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A SYSTEMS APPROACH TO DESIGN OF AGRICULTURAL DRAINAGE SYSTEMS IN EGYPT

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PREFACE

Agricultural drainage systems provide the principal means of coping with waterlogging and salinization of soils, two of the major environmental problems of agriculture. To illustrate the enormity of the problems caused by salinization, one need only note that the total soil loss in the world due to secondary salinization is larger than the amount of soil presently irrigated worldwide.

Dr. Strzepek's paper is written from a perspective unusual at IIASA. Generally, the type of decision which concerns IIASA scientists is one of feasibility - whether a specific project should be developed and what the principle features of such a project would be. In contrast, Dr. Strzepek's approach is to discuss the ways in which the techniques of systems analysis can be used to solve universal problems of engineering design. This methodological point of view is thus of interest not only to the task "Environmental Problems of Agriculture," but also to the entire institute and decisionmakers in general.

The background work for this paper was initiated at the Massachusetts Institute of Technology, but the paper was written at IIASA.

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of Agriculture

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INTRODUCTION

The growing demand for food to feed the world's increasing population has put great stress upon the agricultural community worldwide. Research into new varieties of seeds and farming methods progresses daily, while at the same time, water resources and agricultural projects are being implemented to bring more land under cultivation. Faced with the pressures of increased food demand, any decline in the productivity of existing land is viewed as a serious problem in meeting this demand.

Many agricultural lands do not have sufficient natural drainage to remove excess water due to rainfall or irrigation. This inability can lead to the problem of waterlogging. Furthermore, in arid zones, much irrigated agriculture is faced with the problem of salinity buildup due to high evapotranspiration rates and poor water quality because of excessive reuse. The problems of waterlogging and salinity cause a reduction in productivity of existing agricultural lands;

consequently, the field of agricultural drainage was developed address these problems.

> ... Agricultural drainage can be summed up as the improvement of soil water conditions to enhance agricultural use of the land. Such enhancement may come about by direct effects on crop growth, by improving the efficiency of farming operations or, under irrigated conditions, by maintaining or establishing a favorable salt regime. Drainage systems are engineering structures that remove water according to the principles of soil physics and hydraulics. The consequences of drainage, however, may also include a change in the quality of the drainage water.... (Van Schilfgaarde, 1974).

THE NEED FOR AGRICULTURAL DRAINAGE IN EGYPT

Since the completion of the High Aswan Dam in 1965, the Nile's flood waters have been stored in the Lake Nasser Reservoir and are available for distribution over the entire year. The year-round availability of water has led to more land being brought under multiple crop cultivation. This gradually created the situation where the present cropping intensity in the Nile valley is approximately one hundred ninety percent.

This intensive irrigation then created a problem. In the past, with both wet and dry periods, the initial flood waters provided a mechanism for flushing away any salts that might have built up in the soil, and the groundwater table had time to recede slowly after the flood. Now, due to year-round irrigation, the water table is constantly high and salts are not flushed. The result is that crop yields have been severely affected by waterlogging and salinity. These problems are due to poor irrigation practices and the soil properties of the Nile valley.

It is possible to alleviate the problems of waterlogging and salinity by introducing better farm water management and agricultural drainage systems. Drainage systems allow the groundwater table to be controlled, preventing waterlogging and allowing for sufficient leaching of excess salts from the crop root zone.

The widespread adaptation of new farming techniques is decades away. Therefore the Egyptian government has embarked upon a monumental project of installing agriculture drains on most cultivated land in Egypt.

A SYSTEMS APPROACH TO THE PROBLEM

The goal in taking a systems approach is to synthesize into a model information about the physics of drainage, the economics of drainage, and the social and political process of drainage planning. The model should allow each component to reflect its true impact upon the ultimate goal of improved agricultural production.

This work examines the process of planning drainage systems as well as the problems confronting the components of the design process. In this way, methodologies developed for the design components can take into account the interactions between the system processes and can address problems that affect the drainage system as a whole.

