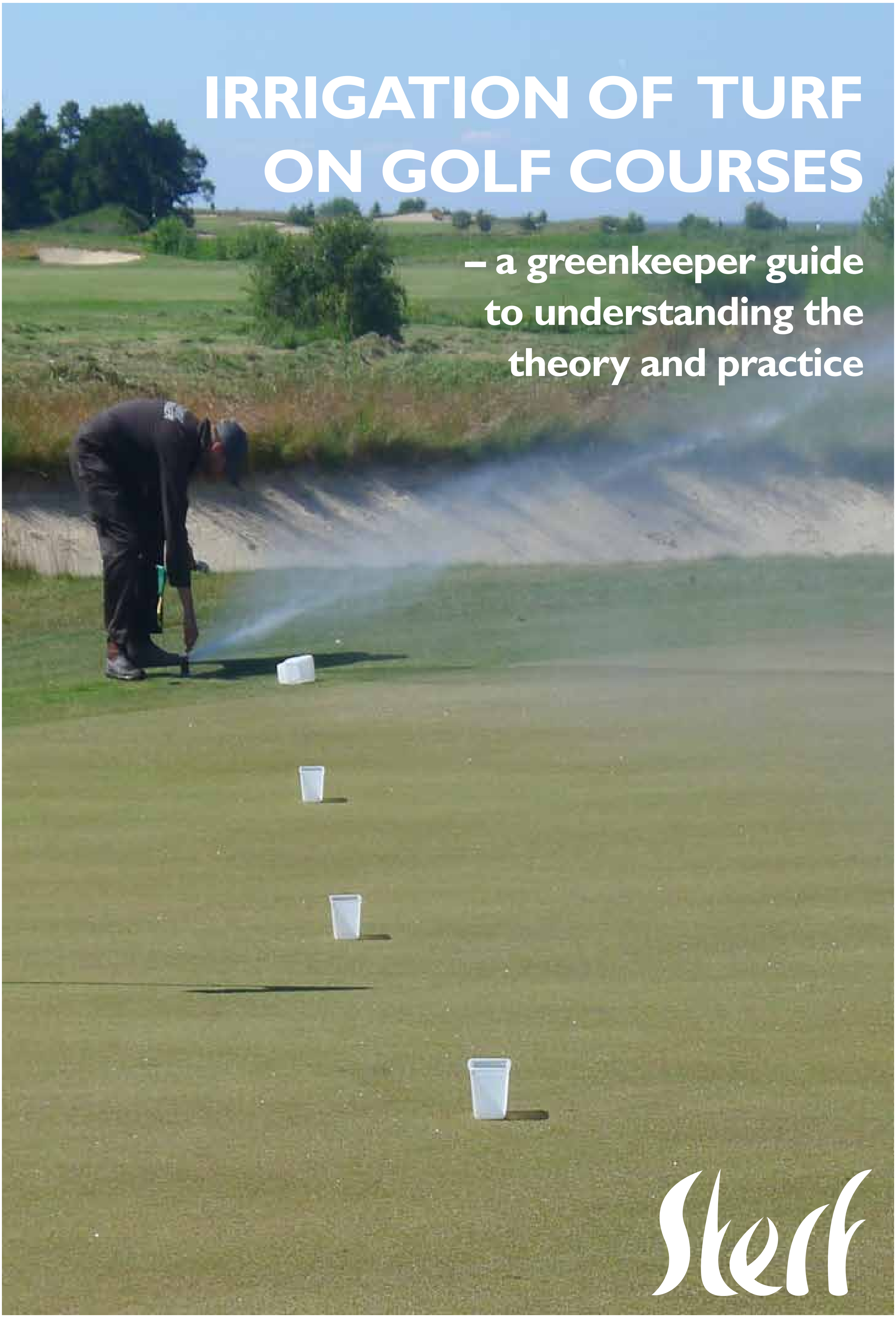
IRRIGATION OF TURF ON GOLF COURSES

– a greenkeeper guide to understanding the theory and practice



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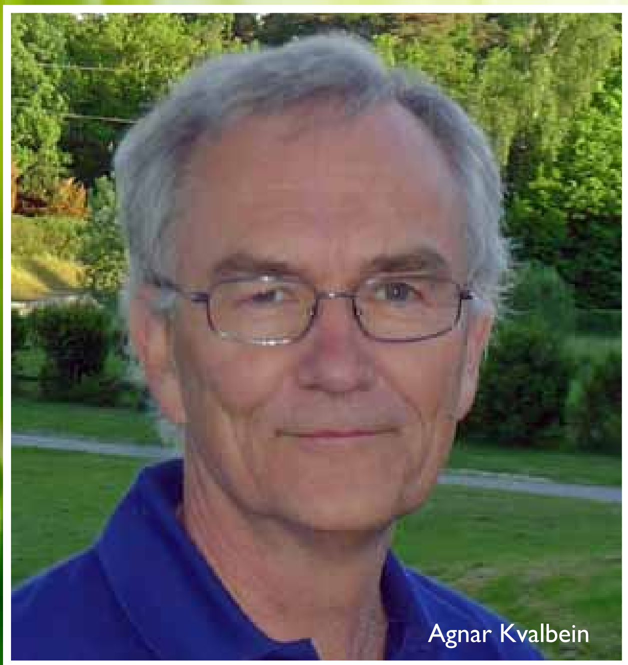

PREFACE

This manual is based on general knowledge of soil and plants, but also on new information on turfgrass water use and quality. From 2009 through to 2011 several field trials were carried out at the Norwegian Institute for Agricultural and Environmental Research (Bioforsk) Turfgrass Center at Landvik, Grimstad, SE Norway. A major finding in these trials was the excessive water consumption by turfgrass having unrestricted easy access to water. This new understanding of the close relationship between water availability and water use provides major scope to save significant amounts of water through improved irrigation management practices.

Irrigation is considered to be a difficult subject in the field of crop science. Water availability affects plant growth in many ways. Not only plants, but even growing media and natural soils are affected by drought and irrigation. There are currently no technical solutions that can replace your role as the golf course irrigation manager. To be able to irrigate properly, you must know the different parts of your course, and you must take the time needed to plan your irrigation, implement it and monitor the impacts.

We thank the Scandinavian Turfgrass and Environment Research Foundation (STERF) and the Research Council of Norway (NRF) for funding the research project *Evaporative demands and deficit irrigation on sand-based golf greens* and for contributing to the publication of this manual. We also thank Rainbird Irrigation Company for providing an automatic weather for the research , and turfgrass agronomist Mikael Frisk, Swedish Golf Federation, and Dr. Jerry Knox, Cranfield University, for valuable comments to this manual.

It is our hope that this manual will provide you with a sound understnading and basis for improving your irrigation management practices in order to produce high quality turf with reduced environmental and economic cost. We also hope that in the future new technical advances and innovation in irrigation control will help provide more uniform irrigation than is currnetly available with today's sprinkler technology.

Landvik, February 1st 2014

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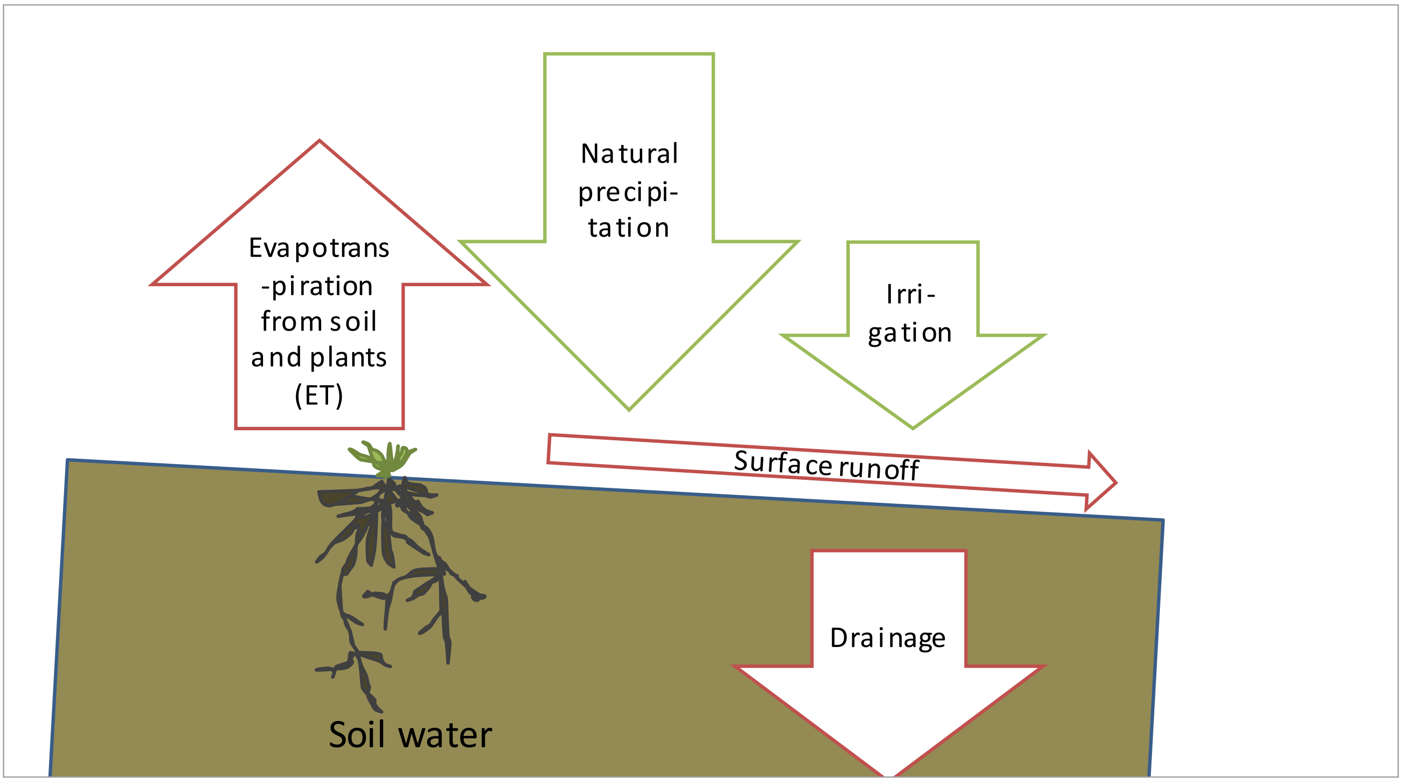


Figure 1. The soil water balance.

