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Revision Approach for Optimum Design of Pressurized Irrigation Systems

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The great target for mankind is always to achieve the optimum use of available resources against the increasing food and other demands of the world population versus the shrinking resources. This paper provides snapshots of research and practical implementation of optimum design concepts and criteria of pressurized irrigation systems. Technical papers, reports and case studies are reviewed addressing revision approach for the optimum design of pressurized irrigation systems. The definition of the optimum irrigation has to be as widely as maximization of overall benefits including nonmonetary benefits; such as water quality protection and food security. Reliable information on irrigation methods is important for determining agricultural water demand trends. The model HYDRUS-2D can be employed to derive characteristic irrigation control functions to determine optimal irrigation times and water amounts. Also, a software application for Android mobile devices is available to evaluate the responsiveness of all available optimum commercial diameters to operational changes.

The optimization of the irrigation system is an important factor to enhance water use efficiency. To get optimum pressurized irrigation systems, the common employed optimization techniques are linear programming, recursive design and genetic algorithm.

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1. INTRODUCTION

This paper provides snapshots of research and practical implementation of optimum design concepts and criteria of pressurized irrigation systems. The revision approach reflects diverse approaches and interdisciplinary resources that can be called upon to achieve the optimum pressurized irrigation systems. Technical papers, reports and case studies are reviewed addressing revision approach for the optimum design of pressurized irrigation systems.

2. WATER IN THE WORLD

Only 2.5% of all water on earth is fresh water. Available water for direct human uses is only 1% of the fresh water in the world. This available water is found in lakes, rivers, reservoirs and underground sources and it is regularly renewed by rain and snowfall.

Agriculture is responsible for 87% of the total water used globally. It accounts for 86% of total annual water withdrawal in Asia compared with 49% in North and Central America and 38% in Europe [1]. The irrigated land worldwide is about 16% of the total agricultural area, and the crop yield is roughly 40% of the total yield, [2]. That means that the productivity of irrigated land is 3.6 times that of non-irrigated land.

Irrigated land in the world in the year 2003 includes 188 million hectare in Asia, 22 million hectare in USA, 24.1 million hectare in 4 countries (with 5 – 10 million hectare), 53.2 m ha in 16 countries (with 2 – 5 million hectare) [2].

The tabulated data for water resources and irrigation, [3], are presented graphically by the author in the following four figures.

3. OPTIMIZATION TECHNIQUES

Optimization is the magic key that is involved in all engineering fields. That is to achieve the optimum use of available resources against the increasing food and other demands of the world population with the shrinking resources. Optimization can be considered as the ensemble of steps which must be taken to find the minimum, or maximum, of a function that is usually called an objective function.

A review of various optimization techniques has been provided by Singh [4]. Good quality land and water resources are limited and they are becoming degraded due to urbanization and population growth. Optimum use of these resources is essential to fulfill the needs of the growing global population. Various optimization techniques have been used for optimal use of available resources for the maximization of net benefits from irrigated agriculture. It was shown that linear programming (LP) and dynamic programming (DP) techniques are very popular in irrigation management, while dynamic programming, mixed integer programming (MIP), genetic algorithm (GA) and quadratic programming (QP) are most used for groundwater management. Non linear programming (NLP) has not been widely used because of rigorous mathematics involved.

