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IRRIGATED AGRICULTURAL EXPANSION PLANNING IN DEVELOPING COUNTRIES: PERFORMANCE VS. RESILIENCE VS. RELIABILITY

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HYDROLOGY AND WATER RESOURCE SYSTEMS

Department of Civil Engineering
Massachusetts Institute of Technology

Report Number 291

Prepared under the support of the
Agency for International Development
U.S. Department of State

June 1983

DEPARTMENT
OF
CIVIL
ENGINEERING

SCHOOL OF ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139

R83-14

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ABSTRACT

Agricultural expansion planning in developing countries where there is extensive government involvement in the planning process can be defined in a two level hierarchy. At the first level, strategic planning on the agricultural sector level is to be performed. At this level, the feasibility of the agricultural expansion as well as the other investments is to be examined and the role of each investment in achieving the strategic goals of the sector is to be determined. At the second level, analysis to the planning issues of agricultural expansion investment is to be provided. The analysis should be developed in such a way that the strategic decisions from the first level can be implemented. This report focuses only on the second planning level. Three issues are addressed. First, is the investment scheduling in such a way that the growing agricultural demands can be satisfied and the budget and resource constraints are not violated The second issue is the income redistribution. The third issue is the uncertainty and its effect on the performance of agricultural expansion investment.

A mathematical optimization model is built to aid in analyzing the scheduling problems of land development, crop selection, drainage water reuse, and capacity expansion of the irrigation and drainage networks. A minimum cost criterion is used, where costs of land development, farming, irrigation and drainage infrastructures, maintenance and operation, and pump stations are considered. The model is presented with a nonlinear objective function accounting for economies of scale and linear and nonlinear constraint sets. A fixed charge approximation is used for the non-convex cost functions and a mixed integer programming algorithm along with an enumeration procedure is used for solving the model. The solution procedure guarantees global optimality for the approximated problem. A hypothetical expansion on the order of 70,000 acres based on data from the Nile Delta in Egypt is used as a case study. The expansion extends over five areas of different sizes and soil types, and has only one source of fresh water for irrigation. The model is used for developing three alternate planning schemes for the case study. The first alternative is based on using fresh water for irrigation. The second alternative is based on using only saline water (drainage water of the existing cultivated areas) in irrigation. In the third alternative, the possibility of recycling the drainage water of the new land in irrigation after being mixed with fresh water is considered.

The role of agricultural expansion investment in improving the income redistribution conditions in a society is investigated. The approach of distributing the new land to a poorer sector (landless farmers) is selected. A mathematical optimization model is built to determine the distribution of the land and a pricing policy established for the new areas in such a way that: 1) a specified income increase to the farmers can be achieved; 2) a predetermined level of recovery of the expansion cost can be insured; 3) high agricultural efficiency in the new lands can be maintained; and 4) redistribution benefits can be maximized.

In a case study application of the model, no conflict is found between the economic efficiency and income redistribution criteria. For a specified cost recovery condition, it is found that the least cost planning alternatives give the opportunity to the largest number of landless farmers to own the new land and get a specified income increase from the agricultural revenues. But a conflict between the government return from the investment and income redistribution objectives is found. This conflict is addressed and the trade-off between the two objectives is illustrated.

A multi-criteria optimization model is built to determine performance as well as operating rules of the agricultural systems under future uncertainties inherent in the planning parameters. Performance of agricultural systems is measured in terms of the economic efficiency and income redistribution criteria. The operating decisions are determined in such a way that the reduction in performance due to unpleasant surprises in the planning parameters can be minimized. The multi-criteria model is used in deriving the relationship between the performance of the case study under the different planning schemes and the unpleasant changes in the planning parameters. A resiliency index in terms of gradients of these functional relationships is provided. It is developed in deterministic as well as probabilistic framework. Based on this resiliency index, a definition of resilient system design is reached.

A conflict between the resiliency and the cost of agricultural system designs is found. It is found that the overbuilt designs (the most costly designs) are the most resilient ones. The trade-off between the cost and the resiliency of the case study is derived and investigated.

ACKNOWLEDGEMENTS

This study was sponsored by the M.I.T. Technology Adaptation Program which is funded through a grant from the Agency for International Development, United States Department of State.

I would like to thank my Committee, Professor David H. Marks, Professor Ann F. Friedlaender and Professor Arnoldo C. Hax, for their guidance, support and friendship.

Special thanks are extended to my office-mates and dear friends whose comments greatly contributed to the thesis, namely, Karnik Saferian, Fadi Karaa, Stefanos Andreou, Aris Georgakakos, Daniel Goode and Mark Alexandridis.

Gratitude is extended to Connie Choquet who typed this report so skillfully.

This thesis could never have been completed without the prayers, support and encouragement of my parents. I am really grateful to them.

Finally, I dedicate this work to my lovely wife, Somia, and beautiful daughter, Sarah, who are behind every success I have achieved.

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CHAPTER 1

INTRODUCTION

1.1 Agriculture Expansion Planning in Developing Countries

Planning of large scale public investment in general and agricultural expansion in particular is a complicated problem. Many issues are involved, among the most important of which is investment scheduling. In development planning it is often the case that resource constraints limit the size of investments that can be undertaken in a given time period. Examples of such constraints include budgetary limitations, foreign exchange shortages and resource bottlenecks. Scheduling decisions for an agriculture expansion investment are for every year of the time horizon: 1) size and location of land to be reclaimed; 2) crop pattern in these lands; 3) mixing ratio between drainage and fresh water if mixing is possible (in case of drainage water reuse) and, 4) correct capacity expansion timing of irrigation and drainage networks. These decisions should be determined in such a way that the budget and resource constraints are not violated and that the social welfare of the society can be maximized.

Income redistribution is another important issue in the planning of large scale public investments. In the real world, governments are not able to maximize the social welfare but only the economic efficiency. In general, governments lack the analysis tools to achieve optimal income distribution. However, large public investments are usually used to improve the income redistribution conditions and drive the society toward the social welfare frontier. In agriculture expansion this objective can be achieved by giving the poor (landless farmers) an opportunity to own the new lands and gain agricultural return. In implementing this policy, two decisions are needed. The first is a pricing policy for the new areas in which prices are charged in annual payments less than the agriculture revenues to be affordable by the farmers. The second is the distribution of land among the farmers. These decisions should be determined in such a way that: 1) expansion cost can be recovered (or even some return to the government an be achieved); 2) an increase (assigned by the government) to the farmers' income can be achieved; 3) high agriculture efficiency can be maintained; and 4) equity between the farmers in achieving the same income level is insured.

Uncertainty is a crucial issue in this planning problem for it plays a major role in agriculture expansion investments. Uncertainty in crop water requirements, crop yields, quality and quantity of irrigation water, technology, prices and changing objectives make the system performance hard to predict. Recently, the concept of resilience has been used to deal with future uncertainties as a measure of system performance (Fiering and Holling (1974), Krzystofowicz (1980), Marks (1981), Fiering (1982) and Hashimoto et al. (1982)). System resilience is a measure of a system's capability to absorb and adapt to the impacts of surprises in any of the system parameters. Various methods for measuring a system resilience have been suggested (Fiering (1982) and Hashimoto et al. (1982)). These measures have been developed in such a way that they can be used to compare alternative designs in terms of their resiliency but not to determine if a certain design is resilient or not. In addition, these measure have been developed for cases in which only one source of uncertainty exists. More research is needed to overcome these drawbacks and obtain a more unique resiliency measure applicable to large-scale problems in general, and agricultural systems in particular.

A planning scheme for agricultural expansion sensitive to the above issues in a country should not be prepared in isolation from the national plan of this country. Budget limitations, foreign exchange shortages and resource bottlenecks are national constraints. The number of landless farmers who may own newly developed lands as well as their income increase cannot be decided without information about the national economy and income redistribution conditions. The social rate of discount, which represents a crucial factor in testing the economic feasibility of the investment, is a national parameter. It should reflect (Tresh (1981)) the opportunity cost of public funds, reinvestment rate of the net-benefit of public investments and society's rate of time preference. Shadow prices of the crops, farming inputs and foreign exchange rate are national figures. The population growth rate and domestic agricultural requirements, which are essential to determine the cropping pattern in the new areas, are national parameters. These national decisions, parameters and constraints are usually provided by the central planners (Guidelines for Project Evaluation (1972) and Little and Mirrlees (1974)) on the basis of data supplied in the national plan (Figure 1-1).

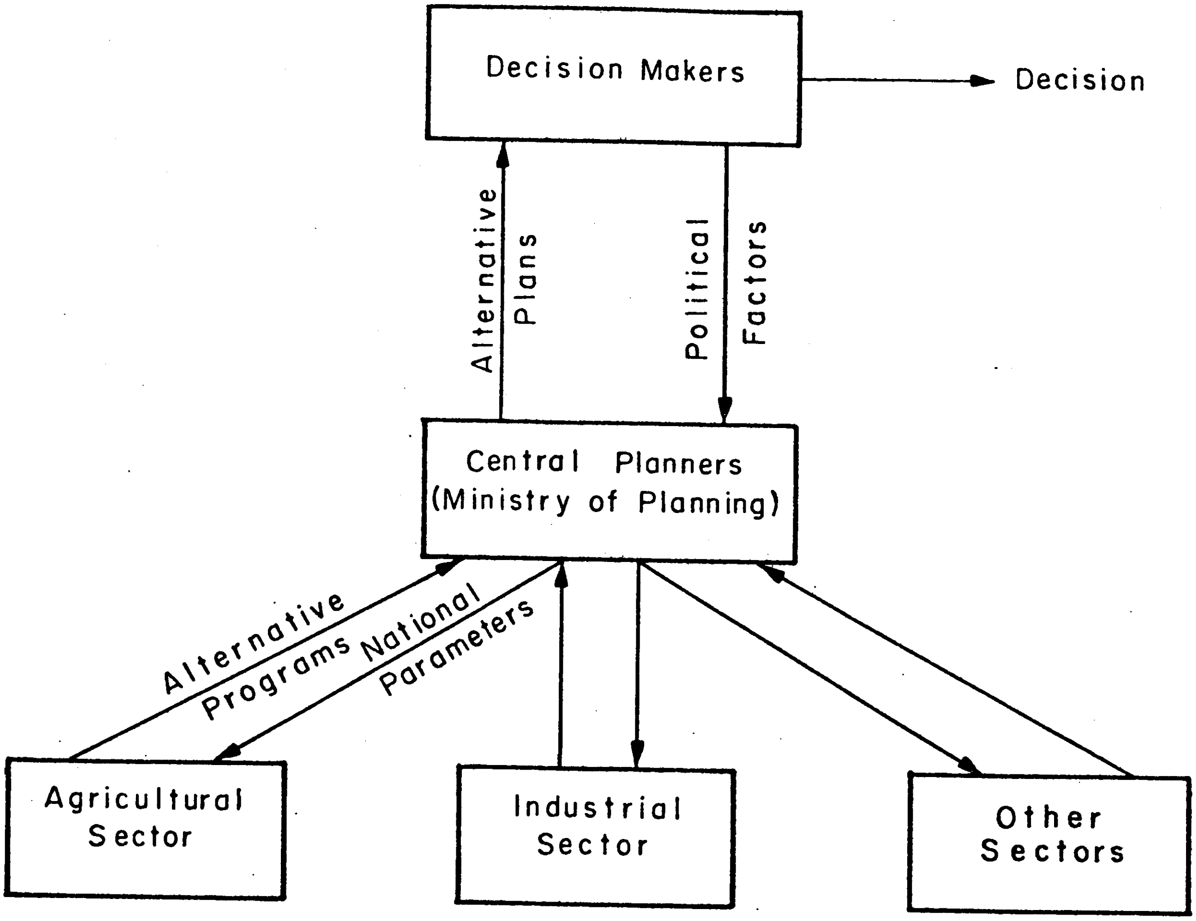

Figure 1-1 Planning Process of Public Investments

Having this input data, planning of agriculture expansion as well as other agriculture investments is usually carried out in parallel on the agriculture sector level. This is to minimize the conflict between the various projects and to optimally allocate the budget as well as scarce resources among them. The next step is to provide the central planners with competent programs of agriculture investment plans. Then a screening process of these alternatives would be carried out based on their consistency with the development plans of the other sectors of the economy. The screened plans will be provided to the decision makers to select the best plan or to impose more issues (political, social, etc.) to be taken into account in the planning process. This procedure continues until a satisfactory development program can be reached.

In this report the focus of the research is on the analysis of agriculture expansion planning within the agricultural sector level. The iterations between the agricultural sector, central planners and decision makers are beyond the scope of this research.

1.2 Research Objectives

As discussed above, agriculture expansion planning should be sensitive to the issues of scheduling, income redistribution and uncertainty. In addition, it should be coordinated with the other agriculture investment plans. One way of looking at this problem is to consider a two-level hierarchy. On the first level, strategic planning to the agricultural sector as one unit is to be performed. At this level the feasibility of the agricultural expansion investment, as well as the other investments is to be examined and the role of each investment in achieving the strategic goals of the sector is to be determined. At the second level, solutions to the planning issues of the expansion are to be provided. The solutions should be developed in such a way that the strategic decisions from the first level can be implemented. However, a feedback from the second level with a better estimate of costs, agricultural parameters and income distribution conditions to the first level for adapting the strategic role of the investment should be considered.

Planning (strategic) decisions at the first level considering the agricultural expansion investment may include: 1) production targets of the new land, 2) allocated budget, foreign exchange and resource inputs (water, labor, fertilizer, etc.), 3) assigned increases to the landless farmers' income, and 4) desired pay-back period of the expansion cost. In real life, the strategic decisions are usually determined in a heuristic way as many political, economic, social and institutional factors should be considered. In the literature, modeling approaches for analyzing this planning problem based on an economic efficiency criterion is available (Kutcher (1972 and 1981) and Grossman (1980)). There is still more work to advance the available planning approaches at this level to account for the redistribution objectives as well as the uncertainties of the planning parameters and their effects on the strategic decisions. This is not the focus of this research. The main emphasis here is on the issues of agricultural expansion planning.

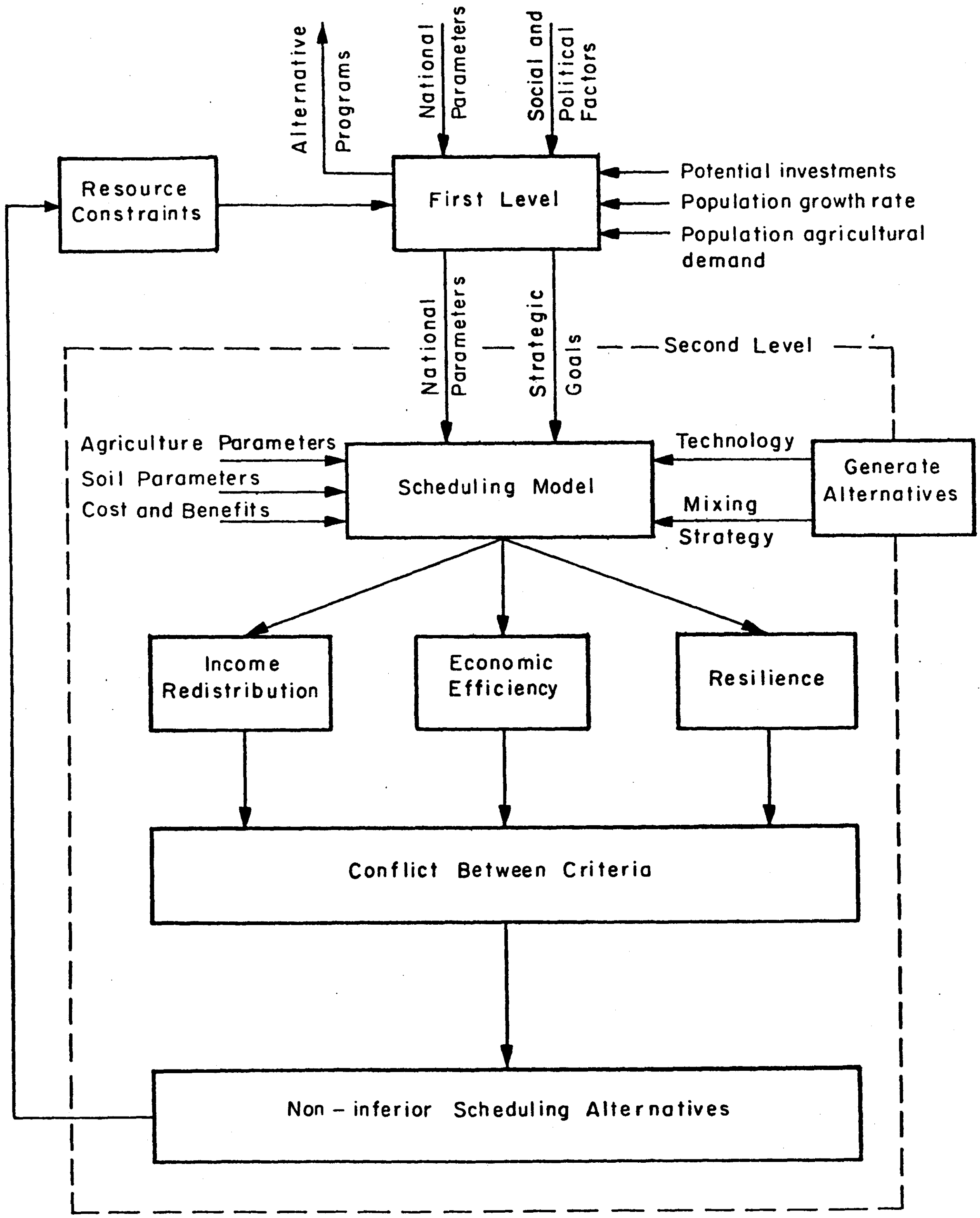

Figure 1-2 A Schematic Presentation of the Multi-level Planning of Agricultural Expansion Investment on the Agricultural Sector Level.

The objective of this report is to provide the analytical tools for the planning issues of agricultural expansion investments. The goal here is to develop modeling approaches for the three planning issues in such a way that they can be put together in one framework through which the best planning alternatives can be distinguished. This framework is presented in Figure (1-2). The framework starts with a mathematical model [Scheduling Model] for analyzing the scheduling issue based on an economic efficiency criterion. Given information about the national parameters as well as the strategic goals of the investment, the model can be used to generate various alternate plans for different conditions of irrigation water quality, irrigation and drainage technology, etc. Then a redistribution model [Income Redistribution] can be used to determine the redistribution benefits and decisions for the various alternatives. Similarly, through a performance model [Resilience], the resiliency of the planning alternatives can be measured. The next step is to compare the different plans via the planning criteria and to distinguish the best alternatives,

From the above discussion, the objectives of the research can be summarized as follows:

1. To develop a modeling approach to guide scheduling decisions and to generate competent planning alternatives.
2. To develop a modeling approach to determine the redistribution beneftis and decisions for the various alternatives.
3. To develop a modeling approach to measure the performance of the agricultural systems under uncertainty.
4. To investigate the conflict between the planning criteria in irrigated agricultural development.

In this planning framework, it should be noticed that a minimum cost criterion is equivalent to the economic efficiency criterion in determining the scheduling decisions for the agricultural expansion investment. This is because as explained above, that the scheduling decisions should be determined in such a way that the agricultural production target of the new land (a strategic decision from the first planning level) can be achieved; i.e., the gross benefits (in terms of value of the crops) of the investment is given and fixed. Then, via a minimum cost criterion, the most efficient scheduling scheme for the investment should be obtained.

A conflict between income redistribution and minimum cost (economic efficiency) criteria within this planning framework should not exist. As discussed above, that income redistribution objective can be achieved in agricultural expansion investment by giving up some of the investment net-return to the farmers to improve their income conditions. The remainder from the investment net-return will be gained by the government for more beneficial investments to the society. Then, for a specified return to the government from the investment, the least cost design (the most efficient design) should achieve maximum return to the farmers (maximum redistribution benefits). On the other hand, at the first level, a conflict between the economic efficiency and income redistribution criteria, may exist. Large investment will give the opportunity to a large number of landless farmers to own the new land and improve their incomes. But a smaller investment might be economically more efficient. This case is out of the scope of this research.

1.3 Description of the Report

Three mathematical optimization models are introduced. The first is a deterministic dynamic model to aid in analyzing the scheduling problem. An economic efficiency (least cost) criterion is used where costs of land development, farming, irrigation and drainage infrastructures, maintenance and operation, and pump stations are considered. The model is formulated in such a way that the optimum scheduling decisions which achieve the agricultural production targets of the new land (from the first level) can be determined. The possibility of reusing the drainage water for irrigation in its status quo or after being mixed with fresh water is investigated. The effects of drainage water salinity on both yields and water requirements of the crops are studied and included in the model formulation.

The model consists of a nonlinear objective function accounting for economies of scale and linear and nonlinear constraint sets. A fixed charge approximation is used for the non-convex cost functions. A mixed integer programming algorithm along with an enumeration procedure is used for solving the model. The solution procedure guarantees global optimality for the approximated problem. The model is applied to a case study which is based on a hypothetical expansion on the order of 70,000 acres. This expansion extends over five years of different sizes and soil types. The effects of the soil type on the crop water requirements and yields, conveyance losses, and land development cost are considered. One source of fresh water for irrigation is assumed. The scheduling model is used for developing three alternative planning schemes for the case study. The first plan is based on using fresh water for irrigation. The second alternative is based on using only saline water (drainage water from the existing cultivated areas) in irrigation. In the third alternative, the possibility of reusing the drainage water of the new land in agriculture practices after being mixed with fresh water is considered.

The second optimization model is built to determine the redistribution decisions for the various alternate plans. The income redistribution criterion in terms of maximum redistribution benefit (number of investment beneficiaries x their income increase) is used. To evaluate the model's solutions, marginal and average costs approaches are used for estimating the land prices for the case study and the solutions are compared. It is found that the model is better in insuring the recovery of the expansion cost as well as achieving the assigned income increase to the farmers and insuring equity between them. The model is used in deriving the trade-off between the Government return from the investment and the redistribution benefits for the case study under different conditions of payment time horizon. This trade-off is prepared in graphic formats for easy use by decision makers. The factors which usually affect the decision makers in solving the trade-off are discussed and an illustrating example is used. The conflict between the economic efficiency and income redistribution criteria is also investigated in this planning problem.

The third mathematical model is built to determine the performance as well as the operating rules of the agricultural systems under future uncertainties inherent in the planning parameters. Performance of the agricultural systems is measured in terms of the economic efficiency and income redistribution criteria. The operating decisions are determined in such a way that the reduction in performance due to unpleasant surprises in the planning parameters can be minimized. An extensive use of this multi-criteria model in deriving functional relationships between the performance of each planning alternative to the Case study and the unpleasant changes in the planning parameters is performed. A resiliency index in terms of the gradients of these functions is developed. This index gives the degree of degradation of system performance toward changes in the planning parameters. It is computed in deterministic as well as probabilistic frameworks. Based on this resiliency index, for the first time a definition of the resilient system design is reached.

A comparison between the three planning alternatives for the case study via the planning criteria (economic efficiency, income redistribution, and resilience criteria) is carried out. A conflict between these criteria is found. This conflict is addressed and a solution is tried.

