RELIABILITY CRITERIA FOR RE-ENGINEERING OF LARGE-SCALE PRESSURIZED IRRIGATION SYSTEMS

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ABSTRACT

A study was conducted in a pressurized irrigation district in southern Italy to analyze current delivery performance and determine improvements needed to meet current and future delivery needs. Such an analysis is required due to changes that have occurred, since the system was first put into service, in cropping patterns, farming practices and irrigation techniques. The **C**ombined **O**ptimization and **P**erformance **A**nalysis **M**odel (COPAM) was used to evaluate the irrigation system present performance under different operating conditions, to identify the areas within the irrigation district where rehabilitation and modernization are more urgently needed, and to suggest the most effective engineering and operational improvements. Post-intervention operating scenarios were simulated and analyzed to refine and validate the re-engineering process. Results show the usefulness of simulation models when analyzing modernization alternatives for irrigation schemes.

INTRODUCTION

In the arid and semi-arid regions of the Mediterranean, most of the economically viable water resources development has already been implemented. Population growth and cyclic droughts have put pressure on available water resources. These conditions create a structural imbalance between increasing water demand and limited water supply (Hamdy and Lacirignola, 1999). Moreover, many large-scale irrigated areas have recently experienced an increase in water demand for municipal and industrial use, and a reduction in the amount of water available for agriculture. Therefore, irrigation agencies and farmers' associations have been asked to improve the efficiency of their irrigation networks and delivery systems by means of more rational use of limited water resources (D'urso, 2001). New methods are needed to assess irrigation system performance and to support decision-making in regional water management. Reliable information is needed with regard to spatial and temporal patterns of farmers' water demands, farming

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and irrigation practices and physical and operational features of large-scale irrigation systems. Future projections and simulation of alternative management scenarios need to be conducted to understand how irrigation systems respond to changes in operating conditions. Simulations of feasible management scenarios are helpful for identifying the most promising directions with the greatest impacts on irrigation system performance (Prajamwong et al., 1997). Simulation models can enable managers and planners to predict the effects of various management strategies under different climatic and operational conditions. They can be used as analytical tools by researchers and practitioners responsible for investigating water management alternatives.

OBJECTIVES, METHODOLOGY AND APPROACH

Our goal is to provide a methodology for performing diagnostic analyses on large-scale pressurized irrigation systems. These analyses are required to address the main issues in rehabilitation processes and to support decision-making in re-engineering and in water management for irrigated agriculture.

A large-scale irrigation system located in Southern Italy and managed by a local Water Users Association (WUA) was investigated. This irrigation scheme was originally designed to operate by rotation delivery schedule. Nevertheless, changes in cropping patterns occurred and progresses in irrigation were achieved. As a result, the actual operating conditions and farmers' irrigation demands are now different from those foreseen during the design stage. As a result, the system performance has greatly decreased with time. Rehabilitation and modernization are required to improve the system performance and the level of farmers' satisfaction. To achieve this, potential and actual failures of the system and their related causes were first identified. Changes in the actual operation, capable to positively affect performance, were envisaged. Physical and operational rehabilitation measures were pointed out. Several analyses were carried out in order to evaluate the hydraulic response of the system under different operating conditions. The Combined Optimization and Performance Analysis Model (Lamaddalena and Sagardoy, 2000) was utilized for these analyses. COPAM software includes the ICARE and AKLA simulation models.

DESCRIPTION OF THE STUDY AREA

The analysis was conducted on District 7 of the large-scale irrigation scheme "Sinistra Bradano" located in southern Italy (Apulia Region) and managed by the "Stornara e Tara" Water Users Association. The district covers a net irrigated area of 392 ha. Its spatial extent has coordinates 2669919 E, 4493641 N and 26900994 E, 4472609 N (UT 1983, Zone 33 N). The elevation ranges from 3.0 to 45.0 m above the sea level. Water is conveyed from a regional reservoir located in a neighboring region by means of a main conveyance canal. From the canal, water is then diverted into district distribution networks, which consist of pressurized underground pipelines. Water is finally delivered to farms by means of multi-user hydrants, designed to provide a nominal flow rate of 10 l s^{-1} or 20 l s^{-1}. The WUA performs the rotation at two different levels: a) the district level, by opening the sectors in certain days of the week and for pre-fixed durations; b) the sector level, rotating the farm stream among the different farms composing the sector. The existing cropped areas and the cropping patterns considered at the designed stage for the future agricultural development of the district are shown in Table 1.

