GENERAL MECHANICS

A COMPUTER PROGRAM FOR DRIP IRRIGATION SYSTEM DESIGN FOR SMALL PLOTS

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Abstract. A computer program has been developed for design of surface drip irrigation system. It could be applied for calculation of small scale fields with an area up to 10 ha. The program includes two main parts: crop water requirements and hydraulic calculations of the system. It has been developed in Graphical User Interface in MATLAB and gives opportunity for selecting some parameters from tables such as: agro-physical soil properties, characteristics of the corresponding crop, climatic data. It allows the user of the program to assume and set a definite value, for example the emitter discharge, plot parameters and etc. Eight cases of system layout according to the water source layout and the number of plots of the system operation are laid into hydraulic section of the program. It includes the design of lateral, manifold, main line and pump calculations. The program has been compiled to work in Windows.
Key words: Drip irrigation, crop water requirements, hydraulic design, graphical user interface.

I. Introduction

The world population will rise from 6.8 billion today to 9.1 billion in 2050, according to the latest UN projections, – "a third more mouths to feed" than there today. Nearly all of the population growth will occur in developing

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countries [1]. Using natural resources more efficiently and adapting to climate change are the main challenges world agriculture will face in coming decades, producing 70 percent more food for an additional 2.3 billion people by 2050 while at the same time combating poverty and hunger, according to an FAO discussion paper published on 23 September 2009, Rome. Agriculture accounts for 24% of water abstraction in Europe – up to 80% in some southern member states – compared to 44% abstracted for cooling water in energy production, according to the European Environment Agency. Therefore, the Commission has identified agriculture as the priority sector in which measures to combat water scarcity need to be considered [2]. Fostering water efficient technologies and practices is one of the main policy options of European Commission since 2007 [3].

Drip irrigation offers the most efficient and productive way for applying water and nutrients to crops. The systems conveying the water and their emitter devices and the whole system control must be very precise. They need a proper design and management. The efforts of some scientists are devoted to improve the components of drip irrigation system: emitters, valves, control equipment. Another group of scientists develops computer programs for performing hydraulic calculations of drip irrigation system. Such products are Hydrocalc (Netaphim), AquaFlow 3.0 Design (Toro), Norveco and etc. All of them offer only hydraulic calculations of a drip irrigation system. A computer program is developed by [4] for hydraulic evaluations of drip irrigation system and its' optimization.

The subject of this paper is to describe the developed program for drip irrigation system design. It is accomplished in Graphical User Interface (GUI) in MATLAB. The program includes two main parts: crop water requirements and hydraulic calculations. It gives convenient way for choosing soil, crop, climate data and emitter characteristics. GUI in MATLAB offers variety of interactive elements: tables, edit texts, radio buttons, pull down menus and push buttons, which can be easily implemented and additionally coded for performing the necessary calculations.

II. Crop Water Requirements

1. Total Available Water Capacity, TAWC

The methodology, which the program is based on, is with closed connection with adopted knowledge during the attended course on modern irrigation technologies in Israel. Total available water capacity can be calculated according to the following formulae:

(1) $$TAWC = (FC - WP) \times BD \times 10, \quad [\text{mm}]$$

where: FC – the Field Capacity, [%] (weight basis), (Table data according to [5]); WP – Wilting Point, [%] (weight basis), (Table data according to [5]); BD – Bulk Density of the soil, [g/m^3], (Table data according to [5]). We can choose from first window of the program (Fig. 1) soil characteristics holding the button CTRL. They are for clay-loam soil the following: They are for clay-loam soil the following: $FC = 40\%$, $WP = 25\%$ and $BD = 1.3$ g/m^3 (Infiltration rate $IR = 4$ m/s will be used later) and $TAWC$ can be calculated by the program.
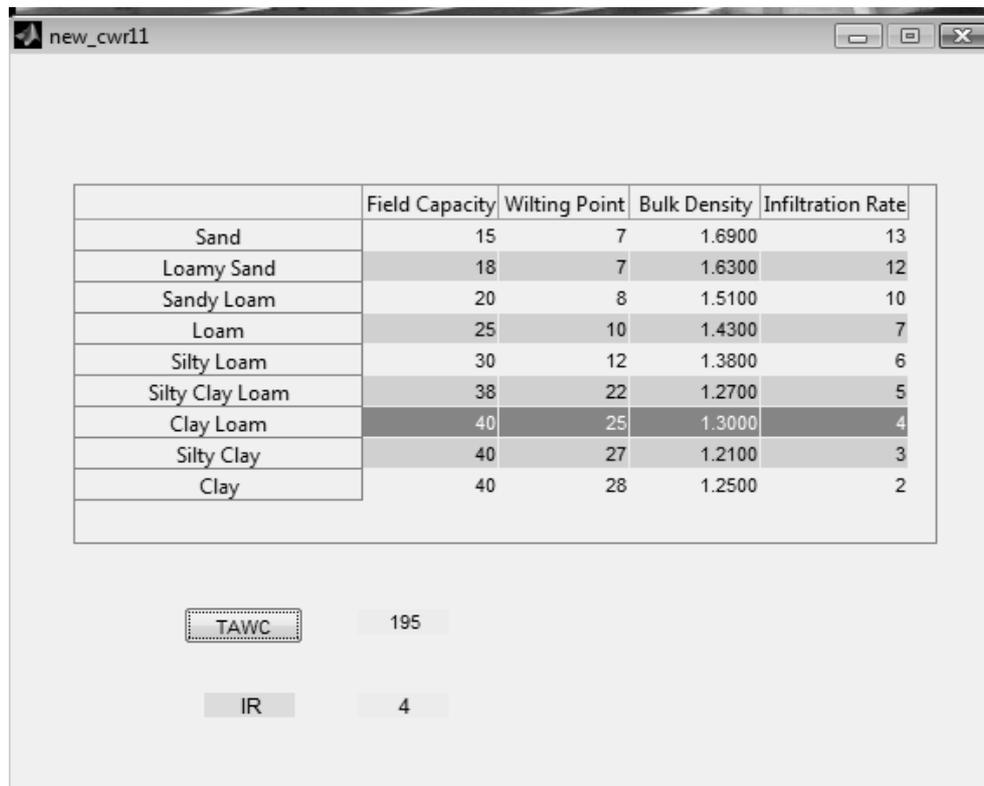
new_cwr11				
	Field Capacity	Wilting Point	Bulk Density	Infiltration Rate
Sand	15	7	1.6900	13
Loamy Sand	18	7	1.6300	12
Sandy Loam	20	8	1.5100	10
Loam	25	10	1.4300	7
Silty Loam	30	12	1.3800	6
Silty Clay Loam	38	22	1.2700	5
Clay Loam	40	25	1.3000	4
Silty Clay	40	27	1.2100	3
Clay	40	28	1.2500	2

TAWC   195

IR   4

Fig. 1. Crop Water Requirements – first window of the program

2. Readily Available Water (RAW) in the main or the effective root zone

This crop characteristic is determined by means of the next equation:

$$(2) \qquad RAW = TAWC \times DRZ, \quad [\text{mm}]$$

where: DRZ – the Design Root Zone or the effective root depth, [m], (Table data according to [6]).

3. Design Net Water Requirement (NWR)

It can be obtained by calculating the following expression:

$$(3) \qquad NWR = RAW \times MAD \times WAR, \quad [\text{mm}]$$

where: MAD – the Maximum Allowable Depletion for the corresponding crop, [%], (Table data according to [6]), $MAD = 30 \div 70\%$; WAR – the Wetted Area Ratio, [%].

4. Calculating wetted diameter (WD) by the emitter

The equation developed by Zazueta (1992) is the following:

$$(4) \qquad WD = 0.01 \left(\frac{q_e \times DRZ}{IR} \right)^{1/3}, \quad [\text{m}]$$

where: WD – the Wetted Diameter by the emitter, [m]; q_e – the emitter discharge [l/hr]; IR – the Infiltration Rate [m/s].

4.1. For non-overlapping wetted area (for wide spaced crops)

The wetted area for non-overlapping drippers can be estimated by the following formulae:

$$(5) \qquad WAR = \frac{S_{wet}}{s_e \times s_l} = \frac{\pi \times WD}{4 \times s_e \times s_l}, \quad [\%]$$

where: S_{wet} – the area wetted by the emitter, [m²]; s_e – the spacing between the emitters, [m]; s_l – the spacing between the laterals, [m].

