Final Report

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TITLE OF PROJECT: AGROMETEOROLOGICAL APPROACH TO CROP WATER USE EVALUATION FOR IMPROVED IRRIGATION EFFICIENCY

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Table of Contents

1 Executive Summary **3**

2 Research Objectives **3**

3 Methods and Results **4**

3.1 Comparing model against traditional methods *4*

3.1.1 Specifications of the experimental plot 4

3.1.1.1 Location 4

3.1.1.2 Climate 4

3.1.1.3 Water-soil and surface data 5

3.1.2 The water regime of the apple orchard 7

3.1.2.1 Terms and norms of watering 7

3.1.2.2 Dynamic of soil moisture for irrigation 11

3.1.3 Total water use of the irrigation orchard 14

1.3. Qualitative analysis of data of the model by results of field experience 19

3.2 Corn water uptake response to drought *20*

3.2.1 Stomatal response of corn to water stress 20

3.2.2 Root water uptake response to drought 25

3.3 Productivity *25*

3.4 Data obtained with the use of the model *25*

3.5 Conclusion *25*

4 Impact Relevance and Technology Transfer **27**

5 Project Activities/outputs **28**

6 Literature Cited **28**

1 Executive Summary

The purpose of the project was to develop a method for crop water use evaluation that would improve irrigation efficiency in the conditions of Kyrgyzstan and to transfer technology tested in Israel for implementation in Kyrgyzstan. The project required the purchase of Campbell Scientific, USA, automatic agrometeorological station (AMS) and sensors. Two scientists from Kyrgyzstan visited Israel to study the new technology, the software and the model of crop water evaporation developed by Prof. M. Fuchs. AMS was installed in an apple orchard of the Chu valley in Kyrgyzstan. A comparative analyze of irrigation scheduling methods in the apple orchard based on the lower limit of topsoil moisture content (local method by Ivanov) and on modeling using data obtained from AMS concluded that the second method is more reliable and accurate.

At first irrigation was conducted according to the limit of the topsoil moisture content using a gross norm 689 mm for six irrigations. Leaching below the root layer was 395.7 mm amounting to a loss of 56.7% the water resource. The AMS based model lead to 8 irrigations totaling 595.2 mm, with a leaching loss of 47.0 mm or 7.9%, saving 45.8 % of irrigation water and increasing apple fruit yield. The treated apple orchard produced on the average 31.7 tons/ha, for a total water use 826 mm and a planting density of 5×6 m. Specific water use was 26 mm/ton compared with 38-44 mm/ton obtained in the traditionally managed orchards. This comparison shows the benefits of the model's application to increased water use efficiency and production. Application to the main crops of Kyrgyzstan: corn, winter and autumnal wheat, sugar beet, alfalfa, barley and potato of these findings are very important for farmers, faced with agriculture reforms from centralized market oriented economy.

The research in Israel consisted of refining the model to allow its use under conditions of suboptimal water supply. Corn was the crop that served as the test plant for the investigation as defined in the original proposal. It resulted in the study of water stress on the stomatal conductance of corn, and the response of root water uptake to drought.

2 Research Objectives

This project was conducted because proper use of water resources in Kyrgyzstan as well as in Central Asia countries has vital importance. Israeli scientists in this field have a rich experience and achievements. For Kyrgyzstan it is also very important to increase crop yields. Technology transfer of modern irrigation methods and of crop production systems will solve agricultural reform problems in Kyrgyzstan. Results and achievements of this project would be useful for developing more complicated projects (S. Cohen, R.Sudhakara Rao, Y. Cohen, 1997). The Department of Science and new Technology of Kyrgyzstan is interested in continuation of this project and has provided additional finance support, but this support is very little because the Government has deficit of budget. Department of Water Economy supported this project and its results were included in the SIMIS project carried out in the Scientific and Research Institute for Irrigation under the directives of FAO. The Global Environmental Facilities (GEF), in frame of the Aral Sea project A1 fund, will also use skills and experiences acquired during the implementation of the project.

3 Methods and Results

3.1 Comparing model against traditional methods

3.1.1 Specifications of the experimental plot

3.1.1.1 Location

The experimental orchard is located in Kok-Jar, 16 km of the southern outlying districts of Bishkek. It is in foothill district at an altitude of 1000 m above a sea level, 30 km north of the high-mountainous glacier that rise to 4000 m altitude. The general slope of the orchard surface is within the limits of 0.05-0.07.

3.1.1.2 Climate

The analysis of the climatic factors obtained with the help of automatic meteorological station (AMS) in 1999 has been shown the large variability of the climatic component. The main parameters of weather - temperature and relative humidity of an air, were sharply changed both within months and day. So, in the warmest month - July, the daily average temperature of the air changed from 17.2° up to 23.6°C. And within day oscillation frequency made from 15°C in night time up to 30°C in the day. In August during falling abundant precipitation - 31.9 mm per day, daily average temperature was lowered up to 26.5-27.9°C. Within daily allowance oscillation have made from 9-15°C in night time up to 20-29°C in daylight. September was colder. Maximum daily average temperature has made 21.9°C, minimum - up to 9.3°C. Within daily allowance oscillation of temperature in the first decade have made from 7.2°C at the night up to 26°C in day times and from 6.5°C up to 27.7°C accordingly in the third decade. Began fall of the apple-trees leaves.

The humidity of the air was in the large oscillations. In July the daily average humidity of the air was changed from 42.1 up to 84.0 % within the daily allowance oscillations from 35 up to 82 % in day time and night hours and up to 92 % during falling precipitation.

In August oscillation within the daily allowance humidity have reached 55.7 % - from 28.1 % up to 83.8 % for falling precipitation. The driest period was marked in the extremity during the second and beginning of the third decade. The daily oscillations of humidity have made from 20-22% till 55-72% for the clear weather and from 55 % up to 97 % for the falling precipitation.

In September the humidity of the air was changed from 33.4 % up to 88.6%. Within day it changed from 21-24% in the day time, till 65-68% in night, being lifted during falling precipitation up to 97-99%. The wind for the period of observations did not exceed the velocity 3.4-4.0 meter per second (m/s) and only from time to time for bursts of wind reached 6-7 m/s. In similar sharply varying conditions of the temperature for the possible intrusion of masses of a cold air from close glaciers in night hours and for precipitation it is possible to grow only earmarked type of apple-trees for the given area, but their flowers and ovaries are damaged in such sharp changeable climate.

The duration of the vegetation period of the apple orchard rather changes depending of the temperature of the warm period of each year. In this respect 1999 was most unfavorable. At the beginning of May, for flowering of the apple-trees, the snow

with lowering of temperatures up to 6°C has dropped out and the apple harvest practically was absent.

The analysis of the climatic factors obtained with the use of automatic meteorological station (AMS) in 2000 has shown the large variability climatic component too. The main parameters of weather, air temperature and relative humidity fluctuate sharply during the season, from day-to-day and hourly. At the beginning of irrigation period, end of May, daily average air temperature changed from 16.3° up to 20.2°C. Within a day the temperature passed from 8°C minimum at night to a daytime maximum of 22°C. In June daily average temperature increased from 13.3 to 28.6°C from beginning to end of the month. Diurnal fluctuations were from 10-12°C at night and 27-30° during the day. July was warmer, with maximal daily average temperatures of 27.8°C, and minima of 15.8°C. Diurnal oscillations of temperature in the first decade were from 17.2°C at the night up to 33°C in daytime and from 16.5°C up to 29.7°C in the third decade. In August air temperature was more stable, ranging from 21.3°C to 28.0°C during the first, and from 17.9°C to 26.6°during the third decade. Corresponding diurnal variations were from 17°C at night to 30°C in daytime and from 12-14°C to 25-28°C. First two decades of September were warm with average temperature from 15.2°C to 22.9°C, and diurnal variations from 6-12°C at night to 22-25°C during the day. During the third decade, temperature dropped sharply from a range 11.2° -16.7°C in the beginning of decade down to 3.6° -13.8°C in the end. From 26.09, night temperature did not exceed 1.6-5.3°C, day's 8-20°C. The first of October active vegetation of the apple trees terminated and observations on AMS were stopped.

The humidity of air is subject to the large variations. In June the daily average humidity of air changed from 39.3 to 68.3 % for diurnal variations from 20 % up to 75 % from day to night, and up to 92 % during precipitation.

In July and August variation of diurnal humidity reached 11% and 72-93% for precipitation. The driest period was occurred at the end of the third decade of August. In August the daily variations of humidity have made from 22-39% up to 48-65% for clear weather and from 72 % up to 99 % for precipitation.

In September the humidity of air fluctuated from 28.0 % to 54.3 % in dry weather and from 63.0 to 94 % for precipitation. Within day it changed from 18-25% during day up to 55-73% at night increasing to 97-99 % during precipitation. The wind for period of observations did not exceed a velocity 1.4-3.0 m/s and only from time to time for gusts reached 5-7 m/s. Intrusion of cold air masses from neighboring mountain glaciers imposes cultivation of regionally adapted apple tree varieties.

The vegetation duration of the orchard varies annually depending on the duration of the warm period of each year. Vegetation in 2000 was favorable. However, in the beginning of May, blossoms suffered from cold temperatures down to 6°C and winds, lowering the proportion of apples graded "excellent" in the final yield.

3.1.1.3 Water-soil and surface data

The territory of the orchard is located on the piedmont deposit of the river Ala-Medin. Stony lands occupy 15 % of the territory. The soil type is serozem. In the loam soil forming a main part of the orchard, there are lenses and layers of sand, gravel giving a lighter mechanical structure to the soil.

The water-physical properties of the soil, moisture content at Field Capacity (FC) and water deficit (W_{def}) in mm of water at the moisture content that is critical to plant growth, were mapped according to contour lines (table 1.1).

Table 1.1

Hydraulic properties of the apple orchard soil.

Soil horizon, m	Moisture content at Field Capacity (β_{FC}) %	Volumetric mass, t/m^3, d	Critical moisture content		Deficit of a soil moisture	
			Fraction of γ_{FC}	% Moisture content $\beta_{kr\%}$	% Moisture content β_{def}	mm of water, W_{def}
0-20	21.3	1.36	0.65	13.84	7.46	20.3
20-40	21.3	1.36	0.65	13.84	7.46	20.3
40-60	23.6	1.32	0.71	16.76	6.84	18.1
60-80	24.5	1.29	0.72	17.64	6.86	17.7
80-100	23.7	1.31	0.71	16.83	6.90	18.1
0-100	22.88	1.33	0.69	15.78	7.10	94.5

To prevent erosive processes, soil between tree rows was sown with perennial grasses, pink clover, motley grass and wild grasses. The community of grasses is the natural consumer of moisture of the irrigated orchard. Therefore, for account of total water use by the orchard, it is necessary to take into account water use of grasses.

The general slope of district within the limits of 0.05-0.07 hinders surface watering of orchard. Watering was made on undeviating ring and half-ring furrow, as in 1999, sharply reducing a possibility of development of irrigation erosion for watering on steep slopes.

The experiment site for definition of norms and periods of watering of strawberry in 2001 was setup near the river Ala-Archa and village "Rechnoe", 20 km from an orchard garden at height of 1100 m. Soil type is loamy sand - sandy, gravelly in places. The site is level allowing furrow irrigation. Furrows are 20 m long. Planting strawberry by scheme 70x30x15, is produced 5 years back. The active layer of soil for strawberry is 0.5 m, the depth of the root system is 0.4 m. The main water-physical properties of soil are given in table 1.2.

Table 1.2

Water-physical properties of ground in experiment with strawberry

Soil horizon, m	Moisture content at Field Capacity (β_{FC}) %	Volumetric mass, t/m^3, d	Critical moisture content		Deficit of a soil moisture	
			Fraction of γ_{FC}	% Moisture content $\beta_{kr\%}$		
0-0.1	15.03	1.22	0.50	9.02	5.41	6.6
0.1-0.3	15.05	1.34	0.62	9.33	5.72	15.3
0.3-0.5	16.08	1.31	0.65	10.45	5.63	14.8
0-0.5	15.46	1.30	0.63	9.72	5.63	36.7

The experiments for finding the norms and periods of watering of barley in 2001 were conducted in the same soil-climatic conditions, as strawberry. Soil is a sandstone-sandy, places gravelly. The experiment sites are at a distance of 15-20 m to the East of AMS . The experiments were conducted on allotments by size 5x15 m in triple recurrence. The surface carefully is levelled. The watering was made by hoses. The definition of watering norms was conducted by a volumetric way through capacity.

Barley summer, doubled sort "Cutans 87":

- Crop - 26.03.01

- Young growth complete - 11.04.01
- Third page - 20.04.01
- Bushing out - 12.05.01
- Output in a handset - 17.05.01
- Heading - 31.05.01
- Flowering - 3.06.01
- Lactic ripeness - 13.06.01
- Waxen ripeness - 23.06.01
- Complete ripeness - 2.07.01

3.1.2 The water regime of the apple orchard

3.1.2.1 Terms and norms of watering

In 1999 in both variants of the experiments before installation of AMS watering was initiated when moisture depletion in 1 m topsoil was 70 % of FC. On 30.06.99 the AMS was installed, and soil moisture sampling were initiated. The humidity of the soil was 15.5 % from absolute-dry soil or 72.0 % below FC. The stocks of moisture amounted to 219.5 mm. The deficit of moisture was 85 mm. Because of absence of an irrigation network in a orchard, the watering was not made. In 08.07.99 watering with norm of 72.5 mm was made. The decrease of norm of watering and later it realization was promoted by repeated precipitation from 28.06 till 07.07, with total volume of 37.5 mm. The stocks of moisture in the soil per the starting day AMS reached 251.4 mm or 82.5 % from FC.

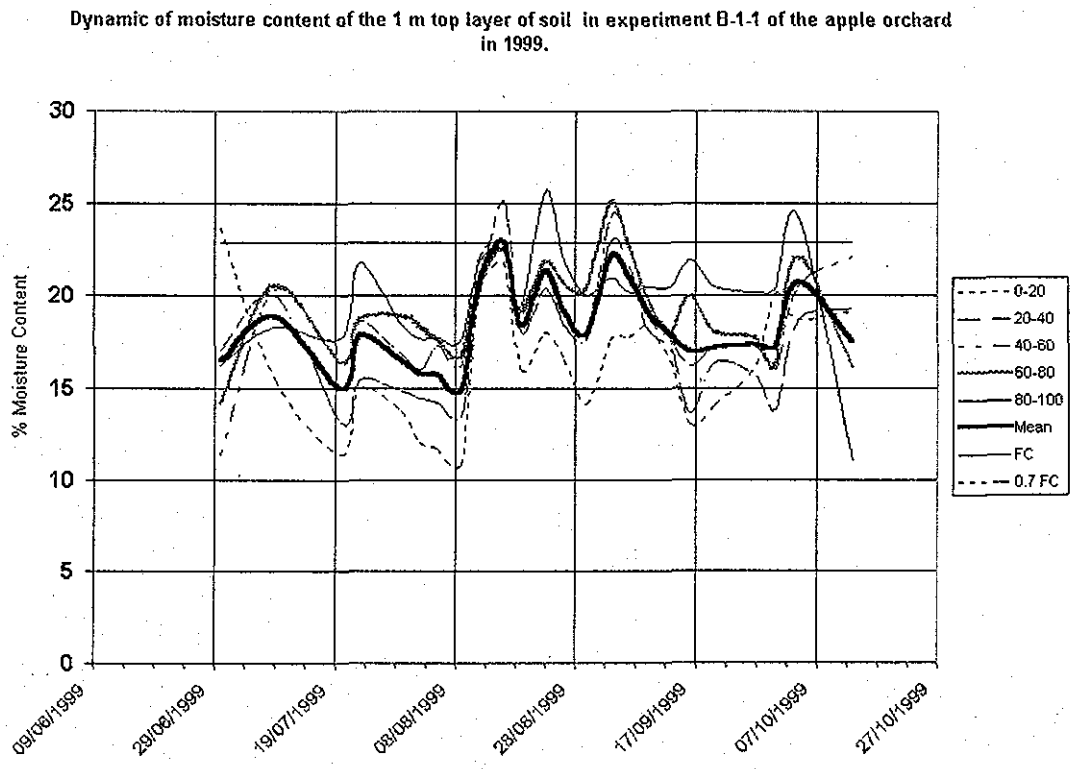
Table 1.3
Account of irrigation net norms and volumes of percolation of irrigation water for 1 m of layer of soil for watering of the apple orchard in 1999 (average in experiment)

№ of watering	Date of watering	Stock of a moisture, mm		Net norm, mm	The irrigation gross norm, mm			Filtration	
		After watering	Before watering		B-1-1	B-1-2	Average	Mm	% From irrigation gross norm
1	08.07	251.6	219.5	32.1	65	80	72.5	40.4	55.7
2	22.07	240.6	203.1	37.5	75	82	78.5	41.0	52.2
3	10.08	265.6	197.8	69.8	170	244	107	137.2	66.3
4	21.08	293.5	246.7	46.8	87	104	95.5	48.7	51.0
5	02.09	291.9	242.6	49.3	95	90	92.5	43.2	46.7
6	03.10	283.4	225.6	57.8	142	144	144	85.2	59.6
The sum				293.3			689	395.7	56.7

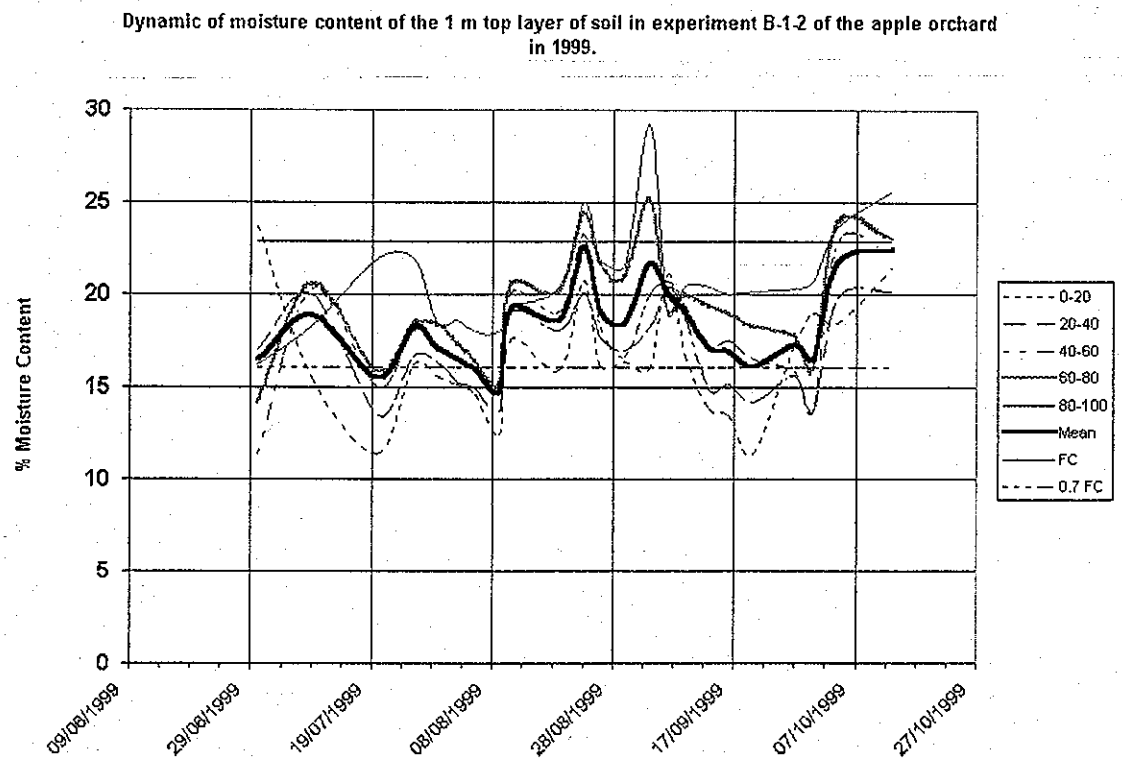
Two watering were given on 22.07 and on 08.08 with the average gross norms 78.5 and 207.0 mm when depletion reached 66.7; and 64.9 % from FC. Two consequent watering with average gross norms of 95.5 and 92.5 mm were applied on 20-21.08 and 02.09 at depletion of 81.0 and 79.7 % from FC. The watering has made according to accumulated evaporability obtained by AMS. The last vegetation watering was made in the beginning of October 03.10, when the stocks of a moisture in 1 m top-layer reached 225.6 mm or 74.06 % from FC average on both experiments. Autumn irrigation with norm of 200.0 mm was given 10-12.10 to store 87.5 % FC mois-

ture content. To the end of orchard vegetation 6 waterings with gross norm of 689.0 mm provided a net water input 293.3 mm or 43.3 % and 395.7 mm or 56.7 % of leaching loss. The total irrigation water for the apple orchard and grasses between rows and accumulated moisture was 889.0 mm. From them 363.6 mm - were net irrigation and 525.4 mm or 59.1 % from m_{br} (brutto amount) were drained. Deep percolation allowed moisture supply to 2nd and 3rd order roots that in apple-trees can reach 9 m depth and more.

The account of irrigation net norms and volumes of a filtration of irrigation water for 1 meter layer of soil is indicated in table 1.3. On April 2, 2000 soil moisture sampling were initiated at the site of AMS. Soil moisture to a depth of 1.5 m averaged 14.7 % or 80.6% of FC, or a water equivalent of 64 mm in 1.5 m of soil. Stored moisture was sufficient for normal development of the apple trees. The first irrigation of 57.5 mm was applied at the start of AMS operation. At the time, the moisture content of the 1.5 m topsoil layer was 299.6 mm or 76.7 % of FC. The following two watering were conducted on 08.06 and 20.06 with average gross norms 74.5 and 73.7 mm. Moisture contents before-watering were 73.4 and 85.1 % from FC (fig.1.1-fig.1.3). The next two irrigations applied 74.5 and 54.2 mm on 05.07 and 20.07 at soil moisture contents 78.4 and 85.4 % from FC. The 6-th and 7-th irrigations on 10.08 and 28.08 applied 120.3 mm and 69.6 mm at moisture contents of 71.9 % and 80.5 % from FC to a profile depth of 1.5 m.



Dates of watering: 1 - 08/07, 2 – 22/07, 3 – 10/08, 4 – 21/08, 5 – 02/09, 6 – 03/10.
Fig. 1.1.



Dates of watering: 1 – 08/07, 2 – 23/07, 3 – 10/08, 4 – 21/08, 5 – 10/09, 6 – 10/10

Fig. 1.2.

