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KEYNOTE PAPERS

DIAGNOSYS OF PRESSURIZED IRRIGATION SYSTEMS

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SUMMARY - Pressurized distribution systems have been developed during the last decades with considerable advantages with respect to open canals. In fact, they guarantee better services to the users and higher distribution efficiency. Greater surface may be irrigated by using similar quantity of water. Topographic constraints may be easier overcoming and water fees based on water volumes delivered by farmers may be easier established. Consequently, important quantity of water may be saved since farmers tend to maximize the net income by making an economical balance between costs and incomes. Thus, because the volume of water represents an important cost, farmers tend to conduct soundly their irrigation. Furthermore, operation, maintenance and management activities are more technical but in a way easier to control and maintain a good service. Since farmers are the ones who take risks in their business, they should have water with as much flexibility as possible, i.e., they should have water on-demand. By definition, in irrigation systems operating on-demand farmers decide when and how much water to take from their hydrants, connected to the collective distribution network, without informing the system manager. Unfortunately, one of the most important uncertainties the designer has to face for designing an on-demand irrigation system is the calculation of the discharges flowing into the network. Because of the freedom given to farmers in conducting their irrigation, it is not possible to know, a-priori, the number and the position of the hydrants in simultaneous operation. Important spatial and temporal variability of hydrants operating at the same time occur in such systems in relation to farmers' decision over time depending on the cropping pattern, crops grown, meteorological conditions, on-farm irrigation efficiency and farmers' behavior. This variability may produce failures related to the design options when conventional design techniques are used. Moreover, during the life of the irrigation systems, changes in market trends may lead farmers to deep changes in cropping patterns relatively to those envisaged during the design. Consequently, water demand may change. All the above conditions were identified in the case of a Tunisian irrigation system located at north-west area of Tunis (Ghezala irrigation system). New criteria using appropriate performance analysis models were applied in order to identify failures of the system at the hydrant level and to identify the appropriate ways to conduct rehabilitation and/or modernization interventions.

Key words: pressurized irrigation systems, on-demand systems, peformance analysis model, Ghezala, Tunisia.

INTRODUCTION

The analysis of irrigation systems is the process of using computer simulation models, aiming to evaluate the state of satisfaction of the schemes (performance) and to define the appropriate measures ensuring their improvement (AWWA, 1989). In the case of large scale pressurized irrigation systems, the performance evaluation is referred to standard values of pressure and/or discharge required at the hydrants for an appropriate hydraulic operation of the served on-farm systems. In order to satisfy the farmers requirements, designers and managers are often oriented to on-demand delivery schedules allowing a greater freedom regarding the users decisions. However, this freedom leads to a wide variability of users behavior, difficult to be guessed in the design phase. Therefore, a deep study of the hydraulic performance of such systems under different operation conditions is necessary. Moreover, the ability to identify at the design or operation state (if the systems does exist), the possible structure and/or management interventions capable of satisfying the different requirements is a must.

A deep literature review proved that the numerous models formulated for the calculation of the irrigation systems, are in general, not integrated with any analysis model leading to a difficult quantification of the system performance with time (Lebdi et al., 1993). Nevertheless, the complexity of the management and the manipulation of the data, together with the difficulty of interpretation of the results, mainly delivered under a tabular form, make such models useless for managers and designers (Lebdi and Parent, 1992).

In order to overcome, even partially, the mentioned difficulties, an integrated software with a user-friendly interface has been developed. It allows both the optimal calculation of diameters and the performance analysis of on-demand pressurized irrigation systems. This software has been associated to a Geographical Information System (GIS) able to read the software outputs and to visualize graphically, on maps previously digitized and geo-referenced, the critical zones of the system using different colors denoting for the importance of the deficit in space and time. This procedure allows the identification of the appropriate measures for improving the hydraulic performance of the analyzed system.

In the framework of the present study the integrated software with its main functions will be briefly described. Furthermore, the analysis model which allows the identification of the critical zones of the system at the hydrant level and the interface with the GIS will be presented. Finally the results of the approach applied to a case study will be illustrated.

CONCEPTUAL FRAMEWORK

In the case of large scale pressurized irrigation systems, the performance is evaluated referring to standard values of pressure and/or discharge required at the hydrants level for a good hydraulic operation of the on-farm systems fed downstream. The model used in the present study (Lamaddalena, 1995) allows the analysis of the state of satisfaction of each hydrant in the different operating scenarios and the identification of the critical zones of the scheme using two performance indicators: the relative pressure deficit, ΔH, and the reliability,α, both defined in mathematical terms at the hydrant level. These indicators are given in a tabular and graphical form by the software COPAM.

Under the hypothesis that any operating hydrant may deliver the nominal discharge even for pressures different from those of design stage (this is true for the major part of the existing commercial hydrants), a configuration (i) is defined as a group of operating hydrants (j) corresponding to a fixed value of the nominal discharge Q at the upstream end of the network.

Once the minimum head at the hydrants, H_{min}, required for an appropriate on-farm operation is fixed, a configuration (i) is said satisfied when, for all its operating hydrants (j), the following condition is respected:

$$(H_j)_i \geq H_{min} \tag{1}$$

For each generated configuration (i), a hydrant (j) is defined as satisfied if the following relation is verified :

$$Hj\ ,i \geq Hmin \tag{2}$$

The state of each single hydrant is expressed using the relative pressure deficit defined as follows:

$$\Delta H_{j,i} = \frac{H_{j,i} - H_{min}}{H_{min}} \tag{3}$$

The model is based on the random generation of the operating hydrants configurations and, under the hypothesis that each hydrant may withdraw the nominal discharge (d), when the discharge (Q0) is fixed at the upstream end of the network, the number of hydrants simultaneously operating (K), is given by the following relationship

$$K = \frac{Q_0}{d} \tag{4}$$

Once the available piezometric head at the upstream end of the network, Z0, and the operating discharge, Q0, are set, the verification under the permanent flow condition allows to compute, for each configuration, i, the pressure head of each hydrant Hj,i and, consequently, the relative pressure deficit □Hj,i. All of these values could be classified in a decreasing order and grouped in percentage curves ranging from 10% to 100% by a 10% step in order to synthesize, and to visualize graphically the results. The graphical representation (hydrants numbering; □Hj,i) allows the identification of the critical zones of the system.