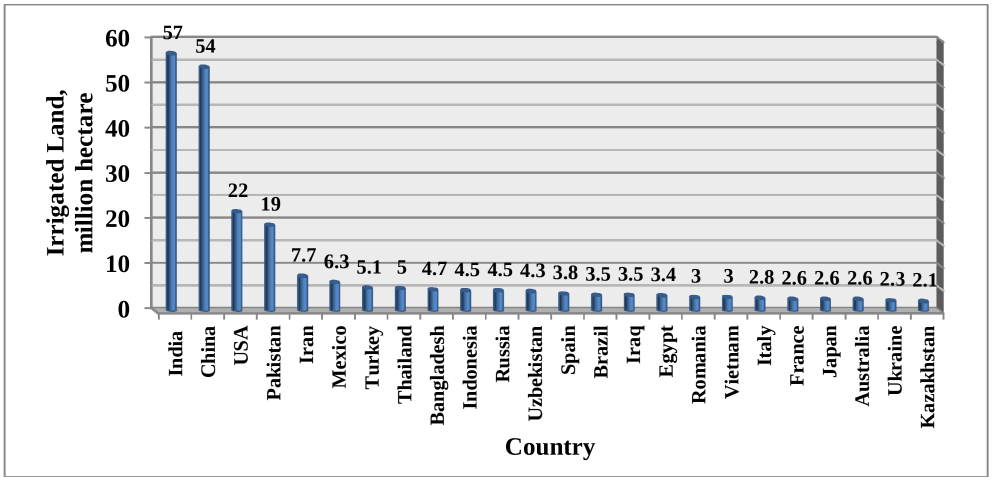

Fig. 1. Irrigated land in major countries

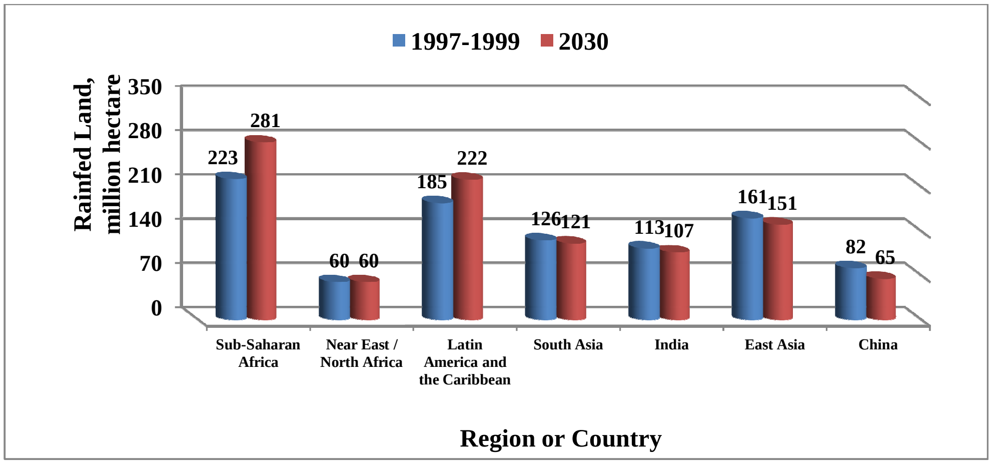

Fig. 2. Rainfed land till the year 2030

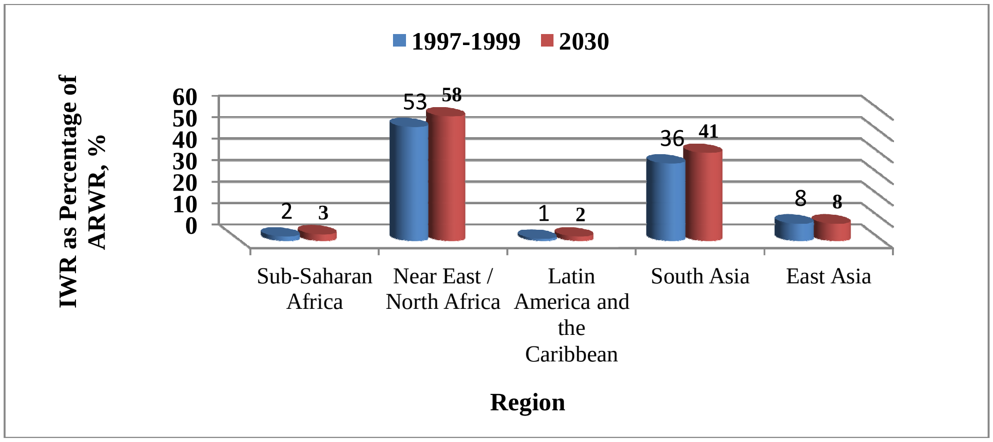

Fig. 3. Irrigation water requirements (IWR) as percentage of annual renewable water resources (ARWR)

