USERS MANUAL
Version 1.0

OPTIMUM

By

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Disclaimer

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Although a reasonable effort has been made to assure that the results obtained are correct, the computer program described in this manual is experimental. Therefore the author and the Mediterranean Agronomic Institute are not responsible and assume no liability whatsoever for any results or any use made of the results obtained from this program, nor for any damages or litigation that result from the use of this program for any purpose.

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I-Introduction

Optimum is a computer program package that allows you to optimize the pipe size diameters of any irrigation network and to analyze a single sprinkler characteristics or a sprinkler network performance. It is subdivided into two separate parts:

- The first part of "Optimum" is dedicated to the analysis of sprinkler performance under a given spacing, operating pressure and wind conditions. The effect of the temporal variation of working pressure and/or wind parameters on the water profile of the sprinkler under analysis could also be simulated with emphasis on water distribution uniformity and application efficiency.
  Sprinkler water profile for a given working pressure is simulated using linear interpolation techniques between the water distribution patterns of the same sprinkler measured using the indoor single radial test at different operating pressure. While the distortion of the water distribution pattern of the sprinkler by the wind is simulated using the ballistic theory on a single drop. After that, the water distribution pattern of adjacent sprinklers are overlapped according to the distance assigned by the user or the designer. This operation is necessary to perform a statistical analysis on the amount of water applied in the fictive catch cans thus revealing the irrigation uniformity and efficiency (Figure1).

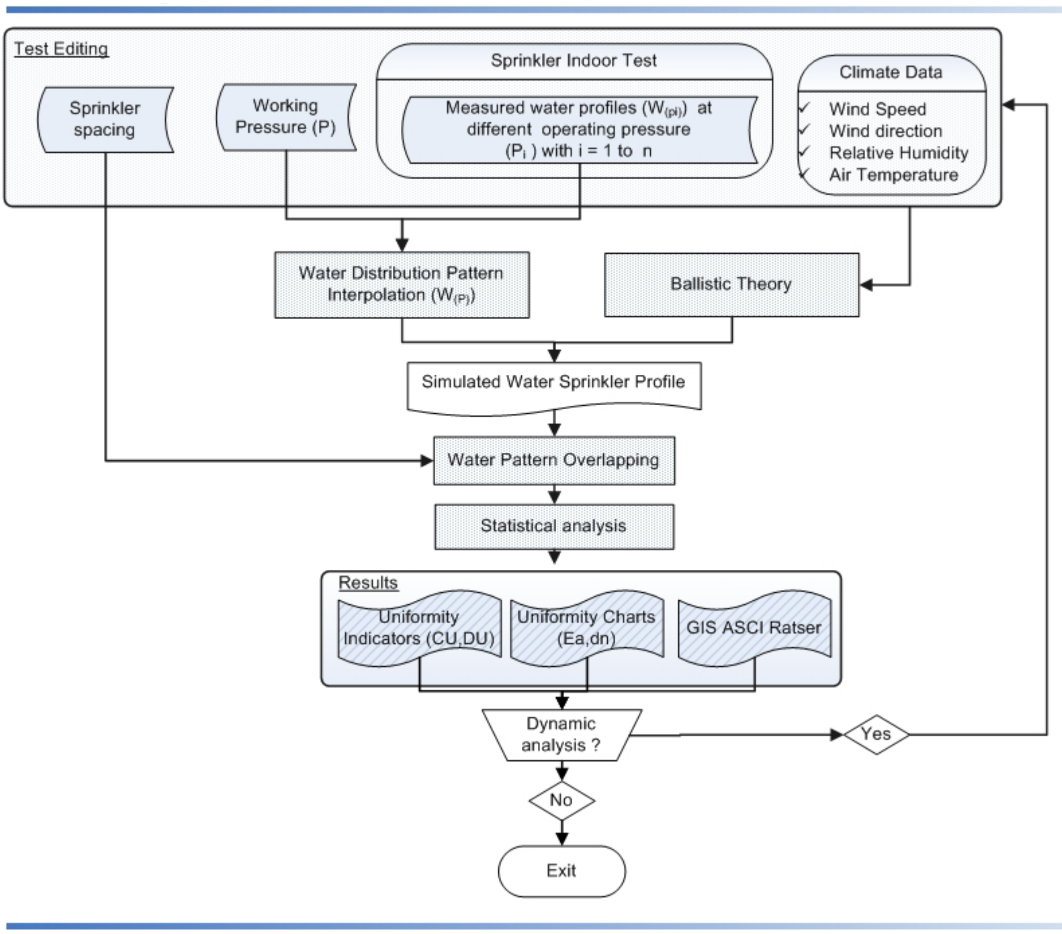


Figure 1: Flow chart of Sprinkler performance analysis in "Optimum" software

Sprinkler water distribution patterns distorted by wind or modified by pressure change are fundamental information for the designer to define the best sprinkler spacing for a high irrigation performance.

- The second part of the software combines pipe sizing, network analysis and performance evaluation of sprinklers network. For a given irrigation system layout, "Optimum" can analyze the network by computing the working pressure at each node of the system or/and could use the Labye Iterative discontinuous method to choose the cheapest pipes from a the pipes list without disrespecting the minimum required pressure at the node level. Network analysis and optimization could be used on any branched system supplying nodes with different discharges.

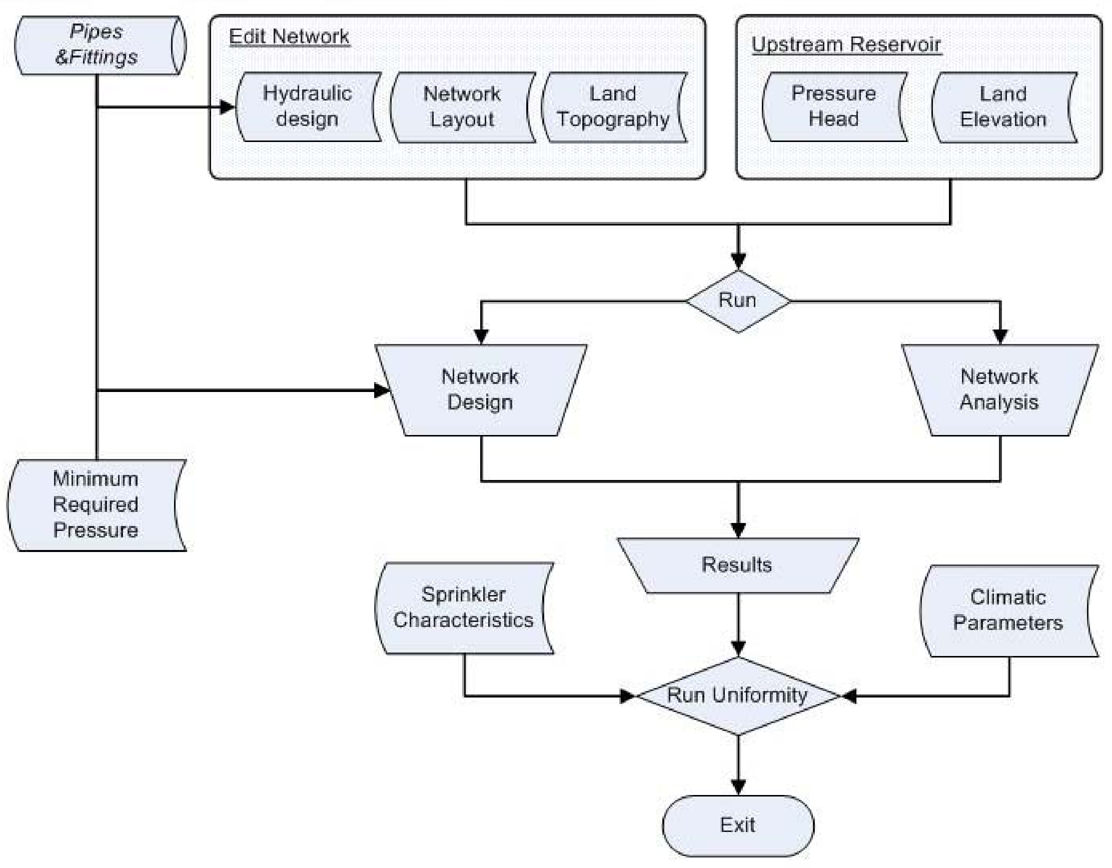


Figure 2: Flow chart of network designing and performance analysis in "Optimum" software

Once the network is analyzed or designed as previously described, the performance of a sprinkler system could be evaluated by simulating and overlapping the sprinkler water distribution patterns at any working pressure and wind parameters conditions. The statistical analysis conducted on the amount and on the spatial distribution of water will reveal the performance of the sprinkler network in terms of uniformity and irrigation efficiency.

II- Installing Optimum

Optimum version 1.0 is designed using VisualBasic.net to run under Windows XP/Vista operating system.

To install Optimum:

1. Select **Run** from the Windows Start menu
2. Enter the full path and name of the "**setup.exe**" file or click the browse button to locate it on your computer
3. Click the **OK** button to begin the setup process.

The setup program will ask you to choose a folder where optimum files will be placed. The default folder is ***C:\Program Files\IAMB\Optimum***. After the files are installed your ***Start Menu*** will have a new item named ***Optimum***. Beside a new shortcut icon  will be placed on your desktop. To launch Optimum software, from the Start Menu select Optimum or simply click on the Optimum shortcut placed on your desktop.

Should you wish to remove Optimum from your computer, you can use the following procedure:

1. Select **Settings** from the Windows Start menu.
2. Select **Control Panel** from the Settings menu.
3. Double-click on the **Add/Remove** Programs item.
4. Select **Optimum** from the list of programs that appears.
5. Click the **Add/Remove** button.

Troubleshoots

- Since it was developed using visual basic.net, the dotnet framework version 2.0 is required. If this latter was not installed on your computer, the installation wizard will ask you to install the .net framework. You can download the .net framework directly from the website of Microsoft or you can find it with Optimum installation CD under the name of "dotnetfx_ver2.exe". Note that installation of .net framework might take few minutes for complete installation. Once done, you can retry installing Optimum as previously described.
- Some computers could fail in registering "MapWinGIS.ocx", in that case you might need to install the MapWinGIS ActiveX control on your computer. To do that, click on"MapWinGIS44OCXOnly.exe" that you can find in the installation CD, or you can download it for free using the following link:
  http://www.mapwindow.org/download.php?show_details=2

N.B: Before start using Optimum software, be sure that the number format on your computer uses the "." as a decimal separator and not the ",".

III-Quick start tutorial

In the ***File*** main menu, you can find two items. ***Exit*** item that could be used together with the close button located on the top right of the main form to get out of the program and the ***New*** item used to start a new analysis or designing process.

1-Sprinkler Analysis

In this part of the tutorial we will analyze the performance of a sprinkler under given spacing and wind condition. The first step to do is to select from the main menu ***Sprinkler Analysis*** >> ***Edit*** to open the window form shown in figure 3. The ***Sprinkler*** and ***Edit Test*** pages will be used to insert the input data required for this type of analysis.