The head losses have been calculated using Darcy-Weisbach relationship:

$$J = \frac{\lambda v^2}{D\ 2\ g} \tag{5}$$

where:
J is the unitary linear head (m/m),
λ is the non dimensional parameter,
v is the velocity (m s-1),
D is the diameter and g the gravity acceleration (m s-2).

The relative pressure deficit is an indicator of the spatial variability of the hydrant pressure head. An additional indicator of a system performance is the reliability (Hashimoto, 1980; Hashimoto et al., 1982). The definition of this indicator implicates that the system performance could be represented using a stationary statistical procedure which, in our specific case, means that the distribution of the probability which describes a temporal series of pressures and /or discharges at the hydrants level does not change in time. This hypothesis is acceptable, during the peak periods, where the analysis assumes a greater importance.

Let Xt be the random variable denoting the state of the system at a time t (where t may assume the values 1, 2,......, n). In our specific case, Xt is identified as the pressure head at the hydrant level. In general, the possible values of Xt may be shared into two sets: S, the set of all satisfactory outputs (and then the pressure heads at the hydrants are satisfactory when Hj,i ≥ Hmin), and F, the set of all unsatisfactory outputs (failure state: Hj,i < Hmin). At each instant t, the system may fall in one of the above sets.

The reliability of the system could be described as the probability α, that the system has a satisfactory state:

$$\alpha = \text{Prob}\ [Xt \in S] \tag{6}$$

the above general definition of the reliability has been given in the case of distribution irrigation systems (Lamaddalena, 1997) using the following relation, deriving from (6):

$$\alpha_j = \frac{\sum_{r=1}^{C} Ih_{j,i}\ Ip_{j,i}}{\sum_{r=1}^{C} Ih_{j,i}} \tag{7}$$

where:
α j = reliability of the hydrant j,
Ihj,i = 1, if the hydrant , j, is open in a configuration i,
Ihj,i = 0, if the hydrant , j, is closed in a configuration I,
Ipj,i = 1, if the pressure head at the hydrant j, open in the configuration i, is higher than Hmin,
Ipj,i = 0, if the pressure head at the hydrant j, open in the configuration i, is lower than Hmin,
C = total number of generated configurations.

In order to geo-reference and propagate the results given by AKLA, an integrated software package with an user-friendly interface was developed (Lamaddalena, 1997, Lamaddalena and Sagardoy, 2000). Furthermore, the results were linked with a Geographical Information System.

THE INTEGRATED SOFTWARE COPAM

In order to facilitate the calculation and the analysis of the pressurized irrigation systems, an integrated software has been developed (Lamaddalena, 1997; Lamaddalena e Sagardoy, 2000). It is called COPAM (Fig. 1), and is available with an English "user-friendly" interface.

The COPAM software consists of 3 different programs modules: "Discharge computation", "Pipe size computation" and "Analyses" (Fig. 2). In the "discharge computation" module, two programs are available: the first allows the discharges calculation using the probabilistic approaches of Clément (Clément, 1966), the second allows the simulation of the discharges occurring in the system using a random generation model of hydrants simultaneously operating. The module "Pipe size computation" allows the calculation of the optimal diameters using the iterative discontinued method (Labye,1981) with respect to the boundary and the initial conditions. In the module Analyses, two programs are available: the first allows the global analyses of the system, the second (called AKLA), the identification of the critical zones in the system at the level of each hydrant.

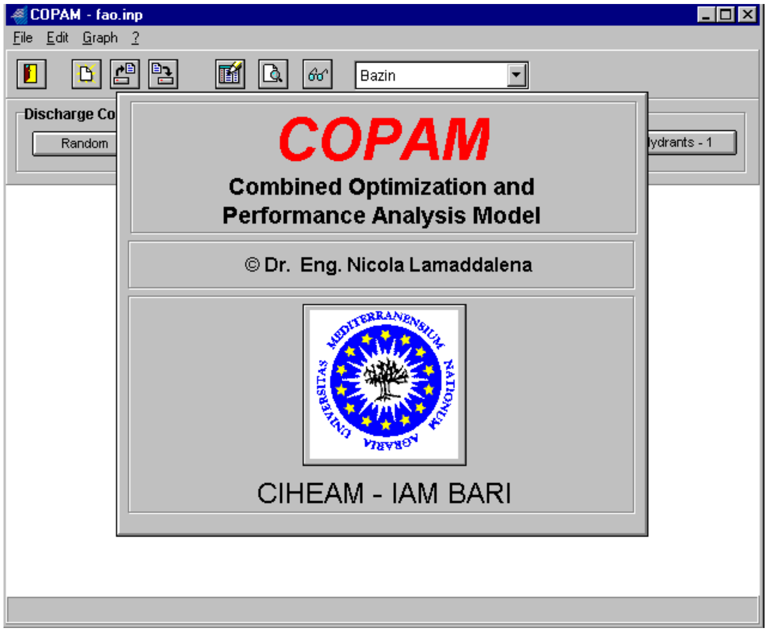


Fig. 1. Introductive slide of COPAM software

In the following, we will concentrate on the description of this last analyses model better adapted to the preset objectives of this study. The performance indicators (Relative Pressure Deficit and Reliability) are presented under tabular and graphical format by the software COPAM.