The problem of data uncertainty confronts the planning and design of agricultural drainage. In many cases, decisions on economic feasibility of drainage projects must be made with very little and uncertain data on soil parameters, water application rates, and efficiency of irrigation practices needed for preliminary design. Furthermore, economic data on benefits and costs are also scarce. This uncertainty can result in under-design of the system, causing losses in crop production, or over-design of the system, thus wasting capital, resources, and in some cases, resulting in production losses.

This paper looks at the process of drainage planning and design, and how it is affected by uncertainty. The first objectives of the research are to identify the present planning methodologies and to develop tools for better planning under uncertainty, given the present process. The second objective is to develop a new methodology for drainage design which incorporates uncertainty and system interactions in a formal design procedure.

The drainage planning process is defined as a multilevel process (see Figure 1). The first level is the project evaluation level, that is, where the decision of whether the project should be undertaken or not is made, e.g., are the benefits of the project greater than the costs? The first level of drainage planning is not the focus of this paper. Rather, the emphasis of this study is on the design of the collector and lateral drains which are the essence of the second and third levels of the drainage planning problem.

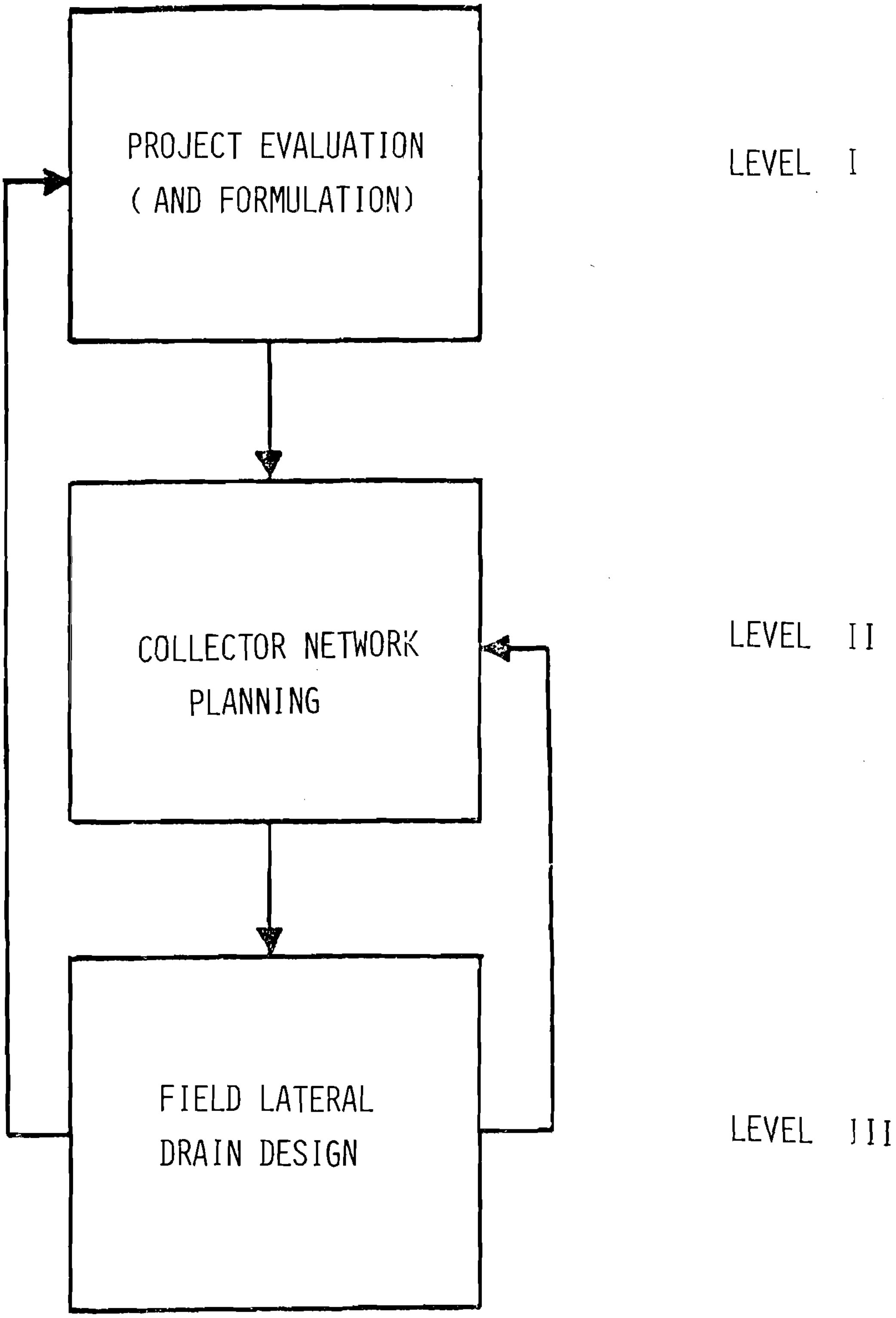

Figure 1. Multilevel Drainage Planning

If the first level decision concludes that the drainage project is beneficial to the nation, it is necessary to proceed to the detailed design of the drainage system. The procedures involved in the second level process are the design of the network of the collector and main drains. This will include the placement,sizing, and type of collector drains in the collection network. The third level is that of the design of the field lateral drains or field level planning. This level planning involves the choice of the depth and spacing of subsurface lateral drains.

The objective then is to identify uncertainty in each of the levels of drainage planning and develop tools to deal effectively with these uncertainties in an explicit manner. In this paper, the physical parameter uncertainty is addressed, with the emphasis upon the spatial variability and uncertainty of soil permeabilities.

The spatial variability found in level two planning was addressed by developing a simulation model for standardized, efficient collector network planning. This model provides for analysis of the economic cost of a proposed network design and for the determination of the least cost network.