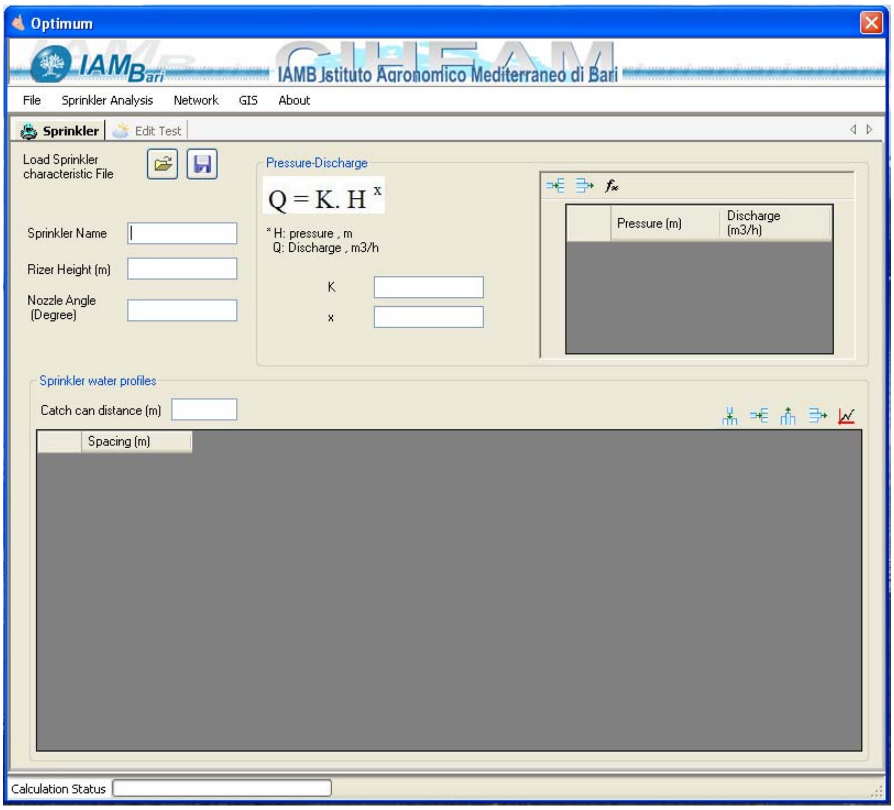
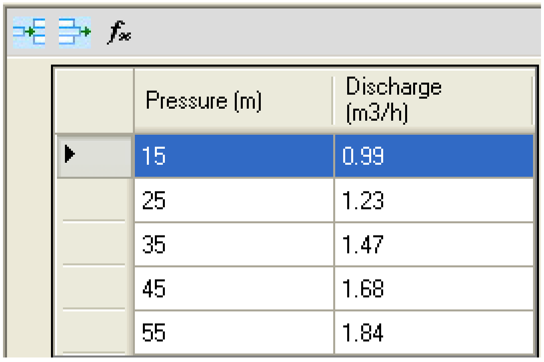


Figure 3: Input form for sprinkler analysis

1.a- Sprinkler

Sprinkler page must be used to insert the indoor radial test results of the sprinkler under study. In the following an example of the double nozzle (4+2.4mm) Agros 40 sprinkler is used to illustrate how the indoor radial test data are inserted in Optimum software. In their appropriate text boxes and data grids insert the following:

1. ***Sprinkler Name:*** Agros 40 (4+2.4mm)
2. ***Riser Height:*** 0.6 m
3. ***Nozzle Angle:*** 27°
4. The ***K*** and ***x*** parameters of the characteristic equation that relates ($Q = \boldsymbol{K}.H^x$) the sprinkler working pressure *(H)* with the discharge *(Q)* could be assigned directly in their appropriate text box or could be calculated using a power trend line from at least three pairs of pressure-discharge data as following:
   a. In the ***Pressure-Discharge*** group box, click ***Add Row*** button to add a new row on the table and add a pair of sprinkler pressure-discharge data.
   b. Repeat this operation until you add the data shown in figure 4.



Pressure (m)	Discharge (m3/h)
15	0.99
25	1.23
35	1.47
45	1.68
55	1.84

Figure 4: Example of sprinkler Pressure-Discharge pair data

   c. To remove the last row from the list click on the ***Remove Row*** button.
   d. Once all the pressure-discharge data are added, click the ***Trend Line*** button and the values for ***K*** and ***x*** will be assigned automatically and the characteristic equation of the sprinkler under study will have the following form:

$$Q = 0.264.H^{0.48} \tag{1}$$

5. Now we will add the data of the indoor single radial test obtained at different sprinkler operating pressure. Click on the ***Add Pressure*** button in the ***Sprinkler water profiles*** group box and insert the operating pressures used in the test (*Fig.5*).

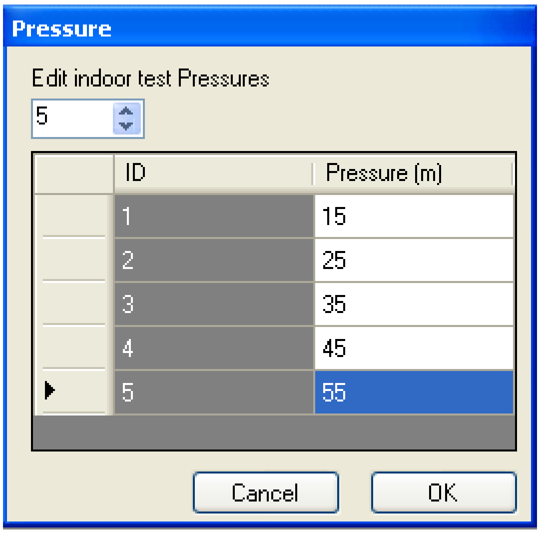


Figure 5: Pressures used in the sprinkler radial test

Click ***Ok*** to close the form and automatically, the pressure columns are loaded in the indoor test table. Should you wish to remove some pressure from the test, click the ***Remove Pressure*** button .

6. Assign the catch can distance to 0.6m and Click the Add Row button to add new row or on the Delete Row button to remove the last row of the table. The first column of the table named ***Spacing (m)*** represents the catch can distance from the sprinkler while each cell of the table represents the amount of water applied by the sprinkler at a given distance and under a given operating pressure.
Use ***Save*** button to save the sprinkler file as ***.spr*** file. To open an existing saved **"*.spr*"** file use the ***Open*** Button .

The following table represents a real data obtained from an indoor single radial test of Agros 40 *(4+2.4mm)* tested at a pressures of 15, 25, 35, 45 and 55m (*Fig.6*).

Spacing (m)	H = 15 m ; Applied water (mm/h)	H = 25 m ; Applied water (mm/h)	H = 35 m ; Applied water (mm/h)	H = 45 m ; Applied water (mm/h)	H = 55 m ; Applied water (mm/h)
0	9.55	9.05	9.35	10.15	10.41
0.6	7.54	7.71	8.4	9.47	9.95
1.2	5.53	6.38	7.44	8.8	9.5
1.8	3.62	4.37	5.08	6.03	6.13
2.4	3.37	3.72	4.17	4.83	4.62
3	3.37	3.67	3.97	4.42	4.73
3.6	3.22	3.47	3.72	4.37	4.62
4.2	2.61	2.92	3.42	4.17	4.52
4.8	2.36	2.76	3.22	4.12	4.57
5.4	2.01	2.61	3.17	3.82	4.47
6	1.61	2.41	3.12	3.72	4.27
6.6	1.66	2.31	3.17	3.87	4.27
7.2	1.56	2.11	3.02	4.02	4.37
7.8	1.96	2.26	2.92	3.92	4.47
8.4	1.91	2.26	2.66	3.42	4.12
9	1.71	2.21	2.41	3.12	3.32
9.6	2.11	2.01	2.21	2.61	2.82
10.2	2.41	1.96	2.16	2.46	2.51
10.8	2.61	2.11	2.21	2.31	2.41
11.4	1.71	2.11	2.11	2.26	2.21
12	0.35	1.81	1.56	1.96	1.91
12.6	0	1.06	0.96	1.61	1.51
13.2	0	0.3	0.25	1.06	1.01
13.8	0	0	0	0.5	0.5
14.4	0	0	0	0	0

Figure 6: Amount of water applied(mm/h) at different distances from the Agros 40 sprinkler operating at different pressure (15, 25, 35, 45 and 55m)

You can illustrate graphically the indoor radial test of the sprinkler under study at different operating pressure by selecting the ***Water Profile*** button. Consequently a new page will be added to your main window form named ***Water Distribution Pattern*** showing graphically your indoor radial test table as in figure 7. By hovering the mouse cursor over the curves, a small text box will show you the value of the water applied at the selected pressure. Right Click on the figure and several options for saving, copying and printing options will appear.

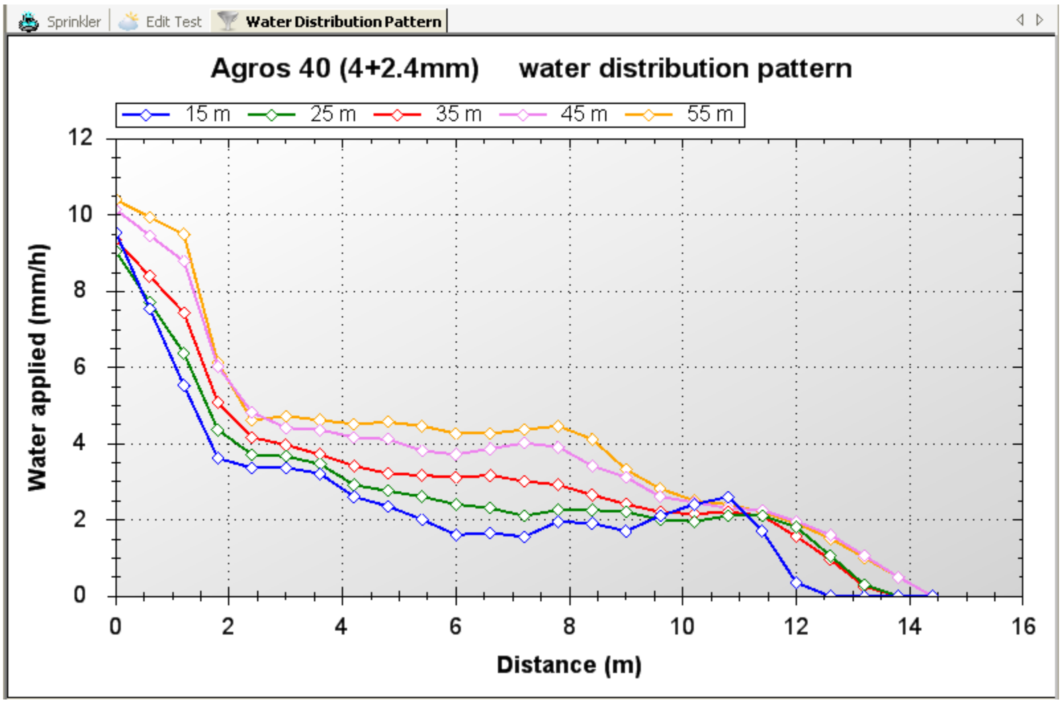


Figure 7: Water distribution patterns of "Agros 40 (4 +2.4mm)" when operating at different pressure (15, 25, 35, 45 and 55m)

1.b- Edit Test

In the ***Edit Test*** page, you should define the sprinkler spacing, working pressures as well as the climatic parameters necessary for simulating the wind effect on the water distribution pattern using the ballistic theory.

As an example, set sprinkler distance and lateral distance to 15m and 20 m. These values represent 4 sprinklers working together at a separating distance of 15 x 20 m. ***Sprinklers with the same pressure*** check box indicates that these 4 sprinklers are working at the same operating pressure. If you want to assign for each sprinkler a different pressure, uncheck ***Sprinklers with the same pressure*** and assign the working pressure of each sprinkler in the grid box below. In this tutorial example we assumed that the 4 sprinklers are working at the same pressure of 30 (Fig.8).

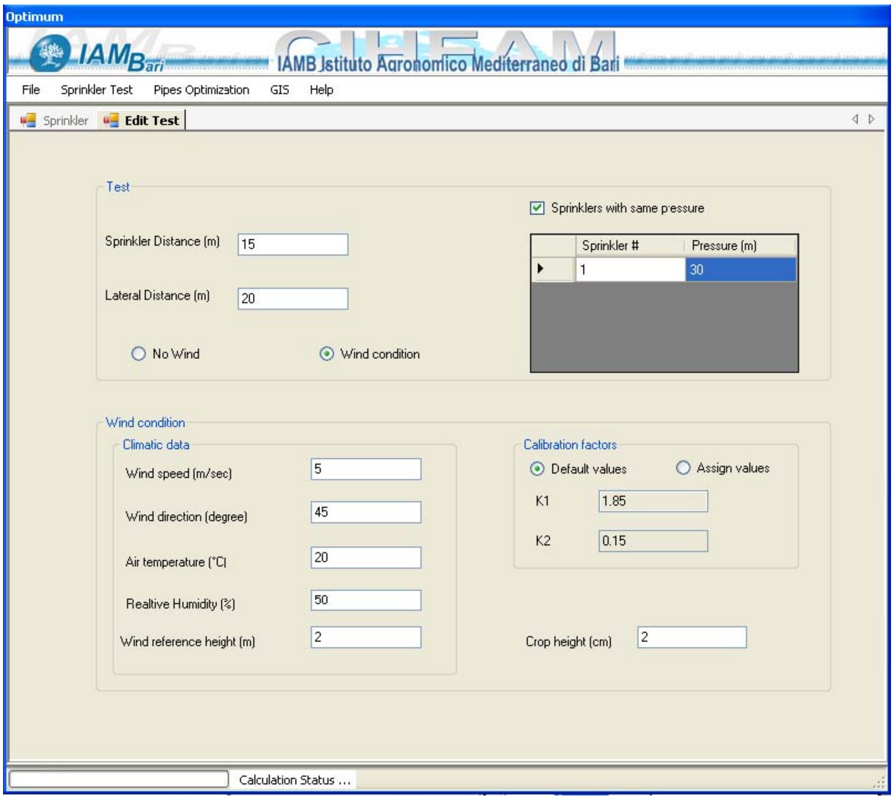


Figure 8: An example of a sprinkler analysis test taking into consideration sprinklers distance, working pressure and climatic parameters

By default, the test is simulated under no wind condition but the user can perform the analysis in a windy status by checking the ***wind condition*** radio button and filling all the climatic parameters necessary for wind effect simulation using the ballistic theory.
Let suppose that wind have an average speed of 5 m/s at 2 m above the ground and is blowing at 45° from the west, in another words from the south west. While air temperature and relative humidity are registering 20°C and 50% respectively.
The uniformity of water distribution will be tested at the crop height level which in this example was set to 2 cm.
Calibration factors are necessary to give the elliptical shape of the sprinkler water profile distorted by wind. By checking the ***Default values*** radio button default values of 1.85 and 0.15 for K_1 and K_2 will be assigned respectively.

