Chapter 5

Analysis of performance

ANALYSIS OF PRESSURIZED IRRIGATION SYSTEMS OPERATING ON-DEMAND

Introduction

Irrigation systems analysis is the process of using a computer simulation model to analyse performance capabilities and to define the system requirements necessary to meet system design standards for pressure and/or discharge (AWWA, 1989). The most important advantage of computer modelling is that it makes the network analysis feasible. In fact, without computerized techniques, analysis is impractical except for simple systems. Based on a computer model, network analysis is used to determine the adequacy of the existing irrigation systems, to identify the causes of their deficiencies and to develop the most cost-effective improvements.

Network analysis is often used also for improving design techniques. In fact, before the advent of computer system analysis, over-design was the common reaction to account for uncertainties in the design stage. Actually, models for analysis and performance criteria may contribute to support design of new irrigation systems that should be able to operate satisfactorily within a wide range of possible demand scenarios.

In this chapter, two models for the analysis of irrigation systems operating on-demand are illustrated and a discussion on the power and weakness of those models is presented. In particular, the first model provides information on the global performance of the irrigation system, while the second model gives more precise information that allows for determination of the percentage of unsatisfied hydrants, their position and the magnitude of their pressure deficit. Furthermore, mathematical definitions of some performance indicators (i.e. reliability and relative pressure deficit) are formulated to help both the designer and manager in selecting a satisfactory solution.

Indexed characteristic curves

The indexed characteristic curves model (CTGREF, 1979; Bethery *et al.*,1981; Labye *et al.*, 1983) provides information on the global performance of an on-demand irrigation system. This information may be used for a variety of applications, as described below.

Description of the model

Under the hypothesis that any operating hydrant may deliver the nominal discharge, d [l s^{-1}], even when the pressure head changes (see Figure 46) (usually this is true when the hydrants incorporate a proper flow limiter), let us redefine "configuration" (r) as a group of operating hydrants (j) corresponding to a fixed value of the nominal discharge, Q [l s^{-1}], at the upstream end of the network.

FIGURE 46
Characteristic curve of a hydrant
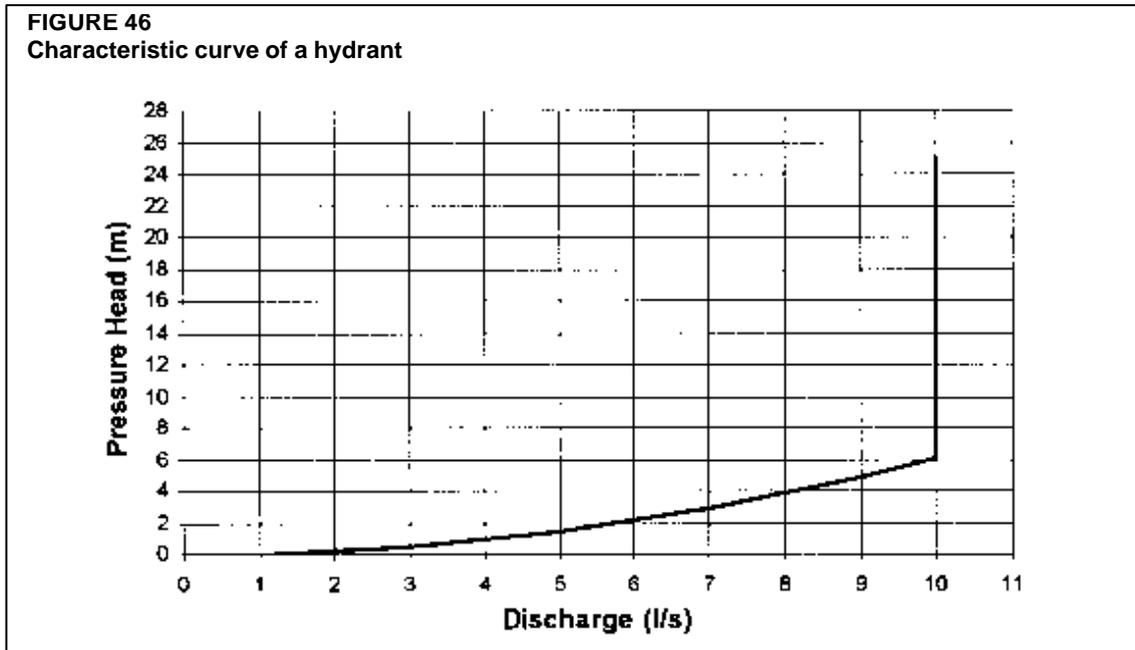
A configuration is satisfied when, for all the operating hydrants of the configuration, the following relationship is respected:

$$(H_j)_r \geq H_{min} \qquad\qquad (47)$$

where $(H_j)_r$ [m] represents the hydraulic head of the hydrant j within the configuration r, and H_{min} [m] represents the minimum required head for appropriate operation of the on-farm system.

For each configuration, the satisfaction of the condition (47) depends on the plano-altimetric location of the operating hydrants. In general, the network is able to satisfy only a percentage of the possible configurations. For any value of the discharge Q flowing in the upstream section of the network, within zero and Q_{max} (discharge corresponding to the total number of hydrants in operation), different values of the piezometric elevation, Z_r [m a.s.l.], satisfy the relationship (47), each one corresponding to a different hydrant configuration. Therefore, if for all the possible configurations r, the couples (Q_r, Z_r) referred to discharges ranging between 0 and Q_{max} are calculated, a cloud of points (Figure 47) is observed within an envelope in a plane (Q, Z). Each point $P_u(Q_r, Z_r)$ of the upper envelope curve gives a piezometric elevation Z_r, at the upstream end of the network, which fully satisfies condition (47) for every discharge Q_r. Each point $P_l(Q_r, Z_r)$ of the lower envelope curve gives a piezometric elevation Z_r for which it is not possible to satisfy the condition (47). In other words, the upper envelope corresponds to 100% of satisfied configurations (relationship 47), while the lower envelope concerns a situation where any configuration is not satisfied (CTGREF, 1979; Bethery *et al.*,1981; CEMAGREF, 1983; Bethery, 1990).

It is then possible to obtain other curves, between these two envelopes (i.e. indexed characteristic curves) that represent a percentage of satisfied configurations.

The complete investigation of all the possible configurations leads to a large number of cases, equal to

FIGURE 47
Representative points of the hydraulic performance of a network
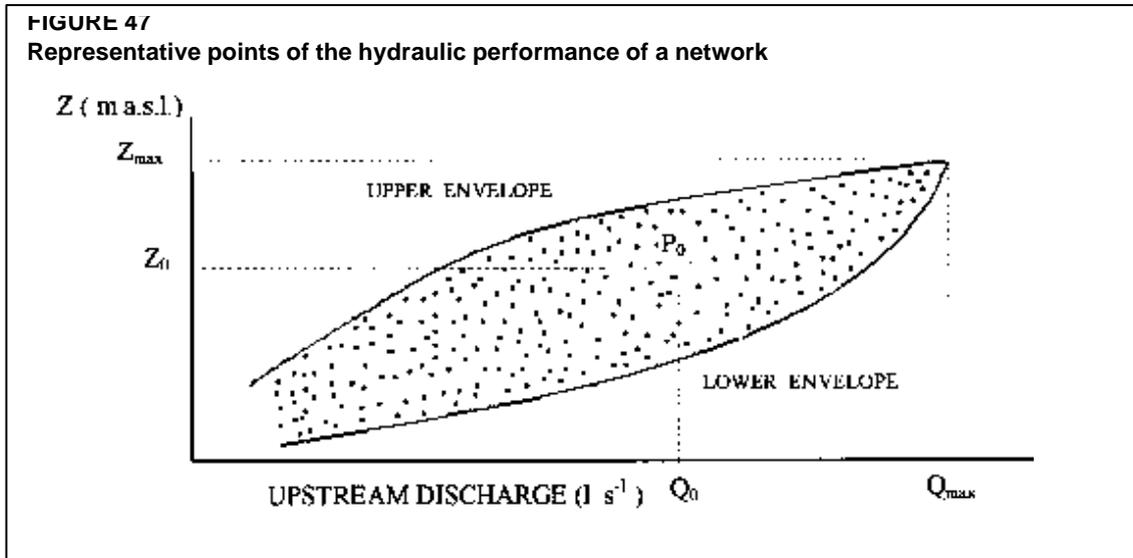
$$C_R^K = \frac{R!}{K!(R-K)!} \qquad (48)$$

where C_R^K represents the number of possible configurations when the discharge Q_r is delivered, corresponding to K hydrants simultaneously operating, and R is the total number of hydrants in the network. Therefore, in order to calculate the indexed characteristic curves, an equivalent model is used that reduces the number of cases investigated.

One can establish a given discrete number of discharges where each of them corresponding to a number, K, of simultaneously open hydrants:

$$K = Q_r/d \qquad (49)$$

This assumes that all the hydrants have the same nominal discharge, d [1].

The number C of configurations to be investigated for each discharge should be close to the total number of hydrants (R) according to the results obtained by Bethery (1990). Therefore, once C is known, a generator of random numbers, having uniform probability distribution, is used. Thus, the K hydrants for each configuration are drawn in the range between 1 and R.

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[1] In the case of different hydrant discharges, the number of hydrants simultaneously opened will vary as a function of the classes of hydrants drawn. In this case, random drawing will be performed to satisfy the relationship:

$$|Q_{tir} - Q_i| < \varepsilon_\tau$$

where Q_{ir} [l s^{-1}] is the discharge corresponding to K hydrants drawn at random, and ε_τ is the accepted tolerance. In general, ε_τ is assumed as equal to the value of the lowest hydrant discharge (Bethery *et al.*, 1981).

FIGURE 48
Characteristic curves program
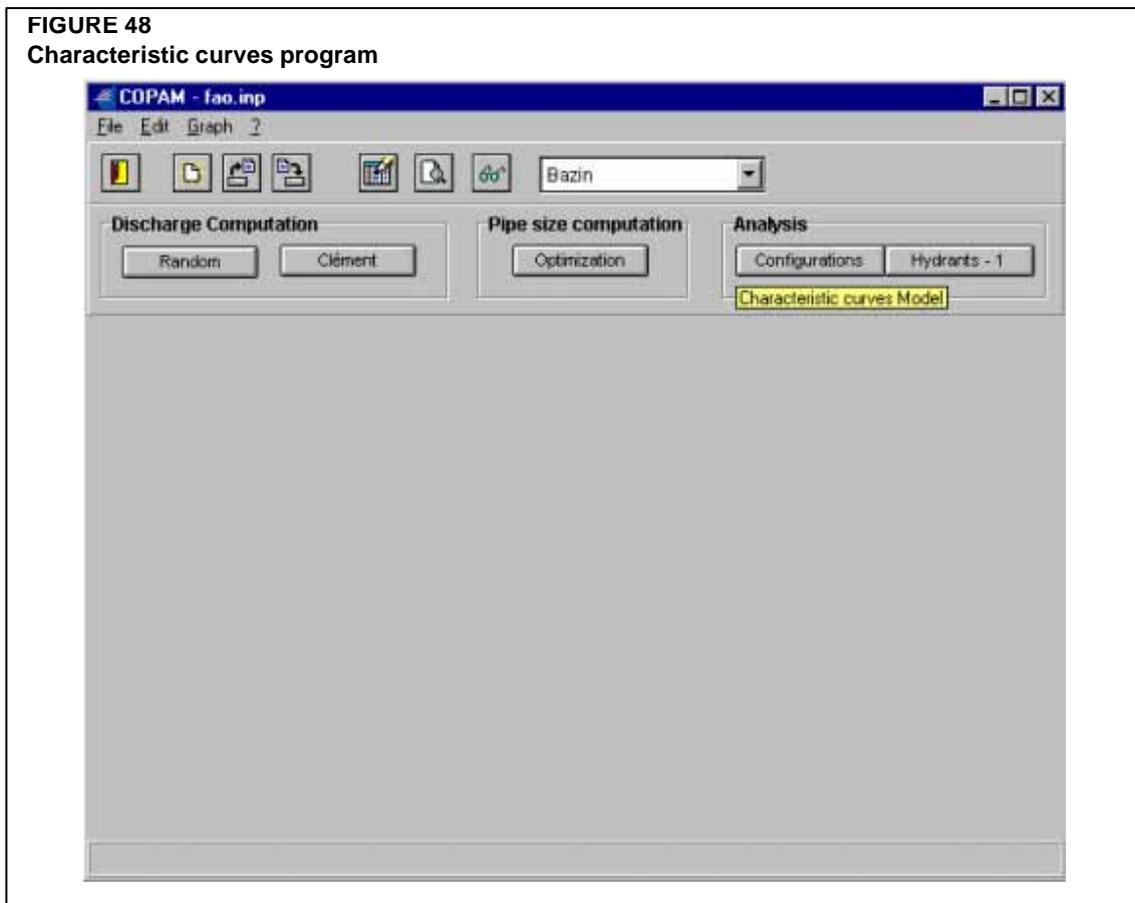
When testing the network under steady flow conditions, it is possible to associate a piezometric elevation at the upstream end of the network to each discharge configuration, such that it satisfies relationship (47). Once the C configurations are investigated, a series of piezometric elevations (Z_r) at the upstream end of the network is associated to each discharge Q_r, so that each one represents the piezometric elevation able to satisfy a given percentage of C configurations.

The indexed characteristic curves are drawn by plotting, in the plane (Q, Z), the discharge values chosen and the corresponding vectors, as well as by joining the points having the same percentage of configurations satisfied. The shape of these curves depends on the geometry of the network and on the topography of the area to be irrigated. Therefore, indexed characteristic curves with smooth or steep slope are obtained.

Let Z_0 [m a.s.l.] be the design piezometric elevation at the upstream end of the network and Q_0 [l s^{-1}] be the upstream design discharge. Let us define P_0 (Q_0, Z_0) as the "set-point" of the network. The performance of the network is then associated to the percentage of satisfied configurations corresponding to the coordinates of the set-point.

The indexed characteristic curves provide information on the global performance of irrigation systems. Nevertheless, the above indexed characteristic curves are drawn following the principle that a configuration is said to be unsatisfied even if the head H_j of one hydrant only is lower than the minimum required H_{min}. Therefore, if the set-point (Q_0, Z_0) falls on an indexed characteristic curve corresponding to a low percentage of satisfied configurations, then the model is not able to give a precise evaluation of the performance of the network. Consequently,

a new model was formulated to give a more precise picture of the behaviour of the network. It is reported in the next sections.