4.2. For overlapping wetted area (for closed spaced crops)

The wetted area for overlapping drippers can be determined as follows:

$$(6) \qquad WAR = \frac{S_{wet}}{s_{e_{reduced}} \times s_l} = \frac{\pi \times WD}{4 \times s_{e_{reduced}} \times s_l}, \quad [\%]$$

where: $s_{e_{reduced}}$ – the reduced spacing between the emitter as a result of overlapping.

The area of overlapped circle segment will be kS_{wet}, $k = 0.2$ for 20% overlapping. We know wetted diameter and the area to be overlapped. Than, we calculate the apothem and multiplying it by two to obtain the reduced spacing between drippers:

$$(7) \qquad S_{segment} = S_{sector} - S_{triangle} = \frac{1}{2}R^2 \left(\theta - \sin\theta \right) = kS_{wet},$$

where: R – is the radius of the wetted area, $R = \dfrac{WD}{2}$. We can obtain θ in radian from the next equation:

$$\sin\theta - (\theta - k\pi) = 0, \tag{8}$$

$$R_{reduced} = OM = R\cos\left(\frac{\theta}{2}\right). \tag{9}$$

Table 1. Coefficients of overlapping and coefficients of radius reduction

coefficient of overlapping k	Central angle θ	Coefficient of radius reducement
0.1	$0.4\,\pi$	0.809
0.2	$0.5\,\pi$	0.707

For example, for 20% drippers' overlapping $k = 0.2$, $\theta = 0.5\pi$ and $R_{reduced} = 0.707R$

The reduced emitter spacing will be as follows:

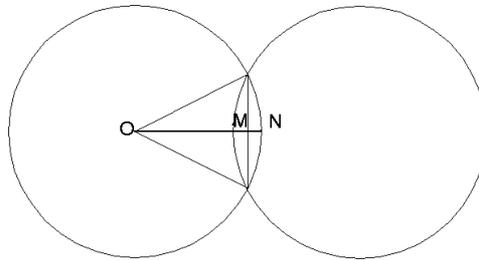$$s_{e_{reduced}} = 2R_{reduced} \tag{10}$$

Fig. 2. Overlapped wetted area

We can give a value for emitter discharge and choose $DRZ = 0.45$ m and $MAD = 35\%$ for pepper, and to assume values for the emitter spacing and the lateral spacing. The program either calculates the reduced emitter spacing or equates the value of emitter spacing to the one assumed previously by choosing one of the radio buttons for non-overlapping drippers or 20% overlapping drippers. The program calculates the corresponding values for the wet area ratio WAR and the net water requirement NWR, pressing push buttons for wetted diameter WD.
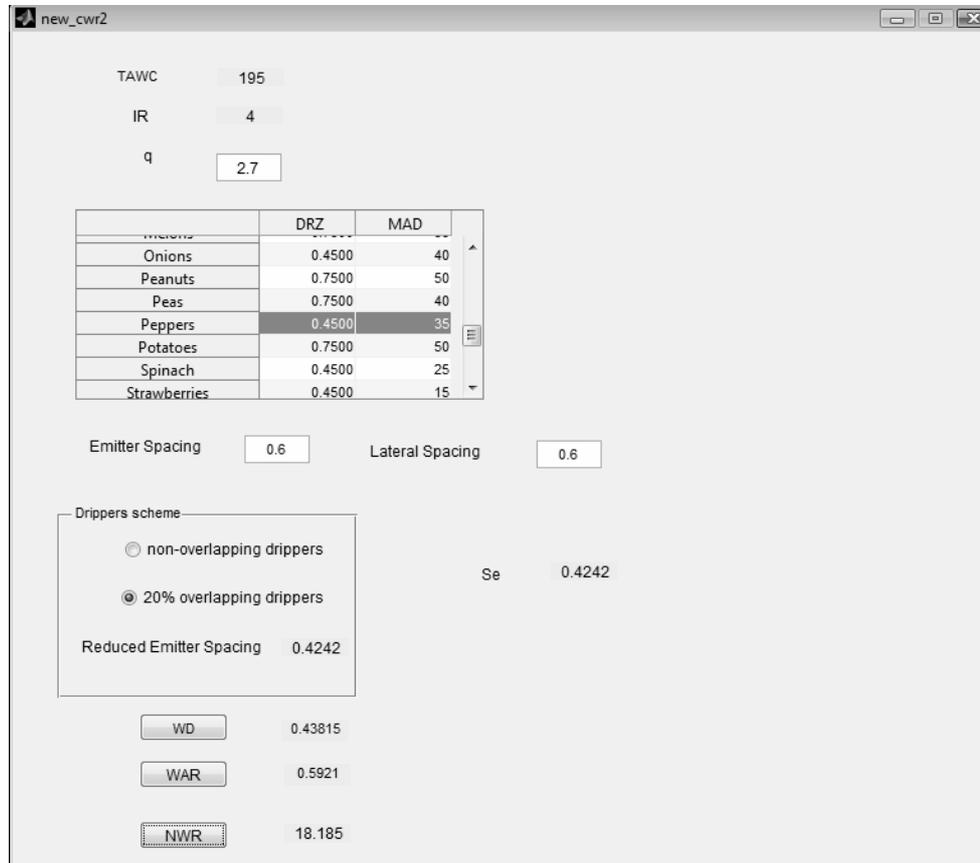
Fig. 3. Crop Water Requirements – second window of the program

