occurs throughout the seven days of the simulation. The vertical dimension is exaggerated 10-fold for the 100-ft long by 2-ft deep slice through the green.

This was consistent with our goal to challenge the water retention properties of the simulated greens.

Having supplied all required data for the problem, each seven-day simulation was run on a 3.4 GHz personal computer, requiring a run time of about eight days and generating about 180 Mb of data. Output from the simulation includes volumetric soil water content, drainage rate, and actual turfgrass evapotranspiration ( $ET_a$ ) over seven days. The water content values are generated for all soil depth and lateral distance values included in the problem (e.g. the entire area of Figure 1).

The drainage rate values are the total for seven drainage trenches and the  $ET_a$  values are the integrated response across the green surface. It is important to note that the  $ET_a$  values are the actual turfgrass evapotranspiration rates in response to an atmospheric demand. As such, if any portion of the root system is exposed to limiting water content or air-filled porosity values this will reflect drought or aeration stress and the  $ET_a$  values as generated by the simulation will be less than the 0.014 inch  $h^{-1}$  atmospheric demand used in the simulation.

## Results

### Water Flow and Drainage in the USGA Green

A time sequence of volumetric soil water contents within the USGA green soil profile is shown in Animation 1. In this view, the colored area is the entire soil profile of this simulation and water contents within this soil profile are shown by a color scale. The time slices are spaced at 0.5 hours during the early phases of the animation and progressively increase to 12 hours at the end of the animation.

The first time slice of this animation is coincident with the start of the rainstorm, so subsequent time slices (from 1.5 to 5 hours) show water infiltration into the soil. Also shown is the accumulation of perched water above the interface between the lower rootzone and gravel layers

(from 3 to 3.5 hours). The upper surface of the perched water zone occurs at the interface between green and blue, or at water contents of about 27% (by volume). This perched water, however, accumulates only to a limited extent in a USGA green so that the continued rainfall (from 3.5 to 5 hours) simply displaces an equivalent volume of water into the gravel layer. This implies that if the 1 inch  $h^{-1}$  rain rate were to continue indefinitely, there would be no further accumulation of water within the soil profile and an equivalent volume of water would just as rapidly be drained from the soil.

Water flow through the gravel starting at 3.5 hours is evident by the large water content values within the gravel layer just above the interface with the subgrade. This distribution of water within the gravel layer reaches its maximum extent at four hours with the characteristic pattern of lower water contents adjacent to the drainage trenches and (within the flat reaches) higher water contents in between. This pattern remains stationary during the final hour of rain indicating a steady rate of water flow from the gravel into the drain. Finally, during the rain period, the subgrade transitions from very wet to nearly saturated.

Although there is a slight decline in rootzone water contents during the hour following the rain, the results clearly show the establishment of a uniformly thick perched water layer from hours six to 12. This perched water layer appears to be only about three inches thick, characteristic of the lesser water retaining rootzone employed in this simulation. If the simulation were to have used a rootzone mix with smaller air-filled porosity values and greater capillary porosity values, this would have resulted in a thicker perched water layer. The uniformity of water perching across the green is, however, rather short-lived as down slope, lateral water flow in the more steeply sloped sections removes the perched water from the crest of these slopes. This becomes apparent at 24 hours as evidenced by lower water contents above the rootzone/gravel interface at the crest of the terrace face and, to a lesser degree, at the high point of the green and the crest of the false front. Down slope lateral water flow in sloped, USGA



The results of these simulations show how rootzone properties, the soil profile and surface contouring interact to influence irrigation requirements.

greens has been experimentally observed by both Prettyman and McCoy (7) and Frank et al. (4).

After 24 hours, lateral flow has substantially slowed so that for the remaining hours of the simulation (from 24 to 162 hours) the rootzone simply becomes progressively drier due to water uptake by the turf. It is interesting to observe during this period that the organic-enriched layer maintains greater water contents than the adjacent portion of the lower rootzone. This is because the soil of the organic enriched layer has greater water holding properties than the lower rootzone layer (Table 1). Also the progression of drying appears to be independent of rootzone depth. This is interesting in that water uptake is shown to occur in the 6- to 12- inch depth increment even though roots were not present below six inches. Seemingly, the water retained at these deeper depths was adequately "wicked" nearer the surface and taken up by the roots. Consequently, perched water occurring from 9- to 12-inches deep can apparently serve as a reservoir for subsequent turf uptake in these systems.