1.4 Organization of the Later Chapters

In Chapter 2, a mathematical formulation of the scheduling problem of agricultural expansion investments is introduced. An application of the scheduling model for a case study is presented. A planning scheme for the case study based on using fresh water for irrigation is obtained. In Chapter 3, a modification to the formulation of the scheduling model to account for drainage water reuse in agricultural practices is presented. The effects of the low quality (saline) drainage water on the yields and water requirements of the crops are discussed. These effects are included in the model formulation. The modified version of the model is applied to the case study and two alternative planning schemes are obtained. The first alternative is based on using only drainage water in irrigation. In the second scheme, water mixing (fresh and drainage water) is allowed for irrigation.

Chapter 4 presents a mathematical formulation of the income redistribution problem in an optimization framework. An extensive use of the model in deriving a wide range of payment policies for the new land which achieve the redistribution objectives is shown. The use of the marginal and average cost approaches in estimating land prices for the case study is presented. A comparison between the model and the marginal and average cost approaches in land pricing is carried out. The use of the redistribution model in deriving the trade-off between Government return from the investment and redistribution benefits is presented. The factors which usually affect the decision makers in solving this trade-off are discussed. In Chapter 5, the redistribution model is used in measuring the redistribution benefits of the three planning alternatives. A comparison between the planning alternatives via the income redistribution and economic efficiency criteria is carried out. The conflict between criteria is addressed.

In Chapter 6, a multiobjective mathematical model for measuring the performance of agricultural system design under unpleasant changes in the planning parameters is developed. The use of this model in deriving an index for measuring the resiliency of large-scale investment in general and agricultural expansions in particular is presented. A definition of the resilient system designs is reached. In Chapter 7, the resiliency of the planning alternatives is measured.

In Chapter 8, the conflict between the planning criteria (economic efficiency, income redistribution and resiliency criteria) is addressed. The trade off between the resiliency and the performance of agricultural systems in terms of the economic efficiency and income redistribution criteria is derived.

Finally, Chapter 9 presents a summary of the report, and the main conclusions and findings that can be made from the research. The Chapter ends with recommendations for future research.

CHAPTER 2

A SCHEDULING MODEL FOR IRRIGATED AGRICULTURAL EXPANSION

2.1 Introduction

In this chapter, a deterministic dynamic optimization model to guide decisions required for scheduling agricultural expansion investments is presented. These decisions are for every year of the investment horizon: 1) size and location of land to be reclaimed, 2) crop pattern in these lands, and 3) correct capacity expansion timing of irrigation and drainage networks. An economic efficiency criterion (least cost) is used, where costs of land development, farming, irrigation and drainage infrastructures, maintenance and operation, and pump stations are considered. The model is formulated in such a way that the optimum scheduling decisions which achieve the agricultural production targets of the new lands (strategic decision from the first planning level) can be determined. The model consists of a nonlinear objective function accounting for economies of scale and linear constraints. To test the model's applicability, a hypothetical expansion on the order of 70,000 acres has been used as a case study. This expansion extends over five areas of different sizes and soil types where only one source of fresh water is available for irrigation. A fixed charge approximation to the non-convex cost functions is used and a solution to the case study via mixed integer programming is obtained. The solution procedure guarantees global optimality for the approximated problem

2.2 The Scheduling Model Forumulation

In order to derive a mathematical formulation for the scheduling problem, the following assumptions are made:

a. The planning time horizon is finite and is given.

b. The discount rate is given and remains constant over the planning time horizon.

c. The full agricultural production of the new lands will start after the time period t_1, which is required for land development.

d. The new lands can be divided into sub-areas. Each sub-area should be confined to a single soil type for determining the appropriate cropping pattern, and to a relatively local and homogeneous region to insure that the transportation costs of any resource input are essentially uniform.

Before going through the model formulation, let us define the following:

r = discount rate

α^t = $\frac{1}{(1+r)t}$ (Present value factor for a single investment t time periods in the future.)

T = time horizon of scheduling

TT = time horizon of the investment

N = number of the new areas

M = number of the water sources and diversion nodes of the irrigation network

P = number of crops per season

S = number of seasons per year

A_i = size in acres of area *i*

$X^{s,t}_{i,p}$ = size in acres of land to be cultivated with crop *p* during season *s* of year *t* at area *i*

$f^{s,t}_{i,j}$ = flow through canal (i.j) in season *s* of year *t*

$CP^{t}_{i,j}$ = increment in canal (i.j) capacity at beginning of year *t*

$CPD^{t}_{i,j}$ = increment in drain (i,j) capacity at beginning of year *t*

$fd^{s,t}_{i,j}$ = flow through drain (i,j) in season *s* of year *t*

$a^{t}_{i}(.)$ = land development at area i in year *t*

$b^{s,t}_{i,p}(.)$ = farming cost of crop *P* at area *i* during season *s* of year *t*

$C^{t}_{i,j}(.)$ = capital cost of increasing canal (i,j) capacity in year *t*

$ISC^{t}_{i,j}(.)$ = capital cost of the irrigation infrastructures along canal (i,j) in year *t*

$MO^{s,t}_{i,j}(.)$ = maintenance and operation cost to canal (i,j) during season *s* of year *t*

$CL^{t}_{i,j}(.)$ = lining cost of canal (i,j) in year *t*

$CD^{t}_{i,j}(.)$ = capital cost of increasing drain (i,j) capacity in year *t*

$DSC^{t}_{i,j}(.)$ = capital cost of the drainage infrastructure along drain (i,j) in year *t*

$MDO^{s,t}_{i,j}(.)$ = maintenance and operation cost to drain (i,j) during season s of year t

$C^{t}_{i}(.)$ = capital pumping cost at site i during year t

$EC^{t,s}_{i}(.)$ = energy cost at pump station i during season s of year t

$POM^{t,s}_{i}(.)$ = maintenance cost to the pump station at site i during season s of year t

$Y^{s,t}_{i,p}$ = yield of crop p at area i during season s of year t

$W^{s,t}_{i,p}$ = water duty of crop p at area i during season s of year t

$L^{s,t}_{i,j}(.)$ = water losses in canal (i,j) in season s of year t as a function of the length and flow

$D^{s,t}_{p}$ = demand for crop P in season s of year t

$d^{s,t}_{j}$ = water required at area j during season s of year t

$dr^{s,t}_{j}$ = drained water at area j during season s of year t

$b^{s,t}_{i}$ = available water at source i during season s of year t

Q^{t}_{i} = increase in pump station i capacity at the beginning of year t

ΔH^{t}_{i} = lifting head at pump station i during year t

$q^{s,t}_{i}$ = seasonal flow at pump station i during season s of year t

$\Delta h^{s,t}_{i}$ = lifting head at pump station i during season s of year t

Decision Variables

The model's decision variables are for every year of the scheduling horizon, the area and location of lands to be cultivated with the various crops ($X_{i,p}^{s,t}$), area and location of lands to be developed every year (X_i^t), seasonal flows in the irrigation and drainage networks ($f_{i,j}^{s,t}$ and $fd_{i,j}^{s,t}$), seasonal flow at each pump station ($q_i^{s,t}$), the yearly incremental capacities of the irrigation and drainage networks ($CP_{i,j}^t$, $CPD_{i,j}^t$) and yearly incremental capacities of the various pump stations (Q_i^t).

Objective Function

A minimum cost criterion is used here where costs of land development, farming, irrigation and drainage infrastructures, maintenance and operations, and pump stations are considered. It should be noticed that at the second planning level, the gross benefit of the expansion investment in terms of agricultural production of the new lands is fixed and given (strategic decision from the first level). Therefore, via a minimum cost criterion, the economic efficiency optimum scheduling scheme for the investment should be obtained.

The objective function may be written as:

$$\text{Minimize } LC + FC + IC + DC + PC \qquad \ldots.(2.1)$$

LC = present value of land development cost

$$LC = \sum_{t=1}^{T} \sum_{i=1}^{N} \alpha^{t} a_{i}^{t}(X_{i}^{t}) \qquad \ldots.(2.2)$$

FC = present value of farming cost

$$FC = \sum_{t=t+1}^{TT} \sum_{i=1}^{N} \sum_{s=1}^{S} \sum_{p=1}^{P} \alpha^{t,s} b_{i,p}^{s,t}(X_{i,p}^{s,t}) \qquad \ldots.(2.3)$$

IC = present value of excavation, lining, infrastructures, and maintenance costs for the irrigation canals

$$IC = \sum_{t=1}^{T} \sum_{i=1}^{N+M} \sum_{\substack{j=1 \\ j \neq i}}^{N+M-1} \alpha^{t}(C_{i,j}^{t} \; (CP_{i,j}^{t}) + ISC_{i,j}^{t} \; (CP_{i,j}^{t}) +$$

$$CL_{i,j}^{t}(CP_{i,j}^{t})) + \sum_{t=1}^{TT} \sum_{i=1}^{N+M} \sum_{\substack{j=1 \\ j \neq i}}^{N+M-1} \sum_{s=1}^{S} \alpha^{t,s} \; MO_{i,j}(f_{i,j}^{s,t})$$

$$\ldots.(2.4)$$

DC = present worth of excavation, infrastructure, and maintenance costs for the drainage canals

$$DC = \sum_{t=1}^{T} \sum_{i=1}^{M+N} \sum_{\substack{j=1 \\ j \neq i}}^{M+N-1} \alpha^{t}(CD_{i,j}^{t}(CPD_{i,j}^{t}) + DSC_{i,j}^{t}(CPD_{i,j}^{t}))+$$

$$\sum_{t=1}^{TT} \sum_{i=1}^{N+M} \sum_{\substack{j=1 \\ j \neq i}}^{N+M-1} \sum_{s=1}^{S} \alpha^{t,s} MDO_{i,j}^{s,t}(fd_{i,j}^{s,t}) \qquad \ldots.(2.5)$$

PC = present value of pumping cost

$$PC = \sum_{t=1}^{T} \sum_{i=1}^{M} \alpha^{t} C_{i}^{t} (Q_{i}^{t}, H_{i}^{t}) +$$

$$\sum_{t=1}^{TT} \sum_{i=1}^{M} \sum_{s=1}^{S} \alpha^{t,s} (EC_{i}^{t,s}(q_{i}^{t,s}, \Delta h_{i}^{s,t}) +$$

$$POM_{i}^{t,s} (q_{i}^{s,t}, \Delta h_{i}^{s,t}) \qquad \ldots.(2.6)$$

Constraints

Agricultural Requirements Constraint

This constraint is to insure that the demand for each agricultural crop P will be satisfied in each season s and year t.

$$\sum_{h=1}^{t} \sum_{i=1}^{N} X_{i,p}^{s,h} \; Y_{i,p}^{s,h} \; Y_{i,p}^{s,h} \geq D_{p}^{s,t} \quad \forall p,s,t \qquad \ldots.(2.7)$$

Land Development Constraint

This constraint is to determine the size and location of lands to be developed every year.

$$\sum_{s=1}^{S} \sum_{p=1}^{P} X_{i,p}^{s,t} \leq X_{i}^{t} \qquad \forall i,t \qquad \ldots.(2.8)$$

Area Budget Constraint

This constraint is to insure that at each area the total acreage to be developed over the time horizon is no greater than the size of the area itself.

$$\sum_{t=1}^{T} X_{i}^{t} \leq A_{i} \qquad \forall i \qquad \ldots.(2.9)$$

Sequential Planting Constraint

Some crops are required to be grown before some other crops. As an example, clover is needed before cotton can be planted to enhance soil nitrogen. If crop a during season s is required before crop b can be planted during season s+1, this constraint can be written as:

$$X_{i,b}^{s+1,t} - X_{i,a}^{s,t} \leq 0 \qquad \forall i,t \qquad \ldots.(2.10)$$

A Constraint on the Water Demands at the New Areas

This constraint is to compute the seasonal water demands for the new areas at every year up to the time horizon.

$$\sum_{h=1}^{t} \sum_{p=1}^{P} W_{i,p}^{s,h} \; X_{i,p}^{s,h} = d_i^{s,t} \qquad \forall i,s,t \qquad \ldots.(2.11)$$

Flow Balance Constraint (Irrigation Networks)

This constraint is to insure the delivery of irrigation water requirements to the new areas.

$$\sum_{i=1}^{N+M} f_{i,j}^{s,t}(1-L_{i,j}^{s,t}(f_{i,j}^{s,t})) - \sum_{\substack{k=1 \\ k\neq i}}^{N+M} f_{j,k}^{s,t} = d_j^{s,t} \qquad \forall j,s,t \qquad \ldots.(2.12)$$

Water Budget Constraint

This constraint is to keep the outflow from each source less than or equal to the inflow to this source.

$$\sum_{j}^{M} f_{i,j}^{s,t} \leq b_i^{s,t} \qquad \forall i,s,t \qquad \ldots.(2.13)$$

A Constraint on the Capacity Expansion of the Irrigation Network

This constraint is to determine the irrigation network incremental capacity at each year of the scheduling period.

$$f_{i,j}^{s,t} - \sum_{h=1}^{t} CP_{i,j}^{h} \leq 0 \qquad \forall\ i,j,s,t, \qquad ....(2.14)$$

Flow Balance Constraint (Drainage Network)

This constraint for the drainage network can be written as:

$$\sum_{k=1}^{N+M} fd_{j,k}^{s,t} - \sum_{\substack{i=1\\ i\neq k}}^{N+M} fd_{i,j}^{s,t}(1 + LD_{i,j}^{s,t}(fd_{i,j}^{s,t})) - dr_{j}^{s,t}(d_{j}^{s,t}) = 0$$

$$\forall\ i,j,s,t \qquad ....(2.15)$$

where:

$dr^{s,t}$ = drainage water at node i during season s of year t

= 0 if node j is a diversion node

$LD_{i,j}^{s,t}$ = seepage water to drain (i,j) during season s of year t.

A Constraint on the Capacity Expansion of the Drainage Network

The yearly capacity expansion to the drainage network can be computed as

$$fd_{i,j}^{s,t}(1+LD_{i,j}^{s,t}(fd_{i,j}^{s,t})) - \sum_{h=1}^{t} CPD_{i,j}^{h} \leq 0.0 \qquad \forall\ i,j,s,t \qquad ....(2.16)$$

Non-negativity Constraint

This constraint is to insure the non-negativity of the decision variables

$$X_{i,p}^{s,t},\ f_{i,j}^{s,t},\ CP_{i,j}^{t},\ fd_{i,j}^{s,t},\ CPD_{i,j}^{t} \geq 0 \qquad \forall\ i,j,s,t \qquad ....92.17)$$

2.3 Case Study Description

A hypothetical expansion in the order of 70,000 acres based on data from the Nile Delta in Egypt is used here as a case study. The expansion is proposed in five areas, where one water source is only available for the irrigation. This water source supplies the main irrigation canal which subsequently feeds the new areas with the irrigation water. The drainage water at the different areas will be discharged to a main drain as shown in Figure (2-1).

A network presentation of the irrigation and drainage networks is introduced in Figure (2-2). The network consists of ten nodes, ten arcs (canals) for the irrigation network, and six arcs (drains) for the drainage network. Nodes' definitions and arcs' lengths are presented in Table (2-1) and Table (2-2), respectively.

Two agricultural seasons (winter and summer) per year are considered while three crops per season are used. The winter crops are short season clover (usually used in the winter for enhancing soil nitrogen necessary for cotton in the summer), beans and wheat; and the summer crops are cotton, maize and rice. Based on the surface irrigation method, yields, water requirements, and farming costs of the various crops are presented in Table (2-3).

Different costs for land development of the various new areas are used. This is based on the assumption that the closes areas to the water sources are in better condition than the other areas and hence less development is needed. In addition, it is assumed that the areas which lie close to the water sources have clayey (silty) soils where the other areas have sandy soils. This soil classification

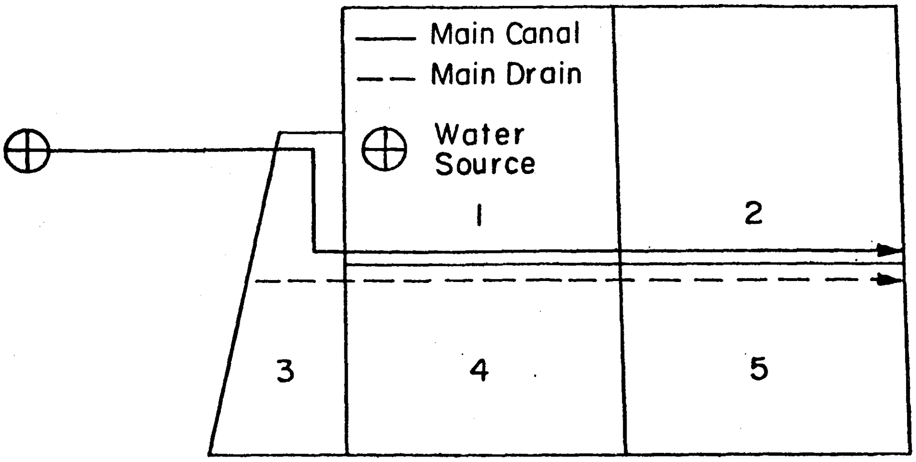

Figure 2-1 A Hypothetical Agricultural Expansion on the Order of 70,000 Acres

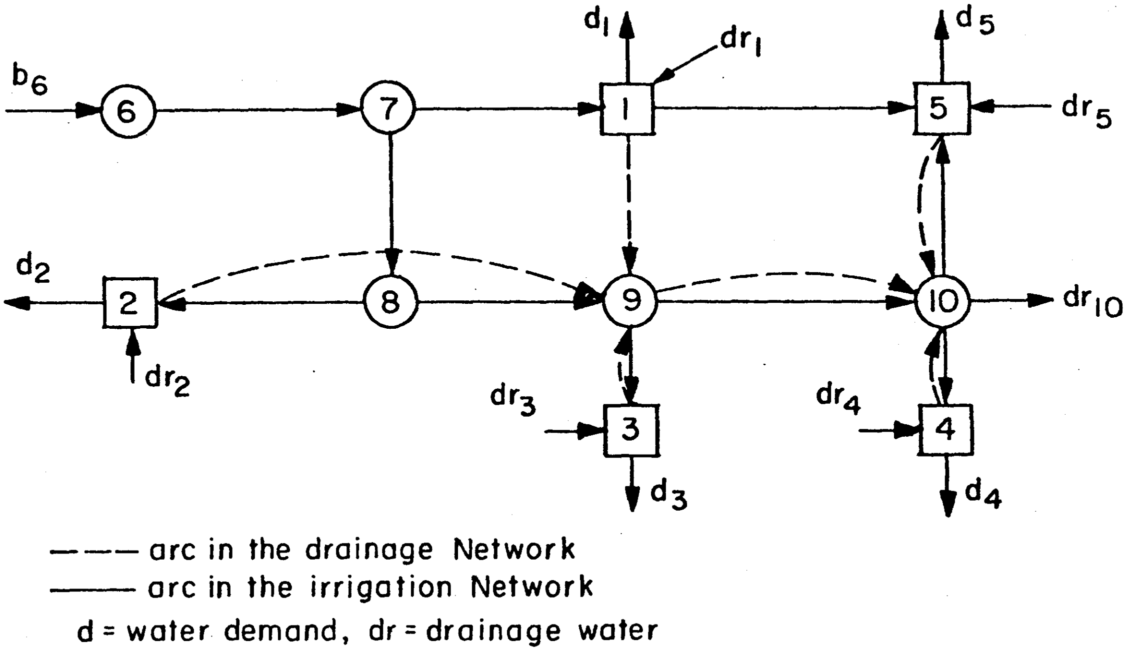

Figure 2-2 A Network Presentation for the Case Study

Table 2-1 Nodes Definitions

Node	State	Node	State
1	Area #1	6	Water source
2	Area #3	7	Diversion node
3	Area #4	8	Diversion node
4	Area #5	9	Diversion node
5	Area #2	10	Diversion node

Table 2-2 Arcs Definitions

Arc	Length in Kms	Arc	Length in Kms
6-7	10.0	2-9	9.5
7-1	4.5	1-9	4.5
1-5	9.0	9-3	3.0
7-8	4.5	9-10	9.0
8-2	5.0	10-5	4.5
8-9	4.5	10-4	3.0

Table 2-3 Agricultural Demands in the Next Three Years (tons/years)

Crops	Year		
	6	7	8
S.S. Clover	80,000	110,000	140,000
Beans	4,000	5,500	7,000
Wheat	15,000	25,000	30,000
Cotton	10,000	15,000	20,000
Maize	15,000	25,000	34,000
Rice	20,000	35,000	46,000

Table 2-4 Input Data to the Scheduling Model

5	4	3	2	1	Area		
12,000	12,000	10,000	18,000	18,000	Size in acres		
1500	1400	1300	1500	1400	Land development cost (dollars/acre)		
8.5	8.5	8.5	8.5	8.5	Y	S.S.Clover	CROPS
.000293	.00026	.00022	.000293	.00026	WD		
38.1	38.1	38.1	38.1	38.1	FC		
1	1	1	1	1	Y	Beans	
.000281	.000246	.000211	.000281	.000246	WD		
50.9	50.9	50.9	50.9	50.9	FC		
1.5	1.5	1.5	1.5	1.5	Y	Wheat	
.00015	.00013	.00011	.00015	.00013	WD		
111.4	111.4	111.4	111.4	111.4	FC		
1.032	1.032	1.032	1.032	1.032	Y	Cotton	
.000269	.000236	.000202	.000269	.000236	WD		
187.9	187.9	187.9	187.9	187.9	FC		
1.7	1.7	1.7	1.7	1.7	Y	Maize	
.00032	.00028	.00024	.00032	.00028	WD		
121.5	121.5	121.5	121.5	121.5	FC		
2.3	2.3	2.3	2.3	2.3	Y	Rice	
.00136	.00119	.00102	.00136	.00119	WD		
126.1	126.1	126.1	126.1	126.1	FC		

Y = Ton/acre

WD = m^3/sec/acre

FC = dollars/acre

is reflected in the estimation of crops' water requirements as shown in Table (2-4) where the irrigation requirements in clayey soils are less than the irrigation requirements in the sandy soils. The water conveyance losses are taken as 0.002 and 0.0025 of the canal's flow per kilometer of canal's length for clayey and sandy soils, respectively.

It is assumed here, too, that the stage of full agricultural production in the new lands will be reached after five years of development, while the investment horizon is taken as twenty-five years. The main objective of this investment is to satisfy the agricultural requirements starting six years from now and for three subsequent years (Table 2-4). The purpose of using the scheduling model in solving this agricultural expansion problem is to determine for each year of the next three years, size, and location of lands to be developed and crop pattern in these lands. In addition, it is to determine the yearly incremental capacity to the irrigation and drainage networks.

2.4 Cost Functions

Land Development Cost (dollars/acre): This cost includes the costs of the drainage works, farm machinery, housing, electricity, machinery for cultivation, transportation, communication, land leveling and social services. This cost is taken here as a linear function in the size of developed land as shown in Table (2.4).

Farming Cost (dollars/acre): This cost includes all the farm input costs such as seeds, pesticides, fertilizer, labor and machinery. This cost is different for the various crops. It is taken here as a linear function in the size of the cultivated lands.