At level three, the issue to be addressed is the optimal design of field drains given uncertainty in input parameters, spatial variability in soil permeability, crop yield functions, and economic criteria. A method was developed to provide for a measure of uncertainty in the field drainage system outputs given uncertainty in the system inputs and a model of the system. The Hooghoudt equation for field drainage design is used as a model for subsurface drainage flow. A first order-second moment

(FOSM) analysis is performed on the Hooghoudt equation to provide the mean and variance of the groundwater level given the mean and variance in soil permeability and drainage rate. Using the FOSM analysis an "optimal" design can be found by Mathematical Programming under Uncertainty. A Stochastic Programming Mathematical Programming Model for field drain design uses empirical crop loss functions and the FOSM result to define an expected loss which is incorporated into the objective function that minimizes the total of capital and expected loss costs. The model results provide the optimal depth and spacing of the field drains.

The overall planning of a drainage system is a two-level process. A dynamic multilevel planning model which incorporates uncertainty in field level design and the simulation approach to level two collector network design is developed. This combined optimization-simulation technique allows for feedback between level two and level three drainage planning for an efficient total system design.

GENERAL APPROACH

Level II

The process of planning drainage collection systems can be cast into a formal mathematical programming problem (MPP). The problem is that due to the complexities discussed above the MPP is impossible to solve using any linear or nonlinear programming package. However, it is possible to build a computer program which will simulate the procedures involved in the planning process. The simulation model does not provide an optimal solution, but rather displays the hydraulic and economic response of a given system input to the model by the engineer.

A simulation model is proposed that allows the engineer to make the same judgements made with present techniques. The simulation model provides the speed of a digital computer to aid in those planning procedures which are defined mathematically or follow specific rules. For example, the pipe sizing portion of the process as well as the placement of manholes every 200 meters apart, can easily be programmed into the computer. However, the alignment of the collector network must be specified by the engineer, using his judgement as well as other important parameters, because the model only simulates a system that is given, but does not generate systems.