Viewing the progression of drying across the green, however, shows more intense rootzone drying in regions of the green where the perched water was removed at 24 hours. Thus, the crest of the terrace slope, the high point of the green, and the crest of the false front all show more extreme

drying throughout the rootzone than other areas of the green. This is consistent with experimental observation of putting green slope effects on rootzone water content by Prettyman and McCoy (8) and Frank et al. (4).

Drainage in the USGA green began a 3.4 hours and within one hour increased to its maximum rate of  $45.8 \text{ inch}^3 \text{ h}^{-1}$ , for a 1-inch thick slice through the green (Figure 2). This rate remained steady till 15 minutes after rain stopped when the drainage rate decreased, rapidly at first and then more slowly. Twelve hours after rain ended, the drainage rate had decreased by over two orders of magnitude. In the USGA green, the maximum drainage rate was comparable to the rainfall rate across the green such that had this rain rate continued indefinitely, water ponding on the surface and runoff would have never occurred.

### **Water Flow and Drainage in the California Green**

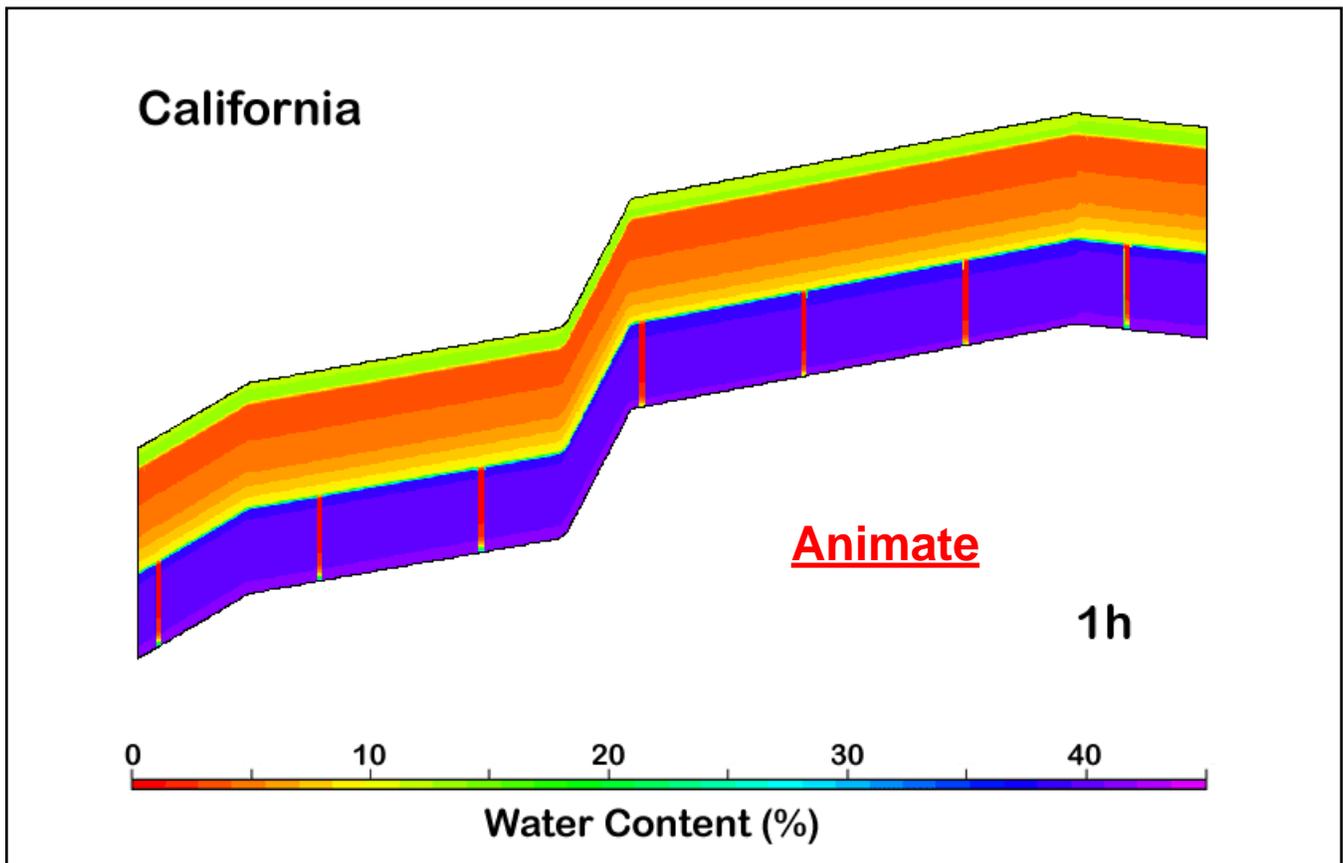
The time sequence of volumetric soil water contents within the California green soil profile, shown in Animation 2, employs the same layout and time slices as the USGA green. Early in the simulation, as with the USGA green, water