5. Gross Water Requirement (GWR)
It can be calculated using the following expression:

(11)
$$GWR = \frac{NWR}{Design\ efficiency,\ \%}. \quad [\text{mm}]$$

6. Irrigation Interval (IrI) (Frequency of irrigation)

It is important for irrigation scheduling and is determined by the next ratio:

$$(12) \qquad IrI = \frac{NWR}{Etc}, \quad [\text{days}]$$

$$(13) \qquad Etc = Et_p k_c, \quad [\text{mm/day}]$$

where: Et_c – the peak daily crop evapotranspiration [mm/day]; Et_p – the reference crop evapotranspiration [mm/day], (Table data according to [7]); k_c – the crop coefficient. (Table data according to [8]).

7. Application Rate (AR) It can be evaluated as it follows:

$$(14) \qquad AR = \frac{q_e}{s_e \times s_l}, \quad [\text{mm/hr}]$$

8. Duration of Irrigation

It can be determined by means of next relationship:

$$(15) \qquad Dur.\,Irr. = \frac{GWR}{AR}, \quad [\text{hr}]$$

9. Number of plots irrigated per day

This number depends on ratio between the assumed time for system operation and the duration of irrigation:

$$(16) \qquad Number \ of \ plots = \frac{Assumed \ time \ for \ system \ operation}{Dur.\,Irr}.$$

To obtain values for the gross water requirement, GWR we point out the design efficiency in % in the edit text on the third window of the program and then we press the corresponding push buttons. Then, we have to select one value for the reference evapotranspiration from the table according to the climatic zone and one value for crop coefficient from the next table. The values for crop coefficient are editable and the user can give his own value, which the program will use in next calculation, but will not save it. Then, we have to double press the push button for ET_c. The program will calculate the corresponding values pressing the buttons of the irrigation interval and the

Fig. 4. Crop water requirements – third window of the program

duration of irrigation. We obtain the calculated value assuming the time for operation and pressing push buttons for number of plots.

III. Hydraulic calculations of lateral

1. Head losses due to friction along the lateral

The Hazen-Williams Equation is used for calculating hydraulic gradient as follows:

$$(17) \qquad J_{\%_{lat}} = 1.13 \times 10^{12} \left(\frac{Q_{lat}}{C_{lat}} \right)^{1.852} D_{lat}^{-4.87},$$

$$(18) \qquad Q_{lat} = N_{e_{latteral}} q_e \, F_Q,$$

where: $J_{\%_{lat}}$ – the hydraulic gradient of the lateral expressed in promiles [%]; Q_{lat} – the emitter discharge of the lateral, [m^3/s]; $N_{e_{latteral}}$ – the number of the emitters along a lateral; $F_Q = 2.7778 \times 10^{-4}$ – the conversion factor from liters