The output of the model is a complete account of the length of each pipe size, the number of manholes, the number of tee-sections, and the number of outlets needed to drain properly the area for this given system alignment. Knowing the economic costs for each of the system components of which the model keeps account, a total cost for this collector system can be obtained. With the speed that a simulation model provides, the drainage engineer is then able to analyze the cost of a number of possible alternative collector systems. Then the engineer selects the system from the various proposed alternatives which provides proper drainage at the least cost. Although this technique might not select the "global optimal solution" due to the consideration of only a few alternative systems, the use of such a model allows experienced engineers to evaluate more alternative tools to help inexperienced engineers overcome their lack of experience. At the same time, the model will standardize many of the procedures of a drainage design office. For this work a drainage collector system simulation model was developed based upon the procedures for collector system planning utilized by the Egyptian Public Authority for Drainage Projects (Strzepek et al., 1980). This model has the added advantage of being connected with a computer graphics input/output device which allows a proposed system to be input by drawing it on a graphical input device. This substantially increases the productivity of the drainage engineer.

Level III

The field level drain design problem can be cast into a formal Mathematical Programming Problem under uncertainty. The stochastic programming approach to uncertainty is possible if there exists a relationship between economic response and system output. With a probability density function of dewatering zone from the FOSM analysis and a yield response, an expected crop yield as a function of drain design can be calculated. This expected yield can be transformed into an expected economic loss and combined with the capital cost function in the objective function of a Stochastic Programming Model. The Stochastic Programming Model will minimize the total cost of drain installation plus the value of crop loss over the life of the drain,subject to physical constraint on the drain system. This approach provides a design where the marginal cost of improved drain performance (capital cost) is equal to the marginal value of the crop loss over the life of the drain due to better system performance. This analysis provides for the efficient utilization of capital which is a scarce resource in many agricultural economies.

Since this method is based upon economic rather than physical criteria, it is straightforward to extend the method to a multiple crop formulation (Strzepek et al., 1980).

DYNAMIC MULTILEVEL SYSTEM DESIGN

At present, the multilevel planning process proceeds sequentially from first to second to third level with no feedback between the levels.

This sequential planning process provides no feedback between level two and level three. For example, there is no provision to analyze how the network alignment affects lateral drain design. Tools for efficient level two and level three planning do not solve the problem, because in many cases, the least cost collector network will not provide the most efficient lateral drain system. A methodology to provide feedback between level two and level three is developed in this section. The approach is to synthesize the collector simulation model with the stochastic programming model for lateral drain design into a dynamic multilevel drainage planning model. The synthesis of these two models is needed for the design of a complete drainage system, because there may often be a tradeoff between the capital costs of the collector system and the total costs of the lateral system. It is then necessary to look at the total costs of the whole drainage system: capital costs for both collector and lateral drains and the expected losses due to lateral design (Strzepek et al., 1980).

APPLICATION TO THE EGYPTIAN CASE

The first level decision of whether to install drainage has been made by the Egyptian government and the World Bank which is providing funding for the project. The Egyptian Public Authority for Drainage Projects has been formed to implement level two and level three planning. The process presently employed is a sequential process of planning level two collection networks based upon topographical criteria. Level three field design is then based upon sampling of parameters within each collector region. A large staff exists for the investigation, planning, and design of drainage systems in Egypt. Even with this large staff the task is so great that the staff is hard pressed to meet the yearly targets for drainage design. More effective and efficient methods of drainage planning and design would be very beneficial to the Egyptian government. The applicability of the approach to Egyptian conditions was demonstrated by undertaking a case study. A region along the Embabe Drain in the Nile delta was selected as being representative of conditions throughout the Nile delta. With data provided by the Ministry of Irrigation the systems approach to design of a drainage system was undertaken. Four alternative drainage systems were analyzed as illustrated in Figure 2. Each system was analyzed using the dynamic multi-level planning model.