infiltration results in the formation of perched water, in this case occurring above the rootzone/subgrade interface. Unlike the USGA green, however, continued rain results in the perched water zone progressively approaching the soil surface till at the end of the rain the soil is nearly saturated to the surface. This progressive wetting of the rootzone, however, does not occur uniformly across the green but mostly forms a pattern relative to the gravel-filled drainage trenches. In this case, water perching approaches the green surface mid-way between the drainage trenches yet remains deeper over the trench.

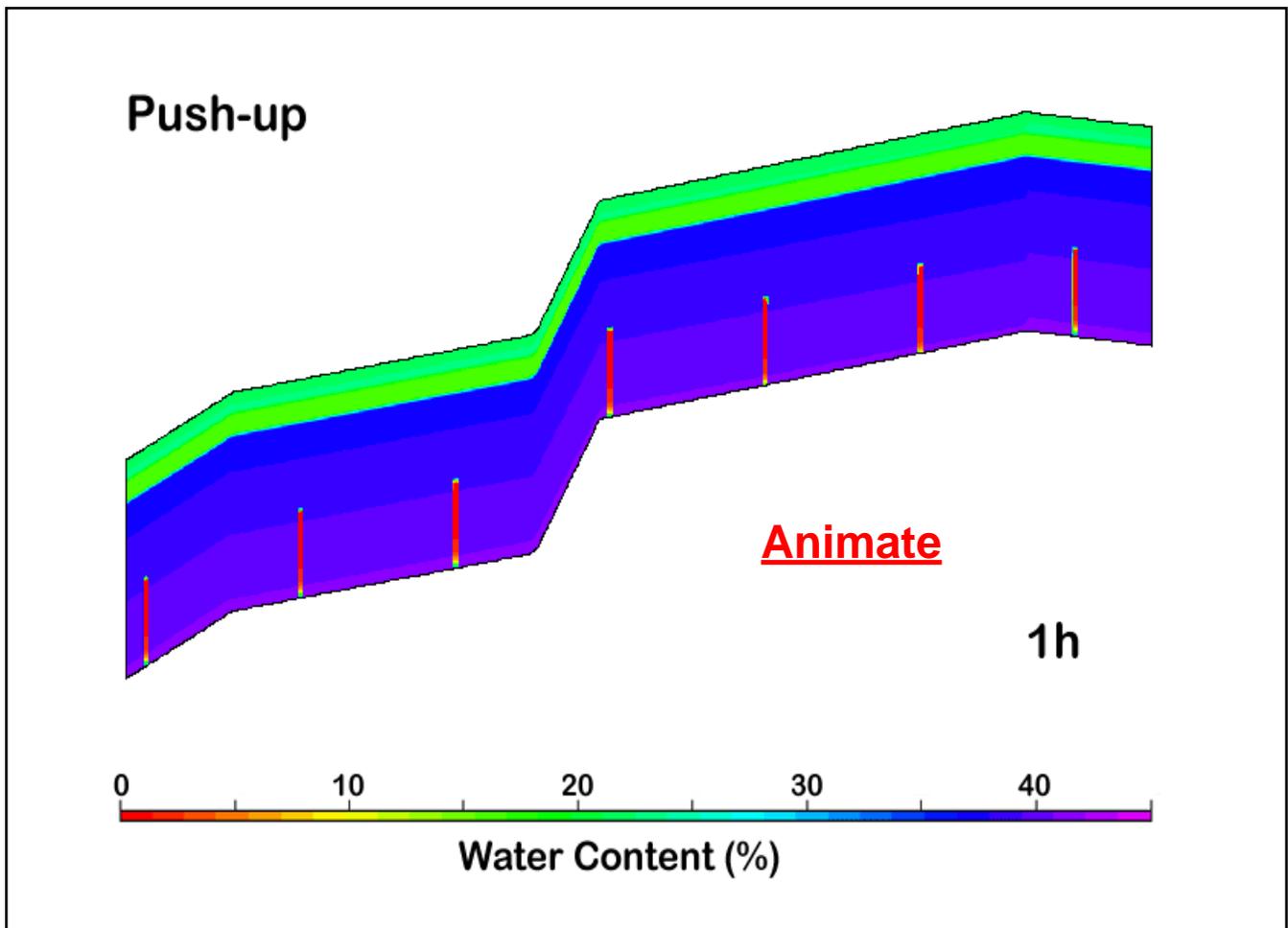
A lateral pattern of water contents coincident with drainage trenches in a California-style green was also observed experimentally by Prettyman and McCoy (7). This pattern forms because a California green lacks a gravel layer underlying the rootzone so that water must travel laterally rather long distances through the rootzone before entering a drainage trench.

