Chapter 14
Soil Hydrology

Zoltan Futo and Karoly Bodnar

Abstract The general introduction of hydrological cycle is followed by the roles of water in plant tissues and physiology. Water management has a predominant role in soil structure and fertility. Water acts as a solvent, as a reagent and as a transport medium. It participates in the physical, chemical and biological processes of the soil. Soils can be characterized as having different water balance depending on structure, location and environmental factors which gives information regarding the water supply of the area and the quantity of water provided for plants. Certain elements of cultivation practice are all important factors of improving the effectiveness of water consumption. The water uptake mechanism through the roots is discussed. Modern irrigation systems are used to prevent water shortage (water stress) to avoid yield loss, and it is advisable to start irrigation before the onset of the visible symptoms of water deficiency, before the moisture content of the soil falls below 50% of its water capacity. Calculation methods are given to determine the irrigation water requirement. A case study on effects of an up-to-date irrigation system on maize yields is presented. A tape drip irrigation method was tested on the level of yields and yielding elements of maize. Irrigation satisfying the 100% water requirement of the crop was supplemented with complex water-soluble fertilizer (N-P-K). The results show that the yields of sweet corn could be significantly increased in the very favourable water supply.

Keywords Hydrological cycle · Water management · Soil hydrology · Irrigation · Plant cultivation · Water influence on plant physiology · Groundwater · Water in cells · Hydrogen bonds

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1 Introduction

Water is a colorless, odorless, tasteless liquid. The pleasant taste of drinking water is due to the dissolved substances. Water is the only substance on Earth which can be found in all three physical states. Water density is the highest at +4 °C. In the winter only the top layer of rivers and lakes freezes over, so wildlife remains unharmed under the ice. In ice water molecules form crystals, i.e. a molecular lattice. Water is a good solvent. One liter of water forms approx. 1750 l of steam. As a result of exposure to high temperatures (e.g. molten metal), decomposition occurs, i.e. water is decomposed into hydrogen and oxygen – the mixture of which is the highly explosive oxyhydrogen. The density of water is maximal (1000 kg/m^3) on 4 °C, 998.2 kg/m^3 on 20 °C.

The oxygen and hydrogen found in water molecules have different electronegativies, thus oxygen attracts bonding electron pairs more towards itself. The resulting charge shift causes the polarity of the bond and the molecule as well. As a result, the water molecule has a negative and a positive pole, which greatly affects the behavior of water molecules in the soil as well as in plants. Water molecules are polar molecules, and as such, it is a good solvent of many ionic compounds, like table salt (NaCl, KCl, etc.). In the water molecule, oxygen atoms are negatively, while hydrogen atoms have poisitvely charged, which is caused by the charge shift described above. Due to their polar nature, hydrogen bonds are formed between water molecules, which give exceptional physical properties to water (Fig. 14.1). Due to the hydrogen bonds, water has a quasi-crystalline structure, which is continuously created, decomposed and reassembled. The colder the water, the stronger the hydrogen bonds are between water molecules and the harder it is for a water molecule to be removed from this aggregate.

Hydrology deals with the manifestations of water on Earth, the laws of the water cycle, and certain elements of the cycle. All of that water forms constitute the "water shell" of our planet, the so-called hydrosphere. In the hydrosphere, water occurs in all three states in a varied distribution in space and time. The hydrosphere overlaps with other terrestrial spheres: the Earth's solid rocks layer the lithosphere (up to a depth of about 5 km), the atmosphere, and the biosphere, respectively (Gombos 2011).

The water cycle, also known as the hydrological cycle, is the continuous and natural cycle of water in the Earth's hydrosphere (Vermes 1997), maintained by energy from solar radiation. Surface and groundwater, as well as atmospheric and groundwater content participate in the cycle (Fig. 14.2). Physical-meteorological factors of the terrestrial water cycle: solar radiation, temperature, air pressure, humidity and wind.

The initial phase of the cycle is evaporation. The water of rivers, lakes and oceans is constantly evaporating, but so are living organisms. Then the light mist rises, precipitates high, and forms clouds. Precipitation falls from the clouds, which can be liquid (rain) or solid (snow, ice). The fallen raindrops are absorbed by the soil on the one hand, and utilized by living beings in the course of their life. Water that infiltrated into the soil flows under the surface and collects. The water flowing

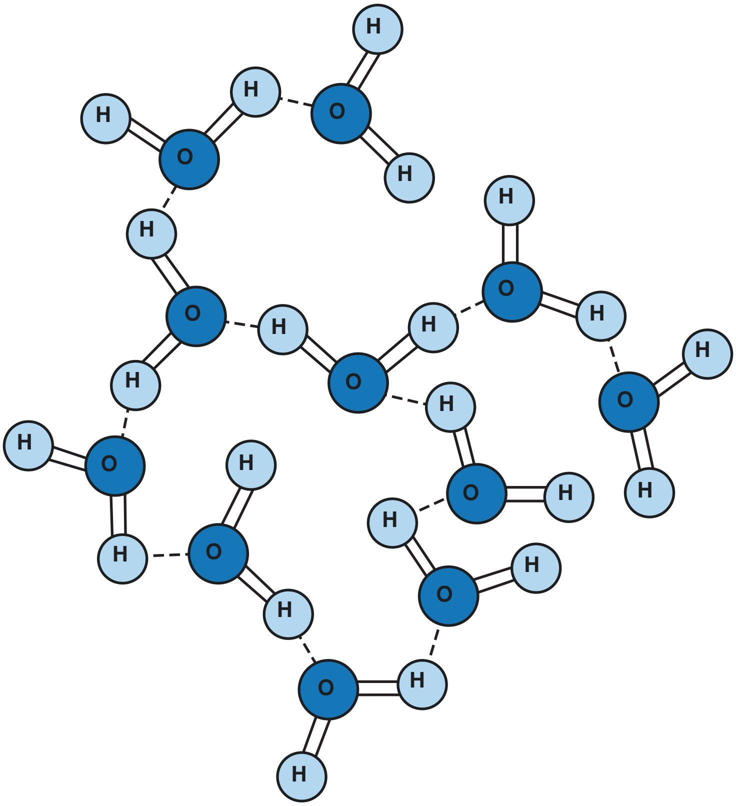

Fig. 14.1 Hydrogen bonds forming between water molecules

beneath the surface reappears on the surface in springs. Eventually, it swells into a small stream and then a river, and it flows into the sea, while its water is constantly evaporating. The volume of water is constant. Approximately 1386 million cubic kilometers of water are in constant motion. The steps of the permanent circulation of water are therefore: evaporation of surface waters and plants, cloud and precipitation, the leakage of precipitation into the soil, the uptake of water by living organisms, the emergence of groundwater, the evaporation of surface and transpiration of living organisms (evapotranspiration).

In the recent chapter the forms and movements of water in the soils and its roles in crop production are discussed with a special focus on the agricultural importance of these phenomena.