1.c- Show results

Check that all your input data for the sprinkler analysis test are set correctly before running the program by selecting ***Sprinkler Analysis*** >> ***Run sprinkler test.*** Wait until the status bar at the bottom left of the form indicates the end of the calculation process. If no message box error appeared, an additional page named ***Uniformity*** will be added to your main window form, illustrating the relative application ration and the minimum net depth of applied water (mm/h) at different percentage of adequately irrigated area (Fig. 9). Right click on this graph to obtain the list of printing, copying, zooming and saving options.

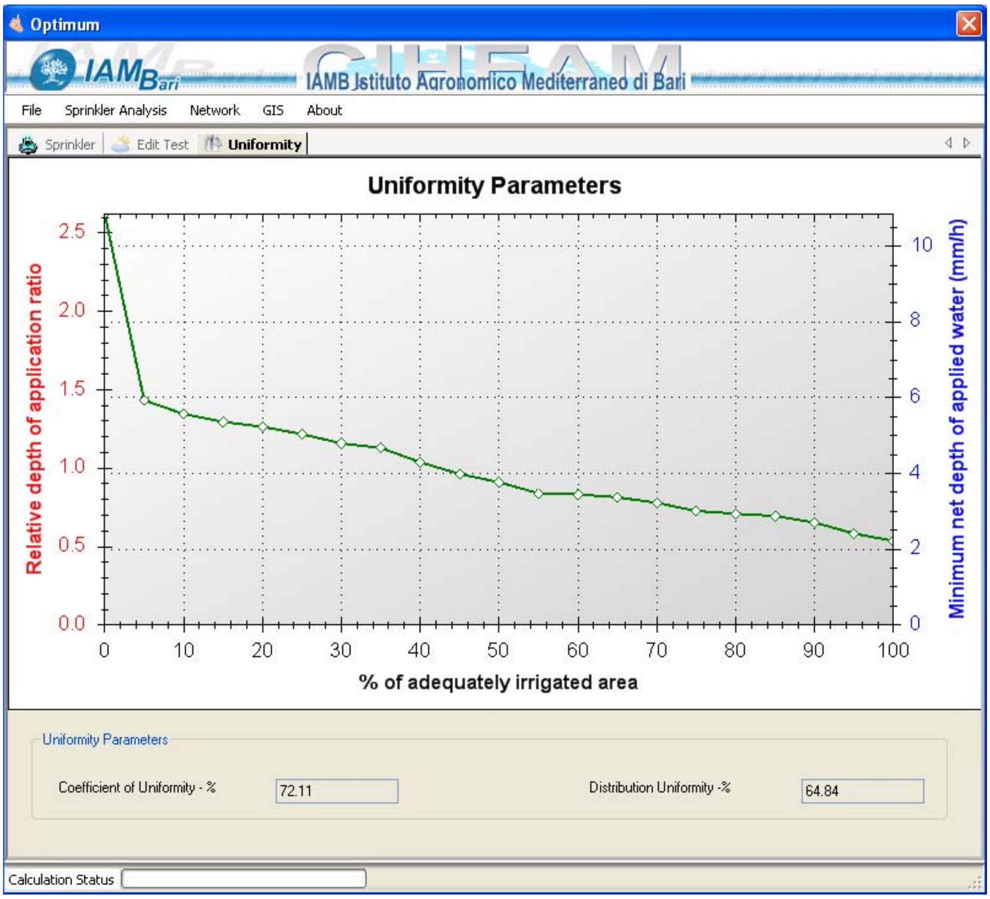


Figure 9: Window form of "Optimum" software showing the uniformity parameters of the sprinkler analysis test

In addition to the Relative depth of application ratio and to the minimum net depth of applied water, the classical Coefficient of Uniformity and Distribution Uniformity parameters are also calculated and presented in the ***Uniformity Parameters*** group box at the bottom of the page (Fig.9).

Water distribution pattern could also be spatially illustrated using the GIS techniques. Therefore select ***Sprinkler Analysis << Save as GIS << Raster File*** or ***Sprinkler Analysis << Save as GIS << Shape File*** to save the spatial distribution of the water as ASCI raster file ".asc" or shapefile ".shp" respectively.

1.d- Dynamic Analysis

The pressure (when supplied by on-demand pressurized water distribution system) and climatic parameters, mainly wind speed and direction, are subjected to high temporal variation. For that reason, Optimum software in the sprinkler analysis part was programmed to simulate the effect of these variations on the irrigation performance.

Select ***Sprinkler Analysis*** >>***Dynamic Analysis*** to open the window form presented in figure 10. In this form, three different pages are loaded: Sprinkler, Edit Test and Dynamic analysis page.

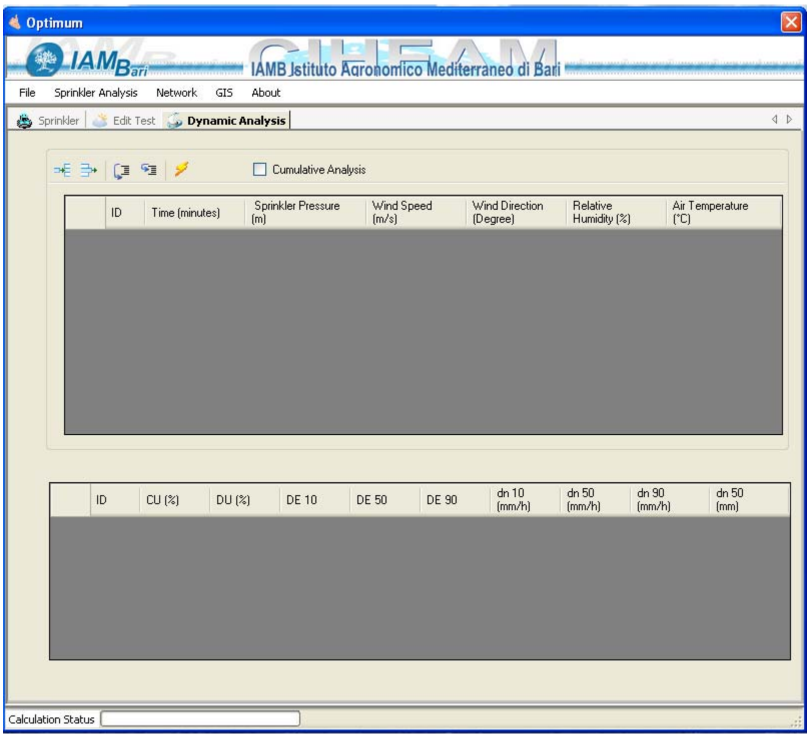


Figure 10: Window form of the dynamic analysis of the sprinkler performance in Optimum software

In the ***Sprinkler*** page load the previously saved sprinkler file ".spr" or insert your data as described in paragraph 1.a . While in the ***Edit Test*** page only the fixed parameters for the test are enabled as sprinklers spacing, wind reference height, crop height and the calibration factors. The dynamic or constantly changing factors must be assigned in the ***Dynamic Analysis*** page (Fig.11).

1. Click on the Add Row button to add a time step in the dynamic analysis. Insert for each time step (T1, T2 ….) its duration in minutes and the corresponding variable parameters (Pressure, wind speed, direction, relative humidity and air temperature). Each time one of these variables change, a new time step must be added.
2. To add a new time step use the Add Row button. To remove it click on the Remove Row button. The other two buttons, named ***Copy all Rows*** and ***Copy one Row*** are used to copy the entire selected row into the successive rows to facilitate the data entry.
   To select the row to be copied, click on the right margin of the table at the desired row level (*Fig. 11*).

	ID	Time (minutes)	Sprinkler Pressure (m)	Wind Speed (m/s)	Wind Direction (Degree)	Relative Humidity (%)	Air Temperature (°C)
	T1	60	20	5	45	50	20
▶	T2	80	40	4	35	45	19
	T3	50	50	0.5	0	48	20
	T4	20	30	2	350	52	22

Figure 11: Example of the data entry for the temporal variation of the sprinkler analysis

3. To analyze the performance of the sprinkler at each time step separately, uncheck the *Cumulative Analysis* check box located at the top of the page. Otherwise, the software will analyze the performance using the cumulative amount of water applied.

4. After you define the fixed parameters in the *Edit Test* page and the variable parameters in the *Dynamic Analysis* page, click the ***Run*** button to launch the dynamic analysis. A folder dialog box will ask you to create or choose a folder in which the report and the spatial water distribution raster files for each time step will be saved as *T1.asc, T2.asc* and so on.

5. On the bottom of the Dynamic Analysis page, uniformity parameters (Coefficient of uniformity and Distribution uniformity), Application ratio (DE) and minimum net depth of applied water (dn) for 10, 50 and 90% of adequately irrigated area are respectively illustrated (Fig.12).

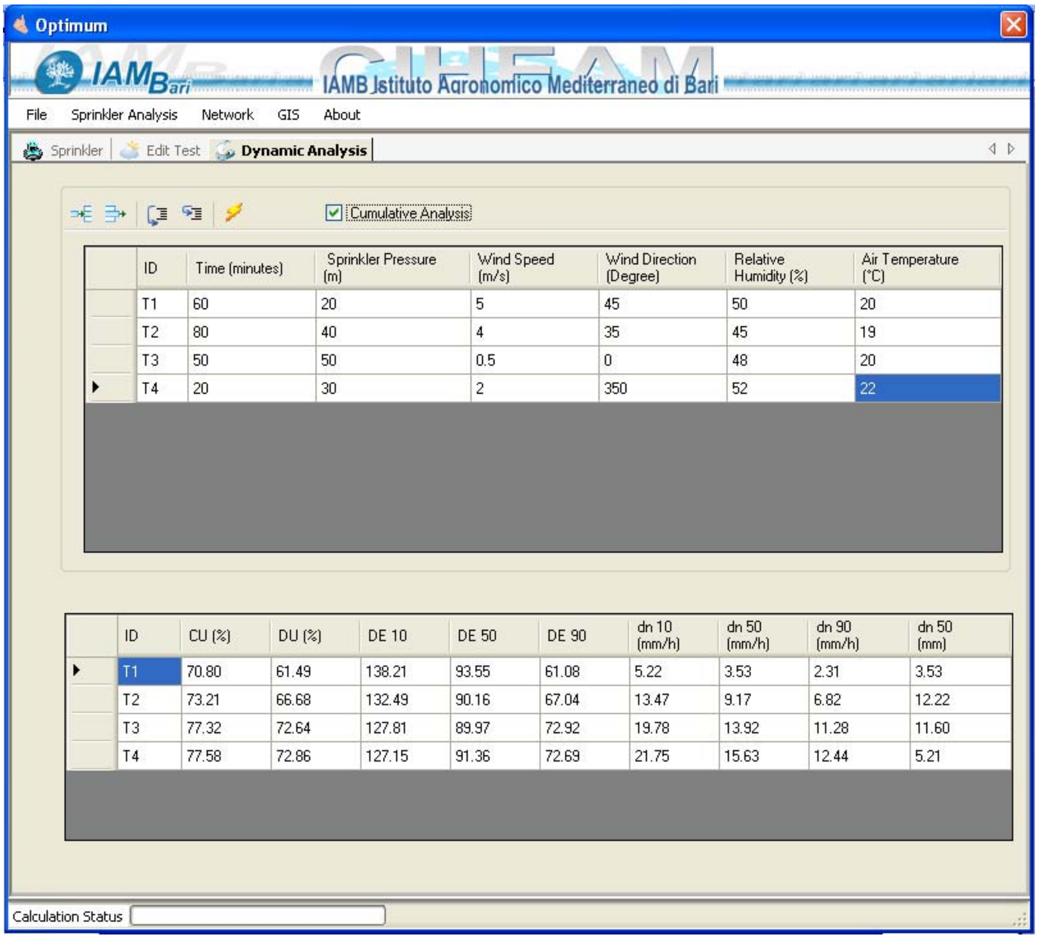


Figure 12: Results of the cumulative dynamic analysis for each time step

2-Network Design and Analysis

As previously mentioned, this part is dedicated to the analysis and designing of irrigation network. To do all that, select ***Network*** >> ***Edit Network*** from the main window form of Optimum software. The form shown in figure13 allows you to insert all the necessary input required to perform the analysis and the design of the network. It consists of 2 steps to be followed consecutively as following:

2.a- Step 1: Pipes and Fittings

In this page you must insert the full list of the pipe diameters with their cost that will be used in the optimization process. At the same time in the *Local Head* losses grid box, insert all the fittings that could create minor losses in the network together with their local loss coefficient (K_L).