Excavation and Lining Costs: Excavation and lining costs for a canal (i,j) with length $\ell_{i,j}$ can be expressed as

$$\text{Excavation Cost } (i,j) = A(V_{i,j})^{B}\,\ell_{i,j} \qquad \text{dollars} \;\ldots\; (2.18)$$

$$\text{Lining Cost } (i,j) = C(A_{i,j})^{D}\,\ell_{i,j} \qquad \text{dollars} \;\ldots\; (2.19)$$

where A is the unit cost of excavation per unit length, C is the unit cost of lining per unit length, B and D are the economies of scale, $V_{i,j}$ is the volume of excavation for canal (i,j) and $A_{i,j}$ is the size of lined surface area of canal (i,j). The volume of excavation as well as the surface area of a canal are functions of the canal's dimensions (depth and width) which sequentially depend on the method of design. In this work, it is assumed that the proposed design of a canal is the most economic one. This method of design can be done by minimizing the cross-sectional area of a canal, given the amount of flow or by maximizing the uniform flow velocity, given the cross-sectional area of this canal. For a trapezoidal canal's section which is the general case of the artificial cross-sections and by using the Chazy equation for open channel flow, the excavation and lining costs have been derived (Allam,1980) in terms of the capacity ($CP_{i,j}$) of canal (i,j) as

$$\text{Excavation cost } (i,j) = A(a \times CP(i,j)^{.8} + b \times CP(i,j)^{.4} + \lambda)^{B}\,\ell_{ij} \;\ldots\; \text{dollars} \quad (2.20)$$

$$\text{Lining cost } (i,j) = C(d \times CP(i,j)^{.4} + e)^{D}\,\ell_{i,j} \;\ldots\; \text{dollars} \quad (2.21)$$

where a, b, d, λ and e are functions of a canal's bed slope (^{S}o), side slope (t) and Chezzy's Coefficient (C). For the case study, the excavation cost is only considered with A = \$1 and B = 0.9. For So = 0.0001, t = 1.5 and C = 100 the values of a, b and λ are computed as 1.5, 6.12, and 9.0, respectively. The excavation cost of a drain is usually higher than that of a canal. This is because the drains have to be deep enough to control the ground water level. This cost is computed as

$$\text{Excavation cost of drain } (i,j) = (3.8\ CPD(i,j)^{.8} + 14.6\ CPD(i,j)^{.4} + 21.5)^{.9}\ \ell_{i,j}\ \ldots \text{ dollars} \quad (2.22)$$

Infrastructure and Maintenance Costs: In a developing country (Egypt), it is found (Advisory Panel for Land Drainage in Egypt (1977)) that structures in open drains cost about 70% of the total excavation cost. The irrigation infrastructures cost more and reach to 100% of the excavation cost. These figures are used here for the case study while the maintenance cost is taken as 20% of the excavation cost.

Pumping Cost Function: The pumping cost function as given by Fu-hsiung (1970) based on a regression analysis consists of three parts: capital cost; operation, maintenance and replacement costs; and energy cost. These costs can be expressed in terms of the lifting head (ΔH) and capacity (Q) as

$$\text{Capital cost} = 24962\ (Q\Delta H)^{.66} \quad \text{dollars} \quad (2.23)$$

$$\text{OMR cost} = 1977\ (Q\Delta H)^{.66} \quad \text{dollars} \quad (2.24)$$

$$\text{Energy cost} = 284\ (q\ \Delta H) \quad \text{dollars} \quad (2.25)$$

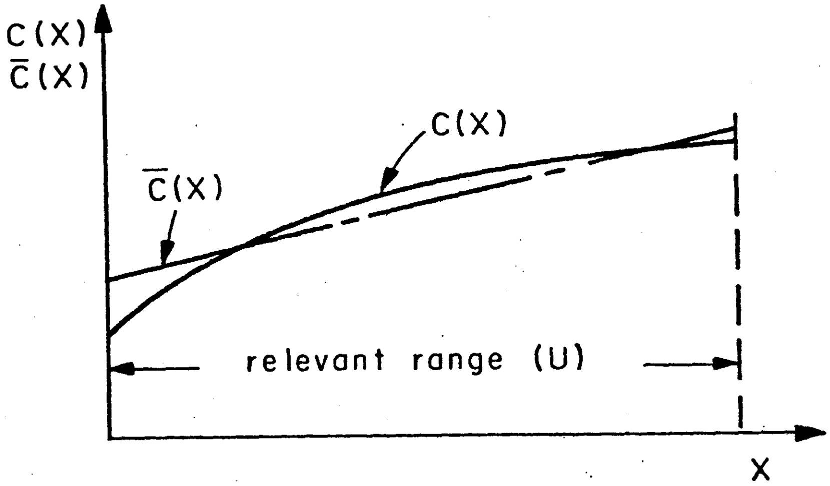

Figure 2-3 Fixed Charge Approximation to a Non-Convex Cost Function

where q is the seasonal flow (m^3/sec).

2.5 Nonlinearity Problem

As shown above, most of the costs in the objective function present economies of scale (non-convex cost functions) and the global optimality for this problem using separable programming is not guaranteed. The fixed charge approximation is used here for the concave cost functions as shown in Figure (2.3). Using this approximation, the cost function can be rewritten in a linear form as

$$\overline{C}(X) = \alpha + \beta X \tag{2.26}$$

The values of α and β for the various cost functions are computed as shown in Table (2-5), Table (2-6) and Table (2.7). The pumping cost function presented in Table (2-7) is for a pump station for mixing the drainage and fresh water for irrigation as will be discussed in detail in the next chapter. By using this fixed charge approximation, a binary variable for each cost function has to be introduced to insure a zero cost at zero flow. Then equation (2.25) should be rewritten as

$$\overline{C}(X) = \alpha\delta + \beta X \tag{2.27}$$

subject to

$$X \leq U\delta \tag{2.28}$$

$$X \geq 0.0 \tag{2.29}$$

where δ is a binary variable, take 0.0 or 1.0 value. Then when X equals zero, δ will be equal to zero and subsequently zero cost ($\overline{C}(X) = 0.0$) will be obtained.

Table 2-5 Fixed Charge Approximation to the Cost Functions of Excavation, Infrastructures and Maintenance of the Irrigation Network

	Excavation and Infrastructures		Maintenance	
Canal	Fixed Cost(α)	Variable Cost(β)	Fixed Cost(α)	Variable Cost(β)
6-7	35	1.22	3.5	1.22
7-1	20	2.33	2.0	2.33
1-5	20	2.33	2.0	2.33
7-8	33	1.28	3.3	1.28
8-2	18	2.95	1.8	2.95
8-9	30	1.43	3.0	1.43
9-3	20	2.3	2.0	2.3
9-10	26	1.63	2.6	1.63
10-4	20	2.33	2.0	2.33
10-5	20	2.33	2.0	2.33

Table 2-6 Fixed Charge Approximation to the Cost Functions of Excavation, Infrastructures and Maintenance of the Drainage Networks

	Excavation and Infrastructures		Maintenance	
Drain	Fixed Cost(α)	Variable Cost(β)	Fixed Cost(α)	Variable Cost(β)
2-9	48	4.33	4.8	4.33
1-9	48	4.33	4.8	4.33
3-9	48	4.33	4.8	4.33
9-10	60	2.33	6.0	2.33
5-10	48	4.33	4.8	4.33
4-10	48	4.33	4.8	4.33

Table 2-7 Fixed Charge Approximation to the Cost Functions of the Pump Station

Cost Function	Fixed Cost(α)	Variable Cost(β)
Capital Cost	10,000	21,000
OMR Cost	400	1,800

2.6 Solution to the Case Study

The mixed integer programming approach is used for solving the scheduling model for the case study with a fixed charge approximation to the concave cost functions (costs of irrigation and drainge canals, infrastructures, and maintenance). This resulted in a problem with 344 constraints, 285 continuous variables and 48 integer variables. A Branch and Bound procedure available on the SESAME Code (SESAME Reference Manual (1979)) is used for solving the model. After about $80 (12 minutes of CPU time) in computational expense on an IBM 370/168 computer the global optimum solution for the approximated problem was obtained as presented in the Tables 2.8, 2.9, and 2.10.

As shown in Table 2.8, the third area, as well as parts of the first and fourth areas, are selected to be developed in the first period of the scheduling horizon while the second and fifth areas are left to later periods. This happened because the first areas have less development cost than the other two areas. In addition they lie closer to the water source and hence the water transmission cost is minimized. Also from the Table, it can be seen that the crops of higher water requirements, like rice, are selected in the closer areas to the water source such as the first and third areas. These selections indicate the model's behavior in minimizing the present worth of land development and water transmission costs which is consistent with its least cost objective.

The advantages of the economy of scale in water transmission cost are used when the incremental capacities in the irrigation and

Table 2-8 Scheduling of Land Development and Crops Selection

Year	Season	Crop	Area (size in acres)				
			1	2	3	4	5
1	1	S.S.Clover				9,690	
		Beans			4,000		
		Wheat	6,696		3,304		
	2	Cotton				9,690	
		Maize			8,000	824	
		Rice	6,696		2,000		
2	1	S.S.Clover		3,482		11,053	
		Beans	1,500		4,000		
		Wheat	7,604	5,759	3,304		
	2	Cotton		3,482		11,053	
		Maize		5,759	8,000	948	
		Rice	13,218		2,000		
3	1	S.S.Clover		7,032		11,053	1,295
		Beans	1,500	1,500	4,000		
		Wheat	10,937	5,759	3,304		
	2	Cotton		7,032		11,053	1,295
		Maize		10,968	8,000	947	85
		Rice	18,000		2,000		

*The discount rate is taken as 10 percent.

Table 2-9. Capacity Expansion of the Irrigation Network

	Year					
Arc	1		2		3	
	Max.flow	Capacity	Max.flow	Capacity	Max.flow	Capacity
6-7	15.0	15.0	26.2	26.2	35.2	35.2
7-1	8.0	8.0	18.7	18.7	27.2	27.2
1-5	-	-	2.8	2.8	5.5	5.5
7-8	6.6	7.4	7.4	7.4	7.4	7.4
8-2	4.0	4.0	4.0	4.0	4.0	4.0
8-9	2.6	3.3	2.9	3.3	3.3	3.3
9-3	2.5	2.9	2.9	2.9	2.9	2.9
9-10					0.4	0.4
10-4					0.4	0.4
10-5						

* Maximum seasonal flow

Table 2-10. Capacity Expansion of the Drainage Network

	Year					
Arc	Max.flow	Capacity	Max.flow	Capacity	Max.flow	Capacity
2-9	1.2	1.2	1.2	1.2	1.2	1.2
1-9	2.4	4.7	4.7	4.7	6.4	6.4
3-9	0.8	0.9	0.9	0.9	0.9	0.9
9-10	4.4	6.8	6.8	6.8	8.6	8.6
5-10			0.8	1.6	1.6	1.6
4-10					0.1	0.1

drainage networks required for later periods are relatively small. This is shown in Table 2-9 for the arcs 7-8, 8-9 and 9-3 of the irrigation network and in Table 2-10 for all the arcs of the drainage network. For the other arcs of the irrigation networks which have higher incremental capacities, it is preferred to install only the required capacity at each time period. This happened mainly because the economy of scale is not very encouraging (for water transmission cost = 0.9).

2.7 Summary

A mathematical optimization model has been built to solve the scheduling problems of land development, crops selection, and capacity expansion of the irrigation and drainage networks. The model has been applied to a medium-sized problem and via mixed integer programming, a solution was obtained. The model solution should prove useful in guiding decisions required in planning of the agricultural expansions.

Solutions to the larger problems via mixed integer programming is expected to be computationally inefficient. Fortunately, the scheduling problem can be decomposed into three sub-problems: land development and crops selection, irrigation network expansion, and drainage network expansion. Moreover, (Ramos, 1981) the network expansion problem can be further decomposed into two smaller problems. One for computing the flows and another to compute the incremental capacities The sub-problems are interactive but a decomposition method (goal coordination or model coordination methods) can be used to decouple them (Haimes (1977), Lasdon (1970), and Singh and Title (1979)).

CHAPTER 3

A SCHEDULING MODEL FOR IRRIGATED AGRICULTURAL EXPANSION: INCORPORATING DRAINAGE WATER REUSE

3.1 Introduction

In this chapter, the scheduling model presented in the last chapter is expanded to account for the possibility of drainage water reuse. This is done by accounting for the effect of low quality water (drainage water) on the yields and water requirements of the crops. When using a low quality water in agricultural practices, various soil and cropping problems are to be expected. The most common problems are salinity, soil permeability and toxicity. The results of numerous studies (U.S. Salinity Lab. (1954), Hayward (1956), Ayers (1976) and Mass and Hoffman (1977)) have shown that the main damage to the plant growth is usually due to salinity of irrigation water. A high content of dissolved salt in the water tends to increase the osmotic pressure of the soil solution, thereby rendering less water available for plant growth. The salinity of the drainage water is the only quality problem considered in this study. The effect of irrigation water salinity on both yields and water requirements of the crops is reviewed and included in the model formulation.

The model is presented with nonlinear objective function accounting for economies of scale and linear and nonlinear constraint sets. A fixed charge approximation is used for the non-convex cost functions and mixed integer programming along with an enumeration procedure are used for solving the model. The solution procedure guarantees global optimality for the approximated problem. The model is applied to the case study and the scheduling decisions including the mixing ratios between the drainage and fresh water are obtained.

3.2 Water Salinity Problem

It has been found (Wadleigh and Ayers, (1945)) that the effect of matric tension on plant growth can be added to the effect of osmotic tension, producing what is called "total soil moisture". The plant responds to this stress without differentiating whether it seems to come from a high salt concentration or from drought, or both. The ability of a plant to extract water from soil is determined by the following relationship (U.S. National Technical Advisory Committee (1968)):

$$TSS = MS + SS \tag{3.1}$$

where

TSS = the total soil suction which represents the force with which water from the soil is withheld from plant uptake,

MS = the matric suction, or the physical attraction of the soil for water, and

SS = the solute suction, or the osmotic pressure of the soil water.

As the water content of the soil decreases due to evapotranspiration, the water film surrounding the soil particles becomes thinner and the remaining water is held with increasingly greater force (MS). Since only pure water is lost to the atmosphere during evapotranspiration, the salt concentration of soil solution (and hence also SS) increases rapidly during the drying process. Since the metric suction of soil increases exponentially upon drying, the combined effect of these two factors can produce critical conditions with regard to soil water availability for plant growth.

To avoid salt accumulation to an excess level, it must be removed in amounts about equal to the salts applied (salt balance concept). To dissolve and remove the salts, adequate water must be applied to allow percolation through the entire root zone (leaching). This can be done in each irrigation but needs to be done only after the salts have accumulated to near damaging concentrations. So leaching enables us to achieve a long-term salt balance. In this state, the average soil salinity of the root zone will be closely associated with the quality of irrigation water applied as well as with the fraction of water moving in the root zone.

To achieve such a salt balance, more irrigation must be applied than is necessary for evapotranspiration alone. This additional quantity of water is the leaching fraction whose quantity can be calculated simply by using the salt balance equation:

$$D_w EC_w = D_{dw} EC_{dw} \tag{3.2}$$

where,

D_w = depth of irrigation water applied,

D_{dw} = depth of water draining from the root zone,

EC_w = salt concentration of the irrigation water, and

EC_{dw} = salt concentration of the soil water draining from the lower boundary of the root zone.

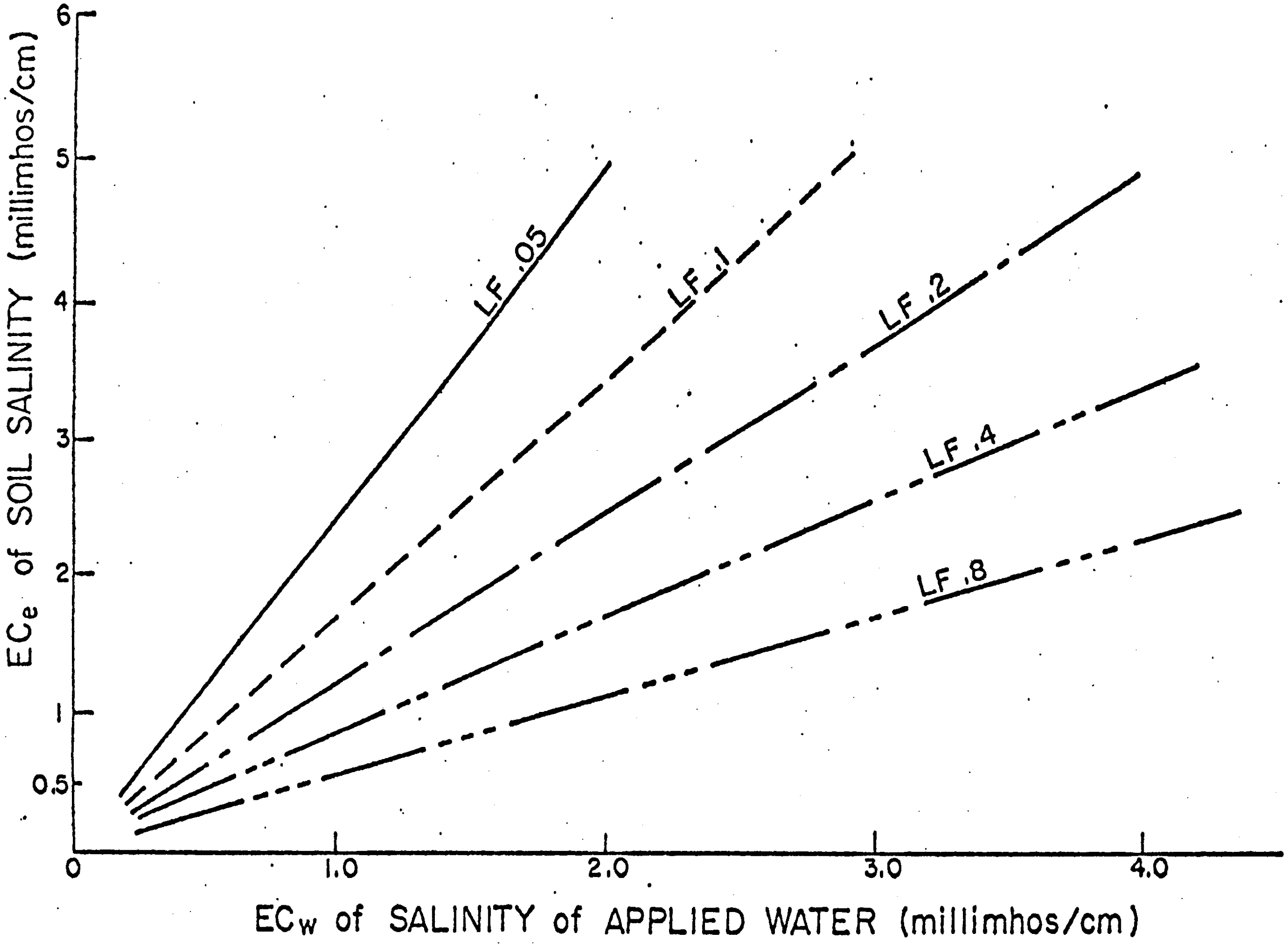

Fig. 3-1 Effect of Salinity of Irrigation Water EC_w on Soil Salinity EC_e Under Varying Water Management (Ayers, 1976).

To calculate EC_{dw} we must take into consideration that some of the irrigation water will move rapidly through the larger pores and reach the lower boundary of the root zone with little increase in salt content. On the other hand, water moving through the finer pores may displace soil water so that the drainage water from the smaller pores will have about the same salt concentration as that of the soil water in the root zone. Thus, the water draining from the lower boundary of the root zone can be considered as a mixture of irrigation water that has passed unchanged through the root zone and soil solution that has been directly displaced by irrigation water. Then the salt concentration of water draining from the root zone can be calculated as

$$EC_{dw} = E_{\ell}EC_{\ell} + (1-E_{\ell})EC_{w} \tag{3.3}$$

where

E_{ℓ} = hypothetical fraction of the drainage water consisting of displaced soil solution (Leaching Efficiency)

EC_{ℓ} = salt concentration of soil water in the root zone.

The Leaching Fraction (LR) which represents the minimum amount of water (in terms of a fraction of applied water) that must pass through the root zone to control salts can be written in terms of EC_{w} as

$$LR = \frac{EC_{w}}{E_{\ell}EC_{\ell} + (1-E_{\ell})EC_{w}} \tag{3.4}$$

Figure 3.1 shows the effect of different leaching fraction values on soil water salinity. It has been found for soils in Iraq, E_{ℓ} appeared to vary from 0.2 for the fine-textured soils to 0.6 for coarse-textured soils. Based on field and laboratory experience, the leaching fraction is found (Ayers (1977)) for surface irrigation method (including sprinklers) as

$$LR = \frac{EC_w}{5EC_\ell - EC_w} \qquad (3.5)$$

where

EC_ℓ = the value of soil salinity which causes a yield reduction of 10% or less for a given crop (Table 3-1)

For a high frequency sprinker or trickle irrigation (near daily):

$$LR = \frac{EC_w}{2(Max.EC_\ell)} \qquad (3.6)$$

where

$max.EC_\ell$ = soil salinity corresponding to 100% yield reduction for a given crop (Table 3-1).

Crops vary greatly in their salt tolerance, and therefore, the suitability of a water for irrigation will also vary with crops. This gives us a wide choice of crops and expands the usable range of water salinity for irrigation. An evaluation of the relative salt tolerance of agricultural crops has been done by Mass and Hoffman (1977). They provided two essential parameters sufficient for expressing salt tolerance, the maximum allowable salinity without yield reduction (salinity threshold) and the percent yield decrease per unit salinity increase beyond the threshold. In computing these parameters, they assumed that yield decrease linearly as salt concentration increases beyond the threshold level as

Table 3-1 Crop Tolerance Table (Mass and Hoffman, 1977)

Crop (1)	Salinity at initial yield decline (threshold) A (2)	Yield decrease per unit increase in salinity beyond threshold B (3)	EC$_\ell$ (4)	max. EC$_\ell$ (5)
Alfalfa	2.0	7.3	3.4	15.5
Almond	1.5	19	2.0	7.0
Apple	-	-	-	-
Apricot	1.6	24	2.0	6.0
Avocado	-	-	-	-
Barley (forage)	6.0	7.1	7.4	20
Barley (grain)	8.0	5.0	10	28
Bean	1.0	19	1.5	6.5
Beet, garden	4.0	9.0	5.1	15
Bentgrass	-	-	-	-
Bermudagrass	6.9	6.4	8.5	22.5
Blackberry	1.5	22	2.0	6.0
Boysenberry	1.5	22	2.0	6.0
Broadbean	1.6	9.6	2.6	12.0
Broccoli	2.8	9.2	3.9	13.5
Bromegrass	-	-	-	-
Cabbage	1.8	9.7	2.8	12.0
Canarygrass, reed	-	-	-	-
Carrot	1.0	14	1.7	8.0
Clover, alsike,ladino	1.5	.2	3.2	19
Corn (forage)	1.8	7.4	3.2	15.0
Corn (grain)	1.7	12	2.5	10.0
Corn, sweet	1.7	12	2.5	10.0
Cotton	7.7	5.2	9.6	27.0
Cowpea	1.3	14	2.0	8.5

(1)	(2)	(3)	(4)	(5)
Cucumber	2.5	13	3.3	10.0
Date	4.0	3.6	6.8	32.0
Fescue, tall	3.9	5.3	5.8	23.0
Flax	1.7	12	2.5	10.0
Grape	1.5	9.6	3.5	-
Grapefruit	1.8	16	2.4	8.0
Harding grass	4.6	7.6	5.9	18.0
Lemon	-	-	-	-
Lettuce	1.3	13	2.1	9.0
Lovegrass	2.0	8.4	3.2	14.0
Meadow Foxtail	1.5	9.6	2.5	12.0
Millet, Foxtail	-	-	-	-
Okra	-	-	-	-
Olive	-	-	-	-
Onion	1.2	16	1.8	7.5
Orange	1.7	16	2.3	8.0
Orchardgrass	1.5	6.2	3.1	17.5
Peach	1.7	21	2.2	6.5
Peanut	3.2	29	3.5	6.7
Pepper	1.5	14	2.2	8.5
Plum	1.5	18	2.1	7.0
Potato	1.7	12	2.5	10.0
Radish	1.2	13	2.0	9.0
Raspberry	-	-	-	-
Rhodesgrass	-	-	-	-
Rice, paddy	3.0	12	3.8	11.5
Ryegrass, perennial	5.6	7.6	6.9	19.0
Safflower	-	-	-	-
Sesbania	2.3	7.0	3.7	16.6
Sorghum	-	-	-	-
Soybean	5.0	20	5.5	10
Spinach	2.0	7.6	3.3	15.2
Strawberry	1.0	33	1.3	4.0

(1)	(2)	(3)	(4)	(5)
Sudan grass	2.8	4.3	5.1	26.0
Sugarbeet	7.0	5.9	8.7	27.0
Sugarcane	1.7	5.9	2.3	18.7
Sweet potato	1.5	11	2.4	10.5
Timothy	-	-	-	-
Tomato	2.5	9.9	3.5	12.5
Trefoil, Big	2.3	19	2.8	7.6
Trefoil, Birdsfoot	5.0	10	6.0	15
Vetch, common	3.0	11	3.9	12.1
Wheat	6.0	7.1	7.4	20
Wheatgrass, crested	3.5	6.9	6.0	28.5
Wheatgrass, fairway	7.5	6.9	9.0	22
Wheatgrass, slender	-	-	-	-
Wheatgrass, tall	7.5	4.2	9.9	31.5
Wildrye, Altai	-	-	-	-
Wildrye, Beardless	2.7	6.0	4.4	19.5
Wildrye, Russian	-	-	-	-

$$Y = (100 - B(EC_s - A))\overline{Y} \qquad (3.7)$$

where,

A = salinity threshold, in millimhos per centimeter,

B = percent yield decrease per unit salinity increase beyond threshold,

EC_s = soil salinity which is found by Mass and Hoffman equal to 1.5 times the irrigation water salinity,

$\overline{Y}$ = yield when using fresh water for irrigation.

