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DIURNAL DYNAMICS OF WATER INTAKE BY ROOTS OF CELERIAC

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ABSTRACT

The study presented in this paper was concerned with the search for a method for determination of the temporal and spatial distribution of the intensity of water intake by celeriac roots. A field experiment carried out permitted the demonstration of the applicability of the TDR technique for the determination of the dynamics of moisture in the active layer of soil surrounding celeriac roots. Knowledge of the dynamics was used to design a water balance in which the only unknown was the amount of water taken up by the crop under study. It was found that water intake by celeriac roots takes place primarily close to the axis of symmetry of the plant, in the layer immediately adjacent to the main root. Moreover, it was found that approx. 90% of water is taken in by the plant during the daylight period. The information may be treated as indicative in the design of irrigation systems placement – e.g. of drip-irrigation lines, and of the timing of their operation. Ultimately, it was demonstrated that drip-irrigation lines should be located as close as possible to the centre point of celeriac roots and coincide as much as possible with the axis of symmetry of the plant, and that the irrigation systems should be turned on only during the daytime.

Key words: TDR technique, root celery, water requirements.

INTRODUCTION

USA is the greatest producer of celery in the world. The celery cultivation areas are concentrated mainly in the states of California and Florida, and the annual crops are at the level of 700,000 tons. Poland, on the other hand, is the greatest European producer of celeriac, the production of which, at the level of 109,100 tons, is approximately twice as high as that of the producers classified as runners-up, i.e. France and Holland [6,15]. All celeriac cultivars require large amounts of water in the course of the vegetation period [1,9,11,14]. In dry years, the necessary amount of water supplied additionally attains the level of as much as about 250 mm. The result of such irrigation is crop yield increase by 38% up to even 100%. Moreover, satisfying the optimum water requirements of the plants permits avoidance of unnecessary growth of lateral roots. The benefits resulting from irrigation are, however, related with the costs involved in supplying water at suitable times and locations, so that the largest possible amount of the water is taken up by the plants. This requires detailed knowledge of the spatial and temporal distribution of water intake by celeriac roots.

The objective of the study was the presentation of a method for the determination of the intensity of water intake by celeriac roots with the temporal (diurnal) and spatial (with relation to the centre point of the root) variability shown.

MATERIAL AND METHODS

In recent years, more and more extensive application of the TDR technique for moisture measurement in porous media is observed. Soil moisture measurement by means of apparatus based on that technique is virtually non-invasive compared to the conventional methods. This permits measurements to be taken, at high levels of accuracy, several times at the same point. Moreover, the design of elements controlling the operation of such a meter permits the recording of moisture readouts at relatively high frequency, even at 1 minute intervals. Continuous monitoring of moisture constitutes the basis for building the water balance for any designated soil spaces, e.g. within the root mass of a plant [7,8,16]. Fig. 1 presents a proposal for the division of the active soil zone surrounding a celeriac root. The markings in Figure 1 can be used to calculate, for each of the ten spaces, the increment or loss of water volume in time Δt, based on the relation [1]:

$$\Delta Q_i^{\Delta t} = \frac{Vi\left(\theta_i^K - \theta_i^P\right)}{\Delta t} \quad , \tag{1}$$

where:

$\Delta Q_i^{\Delta t}$ – increment of water volume in i-th space in time Δt, [$cm^3 \cdot h^{-1}$],
V_i – volume of i-th space, [cm^3], ($V_i = P_i \cdot L$; P_i – i-th space cross section area, [cm^2],
L – plant spacing in a row [cm]),
θ_i^P – initial moisture content by volume in i-th space, [$cm^3 \cdot cm^{-3}$],
θ_i^K – final moisture content by volume in i-th space, [$cm^3 \cdot cm^{-3}$],
Δt – time step, [h],
i – index of soil space, i=1.2...10.

