

Performance analysis of on-demand pressurized irrigation systems

FAO
IRRIGATION
AND DRAINAGE
PAPER

59



CIHEAM
International Centre
for Advanced
Mediterranean
Agronomic Studies
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ISBN 92-5-104437-6

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Foreword

Pressurized irrigation systems working on demand were the object of considerable attention in the sixties and seventies and a considerable number of them were designed and implemented in the Mediterranean basin mainly but also in other parts of the world. They offer a considerable potential for efficient water use, reduce disputes among farmers and lessen the environmental problems that may arise from the misuse of irrigation water. With the strong competition that is arising for the water resources, modernization of irrigation systems is becoming a critical issue and one of the alternatives to modernize is the use of pressurized systems to replace part of the existing networks. This approach is being actively pursued in many countries.

Much of the work done in the past concentrated in the design and optimization of such systems and FAO through its Irrigation and Drainage Paper 44: "Design and optimization of irrigation distributions networks" (1988) contributed substantially to this area of knowledge. However, practically no tool existed to analyse the hydraulic performance of such systems, which are very complex due to their constantly varying conditions, until few years ago where the new computer generations permitted complex simulations.

The present work was started with the idea of developing such tool based in the great capacity of computers to generate randomly many situations which could be analysed statistically and provide clear indications of where the network was not functioning satisfactorily. However this work put rapidly in evidence that the same criteria could also be used to analyse a network designed according to traditional criteria and improve the design. This led to the conclusion that the design criteria also needed revision and this additional task was also faced and completed.

The present publication, therefore, has as its main objective the development of a computer tool that permits the diagnosis of performance of pressurized irrigation systems functioning on demand (also under other conditions), but also provides new and revised criteria for the design of such irrigation networks. The publication intends to be complementary to Irrigation and Drainage Paper 44 and where necessary the reader is referred to it for information or methodologies that are still valid.

An effort has been made to reduce the development of formulae but the subject is complex and their use is unavoidable. Calculations examples have been included to demonstrate the calculation procedures and facilitate the understanding and practical use of formulae. The computer program (COPAM) performs these calculations in a question of seconds but it is important that the user has full understanding of what is being done by the program and has the capacity to verify the results.

The computer model has been tested in several field situations in the Mediterranean basin. It has proved its usefulness not only by quickly identifying the weak points of the network but also by identifying the power requirements of pumping stations needed to satisfy varying demand situations and often proving that the powerhouses were not well suited (overdesigned or underdesigned) to meet the requirements of the network.

The present publication is intended to provide new methods for the design and analysis of performance of pressurized irrigation systems, and should be of particular interest to district managers, consultants irrigation engineers, construction irrigation companies, university professors and students of irrigation engineering and planners of irrigation systems in general.

Comments from potential users are welcomed and should be addressed to:

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Acknowledgements

The past involvement of FAO in the subject of this publication, the potential that the subject offers for the future modernization of irrigated agriculture and the interest and experience of the CIHEAM in this area have made it particularly suitable for the association of both organizations in the preparation of this publication, which was of mutual interest.

The author wishes to acknowledge the Director of CIHEAM-Bari Institute and the Director of the Land and Water Development Division of FAO for the continuous support to the undertaking of this activity.

Special mention is due to several students who have participated over the years in the Engineering Master courses at the CIHEAM-Bari Institute and have contributed to the evolution of the modelling approaches presented in this paper.

Special thanks are due to L.S. Pereira, Professor at the Technical University of Lisbon (Portugal) and to M. Air Kadi, Secretary General at the Ministry of Agriculture of Rabat (Morocco) who have been the source of constant inspiration and advice.

Special thanks are also due to the reviewers of the publication, Messrs J.M. Tarjuelo, Professor of the University of Castilla-La Mancha, Spain, T. Facon, Technical Officer, FAO Regional Office for Asia and the Pacific, and R.L. Snyder, Professor, University of California.

This work is dedicated to the memory of Yves Labye who contributed greatly to the scientific background of the approaches used in the present paper and whose works still remain an outstanding intellectual reference.

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List of symbols

A	irrigated area	[ha]
C	number of configurations	[]
C_R^K	number of combinations of R hydrants taken K at a time	[]
d	nominal discharge of the hydrant	[l s ⁻¹]
dH	variation of the head at the upstream end of the elementary scheme of the network	[m]
d_j	discharge for supplying the network downstream the hydrant j	[l s ⁻¹]
dP	minimum cost variation	[ITL]
dY_k	variation of the friction losses in section k	[m]
D	diameter of the pipe	[mm]
D_{c_k}	commercial diameters for section k	[mm]
$(D_{max})_k$	maximum commercial diameter for the section k	[mm]
$(D_{max})_{k,r}$	maximum commercial diameter of the section, k , for the configuration r	[mm]
$(D_{min})_k$	minimum commercial diameter for the section k	[mm]
$(D_{min})_{k,r}$	minimum commercial diameter of the section, k , for the configuration r	[mm]
EH_i	minimum value of the excess head prevailing at all the nodes where the head changes	[m]
f	input frequency of the network (50 Mz standard)	[Mz]
F	set of all unsatisfactory states (failure)	[]
$F(u')$	ratio between $\Psi(u')$ and $\Pi(u')$	[]
F_h	cumulated frequency of the hourly withdrawals during the peak period	[]
FP_{SE}	empirical function indicating the cost variation of the sectors' network, SE, for the variation of its upstream piezometric elevation (Z_{SE})	[]
g	acceleration of gravity	[m s ⁻²]
$H_{j,r}$	head of each hydrant j within the configuration r	[m]
$(H_j)_r$	head of the whole set of hydrants j within the configuration r	[m]