A software package generating the indexed characteristic curves is available at the CEMAGREF (France) and it may be coupled with the software XERXES-RENFORS (CEMAGREF, 1990), which was reported in chapter 4. An alternative software for computing the indexed characteristic curves is integrated in the COPAM package (see Figure 48). It is used in the applications presented below. The Darcy equation was used for computing the head losses[1], Y [m], in the network:

$$Y = 0.000857 \, (1 + 2\gamma \, D^{-0.5})^2 \, Q^2 \, D^{-5} \, L = u \, Q^2 \, L \qquad (50)$$

where γ is the roughness parameter of Bazin, expressed in $m^{0.5}$, Q [$m^3 \, s^{-1}$] is the discharge flowing in the pipe, u [$m^{-1} \, s^2$] is the dimensional coefficient of resistance and L [m] is the length of the pipe.

By clicking on the button program "Configuration", Figure 49 will appear on the computer screen.

FIGURE 49
Characteristic curves program: parameters of the analysis

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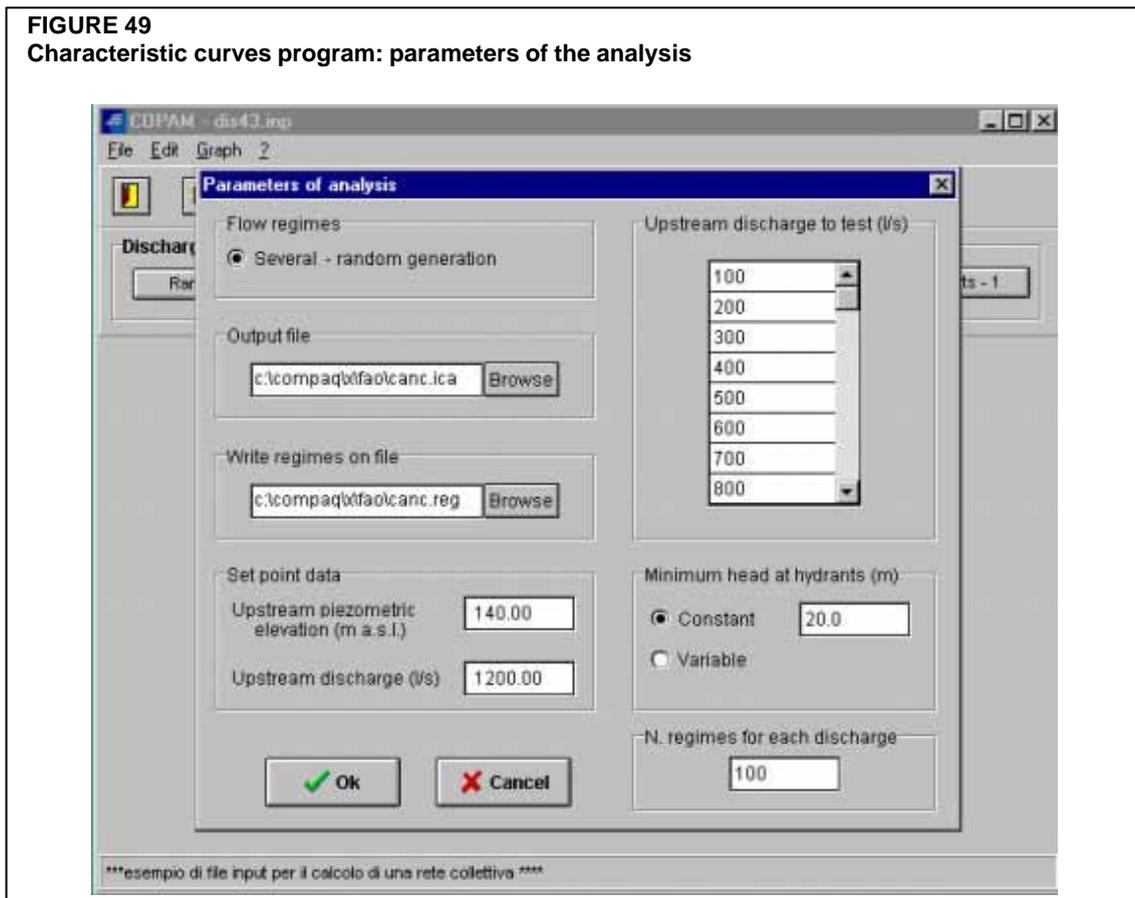
[1]   Local head losses have been neglected in the computations. Usually they are very small respect to the linear head losses, anyway they may be taken into account when the upstream piezometric elevation is analysed.

FIGURE 50
Input file: edit network layout

FIGURE 51
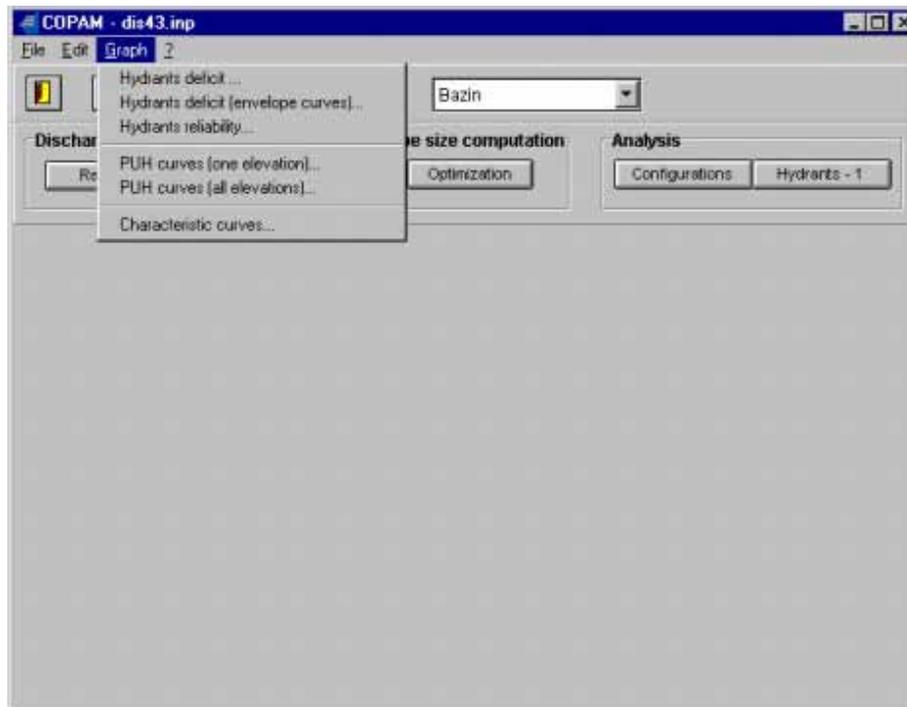**Graph menu bar and sub-menu items**

FIGURE 52
Open file to print the characteristic curves

The name of the output file is typed in the appropriate edit box. The extension ".ica" is automatically assigned by the program. The name of the file for storage of the random generated flow regimes has the extension ".ran" automatically assigned. The piezometric elevation (in m a.s.l.) available at the upstream end of the network, and the design upstream discharge (in l s^{-1}) are written in the "set point data" option. The list of discharges to be tested, flowing at the upstream end of the network, is inserted in the appropriate box, as well as the number of regimes to generate for each discharge. Finally, the program allows the computations where the minimum pressure head (H$_{min}$) required for an appropriate on-farm irrigation is constant or variable. In the first case, the radio button "Constant" is selected in the frame "Minimum head at the hydrants" and the value H$_{min}$ is written in the appropriate box. In the other case, the radio button "Variable" is selected and the values of the minimum head at each hydrant are inserted in the last column of the input file (see Figure 50).

The COPAM package has an easy graphical interface. It prints the characteristic curves of the network by clicking on the "Graph" menu bar and then on the "Characteristic curves …" which is a sub-menu item (Figure 51). The name of the output file (with extension ".ica") is selected for printing the graphic (Figure 52).

Two different analysis are reported in the next sections:

- the first is for an irrigation system under design;
- the second is for an existing irrigation system.

Application 1: Network under design, served by an upstream pumping station

This section describes the application of the indexed characteristic curves model to an irrigation network supplied by a pumping station equipped with variable speed pumps (Lamaddalena and Piccinni, 1993)[1]. The example shows the wide applicability of the model during the design stage.

The irrigation network serves an irrigable area of 582 ha equipped with 175 hydrants out of which 129 with nominal discharges of 5 l s^{-1}, 22 hydrants of 10 l s^{-1} and 24 hydrants of 20 l s^{-1}. It was designed for on-demand operation. The area is upsloping towards the origin of the network, with elevations ranging from 15 m a.s.l. to about 24 m a.s.l. The lifting plant is designed for a maximum discharge of 325 l s^{-1} (calculated with the first Clément model) with an upstream piezometric elevation Z_0 = 66.7 m a.s.l. The total head of the lifting plant is H_{PS} = 62 m (since the land elevation of the pumping station is ZT_{PS} = 2.7 m a.s.l., and the head losses within the pumping station are Y_{PS} = 2.0 m). The minimum design head at each hydrant (H_{min}) is 25 m, aiming at low pressure sprinkler or trickle irrigation methods. Downstream of the pumping station, a flow meter, a pressure meter and an inverter are installed. The inverter serves to modify the rotation speed of a pump by changing the input frequency (50 Mhz standard). It is controlled by a computer which receives information on the discharge and head from the flow and pressure meters.

The indexed characteristic curves are represented in figure 53. They were drawn using 200 random configurations of hydrants corresponding to upstream discharges Q_r between 10 and 600 l s^{-1}. The figure shows that the set-point P_0 (325, 66.7) falls on the indexed curve of 93%. This means that the head at the hydrants is higher than the minimum required in 93% of all the examined discharge configurations. Indeed, the performance of this system, as defined by this model, is 93%. In this case, the application of the model will save energy at the pumping station since it is equipped with variable speed pumps (Lamaddalena and Piccinni, 1993).
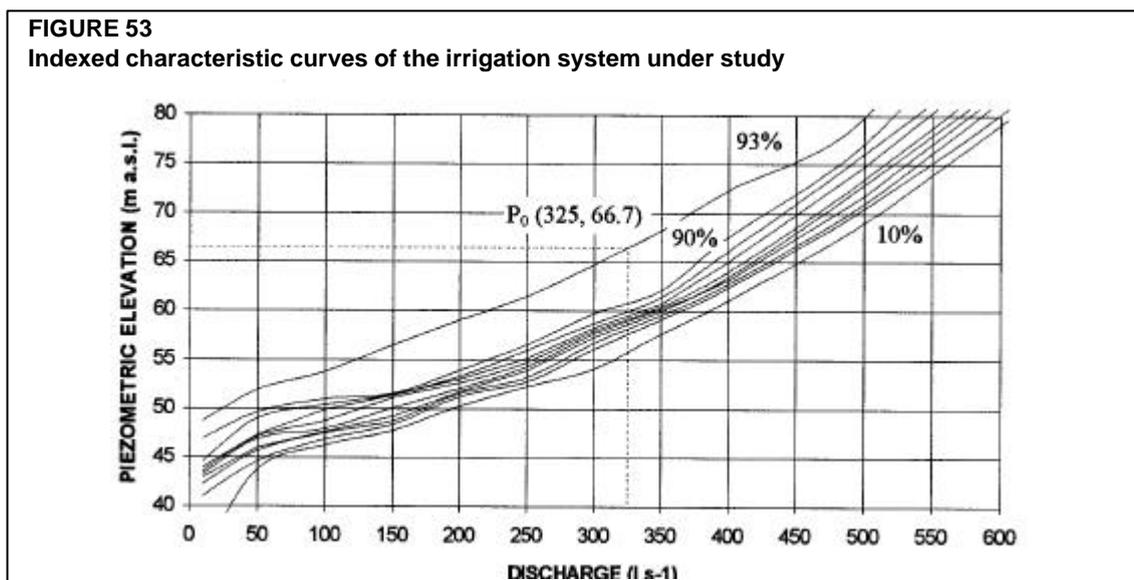
FIGURE 53
Indexed characteristic curves of the irrigation system under study

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From Figure 53, when the discharge decreases from 325 l s^{-1} to 10 l s^{-1}, the same percentage of configurations (93%) may be satisfied when the upstream piezometric elevation decreases from 66.5 m to 52.7 m, or with heads from 62 m to 48 m. Because the lifting station is equipped with variable speed pumps, it is possible to adjust the head of the pumps according to the indexed characteristic curve. Indeed, when discharges are lower than 325 l s^{-1}, the head H$_{PS}$ of the pumping station may decrease with consequent energy saving.

The pumping plant is equipped with five horizontal electric pumps, each designed for a discharge of 65 l s^{-1}, for H$_{PS}$ = 62 m, at 1480 rpm. A smaller pump with a discharge of 20 l s^{-1}, for the same head, completes the pumping station. A scheme of a pumping station equipped with variable speed pumps is reported in Figure 54. The characteristic curves of the pumps when operating in parallel are shown in Figure 55.

The small pump operates up to a discharge of about 30 l s^{-1} to compensate for the low efficiency which would result if one of the main pumps operates at low discharge. As the demand in the irrigation network increases, the pressure head drops to the minimum pre-established head for the operation of the small pump (H=52.0 m as shown in Figure 55). Then the inverter will cause the first main pump to operate automatically at the lowest speed. With further increase of the discharge in the network, the speed of that pump will increase up to the maximum value of 1480 rpm. Successive increases of the demand induce the operation of a successive pump, first at low speed and finally at the highest speed.

As for the required power, with 1300 rpm the plant can supply a discharge of 50 l s^{-1} with a head of 48.9 m, an efficiency of 74.5% and requiring 32.2 kW. If a full speed electrical pump were started at 1480 rpm (to maintain the head at 62.0 m), 50 l s^{-1} would require 40.0 kW. The resulting energy saving is about 21%. Further comparisons are reported in Table 5, where the power required by the plant equipped with variable speed pumps (pumping plant A) is compared with a classical plant (B).