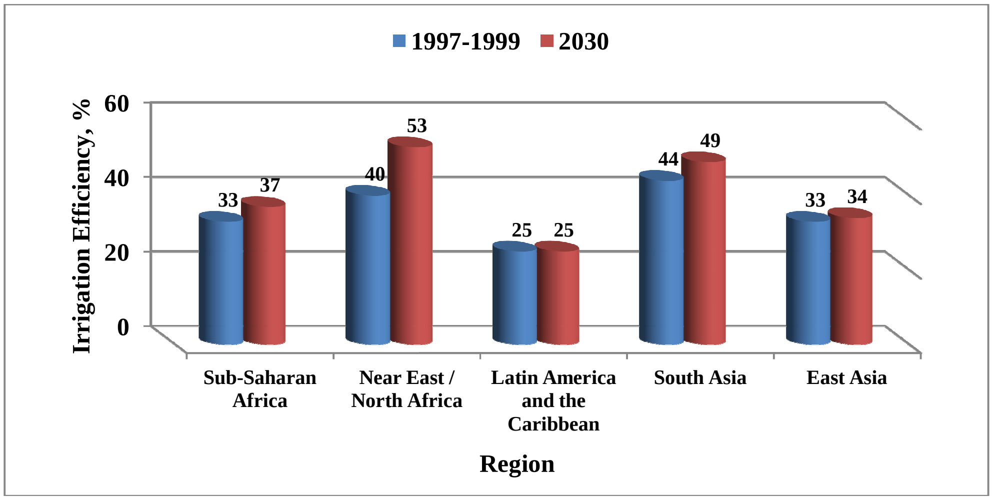

Fig. 4. Irrigation efficiency till the year 2030

4. OPTIMUM PRESSURIZED IRRIGATION SYSTEMS

To achieve optimum design of multi-diameter irrigation laterals, an analytical continuous uniform outflow approach was presented by Valiantzas [5], taking into account the effect of the number of outlets on the multi-diameter lateral hydraulics. The pressure head profile along the multi-diameter pipeline was described by a simple analytical function providing direct calculation of the outlet pressure head along pipeline. The method was significantly improved by introducing an adjusted spatially variable outflow equation for the errors caused by the assumption of equal outlet discharge. The effect of ground slope on hydraulic computation was also considered. Simple equations were derived for the direct calculation of the maximum, minimum, and inlet pressure head along the multi-diameter pipeline. The optimum design problem for two-diameter lateral was also solved analytically. For a specified total length of a two-diameter pipeline, a simple algebraic equation was derived to calculate directly the appropriate lengths of the reaches of different diameters in such a way that the total cost of the pipeline was minimized. Compared with accurate numerical method, the proposed analytical approach was sufficiently accurate.

Optimum design and management of pressurized irrigation systems were presented by Farmani et al. [6], using a genetic algorithm on the basis of rotation and on-demand delivery scheduling. Application was made to two real irrigation systems in Spain. Performance criteria were formulated for the optimum design of a new irrigation system, and better management of a real existing irrigation system. The performance of the developed genetic algorithm was assessed in comparison to traditional linear programming. It was concluded that the methodology developed performed better than the linear programming method. An improvement in capital cost was achieved, and the constraints were satisfied sufficiently. Also, a greater than 50% saving could be achieved in total cost by using rotation delivery.

For optimal design of the pressurized irrigation subunit, a linear programming model was presented by Kale et al. [7]. The objective function of the model was to minimize the equivalent annual fixed cost of pipe network of the irrigation system and its annual operating energy cost. The hydraulic characteristics in the irrigation subunit were insured by using the length, energy conservation, and pressure head constraints. The input data were the system layout, segment-wise cost and hydraulic gradients in all the alternative pipe diameters, and energy cost per unit head of pumping water through the pipeline network. The output data were segment-wise lengths of different diameters, operating inlet pressure head, and equivalent annual cost of the pipeline network. The explicit optimal design was demonstrated with design examples on lateral and sub-main or manifold of pressurized irrigation systems. The performance evaluation of the proposed model in comparison with the analytical methods, numerical solutions, and dynamic programming optimization model revealed the good performance of the proposed model. The verification of operating inlet pressure head obtained by the proposed model with accurate numerical step-by-step method suggested that it was mostly accurate.