$H_{j,\min}$	minimum head required at the hydrant j	[m]
H_j	head at the hydrant j	[m]
H_{\min}	minimum required head	[m]
H_o	hydrostatic head	[m]
H_{pS}	head at the pumping station	[m]
ITL	Italian lire	[]
J	generic slope of the piezometric line	[m m ⁻¹]
$J_{k,s}$	head losses for unit length of the section k, with the diameter D_s	[m m ⁻¹]
$J_{k,s,r}$	head losses for unit length of the section k, for the discharge of the configuration r, with the diameter D_s	[m m ⁻¹]
k	section identification index	[]
L	generic length of the section	[m]
L_k	length of the section k	[m]
$L_{s,k}$	length of the s th diameter of the section k	[m]
N	number of hydrants simultaneously operating	[]
NAD_k	number of allowable commercial diameters for the section k	[]
NAD_k	number of allowable diameters for the section k	[]
N_p	total population of withdrawn discharges	[]
NQ_i	number of discharges included in the class i	[]
N_{SE}	number of sectors within the district to be optimized	[]
N_{TR}	total number of sections	[]
p	elementary probability of operation of each hydrant	[]
P_C	average cost of the network for the configurations C	[ITL]
$P_{G\lambda}$	conditional probability to change from the state j into the state j+1 during the interval dt	[]
$P_{G\mu}$	conditional probability to change from the state j into the state j-1 during the interval dt	[]
$P_{i,C}$	cost of the network for the configurations i of C	[ITL]
P_k	cost of the section k	[ITL]
P_λ	conditional probability for having an arrival during the time interval (t, t+dt)	[]

P_{μ}	conditional probability for having a departure during the time interval $(t, t + dt)$	[]
P_{NET}	cost of the network	[ITL]
P_q	cumulative probability	[]
P_s	cost per unit length of diameter D_s	[ITL m ⁻¹]
P_{SAT}	conditional probability to have saturation when an opening occurs	[]
q_p	peak continuous flow rate 24/24 hours on the total area	[l s ⁻¹ ha ⁻¹]
q_{pi}	peak continuous flow rate 24/24 hours on the irrigable area	[l s ⁻¹ ha ⁻¹]
q_s	specific continuous discharge	[l s ⁻¹ ha ⁻¹]
\overline{Q}	average discharge withdrawn during the peak period	[l s ⁻¹]
Q	generic discharge	[l s ⁻¹]
Q_{Cl}	Clément discharge at the upstream end of the network	[l s ⁻¹]
$Q_{h,d}$	hourly discharges recorded during the peak period	[l s ⁻¹]
Q_k	discharge in the section k	[l s ⁻¹]
$Q_{k,r}$	discharge flowing in the section k for the configuration r	[l s ⁻¹]
Q_t	discharge withdrawn at a generic instant t at the upstream end of the network	[l s ⁻¹]
Q_{t+t1}	discharge withdrawn at an instant t+t1 at the upstream end of the network	[l s ⁻¹]
r	coefficient of utilization of the network	[]
R	total number of hydrants	[]
R_e	number of Reynolds	[]
RN	random number having uniform distribution function	[]
s_j	numerical indicator of the severity of the state x_j of a system	[]
S	set of all satisfactory states	[]
S_k	series of commercial diameters for each section, k, between $(D_{min})_k$ and $(D_{max})_k$	[]
t'	average operation time of each hydrant during the peak period	[h]
t_{irr}	duration of the opening of the hydrant j	[h]
\overline{T}_f	average sojourn time in the failure states during the period under observation	[h]
T	duration of the peak period	[h]
T'	operating time of the network during the period T	[h]

T_f	time period in which the system is in unsatisfactory state	[h]
u	dimensional coefficient of resistance	[m ⁻¹ s ²]
u	standard normal variable in the 1 st Clément's formula	[]
u'	standard normal variable in the 2 nd Clément's formula	[]
$U(P_q)$	standard normal variable for $P = P_q$	[]
v_{\max}	maximum flow velocity	[m s ⁻¹]
v_{\min}	minimum flow velocity	[m s ⁻¹]
V_d	average daily volume	[m ³]
V_h	average hourly volume	[m ³]
V_T	total average volume withdrawn in the average day of the peak period	[m ³]
$x_{i,s}$	partial length of section k having diameter $D_{k,s}$	[m]
X_t	generic random variable denoting the state of a system at time t	
Y	head losses	[m]
Y^*	value of the head losses in the section k for 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	[m]
Y_k	head losses in the section k	[m]
$Y_{k,r}$	head losses in the section k for the configuration r	[m]
Y_{PS}	head losses in the pumping station	[m]
$(Z_0)_{in}$	initial upstream piezometric elevation	[m a.s.l.]
$(Z_0)_{in,r}$	initial upstream piezometric elevation for the configuration r	[m a.s.l.]
Z_0	available piezometric elevation at the upstream end of the network	[m a.s.l.]
Z_j	piezometric elevation at the hydrant j	[m a.s.l.]
Z_{SE}	upstream piezometric elevation at the upstream end of a sector	[m a.s.l.]
Z_{serb}	upstream piezometric elevation	[m a.s.l.]
ZT_j	land elevation at the node j	[m a.s.l.]
ZT_{PS}	land elevation at the pumping station	[m a.s.l.]
α	reliability of a system	[]
$\Delta H_{j,r}$	relative pressure deficit at the hydrant j in the configuration r	[]