The water below the surface of the ground is the groundwater. Within this, we can distinguish several forms based on their location. The water in the top layer of the soil is the soil moisture. Above the first watertight layer, the water that fills the pores of the soil in a coherent manner is groundwater. Below (in water-bearing layers), the water between the watertight layers is called stratified water. Karst water is a form of water found in the fissures and passages of solid-textured rocks. Most of

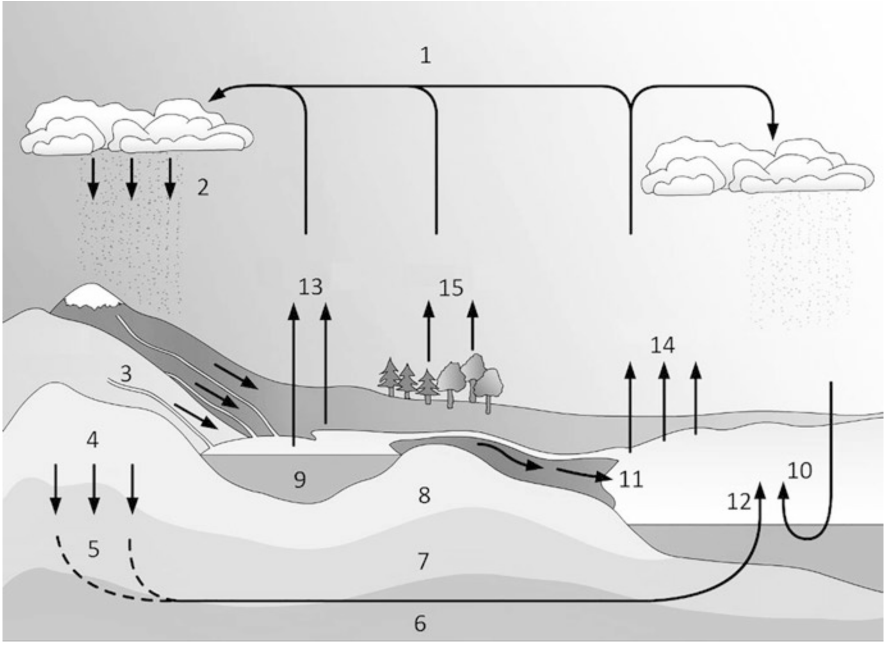

Fig. 14.2 The hydrologic cycle. 1 – Water storage in atmosphere and condensation, 2 – Precipitation, 3 – Surface runoff, 4 – Infiltration, 5 – Percolation, 6 – Groundwater, 7 – Soil moisture, 8 – Land, 9 – Lakes and rivers, 10 – Ocean, 11 – Surface outflow, 12 – Subsurface outflow, 13 – Evaporation from soil and water surface, 14 – Evaporation from oceans, 15 – Transpiration (Based on tudasbazis 2020)

the groundwater is generated by the leakage of rainwater into the soil. These are called infiltrating, otherwise known as infiltration waters. Between deeper layers the movement of water is called percolation.

The precipitating (condensing) water is formed by the cooling or precipitation of water vapor in the pores of the soil, mainly near the soil surface. From a water management point of view, the amount is not significant.

2 Role of Water Cycle in Plant Cultivation Area

2.1 The Role of Water in Plants

The evaporation of live vegetation, seas and land areas on Earth, and the continuous changes in the physical state of water vapor in the atmosphere maintain a constant water cycle, as evaporation is always followed by condensation. Plant vegetation contributes to this circulation with its own water turnover and management.

The water turnover of plants consists of the plant taking up the water, utilizing it during its physiological processes for the synthesis and construction of its own organism, and then evaporating it into the environment. Water management of plants is therefore a very complex, coordinated and highly regulated process consisting of water uptake and water loss. The complexity of the water management of plants is increased also by the fact that plants belonging to different ecological groups have considerably different mechanisms for it.

Transpiration is the evaporation of water through the stomata of a plant. Not only transpiration enables water uptake and continuous solute flow in the plant's transport system, but it also provides for the cooling of the plant. Due to its large heat capacity, water reduces the rate of temperature change in plants. Growing plant tissues are composed of 80–95% water. Plant seeds are the driest; they contain 5–15% water. The water content of chloroplasts and mitochondria is around 50%, while vacuoles might have 98%.

2.2 Water Cycle and its Importance on Plant Physiology

Water uptake and water loss in plants is continuous; under ideal circumstances, plants manage the available water. The water management of plants consists primarily of the available and disposable water resources, and the water built into the tissues and utilized by the plant during its life processes, then evaporated through the leaves.

Depending on their life stage, plant tissues contain large amounts of water in, but in general it can be stated that only a very small portion, 1–2% of the absorbed water is built into the plant's body components. A significant part of the water taken up exits the plant's body by its evaporation activity. However, all of this has a very important role throughout the plant's nutrient uptake, thermal management and organic buildup processes. Water absorbed by the plant and evaporated through the leaves is ideally in a state of equilibrium.

By comparing the two sides, a value characteristic of the plant's water management is obtained, the so-called water balance. Water balance can only be maintained securely if water absorption and water release are in accordance with each other. Water balance becomes negative when water supply does not cover the amount of evaporated water.

In agriculture, this often occurs in two situations. The first case is soil drought, when there is no adequate amount of available water in the soil, while the other is atmospheric drought, when the vapor and water extraction effect of hot, dry air is greater than what can be recovered by the plants through the roots. In either case, wilting and negative water balance can be experienced We define short- and long-term changes in water balance. During the day, the plant's water balance is negative (due to increased transpiration), which is restored during the night. This lasts for a rather short time. During dry periods, however, the water balance of the plant becomes increasingly negative due to the soil's diminishing water resources, which can only be restored in the next rainy period, or by irrigation.

The most important roles and functions of water in plant physiology:

- Water is the most important cellular component of terrestrial and aquatic plant organisms, since all cell components are in a dissolved state, therefore a significant portion of the living plant consists of water.
- Water is the solvent of mineral nutrients, as well as the transport medium of nutrient ions and dissolved assimilates (eg. sugars) in plants.
- It has a fundamental role in all biochemical conversion processes, since it is the reaction medium, as well as a component of organic material (sugars, carbohydrates, proteins, etc.) synthesis.
- Water is essential for sustaining the viability of leaves playing a central role in photosynthesis and carrying out assimilation activities, and for maintaining the specific water saturation degree of tissues.
- For the functioning of plant cells, an appropriate internal pressure (turgidity) is required, and the fundamental and essential basic component of this process is water.
- The temperature of the plant's body is strongly dependent on external temperature. Plants only have limited means for temperature control; one such example is the regulation of high temperatures by means of evaporation and transpiration, of which a main component is again water.
- Significant amounts of water are needed to achieve high yields through unimpeded photosynthetic processes. In the world of plants, it is very common that up to 450–850 l of water are required for the production of 1 kg of dry material.
- The clearest example of water release and uptake can be observed in the life of seeds: the maturation of seeds includes water loss (seed dormancy), while intense uptake is characteristic of germination (swelling and germination).

Water plays a special role in the life and organizational structure of plants. According to the physical laws of osmosis, the concentration difference between the plant cell and the environment determines the direction of water flow.

If the external medium is more diluted, water flows into the cell, among the plant's organelles, the vacuole and the cytoplasm are filled up with water, their volume increases, and the cell becomes swollen. The cytoplasm is pressed against the cell wall, which resist the cell's volume increase depending on its constant of elasticity. Therefore, pressure builds up between the cytoplasm and the cell wall, which is called turgidity. On the organizational level, the sum of each cell's turgidity composes the hydrostatic skeleton of the plant, which is essential for supporting its life. This plant hydrostatic skeleton collapses in a spectacular way if a significant water loss (wilting) event occurs.

If the external medium is more concentrated than the cell, or the plant loses significant amounts of water due to other reasons, water moves out of the plant, the vacuole and the cytoplasm shrink, and plasmolysis occurs. In this case, the turgidity value is zero, the first stage is reversible, but in the case of steady water shortage, the plant enters an irreversible wilting state. This state can lead to the death of the cell, but very often to the death of the whole plant.

The water turnover of arable crops is very complex. For the above-ground plant shoots, the direct source of water is air humidity or precipitation, while the indirect source is the water transported from the roots in the direction of the shoots. For the roots and subsurface shoots, groundwater is the direct water source, the availability of which, however, depends largely on the quality of the soil, its actual water content, and the water's motion in the soil as well. Therefore, water transport from the root to the shoot, and the development of tissues in the shoots that regulate water-loss are of great importance for terrestrial plants.