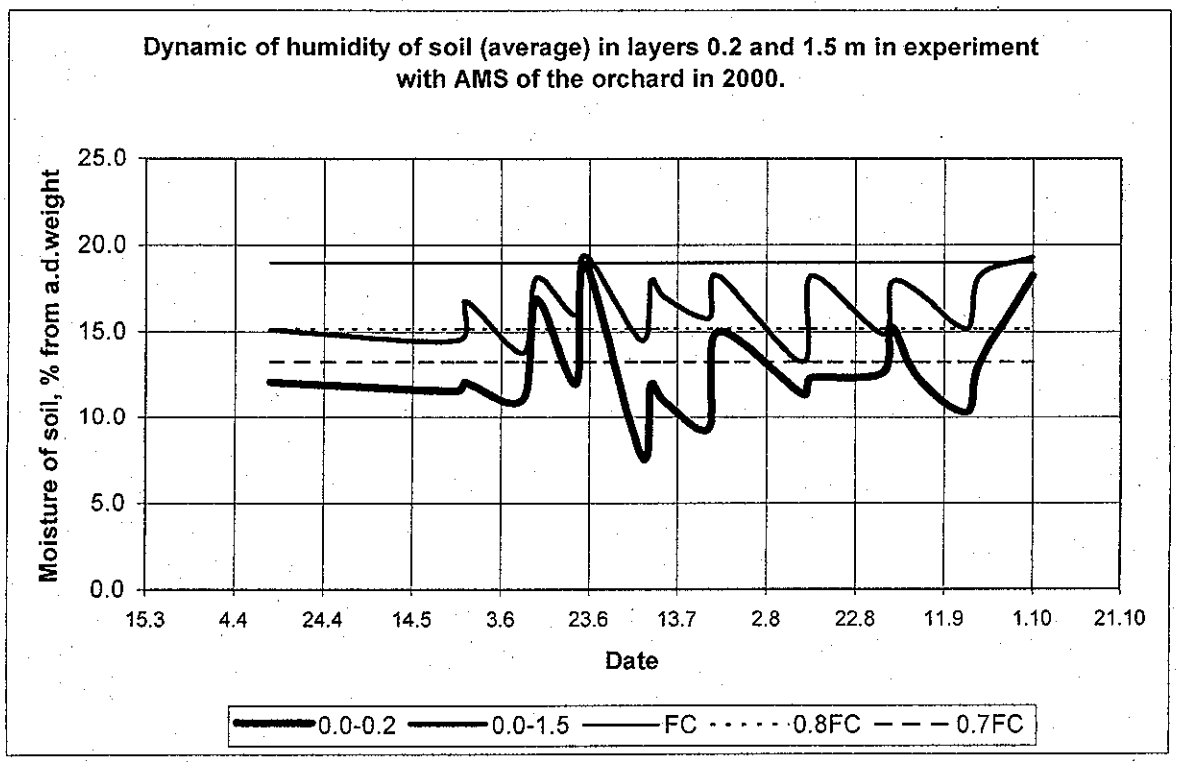


Fig. 1.3.

The last irrigation was applied on 17.09, when the moisture content to a depth of 1.5 m was 299.1 mm or 82.2 % from FC on the average in both experiments. Fall

irrigation was not necessary because of abundant precipitation. The eight irrigations during the vegetation season of the orchard applied 595.2 mm of water, of which 548.2 mm or 92.1 % were retained in the 1.5 m deep root zone and leaching lost 47.0 mm or 7.9 %. The water applications were conducted according to the water use estimated of the model. This procedure resulted in a very small loss by leaching below the root zone. Details of the water balance following the irrigation application are shown in table. 1.4.

Table 1.4
Detailed water balance of the soil to a depth of 1.5 m in experiments of 2000 (average)

Number of watering	Dates of watering	Stored water, mm		Net norm, mm	Irrigation gross norm, mm			Leaching	
		After watering	Before watering		AMS 1-1	AMS 1-2	Average	mm	% of gross norm
1	24.05	344.3	299.6	44.7	58.8	56.2	57.5	12.8	22.2
2	08.06	367.6	280.1	71.2	72.2	76.8	74.5	3.3	4.4
3	21.06	393.8	325.1	68.7	72.6	74.8	73.7	5.0	6.8
4	05.07	363.0	294.0	69.0	78.6	70.4	74.5	5.5	7.4
5	20.07	358.2	312.2	46.0	52.2	56.2	54.2	8.2	15.1
6	10.08	352.8	236.8	116.0	130.6	110.0	120.3	4.3	3.6
7	28.08	360.6	293.9	66.7	71.6	67.6	69.6	2.9	4.2
8	17.09	365.0	299.1	65.9	69.5	72.3	70.9	5.0	7.0
Total				548.2			595.2	47.0	7.9

For the strawberry experiment before installation of AMS, soil moisture samples were taken on 6.04.01. The moisture content in 0.5 m of layer was 15.4 % or 99.6 % from FC at a deficit of 4 mm. The first watering gross norm of 35 mm concurred with operation of AMS when profile average moisture was 78.2 mm or 77.42 % FC. The subsequent 3 waterings before the first collection of berries were conducted on 17, 23 and May 31 with norms of 25, 30 and 22 mm before watering reserves of moisture from 77.49 till 84.28 of % from FC. During collection of berries 2 watering 17 and 28 mm from 8.06 till 17.06 were made at moisture contents of 86.93 % and 78.07 % from FC. After repeated collection of berries a watering of 22 mm was made on 21.06. In total for productive vegetation of strawberry 6 waterings, amounting to a gross norm of 157 mm, were given. The reserves of moisture in the soil after watering exceeded FC by 2.0-10.0 %, which were spent by plants.

In a check experiment, where the watering was made according to the practice norm, strawberry received 4 waterings amounting each from 35.2 to 50 mm for a total of 185 mm. The initial moisture reserves in the 0.5 m layer of soil held 68.55 to 82.02 % from FC. After sprinklings they increased to108.78 and 117.08 % from FC. The value of sprinkling norms in experiments from AMS was assigned according to modeled water use. The practice norm of 4 irrigations put excessive amounts of water below the strawberry root zone with a loss of 28 mm or 16% of 175 mm gross application. In the AMS experiment 6 waterings reduced the loss to 15.4 mm or 9.81 % of M_{brutto} (table 1.5).

The first watering of barley was made shortly after sowing on 17.05.01 with a gross norm of 50 mm, leaving a net 47.1 mm for a soil moisture of 76.04 % from FC. The subsequent 4 sprinklings were made in 5-9 days intervals with net norms ranging from 23.1 to 30 mm as established by modeled evaporability. The soil moisture depletion before waterings was not below 82-86 % FC. For 5 sprinklings irrigation

amounted to 159.2 mm (netto), or 167.3 mm (brutto). The losses constituted 8.1 mm or 4.84%. In field conditions, 3 waterings with norms up to 80 mm were carried through headings and waxen ripeness.

Table 1.5
Calculation of watering net norms and sizes of lost irrigation water for 0.5 m of soil layer at waterings strawberry in 2001 (average in experiments)

Number of water-ing	Dates of water-ing	Stored water, mm		Net norm, mm	Irrigation gross norm, mm			Leaching	
		After watering	Before watering		AMS 1-1			After watering	Before watering
AMC									
1	11.05	110.8	78.2	32.6	34.0	36.0	35.0	2.4	6.86
2	17.05	106.8	84.7	21.9	27.0	23.0	25.0	3.1	12.40
3	23.05	104.2	78.3	25.9	36.0	30.0	30.0	4.1	13.66
4	1.06	102.8	82.4	20.4	21.0	23.0	22.0	1.6	7.27
5	8.06	102.7	87.4	15.3	15.5	18.5	17.0	1.7	10.00
6	14.06	103.9	78.4	25.5	30.0	26.0	28.0	2.5	8.93
total				141.6			157.0	15.4	9.81
The practical norm of watering									
1	11.05	117.6	81.5	36.1	43.8	46.2	45.0	8.9	19.78
2	25.05	109.7	69.1	40.6	47.0	43.0	45.0	4.4	9.78
3	1.06	40.7	82.7	28.0	33.4	36.6	35.0	7.0	20.00
4	9.06	114.2	71.9	42.3	51.0	49.0	50.0	7.7	15.40
total				147.0			175.0	28.0	16.00

3.1.2.2 Dynamic of soil moisture for irrigation

Before the start of the field experiment the farmer irrigated the apple orchard. The first samplings of soil humidity were made before the beginning of the experimental irrigation on three test plots in triple treatments. In experiment B-1, where AMS was installed, the tests of soil were taken for the 2nd day after watering by the method of "wild irrigation" with a small irrigation norm. This watering was number two with wetting depth limited to 0.5 m. The humidity of soil in the upper horizons reaches 111.3 % from FC and dropped to 48.3 % from FC in horizon 0.4-0.6 m.

Table 1.6.
Humidity of 1 m of a soil and moisture in horizons before the beginning of watering of the apple orchard in experimet of 1999.

Horizon, m	Experience B-1			Experience B-2			Experience B-3		
	Humidity of soil, %		Stock of a mois-ture, mm	Humidity of soil, %		Stock of a mois-ture, mm	Humidity of soil, %		Stock of a mois-ture, mm
	From weights of abso-lute-dry soils	From FC		From weights of abso-lute-dry soils	From FC		From weights of abso-lute-dry soils	From FC	
0.0-0.2	23.7	111.3	64.4	15.3	71.8	41.6	13.5	63.4	36.7
0.2-.04	17.1	80.3	46.6	13.7	64.4	37.3	10.0	46.9	27.2
0.4-0.6	11.4	48.3	30.0	11.6	49.1	30.6	9.4	39.8	24.8
0.6-0.8	14.1	57.5	36.4	11.8	48.2	30.4	8.8	35.9	22.7
0.8-1.0	16.2	68.3	42.4	13.9	58.6	36.4	9.7	40.9	25.4
0.0-1.0	16.5	72.1	219.5	13.3	58.4	176.3	10.3	45.3	136.8

In experiment B-2, one week after the 1st watering, the humidity of soil in layer 0.0-0.2 m was 71.8 % from FC, and in layer 0.2-0.4 m - 64.4 % from FC. In the

lower horizons the soil dried down to 48.2-49.1 % from FC. In experiment B-3, where the orchard was never watered, the soil dried to 63.4 % from FC in upper 0.2 m of layer as a result of rain down to 35.9 % in layer 0.6-0.8 m (table 1.6.).

It is necessary to note some increase of humidity in the lower layer of soil 0.8-1.0 m, resulting from autumn-winter-spring precipitation. Inappropriate irrigation of the orchard resulted and the loss of some trees and damage to the remainder. To avoid of the apple-trees from a shock condition happened by a drought, the first 2 watering were made for threshold of humidity in 1m of layer of soil within the limits of 65-70 % from FC. The humidity of the rooted layer of soil was lifted up to 79.0-82.6 % from FC owing to scanty moistening of the upper horizons. The first watering for moisture accumulation occurred in the mid and lower horizons of soil. Humidity after watering was lifted to 84-92% from FC. Further watering was according to data received by AMS. Average humidity of soil in 1 m of layer was kept at the level 80 % from FC before and 95-100 % after watering. Humidity of soil in the lower horizons was not lowered below than 85-90 % from FC, being lifted after watering to 110-115%.

Watering with deep ring furrows transferred main stocks of moisture under apple-trees were from the upper horizons of 1 m meter of layer of soil, subject the fast desiccation by evaporation from the soil and consumption by grass, to deep layers where it is taken up by the apple trees. From a middle of September prior to the beginning of October the orchard was not watered, but the moisture in average and lower horizons of soil remained within the limits of 72-76 % FC. The upper layers of soil were dried down to 48-50 % from FC.

Last vegetation watering increased average moisture content till 91-95% from FC, and in low layers the humidity was lifted above 100%. Winter watering increased moisture reserves above 100 % from FC.

The definition of humidity of soil in periods between watering (3-4 days) has shown, that the moisture from different horizons is not depleted uniformly. So, in the summer period from July, 23 till August, 9 in experience B-1-1 the moisture was uniformly consumed by plants from all horizons layer approximately up to 1 meter depth. In the autumn the lost of moisture from horizon 0.8-1.0 m stopped. Therefore, it is possible to conclude that trees consumed the moisture. In the same period there was a sharp lowering of air temperature at night down to 5-6°C and leaves turned yellow indicating the end of the vegetation season of the orchard. Grasses consumed most of the moisture from the upper horizons.

Initial soil moisture (in 2000) was sampled at the second phase of apple tree development, blossom and beginning of flowering (12.04) before the first irrigation is shown in fig.1.3. The humidity of ground amounted to 80%. For the experiment of 2000 irrigation scheduling was determined from the water depletion calculation of the model and AMS by keeping the moisture balance of the 0-1.5 m soil layer between 70% and 100 % of FC. The last irrigation and a 39.8 mm rainfall raised the average moisture content to 100 %, allowing omitting the irrigation for replenishing soil water storage. The dynamic of moisture content in the soil down to 1.5 m depth in the orchard irrigated according to AMS (average of two replicates) is shown in fig.1.3.

In the experiments of 2001 AMS calculation of evaporability assigned periods and watering norms of strawberry. The moisture balance of 0.5 m soil layer was maintained in the range 77.42-84.28 % and 102.07-110.28 % from FC (fig. 1.4-1.5. The observations were terminated in connection with the termination of period of the agreement 25.06.01. Waterings by norms of 30-35 mm were applied at 7 days intervals. Modeled water consumption is compared with water balance measurements in

fig.1.6. The integral curves show a smoother dynamics of water use in the experiments based on AMS than those derived from recommended practice of watering.

Dynamics of soil moisture under strawberry in experiment from AMS in 2001.

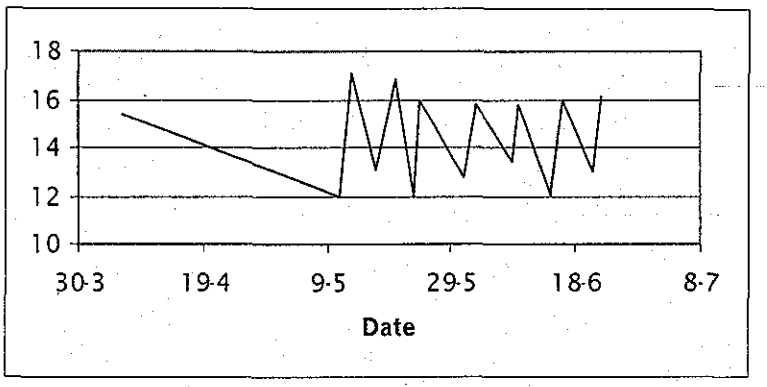


Fig.1.4

Dynamics of soil moisture under strawberry in experiment with recommended practice norm of irrigation in 2001.

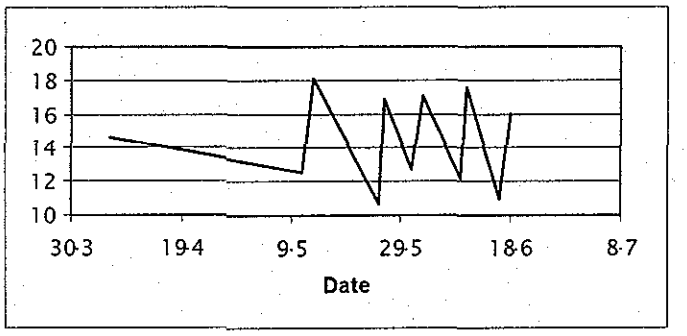


Fig.1.5

General water use by strawberry from a root-inhabited layer of soil in experiments of 2001 (integral)

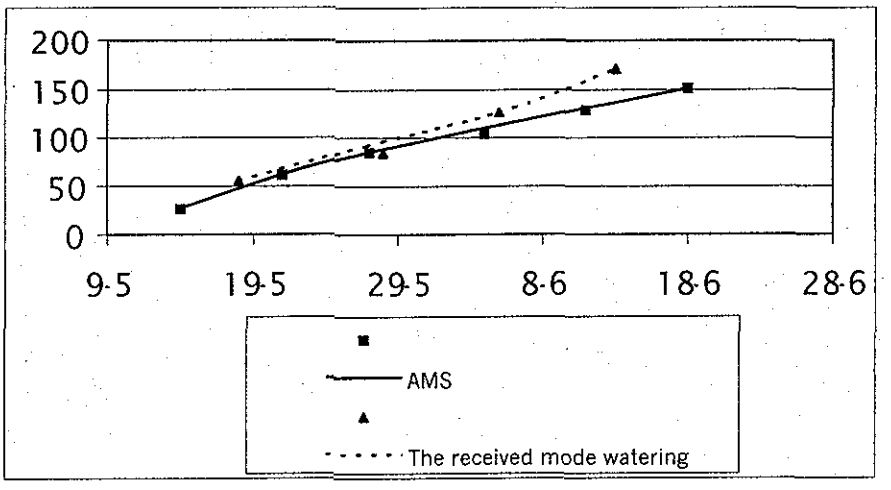


Fig.1.6

The first growth season watering was conducted on 17.05. The moisture of soil was 12 % gravimetric or 76.04 % from FC. The following 3 waterings were applied when moisture in the 0.7 m soil layer was gravimetric 13 % or 83 % from FC. The soil moisture after waterings reached 99.2-109.6 % from FC or 15.7-17.3 % gravimetric. The waterings of barley was suspended at waxen ripeness of a grain at soil moisture 84.54 % FC. At the end of a vegetation the soil moisture was depleted to 63.5 % FC (fig.1.7).

Dynamics of soil moisture in 0.7 m of layer under crops of barley in experiments from AMS in 2001.

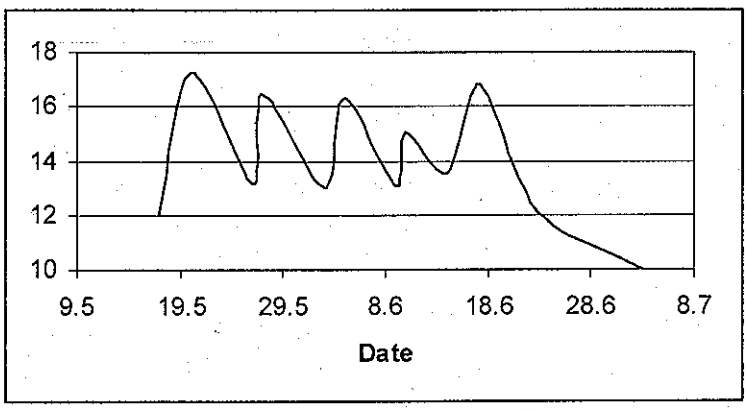


Fig.1.7

3.1.3 Total water use of the irrigation orchard

In parallel with the experimental determination of total water use by the orchard, for monitoring, the water balance equation accounted analytically for water use during a time interval:

$$P + M + Zm + Zx - E - Ev - Mthru + \Delta Wh + \Delta Usur + Kh - Jh = 0,$$

Where:

P – sum of precipitation for the interval, mm;

M – irrigation norm for the same period, mm;

Zm and Zx – run-on from water leaking from main and supply channels upstream of the experimental plot (EP);

E – total water use, mm;

Ev – evaporation from ponded water on the soil or from sprinkled drops, mm;

Mthru –runoff of excess irrigation from the EP, mm;

ΔWh = Whbeg-Whend –moisture content change in the root zone h,

Whbeg and Whend –moisture content at the beginning and end of the interval,

Kh – replenishment of the root zone from the water table, mm;

Usur – run-on from upstream terrain, mm;

Jh – moisture leaching below the root zone, mm.

The supplying flumed channel is far from EP. Run-on of water leaks is insignificant. Therefore, the terms Zm and Zx of the equation in accounts can be omitted.

Excess runoff was excluded by the furrowing technique and the small amounts at each application.

Initial accumulation of moisture in early spring is excluded from water use, because the bookkeeping of water begun on May 25.

Evaporation of free water in buried half-ring furrow is negligibly small and can be discarded.

Water leaching below the root zone is given by the formula:

$$J_F = m_{gn} - m_{nt}, \qquad M_{nt} = W_{aw} - W_{bw}$$

Where:

M_{gn} - the irrigation gross norm for each watering, mm;
M_{nt} – the irrigation net norm, mm;
W_{aw} , W_{bw} – Water stored in soil after and before watering.
The equation of water balance for EP is:

$$W_{beg} + m + P - E - J_F - W_{end} = 0,$$

Accordingly the water use of tree and grass community was:

$$E = W_{beg} + m + P - J_F - W_{end},$$

The account of water balance (in 1999) 1 m of a layer of soil and definition of the total water requirement of the apple orchard is represented in table1.7.

Table 1.7.
Account of water balance 1 m of layer of soil of irrigated apple orchard on periods of observations

Date			Period, days	Stock of moisture, mm		Irrigation net norm, mm	Precipitation, mm	Total water requirement, mm					
								Observed			Indicated,		
Initial	Final	Average		Initial	Final			For period	Daily average	Integrated	For period	Daily average	Integrated
30.06	20.07	10.07	20	219.5	203.1	32.1	50.9	99.4	4.97	99.4	99.4	4.97	99.4
20.07	30.07	25.07	10	203.1	224.2	38.6	6.7	24.2	2.42	123.6	18.1	1.81	117.5
30.07	02.08	01.08	3	224.2	214.9	0	0.7	10.0	3.33	133.6	17.5	5.83	135.0
08.08	05.08	03.08	3	214.9	210.5	0	5.4	9.8	3.27	143.4	8.5	2.83	143.5
05.08	09.08	07.08	4	210.5	197.8	0	0	12.7	3.18	156.1	20.0	5.00	163.5
09.08	19.08	14.08	10	197.8	246.7	70.4	37.8	59.3	5.93	215.4	38.5	3.85	202.0
19.08	26.08	23.08	7	246.7	255.0	46.9	0	38.6	5.51	254.0	52.0	7.42	254.0
26.08	30.08	28.08	4	255.0	242.6	0	0	12.4	3.10	266.4	28.0	7.00	282.0
30.08	06.09	03.09	7	242.6	273.3	49.3	34.4	53.0	7.57	319.4	36.2	5.14	318.2
06.09	09.09	08.09	3	273.3	254.7	0	1.8	20.4	6.80	339.8	26.8	8.03	345.0
09.09	13.09	11.09	4	254.7	232.9	0	0	21.8	5.30	361.6	13.8	3.45	358.8
13.09	16.09	14.08	3	232.9	226.2	0	0	6.7	2.23	368.3	7.2	2.40	366.0
16.09	20.09	18.09	4	226.2	220.2	0	0	6.0	1.50	374.3	6.0	1.50	372.0
20.09	27.09	24.09	7	220.2	231.3	0	9.2	8.1	1.16	382.4	10.0	1.43	382.0
27.09	30.09	28.09	3	231.3	225.6	0	0	5.7	1.57	388.1	6.0	2.00	388.0
30.09	13.10	06.10	13	225.6	267.0	57.9	16.7	33.2	2.55	421.3	9.0	6.69	397.0

Total water use during the observation period from 30.06.99 till 13.10.99 or for 104 days amounted to 421.3 mm, versus indicated 397.0 mm. Daily average water requirement initially was 4.97 mm/day. Maintaining moisture at the level 65 % of FC before irrigation required 2.42 to 3.33 mm. Elevated supply of moisture to plants from the beginning of August to the middle of September meant an increase of use from 3.10 to 7.57 mm/day. Then, drop of plants water requirement in the autumn reduced to 1.16-1.57 mm/day. The increase of water requirement till 2.55 mm/day from 30.09 till 13.10 was for restablishing stock for the next year growing season.