González-Cebollada et al. [8], presented a new method to design pressurized branched irrigation networks. It was called recursive design and was based on application of the problem-solving technique known as backtracking of the problem of the optimum design of pressurized branched irrigation networks with a known delivery piezometric head (pipe-sizing). A simple network, as a design problem, was presented and defined, and the recursive design had been implemented in a fast computer application. The solutions obtained by the recursive design were compared with those obtained by other design methods, such as maximum velocity, recommended velocity, constant hydraulic slope, linear programming, and genetic algorithms. Recursive design obtained satisfactory results. For example, genetic algorithms took more than 20 minutes to offer a solution, whereas recursive design offered a cheaper solution with less than 3 seconds of computation time.

Wu et al. [9], developed a simple procedure to design low-cost, gravity-fed, drip irrigation subunits in hilly areas with laterals to one or both sides of the manifold. The allowable pressure head variation in the manifold and laterals was calculated individually for different pressure zones, and the manifold subunit design was divided into independent processes for laterals and manifold. For the manifold design, a two stage optimal design method was used. In the first stage, the pipe cost was minimized and a set of optimal manifold pipe diameters was obtained. In the second design stage, a list of available diameters was prepared based on the calculated optimal diameters, and also the lengths for available diameters and pressure head of every lateral along the manifold were calculated. Using the proposed methodology, the minimum manifold pipe cost was obtained, and the target emission uniformity was also satisfied.

An optimization model was established and genetic algorithm was used to optimize light-small movable unit sprinkler system, Xingye et al. [10]. The objective function was minimal energy consumption. The constraint conditions were pump and pipeline operating conditions, minimum working pressure of sprinkler, and percentage of sprinkler working pressure range. The decision variables were number of sprinklers, pipe diameter, and sprinkler pressure in the pipeline end. The model and algorithm could optimize the number of sprinklers and pipe diameter. Also, the flow rate, pressure, efficiency, and energy consumption of the unit were calculated out. An example showed that the energy consumption was reduced by 14.2% after optimum design. The algorithm could get the optimum results automatically when know conditions were input, having the advantages of efficiency, accuracy, and reliability.

Optimum design for simple irrigation delivery system was discussed by Dercas et al. [11], presenting two explicit methods with their comparative application. Commonly simple empirical pipe selection methods used to design simple pressure water delivery system did not take into account economic criteria, and consequently did not lead to an optimal solution. Two explicit methods were proposed. The first method developed a simple equation that could allow calculating the critical values of discharges corresponding to the available pipe diameters. The second method could calculate the optimum economic diameter for every pipeline of the network. Also, for the calculation of the friction losses, a new explicit formula was proposed for the Darcy-Weisbach equation.

For the design of subsurface drip irrigation (SDI) systems under limited supply, a new optimization framework was presented by Seidel et al. [12], to identify optimal solutions for maximum profit. To solve this complex optimization problem, decomposition was used which divided the problem into three sub-problems: (i) optimal irrigation control (maximum water distribution uniformity and minimum percolation losses); (ii) optimal irrigation scheduling (minimum irrigation water applied in order to meet a high yield with a specified reliability); and (iii) optimal drip line layout (the solutions of the other sub-problems and maximum profitability). The multi-level optimization framework was tested in France with corn cultivated on two SDI plots with drip line spacing of 1.2 m (SDI 120, with plot size of 0.12 hectare) and 1.6 m (SDI 160, with plot size of 0.11 hectare). The model HYDRUS-2D was utilized to derive characteristic irrigation control functions to determine optimal irrigation times and water amounts. The presented framework significantly increased profit and water productivity for deficit SDI designs. Water productivity for (SDI 120) was increased up to 30% compared to seven other irrigation experiments. The optimal SDI design was achieved by (SDI 160), which increased profitability by 36% compared to (SDI 120).