TABLE 5
Comparing the power requirements for a pumping plant equipped with variable speed pumps (type A) and for a classical pumping plant (type B), as a function of the discharges supplied

DISCHARGE (l s^{-1})	PLANT A (Variable speed pumps)				PLANT B		Power Difference (%)
	rpm	Head (m)	Efficiency (%)	Power (KW)	Head (m)	Power (KW)	
50	1300	48.9	74.5	32.2	62.0	40.0	21
75	1350	49.4	81.0	44.8	62.0	56.3	20
90	1400	49.8	81.0	54.3	62.0	67.5	19
115	1480	50.6	77.5	73.6	62.0	90.2	18
175	1480+1400	53.4	79.8	114.8	62.0	133.3	14
200	1480*2	54.3	80.5	132.3	62.0	151.0	12
260	1480*3	57.6	81.5	180.2	62.0	193.9	7
300	1480*4	60.2	80.5	220.0	62.0	226.5	3
325	1480*5	62.0	78.5	251.7	62.0	251.7	0

Differences between pumping plants are reported in Figure 56 as a function of the discharges supplied. Corresponding energy savings are significant for a wide range of discharges. Considering that the maximum design discharge (and consequently the design head) is in fact required for a short time period with respect to the irrigation season, substantial savings are possible during the lifetime of the system.

FIGURE 54
Scheme of a pumping station equipped with variable speed pumps
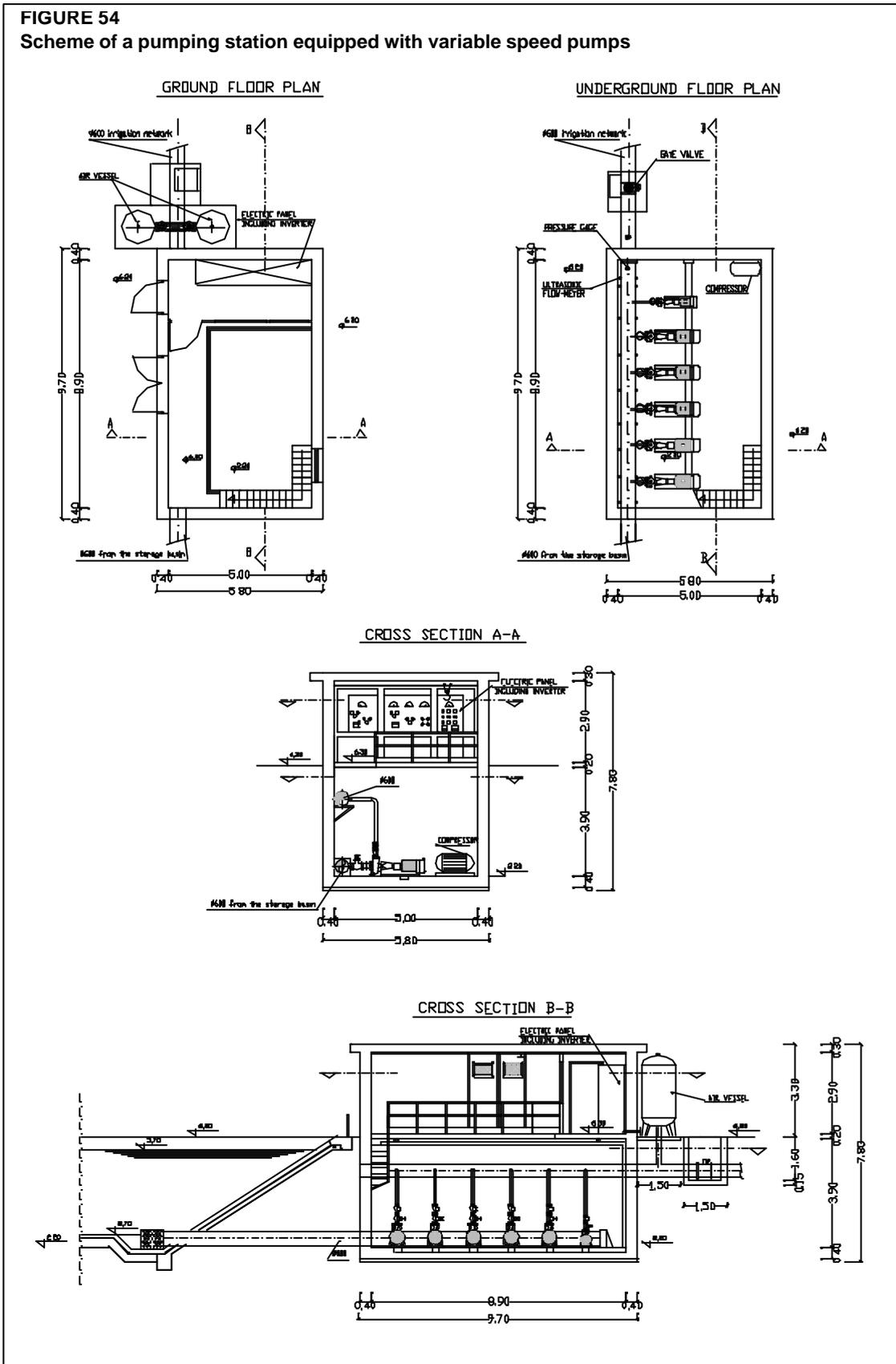
FIGURE 55
Characteristic curves of variable speed pumping station and the 93% indexed characteristic curve of the network. The characteristic curve PP concerns the small pump. The curves 1,2,3,4 and 5 are the characteristic curves resulting from the simultaneous operation of 1,2,3,4 or 5 pumps at 1480 rpm. The dotted lines a,b,c and d concern the modification of those characteristic curves when speed changes to 1440, 1400, 1350 and 1300 rpm respectively.
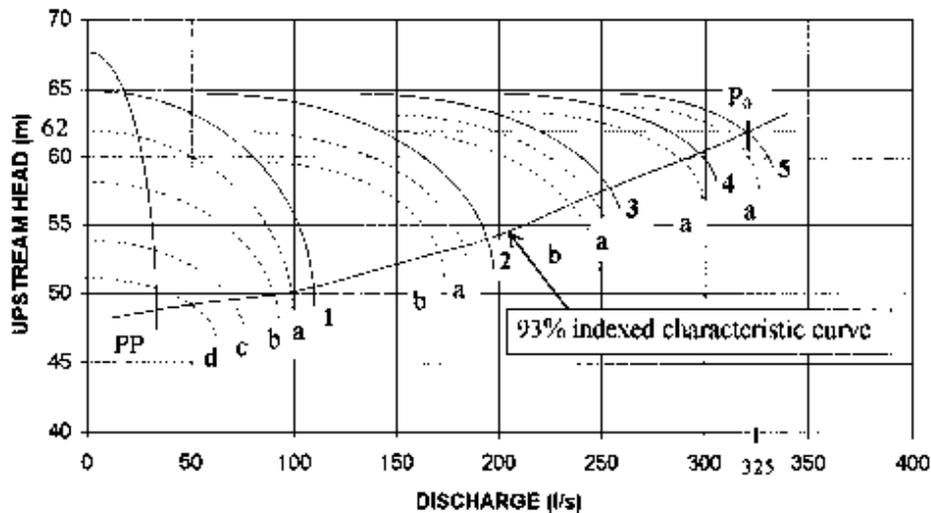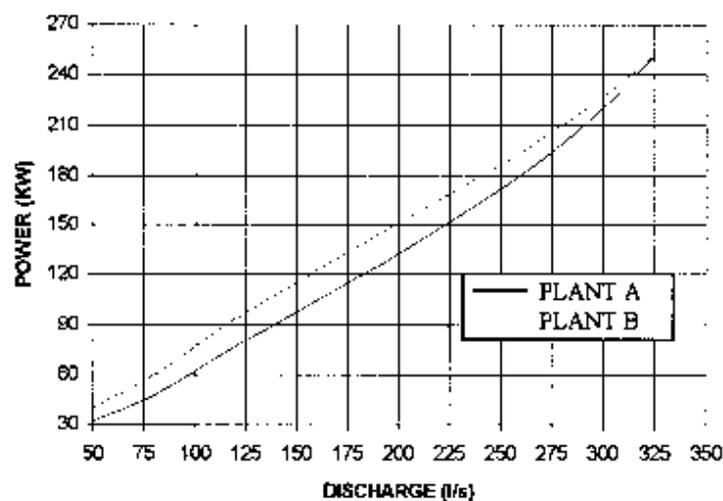

FIGURE 56
Power required by the plant equipped with variable speed pumps (type A) and a classical plant (type B), as a function of the supplied discharges


With the above application, it was shown that the investigation, using the indexed characteristic curves, is an important tool both for testing the hydraulic performance of the network and for designing the associated lifting plants. In the first case, the percentage of satisfied configurations with the variation of the upstream discharge is established and the need to improve the design (or to rehabilitate an existing system) is analysed. In the second case, the investigation is essential to evaluate the need for lifting plants with variable speed pumps, which

could ensure optimal management under the energy point of view. A lifting station equipped with such advanced technologies implies a higher installation cost and a more specialized staff.

Application 2

This irrigation network is located near the town of Lecce (Italy) and serves a total area of 1340 ha. It is equipped with 348 hydrants, out of which 253 of $5 \, l \, s^{-1}$, 62 of $10 \, l \, s^{-1}$ and 33 of $20 \, l \, s^{-1}$. It is designed for on-demand operation. The discharges in the network were calculated using the first Clément model, giving a maximum value of $675 \, l \, s^{-1}$ at the upstream end. The upstream piezometric elevation is 81.8 m a.s.l. The minimum head required at each hydrant (H_{min}) is 25 m, aiming at the low pressure sprinkler and trickle irrigation. The indexed characteristic curves, calculated by the characteristic curves model, are reported in Figure 57.

FIGURE 57
Indexed characteristic curves for the Lecce irrigation network computed using 500 random configurations
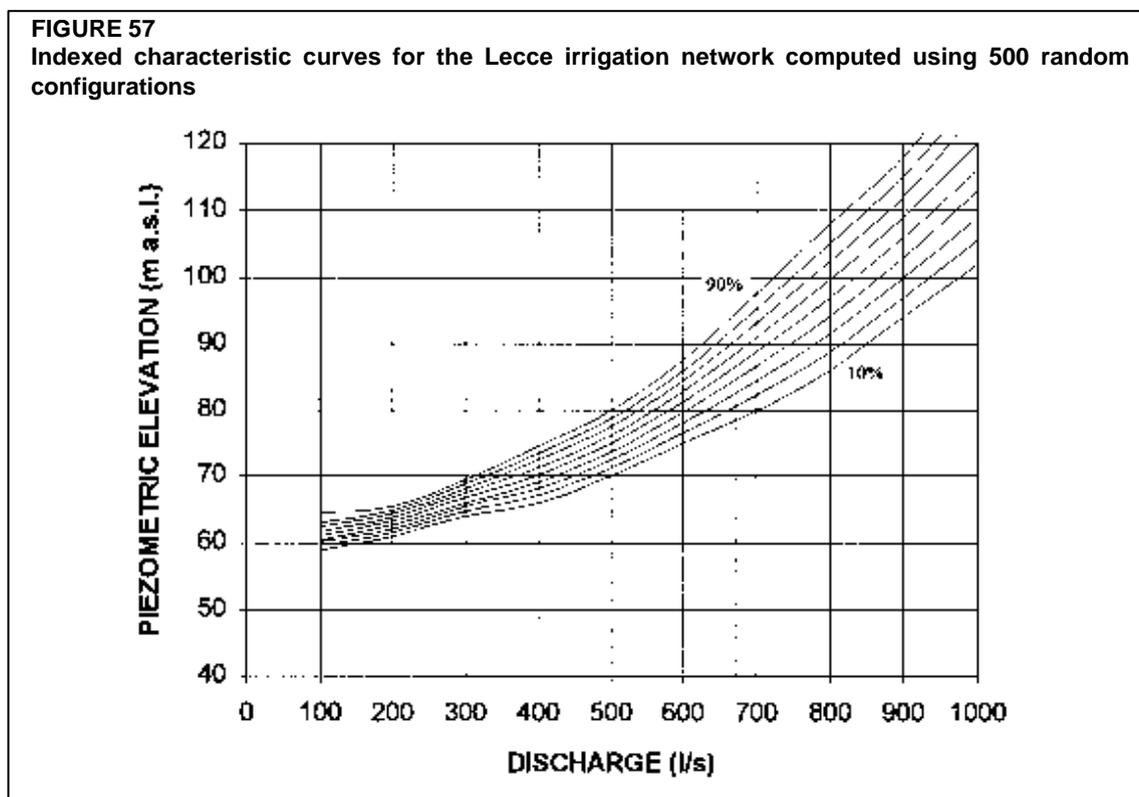
From the characteristic curves, it is observed that the set-point P_0 ($675 \, l \, s^{-1}$, 81.8 m a.s.l.) falls on the characteristic curve of 25%. It means that only 25% of the investigated configurations are fully satisfied, which is a low value.

As mentioned before, the indexed characteristic curves were drawn following the principle that a configuration is said to be unsatisfied even if only one of its hydrant has the head lower than the minimum required. Indeed, especially when the set-point falls on the low percentage characteristic curves (i.e., lower than 50%), a new model is needed for a better evaluation of the system performance and for understanding if any design change is required. This new model, allowing the analysis at the hydrant level, is presented and evaluated in the next section.

Models for the analysis at the hydrant level

The model presented hereafter, called AKLA[1], allows analysis of the pressure head at each hydrant under different operating conditions. This pressure head is compared with the minimum pressure required for an appropriate on-farm irrigation, so a measure of the hydraulic performance for each hydrant is obtained through the computation of the relative pressure deficit defined hereafter. The model is applicable under the hypothesis that the hydrants may deliver a constant discharge for a wide range of operating pressure heads (see Figure 46). This condition is appropriate for a wide range of commercial delivery equipment. Computer software for the model has been developed and integrated in the COPAM package.

The Environmental Protection Agency (EPA) of the United States has also developed a computer program called EPANET (Rossman, 1993) that performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks (branched or looped). For this program, also the demand hydrograph at each node is an input data. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank and the concentration of a substance throughout the network during a multi-time period simulation. The Windows version of EPANET allows input data to be edited, run the simulator and graphically display its results in a variety of ways on a map of the network. The program can be downloaded from the web site: www.epa.gpv/ord/nrmrl/epanet.

Model description

The AKLA model is an improvement of the model described in the previous section. Instead of analysing the whole configurations of hydrants, it permits performance analysis at the level of each hydrant of the network. The model is based on the multiple generation of a pre-fixed number of hydrants simultaneously operating (configuration) using a random number generator having a uniform distribution function (see chapter 3). The computer software has an internal procedure to generate directly the random discharge configurations, or to read the flow regimes from an external file.

Within each generated configuration (r), a hydrant (j) is considered satisfied when the following relationship is verified:

$$H_{j,r} = H_{min} \tag{51}$$

where $H_{j,r}$ [m] represents the head of the hydrant, j, within the configuration r, and H_{min} [m] represents the minimum required head for the appropriate operation of the on-farm systems.

