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Challenges for Optimum Design of Surface 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

There are many challenges to be faced in order 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.

This paper provides snapshots of research and practical implementation of optimum design concepts and criteria of surface irrigation systems. Technical papers and reports are reviewed addressing challenges and different aspects of this issue, in addition to optimum allocation systems of surface water and ground water.

It is concluded that the optimum irrigation may be defined more broadly as maximization of overall benefits, including nonmonetary benefits as water quality protection, food security, increased employment, and resettlement of populations. Linear programming, dynamic programming and genetic algorithms techniques are still very popular to get optimal surface irrigation systems. Surface irrigation parameters identification represents an important way to get optimal surface irrigation systems. Optimal conjunctive use of surface and ground water resources may be needed in some cases, such as water deficits in arid and semi-arid regions and uncertainty.

Keywords: Optimum; water; surface irrigation; water allocation.

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1. INTRODUCTION

This paper provides snapshots of research and practical implementation of optimum design concepts and criteria of surface irrigation systems. The scope of this paper reflects diverse approaches and interdisciplinary resources that can be called upon to frame and address some of the most important present challenges facing our world.

The paper presents technical papers and reports addressing the various aspects and challenges of the optimum design of surface irrigation systems. In addition to the challenges of the optimum allocation systems of both surface water and ground water.

2. WATER IN THE WORLD

Water is life. Water covers over 70% of the surface of earth. Fresh water is about 2.5% of all water on earth. About 70% of that fresh water is frozen in the icecaps. Available water for direct human uses is only 1% of the fresh water in the world.

Agriculture is responsible for 87% of the total water used globally. Consumptive water use refers to water that is not returned to streams after use. Irrigated agriculture is responsible for most consumptive water use, and decreases surface run-off, [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 is 277 million hectare, [2]. About 38% of the total irrigated area worldwide is equipped for irrigation with groundwater. In some places, exploitation of groundwater at rates above that of recharge causes depletion of groundwater reservoirs, [2].

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

Marshall et al. [4], concluded that irrigated agriculture will need to adopt a new management pattern based on an economic objective, the maximization of net benefits, rather than the objective of maximizing yields. Irrigation to meet crop water demand is a relatively simple and clearly defined problem with a singular objective. Irrigation to maximize benefits is a substantially more complex and challenging problem. Identifying optimum irrigation strategies will require more detailed models of the relationships between applied water, crop production, and irrigation efficiency. Economic factors, particularly the opportunity costs of water, will