- To add a new row or a new pipe or fitting, use the ***Add Row*** button .
- To remove the last row from any data grid, use the ***Remove Row*** button .
- To save the pipe list as ***".pipes"*** file or the fitting list as ***".fit"*** file use the Save button .
- To open a saved pipe list ***".pipes"*** or fitting list "***.fit*** "use the Open button .
- To choose the pipe roughness you can use the default values given by the software by selecting the ***Pipe materials from*** the drop down list otherwise uncheck the ***Default values*** checkbox and assign your roughness value in the ***Pipe Roughness*** textbox.

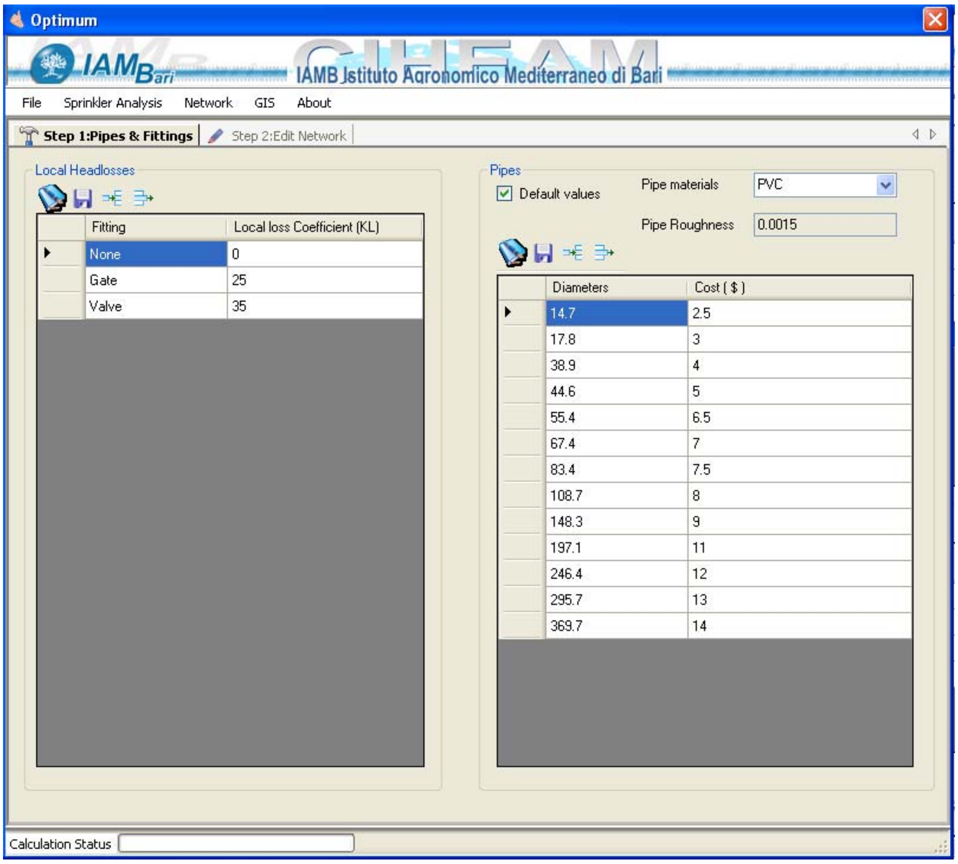


Figure 13: Example of Pipe diameters and fittings lists as used by Optimum software

2.b- Step 2: Edit Network

Edit Network page is reserved to the description of the network layout, design and land topography. It is subdivided into 4 different tabs:

1. ***Network*** Tab: First step to do is to choose the layout of the network by clicking one of the 4 layouts presented on the top of the page (Fig.14).

   a. layout button corresponds to a network made of a mainline and single lateral.

b. layout button corresponds to a network with laterals located on the left side of the manifold.

c. layout button corresponds to a network with laterals located exclusively on the right side of the manifold.

d. layout button corresponds to a network where the manifold is in the middle of the laterals.

Once you select the proper layout of your system, the necessary tables and text boxes for the required data will be enabled while the others will remain blocked. The input and output of this model is limited to the ***Pipe Reach Unit***, which is defined as a single reach of pipe having a given length, diameter, slope and carrying as maximum a single fitting.
In the numeric up down box named ***Mainline reach number*** assign the number of pipe reach unit corresponding to the mainline.

From the main line grid box, set the pipe reach unit length and assign a positive value for the slope to indicate a down hill and negative value for an uphill situation. Select your pipes diameter and fittings type from the drop down list that correspond to the lists of the ***Pipes and Fittings*** page (Fig.13)**.**

In the ***Upstream Reservoir*** group box define the reservoir upstream pressure head and its land elevation. In case you want to apply the optimization technique on the network you must define the minimum pressure head allowable at the sprinkler level in the ***Minimum Head*** text box.

The three buttons named ***Copy all Rows*** , ***Copy one Row*** and ***Copy selected Cell*** located at the top of any data grid are used to copy a selected row or cell into subsequent rows or cells aiming to reduce the time consuming of data entry.

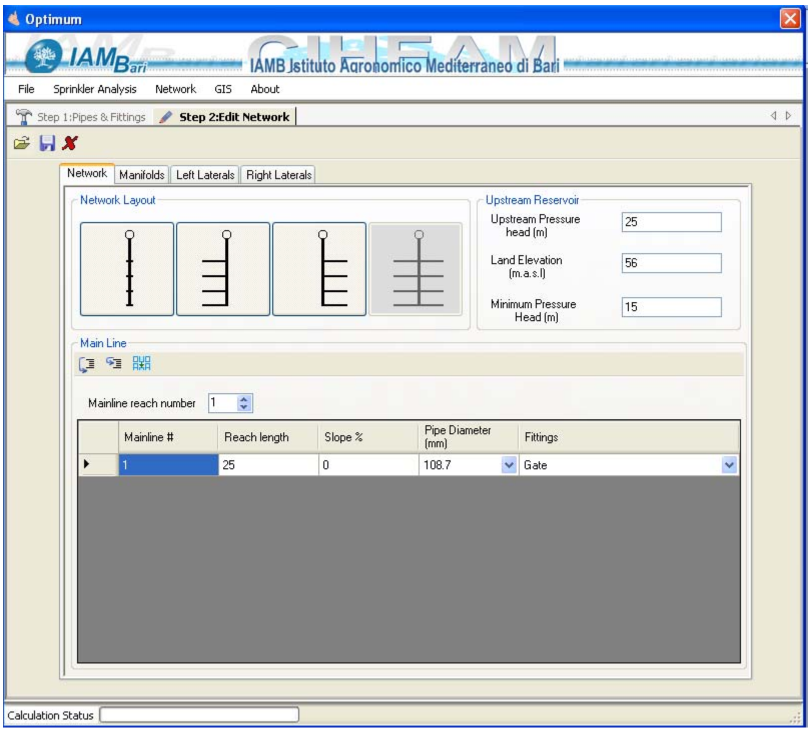


Figure 14: Network layout description and reservoir characteristics as used by Optimum software

2. ***Manifold*** Tab: in this page select from the numeric up down box the number of laterals. Thus, based on the layout of the network the number of pipe reaches in the manifold will be added. For example, the number of laterals in layout should be always pair and to have a manifold reach, the number of laterals must be equal or higher than 4 (Fig.15). In case of layout, due to the absence of laterals, ***Number of laterals*** will be used to assign the number of sprinklers. For that reason an additional column will be added to the manifold grid box to assign the discharge in m^3/h for each outlet (sprinkler).

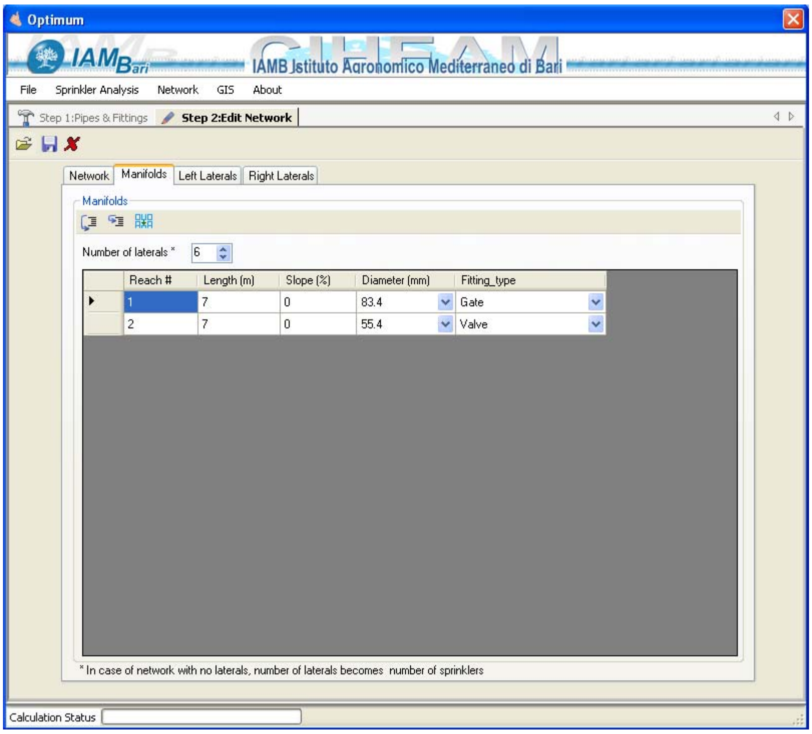


Figure 15: Data entry of manifold reaches as used by Optimum software

3. ***Left laterals*** Tab: This tab is enabled for editing only when or layout button is selected.
    a. In the first upper grid box assign for each lateral the total number of sprinklers in the ***Number of Sprinklers*** column.

    b. Click the Load button to load pipe reach unit in the table below. This allows you to assign for each reach of the network its appropriate length, slope, diameter, fitting and the discharge of the corresponding node (Fig. 16).

Should be mentioned that the enumeration of the laterals and those of the sprinklers starts always from the upstream to downstream end of the network.

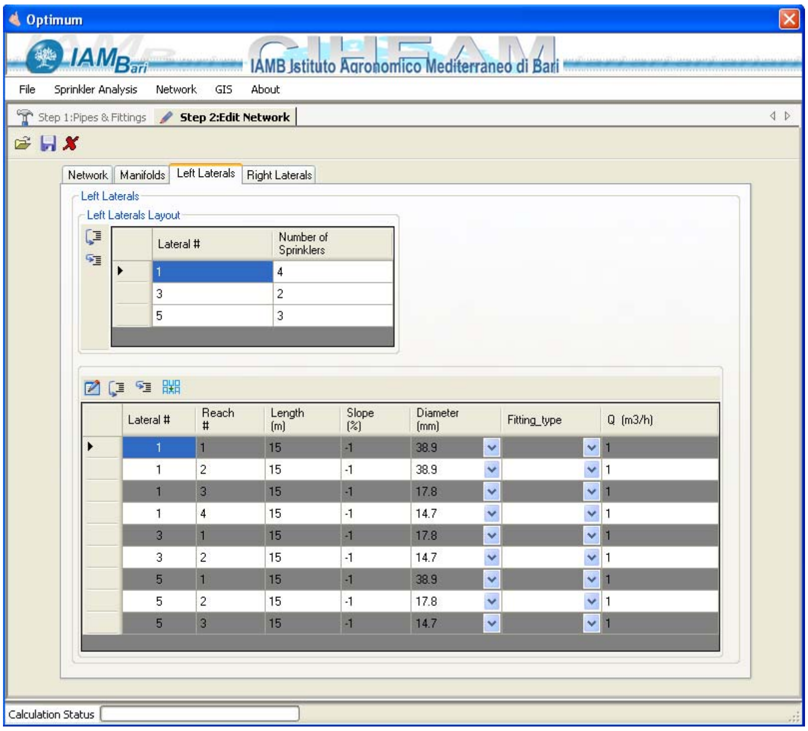


Figure 16: An example of data entry for the left laterals pipe reaches units

4. ***Right laterals*** Tab: This tab is enabled for editing only when or layout button is selected. Data entering is similar to the one previously described for the left laterals tab.

To save the network characteristic file, click on the ***Save network*** button located at the top left of the *Edit Network* page. The network file have a ".opt" extension. It should be mentioned that not only the network layout and hydraulic characteristic is saved but also the list of pipes and fittings too. ***Load network*** and ***New*** buttons are used to open an existing network file ".opt" and to create a new one respectively.