ΔY_i	minimum value of $(Y_{k,i} - Y^*)$	[m]
ΔZ_i	difference between the piezometric elevation at iteration i, $(Z_0)_i$, and the piezometric elevation effectively available at the upstream of the network (Z_0)	[m]
ε	equivalent homogeneous roughness	[mm]
ε_t	discharge tolerance	[l s ⁻¹]
γ	roughness parameter of Bazin	[m ^{0.5}]
λ	constant proportional coefficient	[]
λ_N	constant proportional coefficient for the state N	[]
λ_j	birth coefficient (hydrants opening coefficient)	[]
μ_{exp}	experimental mean value	[l s ⁻¹]
μ_h	average hourly discharges	[l s ⁻¹]
μ_j	death coefficient (hydrants closing coefficient)	[]
μ_{th}	theoretical mean value	[l s ⁻¹]
$\Pi(u')$	cumulative Gaussian probability function	[]
σ^2	variance	
$\Psi(u')$	Gaussian probability distribution function	[]
$\sum_{0 \rightarrow M_j} Y_k$	head losses from the upstream end of the network and the hydrant j along the path M_j	[m]

Chapter 1

On-demand irrigation systems and data necessary for their design

Large distribution irrigation systems have played an important role in the distribution of scarce water resources that otherwise would be accessible to few. Also they allow for a sound water resource management by avoiding the uncontrolled withdrawals from the source (groundwater, rivers, etc). Traditional distribution systems have the common shortcoming that water must be distributed by some rotation criteria that guarantees equal rights to all beneficiaries. The inevitable consequence is that crops cannot receive the water when needed and reduced yields are unavoidable. However, this compromise was necessary to spread the benefits of a scarce resource.

Among the distribution systems, the pressurized 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. Therefore, a greater surface may be irrigated with a fixed quantity of water. They overcome the topographic constraints and make it easier to establish water fees based on volume of water consumed because it is easy to measure the water volume delivered. Consequently, a large quantity of water may be saved since farmers tend to maximize the net income by making an economical balance between costs and profits. Thus, because the volume of water represents an important cost, farmers tend to be efficient with their irrigation. Operation, maintenance and management activities are more technical but easier to control to 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 the distribution network without informing the system manager. Usually, on-demand delivery scheduling is more common in pressurized irrigation systems, in which the control devices are more reliable than in open canal systems.

The on-demand delivery schedule offers a greater potential profit than other types of irrigation schedules and gives a great flexibility to farmers that can manage water in the best way and according to their needs. Of course, a number of preliminary conditions have to be guaranteed for on-demand irrigation. The first one is an adequate water tariff based on the volume effectively withdrawn by farmers, preferably with increasing rates for increasing water volumes. The delivery devices (hydrants) have to be equipped with flow meter, flow limiter, pressure control and gate valve. The design has to be adequate for conveying the demand discharge during the peak period by guaranteeing the minimum pressure at the hydrants for conducting the on-farm irrigation in an appropriate way.

In fact, 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 farmers control their irrigation, it is not possible to know, a-priori, the number and the position of the hydrants in simultaneous operation. Therefore, a hydrant may be satisfactory, in terms of

minimum required pressure and/or discharge, when it operates within a configuration¹ but not when it operates in another one, depending on its position and on the position of the other hydrants of the configuration. These aspects will be treated in detail in the next chapters of this paper.

For on-demand irrigation, the discharge attributed to each hydrant is much greater than the duty². It means that the duration of irrigation is much shorter than 24 hours. As a result, the probability to have all the hydrants of the network simultaneously operating is very low. Thus, it would not be reasonable to dimension the network for conveying a discharge equal to the sum of the hydrant capacities. These considerations have justified the use of probabilistic approaches for computing the discharges in on-demand irrigation systems.

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' behaviour. This variability may produce failures related to the design options when conventional optimization techniques are used. Moreover, during the life of the irrigation systems, changes in market trends may lead farmers to large changes in cropping patterns relatively to those envisaged during the design, resulting in water demand changes. Furthermore, continuous technological progress produces notable innovations in irrigation equipment that, together with on-farm methods that can be easily automated, induce farmers to behave in a different way with respect to the design assumptions. In view of the changes in socio-economic conditions of farmers, a change in their working habits over time should not be neglected. Therefore, both designers and managers should have adequate knowledge on the hydraulic behaviour of the system when the conditions of functioning change respect to what has been assumed.

Improving the design and the performance of irrigation systems operating on-demand requires the consideration of the flow regimes during the design process. It requires new criteria to design those systems which are usually designed for only one single peak flow regime. Complementary models for the analysis and the performance criteria need to be formulated to support both the design of new irrigation systems and the analysis of existing ones. In fact the first performance criterion should be to operate satisfactorily within a wide range of possible demand scenarios. For existing irrigation systems, the models for the analysis may help managers in understanding why and where failures occur. In this way, rehabilitation and/or modernization of the system are achieved in an appropriate way.

MAIN CRITERIA TO DESIGN A DISTRIBUTION IRRIGATION SYSTEM

An irrigation system should meet the objectives of productivity which will be attained through the optimization of investment and running costs (Leonce, 1970). A number of parameters have to be set to design the system (Figure 1). These parameters may be classified into environmental parameters and decision parameters. The environmental parameters cannot be modified and have to be taken into account as data for the design area. The latter depend on the designer decisions.

¹ In this paper, each group of hydrants operating at a given instant is called "hydrants configuration". Each hydrant configuration produces a discharge configuration into the network. The term flow regime is also used as synonymous of discharge configuration.

² In this paper the term duty is used to designate the continuous flow required to satisfy the crop demand and losses of the plot (expressed in $l\ s^{-1}$)

The most important environmental parameters are:

- climate conditions
- pedologic conditions
- agricultural structure and land tenure
- socio- economic conditions of farmers
- type and position of the water resource

Information on the climate conditions is required for the computation of the reference evapotranspiration. Rainfall is important for the evaluation of the water volume that may be utilized by the crops without irrigation.