The soil water balance (in 2000) to 1.5 m and the total water use of the orchard are presented in tables 1.8 and 1.9.

Table 1.8.
Periodic water balance of 1.5 m soil layer of irrigated orchard.

Date			Period, days.	Moisture storage, mm		Effective irrigation, mm	Production rain, mm	Total water use, mm					
								modeled			adjusted		
Initial	Final	Average		Initial	Final			For period	Daily average	Integrated	For period	Daily average	Integrated
25.05	08.06	31.05	15	299.6	280.1	44.7	13.0	77.2	5.15	77.2	77.2	5.15	77.2
09.06	20.06	14.06	12	280.1	325.1	71.2	3.0	29.2	2.43	106.4	38.2	3.17	115.4
21.06	05.07	28.06	15	325.1	294.0	68.7	4.6	104.4	6.96	210.8	69.6	4.64	185.0
06.07	10.07	08.07	5	294.0	360.0	69.0	0.1	3.1	0.62	213.9	59.2	6.84	244.2
11.07	20.07	15.07	10	360	312.2	-	4.2	52.0	5.20	265.9	40.3	40.3	284.5
21.07	10.08	31.07	21	312.2	236.8	46	3.6	125.0	5.95	390.9	74.3	3.55	359.0
11.08	28.08	19.08	18	236.8	293.9	116.0	5.6	64.5	3.58	455.4	79.0	4.39	438.0
29.08	05.09	01.09	8	293.9	346.0	66.7	0.0	14.6	1.75	470.0	46.5	5.81	484.5
06.09	16.09	11.09	11	346.0	299.1	-	0.0	46.9	4.26	516.9	32.5	2.95	517.0
17.09	01.10	24.09	15	299.1	381.9	65.9	39.8	22.9	1.53	539.8	23.0	1.53	540.0

Table 1.9
Soil water balance to 1.5 m depth of irrigated orchard at specified development phases

Phases of development	Date			Period, day	The stocks of a moisture, mm		Net irrigation, mm	Precipitation, mm	Total water use, mm					
									Modeled			Adjusted		
	Initial	Final	Average		Initial	Final			For period	Daily average	Integrated	For period	Daily average	Integrated
1. Fruit set, leaf growth –pruning redundant ovaries, shoot growth	25.05	20.06	07.06	27	299.6	325.1	115.9	16.0	106.4	3.94	106.4	115.4	4.27	115.4
2. Pruning redundant ovaries, shoot growth - beginning strengthened fruit growth	21.06	10.07	30.06	20	325.1	360.0	137.7	4.7	107.9	5.40	214.3	128.8	6.44	244.2
3. Beginnings of strengthened fruit growth beginning of fruit maturing	11.07	05.09	08.08	57	360.0	346.0	228.7	13.4	255.7	4.49	470.0	240.3	4.22	484.5
4. Beginning of fruit maturing end of active vegetation, harvest	06.09	01.10	18.09	26	346.0	381.9	65.9	39.8	69.8	2.68	539.8	55.5	2.13	540.0

Total water use from 25.05.00 till 01.10.00 or for 130 day, modeled and adjusted, was 539.6 mm and 540.0 mm. Initial daily average water use was 5.15 mm/day and varied from 2.95 to 4.64 mm during the irrigation period. Water use by vegetation during the autumnal period was 1.53 mm/day. Water use during the phases of tree development changed at the beginning of leaf growth from 3.94 to 4.27 mm/day. At the start if the irrigation period, it became 5.4 to 6.44 mm/day, ending at 2.68 to 2.14 mm/day at the halt of the active vegetation. The qualitative analysis of data and results of modeling was made for periods of observations and phases of development of apple trees by comparing evaporability according to AMS data and observed water requirements of the orchard (table 1.10 and table 1.11 and fig.1.8).

Table 1.10

Account indicated total water requirement during periods of observations and in the increasing sum, ratio water requirement Ei to AMS evaporability Eo of the irrigated apple orchard

Date of periods of observations			Evaporability on AMS Eo, mm		Total water requirement by a orchard Ei, mm				Factor of ratio		The lower level of humidity of soil for period, % FC
					Balance		Indicated,				
Initial	Final	Average	On periods of observations Eop	Integrated Eoi	On periods of observations	Integrated	Integrated E_{ii}	On periods of observations Eip	K_{ii}	K_{ip}	
01.07	20.07	10.07	262.6	262.6	99.4	99.4	99.4	99.4	0.387	0.387	82.18
20.07	30.07	25.07	175.7	438.3	18.1	117.5	121.0	21.6	0.276	0.123	66.62
30.07	02.08	01.08	40.9	479.2	17.8	135.0	130.0	9.0	0.271	0.220	70.57
02.08	05.08	03.08	58.9	538.1	8.5	143.5	143.5	13.5	0.267	0.229	69.13
05.08	09.08	07.08	94.6	632.7	20.0	163.5	163.5	20.0	0.258	0.211	64.93
09.08	19.08	14.08	182.4	815.1	38.5	202.0	202.5	39.0	0.248	0.214	81.00
19.08	26.08	23.08	170.4	985.5	52.0	254.0	257.0	54.5	0.261	0.320	83.71
26.08	30.08	28.08	54.9	1040.4	28.0	282.0	280.0	23.0	0.269	0.419	79.65
30.08	06.09	03.09	81.0	1121.4	36.2	318.2	321.5	41.5	0.287	0.512	97.10
06.09	09.09	08.09	39.2	1160.6	26.8	345.0	343.0	21.5	0.295	0.548	83.62
09.09	13.09	11.09	55.7	1216.3	13.8	358.8	360.0	17.0	0.296	0.305	76.46
13.09	16.09	14.09	44.6	1260.9	7.2	366.0	366.0	6.0	0.290	0.134	74.28
16.09	20.09	18.09	64.5	1325.4	6.0	372.0	374.0	8.0	0.282	0.124	72.31
20.09	27.09	24.09	68.7	1394.1	10.0	382.0	382.0	8.0	0.274	0.116	75.94
27.09	30.09	28.09	26.0	1420.2	6.0	388.0	385.0	3.0	0.271	0.115	74.06
30.09	13.10	06.10	98.2	1518.4	9.0	397.0	395.0	9.0	0.260	0.102	93.06

Table 1.11

Seasonal total water use during measurement intervals and ratio of accumulated modeled water use Eo over accumulated Ei evaporability of the irrigated orchard (2000)

Date of observations periods			Transpiration from AMS EP, mm		Total water use by orchard Ei, mm				Factor ratio				The lower threshold of moisture of soil for period, % FC
					Balance		adjusted,		Kpi		Kai		
Initial	Final	Average	On periods of observations, Eop	Integrated Eoi	On periods of observations Eip	Integrated Eis	On periods of observations Eap	Integrated E as	Eip Eop	Eis Eoi	Eap Eop	Eas Eoi	
25.05	08.06	31.05	66.90	66.90	77.2	77.2	77.2	77.2	1.15	1.15	1.15	1.15	74.39
09.06	20.06	14.06	54.71	121.61	29.2	106.4	38.2	115.4	0.53	0.88	0.70	0.95	86.25
21.06	05.07	28.06	77.38	198.99	104.4	210.8	69.6	185.6	1.35	1.06	0.90	0.93	78.17
06.07	10.07	08.07	29.46	228.45	3.1	213.9	59.2	244.2	0.10	0.94	2.00	1.07	91.64
11.07	20.07	15.07	43.25	271.70	52.0	265.9	40.3	284.5	1.20	0.98	0.93	1.05	85.17
21.07	10.08	31.07	101.6	373.30	125.0	390.9	74.3	359.0	1.23	1.05	0.73	0.96	71.7
11.08	28.08	19.08	79.38	452.68	64.5	455.4	79.0	438.0	0.81	1.01	0.99	0.97	80.32
29.08	05.09	01.09	32.45	485.13	14.6	470.0	46.5	484.5	0.45	0.97	1.43	1.00	93.26
06.09	16.09	11.09	42.51	527.64	46.9	516.9	32.5	517.0	1.10	0.98	0.76	0.98	81.94
17.09	01.10	24.09	30.33	557.97	22.9	539.8	23.0	540.0	0.75	0.97	0.76	0.97	98.11

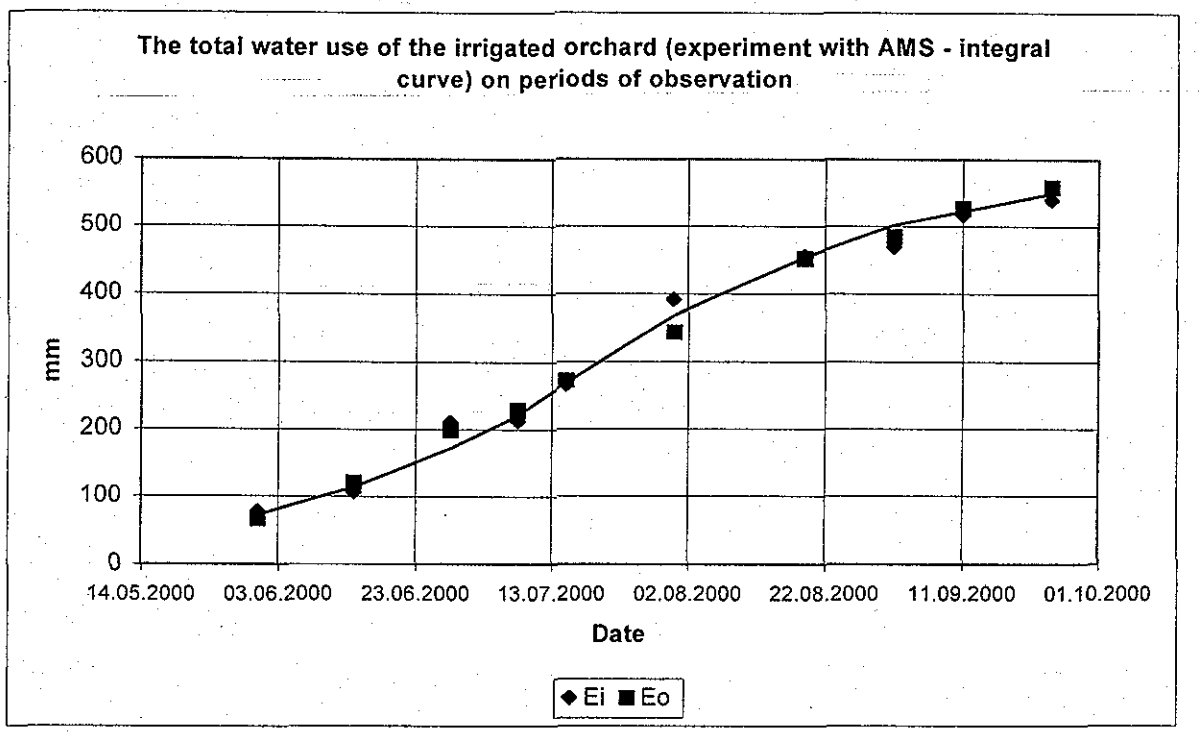


Fig.1.8.

In 2000, orchard water use determination begun at the start of the irrigation season. The dynamic analysis of factors Kpi and Kai shows that their magnitude changed with apple tree development and with meteorological conditions. In the beginning of the season, the threshold moisture content to operate irrigation was above 80 % FC, factors Kpi and Kai are fairly similar through the growth phases of the orchard during the irrigation season. At the end of the season the cold temperature slowed the water uptake resulting in a decrease of the factors. Factors were smaller when the threshold moisture content that triggered irrigation decreased. Calculation of aqueous balance 0.5 m of stratum ground and definition of a general water use strawberry are presented in table 1.12.

Table 1.12

Calculation of aqueous balance 0.5 m of stratum ground of dabbled strawberry on periods of observations

Date			Period, days.	Moisture storage, mm		Effective irrigation, mm	Production rain, mm	Total water use, mm					
								modeled			adjusted		
Initial	Final	Average		Initial	Final			For period	Daily average	Integrated	For period	Daily average	Integrated
AMS													
11.05	17.05	14.05	7	78.2	84.7	32.6	0.6	26.7	3.81	26.7	27.0	3.86	27.0
18.05	23.05	21.05	6	84.7	78.3	21.9	6.2	34.5	5.75	61.2	35.0	5.83	62.0
24.05	31.05	27.05	8	78.3	82.4	25.9	1.5	23.3	2.91	84.2	22.5	2.81	84.5
1.06	8.06	4.06	8	82.4	87.4	20.4	3.6	19.0	2.38	103.5	25.0	3.13	109.5
9.06	14.06	11.06	6	87.4	78.4	15.3	1.1	25.4	4.23	128.9	21.5	3.58	131.0
15.06	21.06	18.06	6	78.4	84.5	25.5	1.7	22.1	3.68	151.0	20.0	3.33	151.0
сумма			41			141.6	14.8		3.68			3.68	
Practical mode irrigation													
11.05	25.05	18.05	15	81.5	69.1	36.1	6.9	55.4	3.70	55.4	55.5	3.70	55.5
26.05	31.05	28.05	6	69.1	82.7	40.6	1.4	28.4	4.73	83.8	40.5	5.79	96.0
1.06	9.06	5.06	9	82.7	71.9	28.0	3.6	42.4	4.71	126.2	30.0	3.33	126.0
10.06	16.06	13.06	7	71.9	71.0	42.3	1.1	44.3	6.33	170.5	44.5	6.36	170.5
сумма			37			147.0	13.0		4.61			4.61	

Watering during the strawberry harvest period from 11.05 till 21.06 for the AMS experiment, for 41 day amounted to 151 mm. The daily average water use var-

ied from 3.86-5.83 mm in an initial stage and 2.81-3.58 mm at maturing of the berries. By comparison the usually practiced norm consisted of irrigations, with amounts varying from 3.7 to 5.79 mm / day, at crop start, falling to 3.33 mm / day when the canopy was established and increasing to 6.36 mm / day at harvest.

The irrigation water use of barley from 17.05 till 3.07 for 49 days amounted to 193 mm. The daily average water use at the beginning of irrigation period equaled 5 mm / day. During heading and flowering the water use from 0.7 m of soil layer was within 4.71-4.9 mm / day. During lactic and waxen ripeness of grain the water use was 3.87 mm / day. At the end of vegetation of complete ripeness of grain the water use in experiments had decreased to 1.4 mm / day (table 1.13).

Table 1.13

Calculation of water balance 0.7 m of soil layer with barley in 2001

Date			Period, days.	Moisture storage, mm		Effective irrigation, mm	Production rain, mm	Total water use, mm					
								modeled			adjusted		
Initial	Final	Average		Initial	Final			For period	Daily average	Integrated	For period	Daily average	Integrated
17.05	25.06	21.05	9	106.7	116.4	47.1	7.2	44.6	4.96	44.6	45	5	45
2.1.05	1.06	29.05	7	116.4	115.8	29.8	1.6	32.0	4.57	76.6	33	4.71	78
2.06	8.06	5.06	7	115.8	116.0	29.2	4.1	33.5	4.79	110.1	34	4.86	112
9.06	13.06	11.06	5	116.0	119.9	23.1	1.3	20.5	4.10	130.6	24.5	4.9	136
14.06	20.06	17.06	7	119.9	118.6	32.0	0.7	32.0	4.57	162.6	27	3.86	163.5
21.06	24.06	22.06	4	118.6	103.9		1.3	16.0	4	178.6	15.5	3.87	179
25.06	3.07	29.06	10	103.9	89.1			14.8	1.45	193.4	14	1.4	193
сумма			49			159.2							

The character of increase the process of an evapotranspiration of barley is defined on an integral curve (fig.1.9).

General water use by crops of barley in 2001 (integral)

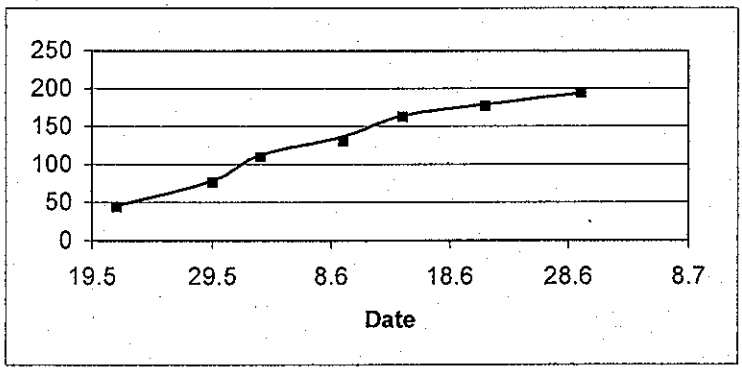


Fig.1.9

1.3. Qualitative analysis of data of the model by results of field experience

The plants of strawberry have a definite specificity for water use. The water use occurs from 0.5 m of stratum ground because the root system of plants penetrates only down to 0.4 m. The consumption of moisture by strawberry increases during formation of the canopy. The crop coefficient Kai during the observation period increases from 0.78 to 1.07. It drops at maturity of berries to 0.52-0.65. The same tendency is observed at matching interval of predicted of water use and evaporability (table 1.14).

Table 1.14
Reduced general water use of strawberry on periods

Date of periods of observations			Transpiration on AMS EP, mm		Total water use by an orchard Ei, mm		Factor of ratio		The lower threshold of humidity of soil for period, % FC
Initial	Final	Average	On periods of observations, Eop	Integrated Eoi	On periods of observations Ei	Integrated Esi	Eap / Eop	Eas / Eoi	
11.05	17.05	14.05	34.44	34.44	27	27	0.78	0.78	77.42
18.05	23.05	21.05	32.68	67.12	35	62	1.07	0.92	84.28
24.05	31.05	27.05	43.10	110.22	22.5	84.5	0.52	0.76	77.49
1.06	8.06	4.06	45.56	155.78	25	109.5	0.55	0.7	81.25
9.06	14.06	11.06	32.85	188.63	21.5	131	0.65	0.69	86.93
15.06	21.06	18.06	40.21	228.84	20	151	0.5	0.66	78.07

Roots of barley penetrated through a dense stony layer to reach 1 m depth, wheras the soil layer under investigation reached only 0.7m. However, relation of water use matched closely evaporability calculated by the model. During development of barley the coefficient was 1.05 and 0.96-0.98 at beginning maturing grain. In phases of waxen and complete ripeness it dropped to 0.9-0.88 (table 1.15).

Table 1.15
Calculation of an integral general water use of barley on periods of observations and coefficients of its relation to evaporability

Date of periods of observations			Transpiration on AMS EP, mm		Total water use by an orchard Ei, mm		Factor of ratio		The lower threshold of humidity of soil for period, % FC
Initial	Final	Average	On periods of observations, Eop	Integrated Eoi	On periods of observations Ei	Integrated Esi	Eap / Eop	Eas / Eoi	
17.05	25.05	21.05	43.03	43.03	45	45	1.05	1.05	76.04
20.05	1.06	29.05	36.67	79.7	33	78	0.9	0.98	83.33
2.06	8.06	5.06	36.49	116.19	34	112	0.93	0.96	82.51
9.06	13.06	11.06	25.76	141.96	24.5	136.5	0.95	0.96	82.7
14.06	20.06	17.06	38.77	180.73	27	163.5	0.7	0.9	85.67
21.06	24.06	22.06	21.62	202.35	15.5	179	0.66	0.88	84.54
25.06	3.07	29.06			14	193			73.95
3.06									63.5

3.2 Corn water uptake response to drought

This section summarizes the findings of the research on model development carried out in Israel.

3.2.1 Stomatal response of corn to water stress

Contributors: M. Fuchs, S. Moreshet., C. Yao and Y. Li

Introduction

The transpiration model based on the combination approach (Monteith, 1964) introduces the physiological control of water vapor flow in the leaves by a leaf

resistance parameter. To adjust for deficit moisture supply from the soil, the leaf resistance increases. In the original formulation of the model, this resistance referred to a lumped resistor representing the foliage, hooked-up in series with the aerodynamic resistance of the atmospheric surface layer. Experimental investigation of the foliage resistance required an inversion of the transpiration model and independent measurements of the transpiration (Van Bavel, 1967). Yet, the relation to direct measurements of the stomatal resistance on leaves remained undefined.
A sub model with identifiable parameters about the mechanism regulating stomatal opening is needed to render the model operational. As light is the main environmental factor, to which stomatal aperture responds it is reasonable to parameterize the relation between incoming photosynthetically active radiation (PAR) and stomatal resistance. Previous research with cotton (Petersen et al., 1991) has shown that moisture stress changed the value of the coefficients in the mathematical function relating leaf resistance to PAR. The current project refines this finding by establishing directly the effect of a soil water deficit on these coefficients.

Methods

A series of stomatal resistance measurements under various conditions of the soil moisture deficit in the soil was made to deal with this problem in two 1000 m^2 plots receiving drip irrigation. The actual transpiration was measured with the heat pulse method. Potential transpiration was computed from the model assuming zero stomatal resistance. The daily value of the actual to potential transpiration ratio was calculated. In the dry treatment a drop to 60% of the initial value immediately after the last irrigation triggered a new water application restoring 60% of the accumulated soil water deficit. In the wet treatment the irrigation triggering value was a 20% drop of the ratio with a full return of the total water depletion. A steady state porometer (LI-1600) measured stomatal resistance. The porometer bears a quantum sensor for *PAR* (LI-190) to measure incident *P*hotosynthetically *A*ctive *R*adiation on the leaf. The measurements were taken on the abaxial and adaxial faces of the leaf. During a measurement the leaf remained in its original position. A time domain reflectometer (TDR) monitored soil moisture content in three replicates at the following locations: depth - 0.05, 0.35, 0.50 m, distance from dipper line - 0.15, 0.30, 0.45 m.

Results and discussion

The diurnal values of the resistances were plotted against incident PAR during several drying cycles. The results are summarized in Table 1. The mathematical form of the relation between measured resistance and incident PAR followed an inverse hyperbolic function:

$$r_L = \frac{r_{L\min}}{1 + \frac{S_{ph}}{PAR}}$$

here $r_{L\,min}$ represents the minimum leaf resistance and S_{ph} is the value of *PAR* for which the actual resistance is twice the minimum value.