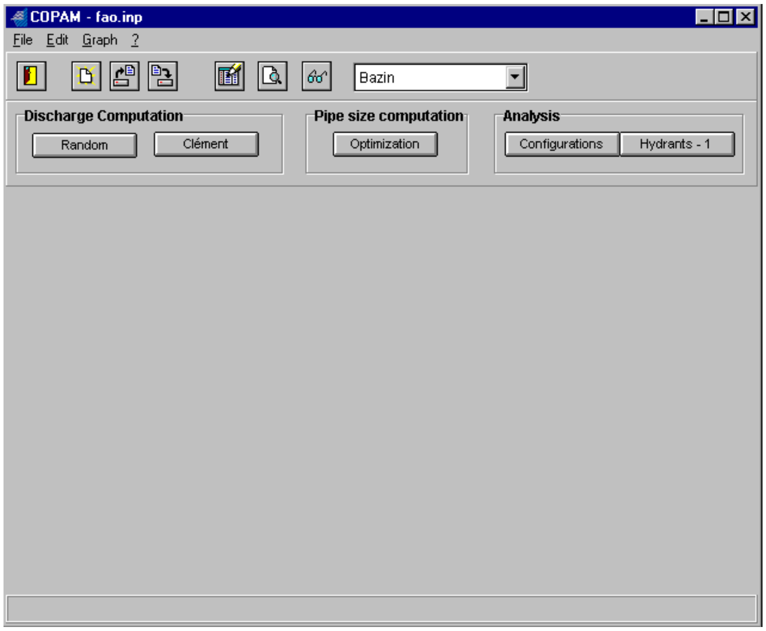


Fig. 2. Layout of COPAM software

THE GEOGRAPHICAL INFORMATION SYSTEM (GIS)

The importance of the spatial geographic component in the on farm irrigation systems performance imposed the involvement of the capabilities able to store, aggregate, manipulate analyze and visualize a huge quantity of data. In the recent last years, to this purpose, the use of GIS has been greatly diffused. These systems, if combined to appropriate simulation models, could support the decisions of designers and/or managers.

A GIS is characterized by a unique ability of a user to overlay spatial layers, each, representing one or more physical and/or functional characteristics of the studied area. Each layer is related to a table, representing the database. Using appropriate models, it’s then possible to actively elaborate the information and to present results under tabular and/or maps form.

There are more than 150 types of GISs on the market. Nevertheless, only few among them are used in the field of water resources (ESRI, 1995). The most diffused one is the ArcView package in Windows version, used in the framework of this study. This package is developed on the easy-to-use main menu which provides the link to the map-view and tabular data management. Moreover, ArcView comes with its own integrated object-oriented programming language and development environment, called Avenue, which performs automated individual tasks, and creates complete applications for interaction with databases and models.

When aiming to develop a decision support system able to furnish detailed, easy reachable and interpretable information on the hydraulic performance of the irrigation systems, the GIS applications could not be underestimated. The collective irrigation systems are in fact integrated systems involving numerous interrelated factors with a spatial (physical characteristics of the networks, distribution of the discharges in the pipes, topography, on-farm irrigation methods, farmers behavior, etc.). All of these factors require an extensive database that must be stored and managed efficiently in order to be easily associated to the analyses models described above.

In this profile, an interface has been created between the software COPAM and ArcView (Lamaddalena and Khadra, 2001), and it allows to:

- Read the values of the relative pressure deficit and of the reliability at each hydrant, computed using the analysis model AKLA and stored in the database of COPAM;
- Visualize the results on a geo-referenced map, previously digitized, where the critical zones and the failure entity are identified through different colors. In the next paragraph the application of the model AKLA associated to the GIS interface to an Italian irrigation scheme is described.

DESCRIPTION OF THE CASE STUDY

The analysis has been achieved on a district of the Ghezala irrigation scheme in the Gouvernorat of Bizerte. The irrigation network originates from the Ghezala dam with a capacity of 5.6 10^6 m^3, located in a dominant position with respect to the served area of 1065 ha. On the upstream network pipe an ultrasonic flow-meter equipped with a data-logger is installed. The irrigation network is a branched distribution network. The total number of hydrants is 147 having nominal discharge of 5 ls^{-1} and 20 ls^{-1}. The distribution network is designed to operate on-demand. The discharges have been calculated with the first Clément formula. The parameters used in the design phase, allow a maximum upstream discharge of 650 ls^{-1} (Minister of agriculture DGETH and 1985).

Hydraulic analysis

In order to perform the analysis in correspondence with the most critical discharges flowing into the network, a flow-meter equipped with a data-logger was installed at the upstream end of the network during 1998 in order to collect reliable data on farmers' withdrawals. Unfortunately that flow-meter sometime was broken and the discharge series was not complete. In any case, we always recorded the delivered daily volumes during the whole period 1998 - 2000 and, in addition, we recorded the hourly discharges for some critical period of the years 1998 and 1999 (see example in Fig. 3).

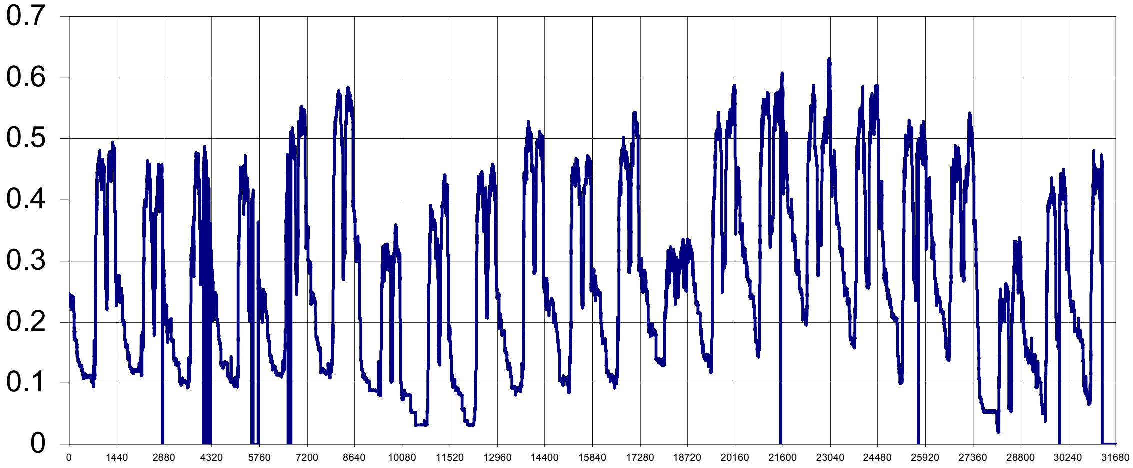


Fig. 3. The registrations of Ghezala flowmeter [in m^3 s^{-1}] for the year 1999, May 1-22