INTRODUCTION

Background

Water is a limited resource and conflicts on water use threaten economic development and political stability. The water consumption of golf courses is large per area unit and supply of irrigation water limits the development of golf in several parts of the world. Although the Nordic countries have surplus of precipitation and few restrictions on water use, better and more efficient utilization of irrigation water is one of the priorities of the Scandinavian Turfgrass and Environment Research Foundation (STERF) (*Strandberg et al. 2012)*

Field trials carried out at Bioforsk' Center for Turfgrass Research from 2009 through to 2011 provide new knowledge regarding the water consumption of various turfgrass species and a scientific basis for saving water on golf courses. However, the strategy called 'Deficit Irrigation' also requires a more even distribution of water than that which is commonly achieved with current golf course sprinkler technology. Therefore, unless new and more uniform irrigation systems can be developed or better approaches to management can be implemented, then deficit irrigation will in most cases require supplemental irrigation by hand watering.

Adequate water supply is critical for growth and development of turfgrass. Irrigation may at first glance appear to be a relatively easy task: It's just filling up the water reservoir around the plant roots when required. If we irrigate too much, then the surplus drains off the surface or through the soil profile (Figure 1). Yet, irrigation is difficult if our aim is to produce an excellent playing surface and beautiful lawns without wasting energy and water, and in a way that does not contribute to pollution or the development of turf related fungal diseases. Dry spots on sandy soils also make irrigation particularly challenging on many golf courses, particularly those where USGA specification greens are installed.

The use of this manual

The first chapters of this manual provide a general description of soil palnt water relationships. Competent readers who want to be updated on the new information arising from STERF`s research project can skip these sections and start with the chapter 'Evapotranspiration from turfgrass species', page 15.

Photo 1. Drain pipes lower the soil water table. Photo: Agnar Kvalbein.

SOIL WATER

Ground water

Rain falling on the ground will either be diverted in the form of surface water or it will infiltrate the soil. The water moves through cracks and pores until it becomes part of the ground water. The upper level of the ground water is called the water table. This is what we see if we look down into a well. Under the water table all pores are saturated with water, and the water can move laterally in sloping terrain.

The water table is usually high in areas where precipitation is higher than evapotranspiration (ET), as is typical in Nordic countries. Because plant roots require oxygen, it is important to lower the water table. This can be done by trenching and inserting perforated drainage pipes into the soil. The ground water enters the pipes from all sides and is diverted to streams, open ditches and/or other outlets.

Groundwater can easily be polluted through poor irrigation management practices. Chemicals contaminating the ground water are degraded very slowly because there is no air available. In many parts of the world, the ground water is an important source for drinking water and for irrigation of agricultural crops and turf.

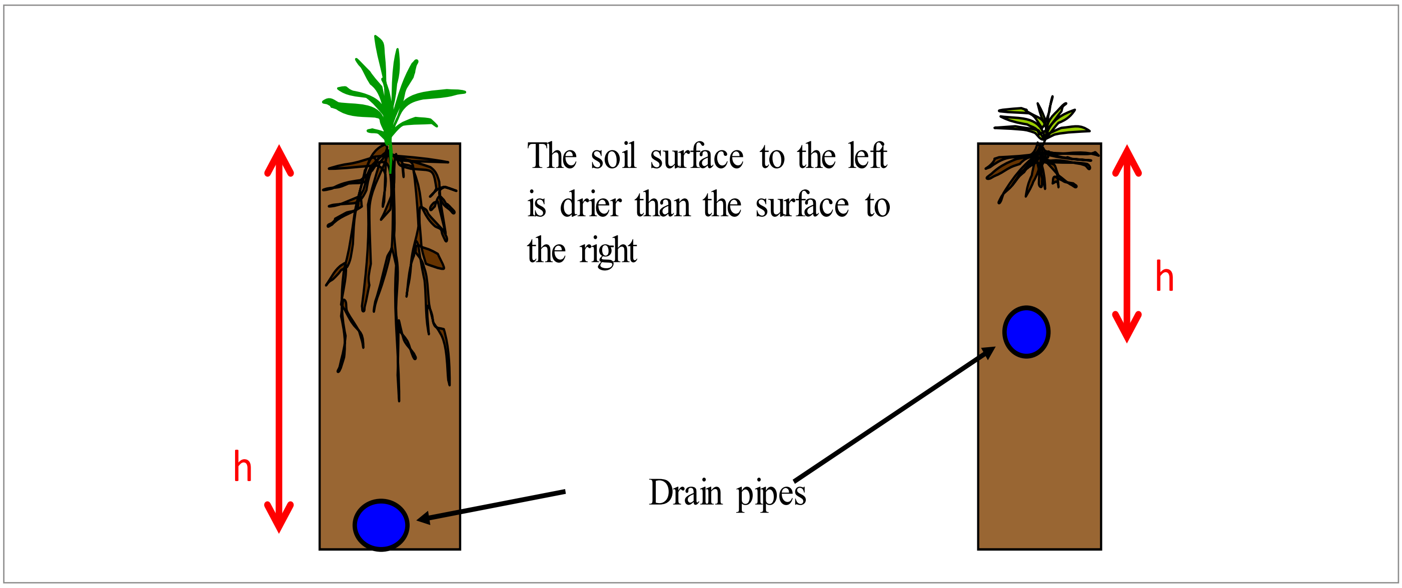


Figure 2. Importance of depth of drain pipes.

Pores and capillary forces

The soil above the water table also contains water. This water is held in place by capillary forces. Capillary forces arise because water molecules adhere to each other (cohesion) and to surfaces (adhesion). Fine-grained soils with many small pores and large inner surfaces have high water retention, whilst coarse-grained soils with large pores drain more easily.

The forces pulling water out of the pores in the soil are mainly the upward evapotranspiration to the atmosphere and the gravitation pulling water down to the water table. Water also moves horizontally from wet to dry areas. Water is sucked out of a large pore because of the weight of the continuous water column from the pore to the water table. The longer distance down to the water table, the greater is the suction. Therefore, the soil will be drier if the drainage pipes are deep in the soil than if they are closer to the surface (Figure 2).

Water moves from open soils to the atmosphere by a process of *evaporation*, but on turf surfaces most of the water will move through the plants as transpiration. Transpiration creates suction in the plant that pulls the water out of the pores in the soil. The combined process of evaporation from soil and plants is termed evapotranspiration (ET)

Micropores of less than 0.005 mm diameter bind the water so tightly that plant roots are unable to absorb it. Soils with a high content of clay particles or degraded organic matter have many small pores that contain significant amounts of water even after plants have started to wilt. This water is referred to as unavailable water. The suction at the plants' wilting point is -1.48 MPa.

Measurement of soil water suction (tension) and pressure

Literature on soil physics usually expresses drainage height as a logaritmic value with 10 as the base.

100 (10^2) cm drainage height is equivalent to pF 2. If a hydrological report gives the soil water content at pF 1.5 or pF 3, the values refer to drainage heights of 31.6 cm = $10^{1.5}$ and 1000 cm = 10^3 cm, respectively. Plants start to wilt at pF 4.18 equivalent to 15135 cm water column.

The correct SI unit for pressure or suction (tension) is Pascal or kilopascal, kPa. Pressure is expressed by positive values and suction by negative values. Values can be converted from cm water column by the factor 10.2 cm = 1.0 kPa.

pF 4.18 = -15135 cm = -1480 kPa.

In other words, plants start to wilt at a suction of -1.48 MPa (megapascal).

Photo 2. A perched water table is established by placing a fine-grained soil above a coarse-grained soil. Photo: Agnar Kvalbein.

Field capacity

The amount of water that a soil retains after free drainage is often referred to as field capacity. This is an important soil character. Sandy soils with larger particles and many large pores have a lower field capacity compared to clay or organic soils which have a smaller matrix structure and hence many small pores.

As shown in the previous section, field capacity also depends on the depth of the drain pipes. If we want to compare the field capacity of several soils, we therefore need to work with a standard drainage height. The most common international definition of field capacity (θ_{fc}) is per cent volumetric water content at a suction of-33 kPa (*Soulis et al. 2011*). This corresponds to a situation in which the water table is 3.4 meters below the soil surface, which is not very relevant to Nordic conditions. In Norwegian agriculture it has been common to define field capacity at the suction of a 100 cm water column (-9.8 kPa). When the water content in the rootzone of a golf green is determined in the laboratory, a drainage height of 40 cm (-3.923 kPa) is often used. This might seem a bit odd since the depth of the rootzone on a USGA-specification green is 30 cm, but *Taylor et al. (1993)* found that the gravel layer under the rootzone gave an additional water suction corresponding to a water column of approximately 10 cm. This was later confirmed by *Bigelow et al. (2001).*

As a theoretical concept, the field capacity is a rather imprecise character because it is measured so differently. It is also affected soil temperature, how the pores are saturated with water before allowed to drain, and many other factors. In practice, the field capacity is, nonetheless, an important definition that will be used in this manual to express the situation after full irrigation or prolonged rainfall. We therefore use the following simple definition:

Field capacity is the amount of water retained in the soil one hour after a long-lasting rainfall.