Table 1 is a summary of total system costs for each system. From Table 1, it can be seen that, although System I has the least cost collector network, it is not the "best" system. System IV is the system with the least total cost or the "best" system. The reason that System IV is the "best" alternative,

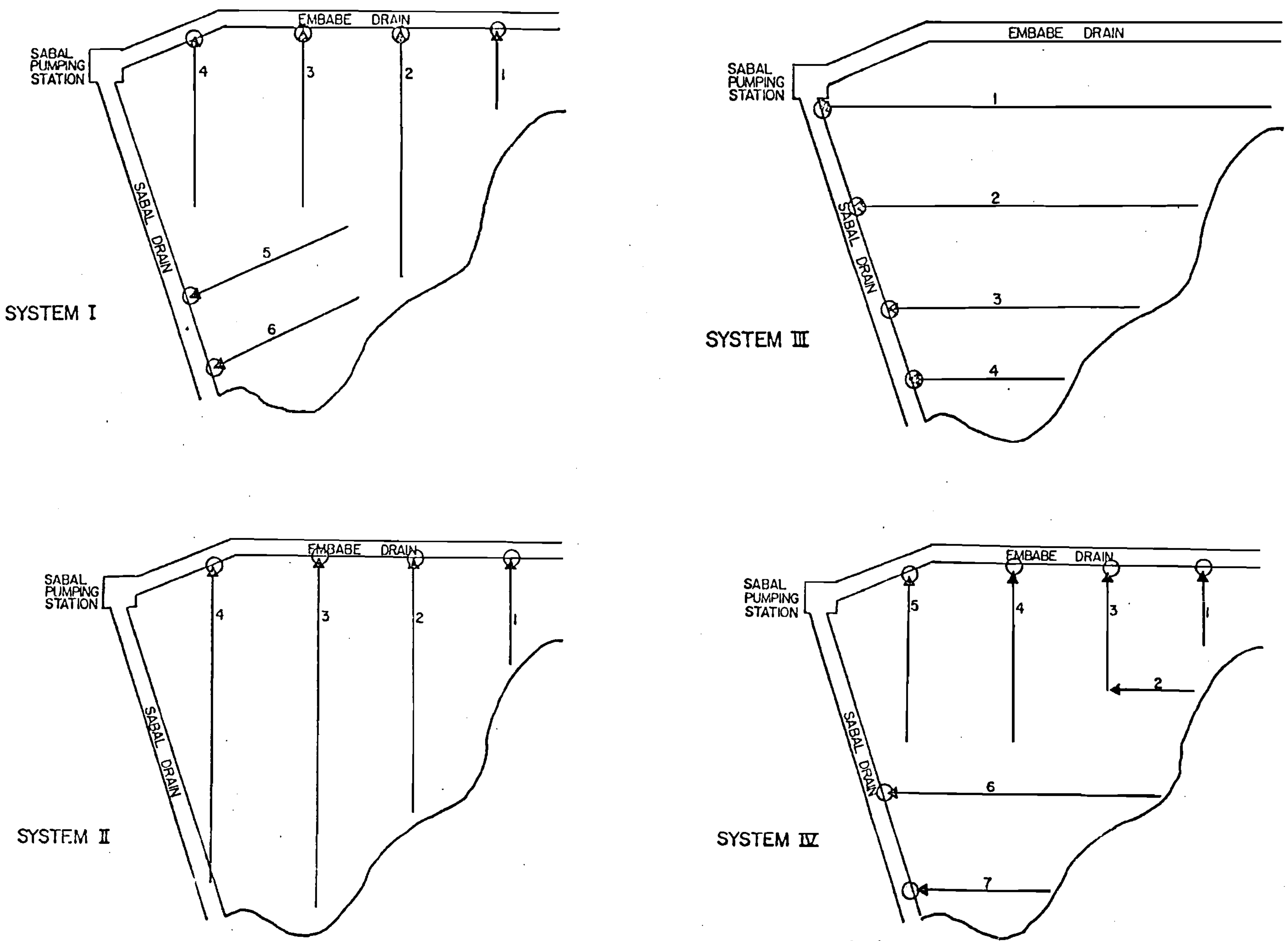

Figure 2. Alternative Systems for Embabe Drainage System

Table 1. Summary of Case Study Results

	System I	System II	System III	System IV
Lateral Drain System Total Costs (LE)	110800	113641	112589	110346
Collector Network Total Costs (LE)	5513	6943	7149	5858
Drainage System Total Costs (LE)	116313	120584	119738	116204

is that the collector network alignment spans the field such that the homogeneous lateral drainage areas provide for the most efficient lateral drainage system of all the alternative collector alignments. The savings in lateral system costs between System IV and System I outweigh the increase in costs of the collector system between System IV and System I. Systems II and III have costs for the collector system and for the lateral system that are higher than both System I and System IV costs.

This example illustrates the importance of feedback between level two and level three. For if the level three or lateral design had been based upon the "best" level two or collector design, the resulting lateral drainage system would have been less efficient. The potential saving for Egypt could be quite substantial. If System II had been implemented rather than System IV, an added cost of 4339.2 LE would have resulted, which is a 3.7 percent increase in cost. This is an average cost of 1.1 LE/feddans, which in the case of Egypt, where the drainage installation rate is 500,000 feddans per year, results in an added cost of 550,000 LE per year.

The use of the dynamic multilevel drainage planning model in the above case study above did not fully illustrate the advantage of the methods developed in this work. The case study showed that by providing feedback between level two and level three drainage planning, an "optimal" total drainage system could be found (rather than combining an optimal level two decision, collector network design, with an optimal level three decision, lateral drain design based upon the level two decision). The example did not illustrate the advantage of the dynamic multilevel drainage planning model as a synthesis of approaches that addresses the issues of uncertainty and spatial variability in design parameters in economic terms.

CONCLUSION