3.3 Scheduling Model and Saline (Drainage) Water for Irrigation

In this section, the possibility of using a saline water for irrigating the new areas is considered. This case corresponds to the real life problem when the drainage water of old cultivated lands is directly, or after being mixed with fresh water, used in irrigating the new lands (Allam (1980) and Allam and Marks (1981, 1982a, 1982b). In order to use the scheduling model for this case two more constraint sets have to be included. These constraints are to account for the effect of water salinity on both water requirements and yields of the various crops. The new water requirements of the crops can be computed by using Equation (4.5) or Equation (4.6) for the leaching fraction (according to the irrigation method) as

$$W_{i,p}^{s,t} = (1 + LR_i^{s,t}(ECW_i^{s,t}))\overline{W}_{i,p}^{s,t} \qquad \forall_{i,p,s,t} \qquad (3.8)$$

where

$W_{i,p}^{s,t}$ = water requirements of crop <u>p</u> at area <u>i</u> during season <u>s</u> of year <u>t</u>

$\overline{W}_{i,p}^{s,t}$ = water requirements of crop <u>p</u> at area <u>i</u> during season <u>s</u> of year <u>t</u> when using fresh water for irrigation

$ECW_i^{s,t}$ = irrigation water salinity in millimhos per centimeter at area <u>i</u> during season <u>s</u> of year <u>t</u>.

$LR_{i,p}^{s,t}(.)$ = leaching fraction (Equation(3.5) or (3.6))

The constraint set which accounts for the effect of water salinity on the yields of the crops can be written in terms of Equation (3.7) as

$$Y_{i,p}^{s,t} = [100 - B(P,S)(1.5ECW_i - A(P,S))\ \overline{Y}_{i,p}^{s,t} \qquad \forall_{i,p,s,t} \tag{3.9}$$

where

$Y_{i,p}^{s,t}$ = yield of crop P during season s of year t at area î

$B(P,S)$ = present yield decrease of crop p during season s per unit salinity increase beyond threshold

$A(P,S)$ = salinity threshold of crop P during season s in millimhos per centimeter

$\overline{Y}_{i,p}^{s,t}$ = yield of crop P during season s of year t at area i when using a fresh water for irrigation.

Solution to the Case Study

The scheduling model after adding the above two constraint sets is used for solving the case study. The salinity concentration of the irrigation water source is taken here as 1.6 mmhos/cm for both summer and winter seasons and is assumed to stay constant through the planning horizon. The effect of irrigation water salinity on yields and water requirements of the different crops at the various new areas is presented in Table (3-2). The Branch and Bound procedure available on SESAME Code was used for solving the scheduling model for the case study (524 constraints). After 22 minutes of computing time on IBM 370, the global optimum solution was obtained as shown in Tables (3-3), (3-4) and (3-5). However, a solution with 98% of the

Table 3-2. Water Requirements and Yields of the Various Crops

(Water Salinity is 1.6 mmhos/cm)

Clover			Beans		Wheat		Cotton		Maize		Rice	
Area	Yield(y) ton/acre	Water duty(WD) m^3/sec/acre	Y	WD	Y	WD	Y	WD	Y	WD	Y	WD
1	7.6	.00029	.735	.000312	1.5	.000244	1.032	.000244	1.62	.00032	2.3	.0013
2	7.6	.000325	.735	.000357	1.5	.000157	1.032	.000278	1.62	.000367	2.3	.00149
3	7.6	.000244	.735	.000268	1.5	.000115	1.032	.000209	1.62	.000275	2.3	.0011
4	7.6	.00029	.735	.000312	1.5	.000136	1.032	.000244	1.62	.00032	2.3	.0013
5	7.6	.000325	.735	.000357	1.5	.000157	1.032	.000278	1.62	.000367	2.3	.00149

Table 3-3. Scheduling of Land Development and Crop Selection (Saline Irrigation Water)

Year	Season	Crop	Area (size in acres)				
			1	2	3	4	5
1	1	S.S.Clover			836	9,690	
		Beans			5,442		
		Wheat	6,695		3,304		
	2	Cotton				9,690	
		Maize			8,000	1,260	
		Rice	6,695		2,000		
2	1	S.S.Clover		4,043	836	10,492	
		Beans	2,041		5,442		
		Wheat	7,438	5,925	3,304		
	2	Cotton		4,043		10,492	
		Maize		5,924	8,000	1,508	
		Rice	13,217		2,000		
3	1	S.S.Clover		6,790	836	10,492	2,099
		Beans	3,491	592	5,442		
		Wheat	10,771	5,925	3,304		
	2	Cotton		6,789		10,492	2,099
		Maize		11,211	8,000	1,508	269
		Rice	18,000		2,000		

Table 3-4. Capacity Expansion of the Irrigation Network (Saline Irrigation Water)

Arc	Year 1 Max.flow**	Year 1 Capacity	Year 2 Max.flow	Year 2 Capacity	Year 3 Max.flow	Year 3 Capacity
6-7	16.4	16.4	28.9	28.9	38.9	38.9
7-1	8.8	8.8	20.7	20.7	29.8	29.8
1-5*			3.35	6.1	6.1	6.1
7-8*	7.4	8.3	7.6	8.3	8.3	8.3
8-2	4.45	4.45	4.45	4.45	4.45	4.45
8-9*	2.85	3.8	3.1	3.8	3.8	3.8
9-3*	2.8	3.1	3.1	3.1	3.1	3.1
9-10					.7	.7
10-4					.7	.7
10-5						

*Use of the economy of scale ** Max Seasonal flow

Table 3-5. Capacity Expansion of the Drainage Network (Saline Irrigation Water)

Arc	Year 1 Max.flow	Year 1 Capacity	Year 2 Max.flow	Year 2 Capacity	Year 3 Max.flow	Year 3 Capacity
2-9	1.32	1.32	1.32	1.32	1.32	1.32
1-9	2.61	5.15	5.15	5.15	7.02	7.02
3-9	.84	.91	.91	.91	.91	.91
9-10	4.81	7.46	7.46	7.46	9.34	9.34
5-10			1.0	1.8	1.8	1.8
4-10					.2	.2

global optimality was obtained after 5 minutes of execution time.

By comparing the results in Table (2-8) and (3-3), it can be noticed that the crops sensitive to salinity (beans and maize) are selected in larger areas when saline irrigation water is used. The beans are selected in 9,525 acres to achieve the same agricultural production level of 7,000 acres when using fresh water for irrigation. Similarly, 989 more acres of maize are needed to satisfy the demanded amounts. These increases in the cultivated areas and the increases in irrigation water due to the leaching requirements are reflected in the design of the irrigation and drainage networks. There is about 10% increase in the capacities of the irrigation and drainage networks compared to the case of only using fresh water for irrigation, as shown in Tables (2-9), (2-10),(3-4), and (3-5). However, the expansion cost for this case is only 144.8 million dollars with less than 2% increase to the cost (142.1 million dollars) when fresh irrigation water was used. This cost comparison can strengthen the belief in the fruitful trend of water reuse in agricultural practices, particularly in the case of fresh water scarcity.

Drainage Water Recycling

The scheduling model before and after above modification can allow the use of fresh and/or saline water (in its status quo) after being mixed with fresh water for irrigation, respectively. The possibility of reusing the drainage water of the new lands in irrigation practices has not yet been considered. In order to take into account this possibility, three more constraint sets have to be included. The first is a set of salt conservation equations to compute the drainage water salinity at each node of the drainage network. This constraint set can be written as

$$\sum_{i=1}^{M+N} (ECWD_i^{s,t}\ fd_{i,j}^{s,t} + ECWLD_{i,j}^{s,t}\ fd_{i,j}^{s,t}\ LD_{i,j}^{s,t}(fd_{i,j}^{s,t}) + ECWdr_j^{s,t}\ dr_j^{s,t} - ECWD_j^{s,t}$$

$$\sum_{\substack{\ell=1\\ \ell\neq j}}^{M+N} fd_{j,\ell}^{s,t} - ECWD_j^{s,t}\ rWD_j^{s,t} = 0 \qquad \forall\ j,s,t \qquad (3.10)$$

where $rWD_i^{s,t}$ = recycled drainage water at node i of the drainage network during season s of year t (decision variable)

$ECWD_i^{s,t}$ = drainage water salinity at node i during season s of year t (endogenous decision variable)

$LD_{i,j}^{s,t}(.)$ = seepage water to drain (i,j) during season s of year t (input to the model)

$ECWLD_{i,j}^{s,t}$ = salinity of seepage water to drain (i,j) during season s of year t (input to the model)

$ECWdr_j^{s,t}$ = salinity of the drained water at area j during season s of year t (input to the model)

The second set is to compute the irrigation water salinity at each node of the irrigation network.

$$\sum_{i=1}^{M+N} ECW_i\ f_{i,j}^{s,t}\ (1-L_{i,j}^{s,t}(fi_{i,j}^{s,t})) - ECW_j \sum_{\substack{\ell=1\\ \ell\neq i}}^{M+N-1} f_{j,\ell}^{s,t} - ECW_j\ d_j^{s,t}\ +$$

$$ECWD_j\ rWD_j^{s,t} = 0 \qquad \forall\ j,s,t \qquad (3.11)$$

In this case, the decision variables are the amounts of recycled water ($rWD_{i,j}^{s,t}$ for all i,j,s and t) and salinity of the mixed water (ECW_j for all j) at every mixing station.

The third set is to determine for each mixing station (pumping station) the incremental capacity at each time period. Similar to Equation (2.16), this constraint can be written as:

$$\sum_{i=1}^{M+N-1} rWD_j^{s,t} - \sum_{h=1}^{t} CrWD_j^h \leq 0 \qquad \forall\ j,s,t \qquad (3.12)$$

where $CrWD_j^t$ is the increase in mixing station *j* capacity at the beginning of year *t*.

In addition to the above four constraints, the flow balance constraints for the irrigation and drainage networks (Equation (2.12) and (2.15)) have to be modified as shown in Equations (2.12′) and (2.15′) and the non-negativity constraint has to be expanded to insure the non-negativity of $rWD_j^{s,t}$ and $CrWD_j^t$ for all values of *i*, *j*, *s*, and *t*. Furthermore, cost of the mixing stations has to be added to the objective function.

$$\sum_{i=1}^{N+M} f_{i,j}^{s,t}\,(1-L_{i,j}^{s,t}\,(f_{i,j}^{s,t})) + rWD_j^{s,t} - \sum_{\substack{k=1\\k\neq i}}^{N+M} f_{j,k}^{s,t} - d_j^{s,t} = 0$$

$$\forall\ j,s,t \qquad (2.12')$$

$$\sum_{i=1}^{N+M-1} fd_{i,j}^{s,t}(1+LD_{i,j}^{s,t}\,(fd_{i,j}^{s,t})) - rWD_j^{s,t} - \sum_{\substack{k=1\\k\neq i}}^{N+M-1} fd_{j,k}^{s,t} + dr_j^{s,t}(d_j^{s,t}) = 0$$

$$\forall\ j,s,t \qquad (2.15')$$

Nonlinearity Problem

In addition to nonlinearity of the objective function, we have two nonlinear constraint sets presented in Equations (3.10) and (3.11) where two sets of decision variables (Canals' (drains) flows and their water salinities) are multiplied by each other. Ocans et al. (1981a) solved a similar but smaller problem via the large-scale gradient method (LSGRG method (Lasdon et al. (1978)). By using an out-of-kilter (OKA) and a linear programming (LP) algorithm to find an initial solution, the (LSGRG) method proved efficient for solving small problems (1-2 minutes for a problem of 68 constraints). For a larger problem of 216 constraints, the method failed to find a local optimum solution after 20 minutes of execution time.* Ocans et al. (1981b) reported that by using a successive linear programming with rejection (SLRP) algorithm which was developed by Palacios-Gomez et al. (1981), a local optimal solution to the problem of 216 constraints was obtained after 30 seconds of computation time when a good initial solution was used. However, the authors concluded that larger problems are very difficult to solve if they are solvable at all.

The disadvantage of using a SLRP algorithm for solving these nonlinearity problems is that only a local optimum solution is obtainable which may be too far from the global optimum. In addition, an initial solution via two more algorithms (OKA and LP) is needed for insuring convergence and reducing the computation time. Moreover, solutions to larger problems (Ocans et al. (1981b)) may not be obtainable.

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* University of Texas CYBER 175/750 System

In solving the scheduling model to the case study (548 constraints) a fixed charge approximation to the concave cost functions is used to insure the global optimality to the solution of the approximated problem (minimization of a convex cost function over a convex feasible region). An enumeration procedure with a gradient search method is used to solve the constraints' nonlinearity problem. The procedure involves the discretization of water salinity values between upper and lower limits which results in a multi-dimensional grid of water salinity values (the dimensions are equal to the number of arcs of the irrigation and drainage networks). Having an initial solution which represents a point on the grid the gradients to the closest points can be measured by running the model for this set of water salinity values. The second step is to move to the grid point which achieves the maximum improvement to the initial solution. The procedure continues until no improvement to the solution can be found. The accuracy of solution will depend mainly on the level of discretization of the salinity values.

Solution to the Case Study

A mixing station is proposed at node 9 of the irrigation network to allow the use of the drainage water of the first and third areas in irrigating the remainder of the new lands. The first and third areas' drainage water salinities were taken as 2.3 and 2.0 mmhos/cm where a value of 0.4 mmhos/cm was assigned to the salinity of the available irrigation water at node 6. The salinity of the mixed water is allowed to vary from season to season but kept constant from year to year during the scheduling period. This has been done for the reason of convenience to the farmers of not changing the amount of irrigation water and expecting different crops yield from year to year through the short period of scheduling (three years) compared to the twenty-five years of the planning horizon.

The Branch and Bound along with the enumeration procedure have been used for solving the model to the case study where six discrete values (0.4, 0.8, 1.2, 1.6, 2.0, and 2.3 mmhos) have been used for the salinity. After 57 minutes of computing time for 12 successive runs to the model (the output of each run was used as an initial solution to the following one), the global optimum solution was obtained. The optimum values for the salinity of the mixed water are 1.6 and 1.2 mmhos/cm during the summer and winter seasons, respectively. The optimum mixing ratios between the drainage and fresh water during the scheduling period are listed in Table (3-10). The crop pattern distribution in the new land is shown in Table (3-7) while the capacity expansions of the irrigation and drainage networks are presented in Tables (3-8) and (3-9).

As shown in Table (3-7), beans, which are the most sensitive crops to salinity, are selected in the first area which has fresh water for irrigation. Rice, which has the highest water requirements, has been selected in the same area which is the closest to the water source for minimizing the transmission cost. From Tables (3-8) and (3-9), it can be noticed that the capacity of most of the arcs of the irrigation and drainage networks decreased compared to the case when only fresh water is used for irrigation.

Surprisingly, the expansion cost decreased from \$142.1 x 10^6 when only fresh water is used for irrigation and to \$141.1 x 10^6 when water recycling is allowed.

Table 3-6. Salinity Tolerance Parameters of the Various Crops

Crop	Salinity threshold A*	Percent Yield decrease beyond the threshold B*	Soil salinity which causes 10 percent yield reduction EC_e**
Short Season Clover	1.5	12	3.2
Beans	1.0	19	1.5
Wheat	6.0	7.1	7.4
Cotton	7.7	5.2	9.6
Maize	1.7	12	2.5
Rice	3.0	12	3.8

*Mass and Hoffman, 1977
**Ayers, 1976

Table 3-7. Scheduling of Land Development and Crops Selection (Drainage Water Recycling)

Year	Season	Crop	Area (size in areas)				
			1	2	3	4	5
1	1	S.S.Clover			1,274	8,415	
		Beans	4,000				
		Wheat	2,715		7,286		
	2	Cotton			1,274	8,415	
		Maize	100		8,706		
		Rice	6,635			2,060	
2	1	S.S.Clover			1,274	9,940	3,321
		Beans	5,500				
		Wheat	7,699	1,683	7,286		
		Cotton			1.274	9,940	3,321
		Maize	100	5,900	8,706		
		Rice	13,120			2,060	38
3	1	S.S.Clover			1,274	9,940	8,166
		Beans	7,000				
		Wheat	10,980	1,734	7,286		
	2	Cotton			1,274	9,940	8,166
		Maize	100	11,194	8,706		
		Rice	17,900			2,060	40

Table 3-8. Capacity Expansion of the Irrigation Network (Drainage Water Recycling)

Arc	Year 1 Max.flow	Year 1 Capacity	Year 2 Max.Flow	Year 2 Capacity	Year 3 Max.Flow	Year 3 Capacity
6-7	12.3	12.3	23.7	23.7	32.4	32.4
7-1	8.0	8.0	17.8	17.8	25.4	25.4
1-5			1.95	3.8	3.8	3.8
7-8	4.1	5.2	4.8	5.2	5.2	5.2
8-2	2.4	2.4	2.4	2.4	2.4	2.4
8-9	1.7	2.8	2.3	2.8	2.8	2.8
9-3	4.8	5.1	5.1	5.1	5.1	5.1
9-10			1.15	2.7	2.7	2.7
10-4			1.1	2.6	2.6	2.6
10-5						
9*	3.1	3.1	4.0	5.0	5.0	5.0

*Mixing Station

Table 3-9. Capacity Expansion of the Drainage Network (Drainage Water Recycling)

Arc	Year 1 Max.flow	Year 1 Capacity	Year 2 Max.flow	Year 2 Capacity	Year 3 Max.Flow	Year 3 Capacity
2-9	.7	.7	.7	.7	.7	.7
1-9	2.4	4.7	4.7	4.7	6.4	6.4
3-9	1.4	1.5	1.5	1.5	1.5	1.5
9-10	1.4	1.5	1.5	1.5	1.5	1.5
5-10			.6	1.1	1.1	1.1
4-10			.4	.8	.8	.8

Table 3-10. Mixing Ratio Between the Drainage and Fresh Water

Season	Year 1	Year 2	Year 3
Winter	.8	.76	.75
Summer	1.9	1.8	1.79

3.4 Summary

The possibility of drainage water reuse in agricultural practices is introduced. The effect of this low-quality water on the yields and water requirements of the various crops are discussed. These effects are added to the constraint sets of the scheduling model to determine the impacts of drainage water reuse on agricultural planning. It is found that with a proper crop selection in the new areas, the reuse of drainage water in irrigating the new land will cause very slight economic losses. Moreover, when the drainage water is reused along with fresh water in irrigating the new areas, an economic gain is obtained. These results can give a strong belief in the fruitful trend of drainage water reuse.

CHAPTER 4

INCOME REDISTRIBUTION OBJECTIVE

4.1 Introduction

One of the main objectives of most public investments is the use of the return benefit flows in raising incomes of the poor in society. In agricultural expansion, this objective can be achieved by distributing the newly developed lands to a poorer sector of society such as landless peasants. In this case, land prices may be charged in annual payments less than the agricultural revenues to be affordable by the farmers. By doing so, the farmers will gain the agricultural benefits reduced by the land payments (B-P). On the other hand, the Government's net-return from the investment will be the land payments minus the expansion cost (P-C). To determine the size of the investment, as well as land repayments, which achieves a better income level to the investment beneficiaries (income redistribution objective), two approaches are available in the literature. The first approach is to consider the redistribution objective in the design of the investment (Eckstein (1961), Haveman (1965), Marglin (1962), and others). Marglin (1962) provided three methods to incorporate the income distribution considerations in the design of an investment. The first method is to assign a higher weight than unity to the redistribution benefits in the maximum net-benefit objective function (Maximize $\nu(B-P) + (P+C)$, where $\nu>1$). The second method is to maximize the investment net-benefits in such a way that at least a certain level of the redistribution benefits can be achieved (Maximize $(B-C)$ subject to $(B-P)\geq A_1$). The third method is to maximize the redistribution benefits subject to the constraint that the net-benefits of the investment should not be less than a certain level (Maximize $(B-P)$ subject to $(B-C)\geq A_2$).

In these three methods, Marglin assumed that the repayments are fixed and given by the authorities. This approach of considering the redistribution objective in the design of an investment - via any of the above methods suggested by Marglin - will lead to an oversized investment beyond the economic efficiency optimum size (Helmers (1979)).

The second approach is not to incorporate the income redistribution considerations in the efficient design of the investment (Harberger (1974), Helmers (1979), and others). The redistribution objective can be achieved in a further step (after investment design) through an income transfer mechanism. The argument against the first approach is that the oversized projects are not the most efficient method to achieve the income redistribution objective. Helmers (1979) found that it is economically more efficient to design the investment at the efficiency optimum size and reduce the payments (P) to the level which achieves the desired income to the target group than increasing the size of the investment. Helmer's finding is behind the structured design of our planning framework to agricultural expansion investments. As shown in the previous Chapters (Chapters 1, 2, and 3), this framework starts with the design of the investment using a scheduling model via an economic efficiency criterion. Having determined the efficiency optimum scheduling decisions (crop pattern in the newly reclaimed areas, capacity of the irrigation and drainage canals, etc.), then the agricultural revenues at the different new areas as well as the expansion cost, can be determined. The further step is to determine the land payments which achieve the desired income level to the peasant farmers.

But, in agriculture expansions, the redistribution problem is more difficult than what Helmers was considering. It is not only to calculate land payments at the various new areas, but also to determine land distribution among the farmers. The objective is not only to achieve a certain income level for the landless farmers but also to determine the maximum number of them who may get this income increase. In addition, other objectives like the equity between the farmers in achieving the same income level, and maintaining a high agriculture efficiency in the new land may also be considered. This redistribution problem which represents the subject of the current debate in Egypt is the motivation of this study. In this paper, an analytical solution to this problem in an optimization framework (income redistribution model) is provided.