In addition to the aforementioned functions, water plays a fundamental role in the transport of minerals in plants as well. For the uptake and transport of minerals, that is, the mineral nutrition of plants is associated with water uptake. In the case of arable crops, minerals are taken up mostly, but not exclusively by the roots. Aqueous solutions absorbed by the roots have to be transported to all living cells of the plant. This transport process may occur in two ways:

- it can take place in the cell wall (apoplastic transport);
- the solution enters the root parenchyma cells (symplastic transport), and from there, the transport of the aqueous solution takes place in the differentiated transport vascular bundles (vessel elements).

This transport process assumes the presence of water as a transport medium in all cases, therefore this role of water is indispensable in plant nutrition.

2.3 Water Cycle of Soils, Water Management

Water management has a predominant role in soil fertility. Water acts as a solvent, as a reagent and as a transport medium. It participates in the (physical, chemical and biological) weathering, formation and degradation processes of the soil.

Water management of soils can be characterized by:

- the amount of water in the soil,
- its movement, and
- its spatial and temporal changes.

In terms of plant production, the fertility of soils is fundamentally affected by:

- the soil moisture content available for plants,
- water movement in the soil (influx and runoff, etc.) and
- the chemical composition of water (i.e. water valuable for crop production, or high salinity groundwater).

Soils can be classified into different groups in terms of water transport (Boorman et al. 1995). Soils can be categorized into four main types in terms of water transport, which are as follows (Fig. 14.3):

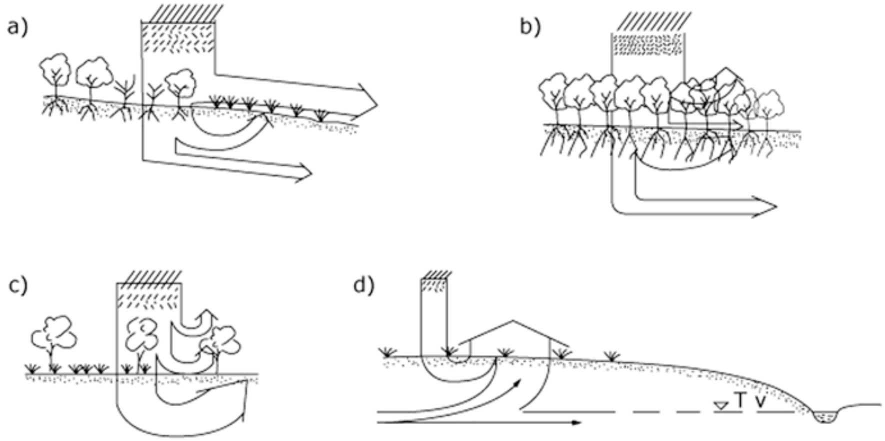

Fig. 14.3 Major types of water transport in soils (*Tv*: level of groundwater)

(a) Strong surface runoff (sloping soil surface, surface runoff, erosion damage) e.g. rocky skeletal soil.
(b) Leaching water flow, strong downward water movement (the greater proportion of the large amount of precipitation trickles into the soil, excessive leaching) e.g. luvisol.
(c) Equilibrium water balance (annual water flow balance of upward and downward water movements, alternations within the year; periodic motion of materials are typical, e.g. calcic chernozem soil.
(d) Evaporative water flow (predominantly upward water movement, low-lying areas, the impact of groundwater, low groundwater salinity → no salinization; effect of stagnant saline groundwaters → salinization) e.g. typical meadow soil, solonchak soils

Water capacity is the amount of water that can be absorbed by a given soil under certain circumstances, or retained against gravitational force.

Soil water capacity provides information about the soil's water content, the amount of water retained against gravitational force and the water supplying capacity of the soil. These soil properties help us make decisions about crop water and nutrient management.

Main types of water capacity (Fig. 14.4):

1. Field water capacity (FWC): The quantity of water that can be withheld by the soil against gravity under natural circumstances.
2. Maximum water capacity (WC_{max}): The quantity of water at which the soil pores are 100% saturated with water. This includes the large gravitational pores as well.
3. Minimum water capacity (WC_{min}): The quantity of water withheld against gravity in case the effect of soil water is negligible. FWC ≈ MWC (under natural circumstances, the values of field capacity and minimum water capacity are not significantly different from each other.)

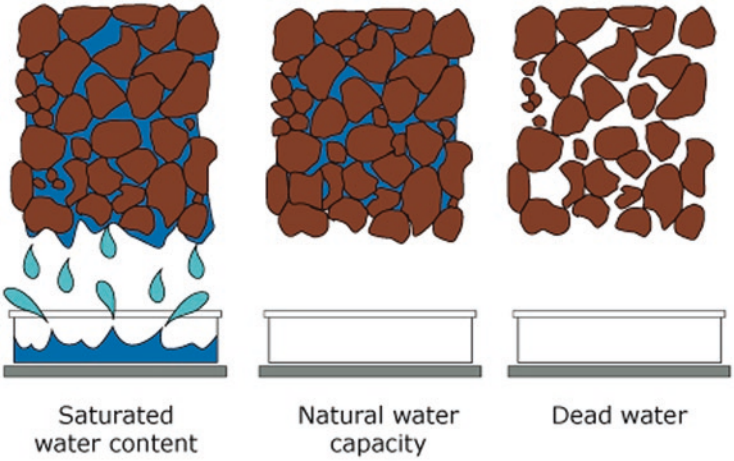

Fig. 14.4 Different forms of water capacity and the pattern of dead water content

4. Capillary water capacity (CWC): moisture content of the soil layer saturated by capillary action (in a 10 cm tall column).

It is essential to clarify two concepts regarding plant cultivation. These are: the dead water content of the soil, and the concept of water resources that can be taken up (available water). These concepts are necessary to clarify so that the total water content of the soil, which may vary depending on the soils, might not confuse the irrigation plan and crop production technology decisions.

Dead water is defined as the water content that is very tightly bound to soil colloids and in the smallest capillaries (smaller than 2 microns). The compaction force is greater than 15 atm (bar).

Determination of dead water (DW) content:

- using the wilting experiment: the vessels of test plants are allowed to dry out until only the dead water content remains, then we can infer the amount of dead water based on the wilting point;
- steel walled pF device: The pF device is capable of measuring the quantity of water that is still bound at 15 bar pressure.
- Calculated from the "Hy" value: The weight percent amount of dead water content can be inferred from the Hy values appearing in the soil test report. The method of calculation: DWc% = 4 Hy.

Available Water Content (AW) is the amount of water that is bounded by less than 15 atm (bar) of force. Available water is the form of water utilizable by plants, since it is bound to soil particles by less than 15 bars of pressure, so the suction pressure of roots can exceed it. Its calculation:

$$\text{AWmax} = \text{AWCmin} - \text{DW}$$

Table 14.1 The effect of soil types on the available and dead water content

	FWC	AW	(DW)	AW	(DW)
Texture	Volume %			In WC%	
Sand	10	8	2	80	20
Loam	31	16	15	51	49
Clay	46	13.	33	28	72

2.4 Water Capacity of Soils

The water binding capacity of soils is primarily the interaction between the solid phase (soil colloids, clay particles, etc.) and water, and it can be attributed to adsorption (adhesion) and capillary forces (Table 14.1). Adhesion moisture forms a thin layer of film on the surface of soil particles, but the impact of forces decreases rapidly farther away from the surface. The first layer of water molecules near the surface of soil colloids is bound with a great deal of force, ~50 bar which decreases with distance, and reaches the value below 15 bar that already available.