Following the rain, however, the zone of perched water recedes rapidly at first and then more slowly so that by 30 hours, the drain trench-induced pattern has disappeared and the perched water zone has a thickness of about three inches distributed somewhat uniformly across the green. The exception to this is the absence of perching at the crest of the terrace face and a 5-inch thick perched water zone at the base of the terrace face.

For the remaining hours of the simulation (from 30 to 162 hours) the rootzone simply becomes progressively drier due to water uptake by the turf. During this period, the dynamics of water flow in the California green is similar to that seen in the USGA green. The principal difference between these simulations is that the upper 6 inches of the California green is much drier for the same time slice than the USGA green. This is due to the smaller capillary porosity values and reduced water retention of the California rootzone sand as compared with the USGA rootzone mix.



**Animation 2.** Water content (% by volume) within the soil profile of a California putting green over a period of 162 hours. Rainfall occurs from hour 1 to 5 and a diurnal ET cycle occurs throughout the seven days of the simulation. The vertical dimension is exaggerated 10-fold for the 100-ft long by 20-inch deep slice through the green.



**Animation 3.** Water content (% by volume) within the soil profile of a push-up putting green over a period of 162 hours. Rainfall occurs from hour 1 to 5 and a diurnal ET cycle occurs throughout the seven days of the simulation. The vertical dimension is exaggerated 10-fold for the 100-ft long by 2-ft deep slice through the green.

Drainage in the California green began 3.1 hours into the simulation and achieved its maximum rate of  $28.3 \text{ inch}^3 \text{ h}^{-1}$  just as the rain ended (Figure 2). The drainage rate subsequently declined, rapidly at first and then more slowly. The California green required 31 hours before the drainage rate had slowed to at rate 2-orders of magnitude less than its peak. In the California green, the maximum drainage rate was about 60% of the rainfall rate implying that had this rain rate continued indefinitely, water would have ponded on the green. The slower maximum drainage rate in the California green than the USGA green is in agreement with the measurements of Prettyman and McCoy (6).

### Water Flow and Drainage in the Push-up Green

Water infiltration into the push-up green and the interruption of flow at the rootzone/clay loam interface resulted in a virtually saturated soil profile when the rain ended at hour 5 (Animation 3). This situation remained virtually unchanged until hour 24 when water contents declined to the 25-35% range at the crest of the terrace face. It was not until hour 42, however, before most of the remaining areas of the rootzone followed suit, opening up air-filled pore space for adequate soil aeration. The exception was the base of the terrace face and low point of the green where the soil remained wet.

This overall result is substantially different

from the USGA and California green observations and is due to the 8-inch thick layer of fine textured native soil between the base of the rootzone and the drainage trench. This disconnect between the sandy rootzone and the drainage system results in long-lived water accumulation following rain. It is also important to note that this water saturation occurred with just one inch of rainfall.