per hour to liters per second; C_{lat} – the Hazen- William coefficient reporting pipe smoothness, $C = 150$ for plastic pipes; D_{lat} – the inside diameter of the drip lateral, [m], [9], [10].
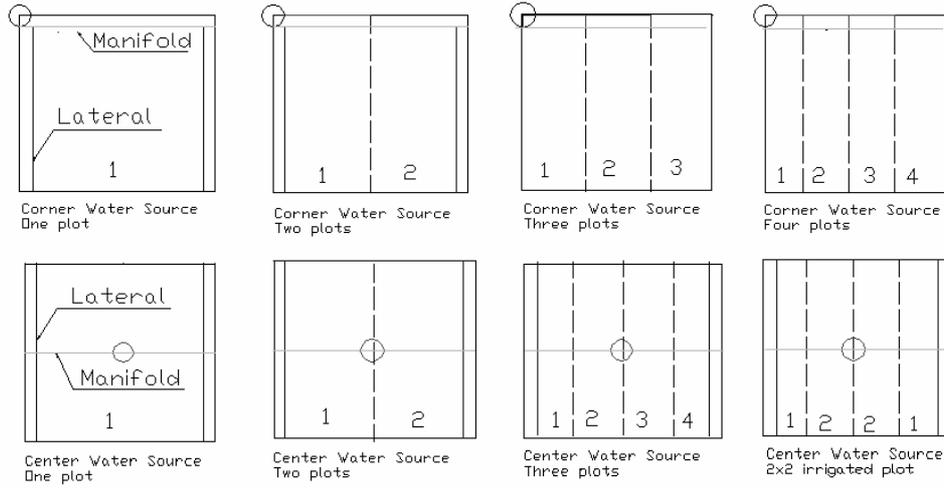

Fig. 5. System layout

The head losses due to friction of the lateral, $\Delta h_{f_{lat}}$ are according to next expression:

$$(19) \qquad \Delta h_{f_{lat}} = \frac{K_{loc\,lat} J_{lat} l_{lat} F_{c_{lat}}}{1000}, \quad [\text{m}]$$

where: $K_{loc\,lat}$ coefficient reporting local head losses of the lateral, l_{lat} – the lateral length, [m]; $F_{c_{lat}}$ – the Christiansen coefficient reporting the number of outlets along the drip laterals. It could be calculated according to the formulae:

$$(20) \qquad F_{c_{lat}} = \frac{1}{m+1} + \frac{1}{2N_{e_{lateral}}} + \frac{\sqrt{m-1}}{6N_{e_{lateral}}^2}, \quad m = 1.852.$$

2. The pressure head by the lateral inlet, h_{lat_u}
It can be determined as follows:

$$(21) \qquad h_{lat_u} = h_s + 0.75\,\Delta h_{f_{lat}} \pm 0.5\Delta z_{lat},$$

where: h_s – the nominal pressure head of the dripper, [m]; Δz – the elevation difference, [m], which is positive for uphill laterals and negative for downhill

laterals, $\Delta z_{lat} = s\, l_{lat}$; s – the slope of the lateral, [%]; l_{lat} – the lateral length, [m], [8], [9];

3. The pressure head by the last dripper, h_{lat_d}.

It can be obtained by means of the next expression:

$$(22) \qquad h_{lat_d} = h_{lat_u} - \Delta h_{f_{lat}} \mp \Delta z_{lat}, \quad [\text{m}]$$

where: Δz – the elevation difference, [m].

4. The pressure head losses along the lateral, Δh_{lat}

They are equal to the difference between the mentioned above two lateral hydraulic parameters:

$$(23) \qquad \Delta h_{lat} = h_{lat_u} - h_{lat_d}, \quad [\text{m}]$$

where: h_{lat_u} – the pressure head by the lateral inlet, [m]; h_{lat_d} – the pressure head by the last dripper, [m].

5. Calculation of local head losses of in-line emitters according to the formulae of Provenzano and Pumo

Local head loss due to a coaxial and an uncoaxial emitter can be expressed as a fraction of velocity head immediately downstream the emitter:

$$(24) \qquad \Delta h_{loc_e} = \lambda_e \frac{V^2}{2g} = 0.065 \lambda_e \frac{Q}{D^2}, \quad [\text{m}]$$

where: Δh_{loc_e} – the local head loss due to a dripper; λ_e – the coefficient synthesizing both local loss due to the contraction and the enlargement of the flow streamlines; $\dfrac{V^2}{2g}$ – the velocity head.

Provenzano and Pumo consider λ_e as a function of ratio $\dfrac{D}{D_e}$, where D – the inside diameter of the dripline; D_e – the "equivalent" emitter diameter, equal to the distance between the inner surface of the emitter and the opposite pipe wall, which can be assumed as an independent value from the Reynolds number.