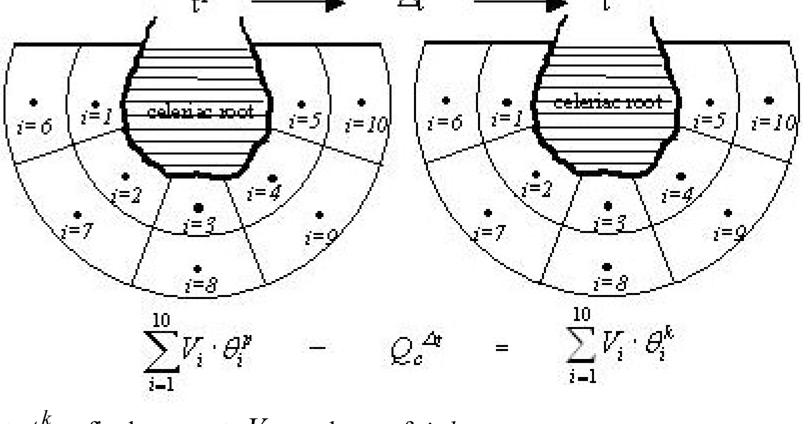
Increase in the water volume within the whole active soil space can be calculated as the sum of increments $\Delta Q_i^{\Delta t}$:

$$\Delta Q_c^{\Delta t} = \sum_{i=1}^{10} \Delta Q_i^{\Delta t} \ , \tag{2}$$

where:

$\Delta Q_c^{\Delta t}$ – increase in water volume in the active soil space in time Δt, [$cm^3 \cdot h^{-1}$], other designations as in relation (1).

Fig. 1. Dynamics of soil moisture around celeriac root as information on the intensity of water intake by the plant (1-10 – points of probe placement)



t^P – initial moment, t^k – final moment, V_i – volume of *i-th* space,
θ_i^P – (θ_i^k) – initial (final) moisture in *i-th* space, $Q_c^{\Delta t}$ – amount of water taken in by the root mass.

Ultimately, the values $\Delta Q_i^{\Delta t}$, $\Delta Q_c^{\Delta t}$ may be accepted as the amount of water taken in be celeriac roots in time Δt, if the following assumptions are adopted:

- the condition of selectivity is met (i.e. changes in moisture θ_i result only from water intake by plant roots, and not e.g. from surface evaporation of the soil or from rainfall),
- moisture measured at i-th point is representative for i-th space (i.e. is constant at every point within that space or is the mean moisture value for that space),
- during time Δt the plant takes water only from spaces from 1 to 10,
- lack of water migration between i-th soil spaces (concerns relation 1); if this condition is not met, relation 2 holds true.

When the above assumptions are met, the values $\Delta Q_i^{\Delta t}$ and $\Delta Q_c^{\Delta t}$ will be subsequently referred to as intensities of water intake by celeriac roots. As the volumes V_i in the example under consideration are different, the comparison of the value of $\Delta Q_c^{\Delta t}$ is meaningful only when we introduce the concept of a unit intensity of water intake by the plant, expressed by the relation:

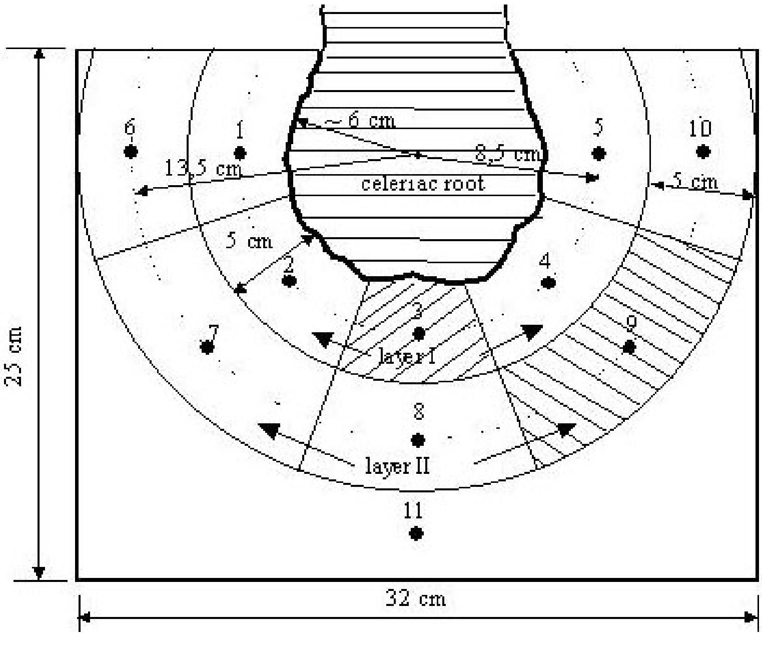
$$J_i^{\Delta t} = \frac{\Delta Q_i^{\Delta t}}{Vi}, \qquad (3)$$