A software application for Android mobile devices was developed by Sesma et al. [13], by which the user could evaluate the responsiveness of all available optimum commercial diameters to operational changes. These operational changes included changing water demands (e.g. cultivation, water needs, and spacing), types of emitters used in the installation, or lateral feeding (from an extreme or from an intermediate point). The input data mainly required by the application were: emitter flow rates, the number of emitters, the spacing between emitters, the average pressure in the lateral, and the pressure tolerance. As a result, the application would indicate if each irrigation lateral was valid or not for the situation provided by the user. Also, it would display some graphics of the pressures in the lateral, which would permit identification of the critical points of the irrigation lateral.

To avoid negative impacts of non-uniform pressure of micro-irrigation systems on crop productivity, water utilization, and nonpoint source pollution, Wang et al. [14], presented an economic optimization method to balance costs and benefits. A custom computer software was developed to implement the method and an irrigation case study was presented. Economic efficiency was achieved with an optimum uniformity at 78% for cotton and at 86% for olive trees. The results also indicated that water cost was the most important factor influencing total cost and economic efficiency, and next was capital cost. Also, irrigation systems with a relatively small subunit size (0.1 – 0.42 hectare for cotton and 0.72 – 2.16 hectare for olive) commonly lead to a high economic efficiency. Finally, to guarantee adequate uniformity, the most efficient micro-irrigation system design would necessarily use the smallest possible size of the manifold.

Big size sprinklers, which work on high flow rates and big layouts spacing, were studied by Sheikhesmaeili et al. [15]. The spray losses and water distribution of sprinkler irrigation system with semi-portable big size sprinkler on semi-arid areas had been characterized. The factors affecting discharge efficiency and irrigation uniformity were analyzed (working pressure, irrigation layout, and weather conditions). A field tests were conducted in outdoor conditions with a single sprinkler system. Six equations were obtained to estimate drift and evaporation losses, knowing operating pressure, wind speed, and vapor pressure deficit. The results showed an increment of 3.26% for spray losses for each increment of 1 m s^{-1} of wind speed. Spray losses increased up to 22.7% at 450 kPa operating pressure when wind speed and vapor pressure deficit increased up to 4.2 m s^{-1} and 6 kPa. The effect of wind was significant on the spray losses and water distribution pattern under different conditions. This behavior was very similar to that obtained with medium size sprinklers.

Evaluation of the efficiency of surface and drip irrigation systems in a research area in Iran was presented by Dastorani et al. [16], where the optimization of the irrigation system was one of the most important factors to enhance water use efficiency. Two different types of irrigation, a traditional used surface irrigation and a simple and relatively cheap subsurface drip irrigation, were applied to two plots in an orchard. Each plot contained 39 pistachio trees and had an area of 720 m^2. Both plots were irrigated using exactly equal quantity and quality of water for 3 years. The ratios of the weight of fresh and dried crop in the subsurface irrigation plot to those of surface irrigation plot were 1.895 and 2 for the second year, and 2.17 and 2.12 for the third year. The values of the plot growth index were calculated as 2238 cm for surface irrigation and 4580 cm for subsurface irrigation. Also, the dried weight of weed grown in the surface irrigation plot was 82 kg, but was only 21 kg in the subsurface irrigation plot. These results showed the relatively higher preference for a subsurface irrigation system over the traditionally used surface irrigation system.

An assessment of irrigation performance was presented by Merchán et al. [17], for a basin with an area of 7.38 km^2 in Spain. The study covered 10 years carrying out water balances for each of the 55 agricultural plots and for the totality of irrigated area. Water balances presented good results with errors below 10% for most of the studied years, and an error of 1.2% across the entire study period. Irrigation efficiency reached 76.1%, while the losses of efficiency were due to evaporation and wind drift of sprinkler irrigation (13.5%) and drainage fraction (10.4%). Also, the irrigation efficiency increased 1.05% $year^{-1}$ and the irrigation drainage fraction decreased 0.95% $year^{-1}$. Optimal water use could be achieved by adjusting irrigation rates to the requirements of crops, and minimization of evaporation and wind drift losses.