The relative pressure deficit at each hydrant is defined as:

$$\Delta H_{j,r} = \frac{H_{j,r} - H_{min}}{H_{min}} \tag{52}$$

A flow chart of the AKLA model is presented in Figure 58. The code of the computer program has been written using the language Turbo Pascal Version 6.

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[1] This model has been developed by Ait Kadi and Lamaddalena. The first version of the computer program has been available since 1991. It has been utilized for the analysis of several irrigation schemes and reported in M. Sc. Thesis at the CIHEAM., Insitute of Bari (Italy) under the supervision of Proff. Ait Kadi and/or Lamaddalena (Abdelwahab, 1992; El Aallouni, 1993; El Yacoubi, 1994; Ben Abdellah, 1995; Nerilli, 1996; Zaccaria, 1998; Khadra, 1999).

The AKLA model computes the relative pressure deficit at each hydrant and determines the percentage of unsatisfied hydrants. The head losses, Y [m], are computed using the Darcy equation:

$$Y = 0.000857 \, (1 + 2\gamma \, D^{-0.5})^2 \; Q^2 \, D^{-5} \, L = u \, Q^2 \, L \qquad (50)$$

where γ is the roughness parameter of Bazin, expressed in $m^{0.5}$, Q [$m^3 \, s^{-1}$] is the discharge flowing in the pipe and u [$m^{-1} \, s^2$] is the dimensional resistance coefficient.

Assuming that each hydrant withdraws the nominal discharge, d [$l \, s^{-1}$] even when its head is lower than the minimum required (H_{min}), if the discharge is fixed at the upstream end of the network, the number of hydrants simultaneously operating (K_r) is[1]:

$$K_r = Q_r / d \qquad (49)$$

where Q_r [$l \, s^{-1}$] is the upstream discharge. Once the available piezometric elevation at the upstream end of the network, Z_0 [m a.s.l.], is established, the set of discharges to be tested, Q_r, and the number of configurations, C, to be investigated for each discharge are selected. From the Eq. 49, the number of hydrants corresponding to each discharge Q_r is calculated. Later, by using the RGM (see chapter 3), the K_r hydrants simultaneously operating are randomly drawn. This procedure is repeated C times for each discharge Q_r.

Based on the analysis of a large number of irrigation systems, the number of configurations to be tested should be higher than the number of hydrants in the network (C>R) when R<200) but the number is smaller when R is very large (R>600). The discharges flowing in each section of the network for each discharge Q_r are obtained by aggregating, from downstream to upstream, the discharges delivered by the selected K_r hydrants.

Starting from the upstream piezometric elevation, Z_0, Eq. 50 is used to calculate the head losses[2] and the head available at each hydrant in each configuration. Indeed, those hydrants having a head lower than the minimum pre-established (H_{min}) are identified and defined as unsatisfied hydrants. The percentage of unsatisfied hydrants (PUH) out of the total number of open hydrants in the investigated configuration is plotted in a plane (Q, PUH).

Selecting a large number of configurations for a given upstream discharge, the analysis provides a variable number of unsatisfied hydrants, thus a range of PUH for that given discharge. Repeating this procedure for several discharges, a cloud of points is obtained in the plot. An upper and a lower envelope curve will contain all points. The upper envelope represents the maximum percentage of unsatisfied hydrants for the range of discharges under consideration and for all the investigated configurations. The lower envelope represents the minimum PUH for the number of investigated configurations. When the number of tested configurations is large, the PUH can be assigned to different probabilities of occurrence. Envelope curves representing equal probabilities that PUH is exceeded for the discharges being considered can be plotted (Fig. 59).
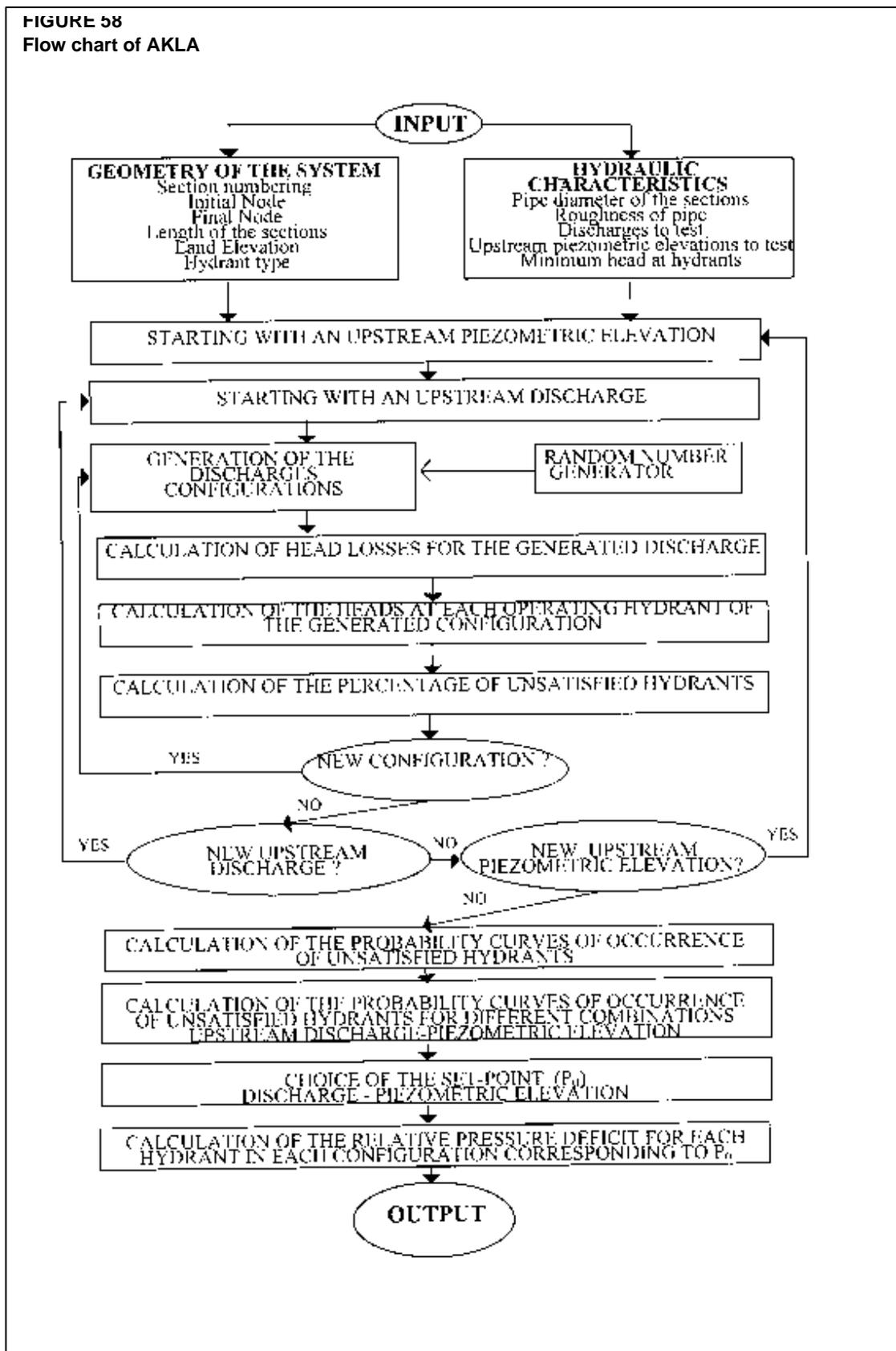
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[1] In the case of different hydrant discharges, the same procedure reported in the previous section is applied. Random drawing will be performed to satisfy the relationship:
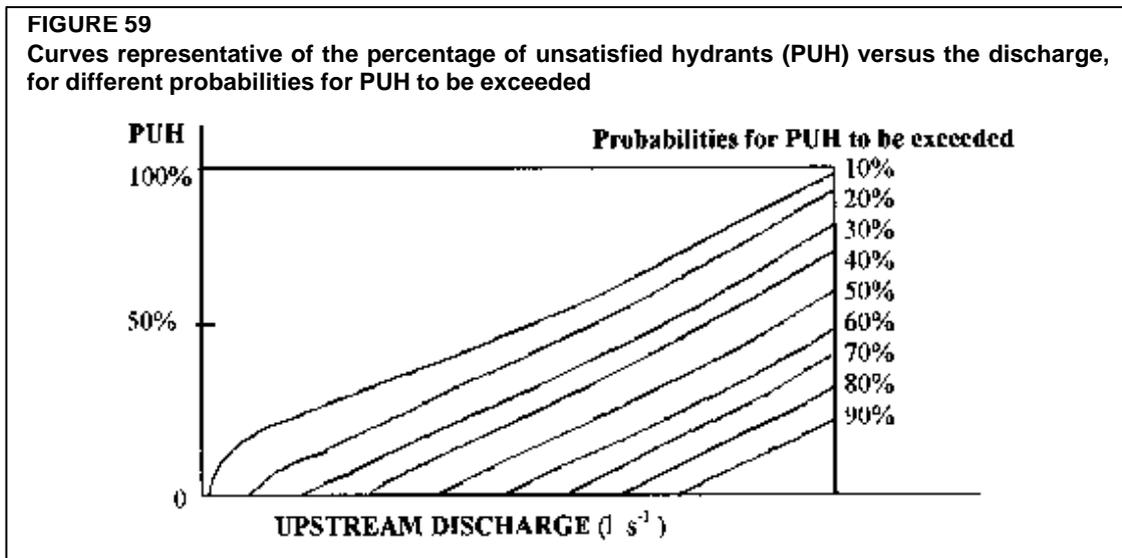
$$| \, Q_{tir} - Q_i \, | < \varepsilon_t$$

where Q_{tir} is the discharge corresponding to K hydrants drawn at random ($l \, s^{-1}$) and ε_t is the accepted tolerance. In general, ε_t is assumed as equal to the value of the lowest hydrant discharge.

[2] Local head losses are neglected in the computations. Usually they are small with respect to the linear head losses and they may be taken into account when the upstream piezometric elevation is analysed.

FIGURE 58
Flow chart of AKLA

FIGURE 59

Curves representative of the percentage of unsatisfied hydrants (PUH) versus the discharge, for different probabilities for PUH to be exceeded
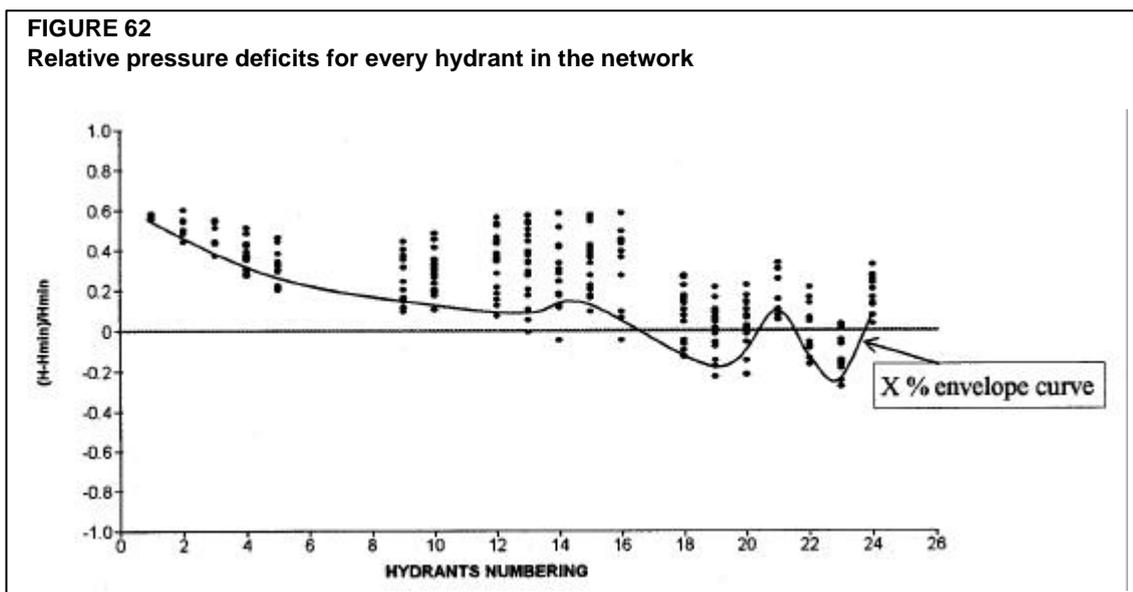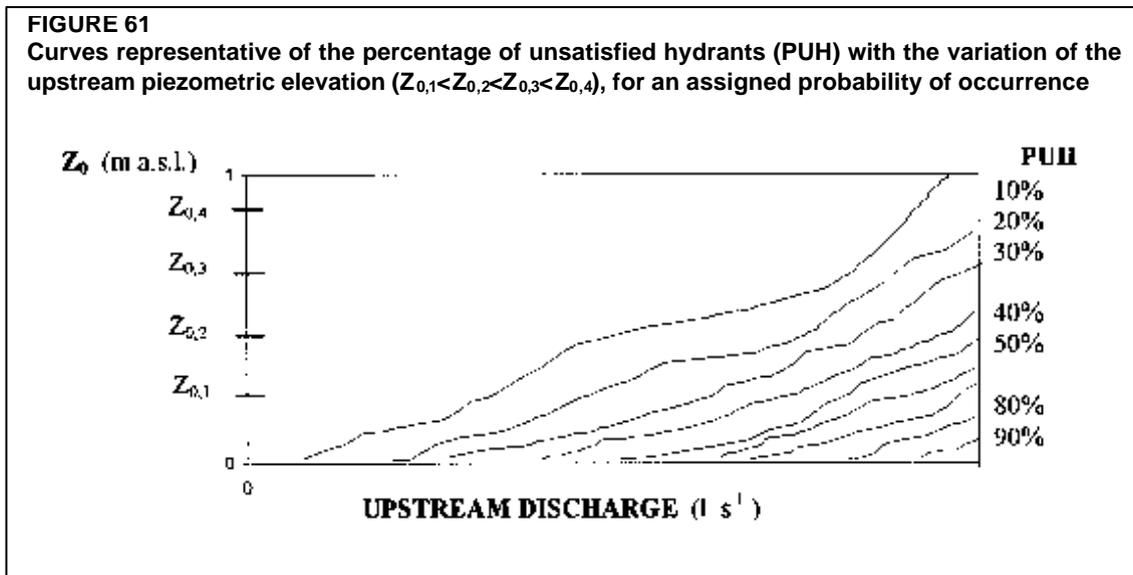

Probability curves can also be plotted for the upstream piezometric elevation (Z_0). Thus, by selecting the 10% of probability of being exceeded curve, a new diagram is obtained giving the percentage of unsatisfied hydrants with the variation of upstream piezometric elevation (Figure 60). From this diagram, through a simple transformation of coordinates, the curves of the PUH (Figure 61) are obtained in the plane (Q, Z).