4.2 Income Redistribution Model

Objective Function

An income redistribution criterion in terms of maximum redistribution benefit is used. The redistribution benefits equal the increase in the farmer's income due to the agricultural expansion multiplied by the number of farmers who may get this income increase. In our case where the income increase to the new farmers is assumed to be known, and given by high authorities, this maximization procedure is equivalent to maximizing the number of investment beneficiaries. Hence, the objective function may be written as:

$$\text{Maximize} \quad z = \sum_{j=1}^{N} A_j m_j \tag{4.1}$$

where,

N = number of the new areas $(j=1,\ldots,N)$

A_j = acres of area j (known)

n_j = acres of land to be owned by a farmer at area j (decision variable)

$m_j = 1/n_j$ (decision variable)

Constraints

Equity Constraint

This constraint is to insure equity between the farmers in achieving the same level of income increase.

$$R_j^t - P_j^t - m_j \Delta I \geq 0 \qquad \forall j,t \qquad (4.2)$$

where,

R_j^t = per acre annual revenue in area j at year t (known)

P_j^t = per acre annual payment in area j at year t (decision variable)

ΔI = assigned income increase by the Government to the farmers (given)

Cost Recovery Constraint

This constraint is to insure the recovery of the desired (by the Government) portion of the expansion cost.

$$\sum_{t=t_o}^{TP} \sum_{j=1}^{N} \alpha^t A_j P_j^t \geq \beta(PTC) \qquad (4.3)$$

where,

t_o = first year of payment (known)

β = fraction of cost recovery required by the Government (known)

PTC = present value of the total expansion cost (known)

r = annual discount rate (known)

$\alpha^t = \frac{1}{(1+r)^t}$ (present value factor for a single payment t time periods in the future)

TP = payment time horizon (known)

Agriculture Efficiency Constraint

If large sized farms are more productive than small farms (due to economies of scale in the farming costs), the agricultural efficiency in the new land will be in conflict with the redistribution objective. Only few farmers will own the land to maintain high agriculture efficiency in the new areas. In addition, the landless farmers who will own the new land will have high income from the large sized farms in comparison to the average income in the developing countries. This will result in more redistribution problems instead of improving the redistribution conditions in society. In Egypt, large sized state farms have been tried hoping for better agricultural production. It is found that small farms generally perform better than state farms and produce higher net-returns per acre (Goueli and Diab (1969), Quintana (1970), and Das (1973)). However, the output of this experiment in Egypt should not be used as a basis for rejecting large sized farms. More research in this area is needed to determine the effect of farm size on agricultural productivity in the developing countries.

The agricultural efficiency in the new land is considered here in the redistribution model through an upper limit constraint on farm size. (Hunting Technical Service, Ltd. (1979), and Pacific Consultants (1980)). This constraint is to insure that the farm will be fully taken care of by the farmer (farmer family).

$$m_j \geq \frac{1}{U} \qquad \forall j \qquad (4.4)$$

where, U is the upper limit to farm size (n_j) at the different new areas.

Lower Limit Constraint on Farm Size

This constraint is to insure a full time on farm employment for the farmer (farmer family) (Hunting Technical Service, Ltd. (1979), and Pacific Consultants (1980)).

$$m_j \leq \frac{1}{L} \qquad \forall j \qquad (4.5)$$

where, L is the lower limit to farm size (n_j) at the different new areas.

Non-negativity Constraint

This constraint is to insure the non-negativity of the annual payments at the various locations of the new land

$$P_j^t \geq 0 \qquad \forall j,t... \qquad (4.6)$$

As shown above, the model is formulated for the case of large scale agricultural expansion which can extend over various areas of different properties and hence of different returns. It is presented with a linear objective function and linear constraint sets. By solving the model, per acre annual payment (P_j^t) and size of land per farmer at each new area (n_j) can be determined in such a way that the stated objectives (maximum redistribution benefits, increase to the farmers' income, high agriculture efficiency, recovery of the expansion cost, and equity between the farmers) can be achieved.

4.3 Case Study

The case study is based on the solution of the scheduling model to a hypothetical agricultural expansion based on data from the Nile Delta in Egypt of 70,000 acres when fresh water was available for irrigation. The expansion is proposed in five areas of different soil properties. Two agricultural seasons (winter and summer) are considered and three crops per season are used. The winter crops are clover, beans, and wheat; and the summer crops are cotton, maize, and rice. Prices, yields, and farming costs of the various crops are listed in Table (4.1). Costs of developing the new areas are presented in Table (4.2). Given the crop pattern distribution in the new areas (output of the scheduling model), the net agricultural revenus ($\sum_{crops}$ prices x yields - farming cost) for the new areas can be computed as shown in Table (4.3).

The current average income of the society is taken as one thousand dollars per person per year while three hundred dollars per farmer is assumed for the current yearly income of the landless peasants. Ten and five acres are used for the upper and lower limits respectively to the size of land to be owned by a farmer. The land payments are assumed to start at the sixth year of the investment horizon at which time the land will reach to the full production stage.

The income redistribution model is used in deriving three payment policies of different payment time horizons. They consist of twenty years, fifteen years, and ten years of fixed annual payments. In order to obtain integer values to the size (in acres) of land per farmer, which is frequently the case in real-life problems (Ministry of Agranian Reform

Table 4-1. Prices, Yields and Farming Costs of the Various Crops

Crop	Price (dollars/ton)	Yield (ton/acre)	Farming Cost (dollars/acre)
Clover	12	8.5	38.1
Beans	240	1.0	50.9
Wheat	171	1.5	111.4
Cotton	583	1.032	187.9
Maize	143	1.7	121.5
Rice	172	2.3	126.1

Table 4-2. Development Cost of the New Areas

Area	Size (acres)	Land Developmet* cost (dollars/acre)
1	18,000	1400
2	18,000	1500
3	10,000	1300
4	12,000	1400
5	12,000	1500

*It includes the cost of housing, electricity, equipment and machinery, transportation, communication, land levelling, and social services.

Table 4-3. Annual Net Returns of the New Areas (dollars/acre)

	Area				
Year	1	2	3	4	5
1	414.6	--	353	298.9	--
2	464.68	284.45	353	298.4	--
3*	463	316.6	353	298.4	302.4
Average**	460	315	353	298	302

* This net return will continue until the end of the planning horizon (25 years).

** The average net return.

and Land Reclamation in Egypt (1972)), mixed integer programming approach is used for solving the model to the case study.
For each payment policy and for full recovery of the expansion cost, the model is solved via the Branch and Bound procedure available on SESAME Code (SESAME Reference Manual (1979)) for different levels of income increase ($600, $700, and $800 per farmer per year). The global optimum solutions for the first (20 years of annual payments) and the second (15 years of annual payments) payment policies are obtained as shown in Tables (4.4) and (4.5), respectively. The expansion cost was unrecoverable when the third payment policy (10 years of annual payments) is tried. The computation time for each run on an IBM 370/168 computer was about 25 seconds (16 constraints, 5 continuous variables, and 30 integer variables).

As shown in Tables (4.4) and (4.5), equity between the farmers is insured as they get the same income increase in the different areas except in some cases with a slight difference (less than one percent of average income) which results from using integer values for n_j (for all values of j). Both of the payment policies succeeded in achieving the recovery of the expansion cost and income increase to the farmers. It can be noticed from the Tables that the first payment is better than the second one in offering a larger number of landless farmers the opportunity to increase their incomes. On the other hand, the farmers are better off under the second payment policy. They will be enjoying the full return of the land with no land payments in the last five years of the investment horizon. However, if the long-

Table 4-4. Income Redistribution Model in Deriving the Twenty Years' Payment Policy

	$\Delta\bar{I}^1=600$				$\Delta\bar{I}=700$				$\Delta\bar{I}=800$			
Area	n^2	AP^3	NR^4	ΔI^5	n	AP	NR	ΔI	n	AP	NR	ΔI
1	5	340	120	600	7	360	100	700	7	345	114	805
2	5	195	120	600	5	175	140	700	5	155	160	800
3	6	252	101	606	9	275	78	702	9	264	89	801
4	5	178	120	600	5	158	140	700	10	218	80	800
5	5	182	120	600	5	162	140	700	5	142	160	800
N^6	11,543				9,956				8,756			

---

1. Assigned income increase
2. Number of acres per farmer
3. Annual payment per acre (dollar/acre/year)
4. Net annual return (dollar/acre/year)
5. Income increase.
6. Number of the new owners

Table 4-5. Income Redistribution Model in Deriving the Fifteen Years' Payment Policy

	$\Delta\bar{I}=600$				$\Delta\bar{I}=700$				$\Delta\bar{I}=800$			
Area	n	AP	NR	ΔI	n	AP	NR	ΔI	n	AP	NR	ΔI
1	9	393	67	603	10	390	70	700	10	380	80	800
2	5	195	120	600	6	198	117	702	8	315	100	800
3	6	252	101	606	8	265	88	704	10	273	80	800
4	10	238	60	600	10	228	70	700	10	218	80	800
5	5	182	120	600	6	185	117	702	5	142	160	800
N	8,741				7,480				6,526			

Table 4-6. Income Redistribution Model in Deriving the Modified Fifteen Years' Payment Policy

	$\Delta\bar{I}=600$					$\Delta\bar{I}=700$				
Area	n	AP	NR	ΔI_1^*	ΔI_2^{**}	n	AP	NR	ΔI_1	ΔI_2
1	5	380	80	400	2300	7	403	57	399	3220
2	5	218	97	485	1575	5	196	119	595	1575
3	6	283	70	420	2118	9	308	45	405	3177
4	5	199	99	495	1490	5	177	121	605	1490
5	5	204	98	490	1510	5	181	121	605	1510
N		11,543					9,956			

*Income increase within the payment horizon.

**Income increase in the last five years of the investment horizon.

term average income increase over the investment horizon is considered, the farmers should be indifferent between the two payment policies. This can be shown for the case study via the redistribution model after modifying the first constraint set to account for the increase in farmers' income during the remaining years of the investment horizon after finishing the land payments. If land payments (P_j) and agricultural revenues (R_j) at the different new areas are not varying with time, then this constraint can be written as:

$$R_j - \frac{\theta}{\beta} P_j - m_j \Delta I \geq 0 \qquad (4.2\ )$$

where,

$$\theta = \sum_{t=t_o}^{TP} \frac{1}{(1+r)^t}$$

$$\beta = \sum_{t=t_o}^{TT} \frac{1}{(1+r)^t}$$

TT = investment time horizon

This constraint will determine the annual payments which insure that the farmers on the long run (over the investment horizon) will get the assigned income increase ΔI.

The modified version of the redistribution model is applied to the case for the second payments policy (fifteen years of annual payments) and the results are listed in Table (4.6). As shown in the Table, although in the long run the equity between farmers can be achieved, a large deviation between the farmers' income in the various areas within the fifteen years of payments exists. At the end of the fifteen years of payments, a large increase in the farmers' income in obtained. This sudden large increase in the farmers' incomes may then create pressure on the society, considering the availability of consumption goods. Moreover, within the payment policy horizon, the farmers' incomes will be significantly less than the assigned one by the government which might be necessary for facing the consumption requirements. For these reasons, it is preferred here to compare the payments policies on the basis of achieving the assigned increase in farmers' incomes, as well as equity between them, within the payments horizon as shown in Tables (4.4) and (4.5). Of course this comparison method will lead to preferring the long-term payment policies which allow a larger number of farmers to own the newly developed land, as shown above.

The marginal and the average cost approaches are usually used in estimating the prices of public goods. In the following section both approaches will be used in pricing the new land and the results will be compared to the pricing scheme derived by the redistribution model.

4.4 Marginal and Average Cost Approaches in Land Pricing

A marginal cost approach is used in allocating the expansion cost among the new areas. Given the cost recovery condition, land prices at the different new areas can be determined. Consequently, for a certain payment horizon, the annual payments can be computed. The allocation of irrigation water transmission cost to the new areas is based on continuity principles (the nearest areas to the water source are to be irrigated first). Having determined the capacity expansion of the irrigation network, and computed the water demands of the new areas in every year of the scheduling period as shown in the last two chapters, then the irrigation transmission cost at each area can be computed as:

$$\text{PITC}_j = \sum_{t=1}^{T} \alpha^t \sum_{m=1}^{M_j} L_m \int_{Q_m^t - \sum_{i=1}^{j} \Delta Q_{i,m}^t}^{Q_m^t - \sum_{i=1}^{j-1} \Delta Q_{i,m}^t} \text{MITC}^t(Q)\,dQ \qquad j=2,\ldots,N \qquad (4.7)$$

and

$$\text{PITC}_1 = \sum_{t=1}^{T} \alpha^t \sum_{m=1}^{M_1} L_m \int_{Q_m^t - \Delta Q_{1,m}^t}^{Q_m^t} \text{MITC}^t(Q)\,dQ \qquad j=1 \qquad (4.8)$$

where,

PITC_j = present value of irrigation water transmission cost to area j (dollars)

T = scheduling time horizon

α^t = present value coefficient = $\dfrac{1}{(1+r)^t}$

M_j = number of reaches of the irrigation canal from the water source till area j

Q_m^t = capacity of reach m at the beginning of year t (cubic meters/second)

$ITC^t(Q)$ = irrigation water transmission cost in year t (dollars/meter)

$MITC^t(Q) = \frac{\partial ITC^t(Q)}{\partial Q}$ = marginal transmission cost of irrigation water in year t (dollars/cubic meters/sec/meter)

L_m = length of reach m (meters)

$\Delta Q^t_{j,m}$ = increase in water demand at area j during year t from reach m (cubic meters/second)

$Q^t_m - \sum_{i=1}^{j-1} \Delta Q^t_{i,m}$ = irrigation water available for area j during year t in reach m

$Q^t_m - \sum_{i=1}^{j} \Delta Q^t_{i,m}$ = irrigation water available for the remaining areas after area j in reach m during year t

In a similar procedure, the transmission cost of the drainage water from the new areas to the ocean (drainage destination) can be determined as:

$$PDTC_j = \sum_{t=1}^{T} \alpha^t \sum_{k=1}^{K_j} Ld_k \int_{\sum_{i=1}^{j-1} \Delta Qd^t_{i,k}}^{\sum_{i=1}^{j} \Delta Qd^t_{i,k}} MDTC^t(Qd)\,dQd \qquad j=2,..,N \qquad (4.9)$$

and

$$PDTC_1 = \sum_{t=1}^{T} \alpha^t \sum_{k=1}^{K_1} Ld_k \int_{0}^{\Delta Qd^t_1} MDTC^t(Qd)\,dQd \qquad j=1 \qquad (4.10)$$

where,

$PDTC_j$ = present value of drainage water transmission cost from area j to the destination of the drainage water (dollars)

Qd_k = capacity of reach $\underline{k}$ (cubic meters/second)

K_j = number of reaches of the drain from area $\underline{j}$ to the drainage destination

$DTC^t(Qd)$ = drainage water transmission cost in year $\underline{t}$ (dollars/meter)

$MDTC^t(Qd) = \frac{\partial DTC^t(Qd)}{\partial Qd}$ = marginal transmission cost of drainage water in in year $\underline{t}$ (dollars/cubic meters/sec/meter)

Ld_k = length of reach $\underline{K}$ (meters)

$\Delta Qd^t_{i,k}$ = increase in drainage water from area $\underline{i}$ to reach $\underline{k}$ during year $\underline{t}$ (cubic meters/second)

$\sum_{i=1}^{j-1} \Delta Qd^t_{i,k}$ = drainage water available in reach $\underline{K}$ before area $\underline{j}$ in year $\underline{t}$

$\sum_{i=1}^{j} \Delta Qd^t_{i,k}$ = drainage water available in reach $\underline{K}$ after area $\underline{j}$ in year $\underline{t}$

Given the water transmission cost functions (Chapter (2)), the present worth of irrigation and drainage costs for each area can then be computed via equations (4.7), (4.8), (4.9), and (4.10). By adding the present values of water transmissions and land development costs, the expansion cost for each area can be obtained as shown in Table (4.7). In case of a full cost recovery, the price of each area is equal to its cost and the annual payments for the different payment policies can be determined as shown in Table (4.8). As shown in the Table, without an income transfer in the region from the areas of higher net-return to the other areas, the farmers in the fifth area will not be able to afford the annual payments and hence the expansion cost cannot be totally recovered. In addition, the rise in farmers' income as well as equity between them cannot be achieved.

Table 4-7. Cost Allocation Using Marginal Cost Approach

Area	Size in acres	PWTC[1]	PLDC[2]	PEC[3]	$Cost/ Acre
1	18,000	1,579,042	21,091,165	22,670,207	1259.45
2	18,000	720,060	21,316,613	22,036,673	1224.26
3	10,000	736,749	11,817,000	12,553,749	1255.37
4	12,000	574,840	15,098,527	15,673,367	1306.11
5	1,380	405,824	1,554,570	1,960,394	1420.58

1. Present worth of transmission cost in dollars
2. Present worth of land development cost in dollars
3. Present worth of the expansion cost in dollars.

Table 4-8. Marginal Cost Approach in Deriving the Payment Policies

	20 years payment policy		15 years payment policy	
Area	AP	NR	AP	NR
1	238	222	267	193
2	255	60	285	30
3	237	116	266	87
4	247	51	277	21
5	325	-23	364	-62

Table 4-9. Average Cost Approach in Deriving the Payment Policies

Area	Average Cost (dollars/acre)	20 Years Payment Policy		15 Years Payment Policy	
		AP	NR	AP	NR
1	1261	239[1]	221	257	193
2	1261	262[2]	53	294	21
3	1261	239[1]	114	267	88
4	1261	239[1]	59	267	31
5	1261	289[3]	13	323	-21

1. Payment will start in the sixth year of the investment horizon.
2. Payment will start in the seventh year of the investment horizon.
3. Payment will start in the eighth year of the investment horizon.

Hoping for better results, the average cost (per acre average cost = $\frac{\text{total cost}}{\text{total area}}$) approach is used in allocating the expansion cost equally (per acre) among the new areas. Given the average expansion cost ($1261/acre) the annual payments for the two payment policies can then be computed as shown in Table (4.9). From the table it can be noticed that the average cost approach is better than the marginal cost approach in insuring the recovery of the expansion cost when the twenty years' payment policy is used. However, the income increase to the farmers cannot be achieved in the fifth area (a farmer has to own forty acres of land, which violates the upper limit constraint, to achieve a minimum increase on the order of $500/year). Considering the fifteen years payment policy, the average cost approach fails in either recovering the expansion cost or in achieving the income increase to the farmer. In conclusion, an income transfer in the new land is necessary to achieve the income redistribution (income raise to the farmers and equity between them) and cost recovery objectives when using either the marginal or the average cost approaches in estimating the prices of the new areas. On the other hand, these objectives are achieved and the income transfer is well established when the income redistribution model is used.

4.5 Conflict Between Income Redistribution Benefits and Government Return in Agricultural Expansion Planning

As discussed earlier in this chapter, in agricultural expansions the income redistribution objective can be achieved by giving up some of the investment return to the landless peasants to improve their income conditions. The remainder from investment return will be gained by the Government for more investments beneficial to the society. Given the economic efficiency optimum design of the investment and cost recovery condition (specified Government return), the redistribution benefits can be identified. On the other hand, the redistribution benefits, as explained before, are equal to the raise in farmers' income (ΔI) multiplied by the number of farmers (NF) who may get this income increase. Given the assigned (by decision makers) value for $\underline{\Delta I}$, the maximum $\underline{NF}$, which can only be achieved if the redistribution benefits are equally allocated among the peasant farmers, can be determined. Then via the redistribution model, the decisions (land payments and land distribution among the farmers) which insure equity between investment beneficiaries and high agriculture efficiency in the newly developed areas, can be obtained.

It can be seen from the above discussion that a conflict between the two objectives of income redistribution and maximum Government return exists. By increasing the Government return from the investment, the redistribution benefits in terms of $\underline{\Delta I}$ and $\underline{NF}$ will decrease. The trade-off between these two objectives for the case study under the three different payment policies is obtained. This is done by solving the

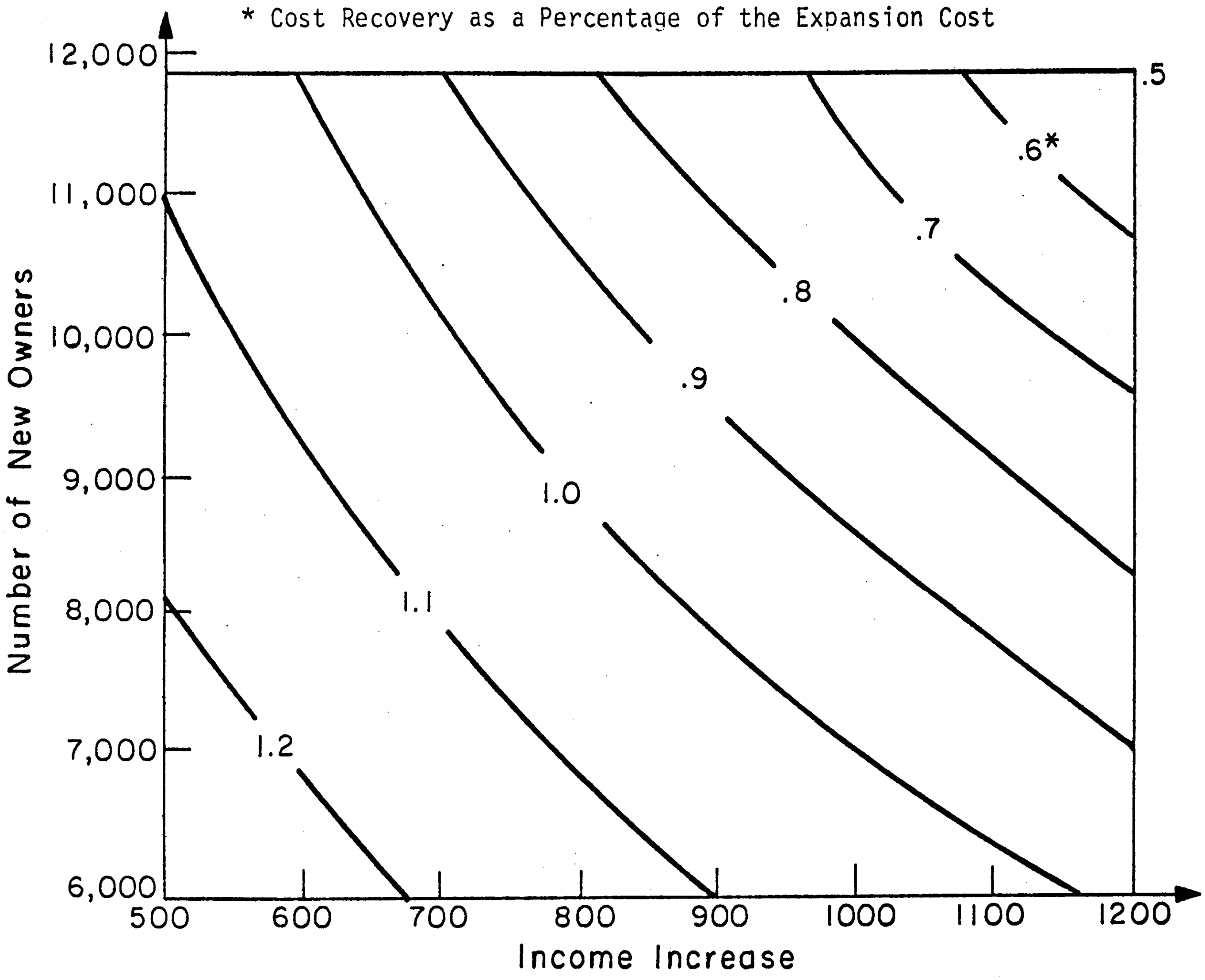


Figure 4-1 Income Increase and Number of New Owners Relationship
(20 Years' Payment Policy)