Fig. 3 shows that, in general, there are hours of the day where farmers prefer to irrigate more than in others. In addition, we can note that the daily discharge distribution has always the same shape. Under this circumstance, the following methodology is proposed for generating the hourly discharges during the periods of lack in measures.

From the daily recorded volumes, the moving 10-day averages, V_w, are computed starting from the day t=1 until the last day of the season, in order to identify the seasonal peak period. The peak period is located around the day t_m, making

$$Vtm = \max (Vw) \tag{8}$$

therefore, the peak period is [tm - 5 , tm + 4].

From the hourly discharges, Qh, recorded in a typical peak day, the average hourly volumes, Vh, are computed

$$Vh = Qh \; \square t \tag{9}$$

as well as the frequency distribution of withdrawals.

$$f_h = \frac{V_h}{\sum_{h=1}^{24} V_h} \tag{10}$$

The frequency distribution may be assimilated to the probability distribution function because a large number of data are available for the analysis, as reported in Fig. 4.

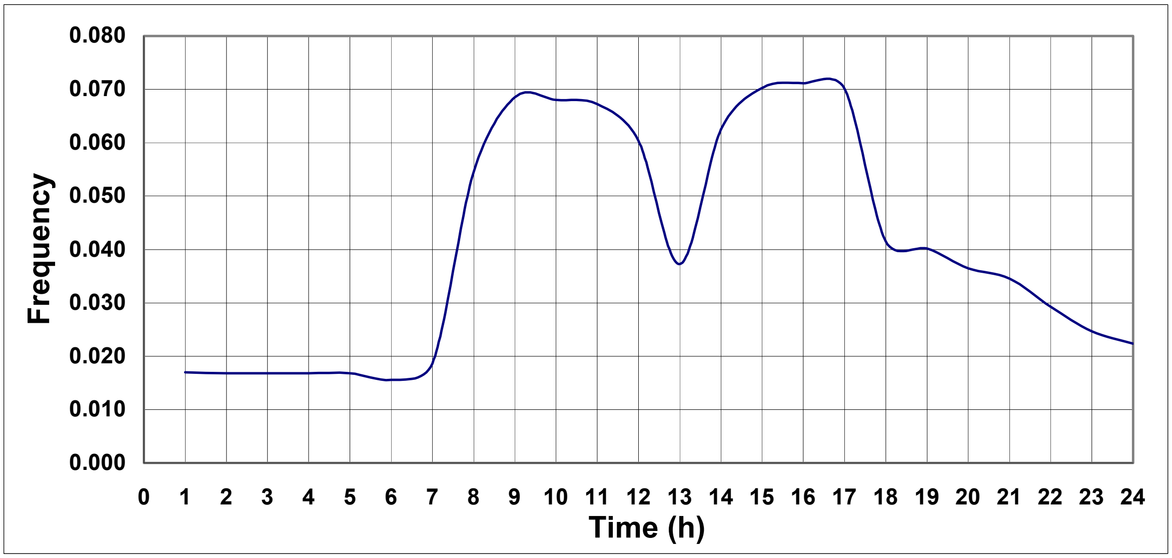


Fig. 4. Probability distribution function of the hourly discharges withdrawn at the upstream end of the network

By using the above frequencies, the hourly discharges, Q_h (in l s^{-1}), can be simulated for the peak period through the recorded daily volumes, V_d (in m^3):

$$Qh = 1000/3600 \; Vd \; fh \tag{11}$$

Through data reported in Table 1, the histogram of the simulated hourly discharges can be computed for the peak period (Fig. 5), as well as the cumulated frequencies (Table 2).

Table 1 - Hourly discharges simulated for the peak period of the year 2000 (from 27 July to 5 August 2000)

Peak period from 27 June to 5 August 2000											
	27	28	29	30	1	2	3	4	5	6	7
hour	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})	Q_h (l s^{-1})
1	180.57	155.04	147.17	180.01	181.48	158.70	158.76	134.61	161.38	161.97	134.61
2	178.77	153.49	145.70	178.21	179.66	157.12	157.18	133.27	159.77	160.35	133.27
3	178.82	153.54	145.74	178.26	179.72	157.17	157.22	133.31	159.82	160.40	133.31
4	178.50	153.26	145.48	177.94	179.40	156.89	156.94	133.07	159.53	160.11	133.07
5	178.45	153.22	145.44	177.89	179.34	156.84	156.90	133.03	159.48	160.06	133.03
6	165.55	142.14	134.93	165.03	166.38	145.50	145.55	123.41	147.95	148.49	123.41
7	198.60	170.52	161.86	197.98	199.59	174.55	174.61	148.05	177.49	178.14	148.05
8	579.79	497.82	472.54	577.99	582.70	509.59	509.77	432.23	518.17	520.07	432.23
9	727.97	625.05	593.31	725.70	731.62	639.82	640.05	542.69	650.60	652.98	542.69
10	722.72	620.55	589.04	720.47	726.35	635.21	635.44	538.78	645.91	648.28	538.78
11	714.05	613.10	581.97	711.83	717.64	627.59	627.82	532.32	638.16	640.50	532.32
12	640.89	550.28	522.34	638.89	644.10	563.29	563.49	477.77	572.77	574.87	477.77
13	395.59	339.66	322.42	394.36	397.58	347.69	347.81	294.91	353.55	354.84	294.91
14	664.12	570.22	541.27	662.05	667.45	583.70	583.91	495.09	593.53	595.70	495.09
15	746.30	640.79	608.25	743.98	750.05	655.94	656.17	556.36	666.98	669.42	655.94
16	755.64	648.81	615.87	753.29	759.43	664.14	664.38	563.32	675.33	677.80	664.14
17	744.56	639.30	606.84	742.24	748.30	654.41	654.64	555.06	665.43	667.86	654.41
18	440.47	378.20	358.99	439.10	442.68	387.14	387.27	328.36	393.65	395.10	387.14
19	426.77	366.43	347.83	425.44	428.91	375.09	375.23	318.15	381.41	382.81	375.09
20	387.32	332.56	315.68	386.11	389.26	340.42	340.54	288.74	346.16	347.42	340.42
21	367.14	315.24	299.23	366.00	368.99	322.69	322.80	273.70	328.12	329.32	322.69
22	311.05	267.07	253.51	310.08	312.61	273.39	273.48	231.88	277.99	279.01	273.39
23	261.86	224.84	213.42	261.05	263.18	230.15	230.24	195.22	234.03	234.89	230.15
24	237.46	203.88	193.53	236.72	238.65	208.70	208.78	177.02	212.22	213.00	208.70