Table 1. Cropped area for the irrigation district 7

Actual cropped areas and cropping pattern foreseen at the design stage		
Crops	**Actual area (ha)**	**Foreseen area (ha)**
Table gapes	158.0	80.0
Citrus	155.0	80.0
Olive trees	40.0	36.0
Vegetables	20.0	116.0
Wheat	19.0	-
Row crops	-	40.0
Fodder crops	-	40.0
TOTAL	**392.0**	**392.0**

As illustrated in Table 1, variations in cropping patterns mostly concerned grapes, olive and citrus. Availability of good quality water and favorable weather and soil conditions pushed farmers to grow these crops to obtain profitable yields; but citrus and grapes have high water requirements. During the peak periods the system is often unable to fulfill the overall district water needs. Organizing irrigation rotations to satisfy the ever-increasing water demands has became troublesome for the technical staff of the local WUA. Improving the system operation according to the actual needs has therefore become of a high priority.

RESULTS AND DISCUSSION

The set of analyses was carried out by using the ICARE model (CTGREF, 1979) and the AKLA model **(**Ait Kadi and Lamaddalena, 1991; CHIEAM internal note not published). These two models are stand-alone components of the COPAM software package. Their use enabled to simulate change of the system's operation, from rotation to on-demand delivery schedule and determine the overall system performance (Zaccaria, 1998). Results obtained from the analyses showed that shifting the system operation from rotation to on-demand delivery schedule would enable a higher flexibility in water distribution and a simplified water management for the WUA. The overall performance and the quality of irrigation service would greatly improve. The models also enabled simulation of the post-rehabilitation operation to evaluate the system performance in the new operational scenario. In order to accomplish the operational change, some rehabilitation and modernization works are required. Application of the above simulation models allowed the identification of critical areas within the irrigation district, where rehabilitation and modernization measures are more urgently needed. Results of the study were then validated by means of field analyses and through interviews with irrigation users as well as to the managers of the local WUA.

In order to apply the ICARE and AKLA models, several input files were prepared. These files contain all the information concerning design assumptions, physical features of the network and its scheduled operating conditions. Node elevations, diameters, lengths, locations of hydrants and their features (such as flow meters and pressure regulators) were identified and reported in the input file. Two different sets of analysis were conducted: 1) verification of the network operation under the actual conditions; 2) hypothesis of rehabilitation and analysis of the system under improved operating conditions.

In the first set of analyses, the system's hydraulic behavior was investigated under actual operating conditions. Current delivery conditions are quite different from those the system was originally designed for. Current deliveries occur on a 10-day basis and have a typical standard rotation lasting 10 days and cycling for the whole irrigation season, except under particular conditions (failures, rain, emergency irrigation, temporary stops). On the basis of this schedule, daily length was subdivided into four six-hour intervals. Within each of these intervals, the sectors simultaneously in operation were set according to the real schedule. Knowing the characteristics of the flow limiters located at the upstream end of sectors, the discharge flowing into the network for each six-hour interval was computed. The AKLA model was run for each six-hour interval, considering the existing piezometric elevation at the upstream end of the network $Z_o = 45.50$ m above sea level and the total discharges (Q_o) as computed for every single interval. The current delivery requirements (flow rate of 5 l s^{-1} with minimum pressure head $h_{min} = 20$ m) were considered. The most representative outputs of the analysis are presented in Figure 1 to 4. Some severe deficit problems may occur for any tested flow rates. For several hydrants (located within sectors 32, 33, 38, 39, 40) the relative pressure deficit sometimes reaches $\Delta H < -1$, which means negative pressure at the hydrants and, consequently, a risk of air entering the pipes. For some other (located within irrigation sectors 42, 43, 44 and 45) the available pressure heads are much higher than 20 m. Such outputs show that there is poor pressure uniformity among the different zones of the district. This reduces the performance of the network, not allowing for a proper operation of on-farm irrigation systems for several areas. In these areas, farmers need to use booster pumps. These results show that the hydraulic performance of the system is rather poor. Consequently, adjustments of operation to meet actual delivery requirements, also considering the physical capability of the network, are strongly required.