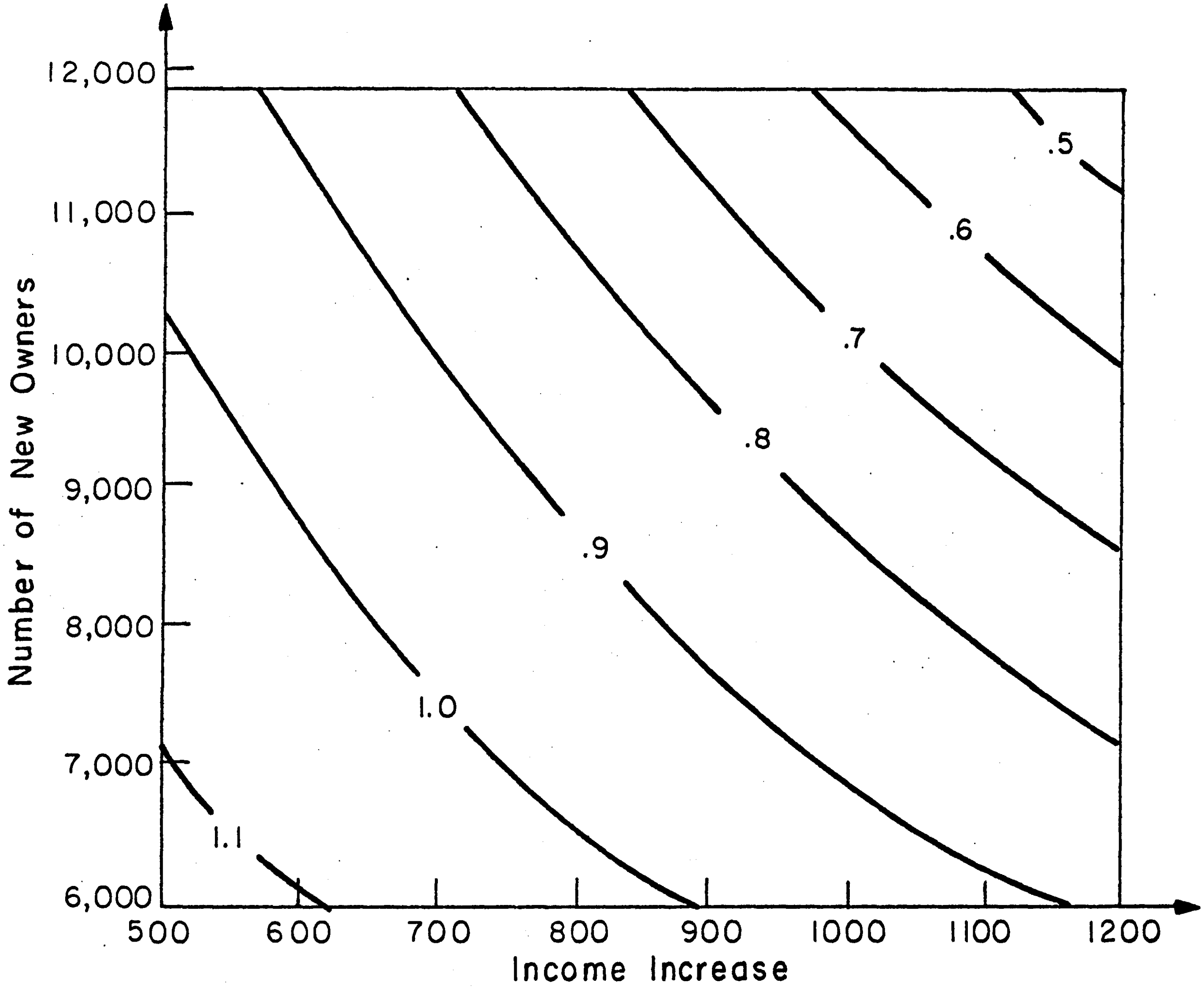


Figure 4-2 Income Increase and Number of New Owners Relationship (15 Years' Payment Policy)

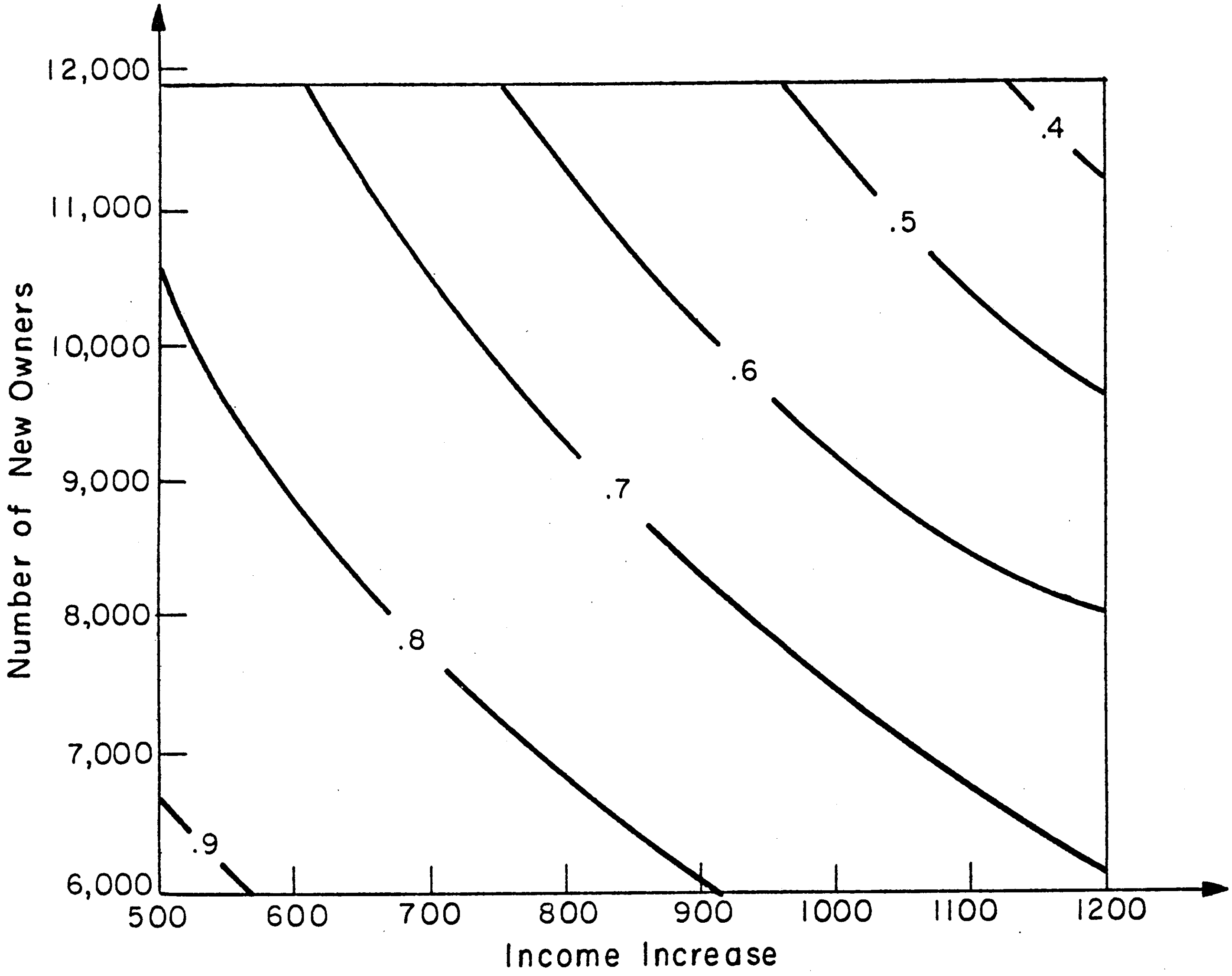


Figure 4-3 Income Increase and Number of New Owners Relationship (10 Years' Payment Policy)

model for each payment policy, via the Branch and Bound procedure available on SESAME Code, about fourty times for different conditions of cost recovery (0.4, 0.5,..,1.2 of the expansion cost) and income increase ($500, $600,...,$1200 per farmer per year). For easy use of this trade-off, it is prepared in a graphic format (Figures (4.1), (4.2), and (4.3). By solving this trade-off and knowing the desired payback period for the expansion cost, the most appropriate payment policy for the newly developed areas can be distinguished. More information about the implementation procedure of the payment policy on per acre annual payments and number of acres per farmer at the different locations of the new land can be obtained (Appendix (A)) from tabulated (output of the same runs used in deriving the trade-off).

In solving the trade-off between Government return and redistribution benefits from agricultural expansion investment, many factors are usually considered by the decision makers (UNIDO (1972)). Among the most important factors is the marginal productivity of landless farmers in their current jobs. The maximum number of landless farmers who can be withdrawn from the region without affecting the agricultural production in the existing cultivated areas represents an upper limit to <u>NF</u>. However, in most of the developing countries the cultivated areas are usually crowded, and this number is relatively high. Another limiting factor to the number of new owners of the newly developed lands is agriculture efficiency. This factor which represents a lower limit to <u>NF</u> is already considered in the redistribution model with upper limit constraint on farm size. The lower limit constraint in the redistribution model on farm size is another limiting factor to $\underline{NF}$. This constraint which insures a full employment of the farmer (farm family) in cultivating the new land represents an upper limit to the number of farmers who may own the land.

The trade-off between consumption and investment represents a limiting factor to the redistribution benefits. By increasing the farmers income, additional consumption through an increase in the purchasing power will be generated. A diversion of resources from investment to consumption may be socially costly if investment is more valuable than consumption. The minimum raise to the farmers income which makes the idea of owning new land attractive enough for the farmers to leave their old jobs, houses, relatives, friends, etc. represent a lower limit to $\underline{\Delta I}$. Another related factor is the total availability of consumer goods. Due to the income increase, the demand of consumer goods may exceed the supply and hence a shortage and social problem may be created. The above factors together with the Government cost recovery condition which may be necessary for the balance of payments, or for pursuing other investments for improving the conditions of another lower income group in the society, represent most of the issues usually considered in solving the income redistribution problem in agricultural development. The effect of these factors on the selection of $\underline{\Delta I}$ and $\underline{NF}$; and on solving the conflict between the redistribution benefits and Government return may be illustrated by the following example: Suppose that the Government objective is to raise the income of landless farmers ($300/farmer/year as the wage of farming either in the old or new lands) to be closer to the average income ($1000/person/year) of the farmers in the existing cultivated areas. The minimum income increase to the farmers which is necessary for facing the consumption requirements and/or

Table 4.10 Payment Policy Options for Achieving a Minimum of Full Cost Recovery

Income (dollars/farmer/year)	% Return	Number of Farmers (NF)	
		20 Years Payment Policy	15 Years Payment Policy
800	120	8,030*	--
	115	9,500	--
	110	10,900	7,150
	105	11,900	8,750*
	100	11,900	10,400
900	120	6,900*	--
	115	8,050*	--
	110	9,200	6,150
	105	10,400	7,500
	100	11,540	8,750*
1000	120	--	--
	115	7,000*	--
	110	8,050*	--
	105	9,200	6,300
	100	10,000	7,500

Table 4.11 Screened Payment Policy Options Which Achieve the Redistribution Objectives

Options	% Return	Payment Horizon (Years)	NF (farmers)	Income (dollars/farmer/year)
1	120	20	8,030	800
2	115	20	8,050	900
3	105	15	8,750	800

for attracting the farmers and convincing them to leave the old jobs and move to the newly developed areas is assumed here as \$500/farmer/year. Suppose now that the Government requires a minimum of full recovery of the expansion cost; then, the third payment policy (the ten years payment policy) which does not achieve a full cost recovery is infeasible to the Government. However, many options still are available to the decision makers to choose when using the other two payment policies as shown in Figure (4.1) and (4.2) as summarized in Table (4.10). The maximum number of landless farmers than can be withdrawn from the old cultivated areas without affecting the current production is estimated as 9,000 farmers. In case of deciding to keep full agricultural production in the old land, then only twelve payment policy options can be used (underlined options in Table (4.10)). Moreover, only seven from these twelve options are non-inferior ones (starred options in Table (4.10)). To select one policy from these seven alternatives, the trade-off between $\underline{\Delta I}$ and $\underline{NF}$ should be solved first. If the decision makers, in screening the available options, gives the high priority to the investment return as well as the number of new owners for political and economic considerations, then the seven options will be reduced to only three options as shown in Table (4.11). By using the first option, the highest return to the Government can be achieved. If the second option is used, a higher number of landless farmers can own the new land and achieve a higher income increase. Although the third option achieves the least return to the Government, it allows the largest number of landless farmers to own the new land and achieve the minimum income increase (\$500/farmer/year). To distinguish the best option, more information about the trade-off of the decision makers between redistribution benefits and Government return is needed. From this example, it can be seen that the limiting factors introduced above can reduce the thousands of options available to the decision makers for achieving the income redistribution objective to a smaller set of options which is easier to handle and evaluate.

4.6 Summary

The role of agricultural expansion investment in improving the income redistribution conditions in a society is investigated. The approach of land distribution to a poorer sector (landless farmers) of society to gain the agricultural revenues and improve their income is selected. A mathematical model (redistribution model) is built to determine the optimum land distribution among the farmers which achieves a specified (by the Government) income increase to them and maintains a high agricultural efficiency in the newly developed land. In addition, the model is formulated in such a way that the land payment policy which insures the recovery of the expansion cost and equity between the farmers can be determined.

The use of the marginal and average cost approaches in estimating the prices of the new land is illustrated. It is found that the objectives of achieving income increase to the farmers and equity between them can not be insured, and the expansion cost cannot be recovered (land payments at some areas are estimated higher than the agricultural revenues of these areas) when using either approaches in estimating land prices. On the other hand, these redistribution and cost recovery objectives are well established when the redistribution model is used.

A conflict between the Government return from the investment and redistribution benefits is found. This conflict is addressed and the trade-off between the two objectives is provided. The limiting factors to this trade-off are discussed and an illustrating example is used.

In real life problems, more complicated payment policies for the new land than what are considered in this work (fixed annual payments for different horizons) may be required. Also, gradual increase in the farmers income may be preferred than the sudden increase as considered here in the paper. Moreover, the expansion investment may serve more than one group of lower income people. All these factors can easily be included in the formulation of the redistribution model.

A modification to the income redistribution model to account for a pricing scheme to the irrigation water in the areas presents a potential area for future research. Water pricing will lead to a higher efficiency of water use, as the farmers will be more careful not to waste water. The possible conflict between the income redistribution objective and agricultural efficiency represents another potential area for future research. More experimental research is needed to determine the effect of farm size on agricultural efficiency in the developing countries. The output of such experiments should be considered in the analysis of the redistribution issue.

CHAPTER 5

CONFLICTS BETWEEN ECONOMIC EFFICIENCY AND INCOME REDISTRIBUTION CRITERIA IN AGRICULTURAL EXPANSION PLANNING

5.1 Introduction

Investigations on the possible conflicts between the economic efficiency and income redistribution criteria need to be carried out. From our work, we found that no conflict exists between these two objectives.

A comparison between three alternate schemes for planning the case study via the least cost and income redistribution criteria is performed. These three alternatives are the solutions of the scheduling model to the case study when used for irrigation, fresh water, saline water and recycled drainage water, respectively. It is found that for specified redistribution decision, the most economic alternative achieves the highest economic return to the government.

5.2 Conflict Between the Economic Efficiency and Income Redistribution Criteria in Agricultural Expansion Planning

If the redistribution objective is considered in the investment design, a conflict between economic efficiency and income redistribution criteria may exist. Large investment may give the opportunity to a large number of peasant farmers to own the new land and improve their incomes but, a smaller investment might be economically more efficient. In our case, where the redistribution objective has not been considered in the investment design but in a further step through a transfer mechanism from the Government to landless farmers, this conflict should not exist. For a specified Government return from the investment, the least cost design which is economically the most efficient design (Allam and Marks (1982a)) should achieve the maximum return to the farmers. In order to show that, a comparison in terms of redistribution benefits between the three planning alternatives for the case study provided in Chapter 2 and 3 is carried out. These three alternatives are the solutions of the scheduling model to the case study when used for irrigation, fresh water, saline water and recycled drainage water, respectively. A cost comparison between these alternate plans is given in Table 5.1. The redistribution model is used for estimating the redistribution benefits of each plan for a full cost recovery condition and different levels of income increase $\underline{\Delta I}$ (600, 700, and 800 dollars/farmer/year). Two payment policies are considered: These payment policies consist of twenty and fifteen years of fixed payments, respectively. When using the first payment policy, it is found that the third alternative which has the least expansion cost is achieving the highest redistribution benefits in terms of number of investment beneficiaries for the different conditions of income increase (Table (5.2)). The first alternative which is the second least cost design has higher redistribution benefits, than the second plan which is the most expensive one. Similar results are obtained (Table (5.3)) when using the second payment policy. These results are in agreement with our expectation that no conflict exist between the income redistribution and least cost (economic efficiency) criteria in our planning framework of agricultural expansion investments.

5.3 Income Redistribution and Economic Efficiency Criteria in Comparing the Planning Alternatives

As shown in Chapter 4, the income redistribution problem is to determine the distribution of land among the farmers and per acre annual payment in such a way that a maximum number of farmers can own the land and get a specified income increase. In the case of having different plans for achieving these redistribution decisions, the best alternative can be distinguished via the economic efficiency criterion.

Table 5.1 A Cost Comparison Between the Planning Alternatives

Alternative No.	Description	Expansion Cost (dollars)	Expansion and Farming Cost
1	Fresh water for Irrigation	84.1×10^6	142.1×10^6
2	Saline water for Irrigation	85.4×10^6	144.8×10^6
3	Drainage water reuse	83.1×10^6	141.1×10^6

Table 5.2 Redistribution Benefits of the Planning Alternatives (20 years Payment Policy)

	Number of the New Owners		
	$\Delta I=600$	$\Delta I=700$	$\Delta I=800$
First Alternative	11,543	9,956	8,756
Second Alternative	10,444	8,942	7,845
Third Alternative	11,773	10,078	8,862

Table 5.3 Redistribution Benefits of the Planning Alternatives (15 years Payment Policy)

	Number of the New Owners		
	$\Delta I=600$	$\Delta I=700$	$\Delta I=800$
First Alternative	8,742	7,480	6,526
Second Alternative	7,776	6,596	Infeasible
Third Alternative	8,958	7,618	6,632

The income redistribution model can be reformulated to determine the redistribution decisions (P_j and N_j) which maximize the net-return to the government and enable a specified number of farmers to own the land and gain an income increase, The objective function of this model is to maximize the government return from the investment (Equation (5.1)). This maximization procedure is constrained with six constraint sets. The first set is to insure that the farmers at the different new areas will get the assigned income increase. The second set is to compute the net-return of the government from the investment. The third set is to insure that the specified number of farmers (NUM) will have the opportunity to own the new land and get the specified income increase. The fourth and fifth constraint sets are for the upper and lower limits on the number of acres per farmer. The last set is to insure the non-negativity of the annual payments at the various new areas.

$$\text{Maximize } \beta(PTC) \qquad (5.1)$$

Subject to

$$n_j(R_j^t - P_j^t) \geq \Delta I \; \ldots \; \forall_k \qquad (5.2)$$

$$\sum_{t=t_o}^{N} \sum_{j=1}^{N} \alpha^t A_j P_j^t - \beta(PTC) \geq 0.0 \qquad (5.3)$$

$$\sum_{j=1}^{N} A_j/n_j \geq NUM \qquad (5.4)$$

$$n_j \leq U \quad \ldots \quad \forall_j \qquad (5.5)$$

Table 5-4. Redistribution Decisions of the Planning Alternatives

Area	First Alternative				Second Alternative				Third Alternative			
	n_j	AP_j	R_j	ΔI_j	n_j	AP_j	R_j	ΔI_j	n_j	AP_j	R_j	ΔI_j
1	5	340	460	600	5	260.7	380.7	600	6	330	430	600
2	5	195	315	600	5	176.6	296.6	600	5	21	141	600
3	7	267	353	602	10	202.7	262.7	600	7	187.3	273	600
4	10	238	298	600	9	355.3	422	600.3	7	356.3	442	600
5	8	227	302	600	5	306.3	426.3	600	5	353	473	600

Table 5-5. A Comparison Between the Planning Alternative via the Income Redistribution and Economic Efficiency Criteria.

Criteria	Issues	Alternatives			Best Alternative
		1	2	3	
Income	ΔI	600	600	600	Indifferent
Redistribution	N	10,000	10,000	10,000	Indifferent
	Cost(c)	$\$84.1\mathrm{x}10^{6}$	$\$85.4\mathrm{x}10^{6}$	$\$83.1\mathrm{x}10^{6}$	3
Economic	Govern. Return(B)	$\$90\mathrm{x}10^{6}$	$\$88.60\mathrm{x}10^{6}$	$\$90\mathrm{x}10^{6}$	1,3
Efficiency	β=B/C	1.07	1.037	1.08	3
	B-C	$\$5.9\mathrm{x}10^{6}$	$\$3.2\mathrm{x}10^{6}$	$\$6.9\mathrm{x}10^{6}$	3

$$n_j \geq L \quad \ldots \quad \forall_j \qquad (5.6)$$

$$p_j^t \geq 0.0 \quad \ldots \quad \forall_{j,t} \qquad (5.7)$$

The model is used here for comparing the three planning alternatives. The mixed integer programming available on SESAME code is used for solving the model to determine integer values for n_j at each new area. The CPU time for each run was about 50 seconds. The redistribution decisions are obtained for the three alternatives as shown in Table (5-4). A comparison between the three alternatives is carried out. The three alternatives have the same redistribution benefits level (ΔI=600 and NUM=10,000) as shown in Table (5-5). By using the economic efficiency in comparing the three alternatives, it is found that the third alternative has the least cost, the highest net-return to the government (B-C) and the highest benefit cost ratio. The third design dominates the other two alternatives and clearly is the best.

5.4 Summary

No conflict between the income redistribution and economic efficiency is found. The most economically efficient design is achieving the maximum return to the farmer.

The income redistribution model is reformulated to determine the redistribution decisions (per acre annual payments and size of land per farmer) in such a way that the government return can be maximized and a specified number of the landless farmers can get a specified income increase. Then a comparison to the various alternative plans via the income redistribution and economic efficiency criteria is carried out. The third alternative in which the drainage water is recycled for irrigation is found as the best alternative.