FIGURE 60

Curves representative of the upstream piezometric elevation ($Z_{0,1}<Z_{0,2}<Z_{0,3}<Z_{0,4}$) with the variation of the percentage of unsatisfied hydrants (PUH), for an assigned probability of occurrence

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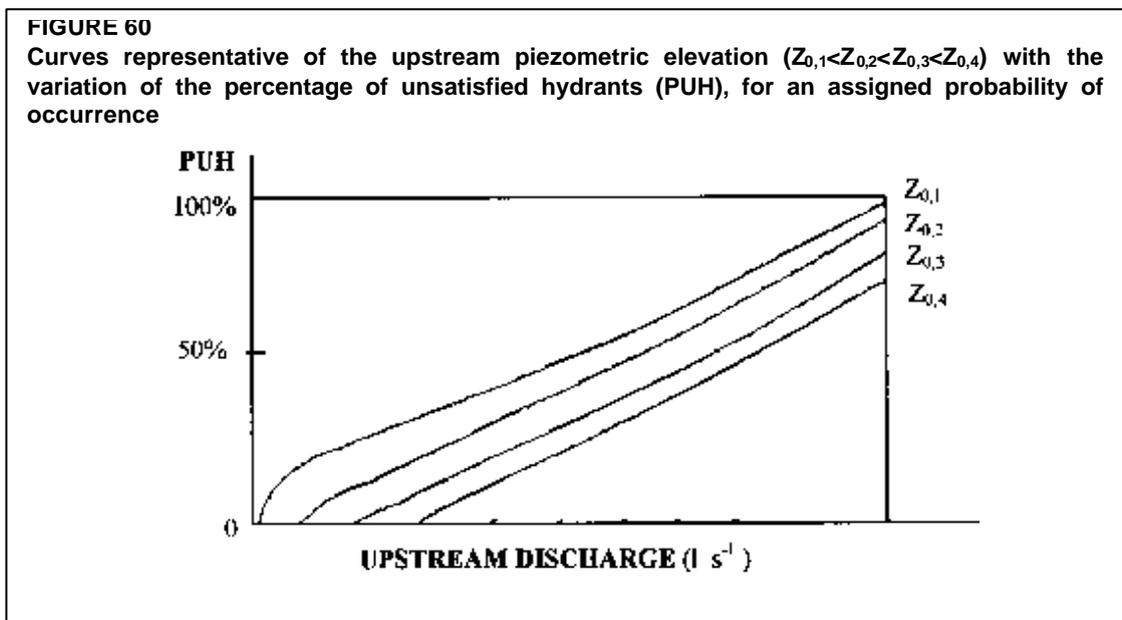
This last representation is interesting because it provides for an immediate and complementary comparison with the indexed characteristic curves model. Indeed, through the analysis of both models, the number of fully satisfied configurations as well as the percentage of unsatisfied hydrants are identified with the variation of the piezometric elevation at the upstream end of the network.

Furthermore, once the analysis is completed, it is also possible to identify, for each configuration, the range of variation of the head at each hydrant. Indeed, the relative pressure

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FIGURE 61
Curves representative of the percentage of unsatisfied hydrants (PUH) with the variation of the upstream piezometric elevation ($Z_{0,1}<Z_{0,2}<Z_{0,3}<Z_{0,4}$), for an assigned probability of occurrence

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FIGURE 62
Relative pressure deficits for every hydrant in the network

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deficit, $\Delta H_{j,r}$ (Eq. 52), may be represented in a plane (Hydrants numbering, ΔH). In this way, the hydrants which are most subject to insufficient pressure head and critical zones of the network are clearly identified (Figure 62). Also, the upper, the lower and the indexed envelope curves (from 10% to 90%) may be represented in the same plane.

Computer software for the computation of the percentage of unsatisfied hydrants and the relative pressure deficits is integrated into the COPAM package (see Figure 63). It is used for the applications presented hereafter.

By clicking on the button program "AKLA" (Figure 63), Figure 64 will appear.

Within the "Options" Tab control, two alternative types of flow regimes are available (Figure 64): the first automatically generates the random flow regimes and the second reads the flow regimes from an external file.

FIGURE 63
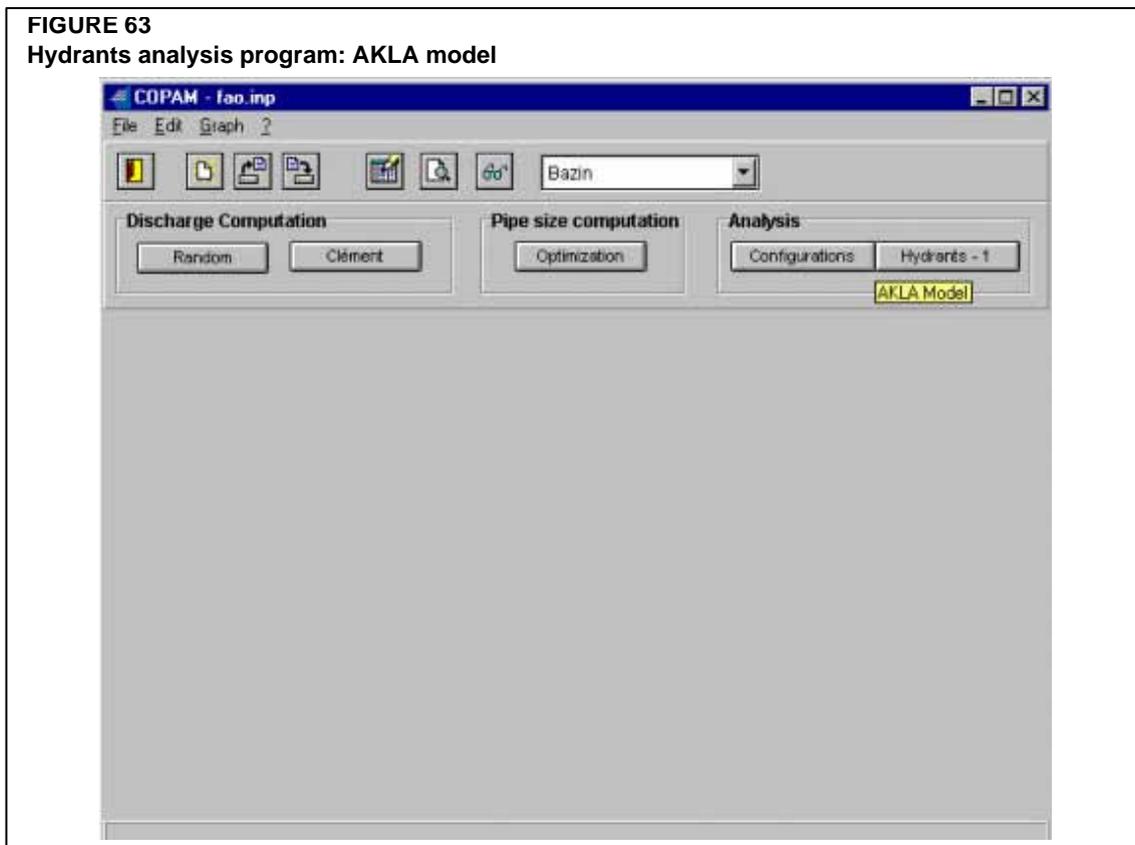**Hydrants analysis program: AKLA model**

FIGURE 64
Hydrants analysis program: "Options" Tab control, "Several-random generation" flow regime
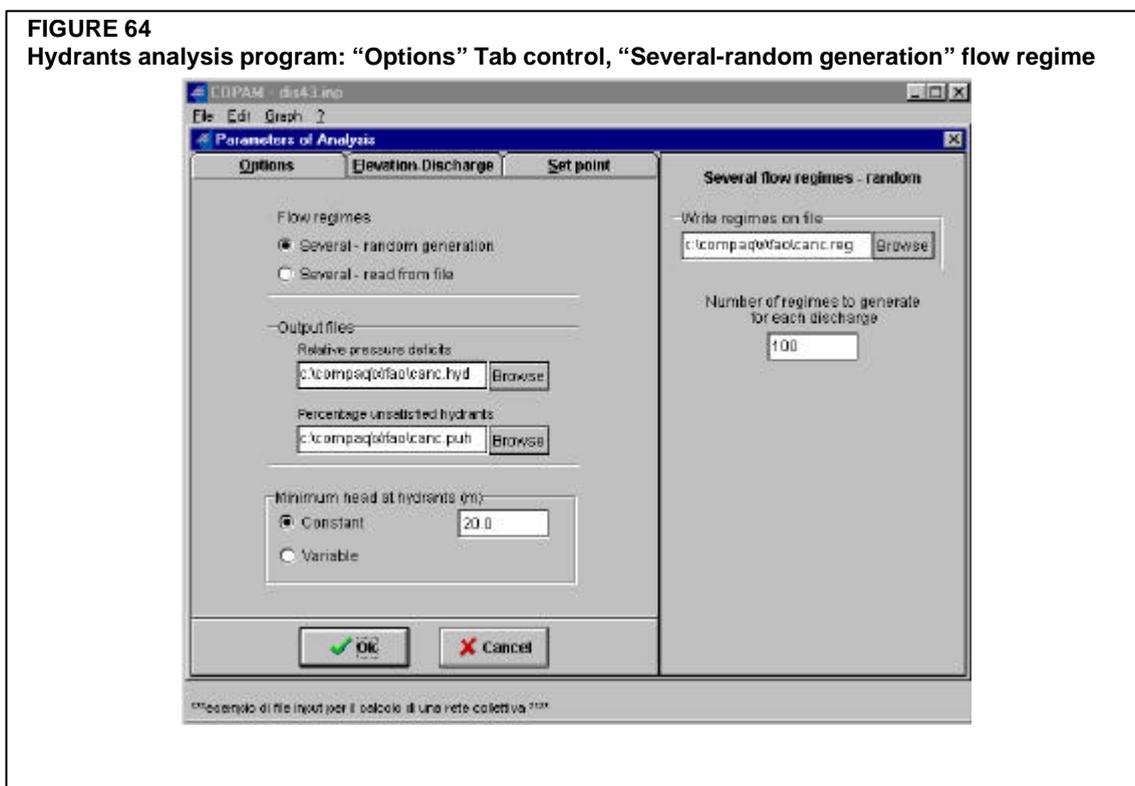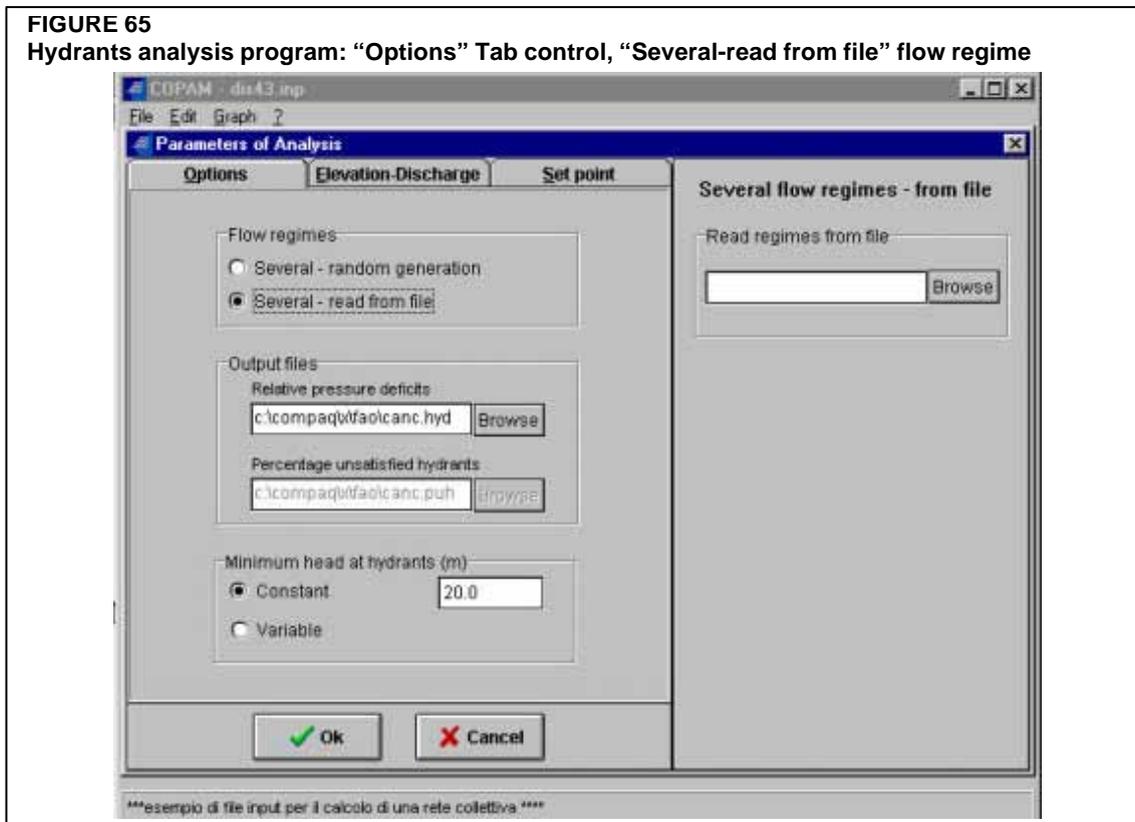
FIGURE 65
Hydrants analysis program: "Options" Tab control, "Several-read from file" flow regime

This second option allows analysis of irrigation systems operating on rotation and/or on arranged demand. In these cases, in fact, the flow regimes are previously generated according to the management rules and stored in an appropriate file to be read by the program (see Figure 65).

The name of the output file for storing information on the hydrants relative pressure deficit (extension ".hyd" is automatically assigned to this file) and on the percentage of unsatisfied hydrants (extension ".puh" is automatically assigned to this file) is written in the appropriate edit boxes, as well as the name of the file in which the random generated flow regimes are stored (Figure 64) (extension ".reg" is automatically assigned to this file).

If the option "Several – random generation" is selected, the number of regimes to generate for each discharge is typed in the appropriate edit box (Figure 64).