A study was conducted by Tindula et al. [18], to collect information on the irrigation methods that were used by growers in California, USA to irrigate their crops in 2010. Reliable information on irrigation methods is important for determining agricultural water demand trends. The results were compared with earlier surveys to assess trends in cropping and irrigation methods. A one-page questionnaire was developed to collect information on irrigated land by crop and irrigation method. The questionnaire was mailed to 10,000 growers in California who were randomly selected from a list of 58,000 growers by the USDA National Agricultural Statistics Service, excluding rice, dry land, and livestock producers. From 1972 – 2010, the planted area had increased from 15 to 30% for orchards and from 6 to 15% for vineyards. The area planted with vegetables had remained relatively static; whereas that planted to field crops had declined from 67 to 41% of the irrigated area. The land irrigated with low-volume (drip and micro-sprinkler) irrigation had increased by approximately 38%, whereas the amount of land irrigated by surface methods had decreased by approximately 37%.

Subsurface drip irrigation systems in California for over 30 years were discussed by Ayars et al. [19], providing examples of the current commercial practices in both annual and perennial crops. These examples demonstrated the adoption and implementation of subsurface drip irrigation systems in California. Significant benefits were identified in terms of increased yield, improved crop quality, reduction in applied water, and reduced costs for weed control and fertilization. Subsurface drip irrigation would be an effective tool available to improve water productivity.

In order to increase water use efficiency, simple relationships were developed by Baiamonte [20], to derive the variables required for the optimal design of paired laterals from a common manifold. An easy method to determine the best position of the manifold associated to the optimal lateral length on uniform slopes was proposed. The proposed procedure was successful compared with that derived by analytical solution. Applications of the obtained relationships, considering different design parameters, were presented and discussed.

A variety of approaches in modernizing irrigation systems had been applied in Spain to address the balance between water and energy use. The technical aspects of this process were presented by Tarjuelo et al. [21], where open channel gravity based systems were replaced by pressurized irrigation systems. Technologies for improving water and energy use in irrigation and main models for improving irrigation infrastructure design and management were reviewed. The benefits of irrigation modernization included increased water efficiency and productivity, improved operation and management of irrigation systems, but increased energy demands and investment amount. It is necessary to analyze the economic, social, and environmental viability of the irrigation modernization process in each case.

The shadow price of water for irrigation was estimated by Ziolkowska [22], where the 2011 and 2012 draughts considerably affected the Ogallala Aquifer supplying irrigation water for agricultural production in the U S High Plains. Farm-budget residual valuation was applied to estimate the shadow price of water for irrigation in 3 High Plains states: Texas, Kansas and Nebraska, for 5 crops: corn, cotton, sorghum, soybean, and wheat. The obtained results showed that the highest shadow price of water was found for wheat production in Texas Northern High Plains (\$ 0.70 / m^3), while the lowest shadow price of water was found for corn production in Texas Southern High Plains (\$ 0.004 / m^3). The study could be helpful for evaluating scenarios and tradeoffs between profitable crop production and conservation of water resources.

Referring to the challenges of water price, water storage through dams was studied by El-Hazek [23] and [24]. Water storage for later use is essential for arid and semi-arid regions. The type of the dam had to be taken into consideration for optimum water storage only for the value more than 4 million m^3. For the value less than 4 million m^3, the type of the dam has no effect on the storage cost. To predict the storage unit cost of water through dams regardless the type of the dam, an equation was obtained. Two other equations were established to predict the storage unit cost of water through earth fill dams. Also, an equation was fixed to predict the storage unit cost of water through concrete dams.

5. DIFFERENT METHODS FOR OPTIMUM DESIGN OF SUBSURFACE DRIP IRRIGATION SYSTEMS, A CASE STUDY

González-Cebollada et al. [25], compared the main methods to design a pressurized irrigation network with application to two networks: A small example irrigation network and a real irrigation network in Spain.