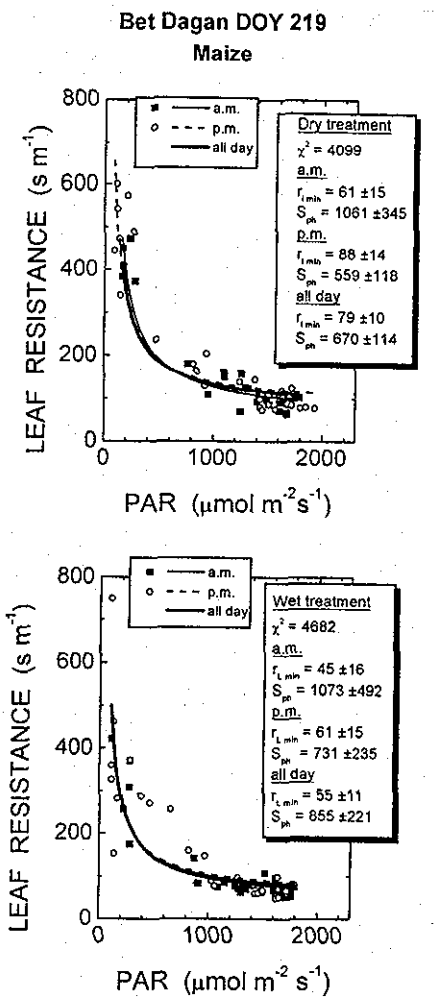


Figure 1. Relation between leaf stomatal resistance and incident photosynthetically active radiation measured during a day immediately following an irrigation.

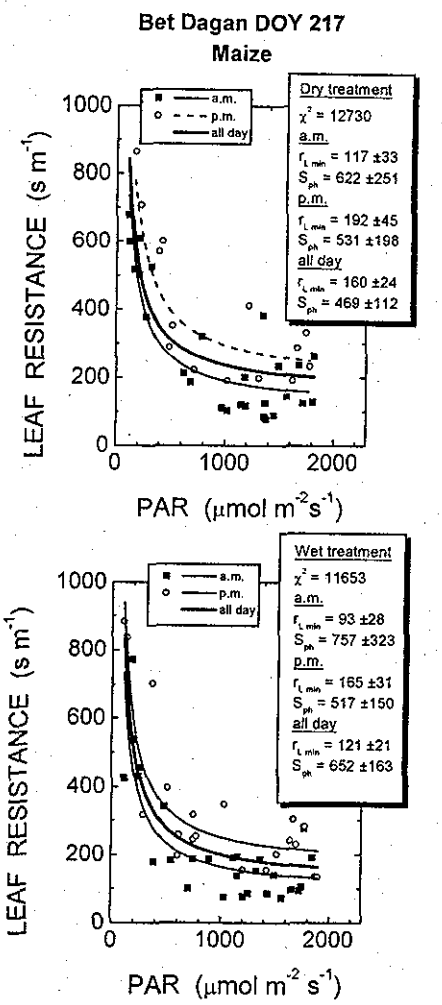


Figure 2. Relation between leaf stomatal resistance and incident photosynthetically active radiation measured during a day with large soil moisture deficit.

Figures 1 and 2 illustrate this relation for two conditions of the soil water status. In Figure 1 a recent irrigation has restored soil moisture to field capacity in the root zone. The soil moisture deficit is low. The parameters of the mathematical functions in the two treatments are similar, with a minimum resistance of the order of 60 s m^{-1}. Figure 2 represents conditions of a large soil moisture deficit. The minimum resistance reaches 120 s m^{-1} in the wet treatment and 160 s m^{-1} in the dry treatment. Yet in the course of the day, the decrease of moisture content due to water uptake causes an increase of the minimum resistance from morning to afternoon. The relative change of resistance with PAR appears independent of the soil moisture condition. The diurnal difference increases as soil moisture deficit increases. Although the value of Sph varies between data sets, the change is not associated with

soil moisture. Therefore, in the application of the model this parameter takes on a constant value of 740 μmol m^{-2} s^{-1}.

The leaf resistance increases linearly with soil moisture deficit (Fig. 3). The least square fit of the linear coefficient and offset shown in Figure 3 were used to update the stomatal function in the transpiration model. In the current version this update is manual once a day. The diurnal change of the minimum resistance at a high soil moisture deficit may impose a modification of the model for use in cases of severe deficit irrigation.

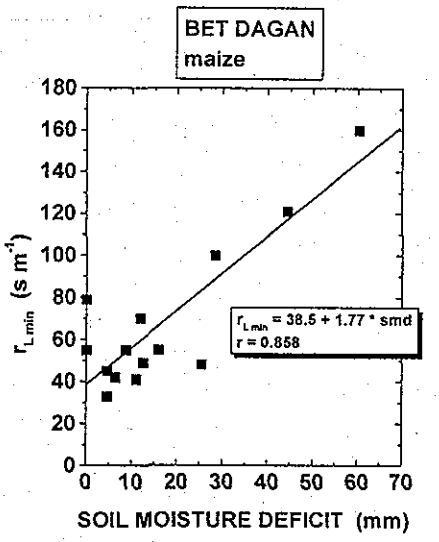


Figure 3. A linear function accounts for the increase of minimum leaf resistance with soil moisture deficit.

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Table 1. Soil moisture deficit increases the minimum leaf resistance ($r_{L\ min}$) and the sensitivity of stomatal response to photosynthetic light (S_{ph}). At a high moisture deficit, the stress condition appears as increase of minimum leaf resistance in the afternoon.

DOY	Treatment	Soil moisture deficit (mm)	a.m.		p.m.		all day	
			$r_{L\ min}$	S_{ph}	$r_{L\ min}$	S_{ph}	$r_{L\ min}$	S_{ph}
198	dry	8.7	51 ± 13	425 ± 182	59 ± 19	617 ± 295	55 ± 11	441 ± 143
	wet	6.4	47 ± 19	575 ± 360	49 ± 24	1106 ± 665	42 ± 15	841 ± 404
200	dry	20.9	29 ± 34	1688 ± 2305	38 ± 36	2186 ± 2266	28 ± 25	2364 ± 2241
	wet	18.6	10 ± 19	2708 ± 5532	44 ± 15	951 ± 372	26 ± 11	1517 ± 697
203	dry	4.6	42 ± 6	357 ± 173	42 ± 5	718 ± 162	45 ± 3	311 ± 60
	wet	4.6	31 ± 6	638 ± 210	31 ± 7	935 ± 400	33 ± 5	636 ± 159
205	dry	12.5	36 ± 38	1516 ± 1810	47 ± 50	1950 ± 2355	49 ± 30	1355 ± 975
	wet	11.0	1 ± 28	38414	54 ± 40	1757 ± 1528	41 ± 23	1487 ± 961
207	dry	28.3	36 ± 34	1604 ± 1765	181 ± 38	370 ± 1434	100 ± 25	638 ± 238
	wet	25.4	26 ± 13	1787 ± 1058	88 ± 15	558 ± 125	48 ± 10	1026 ± 249
217	dry	60.3	117 ± 33	622 ± 251	192 ± 45	531 ± 198	160 ± 24	469 ± 112
	wet	44.4	93 ± 28	757 ± 323	165 ± 31	517 ± 150	121 ± 21	652 ± 163
219	dry	0.0	61 ± 15	1061 ± 345	88 ± 14	559 ± 118	79 ± 10	670 ± 114
	wet	0.0	45 ± 16	1073 ± 492	61 ± 15	731 ± 235	55 ± 11	855 ± 221
222	dry	15.9	53 ± 11	612 ± 226	60 ± 12	610 ± 171	55 ± 8	667 ± 142
	wet	11.9	60 ± 10	472 ± 124	75 ± 10	295 ± 53	70 ± 7	331 ± 45

3.2.2 Root water uptake response to drought

This contribution is the object of an article accepted for publication in Plant, Cell and Environment. The full text is included in the Appendices as Appendix F.

3.3 Productivity

The norm of irrigation, based on magnitude of total water use, received by model of Prof. M. Fuchs with use of data from AMS allowed the optimum water use of the orchard. This was a reason of the increased yield of apple fruit. Mixed apple orchard (varieties, Golden de Luxe, Excellent, Aport) gave an average yield of 31.7 tons/ha, for total water use of 826 mm and planting density of 5×6 m. Specific water use was 26 mm/tons, while in farms, where scheduling did not consider actinometrical and meteorological factors water use increased to 38-44 mm/tons. These data show the increase of irrigation efficiency and productivity that the AMS based model can provide.

The production of strawberry irrigated according to the schedule derived from the AMS for 5 harvests amounted to 5.06 t/ha a water use of 151 mm. The specific water use was 29.84 mm / t. By comparison the standard irrigation norms yielded 3.21 t/ha for a water use of 170.5 mm. The specific expenditure of moisture was 53.11 mm / t.

The barley is a drought-resistant crop. For this reason the grain productivity in the experiments and in field practice differs little. Yields were 4.32 t/ha and 4.26 t/ha for specific water use of 38.7 mm / t and 56.3 mm / t for the experiments and the standard field practice. The major expenditures of water in field conditions are coupled to a less productive technique of irrigation on wide bars by a wild lap joint and jigging of surface field.

3.4 Data obtained with the use of the model

The climatic data received with automatic meteorological station, were treated as follows:

1. Meteorological station, working round the day, with an interval in 10 minutes recorded main climatic parameters (air temperature, relative humidity, direction and velocity of a wind, solar radiation, precipitation, soil moisture(in 2001);
2. The obtained data with the help of memory block were transferred from the meteorological station to the computer and are stored in a data bank;
3. From the data bank the information for the certain days was selected and transferred into the electronic table;
4. From the electronic table the information was treated with the algorithm of Prof. M. Fuchs and the daily average climatic parameters were determined in addition;

The obtained outcomes were reduced in the general table. In the 1999 qualitative analysis of data of the model was made with formulas of Ivanov, and Penman-Monteith. The climatic data obtained from automatic meteorological station, were substituted into the appropriate formulas, output was tabulated and seasonal results are plotted in fig.4.1.

In the 2000 results of climatic data processing are represented on a fig. 4.2.

In the 2001 results of climatic data processing are represented on a fig. 4.3.

3.5 Conclusion

The comparison of methods for scheduling irrigation terms and show that the AMS based model provide the more reliable information. Results of 1999 based on the limit of moisture content determined a water use of 689 mm in six applications. The leaching

amounted to 395.7 mm or 56.7%. In a 2000 scheduling used AMS data and the transpiration model. Water applied in 8 watering was 595 mm, from which leaching losses were 47 mm or 7.9%. The application AMS has allowed to save 45.8 % of the irrigation water.

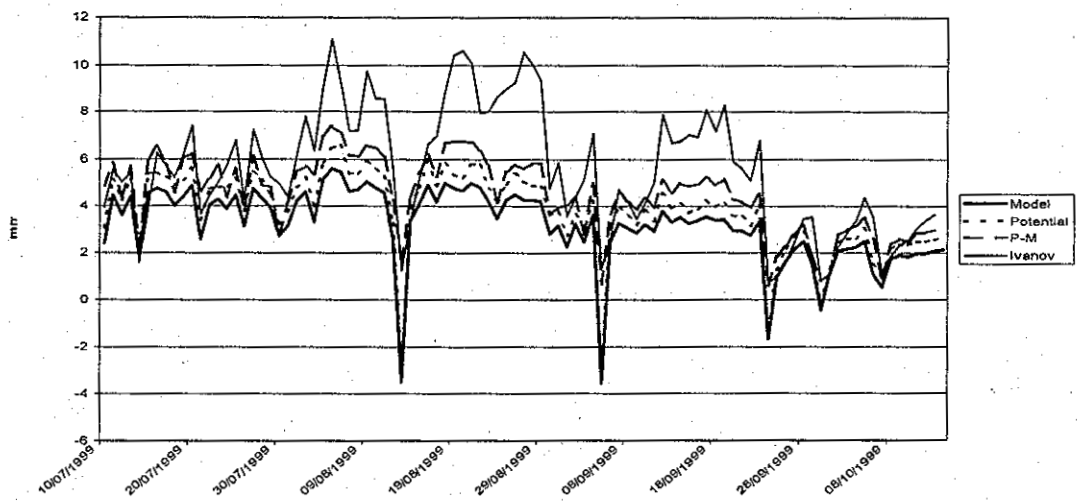

Fig.4.1.

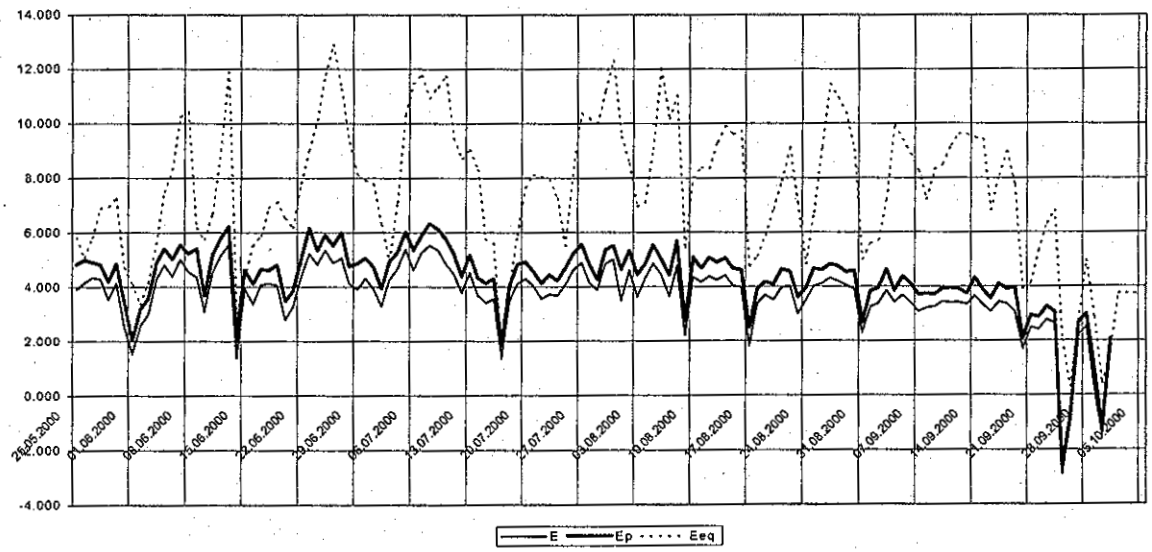

Fig. 4.2.

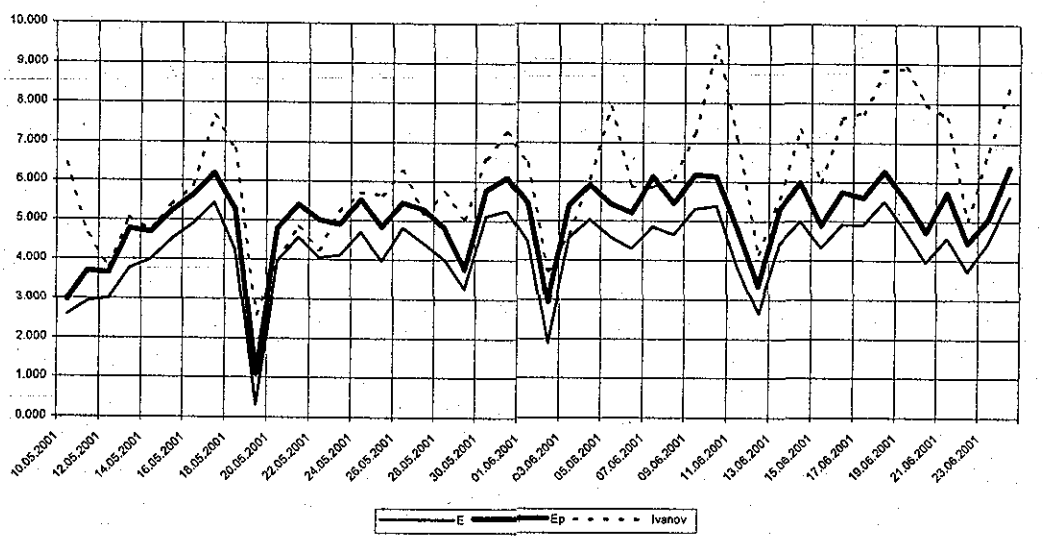

Fig. 4.3.

Adjusting irrigation scheduling of apple orchard and strawberry in 1999-2001 resulted in lower water use than the standard irrigation recommendations. During the experiments of 1999-2000 in the apple orchard this method has helped to save from 12 to 18 mm of irrigation water for each ton of apples and a production of 31.7 t/ha. For strawberry the saving of irrigation water was 23 mm / t. Therefore, the scheduling of irrigation with AMS and the model in mountain and foothill zone of Chui valley increased irrigation efficiency.

4 Impact Relevance and Technology Transfer

Results of this project will be included to the tutorial program of the SIMIS (Scheme Irrigation Management Information System) project carried out in the Kyrgyz Scientific and Research Institute for Irrigation in frame of the World Bank loan organized for farmers and members of water users associations under observation of experts of FAO. At the same time a recommendation will be published for farmers about correct and accurate water regimes for the main crops in Kyrgyzstan. The experimental plot was situated on the orchard of the private farm "Eleman" and the owner was satisfied with results of research because he received an unexpectedly higher yield in 2000. Neighbor farmers of the farm "Eleman" took an interest with results of the experiment and asked questions regarding the determination of the crop water requirements. Scientists recognized the farmers' urgent need for advice about modern technologies and scientific approaches for higher crop production. Experiences and skills have gained from this project will be useful for the GEF (Global Environmental Facilities) projects devoted to the problem of the Aral Sea basin.

During of implementation of the project four scientists acquired good skills in using of AMS and modeling of crop water regimes for efficiency irrigation water management developed in USA and Israel. Capacity of the laboratory was strengthened and six scientist and technicians studied computer and got AMS data processing skills. Staff of laboratory improved the knowledge in oral and written English. The laboratory has purchased an automatic meteorological station and sensors from Campbell Scientific, USA, four personal and two portable computers, Xerox, scanner, two mobile telephones and other laboratory and office equipment. The Institute opened new research directions and intends to expand the cooperation with USAID and Israel. For this purpose several project proposals are under preparation with Israeli scientists.

5 Project Activities/outputs

In June 1998 two scientists from Kyrgyzstan attended training and study sessions in Israel on crop production technologies developed in Israel and learned the modeling of crop water transpiration using of meteorological data collected by the Campbell Scientific weather station, so they can experiment in Kyrgyzstan on crop water use for improved irrigation efficiency. They also observed application of the model cotton and maize experimental fields near Tel Aviv and an apple experimental orchard on the north of Israel.

In June 2000 Dr. J. Rahmanov visited Israel for coordination of project activities and discussion of the results obtained in 1999. During the visit of Dr. J. Rahmanov, coordination and terminology misunderstandings were clarified. The Annual Report was completed.

In November and December 2000 Dr. J. Rahmanov attended Israel for discussion of results of 2000 and completion of the Final Report. During the visit was organized a trip to the irrigation equipment factory "Netafim" in the south of Israel. Recently purchased frequency domain reflectometry soil moisture probes were put in operation. Hook-up and wiring procedures were demonstrated. The data acquisition software was also tested in a set-up that simulates the equipment configuration to be used in Kyrgyzstan.

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APPENDICES

Appendix A A-1

Appendix B B-1

Appendix C C-1

Appendix D D-1

Appendix E E-1

Appendix F F-1

Appendix A

1999 year

The main climatic factors in a hill-foothill zone (under the indications AMS)

Date	The temperature	Relative humidity, %	Velocity of a wind, m\s	Precipitation, mm
09.07.99	23.616	52.382	1.400	7.9
10.07.99	20.428	65.867	1.533	9.6
11.07.99	21.871	54.624	1.310	0.0
12.07.99	21.207	57.702	1.418	0.0
13.07.99	21.831	55.908	1.796	1.5
14.07.99	17.253	84.016	0.808	1.8
15.07.99	21.738	68.370	1.687	0.0
16.07.99	23.143	51.594	1.629	0.0
17.07.99	24.219	57.707	1.518	0.0
18.07.99	22.752	58.856	1.621	0.5
19.07.99	22.110	50.228	1.498	0.8
20.07.99	22.861	42.101	1.380	0.0
21.07.99	18.552	65.691	1.804	6.6
22.07.99	19.593	59.925	1.230	0.0
23.07.99	21.129	57.897	1.145	0.0
24.07.99	21.324	52.043	1.769	0.0
25.07.99	22.421	46.142	1.388	0.0
26.07.99	19.178	61.173	1.391	0.1
27.07.99	22.451	42.542	1.362	0.0
28.07.99	22.752	52.502	1.463	0.0
29.07.99	22.683	58.583	1.188	0.0
30.07.99	22.553	60.830	1.117	0.0
31.07.99	22.240	64.975	1.202	0.7
01.08.99	23.616	53.181	1.234	0.0
02.08.99	25.277	44.895	1.297	0.0
03.08.99	23.804	52.317	1.239	5.4
04.08.99	25.904	37.221	1.352	0.0
05.08.99	27.947	29.426	1.519	0.0
06.08.99	26.459	37.574	1.782	0.0
07.08.99	23.225	44.847	1.486	0.0
08.08.99	23.322	44.782	1.442	0.0
09.08.99	26.174	33.473	1.645	0.0
10.08.99	23.661	35.395	1.479	0.0
11.08.99	23.164	34.198	1.342	0.0
12.08.99	19.074	48.403	1.472	6.5
13.08.99	12.438	83.838	1.493	31.9
14.08.99	15.339	64.013	0.940	0.4
15.08.99	17.725	48.826	1.326	0.0
16.08.99	20.791	43.487	1.815	0.0
17.08.99	22.684	45.297	1.528	0.0
18.08.99	24.850	35.935	1.701	0.0
19.08.99	26.123	28.669	1.326	0.0
20.08.99	26.346	28.154	1.372	0.0
21.08.99	25.743	29.915	1.490	0.0
22.08.99	23.518	39.519	1.782	0.0
23.08.99	24.726	42.010	1.414	0.0
24.08.99	25.620	39.908	1.359	0.0