Perched water table

USGA-spec. greens and expensive football pitches are constructed with a horizontal gravel layer under the sand-based rootzone. The gravel is often referred to as the drainage layer, but the purpose of this layer is not only to drain but also to retain water in the rootzone. The gravel creates a so-called *perched water table* (photo 2). The explanation for phenomenon is that the capillary force in the gravel with many large pores is weak compared to the capillary force in the sand with many small pores. If we measure the volumetric water content in such a construction, we find that the water content increases down towards the gravel layer. After irrigation the pores at the bottom of the rootzone are filled with water.

USGA-specification rootzones have to be constructed with carefully defined growing media. If the pores are too small then the air content might become too low resulting in poor root development.

HOW LARGE ARE THE PLANTS' WATER RESERVES IN THE SOIL ?

This question is not easy to answer because it varies from place to place, not only horizontally, but also depending on the soil profile. You therefore have to measure this yourself.

Greens with a perched water table

In greens or football pitches constructed with a perched water table the water content will increase with increasing depth towards the gravel layer. See Figure 3. However, as grass plants have most of their roots in the top 5 cm, dead roots will eventually lead to a higher content of organic matter and thus a higher storage capacity for water in the top layer. On mature greens, the water content in the top 5 cm is therefore usually higher than shown in Figure 3.

On sand-based greens with a perched water table it is usually easy to determine root depth, and the available water is negligible. For these types of greens, we have created a simple method to determine soil's content of plant available water at field capacity (Figure 3).

Fairways on natural soil

The water content in natural soils varies considerably. Fine sands and silts sometimes retain so much water that they can become unstable.

In clays or soils with a high content of organic matter - a significant part of the water is usually so tightly bound to the soil particles that it cannot be taken up by plant roots. In such cases, the non-available water has to be subtracted from the total water content when determining plants' water reserves. This amount of unavailable water can be determined exactly by analyzing an undisturbed cylinder samples in a laboratory.

On fairways, it is also more difficult to determine root depth than on USGA-greens. Some roots penetrate deeply into the soil, but we don't know how efficient these roots are in exploiting the water reserves at greater depths. For practical reasons we assume that plants are able utilize the water to the same depth as there is visible root development.

Table 1 gives an estimate for plant-available water at field capacity in soils with different textures and organic matter content. This table also takes into account the normal root development in various soil textures.

Depth cm	Volume % water	mm water	mm (accumulated)
5	9	4.5	4.5
10	12	6	10.5
15	15	7.5	18.0
20	35	17.5	35.5
25	40	20	55.5

Figure 3. Soil water content at various depths in a USGA-spec. rootzone with a perched water table. In spite of the low water content (light colour) of the topsoil, the total water reserve is more than 50 mm. The water content in the various layers are from Bigelow et al. (2001) who studied newly constructed greens. On mature greens, accumulation of organic matter will usually lead to a higher water content near the surface.

	Organic matter content (w/w)			
Soil type	<3 %	3-4.5 %	4.5-12 %	12-20 %
Coarse sand	50	50	50	70
Medium sand	50	50	70	70
Fine sand	50	70	70	90
Silty coarse sand	50	50	70	70
Silty medium sand	50	70	70	90
Silty fine sand	70	90	90	110
Sandy silt (silt loam)	90	110	110	130
Silt	110	130	130	130
Loam	70	90	90	110
Silty clay loam	90	110	110	130
Clay loam	50	70	90	110
Clay	70	90	110	130
Loam with 20-40% organic matter	-	-	-	110
Organic soil (> 40% organic matter)	-	-	-	130

Table 1. Plant available water (mm) at field capacity in various soil textures. (Riley et al.)

How to determine the water reserves in your greens?

- The soil water content should be determined at field capacity, i.e. when the soil retains as much water as it can (one hour after long-lasting rainfall or irrigation).
- The best time of year to make this measurement is in July when water comsumption is high and roots are relatively short due to high soil temperature.
- Measure root depth to the deepest white (= active) root. Note: Red fescue has brown roots.
- Extract at least one cylinder sample **to root depth** from each green and put it in a plastic bag labelled with green number. Weigh the sample as soon as possible and dry it in an oven at 105°C for 24 hours.
- Weigh all samples after drying.
- The water content in cm is calculated as weight loss (g) divided by ($3.14 \times r^2$), where r is the radius of the cylinder.
- Multiply by 10 and you get the plant available water content of your greens, adjusted for root depth.

Photo 3. The soil water content increases towards the gravel layer on USGA greens. Photo: Agnar Kvalbein.

WATER IN PLANTS

Uptake and transport

Water is taken up by plant roots. The thin root hairs just behind the root tip penetrate into small pores and create a large root surface that is in contact with the soil. Some fungi also live in symbiosis with plant roots and form mycorrhiza. The hyphae grow out from the plant roots and contribute to uptake of water as well as nutrients. That is why mycorrhiza is often called ' the roots of the roots'.

The water is transported through the xylem to the top of the plant. These vessels are part of the 'leaf nerves' that are visible on the leaf surface. In the leaves, the water moves in and out of cells through cell walls and membranes. Between the leaf cells there are open intercellular spaces in which the air is almost saturated with water vapour.

During daytime, the air surrounding the leaves usually has a water deficit, i.e. it is not saturated. It is the continuous suction from the surrounding air through the plant to the soil that drives the water uptake. The loss of water from plant leaves is referred to as *transpiration*.

Stomata and control of transpiration

Grass leaves are surrounded by an epidermis (skin) with an outer cuticle (wax layer). On both sides of the leaves, there are stomata (openings) facilitating gas exchange, and each of these openings is surrounded by two guard cells. When the pressure (turgidity) in the guard cells increases, the stomata open, and water vapour and oxygen are released to the atmosphere. At the same time, CO_2 -rich air enters the leaf. The exchange is driven by different gas concentrations in the intercellular spaces and in the air that surrounds the leaves. This type of "transport" of elements due to concentration differences is called *diffusion*.

As the CO_2 content in the atmosphere is rather low (currently 0.38 %), the plants receive little CO_2 in exchange for all the water that is lost. As CO_2 often limits photosynthesis and, thus, the plants' energy supply, proper regulation of the exchange of water against carbon dioxide is very important to the plant. The stomata are controlled by several mechanisms providing a reasonable balance between water loss and CO_2 uptake. Essentially, there are three mechanisms controlling guard cell pressure and thus the opening of stomata:

1. Unlimited access to water provides high pressure, while high transpiration rates lead to water loss and low pressure. In other words, stomata opening is controlled by the leaf water balance itself.

2. Sugar is produced by photosynthesis in daylight. The sugar lowers the osmotic potential of the guard cells resulting in increased water uptake and thus stomata opening.

3. The plant hormone abscisic acid (ABA) is produced in the roots during drought stress. The hormone is transported to the leaves where it leads to closing of stomata and later to reduced shoot growth. At the same time, root growth is stimulated.

Supply of carbon dioxide is essential for plant energy production. Photosynthesis is driven by light, but it is usually the supply of CO_2 that limits the process. In order to convert the light energy into sugar, plants must have sufficient access to water to keep stomata open. Temporary drought stress because water uptake does not keep up with transpiration is often seen in the afternoon on warm summer days. The water pressure in the cells recovers during the night and the stomata open to a maximum when the morning light appears. This is one of the reasons why the morning light is more important for turfgrass plants than the afternoon light.

Photo 4. This green was constructed with two different growing media. The dryer part is (in the front) was easily discernible in the morning as there were no guttation droplets. Lack of guttation droplets is often early warning that a dry spot may develop. Photo: Agnar Kvalbein.

Root pressure and guttation

Contrary to the normal situation with a suction in the xylem, the combination of a high sugar content in roots and little or no transpiration from leaves sometimes creates a pressure in root vascular tissues. This typically happens during calm nights following bright summer days with a lot of translocation of sugars to the roots. Near the tip of the grass leaves are hydatodes, i.e. small openings where the sap is released as droplets. The phenomenon is called *guttation*. These water droplets must not be confused with dew caused by condensation of water vapour from the air on cool surfaces, including grass leaves. Small amounts of guttation water are often an early indication of drying areas on a turf surface.

Other effects of plant water availability

We have emphasized that sufficient access to water is important for plants' sugar production because it affects the assimilation of carbon dioxide. The water supply also affects a number of other processes that can be either positive or negative for the playing surfaces on a golf course.

Cell elongation

The elongation of a plant cell is a direct response to the cell's internal water pressure (turgidity). When the cells are getting older, the cell walls become more rigid and elongation ceases. With poor water supply the pressure decreases, and cells become shorter. Theoretically, we can reduce leaf elongation and, thus grass clippings, by limiting plant water supply. This is, however, a delicate balance as it will also affect photosynthesis. It is therefore safer to control growth by nitrogen fertilization and/or chemical plant growth regulators than by limited water supply.

Temperature control

Water transpiration from leaves is important to keep temperatures down. By water shortage, the temperature of the cells will rise. Respiration is a process that occurs in all living cells and accelerates as temperature increases. If the grass surface is not kept cool by transpiration, the incoming radiation from the sun will lead to a rapid increase in soil temperature. High respiration, both by the grass roots and by soil microorganisms, usually results in a higher content of CO_2 and a lower content of oxygen in the soil air than in the atmosphere. In the worst case, plant roots may suffer from suffocation. Air temperatures higher than 30° C often result in heat-stress despite unlimited water supply. In such situations, the plants will start to lose roots, and to avoid this, greenkeepers cool the surfaces by irrigating with small amounts of water in the middle of the day. The purpose of this type of irrigation, called syringing, is not to increase root uptake of water, but to cool down the surface by increased evaporation. However, heat stress and the need for *syringing* is not a big issue in the Nordic countries compared to countries further south.