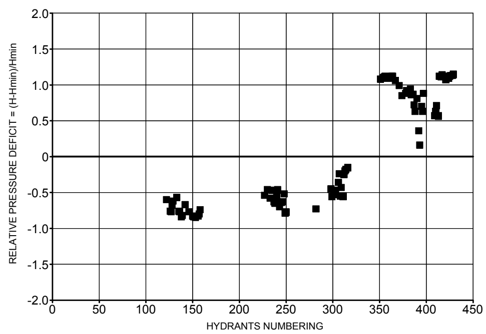

Figure 1 – Relative pressure deficit at each hydrant according to the rotation adopted by the WUA. Interval 12 am – 6 pm of the 1st day of the standard rotation. $d = 5\ l\ s^{-1}$ and $h_{min} = 20$ m

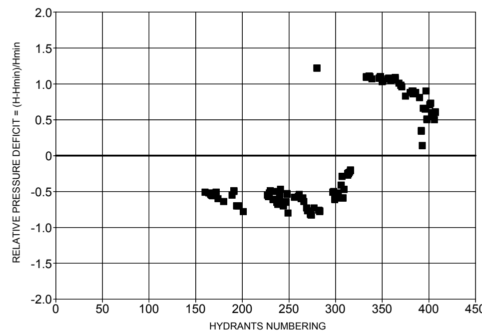

Figure 2. – Relative pressure deficit at each hydrant according the rotation adopted by the WUA. Interval 12 am – 6 pm of the 5th day of the standard rotation. $d = 5\ l\ s^{-1}$ and hmin = 20 m

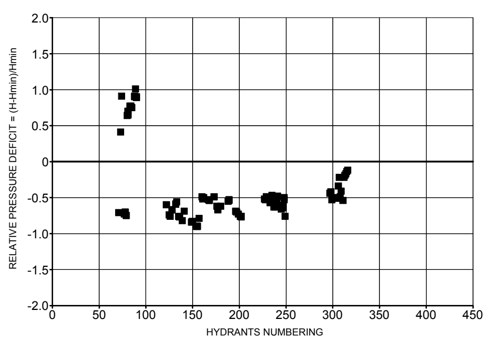

Figure 3. - Relative pressure deficit at each hydrant according the rotation adopted by the WUA. Interval 12 am – 6 pm of the 10th day of the standard rotation. $d = 5\ l\ s^{-1}$ and $h_{min} = 20$ m

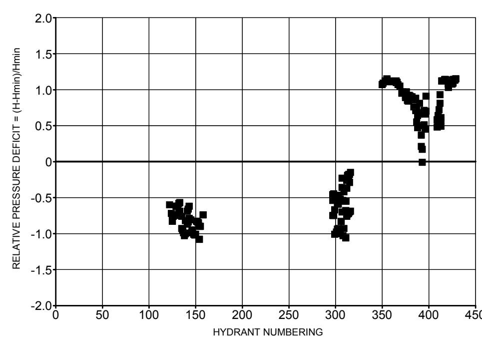

Figure 4. – Relative pressure deficit at each hydrant according the rotation adopted by the WUA. Interval 6 am – 12 am of the 1st day of the standard rotation. $d = 5\ l\ s^{-1}$ and $h_{min} = 20$ m

In the first set of analyses, the hypothesis of operating the system on-demand under the actual conditions was also tested. The change was simulated to determine whether it could lead to an overall improvement of the system operation. Understanding whether the network might be operated on-demand and identifying the consequences resulting from these changes in operation are the main purpose of the analyses.

The range of discharges flowing into the network during the peak period (July) was determined. The range was $40\ l\ s^{-1}$ to $150\ l\ s^{-1}$. The flow rate continuously available at the upstream end of the network was referred by the WUA to be $200\ l\ s^{-1}$. The ICARE model was run for different discharge values, ranging from $40\ l\ s^{-1}$ to $200\ l\ s^{-1}$. For each of the discharge values, 500 different configurations of hydrants operating simultaneously were randomly generated. Results of the analyses are reported in Figure 5.