They obtained the following empirical relationship:

$$(25) \qquad \lambda_e = 0.056 \left[\left(\frac{D}{D_e} \right)^{17.825} - 1 \right],$$

which is true if the inequality $1.00 < \dfrac{D}{D_e} < 1.20$ is fulfilled [11].

6. Calculation of local head losses of on-line drippers according to the formula of Yella Reddy

Local head losses of an on-line dripper are a function of barb protrusion area. Yella Reddy deduced such a formulae by applying regression analysis:

(26) $$\Delta h_{loc} = 1.525 x_1 + 8.427,$$

where: Δh_{loc_e} – the local head loss due to a dripper in terms of equivalent pipe length [cm]; x_1 is barb protrusion area [mm].

To obtain equivalent hydraulic gradient J following formula is used:

(27) $$J' = J \frac{s + fe}{s},$$

where: J is the hydaulic gradient from the formula of Darsy- Weisbach; s is the distance between drippers; $fe = h_{loc} \times x 10^{-2}$, fe – local head loss of a dripper, expressed as equivalent length [12].

IV. Hydraulic calculations of the manifold

1. Head losses due to friction along the manifold

The hydraulic gradient of the manifold is calculated according to the Hazen-Williams equation:

(28) $$J_{\%_{man}} = 1.22 \times 10^{10} \left(\frac{Q_{man}}{C_{man}} \right)^{1.852} D_{man}^{-4.87}, \quad [\%]$$

(29) $$Q_{man} = N_{lat} Q_{lat}, \quad [l/s]$$

where: Q_{man} – the emitter discharge of the manifold; N_{lat} – the number of the laterals per a plot; $J_{\%_{man}}$ – the hydraulic gradient of the manifold expressed in promiles [%]. C_{man} – the Hazen- William coefficient reporting manifold smoothness, $C = 150$ for plastic pipes; D_{man} – the inside diameter of the drip manifold, [m];

(30) $$\Delta h_{f_{man}} = \frac{K_{loc\,man} J_{\%_{man}} l_{man} F_{c\,man}}{1000}, \quad [m]$$

where: $\Delta h_{f_{man}}$ – the head losses due to friction along the manifold, [m]; $K_{loc\,man}$ – the coefficient reporting local head losses of the manifold, l_{man} – the manifold length, [m]; $F_{c_{man}}$ – the Christiansen coefficient reporting the number of outlets along the manifold.

2. The pressure head by the manifold inlet, h_{man_u}

Analogically to lateral hydraulics, the pressure head by the manifold inlet will be according the next expression:

$$(31) \qquad h_{man_u} = h_{lat_u} + 0.75\Delta h_{f_{man}} \pm 0.5\Delta z_{man}, \quad [m]$$

where: h_{lat_u} – the pressure head by the lateral inlet, [n].

3. The pressure head by the last lateral, h_{man_d}

It can also be calculated analogically by means the next formulae:

$$(32) \qquad h_{man_d} = h_{man_u} - \Delta h_{f_{man}} \mp \Delta z_{man}, \quad [m]$$

4. The head losses along the manifold, Δh_{man}

It is equal to the difference between the mentioned above two manifold hydraulic parameters:

$$(33) \qquad \Delta h_{man} = h_{man_u} - h_{man_d}, \quad [m]$$

5. Requirement for allowable pressure variations

The main requirement for allowable pressure variation has to be fulfilled as follows:

$$(34) \qquad \Delta h_{lat} + \Delta h_{man} < 0.2 h_s.$$

V. Hydraulic calculations of the main line. The pressure head by the main line inlet, h_{main_u}

It can be calculated using the previously mentioned formulae referred to the main line:

$$(35) \qquad h_{main_u} = h_{man_u} + \Delta h_{f_{main}} \pm \Delta z_{main}, \quad [m]$$

where: h_{man_u} – the pressure head by the manifold inlet, [m]; Δz – the elevation difference, [m].