Plant diseases

Most plant diseases are caused by fungi thriving under humid conditions. Many pathogens causing foliar diseases depend on moisture on leaf surfaces for germination of spores. Frequent irrigation will therefore increase the risk for such diseases.

Other diseases attack the roots and prevent efficient water uptake. In such cases, frequent irrigation can alleviate the symptoms and give a smoother playing surface. Take-all patch (*Gaeumannomyces graminis*) is an example of such a disease.

Thatch development

Thatch is the accumulation of dead and living organic matter just below turfgrass crowns. The thatch retains the water as a sponge, and heavy or frequent irrigation may keep it so wet that decomposition of organic matter is hampered by lack of oxygen.

Thatch is not a main topic in this manual, but it is a common observation that ample irrigation results in soft greens with poor playing quality. For more information about thatch and thatch control, readers are refered to STERF's handbook on velvet bentgrass (*Agrostis canina*) at http://sterf.golf.se.

Root development

There is not always a consistent relationship between water supply and root development. Because gas diffusion is much slower in water than in air, the diffusion of oxygen into the soil, and thus root development, may sometimes be reduced by a wet thatch layer. On the other hand, root development is rarely hampered by frequent irrigation on ventilated and well-drained soils. What was evident in our irrigation project was that periods of drought stress stimulated root development at greater depths in the soil profile. As already indicated, this response was probably mediated by the plant hormone abscisic acid (ABA). In drought situations there will also be more air in the soil enabling roots to grow deeper without getting too little oxygen.

Weeds

Some weeds have short roots or a tendency to develop roots in moist topsoils. Annual meadow grass (*Poa annua*) is an example of a short-rooted grass species that becomes more competitive with frequent irrigation. Other weeds have deeper root systems and compete better with the seeded grasses under dry conditions. A third group is the mosses. They do not have roots, only rhizoids (filaments that attach the moss to the surface) and their water uptake is only through the leaves. Frequent rainfall or irrigation are therefore likely to result in more moss. During dry periods the mosses have good ability to survive as spores, but their competitive ability is very low.

In wet soils or on moist surfaces	Under dry conditions
Birdeye pearlwort, *Sagina procumbens*	Yarrow, *Achillea millefolium*
Broadleaf plantain, *Plantago major*	Dandelion, *Taraxacum officinale*
Creeping buttercup, *Ranunculus repens*	White clover, *Trifolium repens*

Table 2. Examples of dicot weeds that compete well with turfgrasses under various water supply.

DETERMINATION OF EVAPOTRANSPIRATION (ET) RATES

The amount of water that is released from a plant canopy is called *evapotranspiration* (ET). It is the sum of evaporation from the soil and transpiration from the plants. ET rates are usually expressed in millimeters of water per day (mm/day). Since rainfall is also measured in mm/day, this makes it very straightforward to develop a simple water balance for your course taking into account the water inputs (rainfall and irrigation) and water outputs (ET).

We can calculate the need for irrigation by keeping records of precipitation and evapotranspiration. We irrigate when the calculations show that there are low water reserves left in the soil. Precipitation is easily measured locally by means of a rain gauge. But how do we get appropriate figures for ET ?

Direct measurement of evaporation form an open water surface

In the past, it was often assumed that the ET from a plant canopy was equivalent to the evaporation from the open water surface in an evaporimeter, i.e. an evaporation pan that had been dug into the soil, usually in a short-cut grass canopy. Such pans typically were about 50 cm deep, had a diameter of 60-80 cm, and they were equipped with a ruler enabling users to measure daily evaporation from the open water surface. Such pans required manual reading and daily maintenance and refill of water, and they are hardly in use any more.

Photo 5. A weather station that calculates ET_0 from temperature, solar radiation, wind speed and relative humidity can be connected to the irrigation system (Photo: Agnar Kvalbein).

Calculation of Reference Evapotranspoiration (ET_0)

A standard meteorological reference value (ET_0), common to all species, can be calculated mathematically from weather observations. Solar radiation, temperature, wind and humidity are input factors in equations that calculate daily ET_0 rates. The most commonly used equation is named after two scientists; Penman-Monteith.

Daily ET_0 rates are calculated by many meteorological stations. Since the ET_0 value does not vary much within a district, you can normally use the value from the nearest station. As a rough simplification, we can say that the ET_0 is between 3 and 4 mm on good summer days in the Nordic countries. Precipitation shows much more local variation, especially in the summer, and the amount of rainfall must therefore be measured locally on the golf course. Many suppliers of irrigation systems offer weather stations that measure rainfall and calculate ET_0 automatically. Such equipment is getting more affordable and better.

ET_0

Some define ET_0 as the water loss from a standard short-cut grass canopy, without disease and under optimal growing conditions. There are also many other definitions and equations used to calculate ET_0. This often confusing and makes it difficult to compare ET_0 values in various publications. In the project that formed the basis for this manual, ET_0 was calculated using the FAO (UN's Agriculture Organization) modified version of the Penman-Monteith equation.

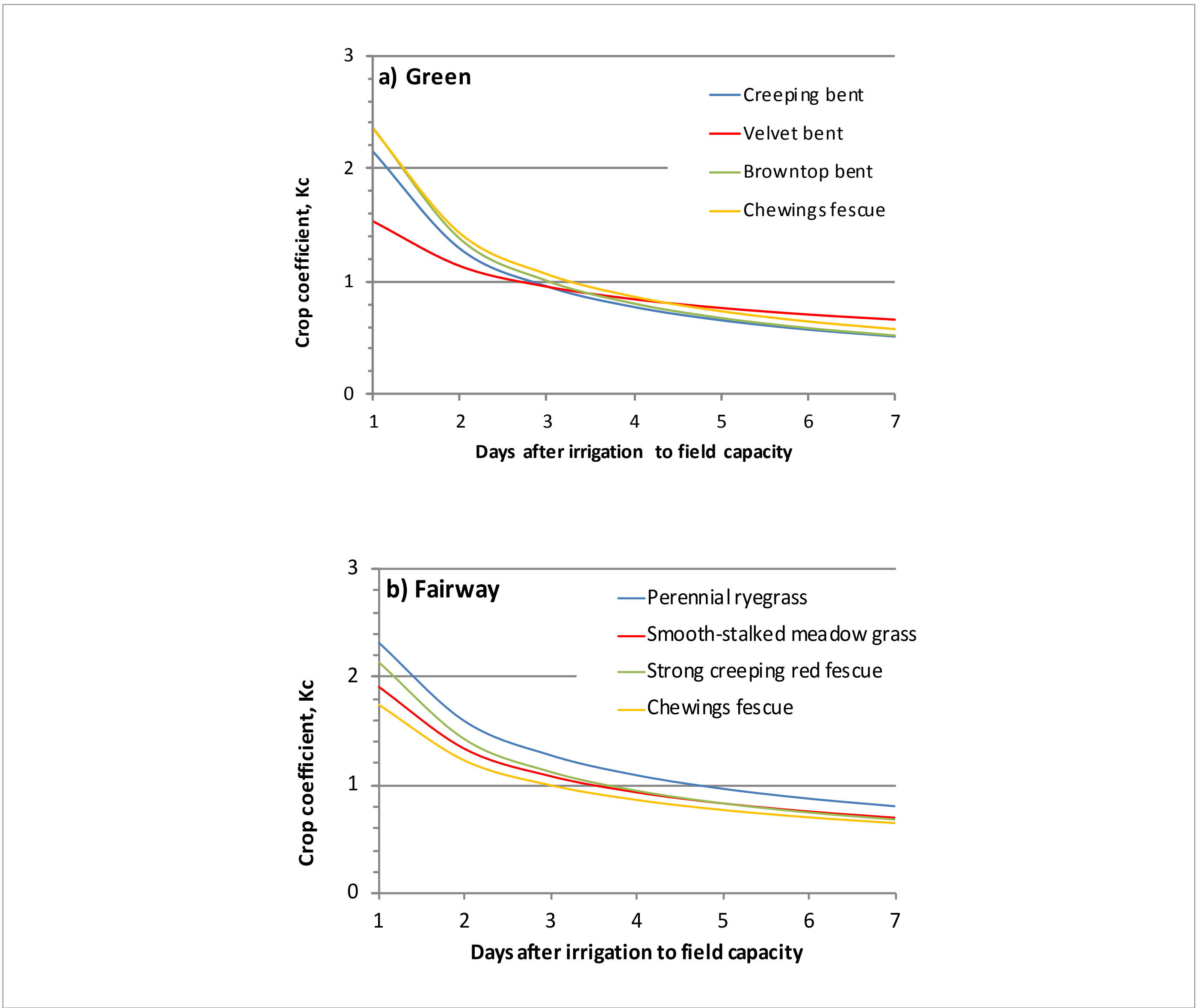


Figure 4. Crop coefficient for various turfgrass species on a USGA-green cut at 3-5 mm and on a fairway cut at 15 mm as a function of day number after irrigation to field capacity.

Transpiration from different turfgrass species

Evapotranspiration varies among plant species. As an example, the ET from a birch forest is higher than from a grass meadow. But how much water does a short-cut turf canopy use? This was measured by Bioforsk in 2009 and 2010. The results were surprising, and the new knowledge gained from the project enables us to save water by smart irrigation. We will return to this in a later chapter.

To adjust ET_0 to the actual ET from a turf canopy, we have to use a conversion factor. This factor is called the k_c (crop coefficient) and the actual crop ET is referred to as ET_c:

$$ET_C = k_c * ET_0$$

There is a k_c value for each plant species, and the height and developmental stage of the plants must also be considered. It has often been assumed that the k_c for short cut cool season grass is 0.80-0.85 (e.g. McCarty 2011). That means that the actual ET from a turf canopy is a little lower than the reference value calculated by weather stations.