For the piezometric elevation of 45.50 m a.s.l. more than 70 % of the simulated configurations are satisfied when the discharge flowing into the network is lower than 100 l s^{-1}. As the flowing discharge increases, the system can satisfy a decreasing percentage of the simulated configurations. For Q_o = 150 l s^{-1}, the system satisfies a percentage ranging from 50 % to 60 % of the configurations. For the maximum continuously available discharge Q_o = 200 l s^{-1}, 30 % to 40 % of configurations can be satisfied. Based on information obtained, one can infer that the system ensures a high performance when on-demand delivery is applied for hydrants discharging 5 l s^{-1} with a pressure head h_{min} = 2 m. A shift from rotation to on-demand delivery does not negatively affect the actual hydraulic performance of the system. Operating the system on-demand is technically feasible and would benefit the WUA and irrigation users. Under actual conditions, however, the system cannot fulfill the farmers' needs even if operated on-demand. At present, the system can deliver an adequate discharge (d = 5 l s^{-1}) at each point of the network, with a pressure head that in nearly all cases is not sufficient for adequately operating the on-farm irrigation systems.

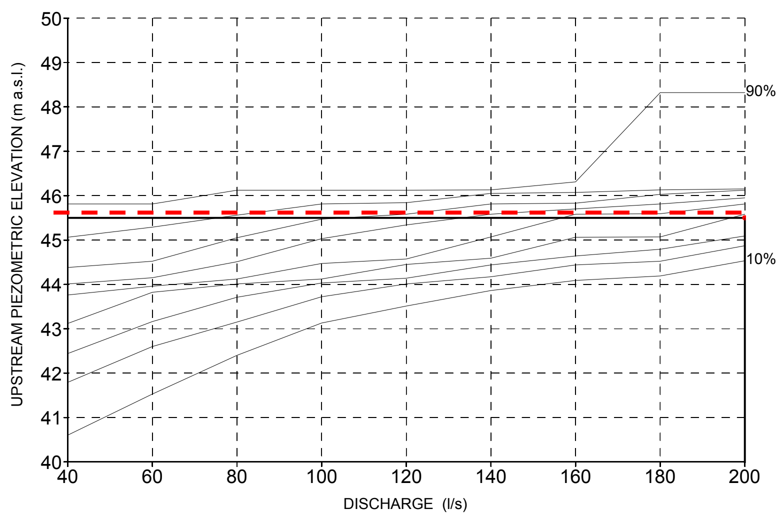

Figure 5. Percentage of satisfied configurations for the distribution network for Zo = 45.50 m a.s.l. And h_{min} = 2 m

For assessing rehabilitation needs, the hydraulic performance of the distribution network under the hypothesis of hydrant discharging d = 5 l s^{-1} and minimum pressure head h_{min} = 20 m was tested. These water delivery conditions correspond to the actual farmers' requirements. The maximum upstream discharge flowing into the network was computed by using the Clément probabilistic model (Clément, 1966). The continuous specific discharge resulted q_{sc} = 0.48 $ls^{-1}ha^{-1}$. This value of q_{sc} was utilized for the determination of the upstream discharge Q_{up} (l s^{-1}) flowing into the network. Based on the continuous specific discharge, the total flow rate Q_{up} = 340 l s^{-1} was obtained. This value of flow rate was used in the ICARE and AKLA models. Twelve different flow rate values, ranging from

50 l s^{-1} to 600 l s^{-1} were analyzed using the ICARE model. For each value, 500 different configurations were generated. A minimum pressure head h_{min} = 25 m and a nominal flow rate of d = 5 l s^{-1} were imposed at the hydrant level. Some representative results are in Figure 6 and 7.