where: $J_i^{\Delta t}$ – unit intensity of water intake by roots from i-th space in time Δt [$cm^3 \cdot cm^{-3} \cdot h^{-1}$], other designations as in relation (1).

DESCRIPTION OF THE EXPERIMENT

The field experiment was conducted at the locality of Sucha Rzeczka in the Warmińsko-Mazurskie Region, in September, 2005. In the first stage, from a field at the locality of Serski Las, a single stem of celeriac was taken, with the soil structure and the root system intact. The mineral parts of the soil indicated the grain size distribution of weakly loamy sand. The whole sample was placed in a cubicoid container that was placed on the ground surface in an open area. The dimensions of the sample are presented in Fig. 2. Since the assumptions adopted earlier require that the condition of lack of direct evaporation from soil surface or absence of rainfall water supply be met, the upper surface of the sample was isolated from the atmosphere, leaving only open spaces for the above-ground part of the plant. In the sample prepared as described above, two rows of 5 TDR probes each were placed in a spherical arrangement. In the first row, the distances of the probe axes of symmetry from the centre point of the plant root was 8.5 cm, and in the second row – 13.5 cm. The points of TDR probe location presented in Fig. 2 (from 1 to 10) were at the same time the representative centre points of the active soil space. It was assumed that in the remaining parts of the monolith (outside of the spaces from 1 to 10) water movement towards the roots was so small during the experiment as to be negligible (moisture reading on probe 11 did not change). The moisture readings on probes from 1 to 10 were recorded for 3 days at 0.5 hour intervals, using the field meter of moisture and salinity (D-LOG/ms) made at the Institute of Agrophysics, PAS, in Lublin.

Fig. 2. Spherical placement of TDR probes in the sample studied (1-11 – points of probe placement).



RESULTS AND DISCUSSION

Figure 3 presents the dynamics of moisture at points located at the distance of 8.5 cm from the centre point of the plant (layer I – points from 1 to 5). Analysing changes in the soil moisture on the first day of the experiment, during the hours from 9 am to 5 pm, a drop in the moisture content was observed at points 2, 3 and 4, by about 2% on average, while at points 1 and 5 by only about 1%. The greater moisture decrease at points 2, 3 and 4 results from more intensive water intake by the lateral roots of celeriac, located in spaces represented by those points. Also observed, beginning from 6 pm, was a slow increase in soil moisture at all the points of layer I that lasted till approximately 6 am of the following day. The level of the increase, however, did not exceed 0.5%. The increase in the amount of water (in the evening and night hours) results from the positive difference between the amount of water taken up from layer II and that taken in by the plant root. In the second 24-hour period the character of the changes was similar, but the initial moisture content was lower, at all the points, by about 1.5%. This is caused by the water intake by the plant during the first day. In the third 24-hour period of the experiment there were no changes in the soil moisture. The differences in the soil moisture at the particular points at the beginning of the first day of the experiment were caused by irregularities in the soil profile resulting from spatial variability of the root mass of the plant [3,19]. That fact, however, has no effect on the accuracy of the structure of the water balance as the equations 1 and 2 consider only the increments $\Delta\theta_i$. Analysing changes in moisture content at points distant from the centre point of the root by 13.5 cm (layer II) (Fig. 4), a decrease in the moisture was observed after the first day at all the points. At points 7, 8 and 9 the decrease was about 1%, while at points 6 and 10 it was approx. 0.5%. This indicates, as in the case of layer I, intensive intake of water within the space concentrated around the axis of symmetry of the plant. The decrease, however, as opposed to that in layer I, was virtually uniform throughout the 24-hour period (no diurnal variability was observed). In the second 24-hour period the character of changes was similar, while in the third the level of moisture was practically constant.