Our research has not disproved this, but it's also not quite that simple. What we found was that grass plants with free access to water have a much higher transpiration than those growing on dry soils. Water consumption on the first day after irrigation to field capacity is two to three times higher than the average consumption on the next five days. Thus, the crop coefficient, k_c, has to be expressed as a function of the water content in the soil. Figure 4 shows how the k_c decreases with day number after irrigation to field capacity.

As a rough approximation, it is fair to say that all grass species used on golf courses in the Nordic region use similar amounts of water. If we go a little more into detail, denser turf will result in less water consumption. This might is probably because has less air circulation and thus a higher relative humidity in the canopy.

Many greenkeepers believe that red fescue (*Festuca rubra*) consumes little water. This is correct on fairways where red fescue has a high shoot density compared with other species, but not on greens. The fact that red fescue competes better with smooth stalked meadow grass (*Poa pratensis*) and annual meadow grass on dry areas is therefore primarily due to a deeper root system, and not to less water consumption.

Velvet bentgrass is different from the other species in that it consumes less water immediately after filling up the soil's water reservoir to field capacity (Figure 4a). We have also noticed that velvet bentgrass retains its green color longer into drought periods than the other grass species used on greens. Velvet bentgrass has a very high shoot density, and there may also be other reasons contributing to the low water consumption in this species.

Of the species used on fairway, perennial ryegrass (*Lolium perenne*) has the highest water consumption (Figure 4b). To a large extent this can be explained by perennial ryegrass having a deeper root system than annual meadow grass, smooth stalked meadow grass and red fescue.

Based on the k_c-values in Figure 4, Table 3 gives an estimate of one week's water consumption of the turfgrass species most commonly used on greens and fairways. Our experiments showed that the species using least water on greens and fairways were velvet bentgrass and chewings fescue (*F. rubra* ssp. *commutata*) respectively.

	Green	Fairway
Velvet bentgrass 'Legendary'	76 b	
Creeping bentgrass 'Independence'	91 a	
Browntop bentgrass 'Barking'	99 a	
Chewings fescue 'Center'	100=32 mm a	100 = 23 mm b
Smooth stalked meadow grass 'Limousine'		104 b
Strong creeping red fescue 'Celianna'		110 ab
Perennial ryegrass 'Bargold'		117 a

Table 3. Relative weekly water consumption of the most commonly seeded turfgrass species/subspecies on Nordic greens and fairways. Values are calculated from the K_c functions in Figure 4 and assume an ET_0 of 3 mm per day. The relative water consumption of chewings fescue ' Center ', which was the only variety tested on both green and fairway, has been set to 100. Larger water consumption on green than on fairway is due to the assumption that the green was irrigated to field capacity twice a week, while the fairway was irrigated to field capacity once a week. Within each column, the same letter indicate that the water consumption was not significantly different ($P < 0.10$ significance level).

Photo 6: Hauger GC, Oslo. Photo: Agnar Kvalbein

IRRIGATION STRATEGIES

The following discussion of is based on field trials at Bioforsk Landvik, Norway, in 2010 and 2011. Different strategies were compared during four drought periods during which precipitation was eliminated by the use of mobile rainout shelters. Irrigation to field capacity was compared with deficit irrigation, while irrigation frequency varied from daily to weekly on greens, and from twice a week to every ten days on fairways.

Irrigation for maximal growth

Plants with an unrestricted supply of water grow rapidly because the cells are turgid and stomata are open most of the day. If a high growth rate is required, the turf must therefore be irrigated frequently, and the soil must be kept close to field capacity.

This strategy applies to turf during establishment and in the spring when fast recovery (repair) after winter damage is required. This irrigation strategy will, however, lead to excessive water consumption, and it should also be kept in mind that the risk of nutrient leaching is much higher when the turf cover is sparse and soil temperatures are low. It is therefore particularly important that this irrigation strategy is combined with frequent nutrient inputs at low rates.

Irrigation for reduced water consumption and better turf quality

The finding that turfgrass water consumption is a function of soil water content forms the basis for significant water savings on golf courses. By avoiding frequent irrigation to field capacity we can reduce water consumption to less than one half compared with daily irrigation to field capacity. There is, however, a limit for how far we can let the soil dry out without sacrificing turf quality. This is especially the case on sand-based rootzones where there is a high risk of development of dry spots (see later chapter).

The highest visual turf quality in the experiment at Landvik was recorded on plots irrigated to 70 % of field capacity six times per week, but differences from plots irrigated to field capacity twice or six times per week were small and not significant (Table 4). The two former treatments gave harder greens, i.e. better playing quality, compared to irrigation back to field capacity six times per week. Irrigation once a week was found to be too infrequent and led to many dry spots forming particularly if soil surfactant was not used.

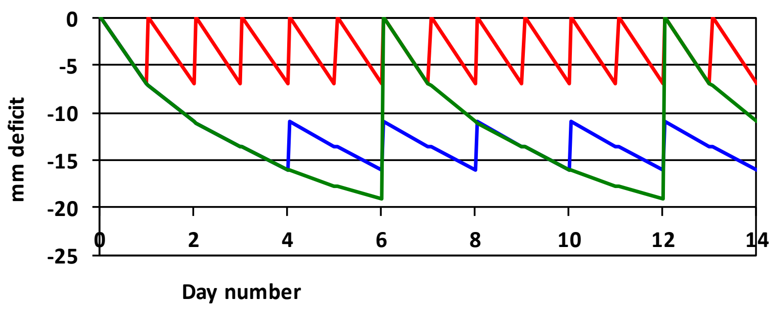
Water consumption during the 63 day experimental period varied from 358 mm in the treatment with irrigation to field capacity six times per week to only 106 mm in the treatment with deficit irrigation only once a week (table 5). The turf that was deficit irrigated six times per week received 123 mm. This represents a saving in water use corresponding to 66 %.

Ballroll and playing quality

Playing quality is often characterized by the three parameters including trueness, fastness and hardness (firmness).

A high trueness of a green means that the ball does not deviate from side to side, but follows a consistent line to where you would expect the ball to roll based on surface undulation. The impact of irrigation strategy on this character is small on greens with a uniform turf cover.

Although it is never seeded, annual meadow grass is often the predominant species on many golf greens. On such greens, the trueness is often reduced by the proliferous flowering of annual meadow grass in spring, and this tendency of annual meadow grass to flower is usually exacerbated by dry conditions. This creates a dilemma, as in the long term, restrictive irrigation will normally reduce the annual mea-



- Saturated irrigation (frequently to field capacity)
- Drought-based irrigations (Infrequently to field capacity)
- Deficit irrigation: (moderate constant drought stress)

Figure 5. Illustration of three principally different irrigation strategies.

Irrigation Strategy	Visual turf quality (1-9)	Dry Spots % of plot area	Daily height increment (mm)	Ballroll, measured with a short stimpmeter (cm)	Hardness measured with a Clegg-hammer (gravities)
1. Field capacity, 6x per week	6.3 a	6 b	0.9 a	100 a	71 c
2. Field capacity, 2x per week	6.1 a	6 b	0.9 a	102 a	74 bc
3. Field capacity, 1x per week	5.4 ab	13 ab	0.8 a	100 a	79 b
4. Deficit, 6x per week	6.4 a	8 b	0.9 a	101 a	76 bc
5. Deficit, 2x per week	5.8 ab	11 b	0.9 a	100 a	75 bc
6. Deficit, 1x per week	4.9 b	27 a	0.8 a	103 a	85 a

Table 4. Impacts of different turf irrigation scheduling strategies based on irrigation experiments conducted in 2011 on a green with creeping bentgrass 'Independence '. It was irrigated to field capacity or to approximately 70% of field capacity at different intervals. Within each column, figures followed by the same letter are not significantly different (significance level: P< 0.10)

Irrigation Strategy	Water consumption during experimental period (63 days)	Water consumption relative to daily irrigation to field capacity
1. Field capacity, 6x per week	358	100
2. Field capacity, 2x per week	233	65
3. Field capacity, 1x per week	173	48
4. Deficit, 6x per week	123	34
5. Deficit, 2x per week	127	36
6. Deficit, 1x per week	106	30

Table 5. Water consumption of creeping bentgrass 'Independence' at different irrigation strategies on a golf green at Bioforsk Landvik in 2011.. The accumulated reference ET during the 63 day period was 174 mm.

dow grass population because this species has a shallower root system than other grass species.

The fastness of a putting surface (green speed or stimpmeter value) usually increases if the green is allowed to dry out, but this will weakens the turf, and cannot be recommended as part of daily maintenance. Different irrigation strategies did not affect ball roll on the creeping bentgrass (*Agrostis stolonifera)* green in our experiment (Table 4).

The quality parameter that is mostly affected by irrigation is hardness. The hardness of a putting surface is correlated with the risk for ball marks and determines how far the ball will bounce or roll after landing on the green. As shown in table 4, the hardness of a putting surface is influenced both by the irrigation frequency and by the total water use.

Irrigation during germination and establishment

After sowing we have to choose an irrigation strategy to fulfil the requirements for seed germination and seedling growth. A seed germinates only once, and the tiny seedlings are very susceptible to desiccation once the root has penetrated the seed coat. Bentgrass (*Agrostis sp.*) seeds are very small and must therefore be placed not deeper than 5 mm from the soil surface. Seeding close to the surface increases the risk for desiccation, and on sunny days, it may be necessary to irrigate a couple of millimeters every other hour just to keep the surface moist. The situation is further complicated by the fact that many sprinklers often apply quite large droplets that can easily displace the seed and/or wash the sand away from the seed. If time permits, hand watering with a hose and a fine nozzle giving much smaller droplets is therefore preferable. Covering the newly seeded area with a permeable tarp that retains moisture and protects the seedbed from high-energy droplets is a good strategy, however, it is important to remove the tarp as soon as the seedings are visible in order to get robust plants.