For an upstream elevation Z_o = 45.50 m a.s.l., none of the generated configurations are satisfied, for any value of discharge tested. Even for very low flow rates, the system cannot adequately fulfill the on-farm needs. In order to get an acceptable performance (at least 50 % of the generated configurations satisfied) for the value of Clément's discharge Q_{cl} = 340 l s^{-1}, the system requires at least a piezometric elevation Z_o = 70 m a.s.l. If the discharge flowing into the network is higher than 340 l s^{-1}, a piezometric elevation at the upstream end Z_o = 70 m enables the system to satisfy a decreasing percentage of the generated configurations. Analyzing the performance of the irrigation network for flow rates higher than 340 l s^{-1} corresponds to simulating different cropping pattern scenarios. If the total irrigated area of the district 7 would be fully converted to citrus, the Q^{1}_{cl} would rise up to 355 l s^{-1}. At this flow rate, the system could satisfy a percentage ranging from 30 % to 40 % of the generated configurations. If the total area of the district 7 was planted with summer vegetables, the discharge would rise to Q^{II}_{cl} = 570 l s^{-1}. With this discharge flowing into the network, not even 10 % of the configurations would be satisfied with Z_o = 70 m a.s.l. A further lift of the piezometric elevation to Z_o = 75 m, would enable a percentage of configurations ranging from 10 % to 20 % to be satisfied. For the actual cropping pattern and for Z_o = 75 m a.s.l., the system performs very well even when Q_o is higher than Q_{cl} = 340 l s^{-1}. In order to obtain more accurate information about the satisfaction of the requirements for every single hydrant within each investigated configuration, a further analysis by running the AKLA model was conducted to overcome ICARE's shortcomings. The AKLA model was run for Z_o = 70 m a.s.l. and flow rates Q_o ranging from 200 l s^{-1} and 600 l s^{-1}. The relative pressure deficit for every hydrant within each configuration was determined, identifying the unsatisfied hydrants. No deficit problem occurs when the discharge Q_o is lower than the Clement's discharge Q_{cl} = 340 l s^{-1}. Starting from the flow rate Q_o = 400 l s^{-1} in sectors 32, 33, 38, 40, pressure heads lower than 25 m were observed. In these areas, the relative pressure deficit is higher than ΔH = - 0.2 corresponding to a residual pressure head h_{min} = 20 m. As the flow increases, the situation in these areas becomes worse, but never critical. In particular, for Q_o = 550 l s^{-1} in the sectors 40 and 41 a maximum pressure deficit ΔH = - 0.3 can be observed. This value corresponds to a pressure head at hydrants h_{min} = 17.5 m, which still provides enough pressure to operate trickle irrigation systems. For Q_o = 600 l s^{-1}, a general pressure deficit is noted for the central portion of the network. By considering the 90 % envelope curve, a pressure deficit at most equal to ΔH = -0.6 corresponding to a pressure head h_{min} = 10 m, is observed. This pressure head does not allow for appropriate trickle irrigation methods.

Figures 8 and 9 provide the identification of unsatisfied hydrants through the curve of Percentage of Unsatisfied Hydrants (PUH). From the results, areas where deficit problems occur correspond to few unsatisfied hydrants which, being within different configurations, result in indexed curves shifted up. ICARE considers all hydrants in one configuration together, while AKLA identifies conditions prevailing at each hydrant. The AKLA model allows more complete analyses with the identification of the zones where important pressure deficits occur.

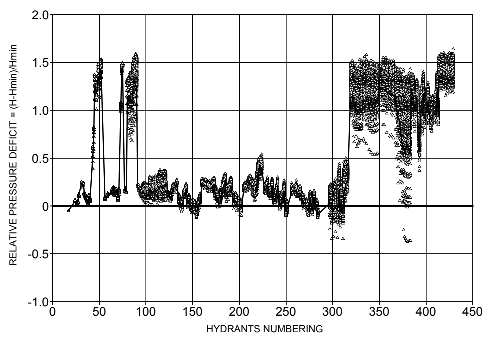

Figure 6 - Relative pressure deficit at each hydrants. Discharge Qo = 400 l s^{-1} , upstream piezometric elevation Zo = 70 m a.s.l. and h_{min} = 25 m.

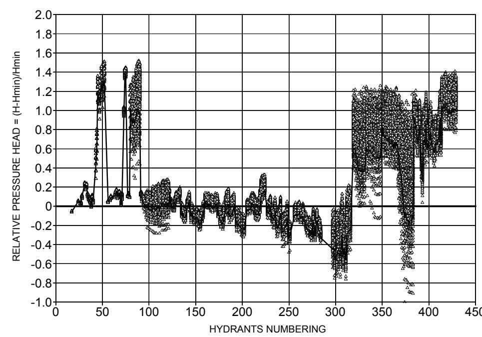

Figure 7 - Relative pressure deficit at each hydrants. Discharge Qo = 600 l s^{-1} , upstream piezometric elevation Zo = 70 m a.s.l. and h_{min} = 25 m.