If "Several - read from file" is selected, the name of the file in which flow regimes have been previously generated and stored is input in the box "Read regimes from file …" (Figure 65). In this case the number of flow regimes to be generated is not required because the flow regimes are already stored in the file

The program allows network computations where the minimum pressure head (H_{min}) required for an appropriate on-farm irrigation is constant or variable. In the first case, the radio button "Constant" is selected in the frame "Minimum head at the hydrants" and the value H_{min} has to be written in the appropriate box. In the other case, the option "Variable" is selected and the values of the minimum head at each hydrant are typed in the last column of the input file (see Figure 50).

FIGURE 66
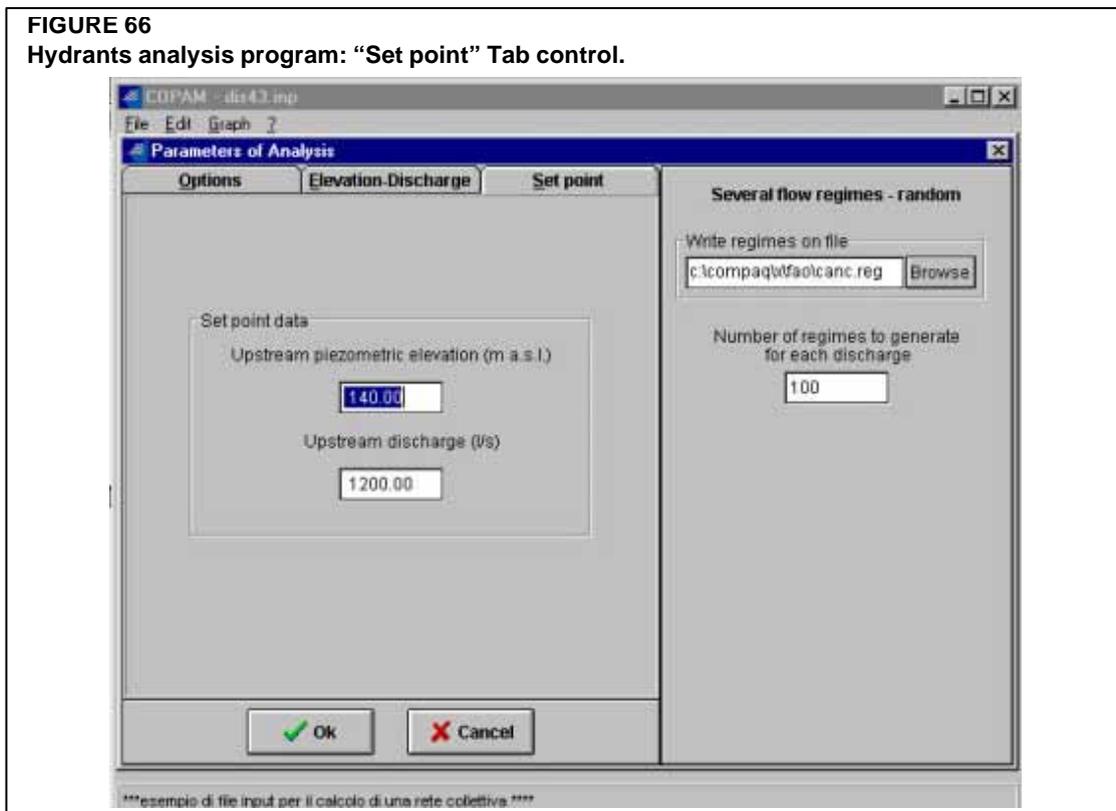**Hydrants analysis program: "Set point" Tab control.**

FIGURE 67
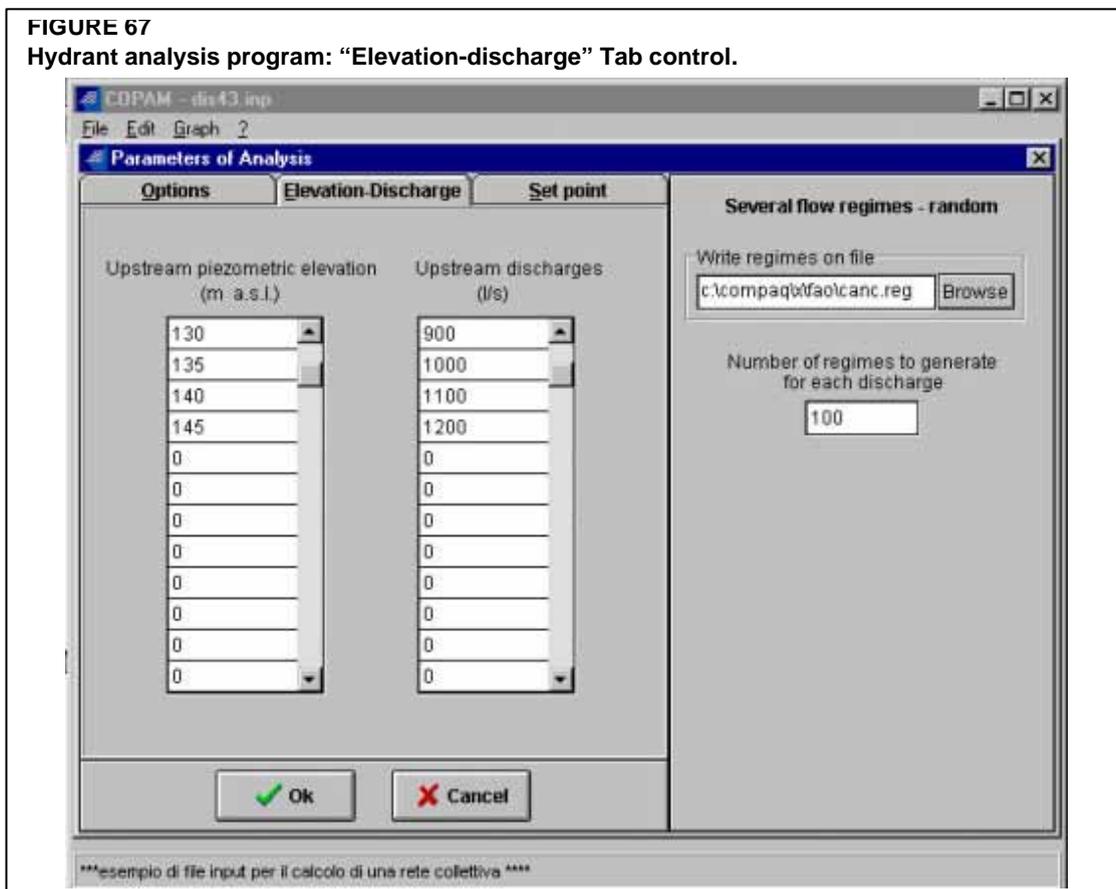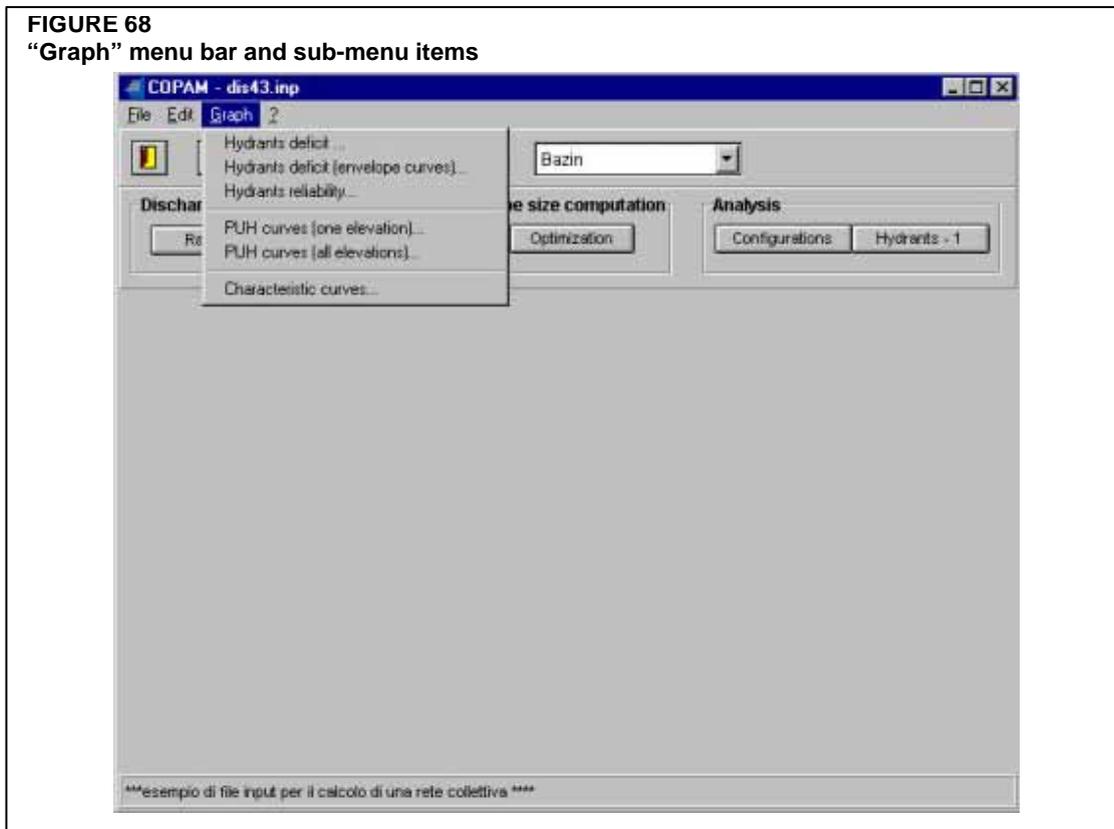**Hydrant analysis program: "Elevation-discharge" Tab control.**
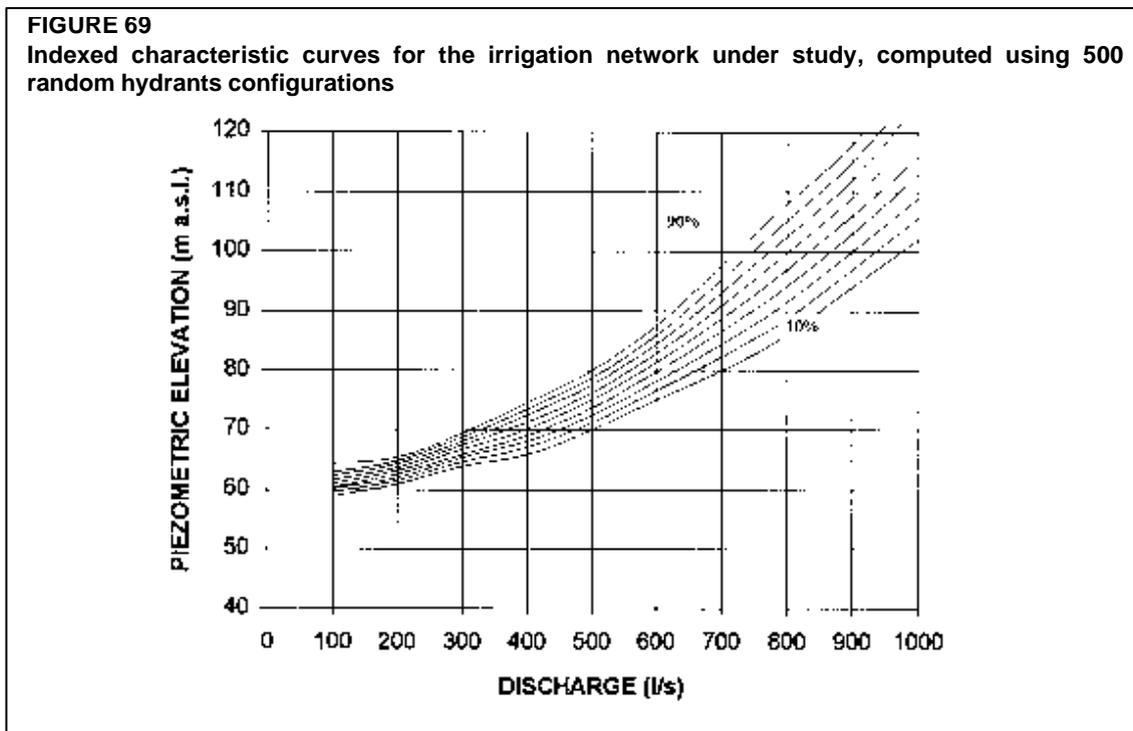
FIGURE 68
"Graph" menu bar and sub-menu items

The piezometric elevation (in m a.s.l.) available at the upstream end of the network, and the design upstream discharge (in l s^{-1}) are typed in the "set point" tab control (Figure 66). The list of the discharges flowing at the upstream end of the network and the list of the upstream piezometric elevations to be tested are inserted in the appropriate boxes under the "Elevation-Discharge" Tab control (Figure 67). These values allow the computation of the percentage of unsatisfied hydrants when the upstream discharges and piezometric elevations vary.

It is important to include the set point data among these values. In fact, the relative pressure deficits are computed only for the set point values. When the user does not need to investigate the variation of the percentage of unsatisfied hydrants but has interest only in investigating the relative pressure deficits for the set point data, only the set point values are typed in the boxes of the "Elevation-discharge" Tab control.

An application of the AKLA model is reported in the next section. It refers to the same irrigation network analysed with the characteristic curves model in the application 2 of the present chapter. This application better shows the target of the AKLA model and its improvements may be better understood by comparing the results of the two models.

The graphical interface of the COPAM package allows easy printing of the information obtained by the AKLA model. In fact, by clicking on the "Graph" menu bar it is possible to select the available sub-menu items (Figure 68): hydrants deficit, hydrants deficit (envelope curves), PUH curves (one elevation), PUH curves (all elevations). The items "PUH curves (one elevation) ..." and "PUH curves (all elevations) ..." are referred, respectively, to the Figures 59 and 60. The graphical interface allows printing of the hydrants reliability, as explained in the next section.

FIGURE 69

Indexed characteristic curves for the irrigation network under study, computed using 500 random hydrants configurations

For printing the hydrants deficit and the hydrants reliability, the output file "*.hyd" is selected, while for printing the PUH curves, the output file "*.puh" is selected.

Application 3

The irrigation network analysed hereafter is the same analysed with the characteristic curves model in the application 2 of the present chapter. It serves a total area of 1340 ha and it is equipped with 344 hydrants, out of which 253 of 5 l s^{-1}, 62 of 10 l s^{-1} and 33 of 20 l s^{-1}. It is designed for on-demand operation. The discharges in the network were calculated using the first Clément model, giving a maximum value of 680 l s^{-1} at the upstream end. The available upstream piezometric elevation is 81.8 m a.s.l. The minimum head required at each hydrant (H_{min}) is 25 m, aiming at the low pressure sprinkler and trickle irrigation. The indexed characteristic curves, calculated by the characteristic curves model, are reported in Figure 69.