CHAPTER 6

RESILIENCY OF AGRICULTURAL EXPANSION PLANNING

6.1 Overview

Uncertainty plays a major role in this public investment. Uncertainty in crop water requirments, crop yields, efficiency of technology used for irrigation and drainage, quality and quantity of irrigation water and prices of the various crops make the system performance in the future hard to predict. Traditional approaches like sensitivity analysis, looking at different scenarios and chance constraint programming are usually used in handling uncertainty problems. The concept of resiliency has been recently used to deal with future uncertainties as a measure of system performance. System resilience is a measure of a system's capability to absorb and adapt to the impact of any surprise in any of the system parameters. The first use of resilience was in ecological systems (Holling (1973) and Fiering and Holling (1974)), and was defined analogously to their definition of robustness -- that even if an unlikely event occurs, a decision has a high probability of being correct or at least good enough. Krzystofowicz (180) has defined system resilience as a system's capability to absorb the impacts of outside random events or to adapt to them without degradation of performance. He classified the random events into short-run events like an error in system operation or an improper deployment of the system and long-run events such as changes in environment and emergence of superior technology. In terms of achieving the planning objectives

Marks (1980) defined the resiliency as a measure of how well a system will operate to meet the stated objectives when actual conditions change. More general definition of system resilience in terms of any surprise -- mechanical, statistical, insititutional -- to the system is given by Fiering (1982a). He defined system resilience as the ability of a system to accommodate the surpirse and survive or even to recover and thrive under unanticipated perturbation. Hashimoto et al. (1982a and 1982b) have differentiated between the system capability to accommodate surprises (robustness) and its capability to recover (resilience). He used the Stigler's definition of economic flexibility (system capability in adapting to a wide range of possible demand conditions at little additional cost) as a definition to the robustness. Hashimoto et al. (1982a) have introduced a probabilistic description of system robustness as a measure of the likelihood that the actual cost of a proposed project will not exceed some fraction of the minimum possible cost of a system designed for the actual conditions that occur in the future. There are several drawbacks to this robustness measure (Allam and Marks (1982d)). The first is considering only cost as a measure of system performance where the other criteria such as the income redistribution efficiency has to be considered particularly in water resources projects which usually are public investments. The second is the difficulty in deriving the probability distribution of the future demand conditions which is necessary for measuring the robustness of a system design. The third is the dependency of the robustness measure on the cost threshold (the function of minimum design cost) which is very difficult to assign. This difficulty is because of the fact that the cost threshold is a percentage of the minimum cost design which cannot be translated into a monetary value.

In distinguishing the difference between resilience and robustness, Fiering (1982a) introduced an approach for measuring each of them in terms of partial and total derivative of the system response functions. According to his definition, the system is robust to a change of a certain decision variable, if the partial derivative of system response with respect to this decision is small. Fiering urged that even if the system is not robust to a change in a certain decision variable, it might be resilient. This is because changes in other decisions might be made to accommodate the unpleasant surprise in this decision. In demonstrating that he used the total derivative for the system response ($\frac{dZ}{dX_i} = \sum_j \frac{\partial Z}{\partial X_j} \frac{dX_j}{dX_i}$, where Z is the system response, and X_j for all values of j are the planning parameters) in which some of X_j refers to operating decision which can change if X_i is perceived to be incorrect. Finally he suggested a linear combination of the total derivatives as a measure of system resilience (system ability to adjust and to utilize redundant capabilities). This resiliency measure is very much in agreement with Mark's definition (1980). In relating the resilience to the dimension of time, Fiering (1982b) urged that the total derivative of system respons allows temporal considerations because the adjustments in some operating decisions are to be more rapid than the other structural, political and institutional adjustments.

Hashimoto et al. (1982b) proposed the average probability of a recovery from the failure state in a single time step as a measure of the resiliency. Other methods for measuring system resilience have been suggested by Fiering (1982b). One is based on the adaptability of a single design to changes in targets, another is based on the residence time in acceptable states and rate of passage along a given trajectory between initial and terminal position as an indication of time available to make adjustments in a policy or a mechanistic surprise. However, for large-scale systems, the combination of the total derivatives method is recommended by Fiering. This method will be developed and used here in measuring the resiliency of agricultural systems, where the system response is expressed with the system performance in terms of the planning objectives.

6.2 Total Derivative Method in Measuring the Resiliency of Agricultural Systems

In order to use the total derivative method in measuring the resiliency of agricultural systems the following should first be identified:

1. The planning parameters and decision which possibly carry future surprises in agricultural expansions.
2. The criteria which can be used in measuring the performance of agricultural systems.
3. The method of measuring the total derivatives of a system performance.
4. The weighting coefficients which can be used in deriving a linear combination between the total derivatives.

The planning parameters of the agricultural investments can be classified into two sets. The first set includes the design parameters such as yields and water requirements of the various crops, efficiency of technology used for irrigation and drainage, and water conveyance losses. The second set includes the input parameters and decisions which are quantity and quality of available water for irrigation, cropping pattern in the new areas and prices of the various crops. This discrimination between parameters is suggested to take advantage of the long period of land development as well as the scheduling period in avoiding the risk which might exist due to uncertainties in the design parameters. Any unexpected changes in the design parameters will probably be recorded in these periods and used in updating the planning strategy. Unfortunately, this is not the case with input parameters. Surprises in the input parameters can occur at any point of the investment time horizon. Surprises in the quantity of available irrigation water can occur in case of drought conditions. Change in irrigation water quality can occur if, for any political, economic or institutional reason, some of the irrigation water should be diverted for another activity (agricultural development, industries, municipals, etc.) in the sense that the drainage water can be reused for irrigation and substitutes for this water shortage. Shadow prices of the agricultural crops are most likely to increase, not to decrease, with time but still the possibility of a decrease in the crops' prices exists. With a higher probability the market-distorted prices due to political and/or institutional reasons may decrease. In summary, the gradient of system design performance may be measured only for a wide range of changes in the input parameters and decisions.

The economic efficiency and income redistribution criteria can be used together in measuring the performance of agricultural systems. Losses in the economic benefits due to surprises in the planning parameters can be measured via the economic efficiency criterion while the income redistribution criterion can account for the uncertainty effects on the farmers' income.

One way of measuring the total derivative of a system performance with respect to a planning parameter is to perform an optimization model for minimizing the decrease in system performance subject to a perturbation in this planning parameter. By measuring the model for different values of perturbances in the concerned parameters, functional relationships between system performance and surprises in these planning parameters can be obtained, and hence the gradients (total derivatives) of these functions can be measured. The decision variables of this model are the planning decisions which can be rapidly readjusted to minimize the reduction in system performance. In agricultural investments, these decisions are the seasonal flows in the irrigation and drainage networks and the crop pattern distribution in the new land. On the other hand, this minimization procedure should be constrained with the physical components which need a long time (years) to be adjusted. Such decisions are capacities of irrigation and drainage networks, infrastructures, size of the reclaimed areas, level of development in the new areas, the used technology for irrigation and drainage and the distribution of land among the farmers. A mathematical presentation of this modeling approach will be introduced in the following section.

In deriving a linear combination of the total derivatives it is very crucial to understand that without a good estimate to the weighting coefficients, the resiliency measure can be a very misleading one. A system design can be very sensitive to unlikely change in a planning parameter and relatively insensitive to a change in another parameter which is likely to occur. Then by neglecting the likelihood of surprises occurring, a wrong estimate of system resiliency will result. Therefore, it seems appropriate to use the occurrence probability of changes in the planning parameters (these can be subjective probabilities gained by means of engineering experience and judgement) after being normalized (their sum equals unity), as the weighting coefficients to the total derivatives of a system performance with respect to these changes.

6.3 Modeling Approach to the Performance of Agricultural Expansion Investment under Uncertainty

In an optimization framework a static operating rules model for agricultural systems is presented below. The economic efficiency and income redistribution criteria are used in measuring the performance of agricultural systems. The economic efficiency criterion is expressed in terms of maximizing the benefits of the investment (minimizing the reduction in the agricultural benefits due to changes in the input parameters). The agricultural benefits are the summation of the benefits of the various crops. The benefit of a crop is equal to its yield multiplied by the unit shadow price of this crop and reduced by its farming cost (Equation 6.1). The farming cost includes cost of seeds, fertilizer, pesticides, labor and machinery. This method of computation of the agricultural benefits is based on the assumption that the output (agricultural production) of the investment is not large enough to affect the prices of the various crops. Otherwise the consumer's "willingness to pay" is the right measure of the investment benefits (Allam, 1982c).

As shown before in Chapters 4 and 5, in agricultural expansions, income redistribution efficiency can be maximized by maximizing the number of lower income people (landless farmers) who can own the new land and get a specified income increase. This criterion, as explained before, can be used to determine the optimum land distribution among the farmers as well as the optimum payment policy for the prices of the new lands which enables the farmers to achieve the assigned income increase and the government to recover the expansion cost or even to achieve some benefits. Unpleasant surprises in the input parameters will cause a reduction in agricultural revenue which will result in a decrease in the incomes of the farmers. Therefore to maximize the redistribution efficiency, the farmers' incomes have to be maximized (minimize the income decrease) as shown in Equation (6.2). In a multi-objective framework, the agricultural performance can be expressed in terms of the economic and redistribution efficiencies as shown in Equation (6.3) where λ is a national parameter which expresses the nation's trade-off between the economic and social benefits (trade-off between consumption and investment).

$$\text{Maximize} \quad \sum_{s=1}^{S} \sum_{p=1}^{p} (SP_p^s - UFC_p^s) \; PR_p^s \tag{6.1}$$

$$\text{Maximize} \quad NUM \times \Delta I \tag{6.2}$$

$$\text{Maximize} \quad \sum_{s=1}^{S} \sum_{p=1}^{p} (SP_p^s - UFC_p^s) \, PR_p^s + \lambda X \; NUM \times \Delta I \tag{6.3}$$

where

S = number of agricultural seasons per year (known)

p = number of crops per season (known)

SP_p^s = shadow price of crop P at season s (dollars/ton) (given)

UFC_p^s = unit farming cost (dollar per ton of crop P at season s) (given)

PR_p^s = agricultural production of the new land from crop P at season s

NUM = number of owners of the newly reclaimed areas (known)

ΔI = income increase (dollars/ton) to the new owners (decision variable)

Constraints Sets

This maximization procedure is constrained with fourteen constraint sets.

1. Agricultural Production Constraints

This set is to determine the agricultural production of the new land from the various crops

$$\sum_{i=1}^{N} X_{i,p}^s Y_{i,p}^s - PR_p^s = 0.0 \qquad \forall s,p \qquad (6.4)$$

where N = number of the new areas (known)

$X_{i,p}^s$ = size in acres of land to be cultivated with crop P during season s at area i (decision variable)

$Y_{i,p}^s$ = yield of crop P at area i during season s (given)

2. Area Budget Constraints

This set is to insure that for every agricultural season at each new area the size of cultivated land with the various crops is less than the size of the area itself.

$$\sum_{s=1}^{S} \sum_{p=1}^{P} X_{i,p}^s \leq A_i \qquad \forall_i \qquad (6.5)$$

3. Sequential Planting Constraints

This set accounts for the need of planting certain crops before others (like clover before cotton) for enhancing of soil nitrogen. If crop a during season s is required to be planted before crop b during season s+1, this constraint can be written as

$$X^{s+1}_{i,b} - X^{s}_{i,a} \leq 0.0 \qquad \forall_i \qquad (6.6)$$

4. Water Requirements Constraints

This set is to compute the seasonal water demands at the new areas.

$$\sum_{p=1}^{P} W^{s}_{i,p} \; X^{s}_{i,p} - d^{s}_{i} = 0.0 \qquad \forall_{i,s} \qquad (6.7)$$

where

$W^{s}_{i,p}$ = water requirements of crop P at area i during season s (known)

d^{s}_{i} = water required for irrigation at area i during season s (decision variable)

5. Flow Balance Constraints (Irrigation Network)

$$\sum_{i=1}^{N+M} f^{s}_{i,j} \; (1-L^{s}_{i,j}(f^{s}_{i,j},\ell_{i,j})) - \sum_{\substack{K=1 \\ K\neq j}}^{N+M-1} f^{s}_{j,k} - d^{s}_{j} = 0.0$$

$$\forall_{j,s} \qquad (6.8)$$

where $f^{s}_{i,j}$ = flow through canal (i,j) in season s (decision variable)

$L^{s}_{i,j}(f^{s}_{i,j},\ell_{i,j})$ = water losses in canal (i,j) as a function of the length ($\ell_{i,j}$) and flow ($f^{s}_{i,j}$)(decision variable)

6. Flow Balance Constraints (Drainage Network)

$$\sum_{i=1}^{N+M} fd^s_{i,j}(1+LD^s_{i,j}(fd^s_{i,j},\ell d_{i,j}) - \sum_{\substack{k=1\\k\neq i}}^{N+M} fd^s_{j,k} + d^s_{r_j}(d^s_j) = 0.0$$

$$\forall_{j,s} \qquad (6.9)$$

where

$fd^s_{i,j}$ = flow through drain (i,j) in season s (decision variable)

$LD^s_{i,j}(fd^s_{i,j},\ell d_{i,j})$ = seepage water to drain (i,j) during season s as a function of the length ($\ell d_{i,j}$) and flow ($fd^s_{i,j}$) (decision variable)

$d^s_{r_j}$ = drained water at area j during season s as a function of the irrigation water requirement at this area (d^s_j) (m^3/sec) (decision variable)

7. Upper Capacity Constraints (Irrigation Network)

This set is to keep the flows through the irrigation canals lower than the existing capacities.

$$f^s_{i,j} - CP_{i,j} \leq 0.0 \qquad \forall_{i,j,s} \qquad (6.10)$$

where $CP_{i,j}$ is the existing capacity (m^3/sec) of canal (i,j) (given)

8. Upper Capacity Constraints (Drainage Network)

$$fd^s_{i,j}(1+LD^s_{i,j}) - CPD_{i,j} \leq 0.0 \qquad \forall_{i,j,s} \qquad (6.11)$$

where $CPD_{i,j}$ is the existing capacity (m^3/sec) of drain (i,j) (given)

9. Water Budget Constraints Set

This set is to keep the outflow from each source less than or equal to the inflow to this source.

$$\sum_{j=1}^{M+N} f_{i,j}^{s} - b_i^s \leq 0.0 \qquad \forall_{i,s} \qquad (6.12)$$

where b_i^s is the available water at source i during season s (m^3/sec)(known)

10. Agricultural Targets Constraints

This is to insure that the agricultural production of the new lands will not exceed the demand.

$$PR_p^s - D_p^s \leq 0.0 \qquad \forall_{s,p} \qquad (6.13)$$

where D_p^s is the demand for crop P in season s (tons/year)(known)

11. Agricultural Revenue Constraints

This set is to compute the net agricultural revenue (per unit area) at each new area.

$$\sum_{s=1}^{s} \sum_{p=1}^{p} X_{i,p}^{s}(GP_{i,p}^{s} Y_{i,p}^{s} - FC_{i,p}^{s}) - A_i NR_i = 0.0 \qquad \forall_i \qquad (6.14)$$

where

GP_{iP}^s = farm gate price of crop P in season s at area i (dollars/ton)(given)

$FC_{i,p}^s$ = farming cost of crop P during season s at area i (dollars/ton)(given)

NR_i = per acre annual agricultural net revenue at area i (dollars/acre)(decision variable)

12. Constraints on Income of the Farmers

This set is to compute the income of the farmers at the various new areas

$$(NR_i - P_i) - M_i FR_i = 0.0 \qquad \forall_i \qquad (6.15)$$

where

P_i = per unit area annual payment at area i (dollars/acre/ton)(given)

M_i = $\frac{1}{n_i}$ (input)

n_i = number of acres per farmer at area i (known)

FR_i = farmers' net-revenue (dollars/year) at area i (decision variable)

13. Equity Constraints

This is to insure the equity between the farmers in achieving the same income level.

$$FR_i - \Delta I \leq 0.0 \qquad \forall_i \qquad (6.16)$$

14. Non-Negativity Constraints

This set is to insure the non-negativity of the operating decisions.

$$X^s_{i,p},\ f^s_{i,j},\ fd^s_{i,j} \text{ and } FR_i \geq 0.0 \qquad \forall_{i,j,p,s} \qquad (6.17)$$

The input to the model includes λ, NUM, SP^s_p, UFC^s_p, $Y^s_{i,p}$, N, A_i, $W^s_{i,p}$, $CP_{i,j}$, $CPD_{i,j}$, b^s_i, D^s_p, $GP^s_{i,p}$, $FC^s_{i,p}$, n_i and p_i. As shown above, the model has alinear objective function and constraint sets and then a linear programming algorithm can be used for solving the model. For a perturbation in a planning parameter of an agricultural system design, the model can determine the optimum adjustments to the cropping pattern in the new areas, and flows in the irrigation and drainage networks which minimize the reduction in the agricultural revenues as well as the farmers' income. By running the model for a wide range of changes in the values of the planning parameters, the relationship between the system design performance and perturbations in the planning parameters can be determined. Having determined this relationship, the total derivatives of system performance can be obtained as will be shown next.

6.4 Model's Application

The performance model is applied for a case study. The case study is based on the solution of the scheduling model to the hypothetical expansion when using fresh water for irrigation (Figure (2-1)). It is assumed here that the decision makers have selected the twenty-year payment policy which achieves a full recovery of the expansion cost and a raise to the farmers' income on the order of $600/farmer/year. Size of the developed land, distribution of land among the farmers and per acre annual payments at the different new areas (Chapter 4) are given in Table (6-1). The capacities of the irrigation and drainage canals (Chapter 2) are summarized in Table (6-2)and Table (6-3) respectively. The agricultural production of the new land under no surprises (changes) in the planning parameters are given in Chapter 2, Table (2-3). In the following section, the performance of the agriculture system will be measured in terms of the economic efficiency and income redistribution criteria under a wide range of changes in the irrigation water quantity, irrigation water quality and prices of the various crops.

Irrigation Water Quantity and System Performance

The model is solved for the case study via the linear programming algorithm available on SESAME Code for different values of λ(0,1,2,3 and 4). It is found that the solution is independent from the value of λ. This is because, as explained in the last chapter, there is no conflict

Table 6-1. Land Distribution Among the Farmers and Per Acre Annual Payments in the Various New Areas

Area	Size in Acres	Acres per Farmer	Annual Payment (dollars)
1	18,000	5	340
2	18,000	5	195
3	10,000	6	252
4	12,000	5	178
5	1,380	5	182

Table 6-2. Capacities of the Irrigation Canals

Canal	Capacity (m^3/sec)	Canal	Capacity (m^3/sec)
6-7	35.1	8-9	3.3
7-1	27.1	9-3	2.9
1-5	5.5	9-10	0.4
7-8	7.4	10-4	0.4
8-2	4.0	10-5	0.0

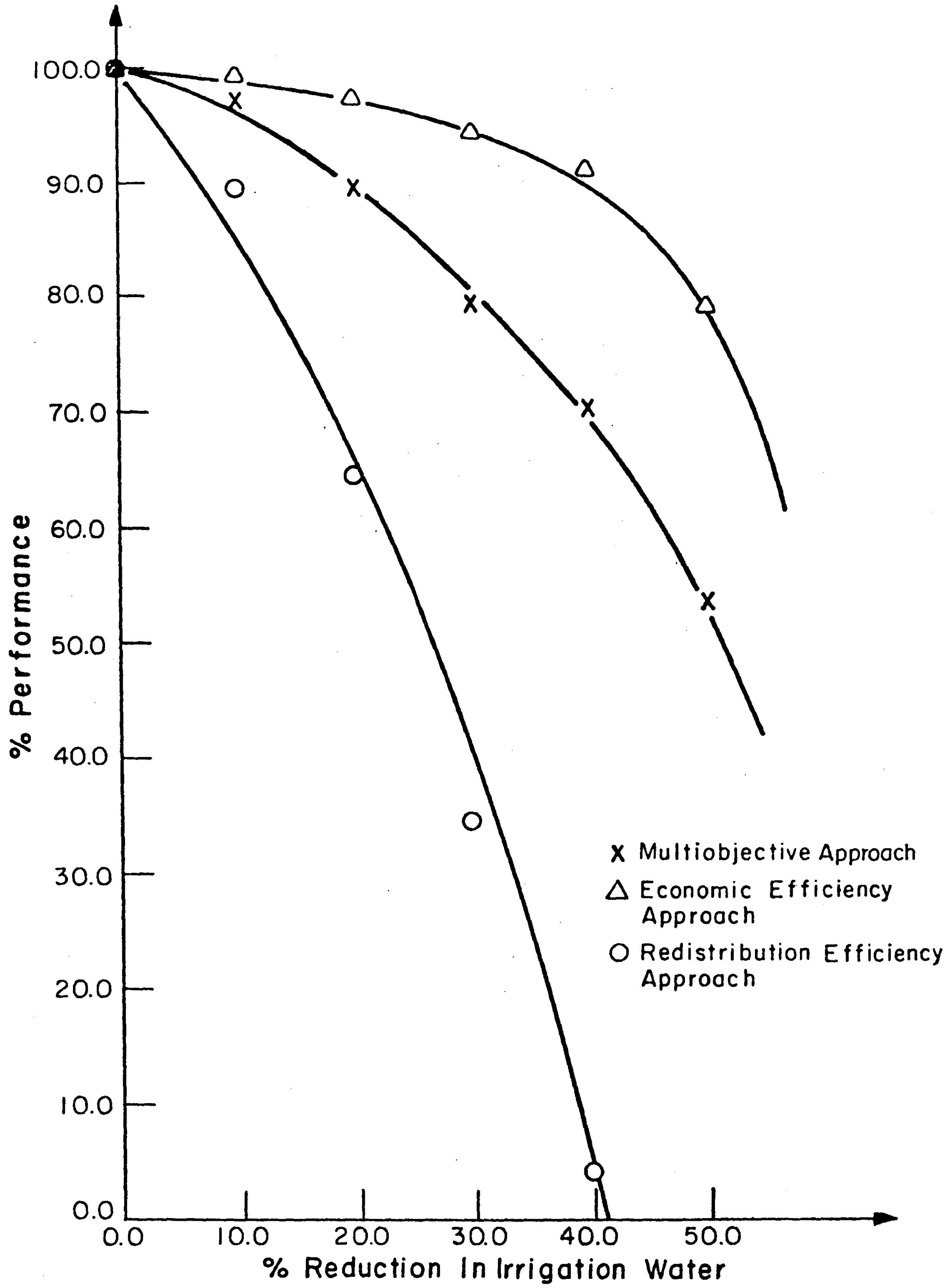


Figure 6-1 System Performance vs. Reduction in Irrigation Water Quantity

Table 6-3. Capacities of the Drainage Canals

Drain	Capacity (m^3/sec)	Drain	Capacity (m^3/sec)
2-9	1.2	4-10	0.1
1-9	6.4	5-10	1.6
3-9	0.9	9-10	8.6

between the redistribution efficiency and economic efficiency exist. The optimum adjustments to the operating decisions under different conditions of irrigation water quantity are given in Appendix B. As shown in the Appendix, the decrease in irrigation water mainly affects the production of beans in the winter and rice in the summer, which have the highest water requirements. As shown in the Appendix, the model succeeds in insuring the equity between the farmers in achieving the same income level. The degradation in system performance under unpleasant changes in the quantity of irrigation water is presented in Figure (6-1). The system design behaves reasonably well in accommodating the surprises in irrigation water. A twenty percent reduction in irrigation water causes only 10% reduction in system performance. But as the size of the surprise increases, the performance degrades more rapidly. A thirty percent reduction in the system performance obtained when the inflow decreased with forty percent.