The water retention and lifting capacity of capillaries can be interpreted as an effect of adhesion forces and the force of attraction between water molecules (cohesion). A portion of the water entering the soil as precipitation of irrigation water is bound in the soil caverns, and this amount is called field water capacity. Water capacity is strongly influenced by soil structure, e.g. loose, coarse-grained soils like sand store less water (approx. 8–10%), and clayey, fine-grained soils can bind more water (max. 31%). Therefore, better structured soils can absorb and store larger amounts of water. In compacted soils containing a lot of clay, the bulk of the large amount of water (more than 70% of the water capacity) is in a firmly bound form, which increases the dead water content, and the amount of water available for plants becomes less.

2.5 Water Balance of Soils

Soils can be characterized as having different water balance depending on structure, location and environmental factors (Fig. 14.5). Water balance gives a good clue regarding the water supply of the area and the quantity of water provided for plants:

$$\mathrm{W_p} + \left(\mathrm{W_i}\right) + \mathrm{W_{cr}} + \mathrm{W_{inf}} = \mathrm{W_{ep}} + \mathrm{W_{tr}} + \mathrm{W_{min}} + \mathrm{W_{eff}} \pm \Delta W$$

Where the factors are the following:

$\mathrm{W_p}$ = recharge from atmospheric precipitation
$\mathrm{W_i}$ = amount of irrigation water
$\mathrm{W_{cr}}$ = rate of capillary rise
$\mathrm{W_{inf}}$ = recharge from influent waters

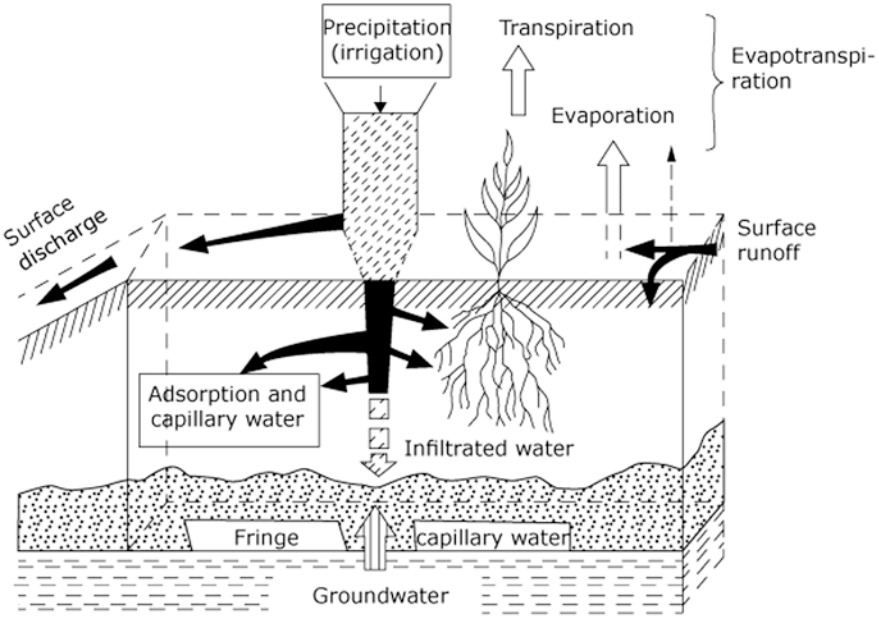

Fig. 14.5 Major factors of water circulation in soils

W_{ep} = evaporation loss of the area
W_{tr} = transpiration loss of the area
W_{min} = amount of percolating ground water
W_{eff} = amount of effluent water
ΔW = change in water storage of the area

When calculating water balance, excess precipitation and water losses of the area are also taken into account. Different soil types have different characteristics. In the case of loose, sandy soils, the primary loss factor in the formula is W_{perc}, the amount of percolating water, while this factor is of less importance in the case of well-structured loamy soil types, and it is almost minimal in the case of soils with clay-type physical structure. Therefore, water balance data give good clues not only for soil water balance or changes in water storage, but also for the components of water management parameters and the properties of the soil (Hunt et al. 2020). Water consumption of plants in field experiments can be well measured using lysimeters (Fig. 14.6). Lysimeters measure evaporation, transpiration, infiltrated water, adsorption and capillary water. The amount of water used for plant biomass can also be measured in lysimeters.

Fig. 14.6 Ploughland lysimeter, in a corn experiment

2.6 Basics of Plant Water Management

One of the most important conditions for the normal vital functions for higher plants is that their water balance – that is the ratio of water absorption and water consumption – shall be ensured for a long time without any prominent deficit.

The water balance of plants, however, is often in the negative range. Although the reason for that may appear to be very simple, still it is the result of an extremely complex phytophysiological process. Plants the functions of life of plants indicate that they evaporate more water than they can absorb.

Given the climatological conditions of Hungary this evaporation is so fast that the entire water content of the plant is replaced within a single day. It means that the water balance of the plant is very dynamic, but it is often fluctuating and extremely unstable. The amount of water absorbed by the plant depends on the extent of evaporation, the dimensions and effectiveness of the root system, and the availability of water in the soil. Water balance is regulated by two factors. One of them is the soil factor, the other one is the plant factor, the physiological status of the plant.

Scarcity of water modifies a number of physiological processes, e.g. it affects breathing (it stimulates the breathing of leaves, while reduces that of seeds due to their receding water content). It generally affects internal biochemical processes (e.g. it reduces the sugar content in tobacco leaves, and increases the quantity of nitrogenous compounds and nicotine in the cells). During the course of evolution plants have developed drought resistance to a certain extent, which depends on the species, and in particular on the given tribe (Nemeskeri and Helyes 2019). Nevertheless, even draught resistant plants are unable to fend off extensive water shortage lasting for a long time. Finally the plant dies in the end after an irreversible process of withering.

The amount of water "flowing through" the plant is incredibly large: during the entire growing season a sunflower or corn evaporates 200–250, or even more litres of water. The water requirement if fruit trees flucuates during the period of vegetation. Their water requirement is larger when their shoots are growing in the spring, and also when fruits are growing. In order to classify these periods, then the one with the biggest water requirement would be shoot growth taking place during the spring months. The second most water-consuming period is flowering and fruiting (the period of pollination and fertilisation), which generally takes place in April–May in our climatic zone. The third most water-consuming period is the one of intensive fruit-growth, the first phase of ripening, which, depending on the relevant fruit type, may last from July until even September. In the case of winter apple and winter pear this period takes place in August in our climatic zone. Of course, the earlier ripening summer fruits need a more abundant water supply earlier in order to be able to grow their fruits to the required size.

The peak of water requirement can be clearly identified in the lives of plants as well. Usually the most water-consuming periods are germination (in this case not the amount of water is important, but the presence of water required for the swelling of seeds is critical), the period around flowering, while the third most water-consuming period is that of intensive crop growth and grain filling.

2.7 Water Consumption of Plant Species and Plant Varieties

Certain elements of cultivation practice, such as soil cultivation, nutrition, crop rotation and plant protection are all important factors of improving the effectiveness of water consumption. The role of plant varieties should not be forgotten, either. Selecting the appropriate variety plays a tremendously important role in improving the efficiency of the available water quantity. In Hungary a sufficient number of varieties of the main arable crops are available for farmers.

There may be significant differences between the varieties or hybrids in terms of water requirement, water consumption and, in this context, drought tolerance. From amongst the characteristics of the varieties the length of the growing season affects water consumption the most. The length of the growing season determines the dynamics and also the quantity of water consumption. Generally speaking, shorter growing season results in less water consumption, therefore better drought tolerance, although obviously there are exceptions. In the case of winter wheat varieties a difference of 2 weeks means 50–70 mm difference in water requirement. As for corn, if the growing season is longer with a month, it will result an extra 100 mm water requirement.