Fig. 3. Dynamics of soil moisture in layer I (spaces from 1 to 5)

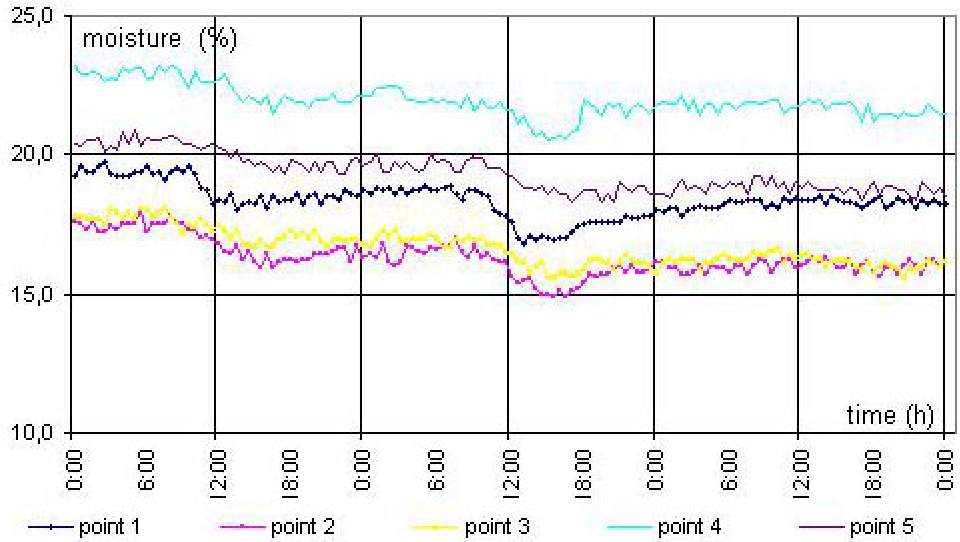
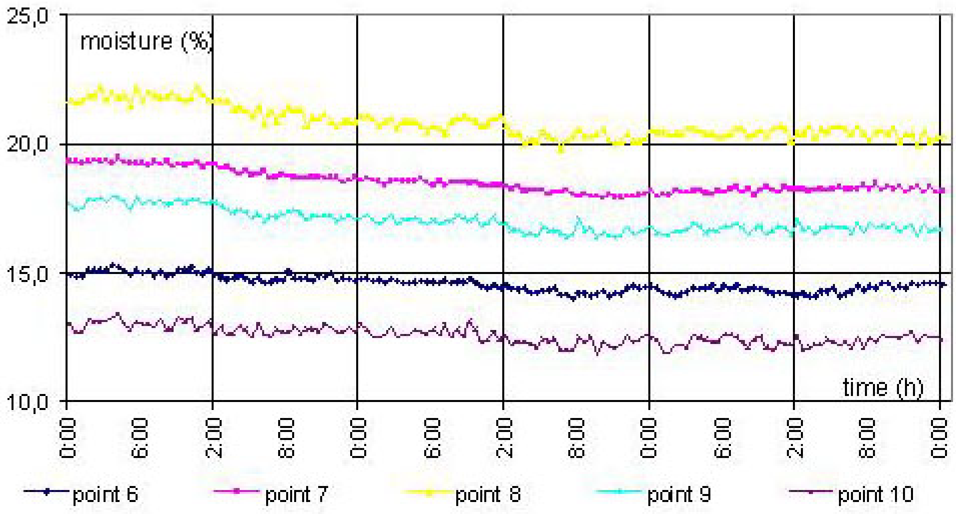


Fig. 4. Dynamics of soil moisture in layer II (spaces from 6 to 10)