For the example irrigation network, Fig. 5, the delivery head was 44 m, the minimum and the maximum velocities were 0.5 m/s and 2.5 m/s. Polyethylene pipes from commercial catalogues from 125 to 710 mm nominal diameter were used.

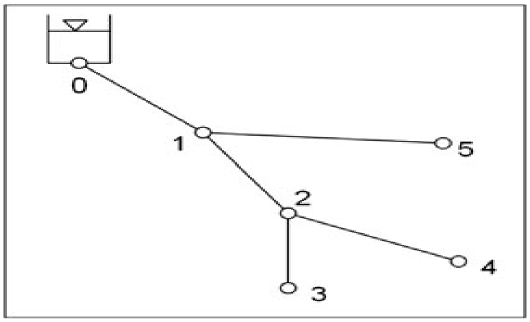

Fig. 5. Small example irrigation network for case study 1

For the real irrigation network in Spain, Fig. 6, water was supplied to a total of 11.52 km^2 from a reservoir providing a total delivery head of 485.48 m with a design delivery flow of 1.59 m^3/s. This network has a total length of 21,188 m, with 95 pipes made of polyester and PVC. There is a 10 m safety margin for pipe pressure and the maximum design velocity is 2.5 m/s. The required pressure at the hydrants was 30 m plus the elevation difference between the highest point and the supply point.

To get the optimum design for the example irrigation network, eight methods were employed: maximum velocity, recommended velocity, Mougnie velocity, constant hydraulic slope, linear programming, Lagrange multipliers, Labye's method and recursive design. To get the optimum design for the real irrigation network, the mentioned methods were employed except for linear programming, where the real project costs were included.

The first four methods (maximum velocity, recommended velocity, Mougnie velocity and constant hydraulic slope) are functional methods that don't take economic criteria into account. Together with the Lagrange multiplier method, they are continuous methods as the obtained theoretical diameters have to be modified to the available diameters. The other three methods (linear programming, Labye's method and recursive design) are discontinuous, where their formulation includes available commercial diameters.

The obtained results are presented graphically in the following Figs. 7 and 8. From the obtained results, it could be concluded that despite the simplicity of the example network, functional methods were clearly inferior compared to those applying economic optimization criteria. The Lagrange multipliers, Labye's method and recursive design methods obtained the same result, which would be probably the optimum design to the problem.

For the real irrigation network, the results were qualitatively similar to previous ones. Again, the functional methods offered the most expensive results. The best result was obtained using the Lagrange multipliers method and recursive