Arable crops also have different water requirements. Paprika, for example, requires a lot of water. On hot summer days (30–35 °C) the plant requires even as much as 3 l of water for optimal growth and crop yield. According to the results of precise measurements, 20–25% of the plant's daily water consumption takes place during the hot and dry period between 12–14 p.m.

The growth rate of the root systems, root mass, and, in this context, the effectiveness of absorbing water and nutrients from the soil may be different in the case of each variety. Water-stress may affect the quantity and quality of the crop yield in a significantly different way, depending on the life stage of the plant it occurs (before or after entering the generative phase). Water-stress occurring during the early period, in the stage of vegetative growth significantly decreases the reproduction potential of the plant. The vegetative growth stage of variables with shorter growing season is shorter, therefore water shortage causing serious damage is less likely to occur.

Varieties with better production potential utilise water more efficiently. Amongst irrigated circumstances, in case the ecological conditions make it possible, it is advisable to choose a variety with longer growing season in order to exploit better production potential.

Evapotranspiration, the extent of water vapour released by the soil and the vegetation mainly depends on the features of vegetation. The connection between the surface of the vegetation and the extent of vapour release is not linear, as the amount of energy per surface unit is inversely proportional to the extension of the surface. The results of lysimeter studies demonstrate that among identical circumstances the water requirement related to the leaf area of the varieties of the same plant species with different leaf areas increases at a decreasing rate. This correlation may be characterized with a saturation curve (Szalai 1989).

During irrigation-related researches the water consumption of plants can be precisely quantifiable and measurable. Based on the research of Sándor Szalóki (1991) the water consumption of main plant species can be determined, which were measured on the lysimeter-plant of IRI (Irrigation Research Institute) during water management research projects (Table 14.2).

2.8 *Water Uptake of Plants*

Higher terrestrial plants take up water with their cuticle-free roots, the emission of which is reduced by the cuticle and the regulated movement of the stoma. In the case of higher plant species water uptake via the parts above the ground is minimal (Berry et al. 2018).

On the root itself water is absorbed by the root-hairs. The root-hairs are located on the root tip, close to the dividing, young cells. Root-hairs are in close connection with the particles of the soil, and absorb nutritive salts from it in the form of of an aqueous solution. Roots keep growing in the soil until they reach the depth where water supply is sufficient.

Table 14.2 The water requirement of plants and the main characteristics of irrigation in dry years occurring with a frequency of 20%

Designation	Critical period	Rooting depth	Moisture requirement	Water requirement (mm)	Irrigation water (mm)
Sugar beet	June-August	D	M	550–600	180–250
Maize (medium-late season)	July-August	M	M	400–550	150–200
Fertilisation of soy bean	July-August	M	MB	400–500	120–180
Alfalfa	June-August	VD	A	600–700	200–300
Intensive lawn	May-September	SH	VB	600–700	300–400
Table grapes	June-July	VD	M	570–670	150–200
Apple, pear (dwarf variety)	July-August	M-D	B	500–600	150–250

S short, *M* medium, *B* big, *VB* very big, *SH* shallow, *D* deep
Based on Szalóki (1991)

The quantity of utilisable water resources in different soil types may extremely vary. In sandy loam and loam soils the ratio of useful and dead water is ideal. Clay soils contain too much colloid material enclosing a larger quantity of dead water, which is water bonded with such a force that it becomes unabsorbable for the plant.

The water uptake of roots is also affected by the temperature of the soil. At lower temperatures the resistance of roots to water flow increases, the intensity of vegetable metabolism decreases, root growth, and, consequently, the pace of water uptake and water transportation slows down because as a result of cooling down the inner substance of cells becomes denser.

Extremely high temperature (35 °C) also affects water uptake – usually it decreases absorption.

Plants are able to absorb both the gravitational water moving freely amongst the soil particles and the weakly bonded water in the capillary columns of the soil. The water of hydration strongly bonded on the surface of soil particles is unabsorbable for plants. Water can only be absorbed if the water potential of the root-hairs is more negative than that of the soil. The active root surface of cultivated plants is very big. The most active root-hairs are around the renewing root tip.

The roots growing in the soil can absorb water in case their own water potential is lower than that of the soil. It can be demonstrated that the changes in the water potential of the root system are directly proportional to that of the soil. The difference varies between 0.2 és 0.8 MPa depending on the water supply. The root system is able to actively reduce its water potential. It takes up the ions required for its growth, and, of course, for water absorption, and stockpiles them in the cell walls and the vacuoles of the cells. Increased salt concentration reduces water potential value, as a result of which the water potential of the root system decreases as compared to that of the soil. This allows the absorption of water from the soil zone located next to the root system, which, in turn, begins to desiccate. Therefore the water potential at the soil part neighbouring the plant also decreases. The desiccation caused by the root system also affects soil zones being farther away, thus a water potential gradient pointing towards the roots are established, which causes water flow towards the roots. This effect applies in a distance of approximately 8–10 cm from the surface of the roots.

In dry weather, when there is no replacement of precipitation for a long time, the soil gets more and more desiccated. Its water potential reduces to such an extent that the root system becomes unable to cause a water potential difference by uptaking ions, thus the water potential of the root system and the soil equalises. In such a case the plant is unable to absorb water fron the soil, but it still loses water via its stomas. Finally the turgor pressure decreases and the plant wilts.

The drier the soil is the more negative its water potential becomes to which plants adapted in several different ways. By increasing the concentration of the solution in the vacuoles, they decrease their osmotic pressure, thus their water potential becomes more negative than their environment. Plant root hairs are able to grow towards soil zones with higher water content, which is required because the movement of water in the soil is slow. The roots may grow asymmetrically, which means that the root hairs remaining dry decay while others vigorously grow. In case the soil desiccates to such an extent that its root system is unable to absorb any water from it, then the plan starts to wilt. It is generally accepted that in case the water potential value of the soil reaches −15 Bars, then it is called permanent wilting point. At this stage cultivated plants begin to perish in case they do not get any water, which means their irrigation shall be started immediately.

2.9 Excess of Water and its Effects

Conditions indicating extreme water balance situations are particularly important for horticultural professionals. The system of conditions leading to harmful water abundance, its reasons and prevention, the possibilities of mitigating the related risks are all important topics with great relevance.

The general objective of agricultural water management is not to let water become a limit of effectiveness during the process of production. Its fundamental aim is to prevent or even cease water management conditions being detrimental to agricultural production.

During the course of crop production water management interventions enable to prevent the occurrence of unfavourable water management situations (drought, harmful excess water), and to cease any existing harmful condition as soon as possible.

Over the last decades drought in Hungary has become increasingly frequent, although certain regions of the country the extent of this change may be different. Therefore in connection with agriculture it is expected that the desired amount of crop yield shall be achieved with a decreasing quantity of water. As far as finding a cure to the problem is concerned, settling for irrigation can only mean a partial solution, as both our surface- and groundwater resources are limited. The decreasing quantity of fresh water reserves is a global problem, the significance of which has not yet been sufficiently recognised by humanity.

Due to the water saturation in the pore space volume, constant oxygen excess is formed. The diffusion of O_2 is approximately 10,000 times smaller than in the air, therefore its replacement from the air practically ceases to exist.