The combination of simulation and optimization techniques into a single methodology captures the essence of the systems analysis approach. The systems analysis approach provides tools for analyzing complex problems in a structure framework. The drainage design problem under uncertainty, as outlined above, is just such a complex process. By combining simulation with mathematical optimization, the areas of drainage design are matched with system tools that fit the characteristics of each area.

In the area of collector network design, many of the design criteria are mathematically describable, so the simulation approach fits quite well. Simulation allows the response of a system to be analyzed in an efficient manner, allowing the designer to analyze many alternatives of complex systems.

The design of field drains is different. Here, the physics and economics of the problem can be described mathematically, allowing mathematical programming techniques to be used to design efficient systems. The synthesis of both approaches into a single methodology allows the complex drainage design problem to be analyzed systematically and efficiently, allowing the characteristics of the system to be modeled most accurately.

This combined simulation-optimization approach combines the benefits of engineering judgement and optimization techniques. It allows an engineer to choose a feasible collector alignment. The collector simulation model then provides a design for the collector system. The model sorts the permeability data and assigns values to the appropriate collector area. Then the spatially distributed loss model produces the optimal lateral drain design for each collector area. The model output is capital costs of the collector network, capital cost of lateral drain systems, expected losses for the lateral system, and the total system cost.

With this model, the engineer can make a number of different collector alignments and find the alignment that meets the design criteria at the least cost. This tool provides the feedback link between level two and level three, allowing a dynamic planning process to design the "best" drainage system. The dynamic multilevel drainage design model addresses in one model the problem of uncertainty in drainage design, the problem of spatially variable soil permeability, the economies of crop yield and drainage design, and the lack of feedback between collector and lateral designs. These are all major problems that have faced the field of drainage for many years.

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