25.08.99	26.194	38.888	1.403	0.0
26.08.99	26.421	37.447	1.689	0.0
27.08.99	27.385	31.302	1.476	0.0
28.08.99	26.619	32.562	1.193	0.0
29.08.99	25.179	33.650	1.350	0.0
30.08.99	20.360	58.835	1.760	0.0
31.08.99	20.874	50.078	1.275	0.0
01.09.99	19.505	67.699	1.270	7.0
02.09.99	19.877	61.521	0.981	0.0
03.09.99	19.373	53.226	1.436	0.0
04.09.99	20.169	37.943	1.321	0.0
05.09.99	11.347	82.060	1.330	27.4
06.09.99	12.172	66.786	1.442	1.8
07.09.99	15.585	48.909	1.525	0.0
08.09.99	16.045	55.348	1.309	0.0
09.09.99	15.069	61.479	1.153	0.0
10.09.99	16.325	56.742	1.503	0.0
11.09.99	18.792	53.867	1.361	0.0
12.09.99	20.946	33.360	1.569	0.0
13.09.99	20.495	42.380	1.297	0.0
14.09.99	21.513	44.298	1.453	0.0
15.09.99	21.950	43.118	1.301	0.0
16.09.99	21.400	42.552	1.405	0.0
17.09.99	21.494	33.185	1.523	0.0
18.09.99	21.174	39.820	1.458	0.0
19.09.99	21.623	31.971	1.563	0.0
20.09.99	17.223	40.602	1.510	0.0
21.09.99	17.492	44.283	1.456	0.0
22.09.99	16.330	46.785	1.203	0.0
23.09.99	19.938	40.014	1.567	0.0
24.09.99	9.381	88.614	1.182	14.3
25.09.99	9.316	85.556	0.840	3.9
26.09.99	9.822	76.752	1.246	1.0
27.09.99	11.473	67.650	1.264	0.0
28.09.99	15.593	62.444	1.031	0.0
29.09.99	15.106	60.643	1.118	0.0
30.09.99	10.350	88.312	0.783	7.8
01.10.99	11.441	85.291	0.604	0.1
02.10.99	12.555	71.699	1.173	0.0
03.10.99	13.369	65.145	1.352	0.0
04.10.99	14.174	60.756	1.415	0.0
05.10.99	15.367	52.441	1.570	0.0
06.10.99	14.334	58.823	1.270	5.6
07.10.99	10.446	83.005	1.296	3.1
08.10.99	9.762	72.329	1.279	0.0
09.10.99	10.864	67.812	1.443	0.0
10.10.99	11.705	66.576	1.575	0.1
11.10.99	12.571	61.514	1.540	0.0
12.10.99	12.069	56.079	1.578	0.0
13.10.99	11.980	52.165	1.486	0.0

Dynamic of humidity of a 1 m stratum of apple orchard soil

Date	Humidity of soil, %					Stock of a moisture, mm	Volumet-ric mass, t/m3	LMC, % from a. d. soil
	from a. d. soil			to volume	from LMC			
	B-1-1	B-1-2	medium					
30.06	16.50	16.50	16.50	21.95	72.05	219.5	1.33	22.9
09.07	18.92	18.92	18.92	25.16	82.62	251.6	1.33	22.9
20.07	15.00	15.54	15.27	20.31	66.68	203.1	1.33	22.9
24.07	17.90	18.28	18.09	24.06	79.00	240.6	1.33	22.9
30.07	16.54	17.18	16.86	22.42	73.62	224.2	1.33	22.9
02.08	15.72	16.60	16.16	21.49	70.57	214.9	1.33	22.9
05.08	15.72	15.94	15.83	21.05	69.13	210.5	1.33	22.9
09.08	14.92	14.82	14.87	19.78	64.93	197.8	1.33	22.9
12.08	20.98	19.30	20.14	26.76	87.95	267.6	1.33	22.9
16.08	23.02		23.02	30.62	100.52	306.2	1.33	22.9
19.08	18.36	18.74	18.55	24.67	81.00	246.7	1.33	22.9
23.08	21.44	22.70	22.07	29.35	96.38	293.5	1.33	22.9
26.08	19.24	19.10	19.17	25.50	83.71	255.0	1.33	22.9
30.08	17.94	18.54	18.24	24.26	79.65	242.6	1.33	22.9
03.09	22.18	21.72	21.95	29.19	95.85	291.9	1.33	22.9
06.09	21.02	20.08	20.55	27.38	94.10	273.3	1.33	22.9
09.09	19.24	19.06	19.15	25.47	83.62	254.7	1.33	22.9
13.09	17.90	17.12	17.51	23.29	76.46	232.9	1.33	22.9
16.09	17.00	17.02	17.00	22.62	74.28	226.2	1.33	22.9
20.09	17.00	16.12	16.56	22.02	72.31	220.2	1.33	22.9
27.09	17.40	17.38	17.39	23.13	75.94	231.3	1.33	22.9
30.09	17.30	16.62	16.96	22.56	74.06	225.6	1.33	22.9
04.10	20.84	21.78	21.31	28.34	93.06	283.4	1.33	22.9
13.10	17.54	22.50	22.50	29.32	98.25	293.2	1.33	22.9

Appendix B

2000 year

The main climatic factors in a hill-foothill zone (under the indications AMS)

Date	Radiation, ΣW/m^2 10 min/day	The temperature, ^{0}C	Relative humidity, %	Precipitation, mm	Ep, mm
25.05.00	39601.170	17.380	46.085	1.500	4.825
26.05.00	52849.779	16.330	50.380	0.000	4.993
27.05.00	55268.986	17.442	46.267	0.000	4.906
28.05.00	46639.834	20.173	43.797	0.000	4.821
29.05.00	34789.479	20.251	43.406	0.800	4.184
30.05.00	47471.629	20.306	41.123	2.100	4.860
31.05.00	31270.107	17.036	55.466	5.400	3.455
01.06.00	27165.071	15.842	58.820	8.500	2.037
02.06.00	26952.182	13.852	63.089	0.100	3.208
03.06.00	38671.169	13.335	52.771	0.200	3.554
04.06.00	56651.829	15.656	43.740	0.000	4.878
05.06.00	56539.188	19.651	37.370	0.000	5.403
06.06.00	44537.546	21.720	36.645	0.000	5.013
07.06.00	53610.532	24.335	29.856	0.000	5.539
08.06.00	39261.709	24.561	29.308	0.000	5.230
09.06.00	46399.093	19.691	48.612	0.000	5.398
10.06.00	29321.089	17.647	47.389	0.100	3.670
11.06.00	55271.649	18.325	40.475	0.000	5.185
12.06.00	56459.457	21.801	31.478	0.000	5.792
13.06.00	52096.453	25.716	22.952	0.000	6.222
14.06.00	15805.661	14.984	68.285	3.900	2.108
15.06.00	46524.081	16.831	58.666	0.000	4.639
16.06.00	25124.019	19.243	53.077	0.300	4.117
17.06.00	47163.096	19.766	51.210	0.000	4.655
18.06.00	41810.028	21.629	47.003	0.000	4.627
19.06.00	32869.542	23.051	48.425	0.000	4.807
20.06.00	15592.331	22.598	52.029	0.700	3.474
21.06.00	28846.471	21.541	52.479	0.000	3.851
22.06.00	43059.251	23.008	43.505	0.000	5.040
23.06.00	50695.403	24.059	37.578	0.000	6.162
24.06.00	49732.518	25.409	33.505	0.000	5.329
25.06.00	49979.861	26.996	27.193	0.000	5.902
26.06.00	42205.597	28.557	25.104	0.000	5.520
27.06.00	38017.251	27.067	30.645	0.000	5.999
28.06.00	38016.441	24.749	37.389	1.000	4.753
29.06.00	34594.051	23.458	42.110	1.700	4.856
30.06.00	43929.723	23.722	44.379	2.100	5.062
01.07.00	30176.353	23.140	43.995	0.100	4.743
02.07.00	27625.841	20.846	49.946	1.000	3.937
03.07.00	52843.804	19.164	57.562	0.000	4.931
04.07.00	53191.128	21.630	45.509	0.000	5.273
05.07.00	55185.716	25.223	31.568	0.000	6.032

06.07.00	37659.270	26.410	27.669	0.000	5.357
07.07.00	51192.300	27.291	28.276	0.000	5.870
08.07.00	51770.180	26.935	32.385	0.000	6.336
09.07.00	46943.480	28.201	33.231	0.100	6.127
10.07.00	34982.520	27.803	29.804	0.000	5.764
11.07.00	40593.260	24.734	36.444	0.100	5.212
12.07.00	33244.323	23.933	39.390	0.000	4.390
13.07.00	42040.362	23.933	37.082	0.000	5.177
14.07.00	28087.571	23.522	41.218	0.000	4.362
15.07.00	32272.486	21.025	54.526	1.800	4.153
16.07.00	34664.476	20.141	54.177	0.400	4.313
17.07.00	16751.550	15.785	81.436	2.900	1.867
18.07.00	40071.451	17.874	63.617	0.900	4.034
19.07.00	43232.860	19.535	50.237	0.000	4.821
20.07.00	42821.024	22.416	43.081	0.000	4.926
21.07.00	37055.322	24.050	43.760	0.000	4.575
22.07.00	25827.471	24.043	44.129	0.000	4.134
23.07.00	30748.951	23.156	42.948	0.000	4.436
24.07.00	33264.484	22.064	45.330	0.300	4.240
25.07.00	45320.987	20.648	55.991	0.000	4.699
26.07.00	50093.642	22.997	39.521	0.000	5.229
27.07.00	48992.982	24.981	30.684	0.000	5.563
28.07.00	32782.020	25.629	33.693	0.000	4.846
29.07.00	36276.559	26.416	37.011	0.000	4.276
30.07.00	47527.648	27.267	31.570	0.000	5.351
31.07.00	44600.180	27.781	26.375	0.000	5.510
01.08.00	14844.132	23.855	33.593	0.000	4.654
02.08.00	45189.144	23.459	39.468	0.900	5.326
03.08.00	37903.712	22.249	48.126	2.000	4.442
04.08.00	48182.393	22.325	46.988	0.000	4.835
05.08.00	48267.602	24.750	39.050	0.000	5.539
06.08.00	34390.951	28.055	28.807	0.000	5.038
07.08.00	24265.030	26.404	35.876	0.200	4.438
08.08.00	37875.480	26.508	30.743	0.000	5.684
09.08.00	18940.563	21.279	57.645	1.800	2.744
10.08.00	45672.843	21.779	38.996	0.000	5.086
11.08.00	44432.785	22.120	37.013	0.000	4.691
12.08.00	45370.143	22.759	39.061	0.000	5.071
13.08.00	39907.752	24.072	35.577	0.000	4.894
14.08.00	44110.290	24.350	32.291	0.000	5.048
15.08.00	35705.751	24.029	33.500	0.000	4.687
16.08.00	34109.311	23.701	31.664	0.000	4.628
17.08.00	16311.466	18.967	58.861	3.600	2.501
18.08.00	37634.145	19.575	57.091	0.000	3.919
19.08.00	41655.655	20.671	52.954	0.000	4.177
20.08.00	31304.825	21.350	46.813	0.000	4.091
21.08.00	36469.440	21.933	40.234	0.000	4.650
22.08.00	40155.023	23.259	34.728	0.000	4.570
23.08.00	33472.053	21.425	45.307	4.400	3.601
24.08.00	43957.205	18.983	58.361	0.000	3.946
25.08.00	43484.674	21.133	47.346	0.000	4.678
26.08.00	42553.480	24.732	38.397	0.000	4.620
27.08.00	41187.590	26.577	28.267	0.000	4.833
28.08.00	41096.162	25.357	28.073	0.000	4.749

29.08.00	40107.153	24.999	30.675	0.000	4.541
30.08.00	38397.541	23.709	36.592	0.000	4.586
31.08.00	21067.225	17.905	54.763	0.000	2.690
01.09.00	40533.900	15.517	43.264	0.000	3.837
02.09.00	40916.971	15.219	41.179	0.000	3.937
03.09.00	39513.215	18.018	35.170	0.000	4.643
04.09.00	33359.581	22.513	26.644	0.000	3.856
05.09.00	33625.362	22.117	29.416	0.000	4.387
06.09.00	30234.514	20.933	29.938	0.000	4.116
07.09.00	26215.425	20.354	32.958	0.000	3.705
08.09.00	34076.014	19.214	38.465	0.000	3.727
09.09.00	35163.304	19.507	30.133	0.000	3.705
10.09.00	36985.509	20.287	30.834	0.000	3.916
11.09.00	34177.834	21.141	28.047	0.000	3.948
12.09.00	32595.661	22.161	27.990	0.000	3.907
13.09.00	34571.051	22.570	29.238	0.000	3.734
14.09.00	32522.049	22.891	31.165	0.000	4.328
15.09.00	30014.793	22.872	31.545	0.000	3.872
16.09.00	32906.275	20.282	44.586	0.000	3.558
17.09.00	34082.265	20.849	35.875	0.000	4.099
18.09.00	34094.154	21.959	32.236	0.000	3.909
19.09.00	30864.395	18.257	31.330	0.400	3.943
20.09.00	16376.918	11.989	52.422	0.100	2.086
21.09.00	31680.184	13.861	54.285	0.000	2.943
22.09.00	27719.438	15.709	46.519	0.000	2.870
23.09.00	32303.484	16.695	39.305	0.000	3.279
24.09.00	29078.185	17.661	37.614	0.000	3.055
25.09.00	4893.562	11.166	74.456	24.000	-2.612
26.09.00	10223.267	3.592	93.990	10.100	-0.793
27.09.00	33917.768	9.224	61.166	0.000	2.679
28.09.00	30878.432	13.845	45.157	0.000	3.021
29.09.00	13825.055	10.948	63.060	8.600	0.991
30.09.00	11447.369	6.062	92.710	13.700	-1.246
01.10.00	28460.417	8.105	76.679	0.000	2.086

Biometrics observations of a growth and development of a winter wheat

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidity in % from HB	Different parameters
Resumption vegetation-an exit in a handset		9.03-17.04	40	0-70	70	
Exit in a handset ear		18.04-26.05	39	0-70	70	
Appearance of ear - flowering		27.05-1.06	6	0-90	70	
Flowering- milky ripeness		2.06-14.06	13	0-90	70	
Milky ripeness-wax ripeness		15.06-26.06	12	0-90	70	
Wax ripeness-full ripeness		27.06-10.07	14	0-90	70	
Harvesting of a crop	15.07					
Date of the latest Irrigation	20.06					
Irrigate norm, m^3/he						3000
Denseness million unit/he						4,0
Average crop, centner/ha						43
Height of plants: maximum, cm						85
Average, cm						77
Need of wheat for heat for period vegetation						1450-1650

Biometrics observations of a growth and development of a sugar-beet

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidity in % from HB	Different parameters
Crops	10.04					
Sprouts	17.04					
Crops-3 sheet		10.04-12.05	33	0-60	70	
The 3-rd sheet beginning thickenings of						
Knee		13.05-2.06	21	0-80	80	
Beginning thickening of seed lobe knee						
Fading of outside sheets						
(period sugar accumulation)		3.06-20.09	110	0-90	80	
Harvesting of a crop	24.09					
Date of the latest Irrigation	14.09					
Irrigate norm, m^3/he						6700
Denseness thousand unit/he						87
Average crop, cent/ha						440
Height of plants: maximum, cm						52
Average, cm						41
Need of sugar-beet for heat for period vegetation						2600-3200

Biometrics observations of a growth and development of a Lucerne of the last years

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidity in % from HB	Different parameters
Resumption vegetation-flowering		20.03-26.05	67	0-120	After each hay-crop 75-80	
1-5 hay-crop		27.05-27.09	124	0-120	75-80	
Harvesting of a crop		monthly				
Date of the latest Irrigation	28.09					
Irrigate norm, m^3/he						7400
Denseness million unit/he						5,9
Crop-hay, centner/he						210
Height of plants: maximum, cm						120
Average, cm						100
Need of Lucerne for heat (crop-flowering) °C						600-800

Biometrics observations of a growth and development of a potatoes

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidity in % from HB	Different parameters
Landing	30.04					
Sprouts	1.05					
Landing-formation inflorescence		30.04-20.06	52	0-50	70	
Formation inflorescence-flowering		21.06-3.07	13	0-70	70	
Flowering- fading of beet tops		4.07-25.08	53	0-70	70	
Harvesting of a crop	1.09					
Date of the latest Irrigation	1.08					
Irrigate norm, m^3/he						6800
Denseness thousand unit/he						165
Average crop, centner/ha						250
Height of plants: maximum, cm						70
Average, cm						62
Need of potatoes for heat for period vegetation, °C						1500-1600

Biometrics observations of a growth and development of a corn

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidifying in % from HB	Different parameters
Planting	30.04					
Sprouts	8.05					
Planting-appearance of panicle		30.04-10.07	54	0-60	75	
Appearance panicle –flowering		11.07-19.07	9	0-80	75	
Flowering-milky ripeness		20.07-3.08	15	0-90	75-80	
Milky-wax Ripeness		4.08-23.08	20	0-90	75-80	
Wax-full ripeness		24.08-8.09	16	0-90	70	
Harvesting of a crop	10.09					
Date of the latest irrigation	27.08					
Irrigate norm, m^3/he						5100
Denseness thousand unit/he						82
Average crop, centner/ha						65
Height of plants: maximum, cm						276
Average, cm						261
Need of corn for heat for period vegetation, °C						2400-2800

Biometrics observations of a growth and development of a spring wheat

Phases of development of plants	Date	Period of phase, in days	Duration of a phase, in days	Settlement stratum of humidifying, cm	Threshold before watering of humidifying in %	Different parameters
Planting	15.03				from HB	
Sprouts	24.03					
Planting-exit in a handset		15.03-22.04	39	0-70	70	
Exit in a handset--------		23.04-29.05	37	0-70	70	
--------- flowering		30.05-6.06	7	0-90	70	
Flowering-milky ripeness		7.06-17.06	11	0-90	70	
Milky-wax ripeness		17.06-26.06	9	0-90	70	
Wax-full ripeness		27.06-10.07	14	0-90	70	
Harvesting of a crop	12.07					
Date of the latest irrigation	22.06					
Irrigate norm, m^3/he						3700
Denseness million unit/he						5,5
Average crop, centner/ha						37
Height of plants: maximum, cm						75
Average, cm						66
Need of wheat for heat for period vegetation						1500-1600

Biological parameters of development of a apple-tree garden, fourth year fructiferous (experience of 2000)

Phases of development	Period of a phase	Duration of a phase, in days	Maximum height of a apple-tree	Average height a apple-tree	Denseness of a plantation, pieces / ha
1.Selling of kidneys - blooming of kidneys	25.03-15.04	22			
2. Blooming of kidneys - beginning of flowering and appearance of leaves	16.04-30.04 (date appearance of a leaves 18.04)	15			
3. Beginning of flowering and appearance of leaves - ovary of a fruit	1.05-24.05	24			
4. Ovary of a fruit and appearance of leaves– fall of a surplus ovary and growth of sprout	25.05-20.06	27			
5. Fall surplus ovary and growth of sprout - beginning of intensive growth of a fruit	21.06-10.07	20			
6.Beginning intensive growth of a fruit - maturing of a fruit	11.07-5.09	57			
7.Maturing of a fruit - completion active vegetation , harvesting of a crop	6.09-01.10	26			
8.Completion active vegetation, harvesting of a crop – fall of the leaves	02.10-26.10	25			
Growth			5	3,7	Scheme of landing 5x6 m 360 trees
Date of a crop and crop, (ton / ha)	2 · 10 (31,7)				
Date of the last watering	17.09				

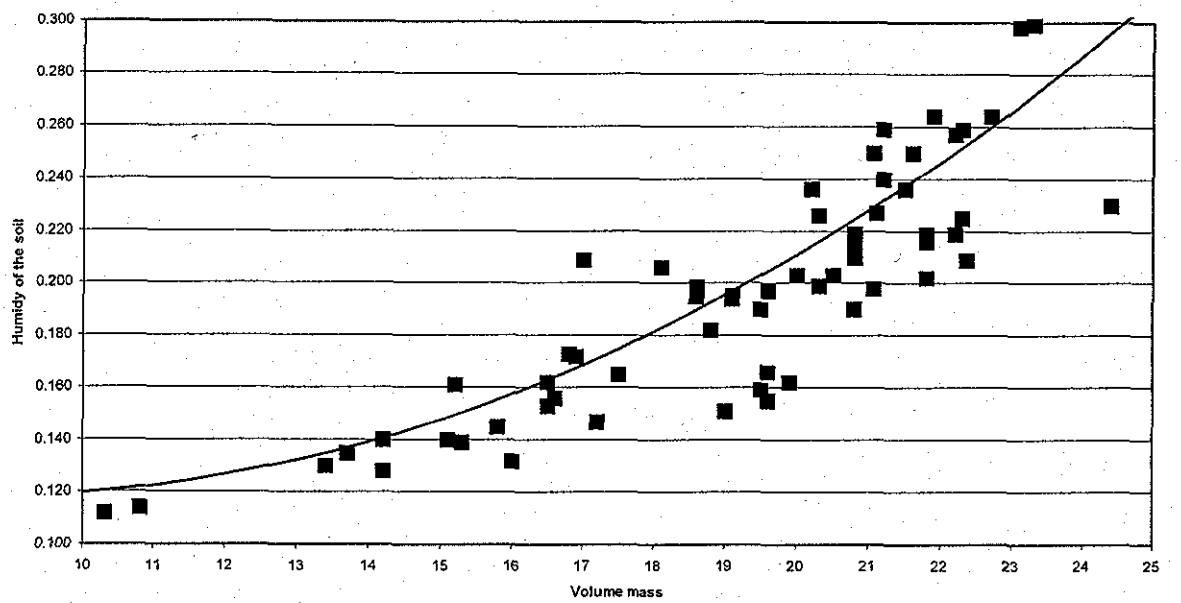
Appendix C

The main climatic factors in a hill-foothill zone (under the indications AMS) in 2001

Date	Radiation, $\Sigma W/m^2$ 10 min/day	The temperature, ^0C	Relative humidity, %	Precipitation, mm	Ep, mm
10.05.01	28966.570	11.688	20.575	0.100	2.960
11.05.01	27406.197	17.776	58.156	0.000	3.678
12.05.01	28175.144	16.692	63.755	0.000	3.640
13.05.01	33610.816	17.895	54.174	0.400	4.777
14.05.01	41459.570	17.474	56.401	0.500	4.690
15.05.01	50409.077	18.395	52.483	0.000	5.230
16.05.01	52760.079	19.365	50.184	0.000	5.642
17.05.01	54026.623	21.238	40.541	0.000	6.180
18.05.01	33773.717	20.357	44.883	0.600	5.271
19.05.01	10351.425	13.172	70.374	8.300	1.080
20.05.01	52128.408	14.175	56.827	0.000	4.791
21.05.01	54354.518	15.393	50.961	0.000	5.408
22.05.01	46765.888	15.797	57.486	0.000	5.022
23.05.01	39862.443	17.233	51.150	0.000	4.902
24.05.01	49974.495	17.948	48.407	0.000	5.537
25.05.01	34671.766	18.273	49.637	0.100	4.840
26.05.01	53240.829	19.724	47.860	0.000	5.455
27.05.01	47090.996	19.148	55.573	0.000	5.290
28.05.01	32752.325	20.499	53.970	0.000	4.827
29.05.01	32436.446	19.484	57.569	0.000	3.753
30.05.01	52886.880	21.345	48.821	0.000	5.777
31.05.01	50248.217	22.455	46.327	2.000	6.109
01.06.01	36255.115	20.952	49.114	0.000	5.462
02.06.01	19698.039	15.767	62.720	5.100	2.938
03.06.01	54908.188	15.638	53.133	0.000	5.400
04.06.01	53844.336	18.595	46.817	0.000	5.918
05.06.01	39141.719	20.669	36.926	0.000	5.436
06.06.01	43846.679	17.734	46.371	0.000	5.216
07.06.01	44272.147	16.952	44.538	0.000	6.129
08.06.01	53187.873	16.458	40.758	0.000	5.460
09.06.01	49769.957	19.387	38.768	0.000	6.178
10.06.01	48473.660	22.213	29.253	0.000	6.131
11.06.01	27732.865	19.894	41.644	0.000	4.806
12.06.01	26817.743	17.822	62.301	1.600	3.337
13.06.01	37255.356	19.418	52.881	0.000	5.309
14.06.01	51104.574	21.107	42.594	0.000	5.985
15.06.01	43695.763	20.213	51.183	0.000	4.882
16.06.01	42764.394	21.377	41.026	0.000	5.743
17.06.01	46864.284	22.230	41.968	0.000	5.594
18.06.01	47977.663	23.970	38.744	0.000	6.263
19.06.01	37664.476	24.068	38.496	0.000	5.576
20.06.01	29987.676	22.875	41.869	0.900	4.728