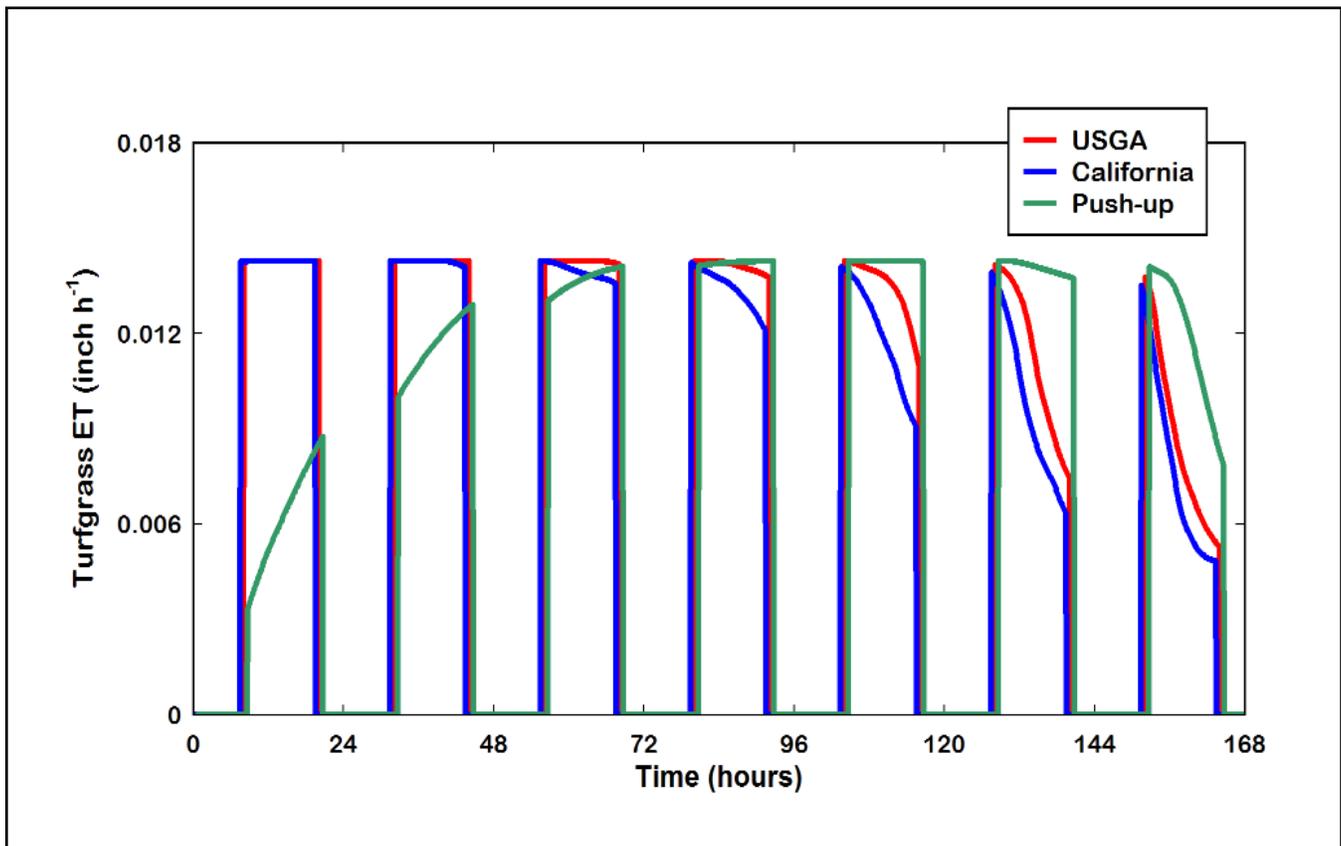
After 68 hours all regions of the surface four inches had dropped below a water content of 35%, opening air-filled porosity for adequate gas exchange. This led to a laterally uniform drying of this layer throughout the remainder of the simulation. At the end of the simulation, water contents were greater across the surface of the push-up green than the USGA or California greens because of the increased water retention of the push-up green rootzone layers (Table 1).

Whereas drainage rates were roughly similar for the USGA and California greens, drainage behavior in the push-up green was quite different

from the others (Figure 2). Drainage in this green began at 14 hours (well after the end of the rain) and peaked at a rate of  $0.064 \text{ inch}^3 \text{ h}^{-1}$  at 35 hours. Because no drainage occurred during the rain event, it is inevitable that surface ponding would occur if this  $0.25 \text{ inch h}^{-1}$  rain had continued. This demonstrates how a relatively impermeable fine-textured soil can serve as a disconnect between rainfall and drainage within these push-up greens. Finally, the decline in drainage rate following the peak in this push-up green was gradual, unlike that seen in the USGA and California greens.