Table 2. Frequencies and cumulated frequencies of the simulated hourly discharges

Q(l s^{-1})	Frequencies	Cumulated frequencies (%)
$350 \leq Q < 400$	0	0.00
$400 \leq Q < 450$	7	7.29
$450 \leq Q < 500$	4	11.46
$500 \leq Q < 550$	9	20.83
$550 \leq Q < 600$	19	40.63
$600 \leq Q < 650$	22	63.54
$650 \leq Q < 700$	17	81.25
$700 \leq Q < 750$	14	95.83
$750 \leq Q < 800$	4	100

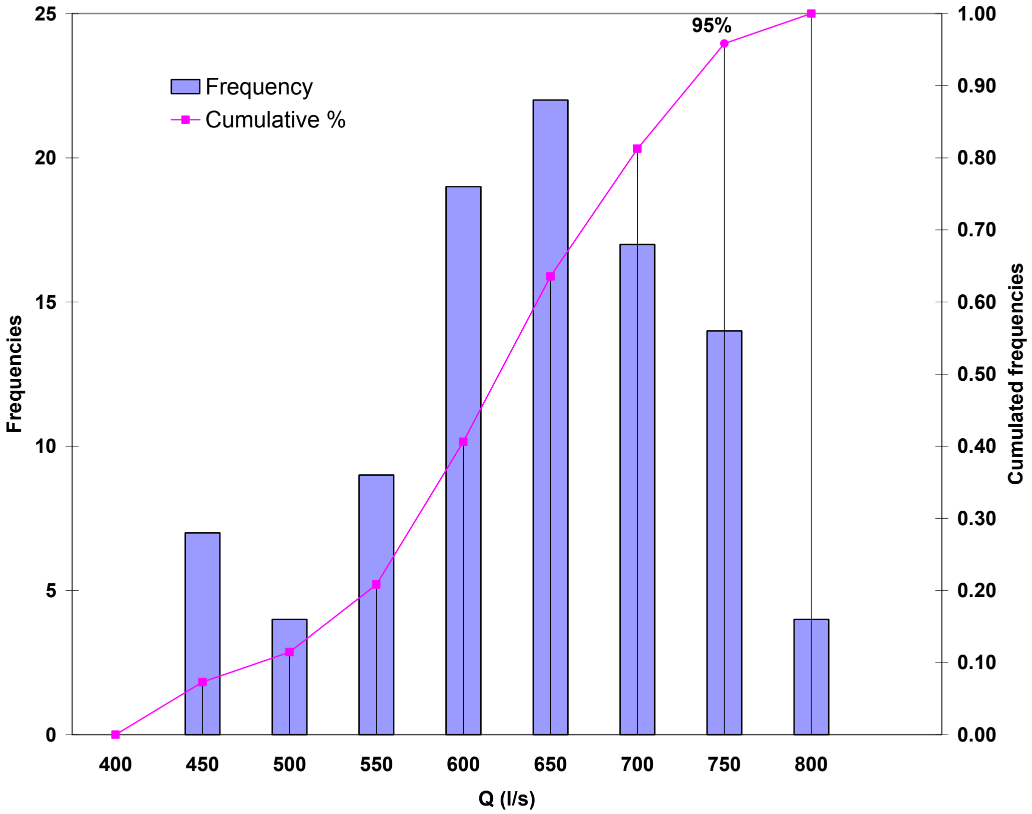


Fig. 5. Histogram of the simulated hourly discharges

From Fig. 5, we selected the discharge having 95% probability not to be exceeded. This discharge, Q95, is equal to 750 l s-1 and it is used for the operation analysis of the Ghezala irrigation network. From Fig. 5, a good fitting of the simulated discharges with the Gaussian distribution function is recognized, during the peak period. Therefore, the AKLA model was applied considering the design discharge, of 750 l/s, and the piezometric elevation (corresponding to the minimum level at the upstream storage reservoir) of 73 m a.s.l.

One thousand different operating scenarios have been generated, corresponding to 1000 different configurations of hydrants simultaneously operating. The model allowed to compute for each hydrant, both the relative pressure deficit and the reliability. The respective results have been reported in the graphs of Fig 5.

These graphs show how more or less the whole network is in deficit conditions with respect to the design minimum head (H_{min} = 20 m). Moreover, we notice some zones where the relative pressure deficit is lower than -1, which means that conditions of negative pressure may occur at the hydrants and they may cause dangerous unsteady flow phenomena in the pipes due to air intrusion. The results of these analyses have been confirmed by the technical staff of the CRDA Bizerte and by the farmers.