Information on the pedologic conditions of the area under study is important to identify the boundary of the irrigation scheme, the percentage of uncultivated land, the hydrodynamic characteristics of the soil and the related irrigation parameters (infiltration rate, field capacity, wilting point, management allowable deficit, etc.).

The water resources usually represent the limiting factor for an irrigation system. In fact, the available water volume, especially during the peak period, is often lower than the water demand and storage reservoirs are needed in order to satisfy, fully or partially, the demand. Also the location of the water resource respect to the irrigation scheme has to be taken into account because it may lead to expensive conveyance pipes with high head losses.

Finally, the socio-economic conditions of farmers have to be taken into account. They are important both for selecting the most appropriate delivery schedule and the most appropriate on-farm irrigation method.

All the above parameters have great influence on the choice of the possible cropping pattern.

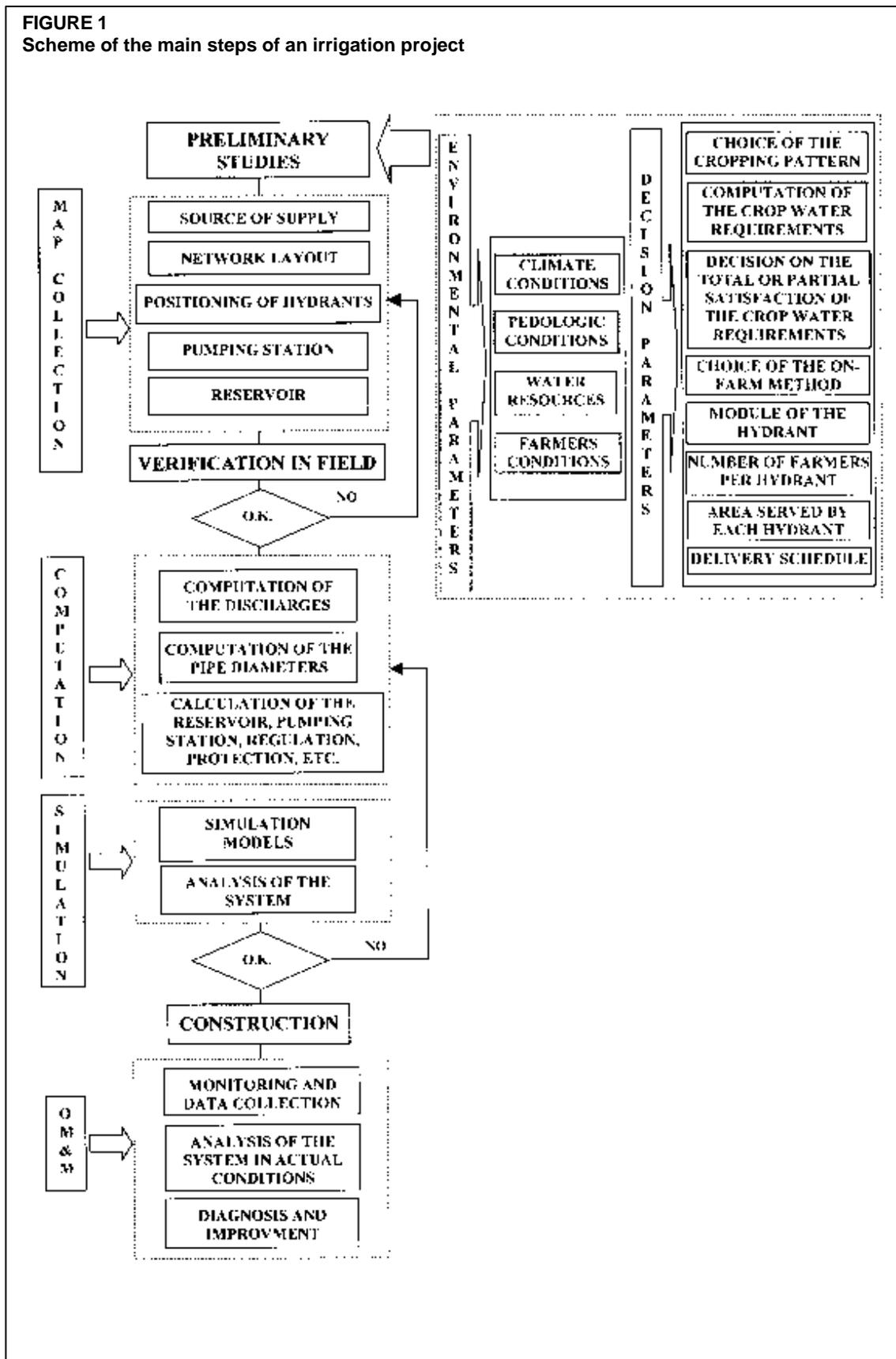
The most important decision parameters are:

- cropping pattern
- satisfaction of crop water requirements (partially or fully)
- on-farm irrigation method
- density of hydrants
- discharge of hydrants
- delivery schedule

The cropping pattern is based on climate data, soil water characteristics, water quality, market conditions and technical level of farmers. The theoretical crop water requirements is derived from the cropping pattern and the climatic conditions.

It is important to establish, through statistical analysis, the frequency that the crop water requirement will be met according to the design climatic conditions. Usually, the requirement should be satisfied in four out of five years. The requirements have to be corrected by the global efficiency of the irrigation system. The computed water volume has to be compared with the available water volume to decide the irrigation area and/or the total or partial satisfaction of the crops in order to obtain the best possible yield.

FIGURE 1
Scheme of the main steps of an irrigation project



The water requirements should account for the peak discharge. This aspect concerns the pipe size computation and will be treated in detail in this paper.