In an oxygen-deprived environment the facultative and obligate anaerobic microorganisms become dominating. Anaerobic decomposing processes come to the fore, therefore, instead of the mineralisation of organic materials, they are reduced and hydrocarbons are formed. Under certain conditions anaerobic microorganisms reduce H^+ ions partially into H_2 molecules, while a part of organic materials are reduced into methane (CH_4). During the reduction processes, for example, NO_3^- ions are transformed into NO_2^-, and through the intermediary of N_2O, they form N_2, while as a result of further reduction they are transformed into NH_4^+ ions, Mn^{4+} and Mn^{3+} are transformed into Mn^{2+}, and Fe^{3+} turns into Fe^{2+}. Reduction of SO_4^{2-} ions into H_2S may also commence; that is why such soils have a characteristic sulphuric acid smell. As a result of long-lasting anaerobic conditions a large amount of reduced compounds and ions may accumulate in the soil, which, on the one hand, results in the deterioration of the soil structure, while on the other hand it is being extremely unfavourable concerning the nutrition of plants. The reduction potential of soils is primarily determined by their airiness, while temperature and pH-value play a modifying role.

Parallel with the progress of processes taking place in the soil as a result of the constant abundance of water, plant communities preferring, or tolerating shallow water coverage or high ground waters are quickly formed.

2.10 Determination of the Soil Water Content

According to traditional views, irrigation was started when the crop was already showing the signs of water deficiency. Research has shown that in the assimilation activity of a plant under water stress conditions is restored only days after the improvement of water supply. When symptoms are visible, such changes have occured in the plant that are still reversible for a while, but can be restored only in a long period of time.

Modern irrigation is used to prevent water shortage. In order to avoid yield loss, it is advisable to start irrigation before the onset of the visible symptoms of water deficiency, when the moisture content of the soil falls below 50% of its water capacity.

At this time, the plants are not yet in a state of water stress, but the moisture content of the soil is unable to cover their water requirements. At less than 30% of water capacity, plants start showing the signs of wilting, and they reach the condition of water stress.

Based on the water balance equation, the estimated current soil moisture content can be determined by daily calculation. The actual values reduce evaporation, precipitation increases the initial set humidity. Using the results, we can determine the starting date for irrigation. Of course, if the area was irrigated, the applied quantity of water is added to the precipitation. Naturally, the current soil moisture content may also be determined by measurements, e.g. using tensiometers that can be installed in various depths. Tensiometers are used for the measurement of soil moisture suction, from which the moisture content of a given layer can be inferred. A cup-shaped object made of a variety of porous materials (plaster, ceramics, plastic) is sunk into the ground, where it is connected to a vacuum monometer by a tube.

The theoretical basis for conductivity based measurement is the significant difference between the conductivity of solid soil and water. Electrodes are inside a gypsum block, their life span is limited, about a year, but there can be significant differences. Resistance increases in proportion with the decreasing moisture content. Soil moisture content can be measured with these tools more accurately in lower ranges, although as moisture content increases, measurement errors increase as well. The measurement is affected by the salinity of soil water content as well.

Methods based on capacity measurement provide rapid result, and they continuously supply data after installation. The theoretical basis for this is the difference between the dielectric constant of different materials. It is a widely used method due to its ease of use.

The method based on the measurement of neutron scattering is fast, and is therefore also suitable for frequent measuerments; its disadvantage is that the device is expensive (Vereecken et al. 2015), probe pipes have to be installed, and in the top 30–40 cm layer where the soil is disturbed, the outcome is uncertain.

Preliminary results show the NASA Land Information System (LIS) model is suitable for estimating percolation indirectly from the equation of soil water balance. Outcomes of deep percolation rates are connected with precipitation meanwhile coupled with the topography. The relationship between surface and ground-water flow is taken into consideration in the LIS model (Elbana et al. 2019).

The current soil moisture supply of the given day is determined by measurement or calculation, then using the daily evaporation values, the number of days for which soil moisture content will be enough for the plants can be estimated. The result of the calculation can be regarded as estimation even with the utmost care, because many other factors are impossible to take into account. For example, precipitate is not utilized in 100% usually – and water moves laterally in the soil as well, and the upper layers may be moistened by the water rising from the lower layers, even if ground water is deeply situated.

Water requirement (wr) is identical with the actual water consumption of stocks of plants with optimal water supply. Calculation of the water requirement of plants:

- by measuring the water balance of lysimeters (cultivation tanks lowered into the soil), by applying different types of lysimeters: floating, weighing and compensating lysimeters;

- by measuring field water balance: one of its preconditions is optimal water supply (satisfying statical water requirements), which enables unlimited water absorption of plants;
- with simulators: meters measuring surface-water evaporation where the surface of evaporated water can be modified, thus imitating the changes in the leaf-surface of plants, therefore its evaporating procedure;
- with calculation, modelling.

Determining water requirement (wr) with simple lysimeters (Zsembeli et al. 2018; Sołtysiak and Rakoczy 2019): this method is the most reliable, the water balance of cultivation tanks lowered into the soil can be easily measured and traced. Its greatest advantage is that there is no surface onflow and leakage, and that the quantity and quality of water leaking and flowing through the soil can be measured. While implementing the method, however, attention needs to be paid to avoid any occurrent edge- or oasis-effect, together with the accuracy of irrigation.

2.11 Calculation of the Irrigation Water Requiretments

The amount of irrigation water can be calculated knowing the water requirements of the plant, the amount of precipitation and the moisture of the soil. The starting available moisture of the soil and the amount of the precipitation are subtracted from the water demand.

$$\mathrm{IW_r = W_r - W_0 - P\left[mm\right]}$$

- IW_r – irrigation water requirement (mm)
- W_r – water requirement of the plant (mm)
- W0 – the starting available water content of the soil (mm)
- P – amount of precipitation (mm)

The amount of precipitation is not previously known, and the fault of prognostication is very high. This can be calculated with the area-specific average precipitation data, therefore irrigation water requirements can be determined in a certain level of probability. If the precipitation is measured, the calculation based on the averages can be corrected by the actual measurements. This way, the calculation becomes more accurate.

The amount of the irrigation water is usually measured in mm or m^3/ha. Conversion is simple: 1 mm of moisture content means 10 m^3 water on 1 ha. It is advisable to carry out irrigation in a way that the dispersed water amount is 70–80% of the total water capacity of the soil. Dispersion above 80% or by the total water capacity can have several negative effects and bear a great risk:

- Moisture content above the static water demand prevents the root system to take up the required oxygen amount, therefore the water and nutrient uptake is being impeded, and damages can occur in the root fibers.
- The microbiological life of the soil changes due top the excessive moisture content, denitrification becomes dominant, and nitrogen loss can occur.
- Chemical processes in the soil shift toward negative reduction, and poisonous reduced ions can develop.
- The structure of the soil is damaged, proliferation can occur.
- On slope areas, run-off water and erosion problems can occur.

To calculate irrigation water needs, the losses during application must be considered, besides the irrigation water needs. Losses originate from evaporation, leakage and run-off water. Losses change depending on several factors. Evaporation losses, for example, primarily depend on the temperature and humidity of the air, droplet size and wind conditions. Losses caused by run-off water are affected by the irrigation intensity, the water capacity of the soil and the slope of the fields.

$$\mathrm{IW_n} = \mathrm{IW_r} + \mathrm{E} + \mathrm{L} + \mathrm{R}\left[\mathrm{mm}\right]$$

- $\mathrm{IW_r}$ = irrigation water requirement
- E – evaporation loss (mm)
- L – leakage loss (mm)
- R – run-off water (mm)

Irrigation water requirement can be calculated by the dispersion efficiency as well: [mm]

$$\mathrm{IW_r} = \mathrm{IW_d} / \eta$$

- $\mathrm{IW_r}$ = irrigation water requirement
- η = dispersion efficiency

Efficiency depends on the irrigation conditions, usually varies between 0.7 and 0.95.