In Fig 6 the graphs show the relative pressure deficit percentage curves of 100% and 90%. The first shows the lower envelope of the relative pressure deficits reported in figure 5 (curve of 100% probability of non exceeding of the relative pressure deficit); the second shows the curve of 90% probability of non exceeding the deficit.

All the information mentioned above (network characteristics, relative pressure deficits, reliability of each hydrant) have been stored in a database generated by COPAM. On the maps previously digitized at a scale 1:5000, 4 different layers have been overlayed : the topographic boundaries of the irrigation district, the irrigation network layout and the hydrants.

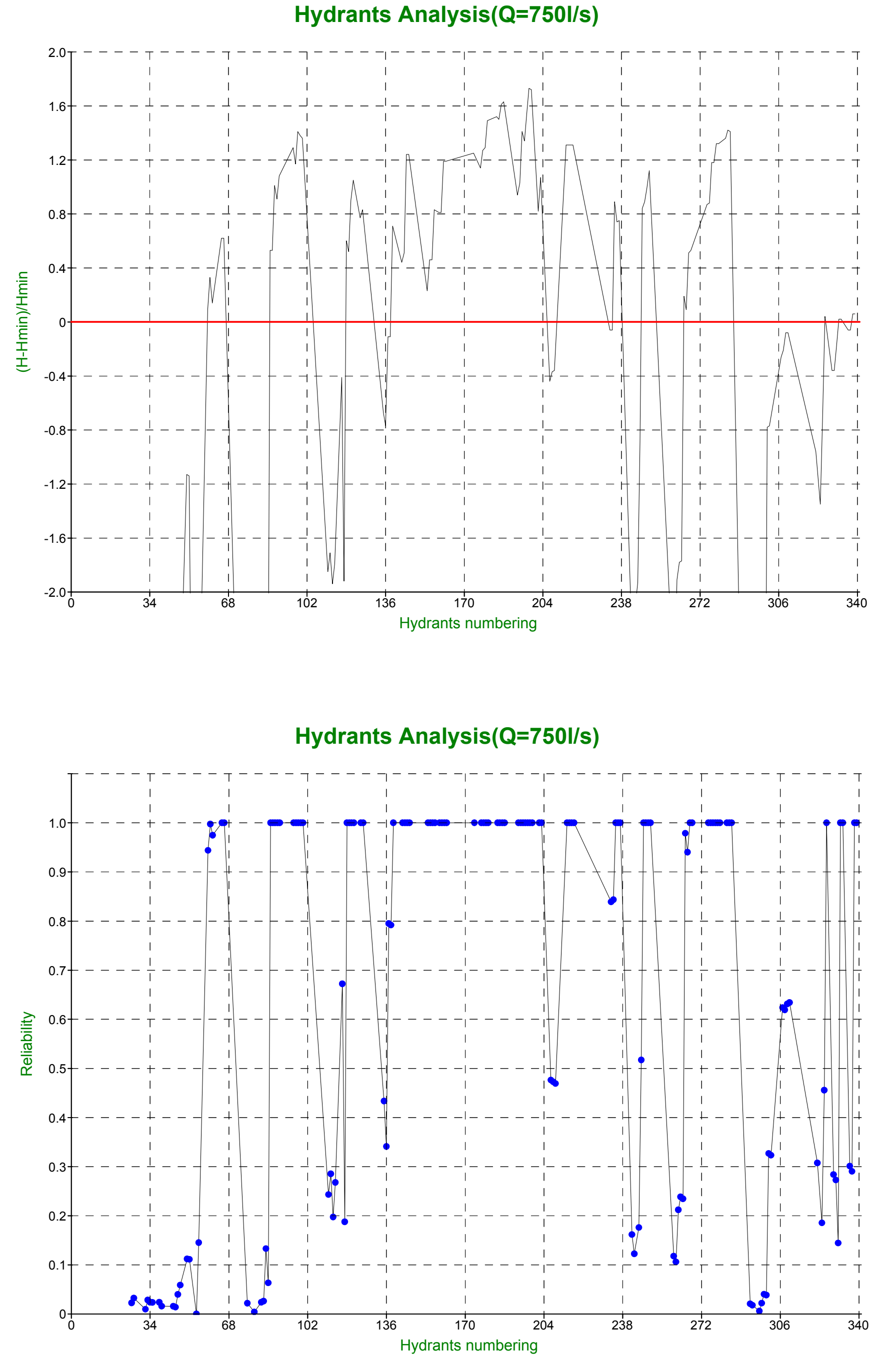
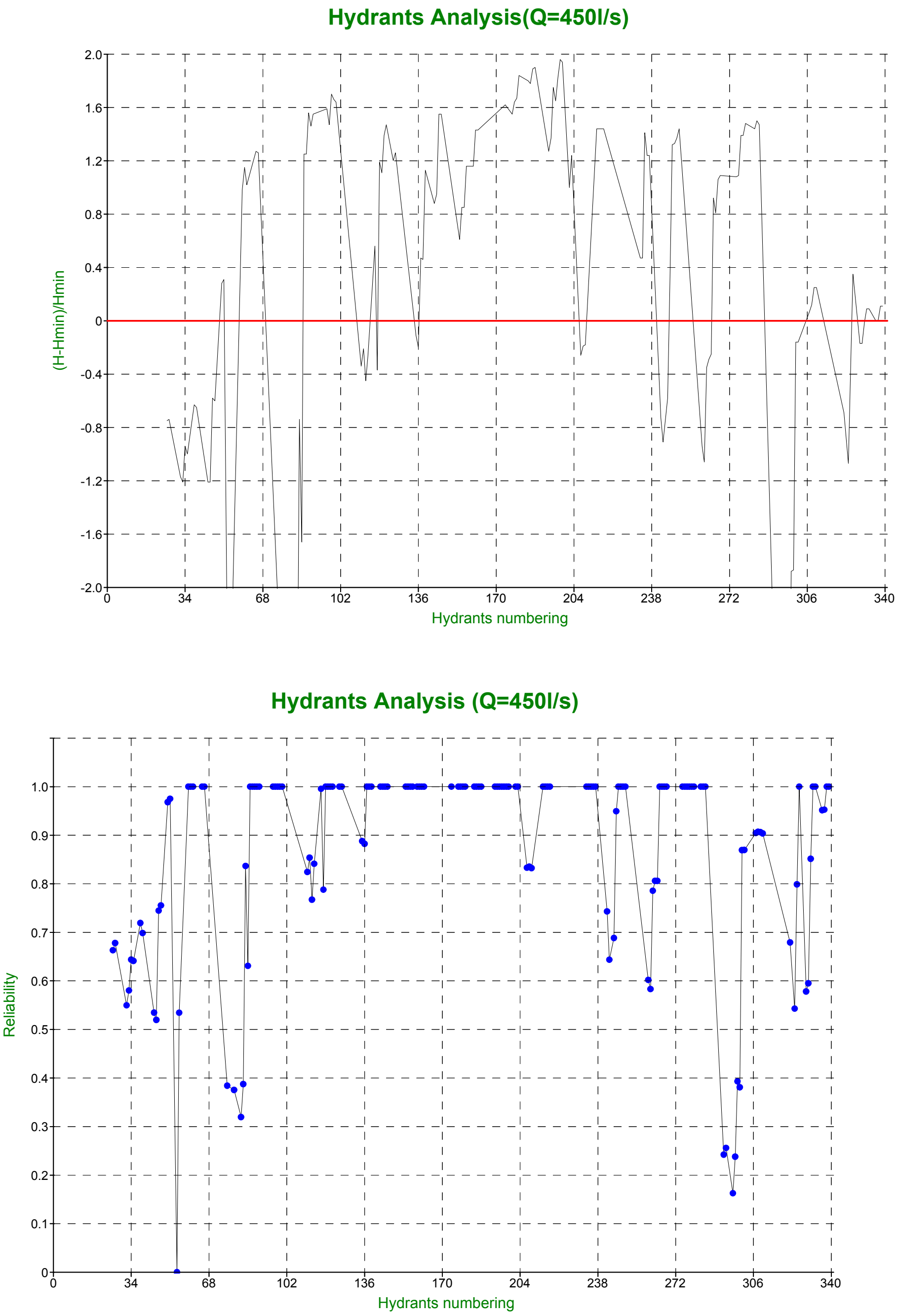