2.c- Network Analysis and Network Design

After accomplishing all the necessary input data, select from the main form ***Network <<Run <<Network Analysis*** to launch the network analysis or ***Network <<Run <<Network Design*** to optimize the pipe size diameters of the network (Fig.17) .

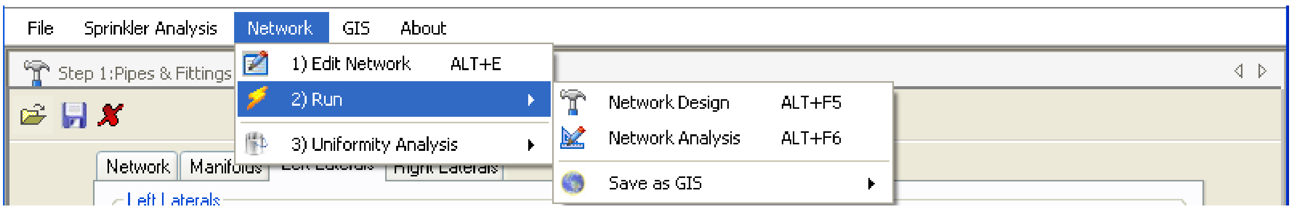
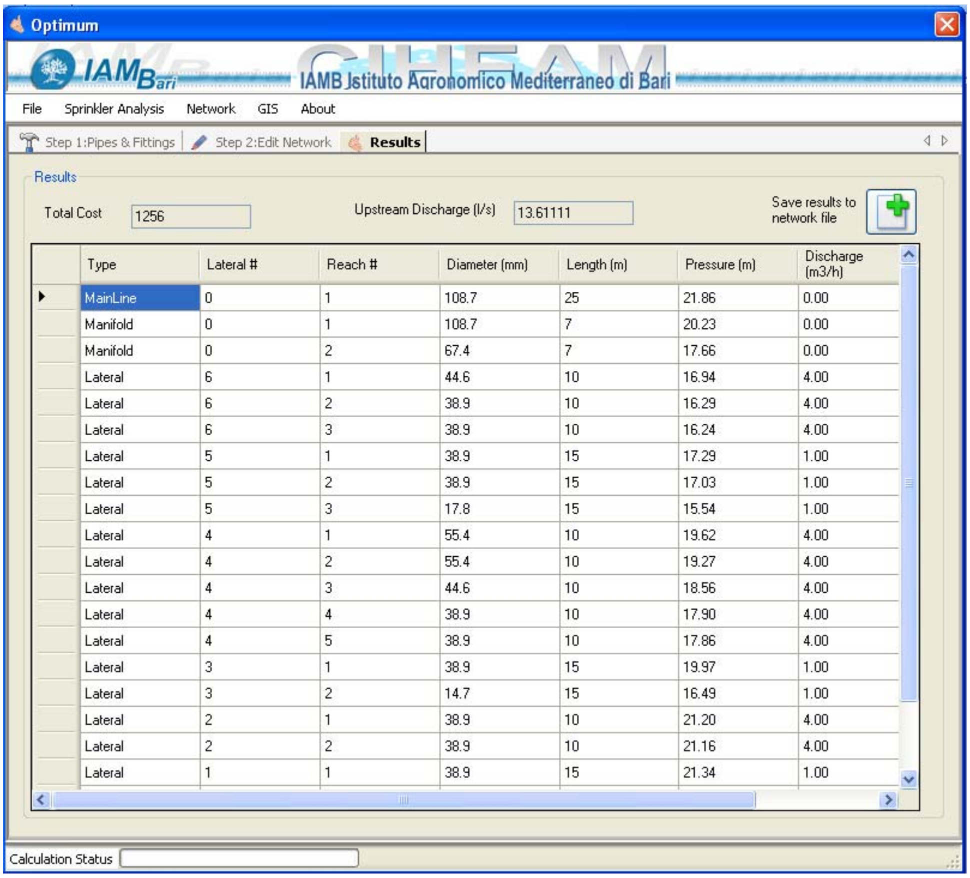


Figure 17: Menu of network analysis and network design in Optimum software

At the end of the designing or the analysis of the network, the results will be illustrated in a new form named Results. Pipes size diameter and sprinklers pressure are the major output of the network design while sprinklers pressure is the only output in the case of network analysis (Fig.18).



Type	Lateral #	Reach #	Diameter (mm)	Length (m)	Pressure (m)	Discharge (m3/h)
MainLine	0	1	108.7	25	21.86	0.00
Manifold	0	1	108.7	7	20.23	0.00
Manifold	0	2	67.4	7	17.66	0.00
Lateral	6	1	44.6	10	16.94	4.00
Lateral	6	2	38.9	10	16.29	4.00
Lateral	6	3	38.9	10	16.24	4.00
Lateral	5	1	38.9	15	17.29	1.00
Lateral	5	2	38.9	15	17.03	1.00
Lateral	5	3	17.8	15	15.54	1.00
Lateral	4	1	55.4	10	19.62	4.00
Lateral	4	2	55.4	10	19.27	4.00
Lateral	4	3	44.6	10	18.56	4.00
Lateral	4	4	38.9	10	17.90	4.00
Lateral	4	5	38.9	10	17.86	4.00
Lateral	3	1	38.9	15	19.97	1.00
Lateral	3	2	14.7	15	16.49	1.00
Lateral	2	1	38.9	10	21.20	4.00
Lateral	2	2	38.9	10	21.16	4.00
Lateral	1	1	38.9	15	21.34	1.00

Figure 18: An output example of the network analysis or network design procedures

If you want to save the new obtained diameters from the optimization model into the Edit Network Page, click on the ***Save results to network file*** button located on the top right of the *Results* page. This button will apply the changes on the *Edit Network* page in order to be saved later on as ".opt" file using the ***Save network*** button of the ***Edit Network*** page .

At the end of the analysis or designing procedure, optimum software is able to save the sprinklers or the network pipes results as shape files by selecting ***Network<<Run << Save as GIS << Sprinklers*** or ***Network<<Run << Save as GIS << Network*** respectively. These files could be visualized by the built in GIS presented in this program or by any other external GIS software.

Before passing to the next step (Uniformity Analysis), it is possible to calibrate the sprinklers pressure by simply modifying the pressure values in the table of the results page. These modifications will be saved and the calibrated sprinklers pressure will be used in water profile simulation.

3-Uniformity Analysis

Once the network is designed or analyzed as previously described, you can study the water application uniformity of the sprinkler network by selecting ***Network << Uniformity Analysis*** .It consists of two steps to be followed respectively:

- ***Step 1:Load Sprinkler/Climatic data***: this step will add two pages on your form, the first one to describe your sprinkler characteristics (Fig.3) and the second one to insert the climatic parameters necessary for the wind effect simulation.

- ***Step 2:Run***: It will launch the simulation of the sprinklers water distribution patterns based on their pressure registered in the ***Results*** page and on the sprinkler characteristics and climatic parameters assigned in step 1.
  At the end of the calculation process, a uniformity page will be added and will illustrate all the uniformity parameters in terms of application efficiency, minimum net depth of applied water , Coefficient of Uniformity and Distribution Uniformity (Figure 9).

- ***Step3***: ***Save as GIS:*** The spatial water distribution could be saved as raster file ".asc" or as a shapefile ".shp" by selecting ***Network << Uniformity Analysis << Save as GIS << Raster file*** or by selecting ***Network << Uniformity Analysis << Save as GIS << shape file*** respectively.

4- Using GIS

As previously mentioned, Optimum software have the ability to save the results as ASCI raster files ".asc" and/or as shape files ".shp". To access on the internal GIS of Optimum software select the ***GIS*** from the main menu. A new GIS page will appear with a tool box showing the following items (Fig19):

- *Add layer* button : allows you to add a shape file ".shp" or a raster file ".asc".
- *Remove layer* button : allows you to remove a selected layer from the GIS page.
- *Identifier* button: allows you to identify the value of the selected layer by clicking on the on the map. The values will be shown in the text box located at the bottom left of the window form.
- *Zoom in* , *Zoom out* and *Zoom to extent* and *Pan* buttons could be used to change the visualization of the maps.

To change the symbology of the loaded layers, select first the appropriate layer. Then right click on the map legend and choose the ***Shape Palette*** or the ***Grid Palette*** according to the type of the selected layer (Fig.19).

- o For a raster file ".asc", choose the grid palette and in the ***layer name*** drop down list select the name of your layer. Change your break number, the minimum and maximum values of the legend as well as the color and click ***Ok*** to apply changes and close the window or ***Apply*** for a preview without closing the grid palette window.

- For a shape file .shp, choose the shapefile palette and in the ***layer name*** drop down select the name of your shape layer. Select the field to be classified and the type of legend to be used and the color from the appropriate drop down lists. Click ***Ok*** to apply changes.

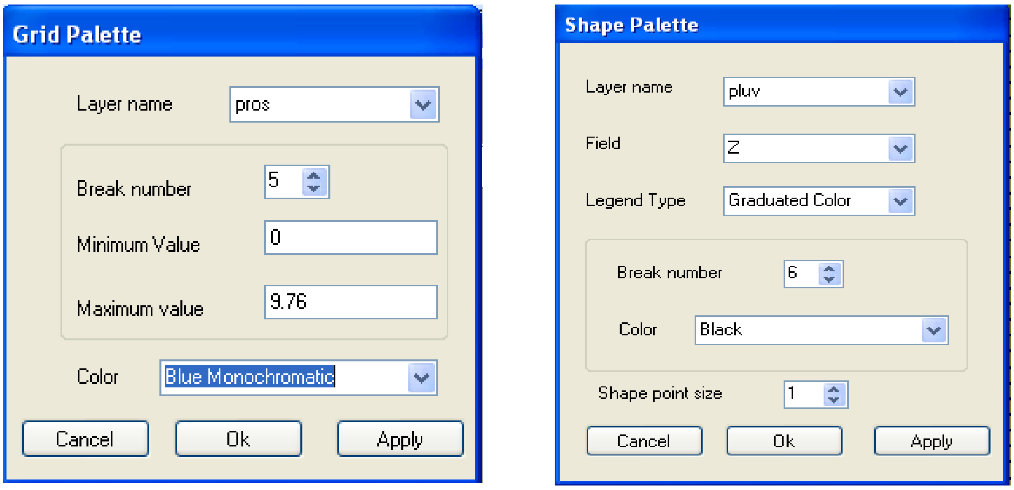


Figure 19: Symbology palettes of a Grid and shape file as presented in Optimum Software

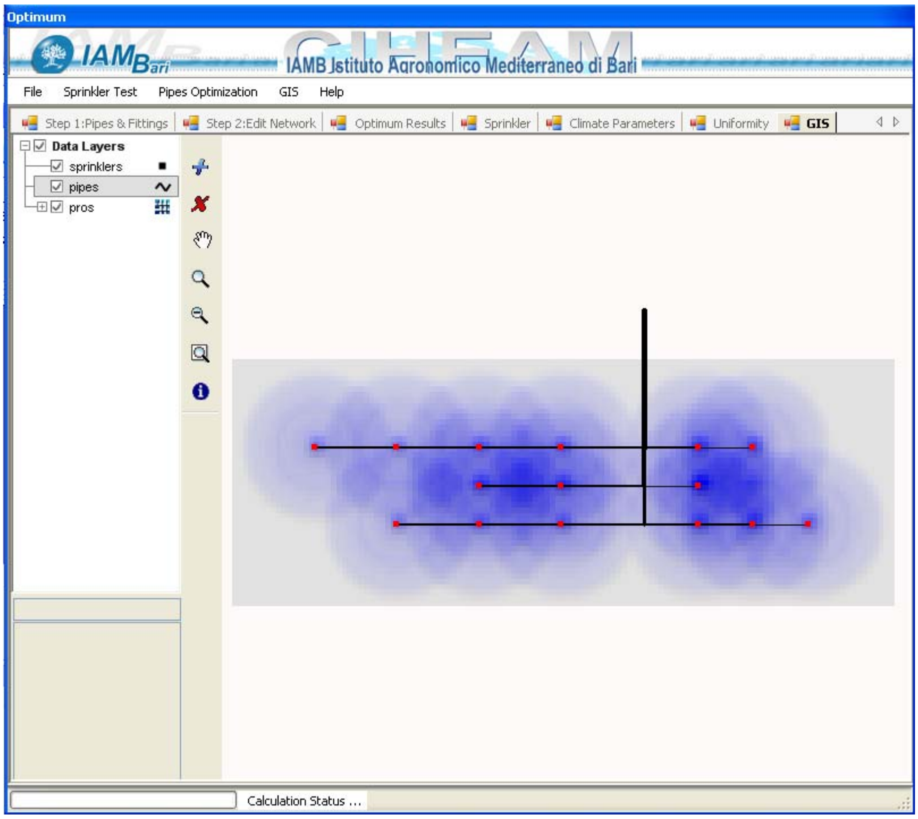


Figure 20: An example of optimum software results as presented in the GIS page

III-Model Description

1- Head loss Calculation

Based on Darcy-Weisbach equation, head losses h_f *(m)* have the following form:

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = f\frac{L}{D}\frac{Q^2}{2gA^2} \tag{2}$$

Where:
V: Flow velocity *(m.s^{-1})*
D: pipe diameter *(m)*
g: gravity acceleration *(m.s^{-2})*
L: pipe length *(m)*
Q: volumetric discharge *(m^3.s^{-1})*
A: cross sectional area of the pipe *(m^2)*
f : Friction factor depends on Reynolds number *(Re)* and on the relative roughness *(e/D)*. It is calculated according to table 1.