The designer needs updated maps at an appropriate scale (1:25 000, 1:5 000, 1:2 000) with contour lines, cadastral arrangement of plots and holdings (i.e. the designer should know the area of each plot and the name of the holder). In fact, it may happen that a holder has two or more plots and might be served by only one hydrant located in the most appropriate point. The maps should allow for drawing of the system scheme.

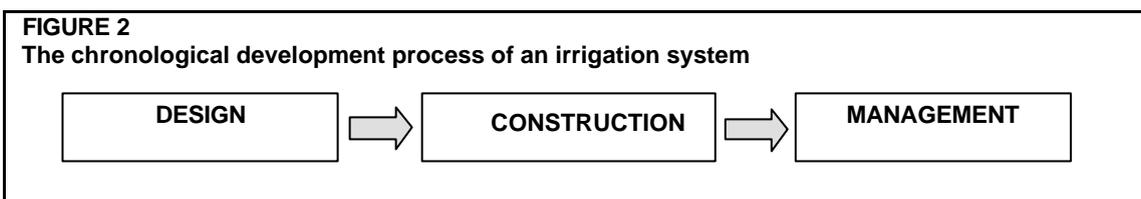
The number of hydrants in an irrigation system is a compromise. A large number improves operation conditions of farmers but it makes for higher installation costs. Usually, for an appropriate density of hydrants it is better to plan no less than one hydrant of 5 l s^{-1} for 2.5 ha and, in irrigation schemes where very small holdings are predominant, no more than three or four farmers per hydrant. These limits will allow a good working conditions of farmers. Also the access to the hydrants should be facilitated. For this reason, in the case of small holdings it is appropriate to locate hydrants along the boundary of the plots. In case of large holdings it may be more appropriate to put hydrants in the middle of the plot in order to reduce the distance between the hydrant and the border of the plot.

The successive steps for designing an irrigation system include defining the network layout and the location of the additional works, like pumping station, upstream reservoir, and equipment for protection and/or regulation, if required. It is important to stress that the above phases are drawn on the maps. Because they are often not updated, field verification is needed in order to avoid passing over new structures that have not been reported on maps.

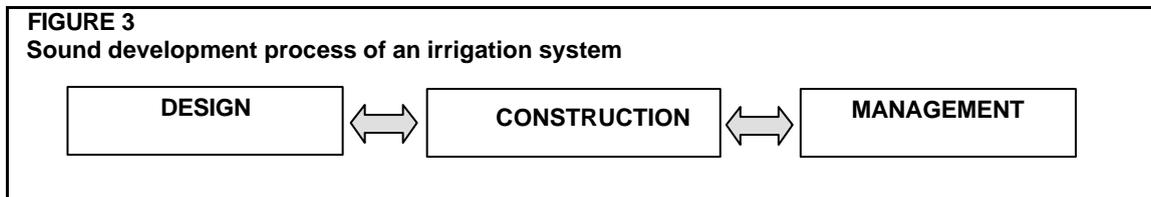
If everything is done well (usually it never occurs), it is possible to move on the next steps, otherwise adjustments have to be done for one or more of the previous steps (Figure 1).

After the previous analysis, computations of the discharges to be conveyed, the pipe diameters of the network, the additional works, like pumping station, upstream reservoir, and equipment for protection and/or regulation, are performed.

The development process of an irrigation system follows a systematic chronological sequence represented in Figure 2.



When this process is a “one-way” process, obviously management comes last. However, experience with many existing irrigation schemes has proven that management problems are related to design (Ait Kadi, 1990; Lamaddalena, 1997). This is because the designer does not necessarily have the same concerns as the manager and the user of a system. It appears beneficial to consider the process in Figure 2 as a “whole”, where the three phases are intimately interrelated (Figure 3).



For these reasons, before moving on the construction of the system, models have to be used to simulate different scenarios and possible operation conditions of the system during its life. The simulation models will allow analysis of the system and will identify failures that may occur. In case of failures, the design has to be improved with adequate techniques that will be described in this paper. Then the construction may start.

After the construction, the designer should monitor the system and collect data on operation, maintenance and management phases. It will allow performing the analysis under actual conditions and will allow calibrating, validating and updating existing models, besides formulating new models, too.

Furthermore, management and all the experience gained on the actual irrigation systems should serve as a logical basis for any improvement of future designs.