Fig 6(a). Relative pressure deficit with 90% probability not to be exceeded; Fig 6(b). Reliability (upstream discharge Q = 750 l s^{-1})

Furthermore, each hydrant represented on the map was linked to the corresponding node of the COPAM input file. Using a reading interface developed within the framework of the present work, each hydrant has been associated to the percentage relative pressure deficit (varying from 0% to 100%) and to the reliability. Finally, using the advantages of ArcView, the results have been represented in 12 layers, 11 of them indicating the percentage relative pressure deficits and one the reliability (Fig. 7).


Hydrants Analysis(Q=450l/s)

Hydrants Analysis (Q=450l/s)

Fig. 7(a) Relative pressure deficit with 90% probability not to be exceeded; Fig 7(b) Reliability (upstream discharge Q = 450 l s^{-1})

So that, the system performance at the hydrant level has been visualized on the digitized maps, linking each hydrant to a color, according to its state (Fig. 8).

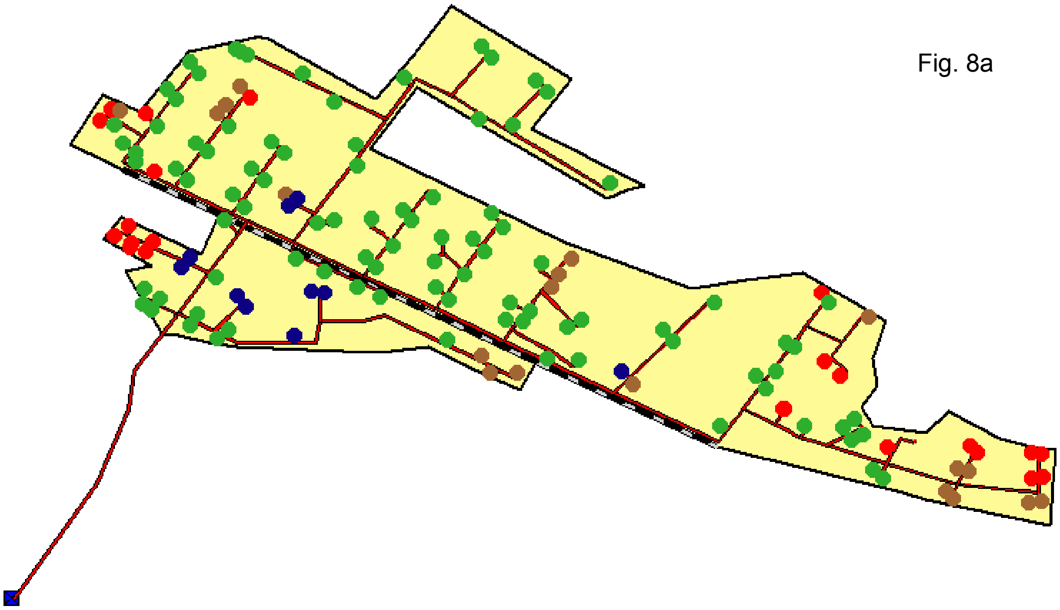


Fig. 8a

Fig. 8b

Fig. 8. Relative pressure deficit with 90% probability not to be exceeded: a) upstream discharge Q = 450 l s^{-1}; b) upstream discharge Q = 750 l s^{-1}