Table 1: *Darcy-Weisbach friction equations for different type of flow*

Type of Flow	Equation for *f*	Range
Laminar	$f = \frac{64}{\mathrm{Re}}$	Re < 2100
Smooth pipe	$1/\sqrt{f} = 2\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 0.8$	Re > 4000 $e/D \to 0$
Transitional Colebrook-White Equations	$1/\sqrt{f} = 1.14 - 2\log_{10}\left(\frac{e}{D} + \frac{9.35}{\mathrm{Re}\sqrt{f}}\right)$	Re > 4000
Wholly Rough	$1/\sqrt{f} = 1.14 - 2\log_{10}\left(\frac{e}{D}\right)$	Re > 4000

Head loss (h_f) within Optimum model is presented as an exponential formula that is function of the pipe flowing discharge (Q):

$$h_f = K\,Q^n \tag{3}$$

To find K and n for the Darcy-Weisbach equation, the friction factor f is approximated over a limited range on the Moody diagram by an equation of the form:

$$f = \frac{a}{Q^b} \tag{4}$$

This equation plots a straight line on Moody diagram (a log-log plot) if a and b are constant. By substituting it into the Darcy-Weisbach equation we obtain:

$$K = \frac{aL}{2gDA^2} \tag{5}$$

With

$$n = 2 - b \tag{6}$$

If the chosen range is too large, then *K* and *n* will cause frictional head losses that differ slightly from predictions that are obtained directly from the Darcy-Weisbach and Colebrook-White equations. If the chosen range is too small, then the actual discharge may fall outside this range, and *K* and n should be re-determined.
To obtain *a* and *b*, an appropriate Reynolds number (discharge, or velocity) range are selected in a way that brackets the expected discharge *Q*. Colebrook-White equation for these two Reynolds number Re_1 and Re_2, are solved and consequently both f_1 and f_2 and the corresponding discharge Q_1 and Q_2 are obtained and presented in the logarithmic form as following:

$$ln\, f_1 = ln\, a - b\, ln\, Q_1 \tag{7}$$

$$ln\, f_2 = ln\, a - b\, ln\, Q_2 \tag{8}$$

Subtracting the second equation from the first and solving for *b* produces

$$b = \frac{ln\left(f_1 / f_2 \right)}{ln\left(Q_2 / Q_1 \right)} \tag{9}$$

The *a* can be obtained as

$$a = f_1 Q_1^{\,b} \tag{10}$$

2- Local Head losses

Local head loss is any energy loss, beside that of the pipe friction, caused by some localized disruption of the flow or by some flow appurtenances such as valves, bends and other fittings. If a loss is sufficiently small in comparison with other energy losses and with pipe friction, it may be regarded as minor loss. However, some local losses can be so large and significant that they could not considered as minor loss and consequently they must be retained (i.e. partly open valve).
Local head losses are usually computed from the following equation:

$$hL = K_L \frac{V^2}{2g} = K_L \frac{Q^2}{2gA} \tag{11}$$

Where:
hL: Local head losses *(m)*
V: Upstream mean velocity *($m.s^{-1}$)*
Q: Discharge flowing in the pipe *($m^3.s^{-1}$)*
A: Cross sectional area of the pipe *(m^2)*
K_L *:* Loss coefficient depend on the nature of local resistance

3- Solving network equations

Optimum model solves the pipeline system based on the junctions continuity principle where in order to satisfy continuity, the volumetric discharge flowing into a junction must equal the volumetric discharge from the junction. Thus at each junction *j* the following equation is obtained:

$$QJ_j - \Sigma Q_i = 0 \tag{12}$$

Where:

QJ_j is the demand at the junction *j*

Q_i is the discharge in one of the pipes that join at junction *j*

To develop the system of continuity equations, we begin by solving the exponential equation for the discharge obtained from *Eq.3* and having the following form

$$Q_{ij} = \left(\frac{h_{fij}}{K_{ij}}\right)^{\frac{1}{nij}} = \left[\frac{\left(H_i - H_j\right)}{K_{ij}}\right]^{\frac{1}{nij}} \tag{13}$$

Where :

Q_{ij} is the discharge flowing between two junctions *i* and *j*

h_{fij} head loss occurred between junction *i* and node *j*

K_{ij} and n_{ij} parameters depend mainly on the hydraulics characteristic of the pipe

H_i pressure head at junction *i*

H_j pressure head at junction *j*

In the second term of *Eq 13*, the frictional head loss has been replaced by the difference in hydraulic grade line values between the upstream and downstream junction. In addition, in this equation a double subscript notation has been introduced; the first subscript defines the upstream node of the pipe, and the second subscript defines the downstream node.

An alternative way to write the previous equation is:

$$Q_K = \left(\frac{h_{fK}}{K_K}\right)^{1/n_K} = \left[\frac{\left(H_i - H_j\right)}{K_K}\right]^{1/n_K} \tag{14}$$

In which *K* is the pipe number.

If the pipe is connected to a booster pump or a device creating local head loss then:

$$H_i - H_j = K_K Q_K^{nK} + \left(AQ^2 + BQ + C\right) - \left(K_L \frac{Q_K^2}{2gA^2}\right) \tag{15}$$

Substituting the previous equations by the junction continuity equations (Equ. 12) then:

$$QJ_j - \sum\left\{\left[\frac{\left(H_i - H_j\right)}{K_{ij}}\right]^{1/n_{ij}}\right\}_{in} + \sum\left\{\left[\frac{\left(H_j - H_i\right)}{K_{ij}}\right]^{1/n_{ij}}\right\}_{out} = 0 \tag{16}$$

In which the summations referred all the pipes that flow to and from junction *j*, respectively.

Once the continuity equations of all the junction of the system are defined, Newton method described hereafter (Larock B et al., 2000) is used to solve these non-linear equations.

The Newton iterative formula for solving a system of equations can be written as:

$$\{x\}^{m+1} = \{x\}^m - [D]^{-1}\{F\}^m \tag{17}$$

Where:

$\{x\}$ is an entire column vector of unknowns (hydrants pressure head)

$\{F\}$ is an entire column vector of hydraulic equations

$[D]^{-1}$ is the inverse of a matrix $[D]$ which is the Jacobian.

The Jacobian occurs in several applications in mathematics, and it represents the following matrix of derivatives:

$$[D] = \begin{bmatrix} \frac{\delta F_1}{\delta x_1} & \frac{\delta F_1}{\delta x_2} & . & . & \frac{\delta F_1}{\delta x_n} \\ \frac{\delta F_2}{\delta x_1} & \frac{\delta F_2}{\delta x_2} & . & . & \frac{\delta F_2}{\delta x_n} \\ . & . & . & . & . \\ . & . & . & . & . \\ \frac{\delta F_n}{\delta x_1} & \frac{\delta F_n}{\delta x_2} & . & . & \frac{\delta F_n}{\delta x_n} \end{bmatrix} \tag{18}$$

Likewise $\{x\}$ and $\{F\}$ are actually

$$\{x\} = \begin{Bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{Bmatrix} \qquad \{F\} = \begin{Bmatrix} F_1 \\ F_2 \\ . \\ . \\ F_n \end{Bmatrix} \tag{19}$$

Eq. 17 indicates that the Newton method solves a system of non linear equations by iteratively solving a system of linear equations because $[D]^{-1}\{F\}$ represents the solution of the linear system of equations

$$[D]\{z\} = \{F\} \tag{20}$$

That is, the vector that is subtracted from the current estimate of the unknown vector $\{x\}$in Eq.17 is the solution $\{z\}$to the linear system of equations that is Eq. 2.36. In practice we therefore see that the Newton method solves a system of equations by the iterative formula

$$\{x\}^{m+1} = \{x\}^m - \{z\} \tag{21}$$

Where $\{z\}$is the solution vector that is obtained by solving $[D]\{z\} = \{F\}$. If the system should actually contain only linear equations, then the first iteration will produce the exact solution.

The development of eq.17, eq.20 and eq.21 follows. We begin by using a multi-dimensional Taylor series expansion to evaluate the individual equations F_i in the neighborhood of an initial solution estimate that we call $\{x\}$ which is presumed to be close the actual solution:

$$
\begin{aligned}
F_1^{(m+1)} &= F_1^{(m)} + \frac{\delta F_1}{\delta x_1}\Delta x_1 + \frac{\delta F_1}{\delta x_2}\Delta x_2 + \;\ldots\; + \frac{\delta F_1}{\delta x_n}\Delta x_n + 0(\Delta x^2) = 0 \\
F_2^{(m+1)} &= F_2^{(m)} + \frac{\delta F_2}{\delta x_1}\Delta x_1 + \frac{\delta F_2}{\delta x_2}\Delta x_2 + \;\ldots\; + \frac{\delta F_2}{\delta x_n}\Delta x_n + 0(\Delta x^2) = 0 \\
&\;\;\vdots \\
F_n^{(m+1)} &= F_n^{(m)} + \frac{\delta F_n}{\delta x_1}\Delta x_1 + \frac{\delta F_n}{\delta x_2}\Delta x_2 + \;\ldots\; + \frac{\delta F_n}{\delta x_n}\Delta x_n + 0(\Delta x^2) = 0
\end{aligned}
\tag{22}
$$

When we use matrix notation and make the substitution $\Delta x_i = x_i^{(m+1)} - x_i^{(m)}$, this system becomes

$$
\begin{Bmatrix} F_1 \\ F_2 \\ . \\ . \\ F_n \end{Bmatrix}^{(m)} + \begin{bmatrix} \frac{\delta F_1}{\delta x_1} & \frac{\delta F_1}{\delta x_2} & . \; . & \frac{\delta F_1}{\delta x_n} \\ \frac{\delta F_2}{\delta x_1} & \frac{\delta F_2}{\delta x_2} & . \; . & \frac{\delta F_2}{\delta x_n} \\ . & . & . \; . & . \\ . & . & . \; . & . \\ \frac{\delta F_n}{\delta x_1} & \frac{\delta F_n}{\delta x_2} & . \; . & \frac{\delta F_n}{\delta x_n} \end{bmatrix} \begin{Bmatrix} x_1^{(m+1)} - x_1^{(m)} \\ x_2^{(m+1)} - x_2^{(m)} \\ . \\ . \\ x_n^{(m+1)} - x_n^{(m)} \end{Bmatrix} = 0
\tag{23}
$$

Which can be written compactly as $\{F\}^{(m)} + [D]^{(m)}\left(\{x\}^{(m+1)} - \{x\}^{(m)}\right) = \{0\}$ and solved for $\{x\}^{(m+1)}$ to produce Eq.21. The iteration will continue until $\{x\}^{(m+1)} - \{x\}^{(m)}$ is less than the acceptable fixed error.

4- Pipe Size Optimization Model

Sizing a piping system has been and still a major task for many engineers, even if a large number of software for solving this problem exists. The cost of realizing the network is a function of the pipe diameters. Smaller are the pipes diameters lower is their price but higher is the head losses and pipe friction. Therefore the aim is to ensure the appropriate pressure head for the emitters (H_{min}) at the minimum pipe cost.