Further on in the study, making use of the relation 3, the unit intensity of water intake by celeriac roots was calculated for all the spaces V_i. As an example, Fig. 5 presents values calculated for space No. 3 with a time step of Δt=0.5h. Analysis of the Figure shows that the values of $J_i^{\Delta t}$ are unstable – they assume positive or negative values in an alternating sequence. That instability results from too low a depletion of water taken during time Δt=0.5h from the analysed space with relation to the accuracy of the measuring instrument. Subsequent calculations of the value of $J_i^{\Delta t}$ were made with the time steps of Δt=1h, Δt=3h and Δt=6h. The results of the calculations are presented in Figures 6, 7 and 8. Analysis of the figures shows that the values of $J_i^{\Delta t}$ are given with sufficient accuracy when the calculations are made with the time step of Δt=6h. Analysis of stability of the proposed method is given in references [2] and [4]. The final calculations of the intensity of water intake by celeriac roots for the whole root mass were made with the time step of Δt=6h.

Fig. 5. Unit intensity of water intake by celeriac roots from space No. 3 calculated for time step of Δt=0.5h. $J_i^{\Delta t}$ - unit intensity of water intake by the roots from i-th space, Δ t – time step

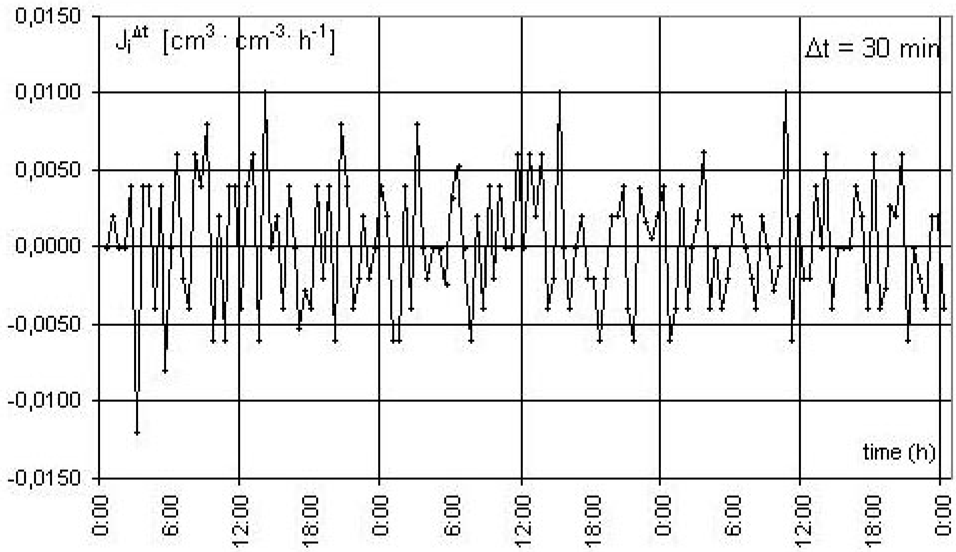


Fig. 6. Unit intensity of water intake by celeriac roots from space No. 3 calculated for time step of Δt=1h. $J_i^{\Delta t}$ - unit intensity of water intake by the roots from i-th space, Δ t – time step