From these curves, it is observed that the set-point P_0 (675 l s^{-1}, 81.8 m a.s.l.) falls on the characteristic curve of 25%. It means that only 25% of the investigated configurations are fully satisfied, which is a low value. In order to understand if any design change is required, the analysis using the AKLA model was performed. The probability curves relative to the percentage of unsatisfied hydrants corresponding to a given upstream discharge are presented in Figure 70.

Each curve of Figure 70 represents the probability that the percentage of unsatisfied hydrants (PUH) exceeds the indicated values. These curves have been drawn for the upstream piezometric elevation of 81.80 m a.s.l. (design condition). When 10% probability of occurrence is considered (upper curve in Figure 70), the PUH corresponding to the design discharge (675 l s^{-1}) is close to 25%. Therefore, it is concluded that 75% of configurations which were not satisfied (Figure 69) are those including only a restricted number of hydrants (i.e. probably the 15% placed in less favourable position. This was confirmed by the analysis concerning the hydrants (Figures 73 and 74).

FIGURE 70

Curves of the probabilities that a given percentage of unsatisfied hydrants (PUH) be exceeded, computed using 500 random configurations. Upstream elevation Z_0= 81.80 m a.s.l.
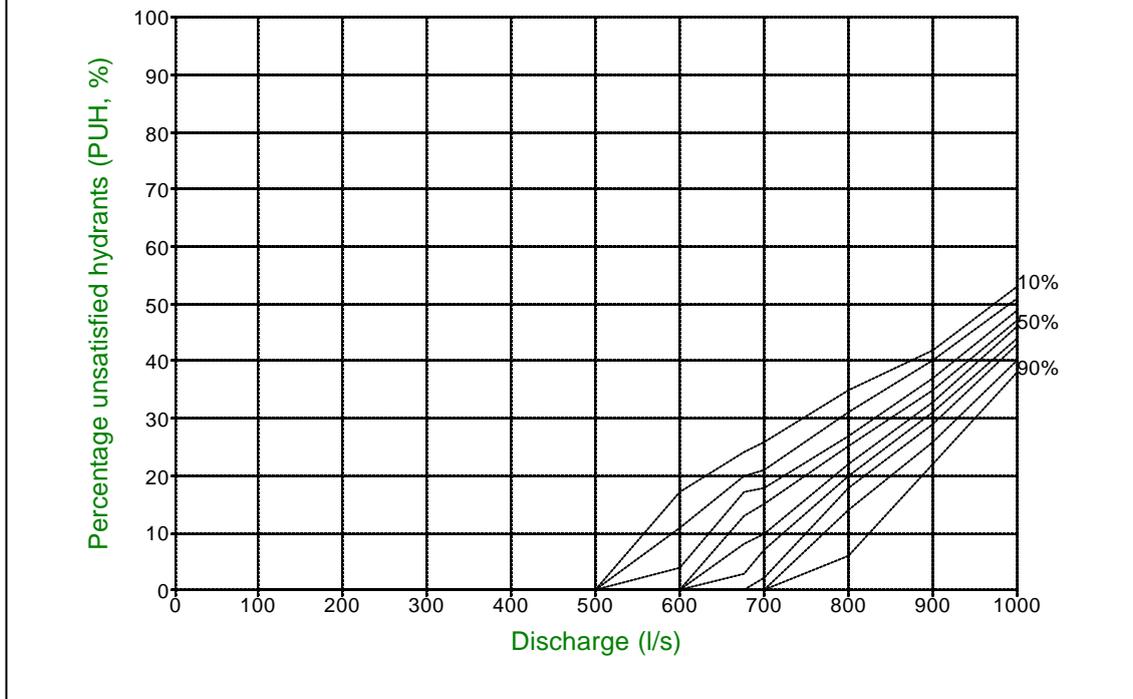
By running the model for different upstream piezometric elevations ranging from 60 to 110 m a.s.l., and by selecting the 10% probability curve (as indicated in Figure 60), Figure 71 was obtained. It shows the variation of the percentage of unsatisfied hydrants (PUH) versus the discharge, for different values of the upstream piezometric elevation and for 10% probability that a higher PUH may occur. This figure gives information on the need, if any, to increase or decrease the upstream piezometric elevation to obtain a lower PUH. At the investigated set-point P_0 (675 l s^{-1}, 81.80 m a.s.l.), this representation confirms a percentage of unsatisfied hydrants equal to about 15%. The whole range of variation of PUH, for the upstream discharge Q_0=675 l s^{-1}, is comprised between 85% at the piezometric elevation of 60 m a.s.l. and 0% at the piezometric elevation of 100 m a.s.l.

Results in Figure 71 indicate the effect of drop in pressure. If the piezometric elevation falls from Z_0=81.80 m a.s.l. to Z=75 m a.s.l., the PUH for the design discharge Q_0=675 l s^{-1} falls to 33%. When a lower value Z=70 m a.s.l. is considered the PUH drops to 50%.

Comparing the characteristic curves in Figures 69 and 71, it is observed that respective results are different. This disagreement between the two models is explained because a part of the project area is located in a zone where land elevation is higher. Indeed, by using the indexed characteristic curves model, anytime one hydrant located in that zone is drawn up, the whole configuration is considered unsatisfied. Consequently, a low percentage of configurations satisfied does result. On the contrary, when using the AKLA model, because only the unsatisfied hydrants, rather than the configurations, are considered, it can be observed that the percentage of unsatisfied hydrants is low.

FIGURE 71

Curves representative of the percentage of unsatisfied hydrants (PUH), with 10% of probability to be exceeded, with the variation of the upstream piezometric elevation from 60 up to 110 m a.s.l.
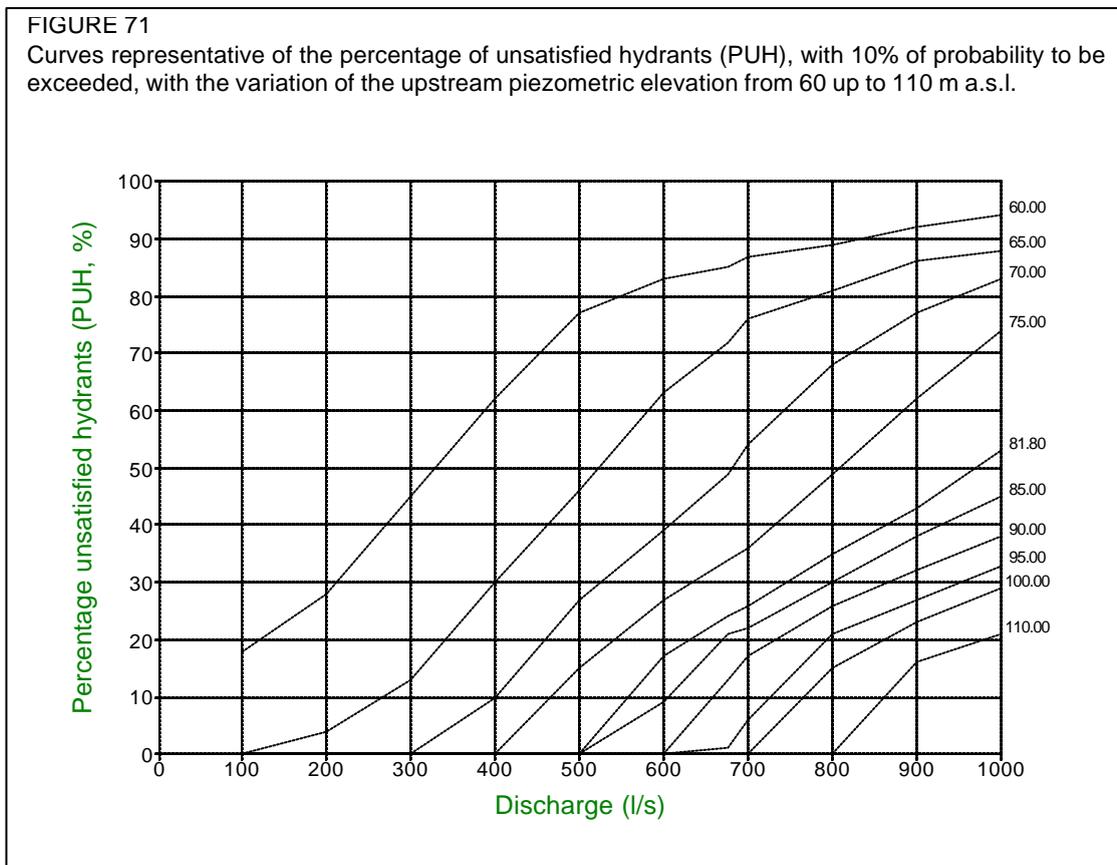

Figure 72 helps to identify the hydrants that are more subject to insufficient pressure and to evaluate the variation range of such dissatisfaction. The corresponding curve obtained when the 10% probability of less satisfactory results are excluded is presented in Figure 73. Both Figures concern the design discharge $Q_0=675$ l s^{-1} and the upstream piezometric elevation $Z_0=81.80$ m a.s.l.

From the analysis of these figures it is observed that, for the whole set of investigated configurations, the zones potentially subject to failure correspond to the hydrants numbered from 90 to 140 and from 165 to 240. By analysing Figure 73 it is concluded that the most critical zones of the network are those relative to the hydrants numbered from 165 to 240. The relative pressure deficit close to $\Delta H =-0.5$ indicates that rehabilitation techniques are required for the hydrants in less favourable elevations. Clearly, models for the analysis of pressurized irrigation networks are extremely useful to determine the hydraulic performance of the systems, particularly those operating on-demand.

It was observed that the indexed characteristic curves model does not provide enough information on the local hydraulic behaviour of a network, despite the usefulness of information supplied both to designers and managers. In fact, the analysis of the indexed characteristic curves can help to support decisions concerning:

- lifting plant design, which can adjust the set-point of the pumps to the characteristic curves of the network and obtain important energy savings;

FIGURE 72
Relative pressure deficits at each hydrant when 500 discharge configurations were generated. Discharge $Q_0=675$ l s^{-1} and upstream piezometric elevation $Z_0=81.80$ m a.s.l.
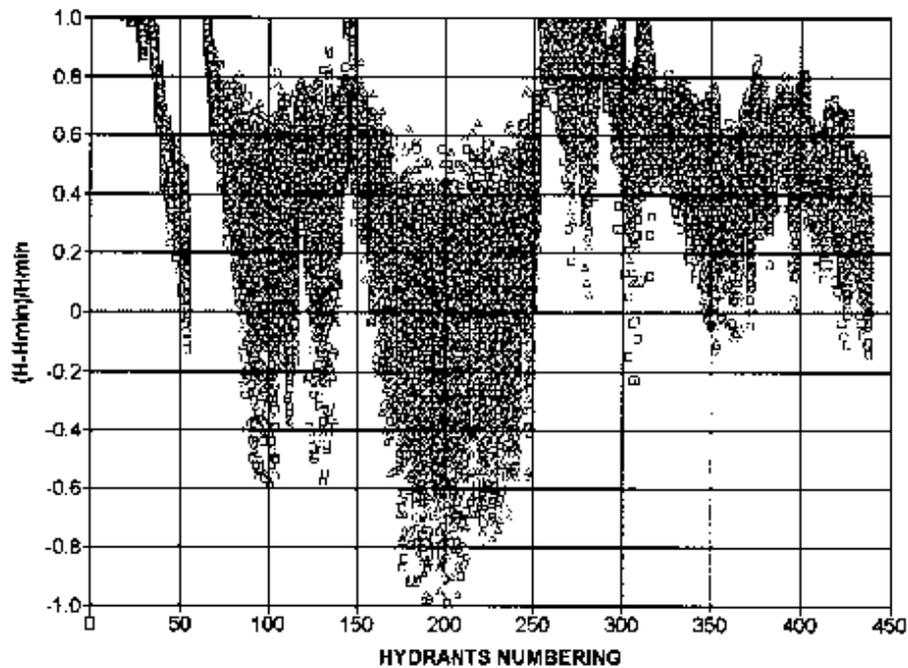
FIGURE 73
Variation of the relative pressure deficit at each hydrant in each discharge configuration. Discharge $Q_0=675$ l s^{-1} and upstream piezometric elevation $Z_0=$of 81.80 m a.s.l. Envelope curve by eliminating 10% of the most unfavourable points.
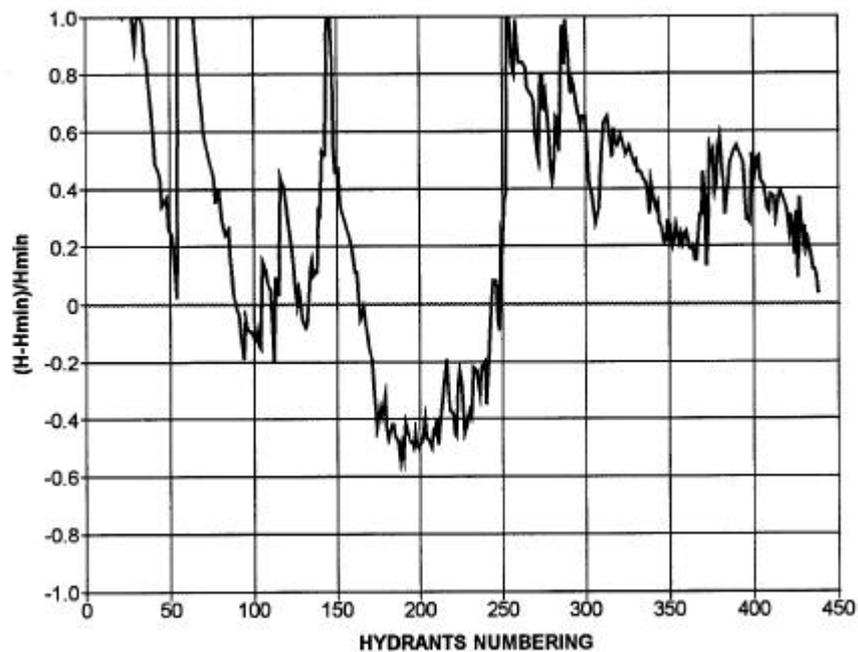
- increasing pipe diameters in the network for reducing head losses to increase the number of satisfied configurations. In fact, introducing these improvements will reduce the slope of the indexed characteristic curves and increase the number of satisfied configurations;

- increasing the upstream piezometric elevation (at the pumping station) in order to satisfy a greater number of configurations.