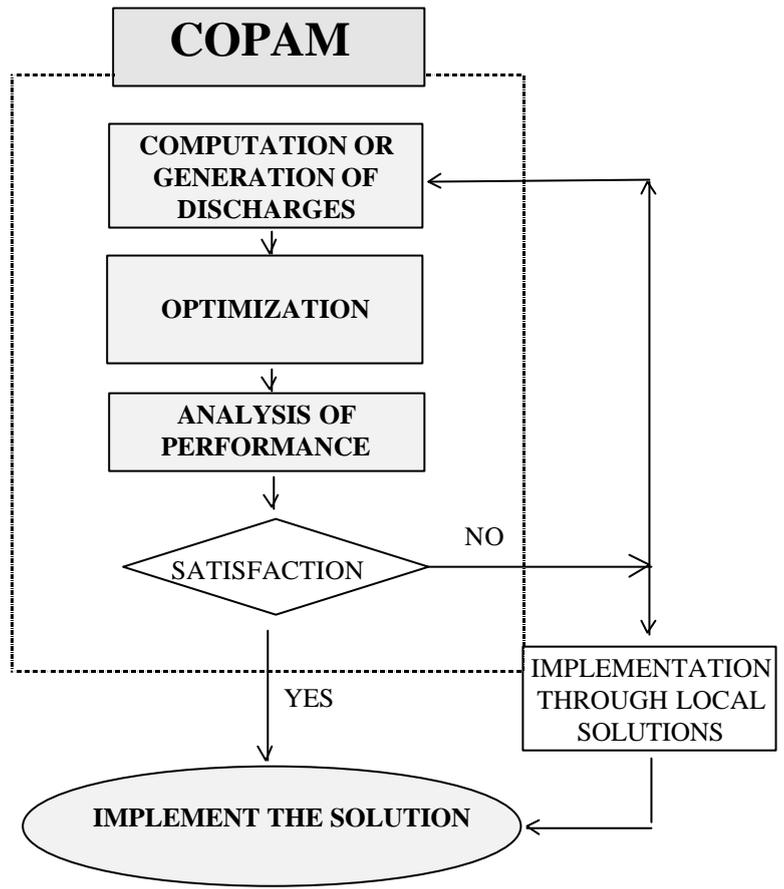
LAYOUT OF THE PAPER

In chapter 1, the definition of on-demand irrigation systems was formulated as well as the main criteria for their design. In chapter 2, criteria for designing the network layout will be analysed. In chapter 3, two probabilistic approaches for computing the discharges in on-demand irrigation systems are presented as well as a model to generate several random flow regimes. In chapter 4, criteria for computing the optimal pipe size diameters, both in the case of one flow regime and several flow regimes occurring in the network, will be formulated. In chapter 5, models for the analysis and performance criteria are identified in order to support design of irrigation systems which should be able to operate satisfactorily within a wide range of possible demand scenarios. Reliability criteria are also presented in this chapter. Finally, the most important management issues are illustrated in chapter 6.

Throughout the paper, a computer software package, called COPAM (Combined Optimization and Performance Analysis Model), is presented and illustrated. COPAM provides a computer assisted design mode. One or several flow regimes may be generated. The optimization modules give the optimal pipe sizes in the whole network. The performance of the resulting design is then analysed according to performance criteria. Based on this analysis, the designer decides whether or not to proceed with further improvements either by a new optimization of the whole system or through implementation of local solutions (such as using booster pumps or setting time constraints for unsatisfied hydrants).

The synthetic flow chart of COPAM is presented in Figure 4.

FIGURE 4
Synthetic flow chart of COPAM



Chapter 2

Network layout¹

STRUCTURE AND LAYOUT OF PRESSURE DISTRIBUTION NETWORKS

Pressure systems consist mainly of buried pipes where water moves under pressure and are therefore relatively free from topographic constraints. The aim of the pipe network is to connect all the hydrants to the source by the most economic network. The source can be a pumping station on a river, a reservoir, a canal or a well delivering water through an elevated reservoir or a pressure vessel. In this publication, only branching networks will be considered since it can be shown that their cost is less than that of looped networks. Loops are only introduced where it becomes necessary to reinforce existing networks or to guarantee the security of supply.

DESIGN OF AN ON-DEMAND IRRIGATION NETWORK

Layout of hydrants

Before commencing the design of the network the location of the hydrants on the irrigated plots has to be defined. The location of the hydrants is a compromise between the wishes of the farmers, each of whom would like a hydrant located in the best possible place with respect to his or her plot, and the desire of the water management authority to keep the number of hydrants to a strict minimum so as to keep down the cost of the collective distribution network.

In order to avoid excessive head losses in the on-farm equipment, the operating range of an individual hydrant does not normally exceed 200 metres in the case of small farms of a few hectares and 500 metres on farms of about ten hectares. The location of hydrants is influenced by the location of the plots. In the case of scattered smallholdings, the hydrants are widely spaced (e.g. at plot boundaries) so as to service up to four (sometimes six) users from the same hydrant. When the holdings are large the hydrant is located preferably at the center of the area.

Layout of branching networks

Principles

On-demand distribution imposes no specific constraints on the network layout. Where the land-ownership structure is heterogeneous, the plan of the hydrants represents an irregular pattern of points, each of which is to be connected to the source of water. For ease of access and to avoid purchase of rights of way, lay the pipes along plot boundaries, roads or tracks. However, since a pipe network is laid in trenches at a depth of about one metre, it is often found advantageous to cut diagonally across properties and thus reduce the length of the pipes and their cost. A method

¹ This chapter has been summarized from FAO Irrigation and Drainage Paper 44. It has been included in this publication for completeness of the treated subject.

of arriving at the optimal network layout is described in the following section. It involves the following three steps in an iterative process:

- "proximity layout" or shortest connection of the hydrants to the source;
- "120° layout" where the proximity layout is shortened by introducing junctions (nodes) other than the hydrants;
- "least cost layout" where the cost is again reduced, this time by shortening the larger diameter pipes which convey the higher flows and lengthening the smaller ones.

The last step implies a knowledge of the pipe diameters. A method of optimizing these diameters is described in Chapter 4.

Fields of application of pipe network optimization

Case of dispersed land tenure pattern

A search for the optimal network layout can lead to substantial returns. An in-depth study (ICID, 1971) of a network serving 1 000 ha showed that a cost reduction of nine percent could be achieved with respect to the initial layout. This cost reduction was obtained essentially in the range of pipes having diameters of 400 mm or more.

In general it may be said that the field of application of network layout optimization mainly concerns the principal elements of the network (pipe diameters of 400 mm and upwards). Elsewhere land tenure and ease of maintenance (accessibility of junctions, etc.) generally outweigh considerations of reduction of pipe costs.

In support of this assertion it is of interest to note that in the case of a 32 000 ha sector, which forms a part of the Bas-Rhône Languedoc (France) irrigation scheme, pipes of 400 mm diameter and above account for less than twenty percent of the total network length. In terms of investment, however, these larger pipes represent nearly sixty percent of the total cost (ICID 1971).