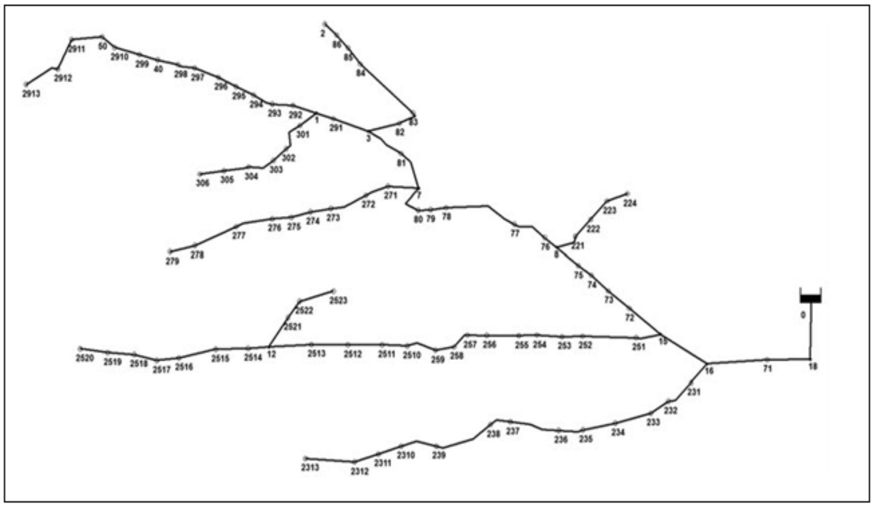

Fig. 6. Real irrigation network in Spain for case study 1

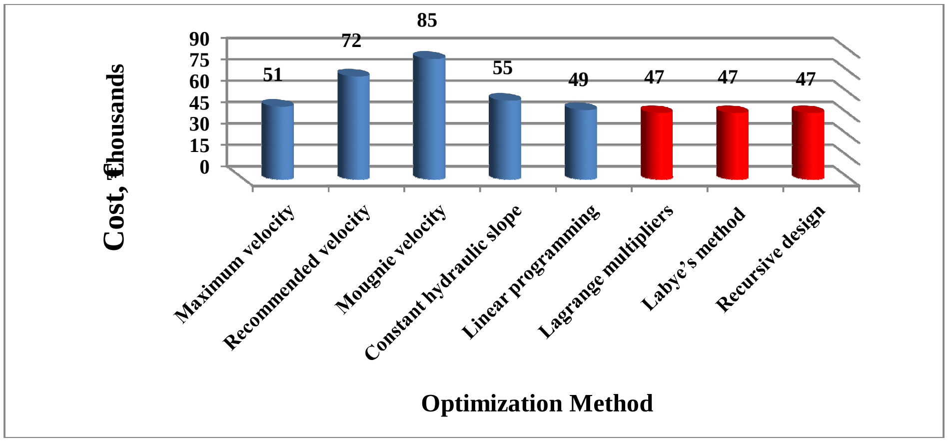

Fig. 7. Costs for example irrigation network for case study 1

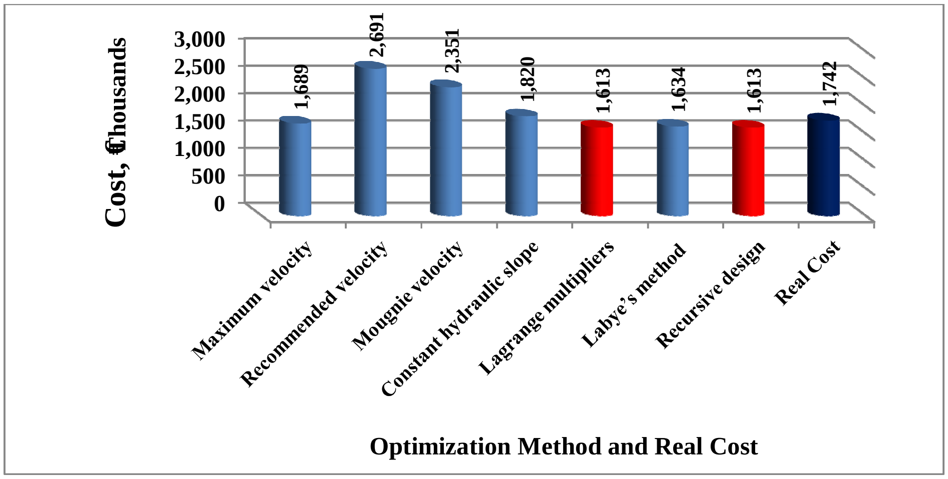

Fig. 8. Costs for real irrigation network for case study 1

design. The results showed that the final cost was very different depending on the method used. Methods without economic considerations (functional methods) were more expensive than the methods with internal economic targets. The Lagrange multipliers method and recursive design method were less expensive in both irrigation networks.

6. CONCLUSIONS

The definition of the optimum irrigation has to be as widely as maximization of overall benefits including nonmonetary benefits; such as water quality protection and food security. Reliable information on irrigation methods is important for determining agricultural water demand trends.

The model HYDRUS-2D can be employed to derive characteristic irrigation control functions to determine optimal irrigation times and water amounts.

Also, a software application for Android mobile devices is available to evaluate the responsiveness of all available optimum commercial diameters to operational changes.

The optimization of the irrigation system is an important factor to enhance water use efficiency. To get optimum pressurized irrigation systems, the common employed optimization techniques are linear programming, recursive design and genetic algorithm.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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