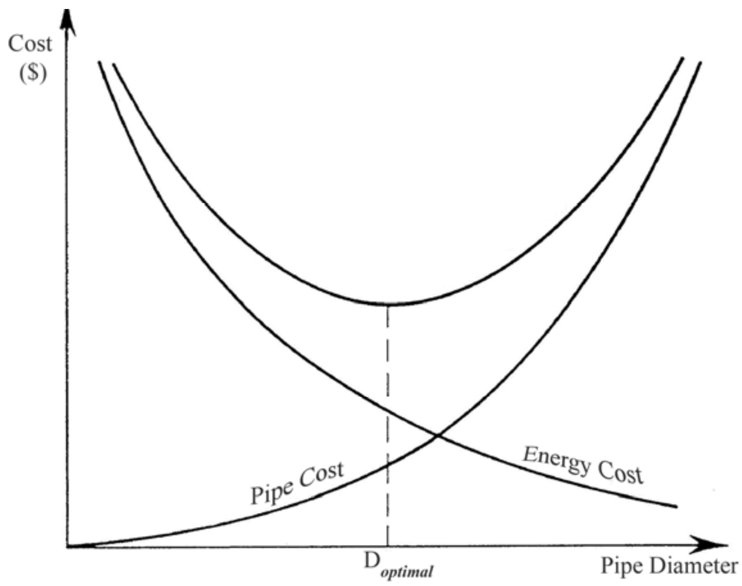


Figure 21: Effect of pipe diameter on energy and pipe cost variation

The mathematical model used in Optimum software aims to optimize the pipes diameters of a branched irrigation system. The optimization method used is called Labye's Iterative Discontinuous Method *(LIDM)* and performs in two steps:

- In the first step, an initial solution is constructed giving, for each section *(k)* of the network, the minimum commercial diameter (D_{min}) according to the maximum allowable flow velocity (V_{max}) in a pipe, when the pipe conveys the calculated discharge (Q_k). The diameter of the section *(K)* is calculated using the following equation:

$$\left(D_{min}\right)_K = \sqrt{\frac{4Q_k}{\pi \ V_{max}}} \tag{24}$$

  Once the initial set of diameters is known, it is possible to calculate the piezometric elevation $(Z_0)_{in}$ at the upstream end of the network that satisfies the minimum head $(H_{j,min})$ at the most unfavorable emitter (Sprinkler/Drip) *(j)* through the following relationship:

$$\left(Z_0\right)_{in} = H_{j,min} + ZT_j + \sum_{0\rightarrow M_j} Y_K \tag{25}$$

  where

  $\sum_{0\rightarrow M_j} Y_K$ are the head losses along the pathway (M_j) connecting the upstream end of the network to the most unfavorable emitter.

- In the second step, the optimal solution is obtained by iteratively decreasing the upstream piezometric elevation $(Z_0)_{in}$ until reaching the effectively available upstream piezometric elevation, Z_0, by selecting, for each iteration, the sections for which an increase in diameter produces the minimum increase of the network cost.

The selection process at each iteration is carried out as described below:
At any iteration (*i)*, the commercial pipe diameters D_{s+1} and D_s *are* known (with $D_{s+1} > D_s$). The coefficient (β_s) is calculated as following:

$$\beta_s = \frac{P_{s+1} - P_s}{J_s - J_{s+1}} \tag{26}$$

Where:

P_s : the cost per unit length of pipe diameter D_s *($. m^{-1})*
P_{s+1} : the cost per unit length of pipe diameter D_{s+1} *($. m^{-1})*
Js : the friction loss per unit length of pipe diameter D_s *(m m^{-1})*
J_{s+1} : the friction loss per unit length of pipe diameter D_{s+1} *(m m^{-1})*

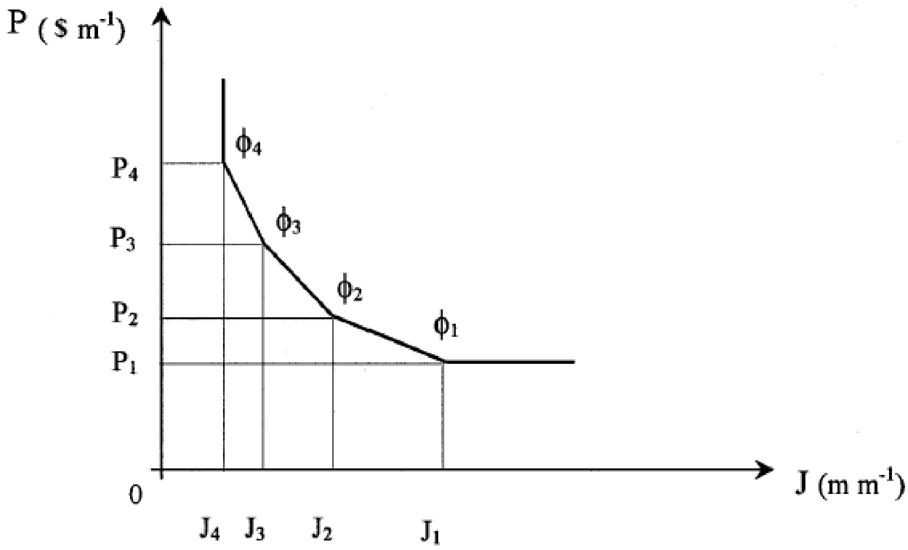


Figure 22 Sections' price-head losses characteristic curve

The minimum cost variation, *dP*, of the elementary scheme *(SN)** (Fig.23) of any sub-network, *(SN)*, and a section *k* in series with *(SN)*, for any given variation, *dH'*, of the head *H'(m)*, at the upstream end of *(SN)**, is obtained by solving the following "local" linear programming (Ait Kadi *et al*., 1990):

$$min\,.dP = -\beta_{s,SN}\,dH - \beta_{s,K}\,dY_K \tag{27}$$

subject to:

$$dH + dY_k = dH' \tag{28}$$

Where

dH the variation of the head at the upstream end of *(SN)* *(m)*

dY_k the variation of the friction loss in section *k* *(m)*

The optimal solution of the equations (27) and (28) is:

$$dH = dH' \quad and \quad dY_K = 0 \quad if \quad \beta_{s,SN} < \beta_{s,K} \tag{29}$$

$$dH = 0 \quad and \quad dY_K = dH' \quad if \quad \beta_{s,SN} > \beta_{s,K} \tag{30}$$

Therefore, the minimum cost variation, *dP*, of *(SN)** can be written as:

$$dP = -\beta^{*}\,dH' \tag{31}$$

with

$$\beta^{*} = min\,(\beta_{s,SN} < \beta_{s,K}) \tag{32}$$

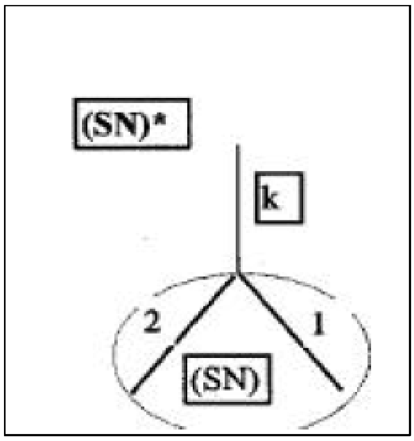


Figure 23:Characteristic curve of a section

Hence, proceeding from any terminal section of the pipe network, (β^{*}) can be used to determine the section that will vary at each iteration. Note that in this process, $\beta_{s,SN}$ of the assembly of two sections in derivation is equal to (Fig.23):

$$\beta_{s,SN} = \beta_{s,1} + \beta_{s,2} \tag{33}$$

whereas, for two sections in series it would be equal to:

$$\beta_{s,SN} = min\ (\beta_{s,1}\ ,\ \beta_{s,2}) \tag{34}$$

In the case of a terminal section with a head in excess at its downstream end $(H_j > H_{j,min})$, the value of $\beta_{s,SN}$ to be used in the process is equal to zero as long as the excess head prevails.
The magnitude of dH_i, for each iteration i, is determined as:

$$dH_i = min\ (EH_i,\ \Delta Y_i,\ \Delta Z_i) \tag{35}$$

where:

EH_i: is the minimum value of the excess head prevailing in all the nodes where the head will change;

ΔY_i: is the minimum value of $(Y_{k,i} - Y^*)$ for those sections which will change in diameters, with $Y_{k,i}$ being the value of the head loss in the section k at iteration i, and Y* is, for this section, the value of the head loss corresponding to the largest diameter over its entire length if the section has two diameters, or the next greater diameter if the section has only one diameter. Note that for those terminal sections with head in excess $(H_j > H_{j,min})$, ΔY_i is equal to the value of this excess $(H_j - H_{j,min})$.

ΔZ_i :is the difference between the upstream piezometric elevation, $(Z_0)_i$, at iteration i, and the piezometric elevation, Z_0, effectively available at the upstream end of the network.

The iterative process is continued until Z_0 is reached, obtaining the optimal solution.

5- Sprinkler Network Analysis

5.a- Simulation of pressure change

For a given working pressure *(P)*, Optimum model simulates from the measured water applied data (*Fig.6*) using the linear interpolating technique, the appropriate sprinkler water profile. Each catch can *(i)* presents a measured water amount $(Y_{i,H})$ obtained at a testing pressure *(H)*.

The linear interpolation technique applied on a set of catch can data *(i)* measured at different testing pressure $(H_1, H_2, \ldots H_n)$ is used to simulate the water applied value *(Y)* of that catch can at the given pressure *P* as following:

$$Y_{i,P} = Y_{i,H1} + (P - H_1)\left(\frac{Y_{i,H2} - Y_{i,H1}}{H_2 - H_1}\right) \qquad for \qquad Y_{i,H1} \leq Y_{i,H1} \tag{36}$$

$$Y_{i,P} = Y_{i,H2} + (H_2 - P)\left(\frac{Y_{i,H1} - Y_{i,H2}}{H_2 - H_1}\right) \qquad for \qquad Y_{i,H1} > Y_{i,H2} \tag{37}$$

With $H_1 \leq P \leq H_2$

The sprinkler water profile for the given working pressure *(P)* is obtained when the amounts of applied water on the entire catch cans are calculated.

5.b - Wind effect simulation

Following the work and the contribution of many researches (Fukui et al. (1980), Von Bernuth and Gilley 1984; Vories et al.,1987; von Bernuth 1988, Seginer et al.,1991; Han et al. 1994; Tarjuelo et al.1994 ;Carriòn et al.(2001) ;Montero et al.(2001)), ballistic theory on an isolated drops was used to simulate the wind effect on the sprinkler water distribution profile.

The process of jet break-up into drops is quite complex. At least two phases can be distinguished. In the first (no more than 1 or 2 m) the jet is quite compact, and in the second the jet has nearly completely disintegrated, with a corresponding transitional phase (Von Bernuth and Gilley 1984; Seginer et al., 1991). To simplifies this process, the following main hypotheses have been considered:

- The jet is disintegrated at the nozzle exit into individual droplets with different sizes, which move independently in the air and present drag coefficients that are a function of Reynolds number of a spherical drop (Seginer et al. 1991).
- The drag coefficient is independent of the sprinkler height over the soil surface, the discharge angle of the jet, the wind velocity, the nozzle diameter and other factors. Consequently different sized drops fall at different distances.

By applying ballistics theory on an isolated drop, the distance (r_i) at which each drop size (D_i) falls is calculated:

$$D_i = f\,(r_i) \tag{38}$$

From the water distribution radial curve, each drop size (D_i) represents a corresponding water volume and is function of the impact point of the drop on the ground after the flight in no-wind conditions (*Fig. 24*). This procedure is first carried out in no-wind conditions, and afterwards taking into account the wind action.

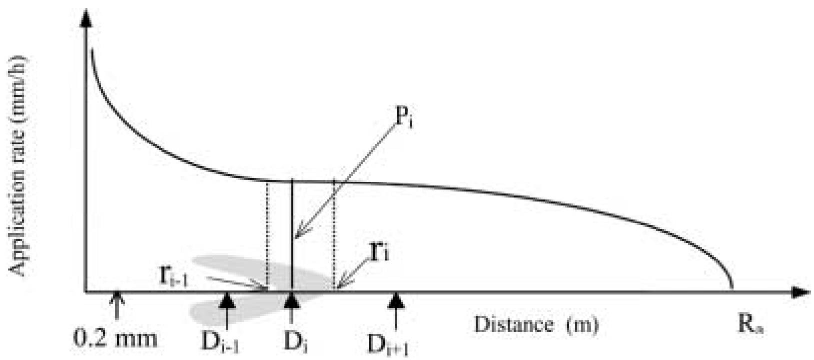


Figure 24:Scheme of the assignation of application rate to each drop diameter (Carriòn et al.(2001))

The water velocity at the nozzle end can be calculated using Torricelli equation:

$$U_0 = c\sqrt{2gH} \tag{39}$$

Where:

U_0 : initial velocity of the drop with respect to the ground at the exit of the nozzle (m.s^{-1})

c : discharge coefficient

g : Gravity acceleration (m.s^{-2});

H : pressure in the nozzle (m)

The drop in the air is subjected to gravity force, in the vertical direction and to a resistance force, which opposes the relative movement of the drop in the air (Vories et al. 1987; Seginer et al. 1991). In absence of wind, the trajectory of a drop moves in the vertical direction, but in general, the trajectories have three dimensions. In no-wind conditions, the drop velocity with respect to the ground *(U)* is equal to the drop velocity with respect to the air *(V)*. When wind acts (Fig. 25) the drop velocity is described by the following equation (Seginer et al. 1991):

$$\vec{U} = \vec{V} + \vec{W} \tag{40}$$

Where

W is wind velocity (relative to the ground), supposing that it acts in a horizontal plane. So, the velocity *(V)* and the resistance force *(F_R)* are not tangential to the segment of the water jet.