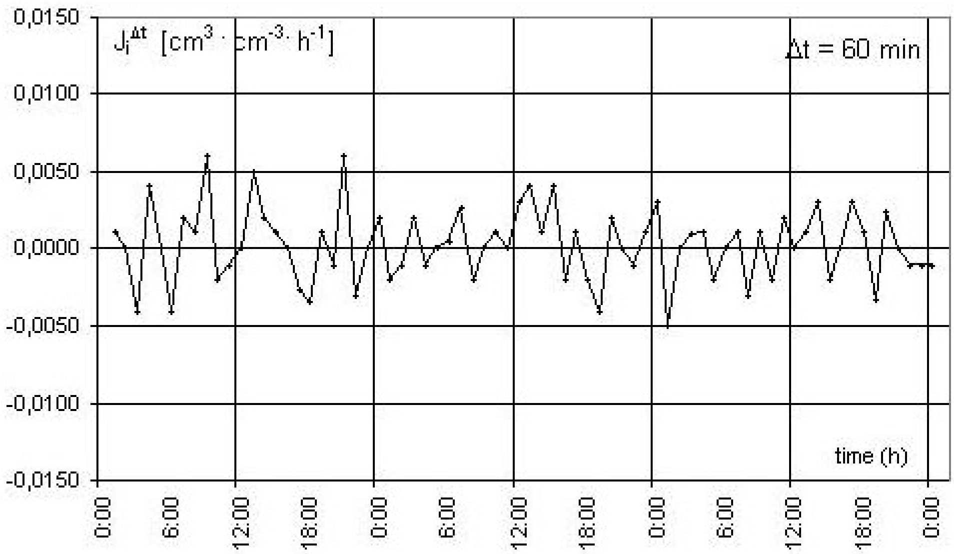


Fig. 7. Unit intensity of water intake by celeriac roots from space No. 3 calculated for time step of Δt=3h. $J_i^{\Delta t}$ - unit intensity of water intake by the roots from i-th space, Δ t – time step

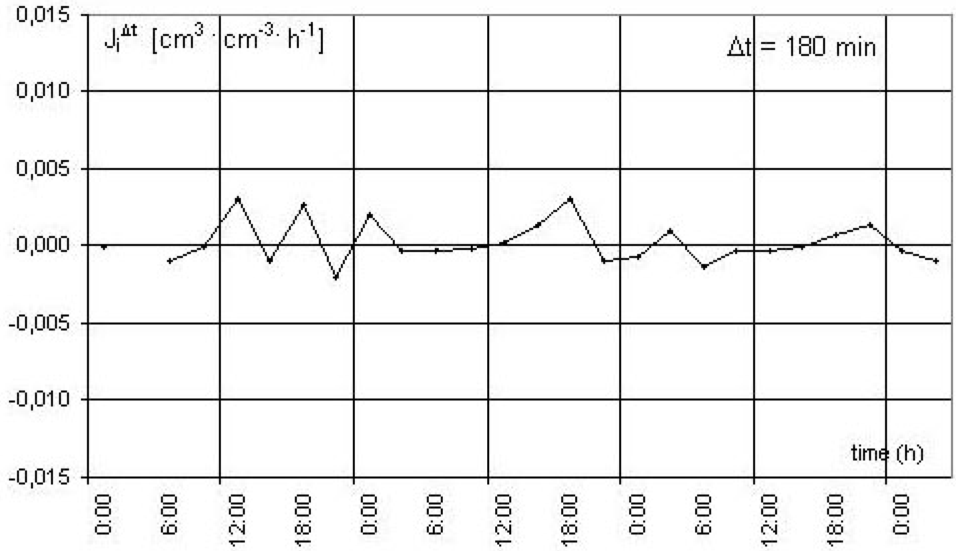


Fig. 8. Unit intensity of water intake by celeriac roots from space No. 3 calculated for time step of Δt=6h. $J_i^{\Delta t}$ - unit intensity of water intake by the roots from i-th space, Δ t – time step

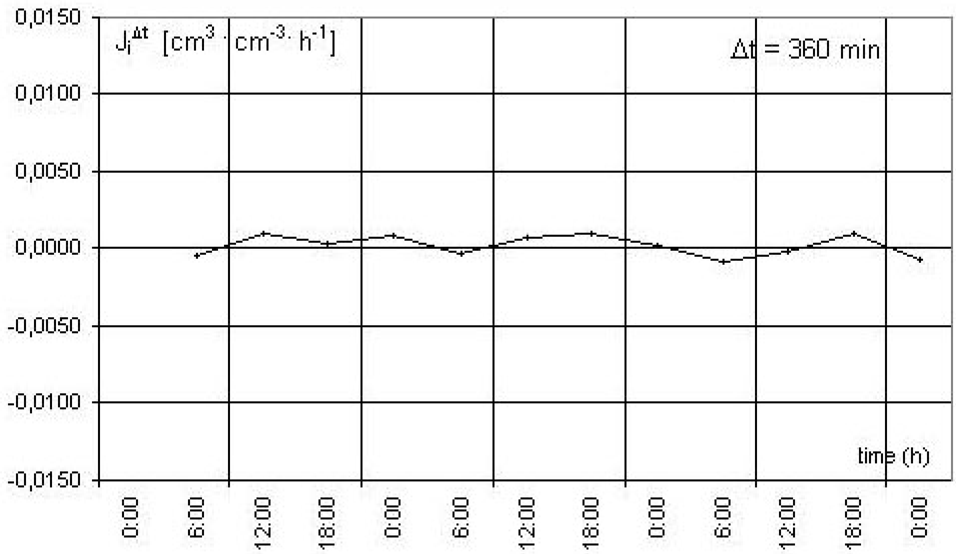


Figure 9 presents the unit intensity of water intake for layer I calculated from the formula:

$$J_{śr}^{I} = \frac{\sum_{i=1}^{5} Q_i^{\Delta t}}{\sum_{i=1}^{5} Vi}, \tag{4}$$

where: $J_{śr}^{I}$ – unit intensity of water intake by the plant roots in layer I, [cm^3·cm^{-3}· h^{-1}], remaining designations as in relations (1) and (2) and the unit intensity of water intake for layer II, calculated from the formula:

$$J_{śr}^{II} = \frac{\sum_{i=6}^{10} Q_i^{\Delta t}}{\sum_{i=6}^{10} Vi}, \tag{5}$$

where: $J_{śr}^{II}$ – unit intensity of water intake by the plant roots in layer II, [cm^3·cm^{-3}· h^{-1}].

As can be seen in the Figure, during the daytime (from 6 am to 6 pm) the unit intensity of water intake in layer I is greater than the unit intensity of water intake from layer II. As an example, during the period from 6 am till 12 noon on the second day of the experiment the value of $J^{I}_{śr}$ was 0.0012 $cm^3 \cdot cm^{-3} \cdot h^{-1}$ and was approx. 3-fold higher than the value of $J^{II}_{śr}$ in the same period of time.

Fig. 9. Comparison of unit intensity of water intake by celeriac roots for layers I and II. $J^{\Delta t}$ - unit intensity of water intake by the roots, Δ t – time step

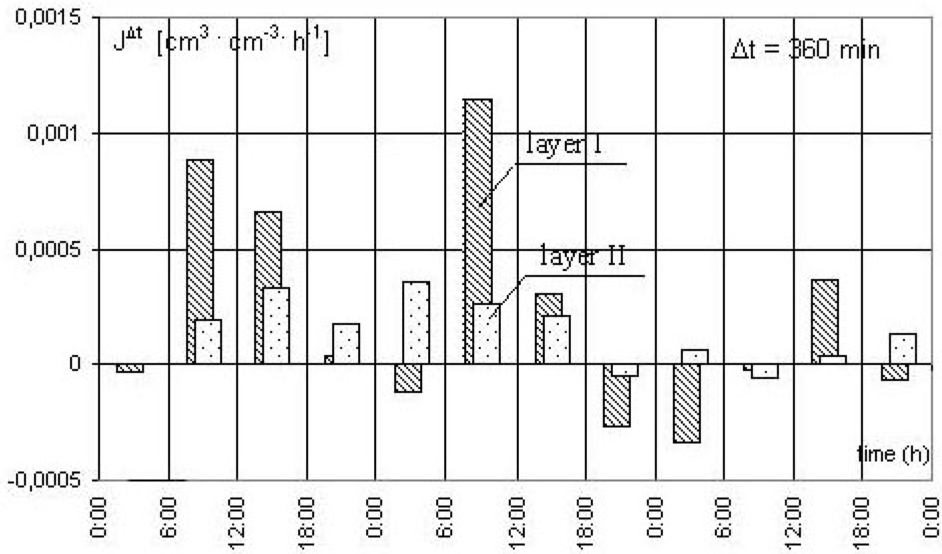
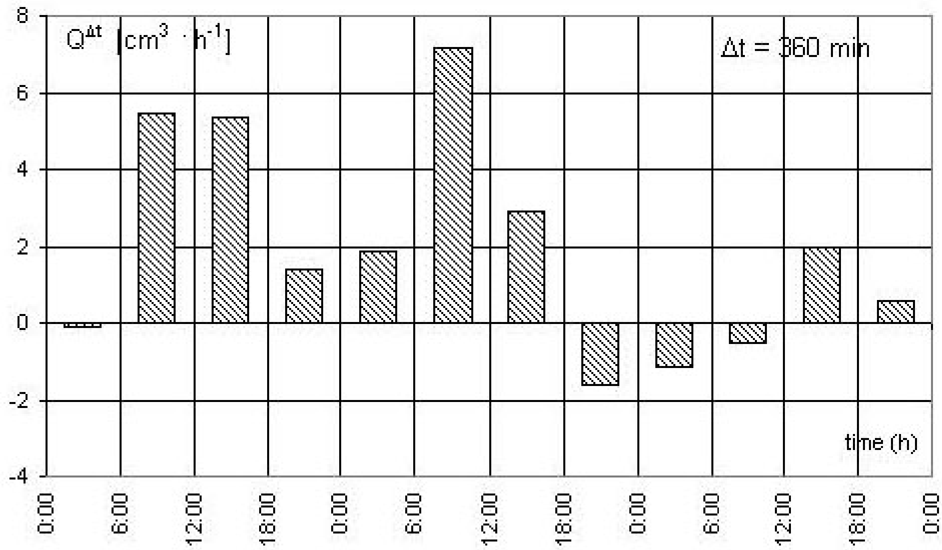