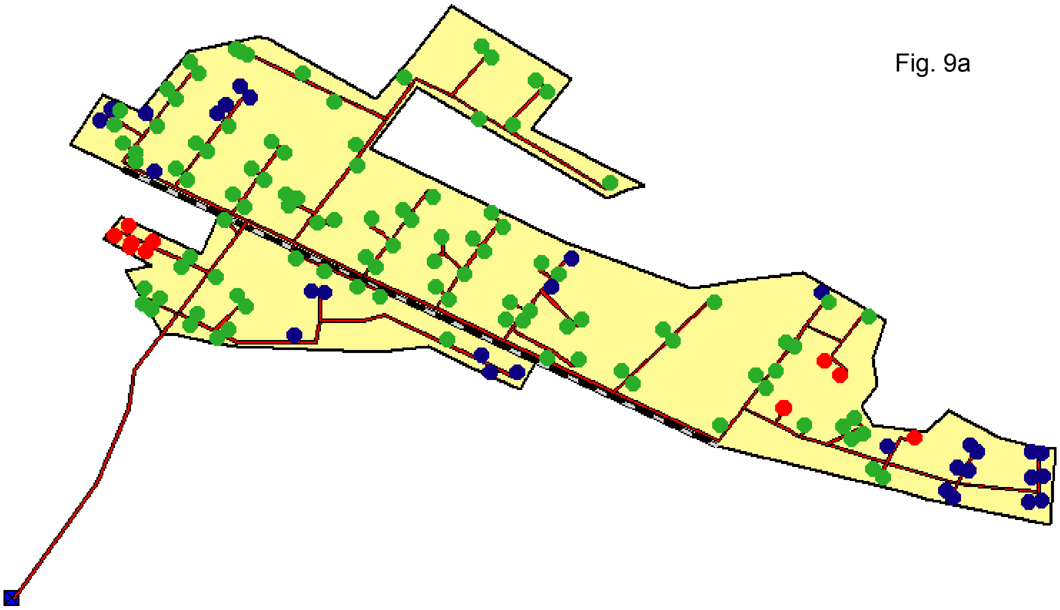


Fig. 9a

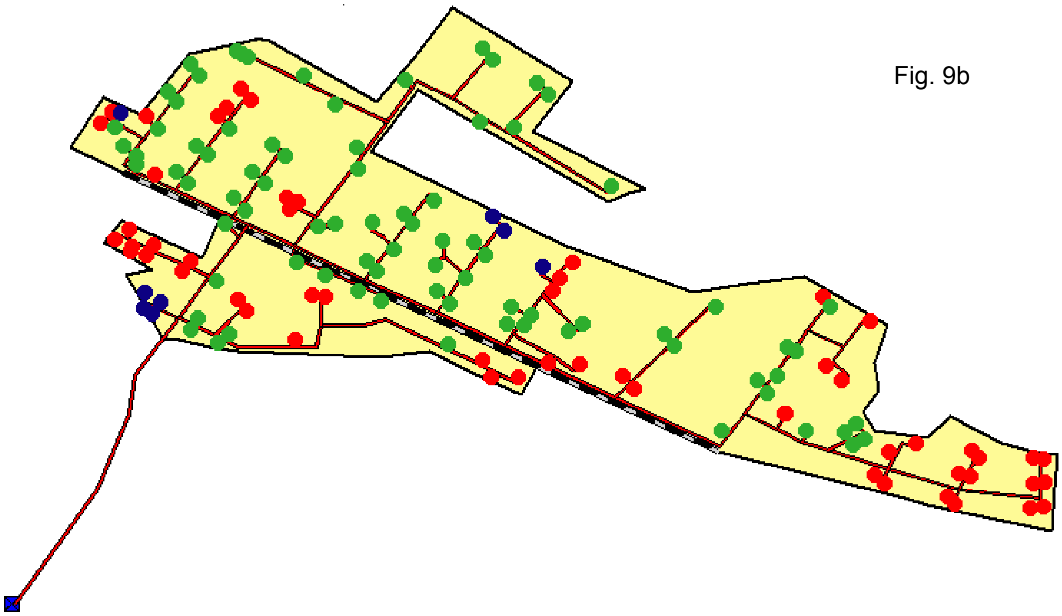


Fig. 9b

Fig. 9. Reliability: a) upstream discharge Q = 450 l s^{-1}; b) upstream discharge Q = 750 l s^{-1}

As an example, Figures 8 and 9 represent respectively, the scenarios of the maximum pressure deficit (corresponding to Fig. 6a) and of the reliability (corresponding to Fig. 6b). From these, the areas of failure and the degree of importance of the failure in space and time are identified. These geo-referenced information, are easily accessible by the designers, the managers and the decision makers of the irrigation schemes who will easily quantify the problems and act consequently. In this specific case, for example, when comparing the Figures 8 and 9, we distinguish many zones of important pressure deficits (represented by the red color in Fig. 8) but of high reliability level (green color in Fig. 9). This is to indicate that in these areas, the failures are verified, in time, with a weak frequency but are of such an entity that they cause very serious problems in the network. On the other hand, zones with a limited reliability (represented with the red color in Fig. 9) are identified and they correspond to areas of weak pressure deficit (green or blue color in Fig. 9). This means that for these areas, the degree of failure is low but the failure persists in time.

CONCLUSIONS

This study demonstrates that by the integration of the analyses models in the geographic information systems, useful and easily accessible information aiming to the improvement of the management of the irrigation systems at on-farm level could be obtained. The application of these tools to an existing network did demonstrate that, even when the design discharge is not exceeded during the operation of the system, important problems that can cause the failure of the system from both of the hydraulic performance and/or pipes security points of view could be verified. The different operation conditions of the hydrants can cause the intrusion of the air in the pipes even if this condition is not frequently verified. However, this condition is to be avoided in both of the management and the design stages. Consequently we conclude that the studied system needs to be rehabilitated using physical means, like the increment of the pipes diameters at the upstream of the identified areas of failure, and/or management means, aiming to the reduction of the discharges during the peak hours.

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