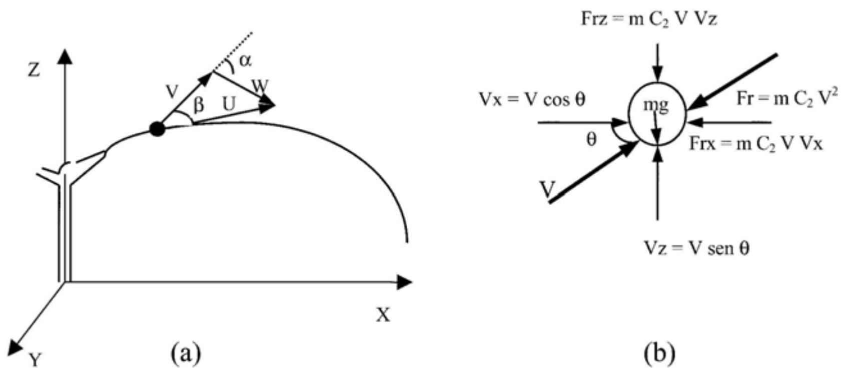


Figure 25: A two-dimensional scheme for a water drop moving into the air and the forces that act upon it. (Carriòn et.al 2001)

The drag force *(F_R)* for an isolated drop is calculated as (Seginer et al. 1991):

$$F_R = \frac{1}{8}\rho_a C \pi D^2 V^2 = mC_2 V^2 \tag{41}$$

Where:

m : mass of the drop,

V : velocity of the drop in the air,

ρ_a : density of the air,

D : nominal diameter of the drop

C : drag coefficient, defined for an isolated drop as a function of the Reynolds' number *(Re)* (Fukui et al. 1980; Seginer et al. 1991) as:

$$Re \le 128 \quad \rightarrow \quad \mathrm{C} = \frac{33.3}{\mathrm{Re}} - 0.0033\mathrm{Re} + 1.2 \tag{42}$$

$$128 \le Re \le 1440 \quad \rightarrow \quad \mathrm{C} = \frac{72.2}{\mathrm{Re}} - 0.0000556\mathrm{Re} + 0.48 \tag{43}$$

$$1440 \le Re \quad \rightarrow \quad C = 0.45 \tag{44}$$

Where

$$Re = V\frac{D}{\gamma} \tag{45}$$

γ : Kinematic viscosity of the air

The relationship existing between *C* and *C2* is (Carriòn e.al 2001):

$$C_2 = \frac{3\rho_a C}{4\rho_b D} \tag{46}$$

Finally, the equations that define drop movement are obtained from their dynamic balance:

$$\Sigma F = m\frac{dU}{dt} \tag{47}$$

$$A_x = \frac{d^2x}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dx}{dt} - W_x\right) = -C_2V\left(U_x - W_x\right) \tag{48}$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dy}{dt} - W_y\right) = -C_2V\left(U_y - W_y\right) \tag{49}$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dz}{dt} - g\right) = -C_2VU_z - g \tag{50}$$

where:

x, y, z are coordinates referring to the ground (with origin in the nozzle of the sprinkler), *dx/dt, dy/dt, dz/dt* are components of drop velocity *(U)*,

t: time

A: acceleration of the drop in the air.

The water distribution pattern for a single sprinkler obtained with this procedure is nearly circular, not reproducing well the real distortion caused by wind. Since droplets interfere with each other in the air, it is necessary to introduce the correction coefficient (*C'*) to better adjust the simulation to reality (Seginer et al. 1991; Tarjuelo et al. 1994; Li and Kawano 1995). This distortion consists basically of a narrowing in the direction perpendicular to the wind as well as a windward shortening and an even greater leeward lengthening (von Bernuth and Seginer 1990). To achieve this deformation, Tarjuelo et al. (1994), following Seginer et al. (1991),
suggested a correction for the *C* air drag coefficient, as a function of correction coefficient K_1 and K_2, in the following way:

$$C' = C(1 + k_1.\sin\beta - K_2.\cos\alpha) \tag{51}$$

Where:

α : Angle formed by vectors *V* and *W*

β : Angle formed by vectors *V* and *U*

$(k_1.\sin\beta)$ shortens the pattern in the direction perpendicular to the wind, but less so in the same direction as the wind. With $(K_2.\cos\alpha)$ a windward shortening and a greater leeward lengthening are produced, without effect on the perpendicular direction of the wind. These correction coefficients are fundamental to achieve a good fit between the simulated models and the field measurements.

Simulation of the evaporation and drift losses implemented in this model is the one used by Carriòn (Carriòn et al. 2001) and described hereafter:

- Based on statistical analysis of field tests and weather conditions, evaporation and wind drift losses were quantified and the following results have been obtained (Montero 1999; Ortega et al. 2000):

$$P_{er} = 7.63(e_s - e_a)^{0.5} + 1.62W \text{ (Tests in block irrigation)} \qquad (52)$$

  where:
  P_{er} : evaporation and drift losses *(%)*
  W : wind speed *($m.s^{-1}$)*
  $(e_s - e_a)$: Vapor pressure deficit of the air *(k_{Pa})*

$$e_s = 0.6108e^{\left(\frac{17.27T}{T+237.3}\right)} \qquad (53)$$

$$RH = 100\left(\frac{e}{e_s}\right) \qquad (54)$$

  e_s : Saturation Vapor Pressure
  RH : Relative Humidity *(%)*
  T : Air Temperature *(°C)*

- Correct the water distribution radial curve, by subtracting the estimated evaporation and drift losses. Edling (1985), Kohl et al. (1987), and Kincaid and Longley (1989) deduce that the evaporation of the drops in sprinkler irrigation is negligible for drop diameter greater than *1.5 - 2 mm*.

  To determine the relationship between the evaporation losses and drop diameter, data from Edling (1985) and Kincaid and Longley (1989) have been used. In this way, the following equation that links the drop diameter with the evaporation percentage loss is used:

$$E_i = 1.8271D_i^{-1.5379} \qquad (55)$$

  Where E_i is the percentage loss assigned to the drop diameter D_i *(mm)*, valid for drops larger than 0.2 mm, due to the fact that in the simulation smaller drop diameters are not considered.

- Once the evaporation and drift losses are quantified, the equation that relates the total losses with the distributed ones must be fulfilled (Carriòn e.al 2001):

$$\frac{(E + D_r)}{100}Q'_s = K\sum_{i=0.2}^{2} E_i Q_i = K\sum_{i=0.2}^{2}\left(1.8271D_i^{-1.5379}\right)Q_i \qquad (56)$$

Where:
Q'_s : Discharge of the sprinkler *($l.h^{-1}$)*
Qi : Discharge of the sprinkler with the drop diameter Di *($l.h^{-1}$)*
Pi : Application rate *($mm.h^{-1}$)*
E : Percentage of the discharge flow lost by evaporation *(%)*
Ri : Higher radius assigned to drop diameter Di *(m)*
Dr : Percentage of the discharged flow lost by drift *(%)*
K : Constant to multiply the losses distribution law for the equation to be fulfilled

- Once K is known, the new corrected distributed flows *(Q_{ci})* is calculated as:

$$Q_{ci} = Q_i\left(K(1.8271)D_i^{-1.5379}\right) \tag{57}$$

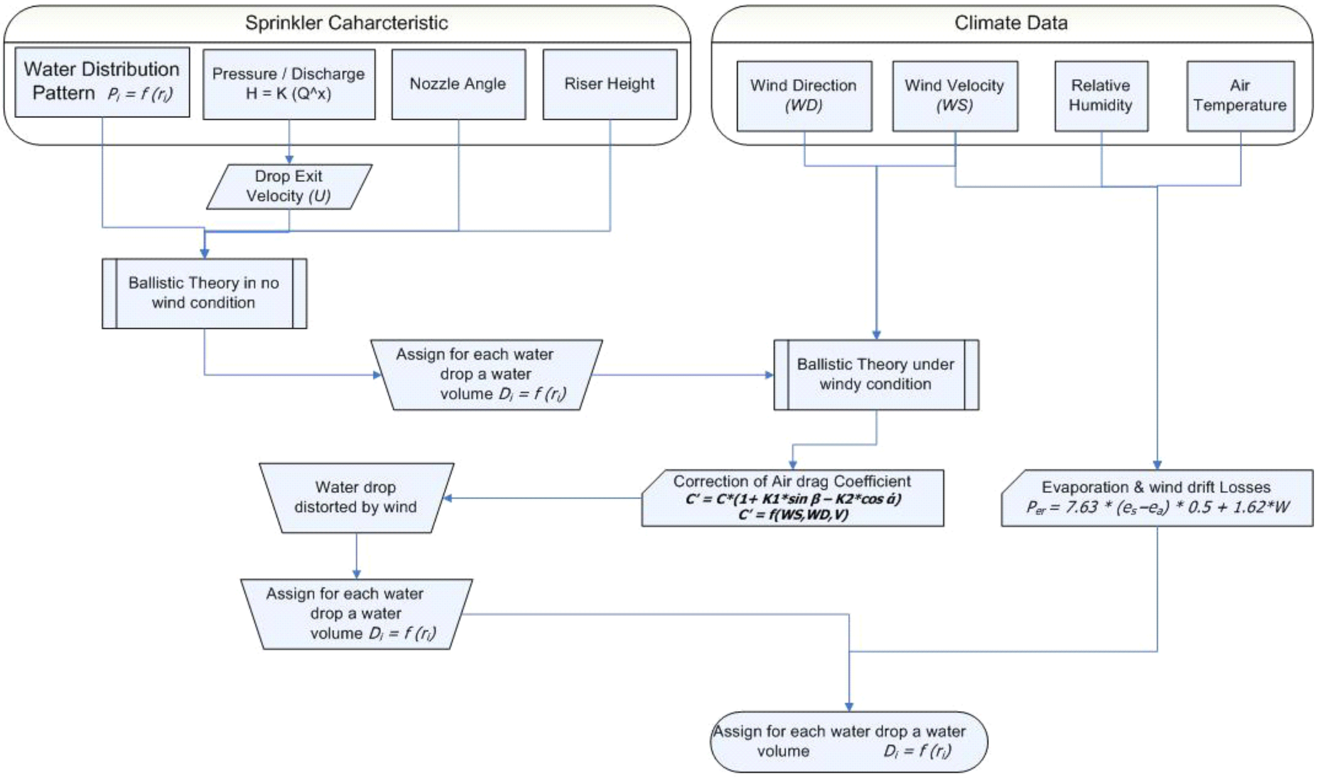


Figure 26: Flow chart of the ballistic theory for wind simulation

5.c- Uniformity Indicators

The sprinklers water profiles calculated using sprinklers pressure head, wind speed and direction, are overlapped according to the network layout. This operation is necessary to perform the statistical analysis on the wetted area in order to evaluate the irrigation performance.
Uniformity of water application in sprinkler irrigation systems is usually reported as either Distribution Uniformity (DU) or Christiansen's Coefficient of Uniformity (CU):

- The distribution uniformity (DU) indicates the uniformity of application throughout the field and is computed by (Heermann et al.,1990):

$$DU = 100 * \frac{Z_{lq}}{Z_{av}} \tag{58}$$

Where:

Z_{lq} average of the lowest one-quarter of the measured values, *mm*
Z_{av} average infiltrated depth in the entire field, *mm*

- The Coefficient of Uniformity (CU), developed by Christiansen (1942):

$$CU = 100 * \left(1 - \frac{\sum |Z - m|}{\sum Z} \right) \tag{59}$$

Where:

Z	: individual depth of catch observations from uniformity test, *mm*
$\lvert Z\text{-}m \rvert$	: absolute deviation of the individual observations from the mean, *mm*
m	: mean depth of observations, *mm*

Distribution Uniformity *(DU)* is based on the low quarter of irrigated area and it does not tell you how uniform is the water distribution but how big or severe the dry spot is. While Coefficient of Uniformity *(CU)* is an indicator of how equal (or unequal) the application rates are throughout the field. A low coefficient of uniformity indicates that the application rates are very different, while a high value indicates that the water is distributed evenly to all plants.

The water distribution efficiency *(DE)* described by Keller and Bleisner (Keller and Bleisner, 2000) is used to give more useful meaning to the concept of *CU*. It is expressed as:

$$DE_{pa} = \frac{Minimum\ \ net\ \ depth\ \ received\ \ by\ \ wettest\ \ pa\%\ \ of\ area}{Average\ \ net\ \ depth\ \ received\ \ over\ \ entire\ \ area} \tag{60}$$

Where:

pa percentage of adequately irrigated area, *%*

DE_{pa} distribution efficiency for the desired percentage adequacy, *%*

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