Winter damage often results in dead spots surrounded by surviving turf. This poses a dilemma for choice of irrigation strategy as frequent sprinkler irrigation is not only necessary for seed germination and seedling growth in the open spots, but it will also lead to more growth and competition from the surrounding turf. This, in turn, increases the need for mowing which may be detrimental to the new seedlings. The best solution to this problem is to irrigate the reseeded spots manually during the critical germinating period.

Newly sodded areas also need frequent irrigation in order to prevent drying out, but a couple of times a day is usually sufficient. All sod contain thatch, and if this is dense, then large amounts of water can reduce the gas diffusion and create problems for root growth. Careful aeration or slicing as soon as the sod can take such treatment may be necessary if root development stops after sodding.

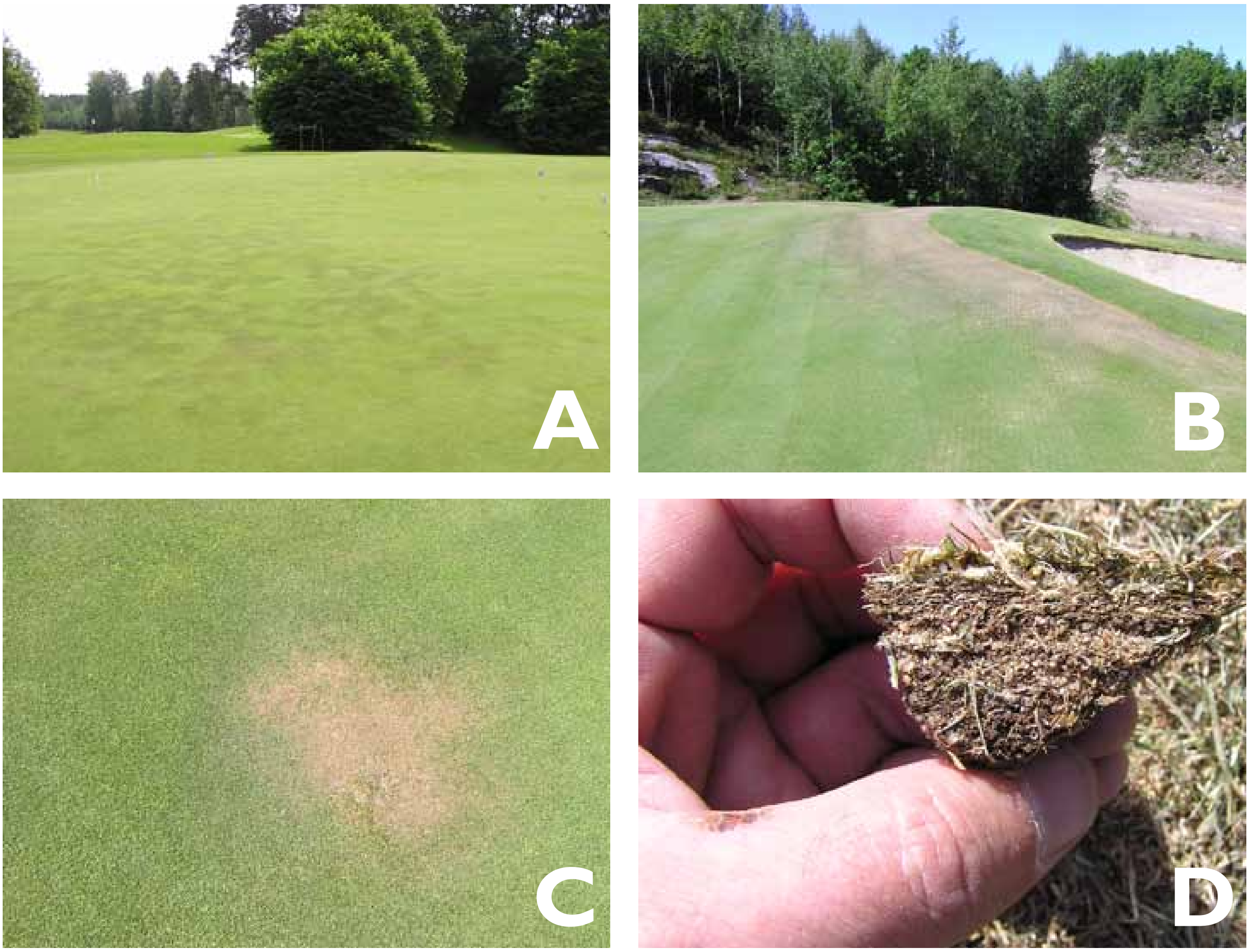


Photo 7. Reasons for dry spots: **A**. Different levels and thicknesses of the growing medium resulted in dry spots to the left in the photo, **B**. Water moved from the green to the more finely textures surrounding soil due to capillary forces, **C**. Discontinuity in the gravel layer, i.e. contact with the growing media and the soil underneath, **D**. Sandwiching, i.e. a think lay of topdress prevented infiltration of water.
Photos: Agnar Kvalbein.

HYDROPHOBIC SOILS AND FINGER-FLOW

Local dry spots

Local dry spots are quite common of golf courses, especially on sandy soils. The phenomenon has been known for a long time, yet, the severe problems arising when a soil becomes water repellent (hydrophobic) seems to surprise turfgrass managers.

It is well documented that wax-like substances are formed during decomposition of organic matter (Doerr et al. 2000). These substances adhere to the surface of the sand grains in the thatch layer and underneath it. As long as the soil is wet, there will be no problem, but the soil becomes water-repellent if it dries under a critical water content. According to our experience, this limit is in the range 7-9 % (v/v) on sand-based greens. If then soil dries out below this limit, it will become hydrophobic which means it is very difficult to re-wet , and is a condition that can last for a long time.

Poor coverage of the irrigation system often results in hydrophobicity, but there may be many other reasons as well.

Photo 8. Extreme dry spots on the green to the left. The water penetrated the surface in the green spots only. This is shown in detail in the photo to the right. The phenomenon is called finger-flow. Photo to the left: Terje Haugen. Photo to the right: Agnar Kvalbein.

We often see dry spots:

- on bumps or the upper parts of strongly undulated greens
- on the edge of sand-based greens, where the water moves from the sand to the surrounding soil due to capillary forces
- at points where there is contact between the growing medium and the soil under the gravel layer (USGA greens)
- on parts of the green where the growing medium is thicker than recommended
- where top-dressing has been so irregular that the thatch is like a sandwich with distinct layers of sand and organic matter.

Dry spots also occur on fairways, but rarely on clay soils.

Hydrophobicity is measured by a simple test: WDPT = Water Droplet Penetration Time. The droplets are usually placed at various depths on a cylinder sample or rectangular sample both immediately after sampling in the field and after letting the sample dry for 48 h at room temperature. These parameters are referred to as actual and potential hydrophobicity, respectively.

Finger flow

Another implication of hydrophobicity is that the water flows unevenly through the soil profile. The water penetrates most easily through the wet areas, and if the surrounding soil is hydrophobic, water will only pass through the moist ”channels”. The phenomenon is called *finger flow*. Finger flow results in uneven turf, and it also increases the risk for leaching of nutrients and pesticides significantly, especially on greens with a low content of soil organic matter (*Larsbo et al. 2008*).

How to avoid hydrophobicity?

We wish we could point out simple methods to eliminate the problem of dry spots, but unfortunately we are not able to do so. Good thatch control from day one after golf course establishment is important in order to avoid layering. When the problem is already apparent, one can add a little clay to the sand on the greens. The large surface of the extremely small clay particles allows the water to “stick” to the surfaces. The clay particles can be dispersed into the rootzone by irrigation.

The negative effects of hydrophobic soil can also be reduced by using soil surfactants. Soil surfactants work like soap and provide a bridge between the hydrophobic wax-like substances and the water molecules. In this way the water is distributed evenly in the soil profile. In our irrigation trials we found the highest number of dry spots on plots with the longest irrigation interval, but the same thing can happen with frequent deficit irrigation if the water is not distributed evenly on the green. If the irrigation system is not sufficiently uniform, the risk for certain areas to become too dry will increase with reduced water use. For this reason, less irrigation water often requires more use of surfactants.

Some surfactants will not only reduce the horizontal variation, but also lead to a general increase in the water content of the topsoil. Soil surfactants that cause more water to be retained in the thatch should not be used too late in the growing season, as more water might lead to more winter damage. Turf managers must therefore read the specifications carefully before choosing soil surfactant.

IRRIGATION AND THE RISK FOR NUTRIENT AND PESTICIDE LEACHING

Some nutrients, particularly nitrogen and phosphorus, stimulate the growth of plants in streams, rivers, dams and lakes. The growth of algae is usually restricted by the nitrogen supply, but cyanobacteria (previously called blue-green algae) can fix nitrogen from the air and are therefore primarily limited by phosphorus.

The risk for nutrient leaching from golf courses is usually low as long as fertilizers are distributed in small portions throughout the growing season. However, in the United States it has been documented that irrigation beyond field capacity, coupled with single applications of large amounts of fertilizers, can result in 90 % of the nitrogen being lost in drainage water (*Petrovic & Barlow 2012*). In contrast, splitting a fertilizer rate of 2-3 kg N per 100 m^2 into frequent applications usually results only5 % loss (*Barton & Colmer 2006).*

Nitrogen leaching from golf greens is usually low as long as fertilizer rates are moderate and there is a dense and healthy turf cover. The highest risk for nitrogen leaching is during establishment and after after winter damage. Analyses of nitrate in drainage water from well-established greens at Landvik always showed values below EU's limit for drinking water *(Aamlid et al. 2009, 2013).* In 2012, the total leaching losses from red fescue greens established on sand-based rootzones amended with peat was only 0.08 kg per 100 m^2, or about 6 % of the amount on nitrogen applied in fertilizers (*Aamlid et al. 2013*).