Case of a rectangular pattern of plots

In the case of schemes where the land tenure has been totally redistributed to form a regular checkwork pattern of plots, the pipe network can follow the same general layout with the average plot representing the basic module or unit. The layout of the pipe network is designed so as to be integrated with the other utilities, such as the roads and the drainage system.

OPTIMIZATION OF THE LAYOUT OF BRANCHING NETWORKS

Methodology

The method commonly used (Clément and Galand, 1979) involves three distinct stages:

- 1 - proximity layout
- 2 - 120° layout
- 3 - least-cost layout

Stage 1: Proximity layout

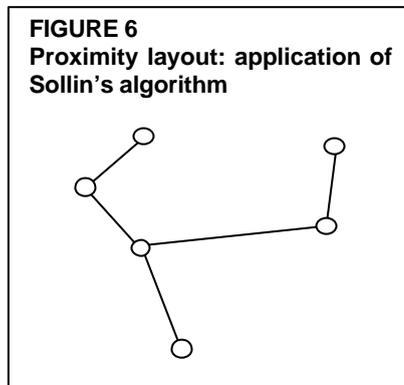
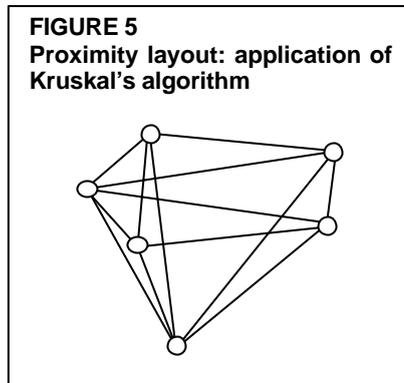
The aim is to connect all hydrants to the source by the shortest path without introducing intermediate junctions here denominated nodes. This may be done by using a suitable adaptation of Kruskal's classic algorithm from the theory of graphs.

If a straight line drawn between hydrants is called a section and any closed circuit a loop, then the algorithm proposed here is the following:

Proceeding in successive steps a section is drawn at each step by selecting a new section of minimum length which does not form a loop with the sections already drawn. The procedure is illustrated in Figure 5 for a small network consisting of six hydrants only.

In the case of an extensive network, the application of this algorithm becomes impractical since the number of sections which have to be determined and compared increases as the square of the number of hydrants: $(n^2 - n)/2$ for n hydrants. For this reason it is usual to use the following adaptation of Sollin's algorithm.

Selecting any hydrant as starting point, a section is drawn to the nearest hydrant thus creating a 2-hydrant sub-network. This sub-network is transformed into a 3-hydrant sub-network by again drawing a section to the nearest hydrant. This in fact is an application of a simple law of proximity, by which a sub-network of $n-1$ hydrants becomes a network of n hydrants by addition to the initial network. This procedure, which considerably reduces the number of sections which have to be compared at each step, is illustrated in Figure 6.



Stage 2: 120° layout

By introducing nodes other than the hydrants themselves, the proximity network defined above can be shortened:

Case of three hydrants

Consider a sub-network of three hydrants A, B, C linked in that order by the proximity layout (Figure 7).

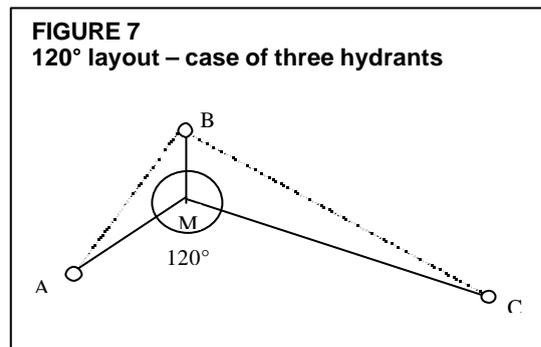
A node M is introduced whose position is such that the sum of the lengths $(MA+MB+MC)$ is minimal.

Let \vec{i} , \vec{j} , \vec{k} be the unit vectors of MA, MB and MC and let dM be the incremental displacement of node M.

When the position of the node is optimal then

$$d(MA + MB + MC) = (\vec{i} + \vec{j} + \vec{k})dM = 0$$

This relation will be satisfied for all displacements dM when



$$\vec{i} + \vec{j} + \vec{k} = 0$$

It follows therefore that the angle between vectors $\vec{i}, \vec{j}, \vec{k}$ is equal to 120° .

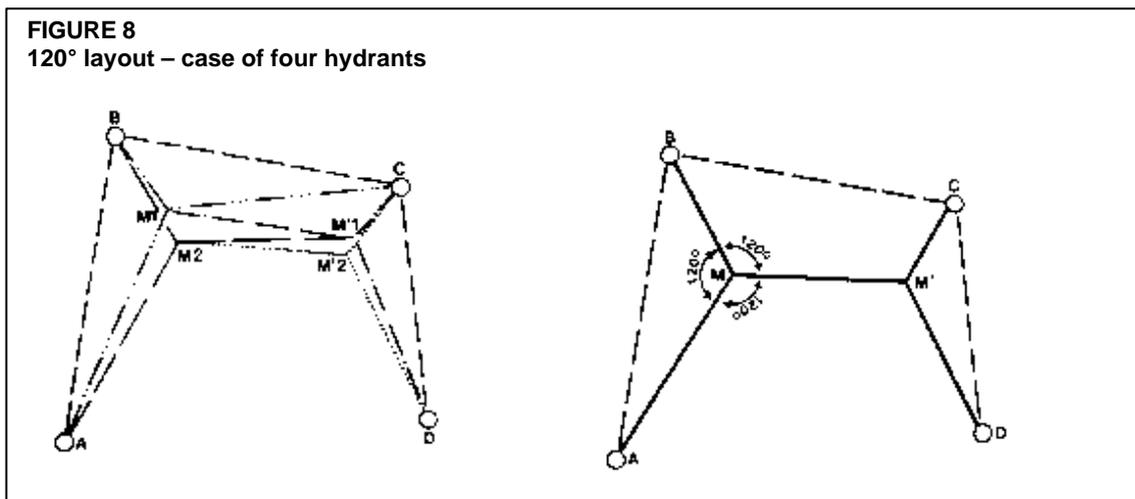
The optimal position of the node M can readily be determined by construction with the help of a piece of tracing paper on which are drawn three converging lines subtending angles of 120° . By displacing the tracing paper over the drawing on which the hydrants A, B, C have been disposed, the position of the three convergent lines is adjusted without difficulty and the position of the node determined.