Traditional irrigation practice disperses a higher amount of water at once (even 60–80 mm). This is disadvantageous from several viewpoints. This method does not consider the requirements of the plant, and water excess can negatively affect the vegetation, the microbiological life of the soil, the chemical processes and the soil structure. Some damages can be permanent, for example the structure damage of the soil. Its advantage is to decrease the number of irrigation turns, and due to less relocation, treading causes less damage and it requires less manpower.

The spreading practice of modern irrigation uses lesser water standard with more frequent irrigation. A single dose is 15–30 mm. This submits to the requirements of the plants. The method can be started earlier and can be finished later, therefore it lengths the irrigation season. This means better utilization of machines and best irrigation practices (Chartzoulakis and Bertaki 2015). Due to lesser water amounts, this enables irrigation of soils that did not allow irrigation due to low water capacity.

Its disadvantage is the frequent relocation, although with modern irrigation equipment (linear system, center pivot) this is not a problem. Lesser water amount means increased evaporation loss.

3 Some Results of Irrigation Experiments (Case Study)

In 2016 and 2017 the effect of tape drip irrigation was tested on the change of corn yields and yielding elements of maize (Futo and Bencze 2018). In the study the Aqua Traxx tape drip system was used, sold by Metra Company. During the experiment, non-irrigated (control) plots were used, then plots satisfying 75% and 100% tape drip irrigation parcels in the maize water requirement and finally, irrigation satisfying the 100% water requirement was supplemented with complex water-soluble fertilizer (N-P-K) in the fourth treatment. In 2017 a humic acid treatment was used instead of water-soluble fertilizer. In the experiment, we investigated a leading Pioneer hybrid, a leading Monsanto hybrid, and a hybrid sweet corn of Martonvasar (Hungary).

The soil of the experiment is characterized by the fact that its physical characteristics is clay, as for its acidity it is acidic and slightly acidic, the cultivated layer does not contain $CaCO_3$, and the N-content of the soil is medium ranged based on humus content. The water management of the soil is characterized by poor water flow capability and high water retention capacity. The cultivated level is compressed, its porosity, and within that, the ratio of gravity pores is smaller.

The results show that water supply increased the relative chlorophyll content of maize only at 100% water demand (Table 14.3). The 75% water supply this year did not differ significantly from the results of the control irrigation plots, due to the excellent precipitation distribution.

First of all, the average yield of sweet corn was examined, which occured only in the 2016 study. During the measurement of the averge yields, we compared the yields of plots without irrigation (control), the irrigated plots to 75% water demand, the irrigated plots to 100% water demand and the irrigated plots with fertilization.

Table 14.3 The relative chlorophyll content of maize in 2016–2017. (SPAD value)

	Control	75% water-based irrigation	100% water-based irrigation	100% water-base and nutrient solution
Sweet corn	41.7	41.6	46.1	46.6
P9903	43.2	43.5	46.7	46.8
DKC4541	43.0	43.6	46.6	46.8
Average 2016	42.63	42.90	46.46	46.73
P9903	44.1	43.7	45.9	46.4
DKC4541	43.2	43.9	45.8	46.7
Average 2017	42.80	43.17	45.67	46.33

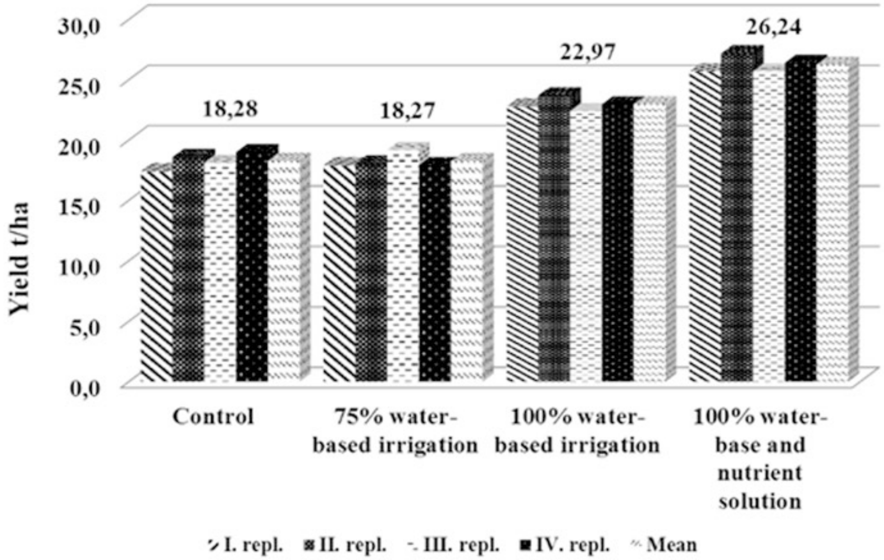

Fig. 14.7 The average yield of sweet corn in a tape-drip irrigation experiment 2016 (Szarvas, Hungary)

The yields of sweet corn were expressed by a higher (~60–70%) moisture content than the average and a cob harvest weight.

From the results, it can be seen that the yields of sweet corn could be significantly increased in the very favorable year 2016 by the use of tape drip irrigation technology (Fig. 14.7). Due to the favorable precipitation, there was no difference between the yield of parcels without irrigation (control) and those with irrigation of 75% water demand in the experiment. However, the crop-enhancing effect of irrigation, which satisfies the entire water demand of the plant, was very significant even in this year's favorable water supply. The yield of sweet corn reached 22.97 t/ha, which is very favorable. This yield in the experiment was only surpassed by the yields of the plots with nutrient supply, the yield reached 26.24 t/ha.

In the next group of studies, we examined two feedstuff maize hybrids whose crops were monitored during the test. The analysis of the yields of feedstock corn showed similar results in 2016 than sweet corn hybrid (Figs. 14.8, 14.9, 14.10 and 14.11). There was no difference between the yields of no irrigation and the yields with irrigation that meet the 75% water demand. This was due to the satisfying amount and distribution of precipitation. However, the total water demand of the plant could not be covered by the naturally falling rainfall even in this favorable year, which meant that the yield could be increased by satisfying the 100% of water demand of corn in 2016. The yields increased by 22.3–24.5% compared to the yields of control plots.

In 2017 precipitation was much less favorable, and precipitation in the growing season did not reach the 30-year average values. Therefore, average yields were significantly lagging behind the results of the previous year.

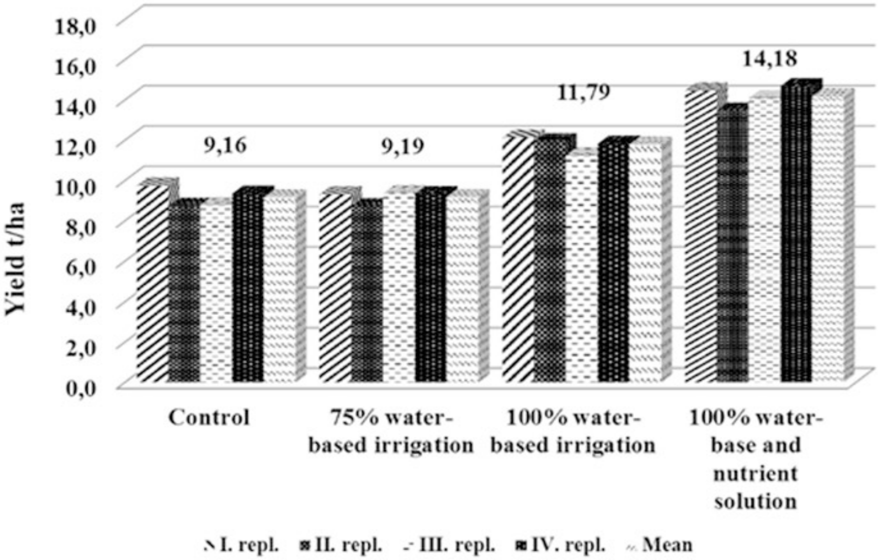

Fig. 14.8 Evolution of the yield of P9903 hybrid in a tape drip irrigation experiment 2016 (Szarvas)