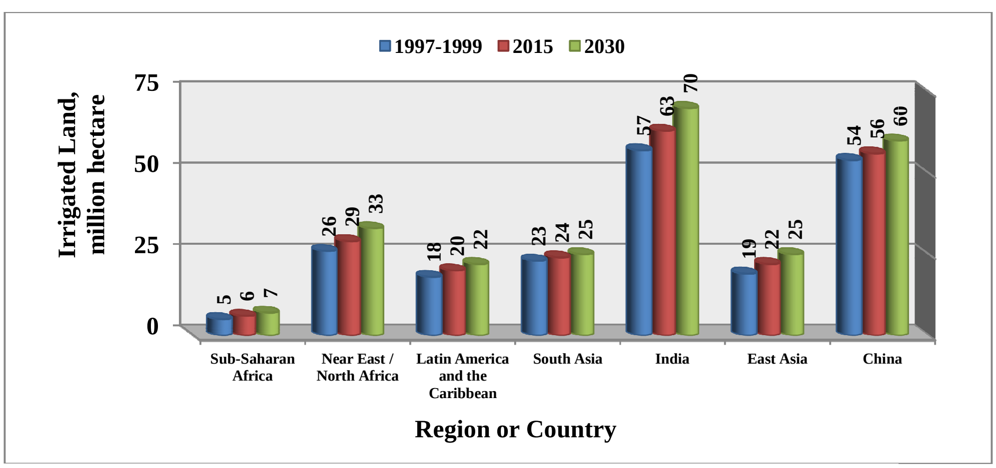

Fig. 1. Irrigated land till the year 2030

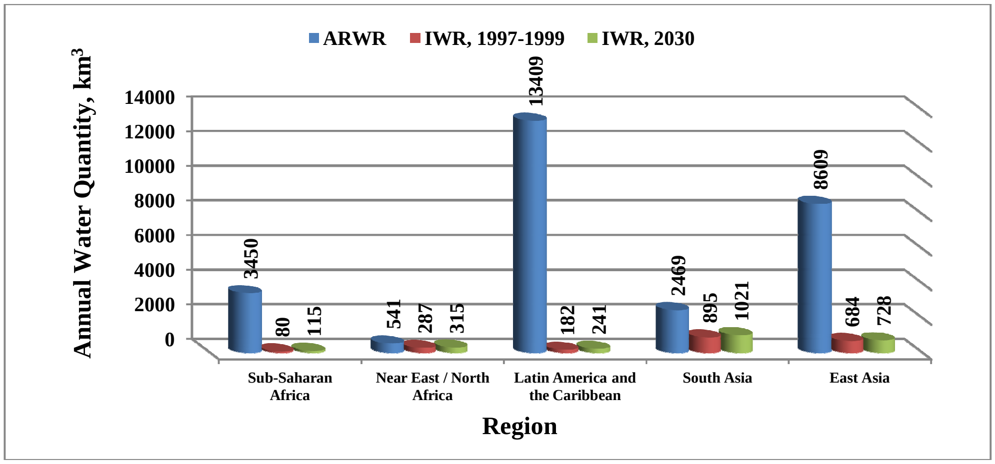

Fig. 2. Annual Renewable Water Resources (ARWR) and Irrigation Water Requirements (IWR)

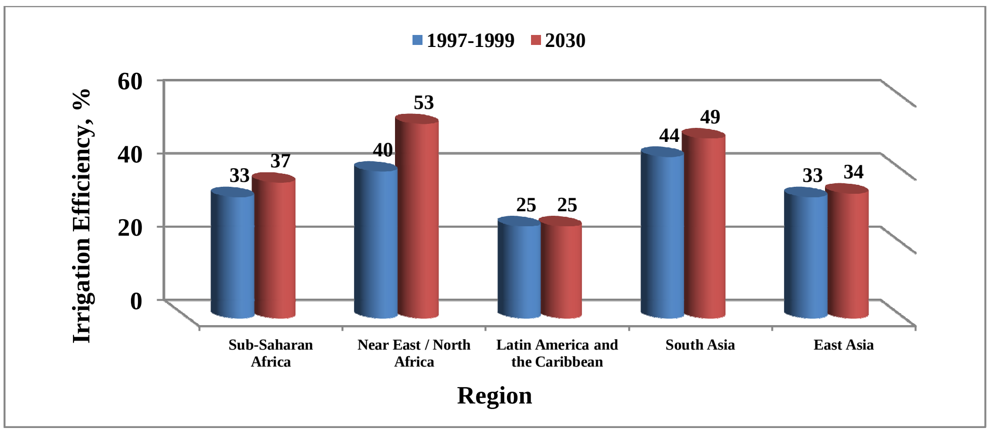

Fig. 3. Irrigation Efficiency till the Year 2030

need to be explicitly incorporated into the analysis. From a societal perspective, optimum irrigation may be defined more broadly as maximization of overall benefits, including such nonmonetary benefits as water quality protection, food security, increased employment, and resettlement of populations.

A review of various optimization techniques has been provided by Singh [5]. 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.

4. SURFACE IRRIGATION SYSTEMS

Surface irrigation includes 94% of the application methods of irrigation water at field level, where the water is spread over the field by gravity. The majority of the remaining 6% is irrigated by methods that require energy, hydraulic pressure and pipe systems such as sprinkler irrigation and drip irrigation, [2].

WinSRFR is a new generation of software for analyzing surface irrigation systems that is founded on an unsteady flow hydraulic model. It integrates event analysis, design, and operational analysis functionalities, in addition to simulation. Bautista et al. [6], provided an overview of functionalities, interface, and architectural elements of the software. Technical enhancements in version 2.1, 2007, and version 3.1, 2009, were also discussed.