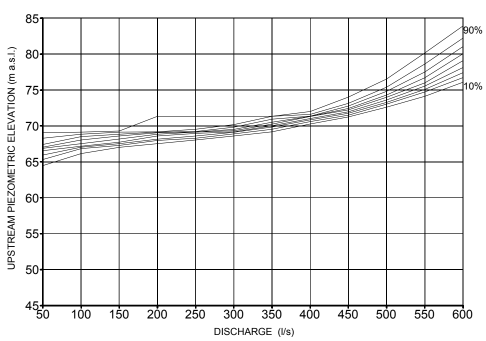

Figure 8 - Percentage of satisfied configurations for the network of the district 7 for Zo = 45.50 m a.s.l. , d = 5 l s^{-1} and h_{min} = 25 m.

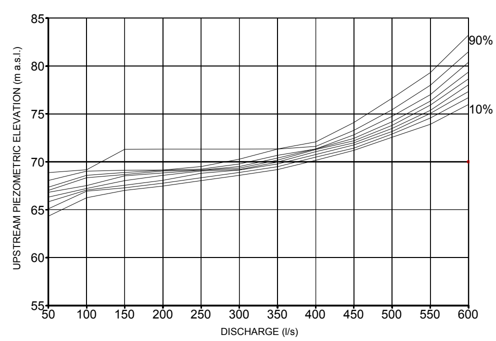

Figure 9 - Percentage of satisfied configurations for the network of the district 7 for Zo = 70.00 m a.s.l. , d = 5 l s^{-1} and h_{min} = 25 m

CONCLUSIONS AND RECOMMENDATIONS

The importance of performance analyses for re-engineering of existing irrigation systems was described. The usefulness of advanced models for monitoring and simulating different physical processes involved in an irrigation system was illustrated. Both models are very helpful to get a better understanding of distribution network behavior, both from usual operation and from rehabilitation perspectives.

For our case study, results show that the system under consideration is not capable of fully satisfying farmers' needs in terms of pressure head at hydrants. Improving system performance is a priority task and should be carried out through technically and economically feasible rehabilitation measures.

In order to obtain acceptable performance levels, for the discharge equal to the maximum design discharge Q_{cl} = 340 l s^{-1}, lifting the upstream piezometric elevation from 45.50 m up to Z_{up} = 70 m a.s.l. is required.

Some operational measures positively affecting system performance are advisable. An effective shift from rotation to on-demand delivery should be implemented to improve the flexibility in water distribution. Since, for operation on demand, the maximum withdrawals may occur during the morning hours, a farm control can be achieved by installing in the critical sectors delivery equipment allowing withdrawals only within pre-determined set-times (Nerilli, 1996). These equipments could also enable to adjust the flow hydrograph to the actual system capabilities. The WUA could restrict, within the critical areas, the withdrawals to certain daily hours in order to modify the flow hydrograph, without necessarily modifying the operation from the full demand to the restricted frequency demand for the whole system. The system management could be improved without seriously penalizing the on-demand delivery schedule.

Establishment of adequate water tariffs according to classes of volumes consumed could contribute to adjusting the flow hydrograph to the system capacity and prevent failures.

The following re-engineering options should also be considered. Within each hydrant flow, limiters should be replaced with others delivering a maximum nominal discharge of 5 l s^{-1}. A storage and compensation reservoir should be built at the upstream end of the district network for ensuring the regular operation of the system during the peak periods, and to reduce the water losses when the system is not operating. The district network should be equipped with a pumping station to lift the piezometric elevation at the upstream end of the network up to 70 m a.s.l. Equipping the lifting plant with variable speed pumps could ensure optimal power management. Finally, a flow recorder installed at the upstream end of the network would allow monitoring daily flow hydrographs and therefore would enable a better understanding of how to adjust operation of the irrigation system to its maximum capacity.

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