Phosphorus is normally strongly bound in the soil as insoluble salts. But if compost is used as organic amendment to sand-based growing media, there might be some leaching of phosphorus, especially during the first years after establishment (*Aamlid et al. 2013*) Otherwise, phosphorus pollution from golf courses is first and foremost a result of soil particles being washed away by precipitation during golf course establishment (soil erosion).

Experiments on pesticide leaching showed that the risk for pollution was much higher by irrigating four times with 25 mm compared to irrigating 16 times with 6 mm of water (*Starrett et al. 1994*).

The conclusion of this section is that even if the problems are small, irrigation above field capacity can lead to some leaching of both pesticides and nutrients. Pollution of ground water is always a special concern because the breakdown of chemicals occurs slowly under the soil water table, and because many people use groundwater as a source of drinking water.

Photo 9. Husavik GC, Iceland. Photo: Edwin Roald.

IRRIGATION IN PRACTICE

How to schedule irrigation?

It's hard to know how much to irrigate and how often in order to obtain the best result in terms of turf quality, economy and low impact on the environment. This uncertainty is a major reason why many greenkeepers often irrigate more than is really needed. Abundant irrigation is often the easiest and safest way to avoid dry spots and criticism. Turf exposed to sun and wind consumes more water than turf in shade. Unlike natural precipitation which usually falls evenly and at a low intensity on one particular green or fairway, fixed, circulating sprinklers will always distribute the water unevenly and usually at higher intensity. Sprinkler performance and hence application uniformity is also dependent on system management; pressure variations can have major impacts on flow rates and hence uniformity. Sub-optimal pressure leads to reduced flow rates which in turn reduced the wetted throw and creates larger droplets. Maintaining optimal operating pressure is therefore the most important management aspect.Wind can also cause non-uniformity, and undulations and dense green surfaces will eventually lead to more water to lower areas than to higher areas and slopes[2] .

In order to take advantage of the benefits of deficit irrigation, we must improve our irrigation system and irrigation practices at several levels. We cannot deny the fact that it is expensive both to obtain knowledge about the water conditions on the course and to follow up and verify measures taken to improve the results. Proper irrigation is therefore a challenge first and foremost on courses that have the resources and ambition to bring the course up to an even higher level with respect to playing quality and environmental stewardship.

[2] **Horizontal runoff on greens:** American studies have shown that the soil water content is usually very uneven on undulated greens (Prettyman & McCoy 2003).This is partly due to surface runoff and partly to gravitational movements in the water table under the surface.The intensity of sprinkler irrigation systems is usually higher than the infiltration capacity of a dry green surface.Although infiltration can be improved by moistening the surface slowly and gently, it is hard to avoid that the lower areas of a green receive more water than the higher ones.There have been successful attempts to construct water barriers that retain the water in terraces on greens with an inclination higher the 5 % (McInnes & Thomas 2012).

Photo 10. Time Domain Reflectrometry (TDR) instrument used to measure volumetric soil water content. Photo: Agnar Kvalbein.

Water balance calculations

The first step for many greenkeepers is to measure irrigation in millimeters rather than in minutes. This is an absolute prerequisite to determine if the amount of irrigation water is reasonable in relation to the plants' water consumption. If we ignore the first day after irrigation to field capacity, the turf on Nordic golf courses transpires 3 to 4 mm on a good summer day. ET can reach 5 mm on the warmest and driest days with maximum temperatures around 30 °C. As an example, if the irrigation system gives 3 mm in 10 minutes, irrigating 4x10 minutes twice a week should be sufficient to meet the turf's requirement for water. Irrigation beyond this will result in loss of water through the drainage system.

A simple irrigation balance can be made if you have a rain gauge and access to ET0 from a weather station in your district. In agriculture, this has been the recommended way for calculating the need for irrigation, i.e. to replenish water loss based on ET values. Some modern irrigation systems include a weather station and can be programmed to irrigate based on such data.

Measurement of soil water content

A better and easier alternative than to calculate the balance between ET and rainfall is to maintain the soil as close as possible to an optimal water content. There are several ways to measure soil water content, but the simplest and most useful instrument nowadays is a TDR instrument that gives you the water content directly as per cent of soil volume.

Time Domain Reflecometry (TDR)

A TDR instrument measures the soil water content in a radius of ca 3 cm around at least two probes of various length. The instrument emits electromagnetic radiation and the reflectance of this radiation depends on soil water content.

The value given in the display of a TDR instrument is the average soil water content in the rootzone as defined by the length of the probes. Within reasonable limits, this value is hardly affected by temperature (0-30 °C), soil density, texture and the soil's content of salts. Stones and voids in the soil are potential sources of error and the measurements may also depend on the soil's content of organic matter.

The accuracy of TDR instruments is usually in the range ±1-3 %.

Most of these instruments are portable, but some versions have sensors that are dug into soil and connected to the irrigation computer with wireless transmitters. Other models have GPS sensors so that data can easily be transferred to a map of the golf course.

Photo 11. The intensity of a modern irrigation system is often higher than the infiltration capacity. On undulated greens this will result in uneven distribution of water even if the sprinklers are correctly placed and well maintained. This photo from Visby GC, Sweden, shows water ponding in lower areas during a distribution uniformity test. Photo: Agnar Kvalbein.

Before using a TDR instrument to control irrigation, the water content at field capacity must be determined (see procedure on page xx). It is not uncommon that this content can vary +/-30 % in the same green. This may be due to different contents of organic matter or different compaction. These differences are themselves interesting because they provide information about the green surface. Often, the content of organic matter is lowest on the areas that are most exposed to wear and tear. At the same time, these are also areas with a lot of compaction that improves soil water retention.

When using a TDR instrument to determine irrigation needs, the aim is to keep the soil water content between 50 and 70% of field capacity. We must never allow the soil water content to become so low that there is a risk for dry spots to develop. This means that we must keep the TDR-value higher than 8 % in all areas. After having surveyed the greens you will know the driest spots. Sometimes you will probably need to irrigate these spots by hand because the irrigation system is not uniform enough.

Direct measurement of plant drought stress

Many attempts have been made to take 'short-cuts' and measure the plants' drought stress directly without determining soil water content (Jones 2004). The advantage of direct measurements is that it includes the effects of poor root development and temporary drought stress during the day. In our experiments we sometimes measured leaf temperature a few degrees higher on the driest plots than on plots with more water. Another method is based on the fact that red light is reflected differently when a plant starts to dry. With this technology we can discover dry areas 12-18 hours before they become visible to our eyes (B. Horgan, turfgrass course 2013). This technology still needs some refinement in order to become available for practical use.

Timing of irrigation

There are many practical reasons why irrigation during night or in the early morning is most advantageous. Most importantly there are less players. Secondly, the wind speed is often lower, thus giving more uniform distribution of water. Thirdly the turf will dry faster if dew and guttation drops have been removed by irrigaton in the early morning.

Irrigation in short sequences

Soil infiltration rates are usually better with light and frequent than with heavy and infrequent irrigation. When irrigating a dry surface, we must always start gently with a small amount of water that merely wets the surface and makes it receptive to subsequent irrigation sequences. Even 4-5 minutes of high-intensity sprinkler irrigation can result in surface runoff and thus uneven water distribution. The best results are obtained with many short irrigation sequences.

A concrete recommendation for deficit irrigation

The last part of STERF's irrigation project aimed at testing deficit irrigation in practice on selected golf courses. Unfortunately, these experiments were carried out in a year with a lot of natural rainfall. We were therefore not able to evaluate differences in turf quality against water use and irrigation costs, but we got an impression of the uniformity of the irrigation systems on several golf courses (see example next page).
Below we have listed some recommendations for how to make your own experiences with deficit irrigation. It is hard work, but following these recommendation step by step will result in less use of water and energy, and most likely improved turf quality on your golf course:

Irrigation of established greens

1. Prepare your greens in the spring by applying a soil surfactant if experience tells you that dry spots can occur.
2. Buy a TDR instrument with various sets of probes corresponding to the root depth on your greens.
3. Determine uniformity of your irrigation system in a quiet morning. Make sure that the nozzles are in order and that the sprinklers are upright (90 °). Place rain gauges or (or small boxes) at regular intervals in both directions and measure the content after 10 minutes' irrigation. Draw a map showing coverage and find the relationship between minutes and millimeters.
4. Determine the soil water content at field capacity (one hour after prolonged rain/irrigation) with a TDR instrument.
5. Start your deficit irrigation program by irrigating every time the soil water content is down to 60 % of field capacity. As your turf becomes drought-hardened, i.e. adapted to less water in the soil, you can gradually lower the criterion for starting irrigation to 50 % of field capacity, but you must never allow the water content to get lower than 8 % (average value; the critical limit may vary somewhat from green to green)
6. In the beginning the amount number of mm is calculated from what is needed to irrigate to 80% of field capacity. When the turf becomes drought-hardened, you turn off the irrigation system at 70 % of field capacity.
7. Check the result with the TDR-instrument on the day after irrigation. Pay special attention to the driest areas.
8. During warm and dry periods it may be necessary to supplement with hand irrigation on the driest areas (where there is poor coverage of the irrigation system or surface runoff due to undulation)
9. Make another application of soil surfactant on the driest areas of your greens if dry spots develop. Pay attention to areas where the water content continues to decline after irrigation. Keep in mind that soil surfactants can be applied both as granules and through the water-hose. Surfactants that retain the water in the thatch layer should not be used after August 1, because higher water content in the thatch can result in increased risk of winter damage.