21.06.01	38236.703	22.569	43.839	1.500	5.727
22.06.01	31752.985	19.670	58.067	0.100	4.448
23.06.01	43311.392	21.019	46.292	0.000	5.072
24.06.01	55484.861	22.118	36.973	0.000	6.374

Dependence of humidity of ground on a volumetric mass



Appendix D

The program of work automatic meteorological station

```
;{CR10X}
;
*Table 1 Program
  01: 600      Execution Interval (seconds)
;
; Initial data
;
; Input of an information from gauges
;
;input HMD Themperature and Humidy-----------------------------
;
;installation of the port, where the orange wire is connected
1:  Do (P86)
 1: 48      Set Port 8 High
; Excitation of the signal channel
2:  Excitation with Delay (P22)
 1: 2       Ex Channel
 2: 0000    Delay W/Ex (units = 0.01 sec)
 3: 15      Delay After Ex (units = 0.01 sec)
 4: 0       mV Excitation
;input Themperature
;SE Channel-number, where the yellow wire is connected
3:  Volt (SE) (P1)
 1: 1       Reps
 2: 5       2500 mV Slow Range
 3: 3       SE Channel
 4: 1       Loc [ TEMP_HMP  ]
 5: 0.1     Mult
 6: -40     Offset
;input Humidy
;SE Channel-number, where the light-blue wire is connected
4:  Volt (SE) (P1)
 1: 1       Reps
 2: 5       2500 mV Slow Range
 3: 4       SE Channel
 4: 2       Loc [ RH       ]
 5: 0.1     Mult
 6: 0.0     Offset
; The dumping of port, where is connected an orange wire
5:  Do (P86)
 1: 58      Set Port 8 Low


6:  If (X<=>F) (P89)
 1: 2       X Loc [ RH       ]
 2: 4       <
 3: 0.0     F
```

```
 4: 30      Then Do

7:  Z=F (P30)
 1: 0.0     F
 2: 00      Exponent of 10
 3: 2       Z Loc [ RH       ]

8:  End (P95)

9:  If (X<=>F) (P89)
 1: 2       X Loc [ RH       ]
 2: 3       >=
 3: 100     F
 4: 30      Then Do


10:  Z=F (P30)
 1: 100     F
 2: 00      Exponent of 10
 3: 2       Z Loc [ RH       ]

11:  End (P95)

;
; Input of temperature thermistor CR10XTCR------------------------
;
;SE Channel- where the red wire is connected
;Excite all reps- where the black wire is connected
12:  Temp (107) (P11)
 1: 1       Reps
 2: 1       SE Channel
 3: 3       Excite all reps w/E3
 4: 3       Loc [ TEMP_CR10 ]
 5: 1.0     Mult
 6: 0.0     Offset
;
; Input of a velocity and direction of a wind ---------------------------
;
; Input of a velocity of a wind
;Pulse Channel- where the red wire is connected
13:  Pulse (P3)
 1: 1       Reps
 2: 1       Pulse Channel 1
 3: 22      Switch Closure, Output Hz
 4: 4       Loc [ WIND_SPD  ]
 5: 0.799   Mult
 6: 0.2811  Offset

14:  If (X<=>F) (P89)
 1: 4       X Loc [ WIND_SPD  ]
 2: 4       < ;
```

```
 3: 0      F
 4: 30     Then Do

15:  Z=F (P30)
 1: 0.0    F
 2: 00     Exponent of 10
 3: 4      Z Loc [ WIND_SPD  ]

16:  End (P95)

17:  If (X<=>F) (P89)
 1: 4      X Loc [ WIND_SPD  ]
 2: 1      = ;
 3: 0.2811   F
 4: 30     Then Do

18:  Z=F (P30)
 1: 0.0    F
 2: 00     Exponent of 10
 3: 4      Z Loc [ WIND_SPD  ]

19:  End (P95)


; Input of a direction of a wind
;SE Channel- where the green wire is connected
;Excite all reps- where the dark blue wire is connected
20:  AC Half Bridge (P5)
 1: 1      Reps
 2: 25      2500 mV 60 Hz Rejection Range
 3: 5      SE Channel
 4: 1      Excite all reps w/Exchan 1
 5: 2500     mV Excitation
 6: 5      Loc [ WIND_DEG  ]
 7: 720     Mult
 8: 0.0     Offset
;
;Input of a precipitation-----------------------------------------------
;
;Pulse Channel- where the black wire is connected
21:  Pulse (P3)
 1: 1      Reps
 2: 2      Pulse Channel 2
 3: 2      Switch Closure, All Counts
 4: 6      Loc [ RAIN      ]
 5: 0.1     Mult
 6: 0.0     Offset
;
; Input of solar radiation
;
;DIFF Channel- where the red and black wires are connected
22:  Volt (Diff) (P2)
```

```
 1: 1      Reps
 2: 22      7.5 mV 60 Hz Rejection Range
 3: 4      DIFF Channel
 4: 7      Loc [ RAD_RATE  ]
 5: 200     Mult
 6: 0.0     Offset

23:  If (X<=>F) (P89)
 1: 7      X Loc [ RAD_RATE  ]
 2: 4      <
 3: 0.0     F
 4: 30      Then Do

24:  Z=F (P30)
 1: 0.0     F
 2: 00      Exponent of 10
 3: 7      Z Loc [ RAD_RATE  ]

25:  End (P95)
;
; Conclusion of outcomes
;

26:  Do (P86)
 1: 10      Set Output Flag High (Flag 0)

27:  Set Active Storage Area (P80)
 1: 1      Final Storage Area 1
 2: 111      Array ID

28:  Real Time (P77)
 1: 1110     Year,Day,Hour/Minute (midnight = 0000)

29:  Average (P71)
 1: 1      Reps
 2: 1      Loc [ TEMP_HMP  ]

30:  Sample (P70)
 1: 1      Reps
 2: 2      Loc [ RH       ]

31:  Sample (P70)
 1: 1      Reps
 2: 3      Loc [ TEMP_CR10 ]

32:  Wind Vector (P69)
 1: 1      Reps
 2: 0000     Samples per Sub-Interval
 3: 1      S, й1 Polar
 4: 4      Wind Speed/East Loc [ WIND_SPD  ]
 5: 5      Wind Direction/North Loc [ WIND_DEG  ]
```

```
33: Totalize (P72)
 1: 1      Reps
 2: 6      Loc [ RAIN     ]

34: Average (P71)
 1: 1      Reps
 2: 7      Loc [ RAD_RATE ]

;

36:  Do (P86)
 1: 41       Set Port 1 High

37:  Do (P86)
 1: 43       Set Port 3 High

38:  Beginning of Loop (P87)
 1: 0000     Delay
 2: 4        Loop Count

     39:  Do (P86)
      1: 72       Pulse Port 2

     40:  Step Loop Index (P90)
      1: 3        Step

     41:  Period Average (SE) (P27)
      1: 3        Reps
      2: 4        200 kHz Max Freq @ 2 V Peak to Peak, Period Output
      3: 9        SE Channel
      4: 10       No. of Cycles
      5: 5        Timeout (units = 0.01 seconds)
      6: 8     -- Loc [ var_1     ]
      7: 0.001    Mult
      8: 0.0      Offset

42:  End (P95)

43:  Do (P86)
 1: 51       Set Port 1 Low

44:  Do (P86)
 1: 53       Set Port 3 Low

45:  Polynomial (P55)
 1: 12       Reps
 2: 8        X Loc [ var_1     ]
 3: 20       F(X) Loc [ water_1    ]
 4: -0.187   C0
 5: 0.037    C1
 6: 0.335    C2
 7: 0.0      C3
 8: 0.0      C4
 9: 0.0      C5

46:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

47:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 222      Array ID
```

```
48:  Real Time (P77)
 1: 1110      Year,Day,Hour/Minute (midnight = 0000)

49:  Sample (P70)
 1: 12        Reps
 2: 20        Loc [ water_1    ]

50:  Do (P86)
 1: 20        Set Output Flag Low (Flag 0)
```

Appendix E

The agrometeorological approach to orchard water use evaluation
in a foothill zone of Kyrgyzstan

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Introduction

The foothill zone of Chu valley is the main manufacturer of fruit-berry cultures and vineyards for areas of urban subordination. In this zone the large half suitable to irrigation lands concerns to inconvenient, located on slopes of an increased steepness (slope from 0,007 up to 0,07), skeletal, low-power and hardly subject of water erosion.

On climatic parameters (temperature of an air in the summer within the limits of 20-30°C, humidity – 22-80 %) the foothill zone concerns to number rather favorable for cultivation of fruit-berry cultures and most solar areas, and it is characterized high supply by the heat with the sum of daily average temperatures above 10°C : Σt = from 3000° up to 3200°C.

Area of instability moistening, where a small amount of atmospheric precipitation (up to 250 mm) falling out in a warm season (April - October) as a rain, deep (more than 15 m) location of ground waters level, the often periods of time without rains dictate urgent necessity of realization here irrigation for deriving high and stable harvests.

However, irrigation here becomes problematic and ineffective because of unsolved problems of authentic definition of orchard total water use, which quantitative expression is the main account article of water balance in accounts of irrigation correct mode.

Until recently the total water use of plants was defined by an empirical way through evaporating under the formula N. N. Ivanov:

$$E_{\circ} = 0{,}00006\ (t^{\circ} + 25)^2\ (100\text{-}r)\ \text{mm / ha / daily},$$

Where: t - daily average temperature of an air, in degrees centigrade,

R - daily average relative humidity of an air, in percentage.

However, such approach to definition of water use though simple, but, nevertheless bears in itself the large errors, because it does not reflect a complete physiological essence of natural processes of evaporation from an active surface of land. All the more, coefficients of recalculation of evaporation in unknown total water use not perfection and doubtful. While in area of instability moistening the accuracy of definition unknown quantity should be rather high, because the sizes of water use here hardly will increase in dry and warm periods of a year on a comparison with damp and moderate. In the long and warm period vegetation the spending of water increased.

Thus, variety of the natural factors (light, total solar radiation, temperature and humidity of an air, velocity of a wind, the atmospheric precipitation) radically influence on sizes of plants total water use, is subject to a scrutiny and evaluation with the use of meteorological stations, capable in the pure state to receive total water use, expressed through transpiration of plants.

For a solution of these problems originally we shall consider problems of a physiological essence of total evaporation, for choice of a reliable method of its definition. On the second step is researched actual outcomes of total water use, obtained by the instrumental way immediately from irrigation area of a orchard and shall discuss problems of choice of a rational and acceptable method of forecasting of total water use in conditions of meteorological station absence.

Physiological essence of the agrometeorologic factors, influencing on growth and development of plants.

For the substantiation of choice of a method of definition total water use, shall consider in a general view, physiological essence of the meteorological factors participating in forming of these processes and a yield.

The productivity of cultures forms in an outcome of interaction of plants with an environment. The vegetative organisms give the greatest productivity for availability of the best conditions, defining their growth and development. To such conditions concern: light, warmly, solar radiation, water, air and elements of food. All of them are completely necessary for plants but significance them during process of live is variously. Light and warmly are defining processes of transformation and accumulation (growth) of organic substance and transition of one stage in other. Development of plants, as the transition during growth from one condition in other (biological form of movement of a substance) happens on nodes of transition - phases of development.

The intensity and duration of inflow of light energy, it magnitude is defined by an amount of the created organic substance in plants. The movement and growth of cells, transition of mineral salts from soil to a green working surface is realized with the use of costs of a thermal energy, which should be instrumental measured and to be taken into accounts of transpiration.

Therefore, the intensity of thermal energy is one of the main factors in the research of water use, which influenced on duration of the passing phases, the growth and development of plants, and, at last, on intensity of the water use and total evaporation.

Thus, the process of total evaporation by the irrigated field, as the constituent of the water use of the orchard (evaporation from soil, plus transpiration by plants of long-term grasses and fruit trees), is connected to various complicated power transformations (transpiration) not only at a surface of land, but also in high layers of an atmosphere. The research of these meteorological variables (solar radiation, temperature and humidity of an air, velocity of a wind, atmospheric precipitation) and physiological properties of vegetation (phase of development), defining delivery of energy and transportation water steams - requires hourly measurements of their absolute value. It is possible for realizing only with application automated meteorological station, equipped special equipment and appropriate gauges.

In this plan the study of a power balance and agrometeorological evaluation of the total water use of a orchard, with reference to a foothill zone of Kyrgyzstan, for the first time has become possible since a 1999 with deriving from Israel and the company "Campbell Scientific JNC" of automatic meteorological station (AMC) of special purpose. A research on an evaluation of water use was conducted on a technique of Marsel Fuchs (Israel). AMC is capable to conduct with adequate accuracy and reliability simultaneous remote measurements of all power formed climate parameters, which are included in account of magnitude total water use of plants.

Total water use of an orchard.

The heat-balance method (on Fuchs) physiologically is reasonable and authentic in definition of actual significance of the total water use of irrigated field. Its calculation dependence do not contain empirical factors, as sources of errors and are perfectly exact, as all meteorological component warm-moisture-transportation "soil - atmosphere" immediately are defined instrumental by gears - gauges of high sensitivity to passing of these atmospheric processes. Though this method is combined and requires the availability of expensive tool definitions of formed climate parameters, but, nevertheless, it cardinally settles a major problem of a solution of the reasonable account of the total water use of community of plants in irrigated agriculture.

In a basis of the heat-balance method is incorporated meteo and biophysical interactions of the formed climate factors, immediately influencing on dynamic of evaporation and transpiration of plants. In physiological understanding this method is based on close connection between absolute sizes of water use by plants and the power resources (about what marked above) of the near-earth stratums of an atmosphere, i. e. the costs of heat on: evaporation, formed steams latent heat, insolation, solar radiation, heat exchange by soil, turbulent stream of heat and water steam in an atmosphere.

The instrumental fixing of formed climate parameters is shown - which part of energy between radiating balance and the stream of heat in soil spends for transportation of heat, and which - on formation a water steam and transportation it in an atmosphere. So, for insufficient supply of plants by moisture the main part of energy of radiating balance is spent, mainly, for formation of a turbulent stream and, on the contrary, for fair supplies of a moisture and optimum humidifying of soil, almost all energy is spent for evaporation and transpiration. The indicated information arrives in settlement program technical complex AMC, conducts the continuous hourly account of magnitude transpiration of plants and evaporation from an active surface of soil, i. e. in aggregate is measured total water use of plants during a season. In consequent such program allows, on account of principles of forecasting meteorological parameters to make the schedules of watering and modes of irrigation of a orchard, proceeding from allowable magnitude water stress of plants.

The definition of the total water use is conducted during two vegetation periods in the acting orchard.

And the first year of researches, because the spring frost took place, ovaries of apples were freeze and crop is not obtained. Per the second year it was possible to receive an apple crop and to trace on all phases of development of plants a course of total water use of the orchard in aggregate with community of long-term grasses.

The outcomes of researches, indicated in tab.1, are characterized by principally new parameters in the area of total water use of the orchard and community of long-term grasses.

Table 1

Total water use of the orchard and community of long-term grasses in the foothill zone of Chu valley of Kyrgyzstan

	Phase of development (Period)	Duration of a phase, days	Daily average temperature, t°C	Total water use for period E, mm	Daily average water use, E_1, mm / day	$\lambda = \frac{E}{t}$, The temperature module of water use, mm / degree/ day.
1	The swelling of kidneys – the blooming of kidneys (25.03-15.04)	22	5,1	44,0	2,00	0,40
2	The blooming of kidneys – the beginning of flowering (16.04-30.04)	15	9,3	46,5	3,10	0,33
3	The beginning of flowering – the setting of a fruit, the appearance of a leaf (1.05-24.05)	24	12,8	100,8	3,58	0,28
4	The setting of a fruit and appearance of a leaf – the pulling-down redundant ovaries and growth shoots (25.05-20.06)	27	19,2	121,6	4,50	0,23
5	The pulling-down redundant ovaries and	20	23,4	106,8	5,34	0,23

	growth shoots – the beginning of strengthened growth of a fruit (21.06-10.07)					
6	The beginning of strengthened growth of a fruit – the maturing of a fruit (11.07-5.09)	57	22,6	251,4	4,41	0,20
7	The maturing of a fruit – the completion active vegetation, harvesting (6.09-01.10)	26	16,6	77,2	2,97	0,18
8	The completion active vegetation, the harvesting – the fall of the leaves (02.10-26.10)	25	8,9	77,5	3,10	0,35
	Total:	216		825		

For conditions of a foothill zone are established a variability on phases of development and norm total water use of plants.

Quantitatively total water use for a season makes 826 mm from each hectare of square of orchard plantings. In inside seasonal distribution water use intensively accrues from 2 up to 5,34 mm / day up to middle vegetation, phase of a beginning strengthened growth of a fruit (10.07). Then the slacking daily average total water use up to a phase of completion active vegetation (01.10) is observed, which magnitude makes 2,97 mm / day. The quantitative evaluation on phases daily average total water use allows to make practical accounts of sizes of total water feed on irrigated fields and norm of watering, and also to issue a mode of irrigation of a orchard.

Obtained through AMC magnitude of an evaporating moisture and the intensity of process transpiration in different phases, periods of development and growth of a orchard, depending on combined weather conditions, is accepted for a basis of installation of a method of forecasting water use for identical objects, where is not real possibility of tool definition of required magnitude E. In account the close connection between the daily allowance water use and temperature of an air is fixed: E = f (t), expressed through the temperature module of water use K_t. The temperature module is defined by statistical processing of actual sizes water use, obtained on a plot with AMC. Knowing actual daily significance of water use E for a past decade it is not complicated to find its significance (E the prognosis) on adjacent forecasting decade (or date) on significance of forecasting temperature of an air.

$$K_t = \frac{\Sigma E daily}{\Sigma t^\circ aver.daily} = \frac{E daily}{t^\circ aver.daily.}$$

Where Kt - specific cost of a moisture by a field per unit of daily average temperature of an air in various phases of development of trees, mm / degree /daily.

Then forecasting water use to be defined on dependence

$$E_{forecasting.} = K_t \bullet t^\circ_{forecasting.}$$

Where $t^\circ_{forecasting}$ – the forecasting temperature of an air for a forthcoming decade (or date), Corresponding the phase of development of trees, °C.

The quantitative data of the temperature module of evaporation are represented in table 1, which reflect average need for water, corresponding to that natural complex, for which were observed actual irrigation modes.

Appendix F

Article in press In **Plant, Cell and Environment.**

Title:
Water uptake profile response of corn to soil moisture depletion

Running title:

Water uptake of corn

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Abstract

The effects of soil moisture distribution on water uptake of drip-irrigated corn were investigated by simultaneously monitoring the diurnal evolution of sap flow rate in stems, of leaf water potential, and of soil moisture, during intervals between successive irrigations. The results invalidate the steady state resistive flow model for the continuum. High hydraulic capacitance of wet soil and low hydraulic conductivity of dry soil surrounding the roots damped significantly diurnal fluctuations of water flow from bulk soil to root surface. By contrast, sap flow responded directly to the large diurnal variation of leaf water potential. In wet soil, the relation between the diurnal courses of uptake rates and leaf water potential was linear. Water potential at the root surface remained nearly constant and uniformly distributed. The slope of the lines allowed calculating the resistance of the hydraulic path in the plant. Resistances increased in inverse relation with root length density. Soil desiccation induced a diurnal variation of water potential at the root surface, the minimum occurring in the late afternoon. The increase of root surface water potential with depth was directly linked to the soil desiccation profile. The development of a water potential gradient at the root surface implies the presence of a significant axial resistance in the root hydraulic path that explains why the desiccation of the soil upper layer induces an absolute increase of water uptake rates from the deeper wet layers.

Keywords index: sap flow, soil water flow, soil water content, soil water potential, leaf water potential, hydraulic resistance, root water uptake, root length density.

Introduction

Non-uniform distribution of soil moisture in the root zone is common in the field (Reid & Huck 1990). Except for the short time period following irrigation or rainfall, a moisture gradient profile develops from dry at the top to moist at the limit of the wetting zone. In this situation, predictions of water

uptake patterns depend on the hypotheses of the plant-soil-water interactions models (Jara & Stockle 1999). The spatial layout of drip irrigation designs and the choice of frequency, amount and rate of water delivery allow controlling the spatial and temporal distribution of water application in the root zone. Yet, root water uptake interacts with the water application scheme to modify the water depletion rate and the resulting water status of plants. Therefore, the design and management of drip irrigation depends on the effect soil moisture distribution has on conduction of water from the soil to the roots and from the roots to the foliage where it evaporates.

Previous investigations show conflicting results about the mathematical nature of the water flux resistance relationship (Boyer 1985; Clothier & Green 1997; Passioura 1988). In case of linearity, plant resistance is independent of flux or water potential (Cohen, Fuchs, & Cohen 1983; Cohen, Moreshet, & Fuchs 1987; Lascano & Van Bavel 1984; Moreshet et al. 1990; Moreshet et al. 1996; Passioura & Munns 1984; Stirzaker & Passioura 1996). On the contrary, Blizzard & Boyer (1980), in an effort to separate soil and plant pathway resistance in potted soybeans (Glycine max L. Merr.) concluded that resistance in the plant increased when soil water potential decreased under conditions they considered as steady state. Brisson, Olioso, & Clastre (1993) also stated that resistance in soybean, in field condition, increased with the decrease of the flux on the basis that they found a constant leaf water potential difference between pre-dawn and the minimum mid-day values. In addition, experimental results for soybean (Jones et al. 1982; Zur et al. 1982) suggest diurnal change of plant resistance. The variations of resistance with flux, potential or time have been attributed to osmoregulation (Brisson et al. 1993) and the effect of plant hydraulic capacitance on the fluctuating fluxes (Boyer 1985; Jones et al. 1982).