Here, the standard value for emitter spacing must be assumed on the forth window of the developed program (it is from 0.3 to 1.0 m for NETAFIM). Then, we have to put the plot dimensions and the slope of lateral, manifold and main line in the corresponding edit texts. The program calculates whole lateral, manifold and main line hydraulics selecting dripline and emitter data and assuming the manifold and main line inside diameters and then choosing the system layout among the 8 cases according to Fig. 5. It compares the
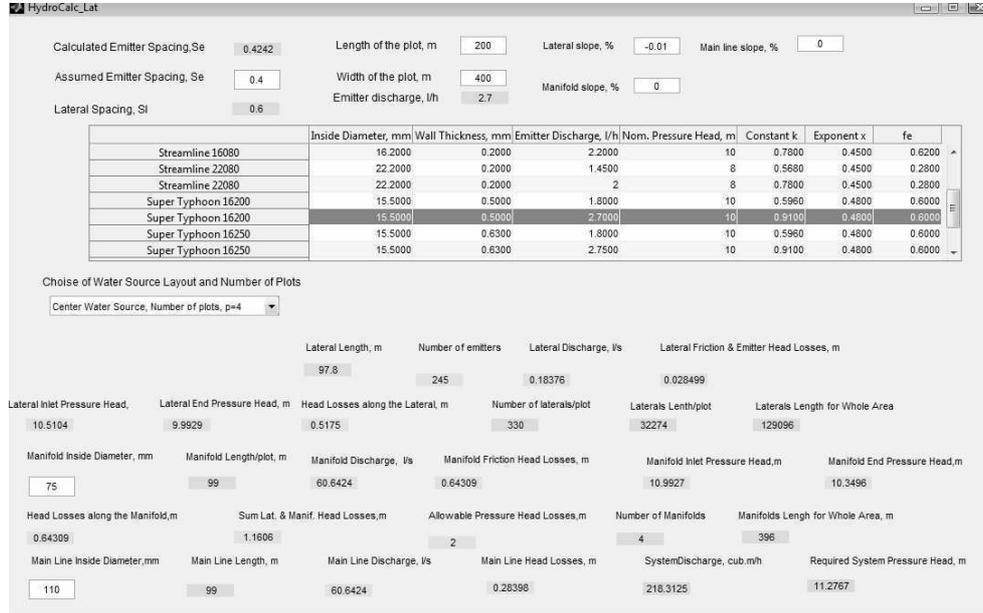
Fig. 6. Hydraulic calculations of drip irrigation system – fourth window of the program

values of the allowable pressure head losses along the lateral and the manifold and these calculated by the program. The program gives the calculated value for the system discharge and the required system pressure head as final results important for the whole system design.

VI. Pump characteristics calculation

1. Total Dynamic Head, TDH

This characteristic is evaluated as follows:

$$(36) \qquad TDH = h_{main_u} + \Delta h_{control\ head} + h_{TSH}, \quad [m]$$

where: h_{main_u} – the pressure head by the main line inlet, [m]; Δh_{TSH} – the Total Static Head, [m]; $\Delta h_{control\ head}$ is the pressure head losses in the control head, which are equal to the sum of pressure head losses in the filter, Δh_{filter}, these in fertilizer tank, $\Delta h_{fertil.\ tank}$ and these in measuring and control devises $\Delta h_{measur.\&contr.devices}$:

$$(37) \quad \Delta h_{control\ head} = \Delta h_{filter} + \Delta h_{fertil.\ tank} + \Delta h_{measur.\&contr.devices}, \quad [m]$$

$$(38) \qquad \Delta h_{TSH} = \Delta h_{suction\ lift} + \Delta h_{elevetion\ lift}, \quad [m]$$

where: $\Delta h_{suction\ lift}$ – the suction lift of the pump, m; $\Delta h_{elevation\ lift}$ – the elevation lift, [m].

2. Pump Power

This pump characteristic is estimated as follows:

$$(39) \qquad\qquad P = \frac{Q_p TDH}{270\eta}, \quad [\text{kW}]$$

where: $Q_p = Q_{syst}$ – the discharge of the system, η – the pump efficiency.

Fig. 7. Pump calculations of drip irrigation system – fifth window of the program

Here, the user can determine the total static head by putting the data for suction and elevation lifts on the fifth window. One can obtain the total dynamic head by pointing the head losses in control head and then giving the value of pump efficiency to have the required pump power, [kW].

VII. Conclusions

An interactive program is developed for the design of small scale drip irrigation systems – up to 10 ha. It is accomplished in GUI-MATLAB and consists of two parts: crop water requirements and hydraulic calculations of lateral, manifold, main line and pump.

It allows the user in an interactive way to take into account all necessary soil, crop, climatic data and the basic parameters for hydraulic calculations. It offers a convenient way for design of small scale drip irrigation systems.

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