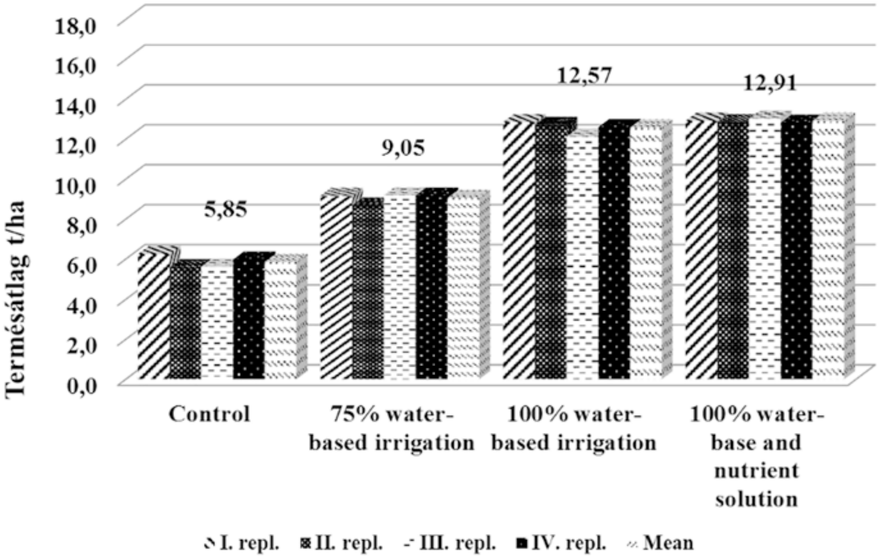

Fig. 14.9 Evolution of P9903 hybrid crop average in a tape drip irrigation experiment 2017 (Szarvas)

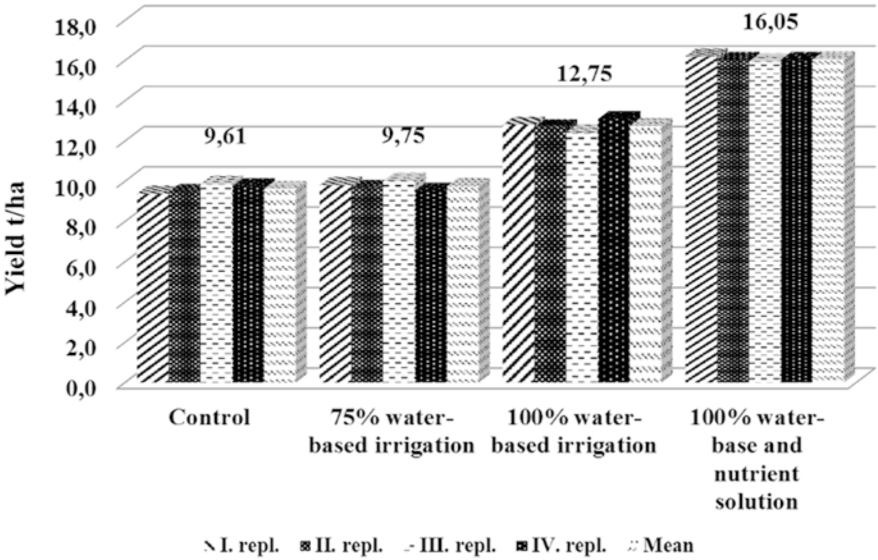

Fig. 14.10 Evolution of the DKC4541 hybrid yield ratio in a tape drip irrigation experiment 2016 (Szarvas)

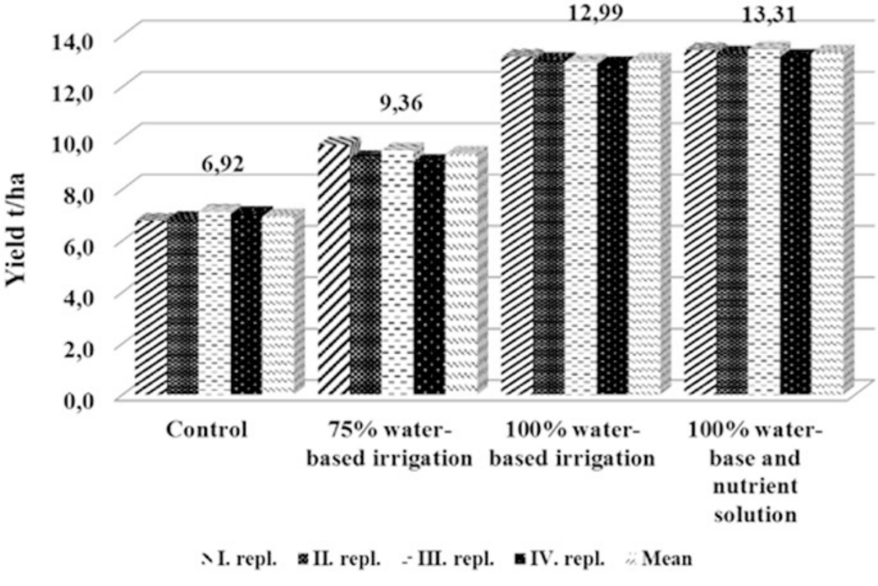

Fig. 14.11 Evolution of the DKC4541 hybrid yield average in a tape drip irrigation experiment 2017 (Szarvas)

The largest drop in yields compared to the previous years was on control plot of no irrigation. This is mainly due to the low precipitation period of maize water supply (July, August). With irrigation of satisfying the 75% of the water demand of the plant, the yields have increased very strongly, for both tested hybrids it exceeded 9 t/ha (9.05 and 9.36 t/ha).

If the water requirement of the plant was 100% satisfied during the irrigation, yields of 12–13 tons of hybrids were formed. The favorable water supply resulting from irrigation in hybrids shows that the decreasing effect of ever-increasing dry periods in climate change is significant, yields decreased in the control plots with bad water supply by 6.72 t/ha (P9903) and 6.07 t/ha (DKC4541).

In 2016, the nutrient parcels could further increase this, which is primarily due to the favorable phytophysiological condition of the plant that the plant immediately comes to the dissolved form of nutrient in the root hair zone of the root. This also refers to the important fact that optimal nutrient supply is possible only in the presence of sufficient amounts of water in the form of being available for the plant. The average yield of the plots with nutrient supply ranged from 14.18 to 16.05 t/ha, which reached the limit of the economically favorable production and profitability by the results of the experiment.

In 2017, instead of the conventional nutrient solution, a humic acid treatment was tested by applying tape drip irrigation. As a result of the treatments, similarly to year 2016, we could measure a further increase in crop average. The yield increase in 2017 was 340 kg/ha (P9903 hybrid) and 320 kg/ha (DKC4541 hybrid).

4 Conclusions

Overall, it was found that tape drip irrigation of maize is of very low water-use, energy-efficient and generally efficient irrigation technology, which can be a major domestic technical innovation for maize irrigation in future for intensive farming.

The yield of maize can be significantly increased by improving the water supply of the plant. In many areas, only little water is available for irrigation. The effect of drip irrigation in our experiment was investigated for corn yields in 2016 and 2017. In 2016, yields increased by 22.3–24.5% compared to the yields of control plots, while the yield gains in the drier year of 2017 reached 46.73–53.46%. In our experiment, the growth of the average yield was economically measurable.

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