WinSRFR is an integrated software package for analyzing surface irrigation systems that was described by Bautista et al. [7], associated with an example application. The analyzed field was a graded basin (close-ended border) irrigation system. The event analysis tools of WinSRFR were used first to evaluate performance of the irrigation system and estimate its infiltration and hydraulic roughness properties. Performance contours in the Operation Analysis World were used to optimize irrigation system inflow rate and cutoff time. The adequacy of the existing design was examined with the performance contours provided in the Physical Design World. Hydraulic and practical constraints were considered in finding optimal operation or design solution. Finally, a sensitivity analyses were used to demonstrate the robustness of the solutions.

The form of infiltration and roughness equations could cause errors in the estimation of actual conditions, as shown by Clemmens [8]. There are many methods that have been proposed for estimating infiltration function from field measurements. Most of these equations assume some functional form of the infiltration equations. For example, assumptions regarding the influence of wetted perimeter on furrow infiltration could result in inappropriate infiltration equations and parameters. Also, the Manning roughness coefficient had been shown to vary with time during an irrigation event as the soil was smoothed by the flowing water. The estimated parameters from evaluation of a measured irrigation event usually give reasonable estimates of actual performance. However, extrapolation to future irrigation events, particularly with a different application depth or flow rate, can lead to inappropriate recommendations.

Rodriguez et al. [9], showed SIPRA_ID as a freeware for surface irrigation parameter identification. It was based on robust multi objective inverse modeling technique for estimating field values of infiltration and roughness parameters of a surface irrigation event under both steady and variable inflow conditions. Its simulation engine was flexible and accurate thanks to combining a volume-balance model with artificial neural networks. SIPRA_ID provided also estimate of the uncertainty and sensitivity of the identified parameters.

Influence of longitudinal slope of a surface irrigation on irrigation uniformity was presented by González et al. [10], providing practical tools to design, analyze and manage surface irrigation systems with longitudinal slope. A set of graphs were obtained to determine the optimal slope of a field, the inflow rate or the length and width of a field, achieving savings of water in surface irrigation. Also, an example was shown where a 20% savings in water is obtained by giving the field the optimal slope.

Multi criteria analysis was used by Darouich et al. [11], in Syria to evaluate and rank a set of furrow and border irrigation alternatives with and without precise land leveling. Results showed that both graded furrow and border alternatives were acceptable, with a slight advantage for graded furrows. Alternatives without land leveling were more appropriate for farm economics, while alternatives including land leveling were selected assigning priority to water savings. Savings of 20 – 28% of irrigation water were achieved and water productivity increased by 42%. It was shown that adopting advanced and costly irrigation technologies to achieve water saving requires appropriate economic incentives, training of farmers and an institutional framework to support the sustainable use of water.

Design of surface irrigation systems depends mostly on irrigation canals. Many researchers paid attention for this issue. El-Hazek [12], employed the popular Microsoft Excel software to obtain the best hydraulic sections for trapezoidal open channels with different side slopes. Non-silting non-scouring velocity of the water through the canal was maintained, where the area of flow has been modified to keep the velocity obtaining the corresponding modified values for the dimensions of the section. The design of best hydraulic sections was efficient, accurate, easy and simple. It could be widely used to obtain the best hydraulic section for any trapezoidal channel in surface irrigation systems.

A simplified multi-objective genetic algorithm optimization model (MOM-GA) for canal scheduling under unequal flow rates of distributary canals was presented by Peng et al. [13]. This model was designed for dynamic rotational scheduling with two objectives: to reduce fluctuations of flow rates of superior canals, and to reduce seepage losses of canal systems. The model was programmed in MATLAB using its genetic algorithm functions, and was applied to a case study of the Nanguan main canal system (NMC) in the Gaoyou irrigation area, China. The results demonstrated effective optimum canal scheduling, where NMC kept running under a relatively steady range and the seepage losses were reduced by about 50%. The model was flexible to be applied to different levels in canal systems. Optimum results given by the MOM-GA could help making better canal scheduling decisions in each irrigation event.