The linearity of the relation between flow rate and potential gradient is even more difficult to establish in compartmented root systems (Reid et al. 1990). Split-root experiments in laboratory conditions indicated that when the two part of the root system were subjected to different soil water potentials, soil water potential of each part determined the local water uptake (Lascano et al. 1984). The relationship between soil water potential and flux in one part influenced soil water potential of the other part, due to apparent hydraulic connection through the root system (Simonneau & Habib 1994). When water availability in one part of the root system decreases while the other part is kept well watered, water absorption by the well-watered roots can increase even without a decrease in leaf water potential (Michel & Elsharkawi 1970; Sakuratani, Aoe, & Higuchi 1999; Simonneau et al. 1994; Tan & Buttery 1982). A possible hypothesis explaining increased uptake in split-root media is the onset of a flux from root in wet to root in dry medium (Simonneau et al. 1994), but decreased hydraulic resistance in roots is a plausible alternative hypothesis (Morizet, Cruiziat, & Falcimagne 1988). If the dry medium decreases total transpiration, water potential at the junction of the vessels from the wet and dry partitions may drop and enhance water uptake through the wet pathway.

For field crops grown in a non-uniformly wetted root zone, quantitative assessment of local and total water uptake responses to soil moisture is essential for optimal irrigation design and management. However, results from laboratory experiments or simulations may not be or are only partially applicable to the field (Clothier et al. 1997). Split-root experiments (Lascano et al. 1984) and simulation (Reid et al. 1990) attempting to establish whether resistance is constant or variable allow soil water potential to decrease down to the range found in transpiring leaves. In normal field irrigation practice, soil water potential never drops to these low values. Its absolute value is negligibly small in comparison to leaf water potential (Moreshet et al. 1996). The apparent non-linear response of the plant hydraulic properties to temporal and spatial fluctuations of water potential casts uncertainty on the extrapolation of laboratory experiments and dictates the need for field studies.

The purpose of the current study was to determine the effect of spatial and temporal change in soil moisture distribution on the water uptake path in corn (Zea mays, L.). To achieve this objective water uptake and two-dimensional soil moisture content distribution were measured with at least hourly

resolution to detect diurnal changes of plant water uptake and water flow in the soil during the drying interval between successive irrigations. The analysis examines the validity of the series resistive flow model from soil to foliage. It attempts to establish the hydraulic resistance of the water pathway through the plant and considers the contribution of roots at different depths in the soil.

Materials and Methods

Experimental site and irrigation regimes: Field experiments were carried out on a sandy soil near Rehovot, Israel (32° 05' N, 34° 48'E) in the summer of 1997. Sweet-corn seeds were hand-sown on 2 May or Day Of Year (DOY) 122 with the aid of rulers to ensure a uniform density of 8 m^{-2} on a plot of 1000 m^2. Row spacing was 0.95 m. No rainfall was recorded during the corn growing period so that irrigation was the only source of water supply. Transpiration T was assumed equivalent to sap flow and was measured by the heat pulse method (Cohen et al., 1988; Cohen & Li, 1996). Potential transpiration T_p was computed with a modified Penman-Monteith equation using measured LAI and assuming infinite stomatal conductance (Fuchs, Cohen, & Moreshet 1987; Petersen et al. 1992). From sowing to the beginning of the silking stage, the plants were irrigated to maintain a steadily high T/T_p ratio. Starting at silking stage, T/T_p was allowed to drop to 0.5-0.6 of its initial value with the intention to allow the soil profile to undergo a varied range of water content without causing permanent damage to the plant, resulting in a 3-day watering period. The amount of water applied for each irrigation event was 125% of total T of the previous cycle, the excess compensating for drainage and direct evaporation. An auto-controlled drip system with one lateral per row (one dripper every 25cm) created a quasi-linear source of water supply. An automatic meteorological station was installed at the experimental site to measure the parameters needed for calculating T_p.

Instrumentation and measurements: A multiplexed TDR system (1502B Tektronix Cable Tester, SDM X50, Campbell Scientific, Logan UT, USA) measured soil water content in the profile at time intervals of 0.5, 1 or 2 hours, depending on the time needed to scan through all the sensors. The high density of plants and drippers along the row allowed the assumption that the water application and distribution, as well as uptake, were uniform along the axis of the rows. Therefore, TDR sensors were installed to measure the 2-dimensional distribution of soil water changes in the plane perpendicular to the crop row at two sites, one main site and one back up site. When a sensor at the main site did not work properly, readings from the corresponding sensor at the alternative site were taken instead. The spatial arrangement of the sampling grid is shown in Figure 1. Layers were 5-20 cm, 20-35 cm, and 35-65 cm. Additional sensors were installed below the root zone and outside the wetted range to verify that TDR in the sampling grid monitored all root uptake activities. A heat pulse system (Cohen et al. 1988) calibrated for corn plants (Cohen & Li 1996) measured sap flow in 10 adjacent plants in the row above the TDR sensors. Heat pulse probes were inserted at the base of the selected plants to ensure that sap flow represented total water uptake. A data logger (CR-7, Campbell Scientific, Logan UT, USA) controlled and recorded the heat pulse data every 15 minutes. Predawn leaf water potential and leaf water potential of ten sunlit leaves were measured with a pressure chamber (Arimad 2, Kfar Haruv, Israel), every hour on the hour, from 8:00 to 19:00 (Israel Summer Time) for eight days, but only the three days pertaining to the drying cycle following the irrigation of DOY 188 were used in the current analysis. Soil water potential was determined indirectly from TDR measurements of volumetric soil water content using an inverted retention function (Assouline & Tessier 1998) fitted to a single moisture release curve for undisturbed soil samples from the three depths shown in Figure 1:

$$\psi_S = \frac{\alpha}{\frac{\alpha}{\psi_h} - \left[-\ln\left(\frac{\theta_* - \theta_S}{\theta_* - \theta_h}\right)\right]^{\frac{1}{\eta}}}$$

$\theta_* = 0.378$ Saturated moisture content (1)

$\theta_h = 0.02$ Lowest moisture content

$\psi_h = -68.6$ KPa Lowest water potential

$\alpha = 4.92$ KPa

$\eta = 1.52$

where ψ_S is the water potential in KPa and θ_S is the volumetric soil moisture content.
Core samples for determining root length density were taken at the end of the experiments at the locations of the TDR sensors. The sampling auger was 5 cm in diameter. Four samples were taken from each grid cell. Sieve washing separated the roots and a computerized scanner (Delta-T Scan, Delta-T Devices, Cambridge, UK) measured the length of the collected roots.

Results

Root distribution

The core sampled root length density in Table 1 shows that roots occupancy decreases with the distance from the stem in the horizontal and vertical directions. The spatial resolution of the samples is insufficient for establishing the exact profile of the root distribution, but core sample taken below 65 cm did not detect roots. A TDR sensor confirmed lack of significant water uptake below 65 cm. Line drippers create a sharp boundary between wetted and dry soil on the horizontal axis across the inter-row space. The variation of root length density along this axis in the drip wetted zone was much less than in the vertical dimension. Therefore, data were averaged to characterize the vertical distribution of soil moisture and water uptake.

Table 1.

Soil moisture and water uptake

The multiplexed TDR system recorded water content every 0.5 or 1 hour for each grid cell. Figure 2 gives the recorded average soil water content of the profile. Layer average in Figure 2 includes only cells of the wetted soil volume. The horizontal limit of the wetting front reached about half of the inter-row space (Figure 1). Third order polynomials were separately fitted for day and night measurements to smooth TDR readings of each grid cell. The rate of soil water content change was taken as the first derivative of the fitted curve. The TDR measurements excluded most of the direct evaporation because the sensors were placed 5 cm below the soil surface (Boast & Robertson 1982). As nocturnal sap flow measurement did not detect root water uptake, changes of soil water content during the night were taken as net water flow across the grid cell boundaries. Net flow during daylight hours was linearly interpolated between night values. Root water uptake rate for each grid cell was obtained by subtracting net water flow from total soil water rate of change. Water content did not increase during night (Figure 2) indicating no capillary rise. Water uptake rate derived from the soil moisture balance matched very closely the hourly sap flow rate measurements (Figure 3).

Figure 4 illustrates the evolution of water uptake during the drying period that followed the irrigation applied on DOY 188. The amplitude of uptake rate, determined from sap flow, decreases with time elapsed from the irrigation application. Water uptake rate from layer A diminished sharply during the drying cycle. Uptake from layer B reached a maximum on the second day. It continued to rise through the third day in layer C. The data show unambiguously that the intense desiccation of the upper soil layer enhanced the absolute uptake rate by the deeper roots.

Resistance of the hydraulic path

Total hydraulic resistance R, for steady-state liquid water transport in the soil-plant is e.g. (Reid et al. 1990):

$$R = \frac{\psi_S - \psi_L}{Q} \qquad (2)$$

where ψ_S is the bulk soil water potential (in MPa), ψ_L is the leaf water potential (MPa), and Q the uptake rate (mm h^{-1}). Soil water potentials calculated with Eq. (1) for the range of soil bulk moisture content in Figure 2 are from –5 to –10 KPa. Contemporary leaf water potentials (Figure 10) vary from -0.5 MPa to –0.9 MPa. Thus, in practice R is simply $-\psi_L/Q$. Figure 5 shows the values of R using the sap flows and the fluxes for each layer as given in Figure 4 for the first day after irrigation, when high moisture content minimized hydraulic resistance of the soil. The salient feature of Figure 5 is the diurnal change of the resistance with highest values in the early morning and in the late afternoon when fluxes vary the most. Since Eq. (2) presumes steady state the largest discrepancies occur when sap flow and leaf water potential change rapidly. This diurnal pattern is very similar to the one modeled by Reid et al. (1990). During mid-day, when fluxes vary slowly, resistances are lower, and remain nearly constant.

Figure 6 shows the relationship between instantaneous sap flow rates and leaf water potential using data measured during the three-day drying cycle that followed the irrigation applied on DOY 188. In addition to the decrease of daily maximal sap flow rates noted in Figure 4, soil moisture depletion lowered the leaf water potential minima from -0.9 MPa on the first day to -1.2 MPa on the second day, down to –2.2 MPa on the third day. Data points of the first day form a straight line. Its slope, $d\psi_L/dQ$, is the hydraulic resistance of the liquid path in the plant (Cohen et al. 1983; Lascano et al. 1984; Moreshet et al. 1996; Passioura 1988; Stirzaker et al. 1996). The intercept on the leaf water potential axis is the leaf water potential ψ_0 for which sap flow ceases, and therefore, represents the water potential at the root surface. Thus, the hydraulic resistance of the plant R_p is:

$$R_p = \frac{\psi_0 - \psi_L}{Q} \qquad (3)$$

The slope of the linear regression yields R_p = 0.609 MPa mm h^{-1} and ψ_0 = -0.53 MPa for the first day of the drying cycle. On the second and third day after irrigation, the points form a loop (Figure 6). The curved arrows marking the sequence of the points show that diurnal fluctuation of ψ_L lagged behind Q.

The hydraulic capacitance or elastic modulus of plant tissues, $d\theta_L/d\psi_L$ (θ_L is the volumetric water content) delays ψ_L behind fluctuating transpiration, because removal of liquid by conversion into vapor in the leaves induces and therefore, precedes the water potential drop. This phase lag has been reported in wet (Jones et al. 1982) and dry soils (Zur et al. 1982). Yet, plant hydraulic capacitance cannot cause the loops in Figure 6. A first reason is that on the day following irrigation, the two variables are in phase indicating an immediate response of sap flow, measured by the heat pulse at the base of the plant, to leaf water potential. A second reason is that the phase lag increase, from one day to the next,

implies a rise of hydraulic capacitance. As hydraulic capacitance of plant tissues augments significantly only at suction well below –2.3 MPa, with extraction of water held inside the cell membranes (Campbell et al. 1979), it cannot cause the widening of the lag shown in Figure 6.

The diurnal loops in the relation between sap flow and leaf water potential in the drying soil can result from either a steady increase of the corn hydraulic resistance or a progressive lowering of ψ_0. The decrease of ψ_L to a midday minimum of –2 MPa could increase the resistance of the corn conducting vessels by cavitation. Cavitation measurements (Tyree et al. 1986) indicate that the diurnal increase of resistance has a sigmoid shape. Assuming a constant ψ_0 set as the extrapolated morning ψ_L at zero sap flow, the data in Figure 6 were used to calculate the apparent diurnal change of the corn hydraulic resistance. As expected from the resistance on the first two days corresponding to wet conditions, the resistance remained nearly constant (Figure 7). On the third day, when corn became affected by drought, the resistance increased in the course of the day, but the curvature of the diurnal change in Figure 7 is opposite to that of the sigmoid related to the cavitation measurements. This different trend in the apparent increase of hydraulic resistance weakens the assumption of a possible effect of cavitation on the loops in Figure 6.

On the other hand, at flow equilibration, Passioura et al. (1984) found that separate morning and afternoon linear flow-pressure relations were parallel showing that the hydraulic resistance remained constant. The shift of the lines implied that the pressure needed to push the water from the soil to the roots in the afternoon increased as a result of the moisture depletion. Therefore, in accordance with experimental findings (Cohen et al. 1983; Lascano et al. 1984; Simonneau et al. 1994; Stirzaker et al. 1996) it is reasonable to assume that R_p remained constant during the three day drying cycle. Under this assumption, the loops in Figure 6 result from a diurnal fluctuation of ψ_0. Rearranging Eq. (3) allows computing the instantaneous value of ψ_0 as:

$$\psi_0 = \psi_L + Q \bullet R_p \qquad (4)$$

The results of this computation for Q from sap flow are shown in Figure 8 that includes also the predawn measurement of ψ_L. Predawn ψ_L immediately following the irrigation was near zero, but it dropped rapidly to -0.5 MPa as sap flow depleted the soil in contact with the root surface. The pressure drop of 0.5 MPa between the predawn ψ_L and ψ_0, the threshold ψ_L below which sap flow starts has been found in many experiments (Cohen et al. 1983; Moreshet et al. 1996) and assigned to the pressure required to open valves possibly located in the plasmodesmata (Passioura et al. 1984). In the course of the first day ψ_0 remained nearly constant as shown by the linearity in Figure 6. Towards the next morning ψ_0 increased to -0.2 MPa. As sap flow started again, ψ_0 fell to -0.75 MPa and continued to decrease to a minimum of -0.9 MPa. Night replenishment of the soil near the roots elevated ψ_0 to -0.3MPa, followed by the accentuated diurnal variation of the third day with a minimum down to -2.0 MPa. The values of ψ_0 calculated by Eq. (4) are in the range that Schmidhalter (1997) measured on soil sheaths adhering to the roots.

The relationship between water uptake from each soil layer measured by TDR and leaf water potential is identical to that found for the sap flow data. The scatter diagrams in Figure 9 have similar straight lines and diurnal loops as those found for the sap flow in Figure 6. Slope and intercept of the straight lines for the first day yield the hydraulic resistance from root to foliage and the root surface potential in each of the three layers of soil, as R_{pA} = 0.81 MPa h mm^{-1} and ψ_{0A} = -0.54 MPa, R_{pB} = 2.83 MPa h mm^{-1} and ψ_{0B} = -0.53 MPa, and R_{pC} = 4.64 MPa h mm^{-1} and ψ_{0C} = -0.63 MPa. Since the same leaf potential data are used for the three resistances the increase of resistances with depth is the direct computational consequence of decreasing water uptake with depth.

Eq. (4) was also applied to compute instantaneous ψ_{0A}, ψ_{0B} and ψ_{0C} in the three soil layers (Figure 10). On the first day after irrigation, root surface potentials for the three depths were roughly equal and remained nearly constant as already shown in Figure 9. During the second day and third day, the water potentials at the root surface of the three layers decreased to reach minimum values in the afternoon, before recovering in the evening. As the soil dried in the course of the second and third day the water potential at the root surface increased with depth.

Discussion

The experimental results challenge the validity of the steady state resistance model of Eq. (2) for the hydraulic path from bulk soil to foliage (Figure 5). The data show that when the soil is wet a linear relationship exists between the diurnal variation of water uptake and the leaf water potential (Figures 6 and 8). This relationship allows deriving directly the resistance of the hydraulic path in the plant, showing that the resistance increases with the depth as expected from the root length density profile. In the course of a drying cycle, the root surface water potential develops a gradient related to the soil desiccation profile. Finally, the soil water depletion profile shows of a progressive increase of the absolute water uptake rate with depth. The following sections discuss the significance of these results and attempts to elucidate the mechanisms involved.

Invalidating the steady state assumption

According to Eq. (3), water uptake ceases when ψ_L approaches ψ_0. Yet, the liquid flow from bulk soil to root surface continues because $\psi_S > \psi_0$. The increase of the water potential at the root surface occurring from sundown to the next morning in Figure 8 provides experimental evidence that liquid flow in the soil continued during the night after cessation of the sap flow. Consequently, the instantaneous flows in the soil and in the plant differ, in violation with the continuity implied in Eq. (2) leading to erratic resistances in Figure 5. In the early morning and late afternoon, when sap flow is less than water flux to the root surface, Eq. (2) overestimates grossly resistances. The errors become smaller toward the approximate steady state of mid-day as indicated by the slower variation of ψ_L. Still, they are likely to underestimate the total resistance because water uptake includes the decrease of moisture of the soil surrounding the roots that is not replenished by the flow from the bulk soil to the root. In Table 2 the mid-day steady state resistances are partitioned into soil and plant resistance components $R = R_s + R_p$ (R_s is the resistance of the soil) for the day following watering. Resistances in the wet soil and in the plant are of similar magnitude. As the soil dries the steady state resistance of the soil in the entire root zone increases. On Day 2, the resistance profile still increases with depth, but on Day 3, the desiccation of the upper layers reverses the resistance profile.

Table 2.

Table 2 also compares the increase of steady state soil hydraulic resistance derived from Eq. (2) with the values calculated from the relative change in hydraulic conductivity of the bulk soil as a function of dehydration (Assouline 2001):

$$\frac{k}{k_*} = \left(\frac{\theta_S - \theta_h}{\theta_* - \theta_h}\right)^{\nu} \qquad (5)$$

$$\nu = 3.5$$

where k is the hydraulic conductivity and k_*, its saturated value (see Eq. (1) for other symbols). The resistances were calculated for Day 2 and 3 using Day 1 resistances as reference values. This calculation yields larger resistances, confirming that Eq. (2) underestimated the mid-day resistances.

Root surface water potential gradients

The results of temporal and spatial variation of water potential at the root surface in Figure 10, strongly suggest a relation with the soil moisture evolution shown in Figure 2. To explain the effect of bulk soil moisture on spatial and temporal variation of ψ_0 in Figure 10, $d\psi_S/d\theta_S$, the reciprocal of hydraulic capacitance was calculated. During the day that followed irrigation, the moisture content of the three layers of soil decreased from 0.21 to 0.12. For this moisture range $d\psi_S/d\theta_S$ increases from 9.2 to 13.7 KPa, indicating that the decrease of water potential with water depletion was slow. In the course of the second day, moisture contents fell from 0.12 to 0.095. The corresponding values of $d\psi_S/d\theta_S$ ranged from 19.0 to 29.4 KPa, inducing faster soil water potential drop than on the first day. For the third day the moisture contents fell to 0.05 in the top layer accelerating the rate of water potential decrease to 109.0 KPa per unit of soil water removal. The value of k/k_* from Eq. (5) in the upper layer at the end of the third day dropped to 0.002 of its first day value, while k in the second and third layer decreased to 0.02 and 0.07 of their respective initial values. The faster variation of soil water potential and the decrease of hydraulic conductivity induced by soil drying led to the increased diurnal variation of root surface potentials shown in Figure 10.

Plant hydraulic resistance profile

The increase of plant hydraulic resistance with depth is clearly related to root length distribution as given in Table 1. If root length density is the only modifying factor, resistance variations between layers should be inversely proportional to root length density. With three data points only, the experiment hints at the proportionality (Figure 11).

Change of root water uptake profile

Changes in soil hydraulic resistance profile explain the reasons for a relative increase of water uptake from the deeper layers of soil during the drying process. However, they cannot elucidate why despite moisture depletion from all the soil layers (Figure 2) the absolute value of the water uptake from the deeper layers during the third day was larger than on the first day when the entire soil profile was wet. The hydraulic regime to which the roots were exposed during the drying period differs considerably from that of the split root study of flux-water potential relationships by Simonneau et al. (1994). In their experimental set-up $d\theta_S/d\psi_S$ of the hydroponics root medium is infinite and R_S is zero. For the roots in air or in oil, $d\theta_S/d\psi_S$ is zero and R_S is infinite. Under these extreme conditions, dehydration of lignified roots in the dry medium may induce the flow from the wet to the dry roots that enhances water uptake by the roots in the hydroponics solution. Potential gradients at the root surface in Figure 10 suggest a different transport mechanism through roots in a soil with distributed moisture profile. The development of water potential gradients in the root system presumes the existence of significant axial resistances along the hydraulic path in the root system. Increased flow induced by pneumatic pressure in detopped roots of maize and tomato (Lycospermum esculentum L.) suggests that axial resistance affects markedly sap flow (Tiekstra, Else, & Jackson 2000). Without these axial resistances, the water potential gradients along the roots would vanish. In the wet soil immediately after irrigation, the root surface potential is uniform through the root zone profile. Therefore, water uptake occurs preferentially from the upper soil layer through the shorter hydraulic path with lower axial resistance. As the interface potential in the upper layer lessens it gets closer to leaf water potential (Figure 10). The suction along this path diminishes resulting in a lower water uptake. The decrease of leaf water potential occurring on the second and third day augments the suction on the deeper layers of the soil, causing the observed rise of the water uptake from these layers. Yet, despite enhanced uptake from the deeper layers, the axial resistance increase of the longer hydraulic path prevents compensation of the deficient water supply from the water depleted upper layer. Thus, the observed changes of the water uptake pattern result from a redistribution of the water potential within the roots in direct response to the water potential profile of the soil neighboring the roots.

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Table 1. Root length density (cm/cm^3) in grid cells and layers measured at the end of the growing season.

		Grid cell					
Layer	Depth	1	2	3	4	5	Average
A	5-20 cm	4.51	3.70	3.18	2.47	2.27	3.23
B	20-35 cm	1.54	3.32	2.47	1.84	1.73	2.18
C	35-65 cm	1.35	0.96	0.75	0.55	0.21	0.76

Table 2. Hydraulic resistance of the soil, $= R - R_p$, where R is derived from the total steady state resistance from Eq. (2) using mid-day fluxes and potential differences, and R_p is from Eq. (3) for the day immediately following irrigation.

	Resistance MPa h mm^{-1}			
	Total	Layer A 5-20 cm	Layer B 20-35 cm	Layer C 35-65 cm
		Resistance in plant, R_p		
Day1	0.61	0.81	2.83	4.64
		Steady state resistance in soil, R_S		
Day1	0.72	1.05	3.53	9.36
Day2	1.25	2.89	2.61	7.62
Day3	5.68	22.54	16.24	9.27
		Calculated soil resistance from Eq. (5)		
Day1 (as above)		*1.05*	*3.53*	*9.36*
Day2		10	9	17
Day3		384	15	18

Figure Legends

Figure 1. Two-dimensional layout of the sampling grid for the TDR measurements.