Fig. 10. Diurnal dynamics of water intake by celeriac roots. $Q^{\Delta t}$ – volume of water taken in by celeriac roots, Δ t – time step



In the night hours, on the other hand, the values of $J^{I}_{śr}$ assume negative values. This is due to the fact of water supply from layer II.

Figure 10 presents the values of intensity of water intake by the whole root mass of the plant (layers 1 and 2). Water intake by a single stem of celeriac during the first day was 72.54 cm^3 (6h x (-0.12) + 6h x 5.47 + 6h x 5.34 + 6h x 1.40 = 72.54 cm^3), during the second – 62.04 cm^3, and during the third – only 0.89 cm^3. The very low water consumption in the third 24-hour period was related to the variable weather conditions. For example, during the first two days the maximum air temperature was 22.1°C and 21.8°, while on the third day it was only 14.5°C. The number of hours with insolation was 7.6h and 7.1h on the first two days, respectively, while on the third it was only 0.5h. Moreover, on the last day of the experiment there was a rainfall of 9mm·day^{-1}. However, the objective of the study was not to describe the relations between water intake by celeriac roots and the atmospheric conditions. The results of the study are only referenced to the conditions. Analysis of Fig. 10 permits estimation of the intensity of water intake by a single stem of celeriac as related to the time of the day. It was found that the main amount of water was taken in the period from 6 am to 6 pm and constituted 89% of the diurnal water requirement on the first day and 97% in the second day of the experiment.

Knowledge of the spatial and temporal distribution of water intake by celeriac roots constitutes important information in the process of designing irrigation systems, e.g. drip-irrigation lines. On the basis of the analyses carried out, it should be stated that drip-irrigation lines should be located as close as possible to the centre point of celeriac root and coincide as much as possible with the axis of symmetry of the plant, as that is where the water intake is the greatest. Moreover, irrigation systems should be turned on only during the daytime, when celeriac roots take in significant amounts of water.

CONCLUSIONS

1. The field experiment carried out demonstrated the applicability of the TDR technique for the determination of the dynamics of moisture in the active soil space around celeriac root.
2. It was found that the greatest unit intensity of water intake by celeriac roots occurs in a 5 cm belt of soil immediately adjacent to the main root and is, during the daytime, about 4-fold higher than the unit intensity in the next 5-cm layer. The strongest intake of water takes place along the axis of symmetry of the plant.
3. The study showed that in the period studied the maximum diurnal water intake by celeriac root was 72 cm^3, and that approximately 90% of the water is taken during the daytime, between 6 am and 6 pm.
4. The information acquired in the study may be used in designing the installation locations of drip-irrigation lines and in determining the timing of their operation. Drip-irrigation lines should be located as close as possible to the centre point of celeriac root and coincide as much as possible with the axis of symmetry of the plant, and their irrigation operation should be turned on only during the daytime hours.

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