The AKLA model gives more precise information by determining not only the percentage of unsatisfied hydrants, but also where these hydrants are located and the magnitude of the pressure deficit. Consequently, it is possible to identify the areas with special problems for which specific measures and special solutions may be adopted. These solutions can be applied both at the collective and the individual levels.

In order to solve problems of insufficient pressure at the hydrants located in critical areas, several solutions are possible:

- reinforce pipe sizes of those sections which are producing a great pressure loss upstream of the critical area;

- install additional in-line lifting units;

- impose limitations to the farmers' freedom to withdraw water in that area. It may be possible by placing, upstream, special devices able to stop irrigation during the peak demand hours;

- modify management rules;

- increase the head of the pumping station.

At the individual level, on the contrary, it is possible to:

- install additional lifting units (booster pumps) downstream of the critical hydrants;

- optimize the design of the on-farm system to reduce head losses and improve operation;

- suggest that the farmers in critical areas avoid irrigating during peak hours;

- suggest that the farmers choose low pressure irrigation methods.

Reliability indicator

Monitoring of existing irrigation systems is often suggested to obtain information on the behaviour of the systems and to formulate models that simulate operational scenarios and identify conditions of poor performance. The ability of an irrigation system to operate satisfactorily within a wide range of irrigation demands is an important system characteristic (Hashimoto, 1980; Hashimoto *et al.*, 1982). In many studies, the operational status of a water resource system can be described as either satisfactory or unsatisfactory. The occurrence of unsatisfactory conditions is defined as failure. A failure in a pressurized irrigation system corresponds to a drop in pressure head (and/or discharge) at the hydrant below the minimum required for an appropriate on-farm irrigation.

In this section the reliability performance indicator for identifying an irrigation system failure, especially during peak periods, is described. It can be utilized for improving both design and analysis of irrigation systems. The system reliability describes how often the system fails (Hashimoto, 1980; Hashimoto *et al.*, 1982). The mathematical definition of this criterion is formulated assuming that the performance of an irrigation system is described by a stationary stochastic process. It means that the probability distributions describing the time series (in this case the time series of pressure heads and discharges at the hydrant being considered) do not change with time. This hypothesis is only an approximation but, particularly during the peak periods, it is a reasonable assumption.

Let X_t be the random variable denoting the state of the system at time t (where t assumes values 1, 2,......, n_t). In general, the possible values of X_t are shared into two sets: S, the set of all satisfactory outputs and F, the set of all unsatisfactory outputs (failure). At each instant t the system may fall in one of the above sets. The reliability of a system is described by the probability α that the system is in a satisfactory state:

$$\alpha = \text{Prob } [X_t \in S] \tag{53}$$

In the case of pressurized irrigation systems, the reliability of each hydrant was defined and computed from the results obtained by the AKLA model. In fact, from the definition of reliability given in the Equation 53, the following relationship is obtained:

$$\alpha_j = \frac{\sum_{r=1}^{C} Ih_{j,r} \, Ip_{j,r}}{\sum_{r=1}^{C} Ih_{j,r}} \tag{54}$$

where:

α_j = reliability of the hydrant j,

$Ih_{j,r} = 1$, if the hydrant, j, is open in the configuration r,

$Ih_{j,r} = 0$, if the hydrant, j, is closed in the configuration r,

$Ip_{j,r} = 1$, if the pressure head at the hydrant, j, open in the configuration r, is higher than the minimum pressure head,

$Ip_{j,r} = 0$, if the pressure head at the hydrant, j, open in the configuration r, is lower than the minimum pressure head,

C = total number of the generated configurations.

For each discharge configuration the analysis performed with the model AKLA gives the available head [m] at each operating hydrant. Therefore, the indexes $Ih_{j,r}$ and $Ip_{j,r}$ are easily calculated and the relationship 54 is solved.

The reliability computation is included in the AKLA program and integrated in the COPAM package. A graphical output of this performance indicator is obtained by clicking on the item "Graph/Hydrants Reliability …" in Figure 68.

Application 4

In this section, both the reliability and the relative pressure deficits indicators for an actual Italian irrigation system are computed. The layout of the network is in Box 2 of Chapter 3. The input file data are reported in the Annex 3. All the hydrants of the network have nominal discharge of 10 l s^{-1}. The minimum pressure head for each hydrant is $H_{min} = 20$ m.

Two sets of 200 random discharge configurations, corresponding respectively to 5 and 6 hydrants simultaneously operating, were previously generated using the Random Generation Model. Each discharge configuration corresponds to 50 l s^{-1} in the first set (i.e. design condition), and to 60 l s^{-1} in the second set.

From the Equation 54, the reliability of each hydrant is computed and reported in the Figure 74. Reliability between 0.3 and 0 is observed for the hydrants 18, 19, 20, 22 and 23. Reliability is between 0.9 and 1 for the hydrants 9, 10, 12, 13, and 24 while values between 0.9 and 0.8 are observed for the hydrants 14, 15 and 16.

FIGURE 74
Analysis with 200 random configurations of 50 l s^{-1}
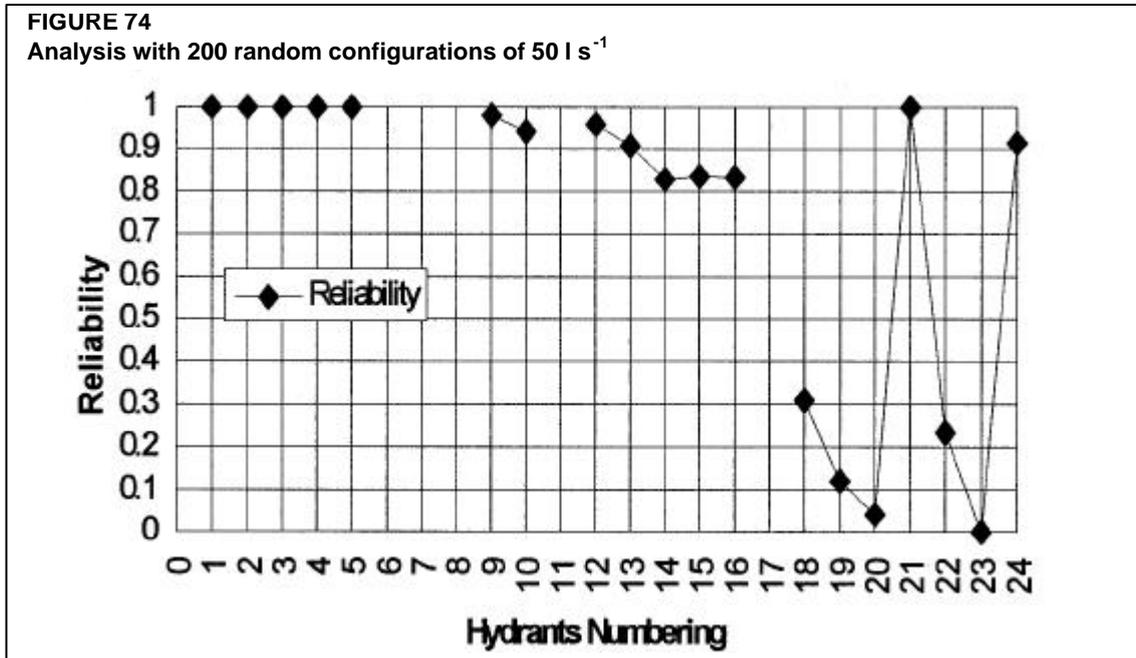
When the analysis is performed with 200 random discharge configurations of 60 l s^{-1}, the reliability at each hydrant is reported (Figure 75). In this case, reliability values between 0.3 and 0 are observed for the hydrants 18, 19, 20, 21, 22, 23 and 24, and between 0.8 and 0.4 are observed for the hydrants 9, 10, 12, 13, 14, 15 and 16. Reliability equals one only for the hydrants 1, 2, 3, 4 and 5.
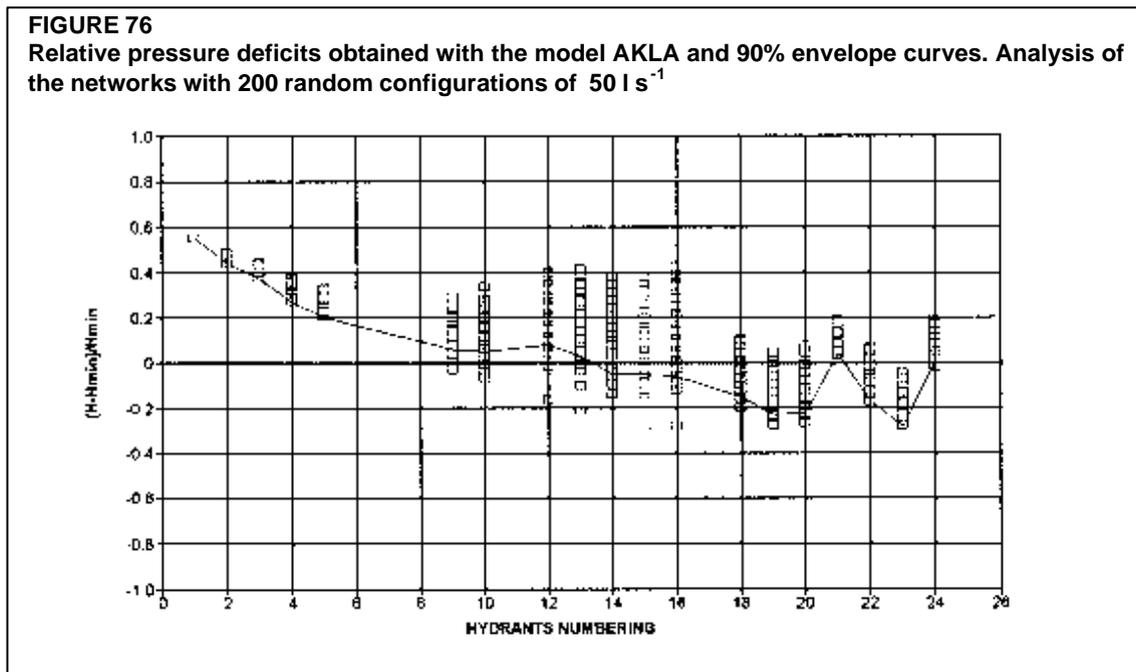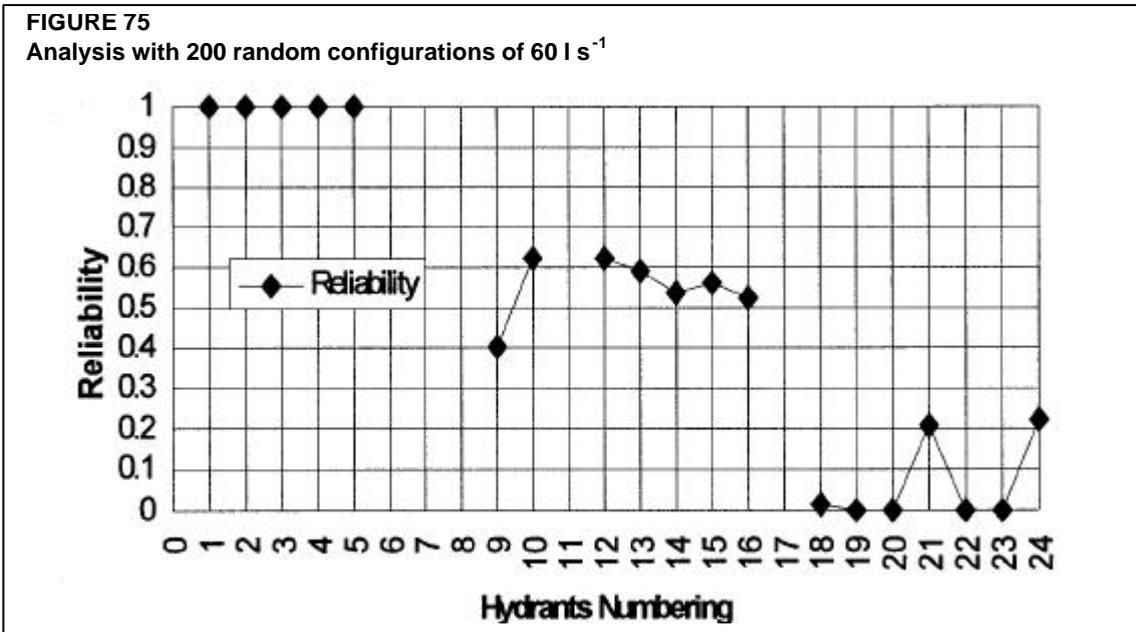
The relative pressure deficits and the 90% envelope curve are reported in Figures 76 and 77. The analyses were performed respectively with the sets S_1 (200 RGM configurations of 50 l s^{-1}) and S_2 (200 RGM configurations of 60 l s^{-1}) of flow regimes.

Important pressure deficits for almost all the hydrants are observed especially when discharges higher than 50 l s^{-1} flow in the network. The performance is low and no assurance of satisfaction exists, especially when scenarios different from the design conditions occur in the system.

These analyses lead to a precise identification of unsatisfied hydrants. Therefore, the rehabilitation and/or modernization processes may be selected for existing irrigation systems.

These processes may concern either physical or management rehabilitation. In the first case, for example, the most critical pipes may be identified and changed through the optimization models presented in section 4. In the second case, the management rules may be modified by changing the on-demand delivery schedule into arranged demand by selecting a more appropriate turn to apply.

One can easily select criteria for modernization. For example, when the manager decides to set constraints for the critical hydrants, special devices (see the next section: "Management issues") activated by an pre-programmed electronic card, could be installed in order to match water resource supply and demand.

FIGURE 75
Analysis with 200 random configurations of 60 l s^{-1}

FIGURE 76
Relative pressure deficits obtained with the model AKLA and 90% envelope curves. Analysis of the networks with 200 random configurations of 50 l s^{-1}

The models for network analysis may be also used in the design process. In fact, an irrigation system that was designed with a classical approach can later be analysed with the above described models. If the performance of the system is not suitable, one can make improvements. The most suitable solution for improving the irrigation system is to agree with the managers about increasing the most critical pipe diameters, setting constraints for the critical hydrants, planning adequate tariff rules, planning different types of delivery schedules, planning special devices, and so on.

FIGURE 77
Relative pressure deficits obtained with the model AKLA and 90% envelope curves. Analysis of the networks with 200 random configurations of 60 l s^{-1}.