Figure 2. Evolution of the soil moisture content profile during three successive irrigation cycles.

Figure 3. Comparison between hourly sap flow rate and water uptake rate from the soil zone sampled by the TDR sensors. The soil water balance accounts for net water flow across zone boundaries.

Figure 4. Evolution of the water uptake rate by the entire root system as measured by heat pulse and by layers in the soil profile as measured by TDR during the 3-day interval that follows the irrigation given on DOY 188.

Figure 5. Steady state resistance of the hydraulic path of water flow from the bulk soil to the foliage, $R = (\psi_S - \psi_L)/Q$, where Q is sap flow for the entire root system or water uptake for the specified layers of the root zone, ψ_S is the water potential of the soil and ψ_L is the leaf water potential.

Figure 6. Relationships between the diurnal courses of sap flow rate and leaf water potential for the 3-day interval that follows the irrigation given on DOY 188. The curved arrows mark the sequence of the data points.

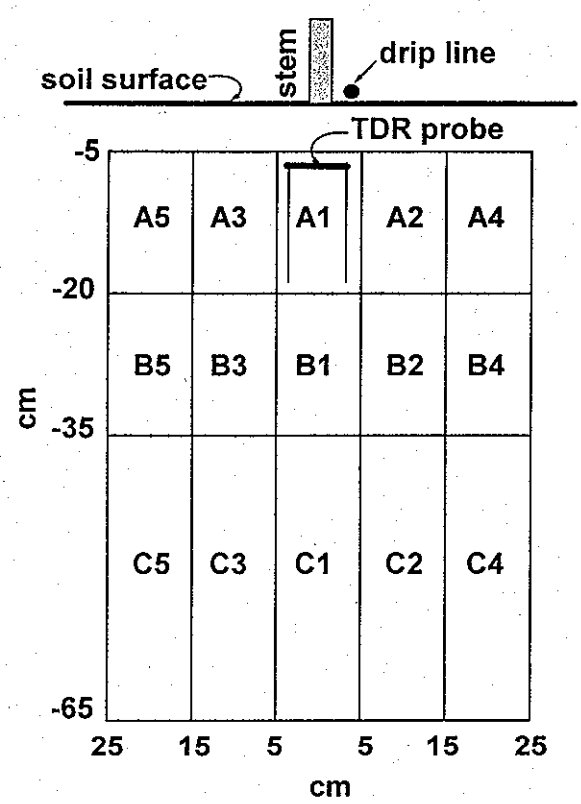
Figure 7. Computed apparent diurnal changes of the hydraulic resistance under the assumption that water potential at the root surface remains nearly constant.

Figure 8. Evolution of the water potential at the root surface for the entire root system deriving from sap flow measurements. Heavy lines on the hour-axis mark night.

Figure 9. Relationship between the diurnal course of root water uptake in the specified layers and leaf water potential for the 3-day interval that follows the irrigation given on DOY 188.

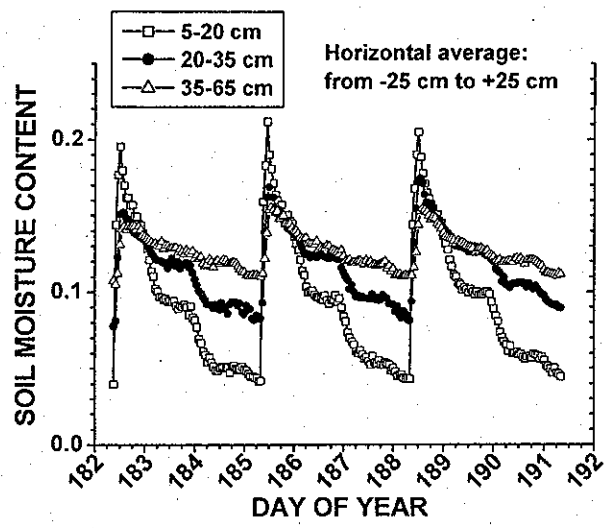
Figure 10. Evolution of the water potential at the root surface for the specified layers and of the leaf water potential during the 3-day interval that follows the irrigation given on DOY 188. Heavy lines on the hour-axis mark night.

Figure 11. Effect of root length density on hydraulic resistance of the liquid path in the plant.



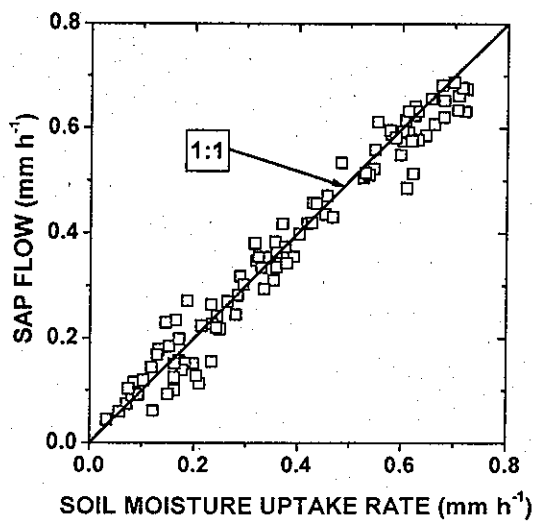
Two-dimensional layout of the sampling grid for the TDR measurements.

Figure 1



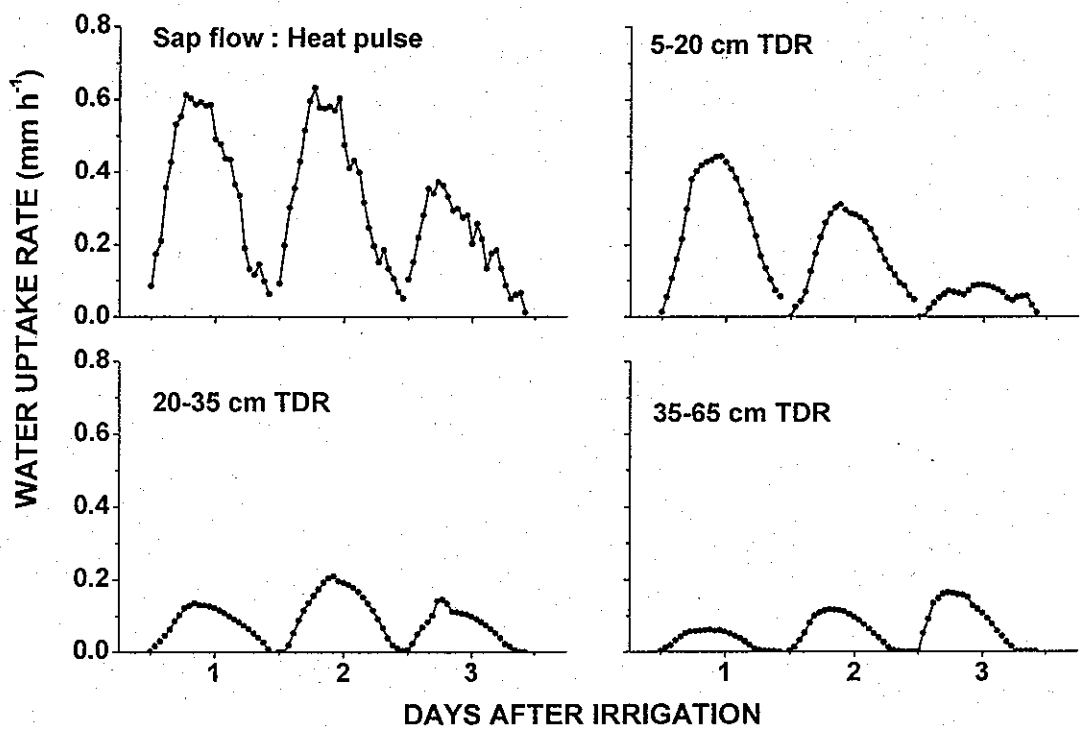
Evolution of the soil moisture content profile during three successive irrigation cycles.

Figure 2



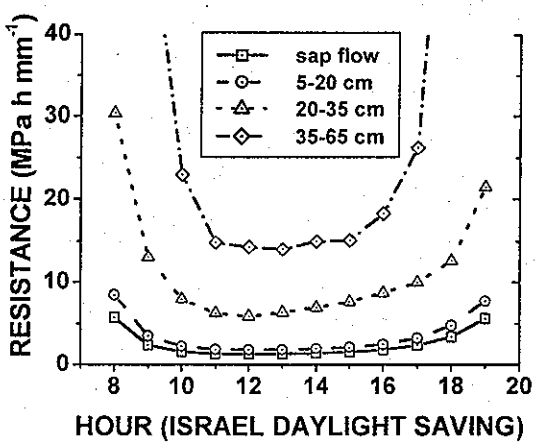
Comparison between hourly sap flow rate and water uptake rate from the soil zone sampled by the TDR sensors. The soil water balance accounts for net water flow across zone boundaries.

Figure 3



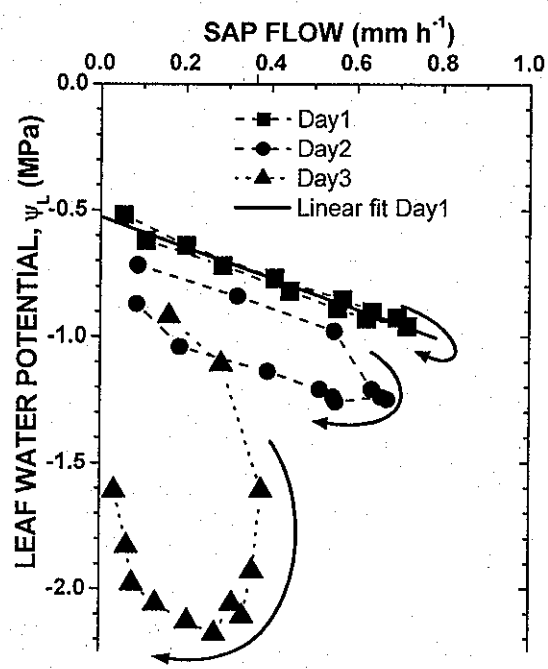
Evolution of the water uptake rate by the entire root system as measured by heat pulse and by layers in the soil profile as measured by TDR during the 3-day interval that follows the irrigation given on DOY 188.

Figure 4



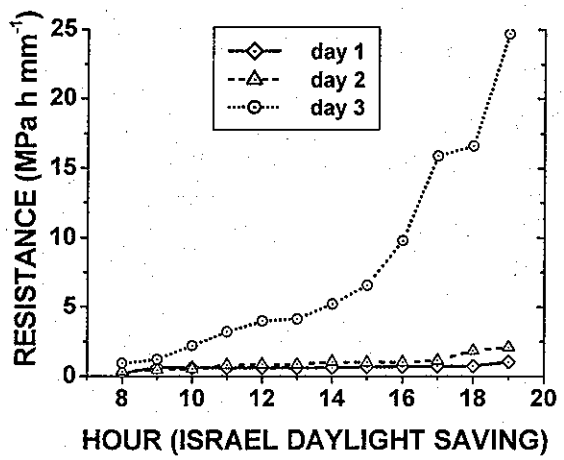
Steady state resistance of the hydraulic path of water flow from the bulk soil to the foliage, $R = (\psi_S - \psi_L)/Q$, where Q is sap flow for the entire root system or water uptake for the specified layers of the root zone, ψ_S is the water potential of the soil and ψ_L is the leaf water potential.

Figure 5



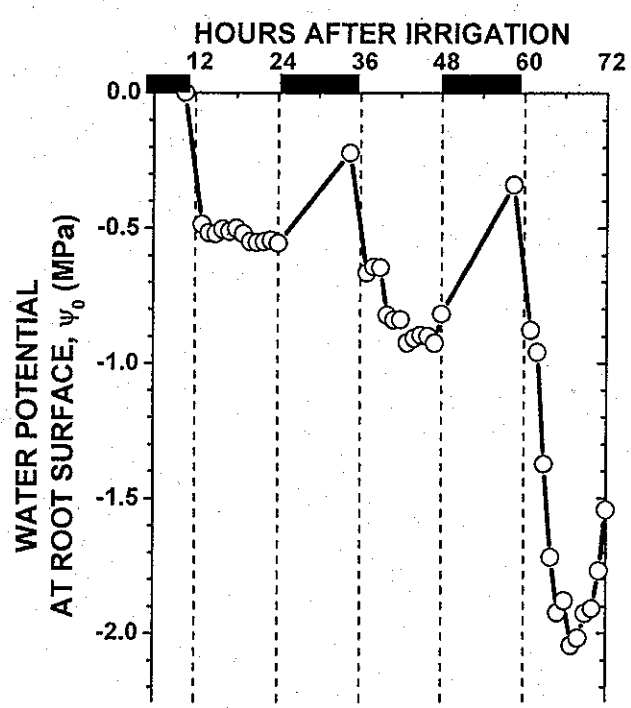
Relationships between the diurnal courses of sap flow rate and leaf water potential for the 3-day interval that follows the irrigation given on DOY 188. The curved arrows mark the sequence of the data points.

Figure 6



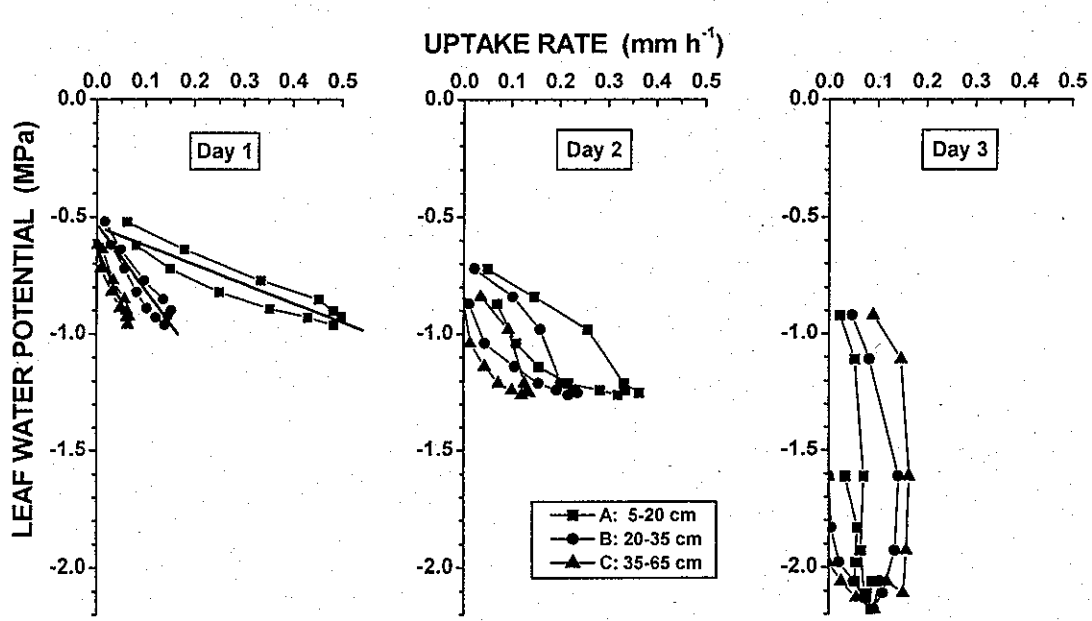
Computed apparent diurnal changes of the hydraulic resistance under the assumption that water potential at the root surface remains nearly constant.

Figure 7



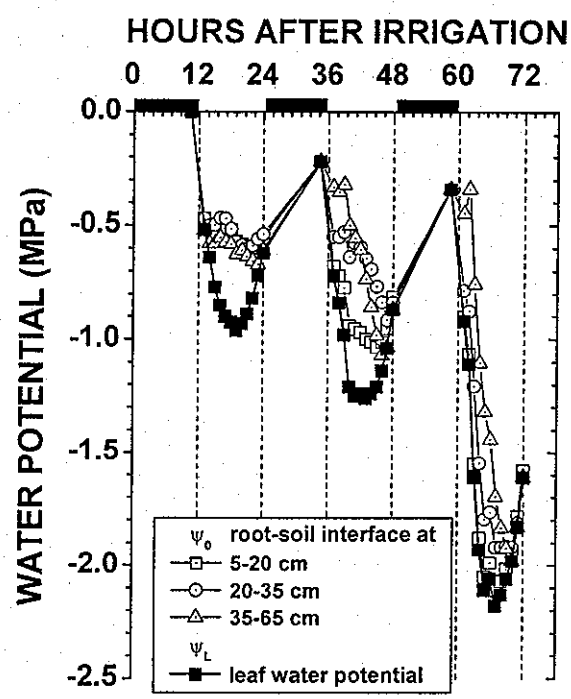
Evolution of the water potential at the root surface for the entire root system deriving from sap flow measurements. Heavy lines on the hour-axis mark night.

Figure 8



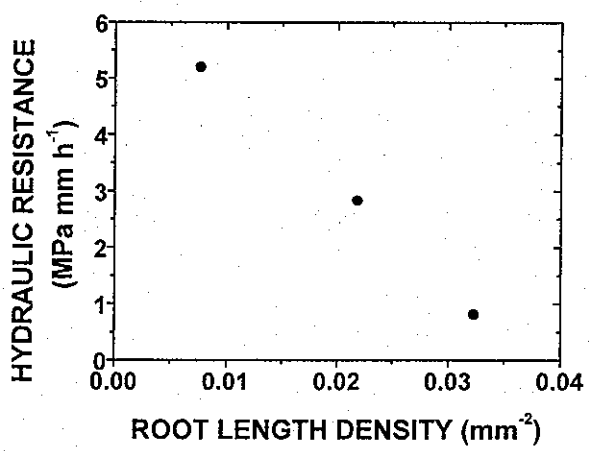
Relationship between the diurnal course of root water uptake in the specified layers and leaf water potential for the 3-day interval that follows the irrigation given on DOY 188.

Figure 9



Evolution of the water potential at the root surface for the specified layers and of the leaf water potential during the 3-day interval that follows the irrigation given on DOY 188. Heavy lines on the hour-axis mark night.

Figure 10



Effect of root length density on hydraulic resistance of the liquid path in the plant.

Figure 11

Management Report

For the Period: January 1, 2000 - June 30, 2001

Submitted to the U.S. Agency for International Development; Bureau for Global Programs, Field Support and Research; Center for Economic Growth and Agricultural Development

TITLE OF PROJECT: AGROMETEOROLOGICAL APPROACH TO CROP WATER USE EVALUATION
FOR IMPROVED IRRIGATION EFFICIENCY

Principal Investigator:	Prof. M. Fuchs
Grantee Institution:	Inst. of Soil, Water and Environment, ARO, Volcani Center, P.O. Box 6, Bet Dagan, 50250, Israel
Collaborator:	Dr. J. Rahmanov
Institution:	Scientific and Research Institute for Irrigation, Bishkek, Toktonalieva 4a, Kyrgyzstan, 720055

Project Number:	CA14-023
Grant Number:	TA-MOU-96-CA14-023
Grant Project Officer:	Boaz Avalon, Science Counselor, American Embassy, and Tel Aviv
Project Duration:	January 1, 1997 to December 31, 2000

1.Scientific Summary:

For the reporting period, the project activities progressed in checking irrigation efficiency using of Prof. M. Fuchs's model for scheduling watering of crops. The model used the agrometeorological parameters collected in a Campbell Scientific automatic meteorological station (AMS) installed in the experimental orchard situated on the mountain-foothill zone of the Chu valley of Kyrgyzstan.

In 1999, a comparison analyze of methods for definition of irrigation dates and norms for the orchard according to the lower limit of moisture stored in the rooted topsoil and on the data obtained using AMS and modeling were conducted. The conclusion was that the second method is more reliable and accurate.

In research of 1999 the irrigation conducted according to the limit of a moisture storage used 689 mm of water for six watering with a leaching loss below the rooted layers of 395,7 mm or 56,7% of the water application. In 2000, AMS and modeling fixed the scheduling parameters. The irrigation gross norm for 8 watering was 595,2 mm, of which only 47,0 mm or 7,9% were lost by leaching. The application of AMS and model allowed saving 45,8 % of irrigation water.

The norm of irrigation, based on magnitude of total water use, obtained in the model of Prof. M. Fuchs with use of data from AMS allowed optimum water use of the orchard. This was a reason of the increased yield of apple fruit. Mixed apple orchard (the varieties Golden de Luxe, Excellent, Aport) gave an average yield of 31.7 tons/ha for total water use 826 mm and 5×6 m planting density. Specific water use was 26 mm/ton, while in farms, where the management of water norms was carried out disregarding actinometrical and meteorological factors water use was higher, 38-44 mm/tons. It allows recognize the positive importance of use AMS and model for the purposes of increase of irrigation efficiency and yields.

In 2000 existing data for several main crops of Kyrgyzstan: corn, winter and autumnal wheat, sugar beet, alfalfa, and potato were collected for possible application of the model's results. These results are very important for Kyrgyzstan farmers, in view of agriculture reforms from centralized planning to market directed economy.

In 2001 were purchased 12 soil moisture probes and tested on the field.

2. Scientific Issues:

Because initial organization and purchase of the equipment in Kyrgyzstan required a long time, the initially planned crop, maize, was changed to apple collaboratively between Israel and Kyrgyzstan. This revision caused a change in the timetable of the research, and the organization of the work. As the infrastructure of the model development had already been installed in the field in Israel, the work continued there. Collecting and processing of data for several main crops for Kyrgyzstan were also decided.

The detailed reasons for the change of plan in Kyrgyzstan were:

The maize experimental site was not sufficiently protected against thieves and too expensive for running the field experiments because of high inflation and transportation expenses.

Apple orchards are an important crop in Kyrgyzstan.

New farmers needed information about irrigation scheduling for the main crops of Kyrgyzstan in view of the competitive requirement of higher water use efficiency and higher productivity.

3.Managerial Issues:

Because of the terminology of Kyrgyz and Israeli scientists was different, the Annual Report for 1999 was completed only in June-July, 2000 and the money for the project continuation has received only in August, 2000.

In May 2000 the Campbell Scientific meteorological station was mounted with the participation of Dr. Alexander Naloichenko for the data collecting and processing.
In June 2001 the meteorological was dismantled.

4.Special Concerns:
No information

5.Collaboration, Travel, Training and Publications:

In June, 2000 Principal Co-Investigator from Kyrgyzstan side Dr. Jalil Rahmanov made a visit to Israel for the coordination of terminology difficulties and further project activities.

In November 2000 Dr. J. Rahmanov arrived to Israel for completion of the Final Report and coordination of the future work.

Using of the findings of research for two years had been prepared materials for publication in Kyrgyzstan.

6.Request for American Embassy Tel Aviv or A.I.D Actions:
No information