Example: Larvik GC, Norway

Green No. 18 at Larvik Golf Course had irregular shape (Figure 6), and even though the sprinklers were placed in triangle, there was a big variation in the amount of water received on different parts of the green. The rain gauges that were put out at a distance of 4 m x 4 m collected between 12 and 30 ml of water, that is, a ratio between the least and most of 1: 2. 5. The Distribution Uniformity (DU) was calculated as 65 % (the average of the 25% lowest values divided by the average of all values). A DU of 55 % is considered bad, 70 % acceptable and 80 % excellent. The irrigation system gave an average of 0.37 mm water per minute, or 22 mm per hour.

The green was seeded with creeping bentgrass (Agrostis stolonifera) and had been top-dressed on a regular basis for 15 years. The growing medium therefore had a thickness of about 40 cm. The concentration of organic matter in the top layer was about 2 % and the growing medium was therefore rather dry.

The root depth varied, but in most places it was around 20 cm. The part of the green that received most water had more annual meadow grass, about 70 %, and shorter roots. Soil water content was measured with a TDR instrument with 20 cm probes (TDR_{20}). The average field capacity (soil water content one hour after prolonged rainfall) averaged 18 %, but there was a variation from 10.0 to 21.4 %.

Our goal was to keep the soil water content between 60 and 70 % of field capacity, i.e. between 10.8 and 12.6 % water in the 20 cm rootzone. Daily mean values (TDR_{20}) measured at 12 predetermined sites on the green are presented in table 6.

After three days (the night before day no 4), the green was irrigated for 15 minutes, i.e. with an average of 5.5 mm water. This irrigation raised the TDR_{20} to 13.0 % on day no 4. On the fifth day the average water content in the whole green was 11.5 %, but the upper-right section with poor coverage of the irrigation system, had only 9 %. (From the location of the sprinklers you would have expected a dry area also near the entrance of the green (lower area in figure 6), but this did not occur as the green sloped against the playing direction.) On day no 6 we measured an average water content of 10.0 % (about 12 % in the area that had been hand-irrigated the day before), hence, during the night to day no 7 it was irrigated for 20 minutes (= 7.4 mm). This brought the water content up to 12.4 % on day no 7. On day no 8 it was raining heavily.

Day number after irrigation to field capacity									
Day no	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Soil water content measured before irrigation (TDR_{20})	18.0	15.1	12.6	11.0	13.0	11.5	10.0	12.4	18.0
Irrigation (mm)				5.5		Hand watering	7.4		20 rain

Table 6. Soil water content and irrigation / rainfall on green no 18 at Larvik GC during an eight day period.

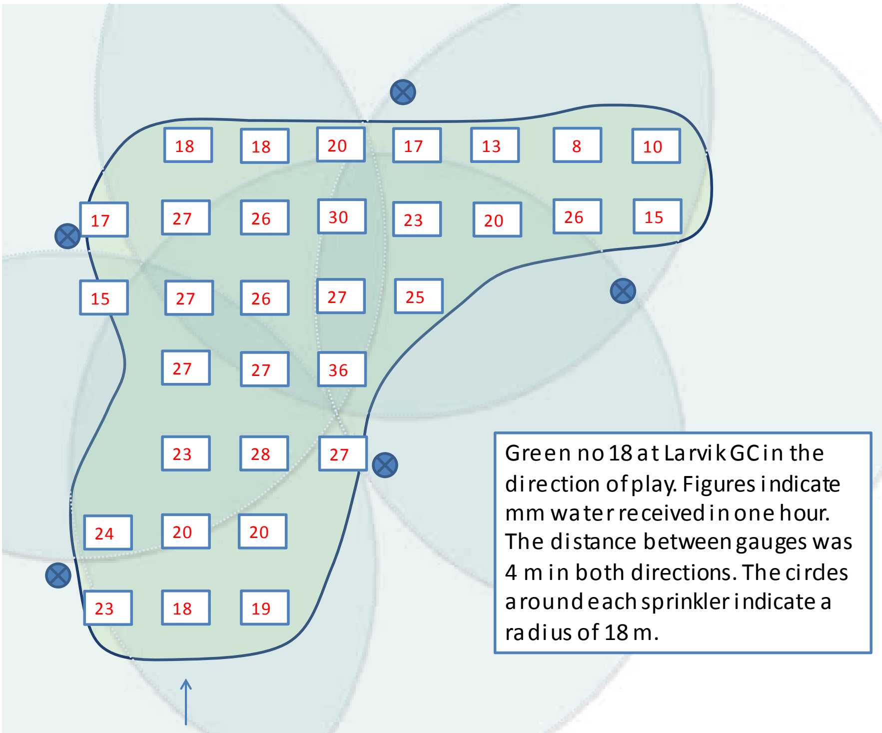


Figure 6 and **Photo 12.**
Green no 18 at Larvik GC, Norway. Please observe the poor turf quality in the central area which received most water and had the highest percentage of annual meadow grass. Photo: Agnar Kvalbein.

Irrigation of fairways

Because there are usually uncertainties related to root depth and plant available water reserves on fairways, we recommend that even the irrigation schedule on the fairway should be based on the TDR measurements on the greens. This is based on the information that there is little difference in water consumption between fairways and greens and as long as we avoid irrigating to field capacity. During a drought period, we therefore recommend to apply the same amount of irrigation water per area unit on fairway as on green.

If the fairway is sand-capped or on a sandy soil, the irrigation interval must be the same as on greens (usually 1-3 days). If the fairway is on a loam soil with larger water reserves, the irrigation interval and the number of mm applied at each irrigation event can both be doubled.
When you introduce deficit irrigation on the fairway, the water consumption (and energy) will be reduced so that it really shows in the irrigation balance!

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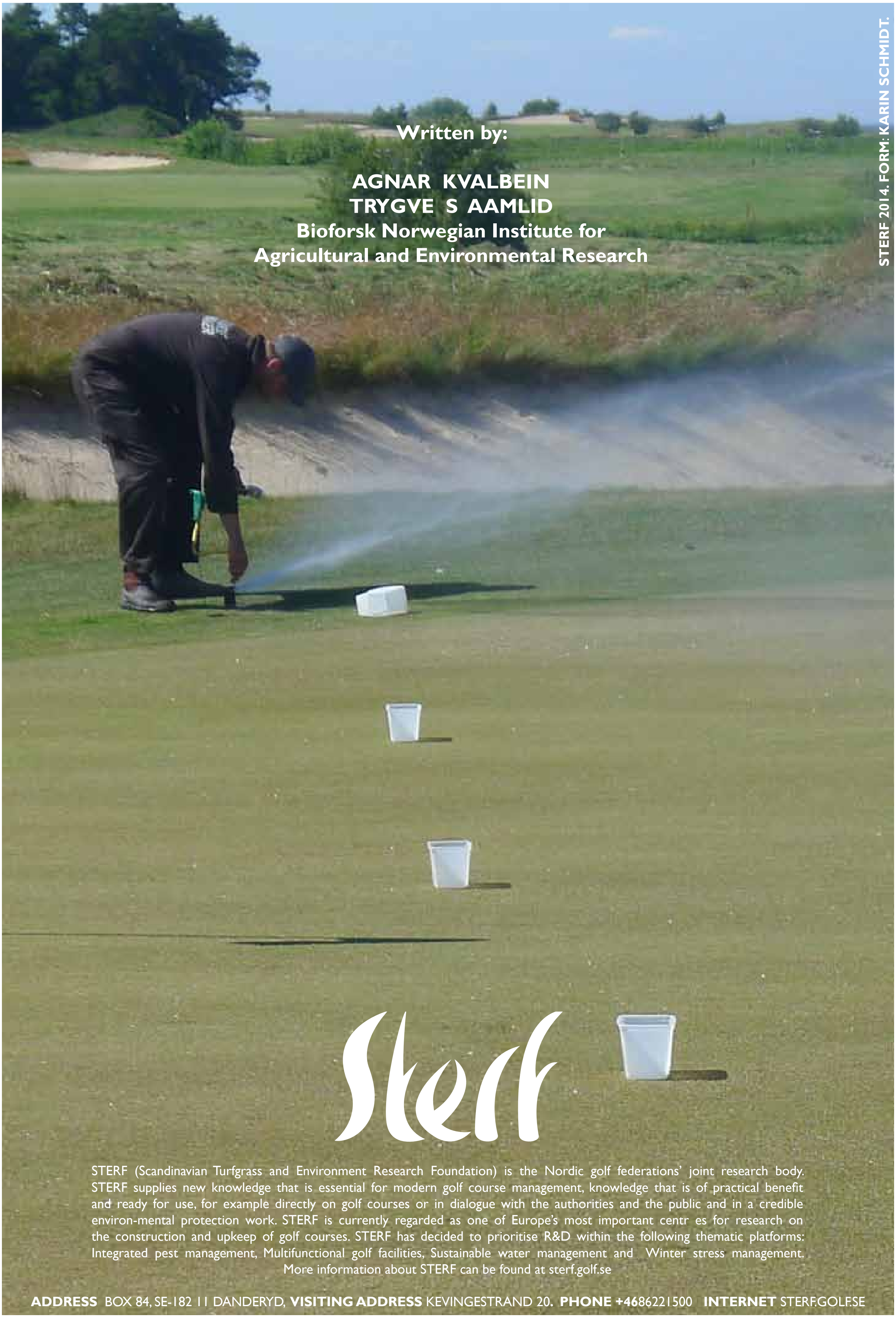

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Agricultural and Environmental Research

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STERF (Scandinavian Turfgrass and Environment Research Foundation) is the Nordic golf federations' joint research body. STERF supplies new knowledge that is essential for modern golf course management, knowledge that is of practical benefit and ready for use, for example directly on golf courses or in dialogue with the authorities and the public and in a credible environ-mental protection work. STERF is currently regarded as one of Europe's most important centr es for research on the construction and upkeep of golf courses. STERF has decided to prioritise R&D within the following thematic platforms: Integrated pest management, Multifunctional golf facilities, Sustainable water management and Winter stress management. More information about STERF can be found at sterf.golf.se

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