Optimizing the control parameters (water delivery and farm size) of surface irrigation plays a significant role to achieve the best performance (maximum total efficiency). To achieve maximum total efficiency, Valipour et al. [14], developed SWDC model. It was a function that obtained from Data Fit software and Curve Expert software, and it represented a model for water infiltration distribution into the soil. The distribution curve for water in the soil was assumed from third degree polynomial in SWDC model, and equations related to irrigation efficiency were determined. Two SWDC and WinSRFR models were used to compare and optimize infiltration parameters in furrow irrigation system. It was indicated that the goal of optimization in WinSRFR model was to achieve full irrigation status, which did not guarantee the best performance. SWDC model showed that the optimal discharge would not occur necessarily in full irrigation, where maximum total efficiency could be achieved by optimizing input discharge.

The upgraded software SRFR 5 is a program for modeling surface irrigation systems that is a central component of WinSRFR, which is a software package for the hydraulic analysis of surface irrigation systems. SRFR 5 was discussed by Bautista et al. [15], providing details about computational methods and new features.

Recent studies have demonstrated that the entropy parameter was dependent on the relative submergence, for the flow in case of high and intermediate roughness. While the mean to maximum velocity ratio could be assumed constant at all water stages for very low roughness or smooth channels. To evaluate the water discharge in rough and smooth irrigation channels based on the knowledge of relative submergence, Greco, [16], presented a methodology derived from one dimensional entropy-based model. Using detailed laboratory data from smooth and rough flumes with different cross section geometries, the relation between the entropy velocity ratio and the relative submergence was discussed to get an operative practical rule for water discharge computation and rating curve assessment in irrigation ditches. The proposed approach was reliable, where the comparison between observed and calculated discharges showed very low errors.

An artificial neural network (ANN) was developed by Mattar et al. [17], to estimate the infiltrated water volume under furrow irrigation system. The results obtained from the ANN model showed a high degree of accuracy. The mode could be applied to various soils and different furrow irrigation hydraulics.

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. [18], 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 widely used semielliptical channels in irrigation systems were studied by Vatankhah, [19], where the main challenge was the calculation of the wetted perimeter. The wetted perimeter of semielliptical sections could be expressed in terms of incomplete elliptic integrals of the second kind. Elliptic integrals could not be computed directly using the popular Microsoft Excel software. So, a simple and accurate expression was proposed for computing the wetted perimeter. Explicit solutions for semielliptical channels had also been obtained using the non-dimensional forms of the governing equations. The maximum errors of critical and normal flow depths were less than 0.1%. The proposed explicit equations had high accuracy, easy calculation and wide application range.

5. IRRIGATION WATER ALLOCATION

Water resources represent the major limiting factor in crop production in arid and semi-arid regions as annual rainfall is low and uncertain. Shortages of surface water supplies have increased the need of ground water development in many canal commands. On the other hand, arid and semi-arid regions are underlain mostly by poor quality groundwater, which is not suitable for irrigation and other uses. Optimization models have been used for the management of poor quality ground water, water logging, and salinity problems of these areas. These problems could be solved by adopting conjunctive use of water resources.

Optimization models compare various combinations of surface water and ground water and select an optimal combination based on hydrological, economic or allocation criteria; for example minimum conveyance, least cost, desirable water quality or resource conservation. Many attempts have been made to study optimal allocation of land, water and other resources for various uses.

Optimizing an irrigation water allocation and a multi-crop planning was presented by Noory et al. [20], where the main objective was to maximize net benefits for irrigated areas in a reservoir irrigation system in Iran. A linear and a mixed-integer linear (MIL) model were established. The linear model was optimized with linear programming (LP), and also continuous particle swarm optimization (CPSO). The optimal allocated areas in the linear model obtained by LP method and CPSO algorithm were not directly applicable in real crop planning situations. Consequently, the MIL model was developed for which a discrete particle swarm optimization (DPSO) algorithm was used to obtain an applicable and allowable solution. It was found that the inapplicable assigned area by the LP method and CPSO algorithm for some crops was eliminated from optimum selected areas by the DPSO algorithm. Also, it was shown that the CPSO and DPSO algorithms were able to limit the variations of annual net benefits within a range of no more than 2%. Finally, it was concluded that the DPSO algorithm could direct the objective function value in a faster way and with more accuracy than CPSO algorithm.