### Turfgrass Evapotranspiration

Turfgrass response to soil water status is shown by tracking actual turfgrass ET ( $ET_a$ ) throughout the simulation (Figure 3). Given an atmospheric demand of  $0.014 \text{ inch h}^{-1}$  between 8 a.m. and 8 p.m. for each of the seven days, an  $ET_a$



**Figure 3.** Simulated, actual turfgrass ET ( $\text{inch h}^{-1}$ ) over 7 days for the USGA, California, and push-up greens. Turfgrass ET resulted from an atmospheric demand value of  $0.014 \text{ inch h}^{-1}$  from 8 am to 8 pm for each of the 7 days. Water associated turfgrass stress is indicated when  $ET_a$  values are less than the atmospheric demand.

value less than this would indicate water associated stress according to the simulation protocol. Further, stress observed early in the simulation following the rainstorm is regarded as a soil aeration (or wet wilt) stress due to inadequate air-filled porosity within the soil where roots reside. Stress observed late in the simulation is regarded as drought stress due to inadequate soil water contents within the depth increment of turf rooting.

Soil aeration stress was observed from the simulation results of the push-up green, occurring mostly throughout the first two days (Figure 3). During daylight hours of the first day,  $ET_a$  averaged 42% of atmospheric demand and in the second day averaged 88%. The reduced severity of aeration stress on the second day matches the progressive opening of air-filled porosity as localized water contents dropped below 35% (Animation 3). No soil aeration stress was observed from the simulation results of either the USGA or California greens (Figure 3). Even though the water content animations for these greens showed substantial differences in water perching, water contents in both cases had sufficiently declined throughout the depth of rooting so as to provide adequate air-filled porosity. The ability of these greens to avoid aeration stress is likely due to the gravel layer of the USGA green and the exceptionally high permeability of the California green, each leading to adequate drainage.

Drought stress, as defined in the simulation protocol, appeared on day 3 in the California green and on day 4 in the USGA green (Figure 3). Although drought stress increased in its severity on subsequent days, both greens showed a daily pattern of lesser stress in the morning with a deepening stress later in the afternoon. This suggests an overnight replenishing of water within the region of turfgrass rooting from the perched water retained below this depth. Although this response has not been documented from experimental water content measurements, it is frequently observed that turf showing drought stress in the afternoon appears to be sufficiently hydrated the following morning.

As with the water content animations where values in the upper six inches of the

California green are much drier for the same time slice than the USGA green, turf drought in the California green precedes that in the USGA green. This, again, is due to the lesser water retention of the California green rootzone sand (Table 1). Finally, drought stress was not observed till day 7 of the push-up green simulation, even though this green received 25% of the total rainfall of the other greens.

The results in Figure 3 show actual turfgrass ET across the entire green surface. Not apparent in this figure is the localized response that can be inferred from the water content animations (Animations 1 to 3). Thus, the early onset of drought stress in the USGA and California greens were isolated principally to the crest of the terrace face and, to a lesser degree, the high point of the green and the crest of the false front. These locations are precisely where the perched water disappeared first. Down slope versus upslope differences in turf drought stress within high sand content putting greens was observed experimentally by Prettyman and McCoy (8).

## Conclusions

Throughout the seven days of this simulation, 70, 63 and 9% of the total rainfall drained from the USGA, California, and push-up greens, respectively. Thus, even though the amount of rainfall occurring on the push-up green was 25% of the others, a disproportionate small fraction of the rainfall found its way to the drainage trenches in the push-up green. Cumulative evapotranspiration over the seven-day simulation was 27% in both the USGA and California greens as contrasted with 106% in the push-up green. The reason why ET in the push-up green exceeded 100% was because some water initially present in the soil profile was used in evapotranspiration over the seven days.

These facts, together with the other simulation results, emphasize that water flow in USGA or California greens are relatively similar when compared to a push-up green. This is principally because both USGA and California greens employ

deep (12-inch), sandy rootzones that (1) establish a direct connection with the subsurface drainage system and (2) displace layer interfaces well below the ground surface.

Differences in water flow that did occur between USGA and California greens included the progressively deepening pattern of water perching during rain in the California green when, at the same time, water perching thickness was self-limited in the USGA green. Associated with this is the slower maximum drainage rate in the California green. Another difference was that the California green showed an earlier onset of drought stress than the USGA green.

These differences are principally due to the presence of a gravel drainage layer in the USGA green and the lesser water holding capacity of the California green rootzone. Yet, both systems' perched water was short-lived at the crest of the steeper slopes. Further, perched water that was retained in the rootzone was taken up by the turf in both systems even though rooting did not extend into this zone. Consequently, the first onset of drought stress in both cases was localized to the crest of the terrace face and, to a lesser degree, the high point of the green and the crest of the false front.

Finally, although there is substantial evidence that the simulations accurately depict water flow in these greens, it is important to remember that the greens were subject to extreme environmental conditions and that the simulations used a rootzone with emphasized transmission attributes.

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