It should be noted that a new node can only exist if the angle \widehat{ABC} is less than 120° . When the angle is greater than 120° , the initial layout ABC cannot be improved by introducing a node and it represents the shortest path. Conversely, it can be seen that the smaller is the angle ABC, the greater will be the benefit obtained by optimizing.

Case of four hydrants

The 120° rule is applied to the case of a four-hydrant network ABCD (Figures 8 and 9).

The layout ABC can be shortened by the introduction of a node M_1 such that sections M_1A , M_1B and M_1C are at 120° to each other.



Similarly the layout M_1CD is shortened by the introduction of a node M_1' such that $M_1' M_1$, $M_1' C$ and $M_1' D$ subtend angles of 120° . The angle AM_1M_1' is smaller than 120° and the node M_1 is moved to M_2 by the 120° rule, involving a consequent adjustment of M_1' to M_2' .

The procedure is repeated with the result that M and M' converge until all adjacent sections subtend angles of 120° .

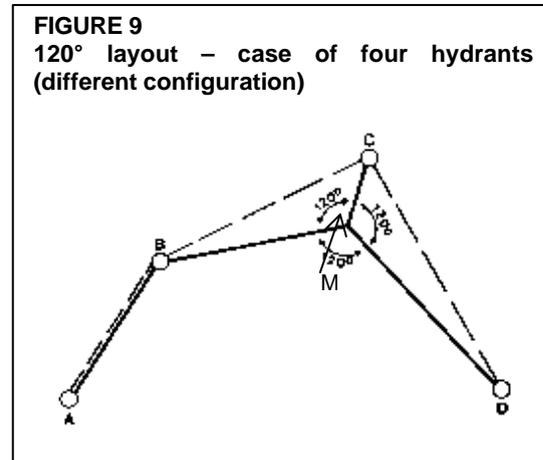
In practice, the positions of M and M' can readily be determined manually with the assistance of two pieces of tracing paper on which lines converging at 120° have been drawn.

A different configuration of the four hydrants such as the one shown in Figure 9, can lead to a layout involving the creation of only one node since the angle ABM is greater than 120° .

Case of n hydrants

The above reasoning can be extended to an initial layout consisting of n hydrants. It can be shown that the resulting optimal layout has the following properties:

- the number of nodes is equal to or less than $n-2$;
- there are not more than three concurrent sections at any node;
- the angles between sections are equal to 120° at nodes having three sections and greater than 120° when there are only two sections.



In practice it is impractical to deal manually with the construction of a network consisting of four or five hydrants, involving the introduction of two or three adjacent nodes, even with the help of tracing paper. Several geometric construction procedures have been devised to facilitate such layouts, but these are rather cumbersome and the problem can only be resolved satisfactorily with the assistance of a computer.

It is rarely necessary to create more than two or three consecutive nodes. Also, the benefit gained by optimizing decreases as the number of adjacent sections increases.

Stage 3: Least-cost layout

Although the layout which results from applying the 120° rule represents the shortest path connecting the hydrants, it is not the solution of least cost since no account is taken of pipe sizes. The total cost of the network can further be reduced by shortening the larger diameter pipes which convey higher flows whilst increasing the length of the smaller diameter pipes which convey smaller flows. This will result in a modification of the angles between sections at the nodes. The least-cost layout resembles the 120° layout but the angles joining the pipes are adjusted to take into account the cost of the pipes.

The step which leads from the 120° layout to the least-cost layout can only be taken once the pipe sizes have been optimized. But this condition induces to a loop. In fact, for calculating the pipe sizes of the network, the layout should be already known. A method for the simultaneous computation of optimal pipe size and layout has been developed for particular distribution systems with parallel branches (Ait Kadi, 1986). Two different approaches have been adopted: the linear programming formulation and a special purpose algorithm. Both these two approaches have been applied to a simple example and their reliability and usefulness was demonstrated. Unfortunately, at this time, no commercial software packages are available for applying such method to actual networks.

Applicability of the layout optimization methods

There is no doubt that the 120° layout is an improvement on the initial proximity layout and that the least-cost layout is a further refinement of the 120° layout. It is not certain however that the complete process produces the best result in all cases.

Usually, “rules of thumb” are applied by designers in selecting the best suitable layout and, later, optimization algorithms are applied for computing the pipe sizes. The optimum attained is relative to a given initial layout of which the proximity layout is only the shortest path variant. It

could be that a more economic solution is possible by starting with a different initial layout, differing from that which results from proximity considerations, but which takes into account hydraulic constraints.

In practice, by programming the methods described above for computer treatment, several initial layouts of the network can be tested. The first of these should be the proximity layout. The others can be defined empirically by the designer, on the basis of the information available (elevation of the hydrants and distance from the source) which enables potentially problematic hydrants to be identified. By a series of iterations it is possible to define a "good" solution, if not the theoretical optimum. Furthermore, it should be noted that the above estimates are based on the cost of engineering works only. They do not include the purchase of land, right-of-way and/or compensation for damage to crops which might occur during construction, all of which would affect and increase the cost of the network and might induce to modify the optimal layout.