Referring to the challenges of water price, water storage through dams was studied by El-Hazek, [21]. Optimum water storage for all types of dams could be accomplished reasonably for the value less than 4 million m^3 employing an obtained equation. Otherwise the type of the dam had to be taken into consideration for optimum water storage.

An equation was obtained to predict the storage unit cost of water through dams regardless the type of the dam by El-Hazek, [22]. Two other equations were obtained to predict the storage unit cost of water through earth fill dams. Also, an equation was obtained to predict the storage unit cost of water through concrete dams.

The shadow price of water for irrigation was estimated by Ziolkowska, [23], 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.

A multi-objective programming model was proposed by Lalehzari et al. [24], for optimal allocation of surface and ground resources under water deficits in arid and semi-arid regions. A non-dominated sorting genetic algorithm (NSGAII) was used as a multi-objective optimization method. Accordingly, there were two maximization objectives: net benefit and relative water use efficiency. Groundwater discharge, economic parameters, and evapo-transpiration were formulated as three groups of constraints and were linked together by linear mathematical functions. The applicability of the irrigation scheduling was evaluated in the experimental field located in Iran. The production functions of cultivated crops were obtained. The results showed that the model did not suggest deficit irrigation for melon and tomato. However, incorporating multi-objective optimization techniques using NSGAII could effectively improve precision in irrigation scheduling.

An overview of the different programming techniques used for the necessary conjunctive use planning and management of irrigated agriculture was presented by Singh et al. [25], due to the continuous increase in global population and simultaneous decrease in good-quality water resources. The past researches on the applications of different programming techniques for the conjunctive use of different water resources were grouped mainly into four categories: linear programming, nonlinear programming, dynamic programming, and genetic algorithms.

A factorial two-stage irrigation system optimization model (FTIM) was proposed by Xin et al. [26], for supporting agricultural irrigation water resource management under uncertainty. The FTIM incorporated fractional factorial design, two-stage stochastic programming (TSP), interval linear programming (ILP), and interval probability and was applied to agricultural water allocation. The results indicated that the effects of parameters on the objective function were evaluated quantitatively, which could help screening out significant parameters, analyzing their interactions in the model, and identifying possible schemes with maximized net system benefit. Especially for the studied problem, the most positive significant factor affecting total net benefits was the water quality at a medium flow.

Physically-based fully integrated surface water (SW) – groundwater (GW) modeling in optimizing water management was implemented by Wu et al. [27], and surrogate modeling was performed to replace the computationally expensive model. Water use conflicts between agriculture and ecosystem in Heihe River Basin (HRB), the second largest inland river basin in China, were investigated. Based on the integrated model GSFLOW (Coupled Ground-Water and Surface-Water Flow Model), the conjunctive use of SW and GW for irrigation in the study area was optimized using a surrogate-based approach named DYCORS (DYnamic COordinate search using Response Surface models). In the HRB case study, the surrogate-based optimization suggested a very different time schedule of water diversion in opposite to the existing one, indicating the critical role of SW-GW interactions in the water cycle. Also, a basin-scale water saving could be achieved by reducing non-beneficial evapo-transpiration. In addition, the followed flow regulation in HRB might not be sustainable, because the ecosystem recovery in the lower HRB would be at the cost of the ecosystem degradation in the middle HRB.

6. CONCLUSIONS

It is concluded that the optimum irrigation may be defined more broadly as maximization of overall benefits, including nonmonetary benefits as water quality protection, food security, increased employment, and resettlement of populations.

Linear programming, dynamic programming and genetic algorithms techniques are still very popular to get optimal surface irrigation systems.

Surface irrigation parameters identification represents an important way to get optimal surface irrigation systems.

There are software and models for analysis, design, simulation, and operational analysis for surface irrigation systems; such as WinSRFR.

Optimal conjunctive use of surface and ground water resources may be needed in some cases, such as water deficits in arid and semi-arid regions and uncertainty.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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