By using only the economic efficiency criterion in measuring the system performance and relaxing the redistribution constraints (6-14), (6-15) and (6-16), the system design looks more resilient

(Figure (6-1)). In fact this measure does not reflect the whole picture because it does not account for the losses in land payments and the subsidies to the disaster areas. The incomes of the farmers at the various new areas are computed according to the readjusted cropping pattern as shown in Table (B-12). A large deviation between the farmers' incomes is found. For 10% reduction in the irrigation water the fifth area is left without irrigation, the farmers in the first area have 40% decrease in their income and the farmers in the second area are not able to afford the annual payments. On the other hand, the farmers in the third and fourth areas have more than 100% increase in their incomes. By reducing the irrigation water more (50% reduction), the disaster will reach the fourth area where the farmers will not be able to afford the land payments, while the farmers in the first area will be achieving more than 100% increase to their incomes. In general, this modeling approach does not insure the equity between the farmers. Moreover, it is overestimating the performance of the system design. By accounting for the government losses in land rent and aids to disaster areas, the economic benefits will be decreasing more rapidly than the first case when using the multiobjective approach in determining the operating decisions.

On the other hand, the only use of the income performance criterion will result in underestimating the system performance. This happens because of neglecting the gain of the government (land payments) from the investment which is insured (reduction of land payments is not allowed in this case). Therefore, the system performance

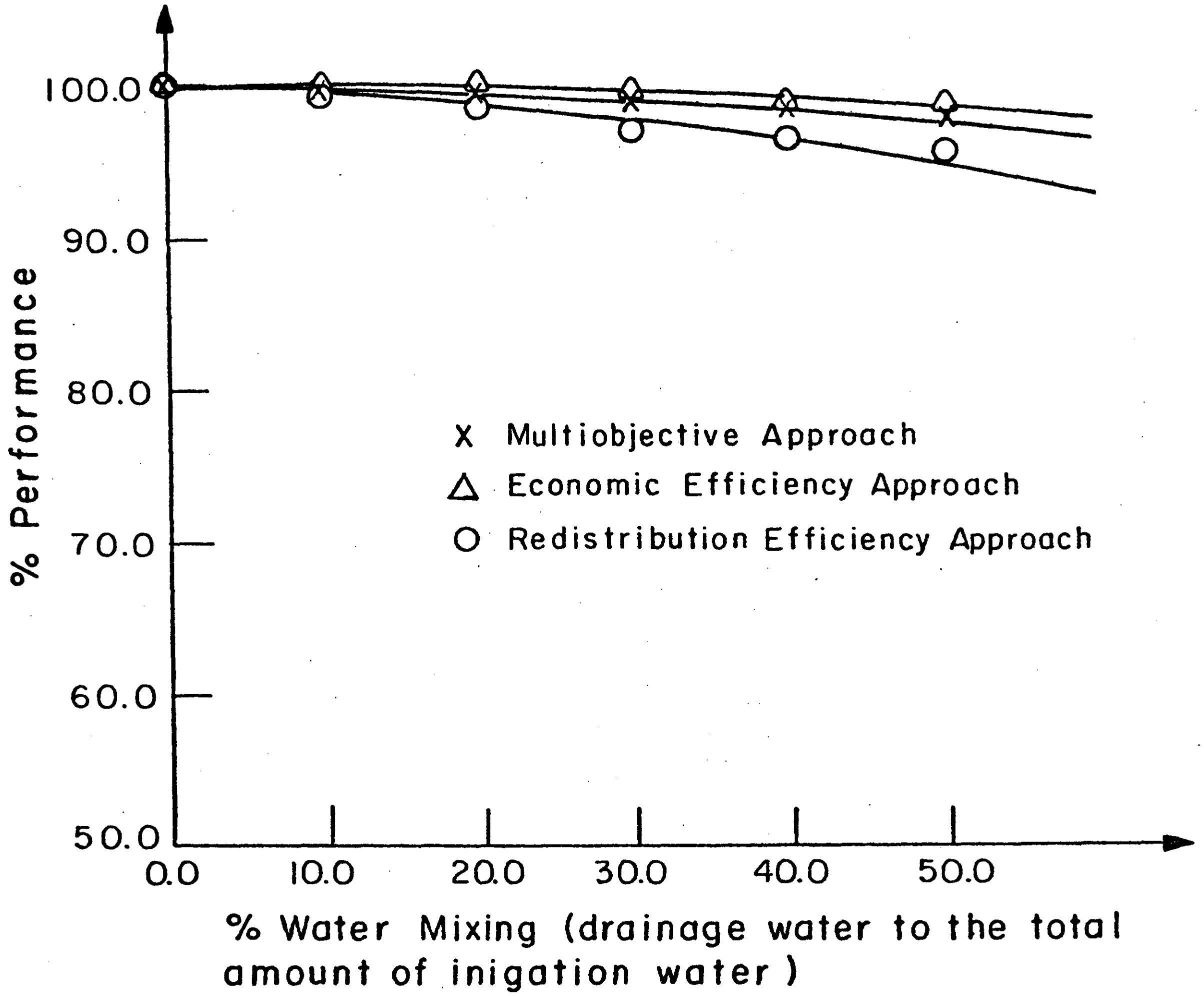


Figure 6-2 System Performance vs. Reduction in Irrigation Water Quality

Table 6-4. Water Mixing and Degradation of Irrigation Water Salinity

Mixing Ratio (Drainage Water to total irrigation water)	Resultant Irrigation Water Salinity (mmhos/cm)
0.1	0.56
0.2	0.72
0.3	0.88
0.4	1.04
0.5	1.20

when using the redistribution criterion looks very degradable under the unpleasant surprise in the irrigation water as shown in Figure (6-1). However, the operating decisions remain the same as the case when using the multi-criteria approach.

Irrigation Water Quality and System Performance

As explained before, changes in irrigation water quality can occur if for any political, economic or institutional reasons some of the irrigation water should be diverted for another activity (agricultural development, industries, municipals, etc.) in the sense that the drainage water can be recycled for irrigation and substitutes this water shortage. The salinity of the fresh and drainage water are taken here as 0.4 and 2.0 mmhos/cm, respectively. The effect of water mixing (fresh and drainage water at the intake of the main canal) on irrigation

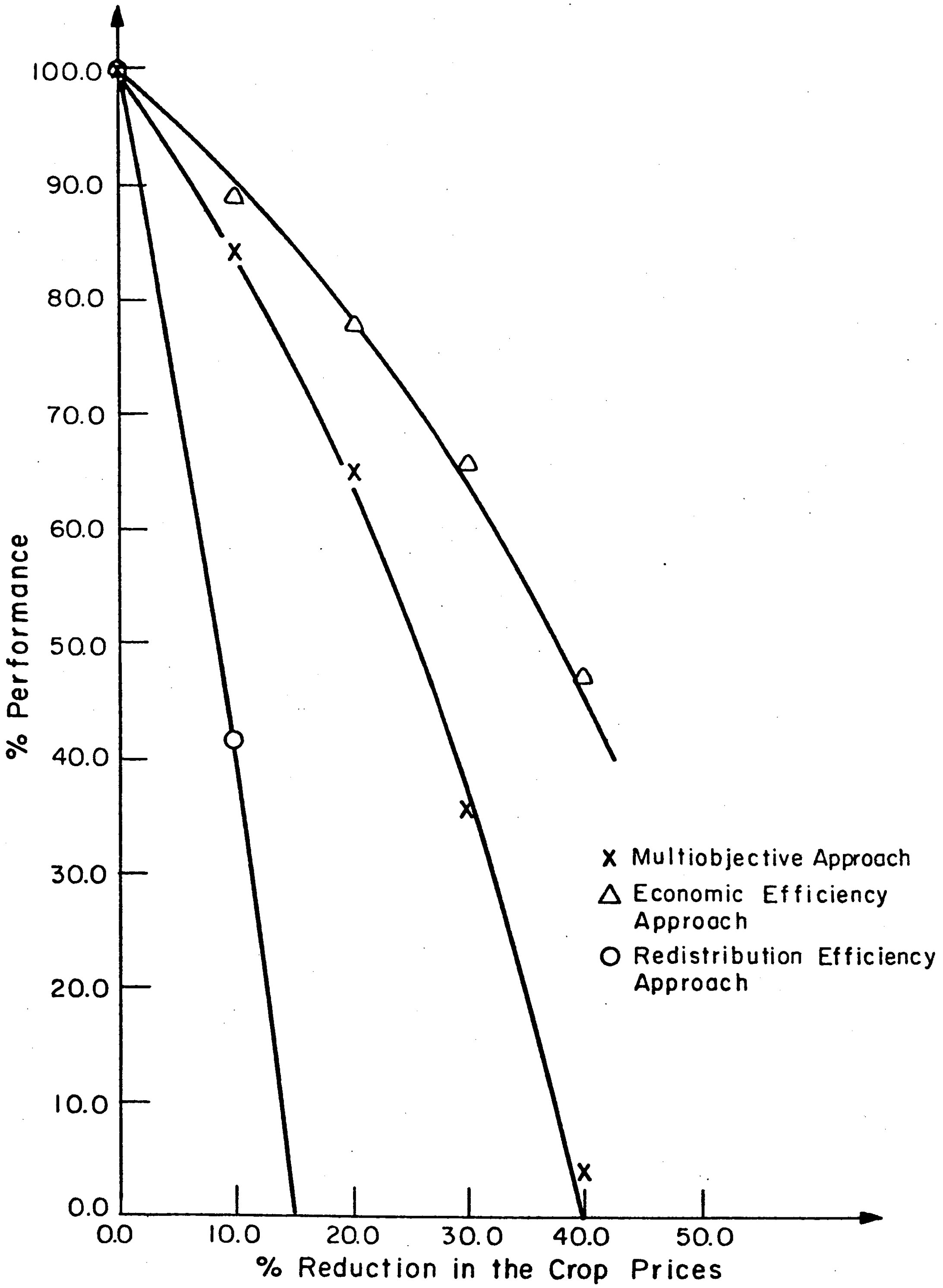


Figure 6-3 System Performance vs. Reduction in the Prices of the Crops

water salinity is given in Table (6-4). As shown in Figure (6-2), the system is very resilient to surprises in irrigation water quality. The degradation in water quality mainly affects beans which are very sensitive to salinity. As water salinity causes an increase in crop water requirements, rice, which has the highest water requirements, is selected in less areas in order to save water for other profitable crops. The production of the new lands from the various crops in the new areas under a wide range of changes in water salinity is given in Appendix B. When using the economic efficiency (redistribution) criterion alone in measuring the system performance, an overestimate (underestimate) of the system resilience is obtained (Figure (6.2)) because of the same reasons discussed above.

Prices of the Different Crops and System Performance

The performance model is solved for the case study for the different conditions of price reductions. As shown from Figure (6-3) the system design is nonresilient toward any decreases in the prices. The redistribution efficiency in particular is very sensitive to price changes. When using only the economic efficiency criterion, the system performance as explained before, is overestimated as shown in the figure. The cropping pattern in the new land under the different changes in the crop prices is given in Appendix B.

6.5 Resiliency Index

A regression analysis using orthogonal polynomials via RLFOR algorithm available in the International Mathematical and Statistical Libraries (IMSL) is carried out to determine functional relationships between the performance and changes in the input parameters. The percentage reduction in system performance in terms of the economic efficiency and redistribution criteria (ΔP) is computed in terms of the unpleasant percentage changes in irrigation water quantity (ΔX_1), irrigation water quality (ΔX_2) and prices (ΔX_3) as

$$\Delta P_1 = 0.2\Delta X_1 - 1.47\Delta X_1^2 - 0.1\Delta X_1^3 \qquad \Delta X_1 \le 0.0 \tag{6.18}$$

$$\Delta P_2 = 0.01\Delta X_2 - 0.066\Delta X_2^2 \qquad \Delta X_2 \le 0.0 \tag{6.19}$$

$$\Delta P_3 = 1.577\Delta X_3 - 0.858\Delta X_3^2 + 3.21\Delta X_3^3 \qquad \Delta X_3 \le 0.0 \tag{6.20}$$

The total derivative of these functions are computed as

$$\frac{d\Delta P_1}{d\Delta X_1} = 0.2 - 2.94\Delta X_1 - 0.3\ \Delta X_1^2 \qquad \Delta X_1 \le 0.0 \tag{6.21}$$

$$\frac{d\Delta P_2}{d\Delta X_2} = 0.01 - 0.132\Delta X_2 \qquad \Delta X_2 \le 0.0 \tag{6.22}$$

$$\frac{d\Delta P_3}{d\Delta X_3} = 1.577 - 1.716\ \Delta X_3 + 9.63\ \Delta X_3^2 \qquad \Delta X_3 \le 0.0 \tag{6.23}$$

These computations of the total derivatives are correct if and only if

$$\frac{d\Delta X_2}{d\Delta X_1} = \frac{d\Delta X_2}{d\Delta X_3} = \frac{d\Delta X_3}{d\Delta X_2} = \frac{d\Delta X_3}{d\Delta X_1} = \frac{d\Delta X_1}{d\Delta X_3} = 0.0 \tag{6.24}$$

where,

$\frac{d\Delta X_2}{d\Delta X_1} = 0.0$, means that the drainage water cannot be reused in irrigation to accommodate in drought conditions an unpleasant surprise in the water flow ($\frac{d\Delta X_2}{d\Delta X_1} \neq +ve$). In fact this assumption is valid in the real life where the construction period of a pumping station necessary for recycling the drainage water for irrigation is probably longer than the surprise duration. However, this cross derivative is not equal to zero in case of using a mixed water (fresh and drainage water) for irrigation. A reduction in the amount of fresh water will result in a reduction in irrigation water quality. The zero value of this cross derivative also means that a reduction in the fresh irrigation water would not cause an improvement in irrigation water quality which is correct in any case ($\frac{d\Delta X_2}{d\Delta X_1} \neq$ -ve).

$\frac{d\Delta X_3}{d\Delta X_1} = 0.0$, means that changes in the prices cannot be made to accommodate the unpleasant surprises in irrigation water flow. As shown before, a reduction in the quantity of irrigation water can cause a reduction in agricultural production. In larger investments (expansions) this decrease in the production will automatically cause an increase in prices. However, for the case study, this decrease in production probably would not cause an increase in market prices ($\frac{d\Delta X_3}{d\Delta X_1} \neq$ -ve). The possibility of having a decrease in the prices is not likely in such investments where the crops are not inferior (Giffen's Paradox) goods ($\frac{d\Delta X_3}{d\Delta X_1} \neq$ +ve)

$\frac{d\Delta X_1}{d\Delta X_3} = 0.0$, means that a reduction in the crop prices would not cause a decrease or an increase in the irrigation water. This assumption is not valid only if the farmers will cultivate less areas to reduce the production which will result in using less irrigation water. But as explained above, changes in the production of the case study can be assumed that are not large enough to affect the market prices. According to this assumption and assuming the farmers have rational behavior, the cross derivative should be equal to zero.

$\frac{d\Delta X_3}{d\Delta X_2} = 0.0$, this assumption means that degradation in irrigation water quality would not cause changes in the prices of the crops. This assumption is only valid for small investments like the case study explained above where the decrease in the agricultural production due to degradation of irrigation water quality would not affect the market prices.

$\frac{d\Delta X_2}{d\Delta X_3} = 0.0$, means that a reduction in the prices would not cause changes in the irrigation water quality. As explained before for the cross derivative $\frac{d\Delta X_1}{d\Delta X_3}$, this assumption is valid for the case study. However, there is a possibility that a reduction in the prices may make the decisions makers decide to divert some of the fresh water for other more profitable investments and reuse the drainage water for irrigation. In this case $\frac{d\Delta X_2}{d\Delta X_3}$ will be greater than zero.

Otherwise the total derivatives have to be computed as

$$\frac{d\Delta P_i}{d\Delta X_i} = \sum_j \frac{\partial \Delta P_i}{\partial \Delta X_j} \quad \frac{\partial \Delta X_j}{\partial \Delta X_i} \tag{6.25}$$

The above assumptions of zero cross derivatives between the input parameters do not represent a necessary step in the computations of the total derivatives. In case of having interactions between some of the planning prameters, it is not necessary to explicitly compute the values of the cross derivatives between these parameters. This can implicitly be taken into account in the computations of the total derivatives by including these interactions in the performance model formulation. This already has been done for the case when the interaction between irrigation water availability and its quality is considered (Table 6.4). Other interactions like those between the prices of the crops on the one hand, and quality and quantity of irrigation on the other hand, can easily be included in the model. This can simply be done by expressing crop prices in terms of the agricultural production (demand functions of the various crops). Similarly, the possibility of reusing the drainage water in accommodating a shortage in irrigation water can be included in the performance model to account for the interactions between quality and quantity of irrigation water. Then the gradients of the resultant system performance will implicitly account for the values of the cross derivatives. In summary, the above assumptions of zero cross derivatives between

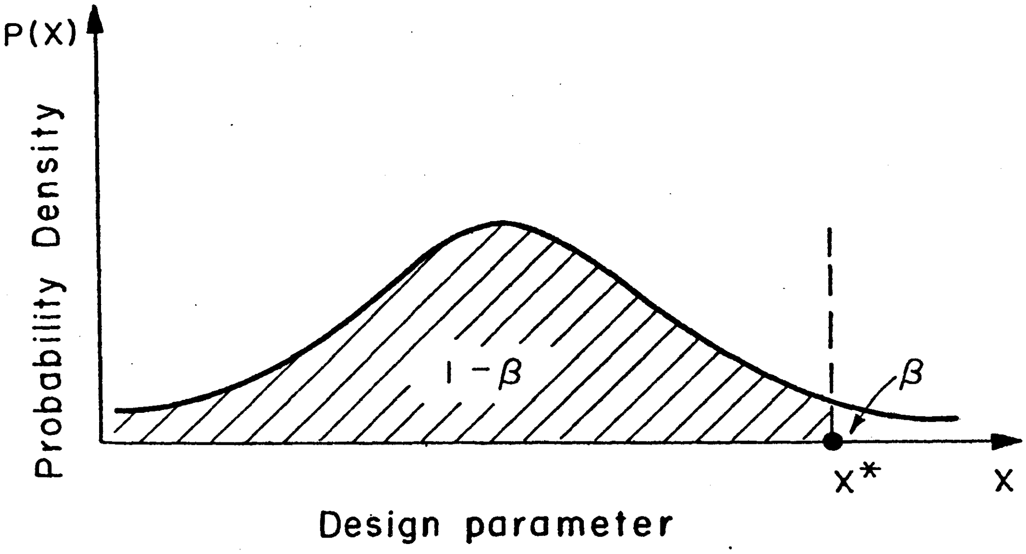


Figure 6-4 Selection of the Design Parameters Based on the Desired Confidence Level

the input parameters -- if they are valid -- can facilitate the computations of the total derivatives, but they are not essential for such computations.

The question now is at what size of surprises in the input parameters we should measure the gradients of the system performance with respect to these surprises? As shown in Equations (6.21), (6.22) and (6.23), the gradients are functions in the changes of the input parameters. By measuring the gradients of system performance at particular changes in the input parameters, the performance degradation rate of the system, whenever it is exposed to these particular changes, will be obtained. The second derivative may be useful in giving an insight on the rate of change of the performance gradients. Unfortunately, they also appear as functions in the size of the surprises.

Usually in real-life problems the engineers select the value X^* to the design parameter X which achieves a desired confidence level $(1-\beta)$ as shown in Figure (6-4). Therefore, there is always a risk with a small probability (β) that parameter X can take a value larger than X^* which is used for design. In this research we are trying to study the system performance under unpleasant changes in the planning parameters $\underline{X}$ (i.e. when $\underline{X} > \underline{X}^*$). Having the normalized probability distribution (this can be done by normalizing the area to the right of $\underline{X}^*$) to the unpleasant surprises in the parameters $\underline{X}$, the probability distribution of degradation rate of system performance $(\frac{d\Delta P}{d\Delta X})$ can be derived. However, we will only be using here the first and second moments of the distribution. In order to determine these moments the probability density functions of the unpleasant surprises in irrigation water quantity, irrigation water quality and crop prices are assumed as given in Equations (6-26), (6-27), and (6-28), respectively.

$$P(\Delta X_1) = 4.0 + 8\Delta X_1 \qquad -0.5 \leq X_1 \leq 0.0 \qquad (6.26)$$

$$P(\Delta X_2) = 2.0 \qquad -0.5 \leq X_2 \leq 0.0 \qquad (6.27)$$

$$P(\Delta X_3) = 5.0 + 12.5\Delta X_3 \qquad -0.4 \leq X_3 \leq 0.0 \qquad (6.28)$$

The resiliency Index (RI) for a system design as explained above can be computed in terms of the total derivatives (Fiering, 1982a) as

$$RI = \sum_j \beta_j \frac{dP}{dX_j} \qquad (6.29)$$

However, it is preferable to express the total derivatives in percentage terms (this is in order to reach a unique definition of the resilient system designs, as will be shown in the next section) as:

$$RI = \sum_j \beta_j \frac{dP/P^\circ}{dX_j/X_j^\circ} \qquad (6.30)$$

or

$$RI = \sum_j \beta_j \frac{d\Delta P_j}{d\Delta X_j} \qquad (6\text{-}31)$$

where, $P/P^\circ = 1.0 - \Delta P$ (6.32)

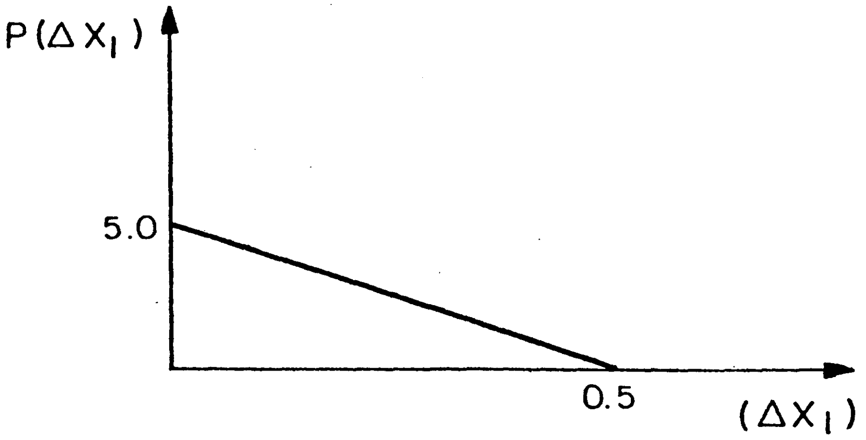
$X_j/X_j^\circ = 1.0 - \Delta X_j$ (6.33)

P° = performance of the system under no surprises in the input parameters

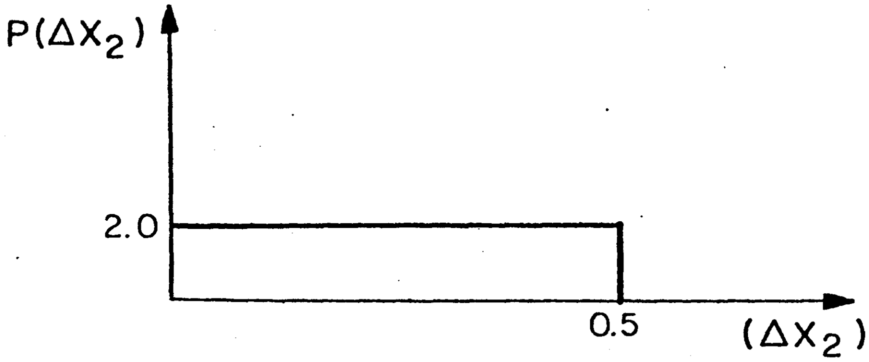
P = performance of the system under a surprise ΔX_j in the input parameter

X_j° = the value of the input parameter $\underline{j}$ under no surprises.

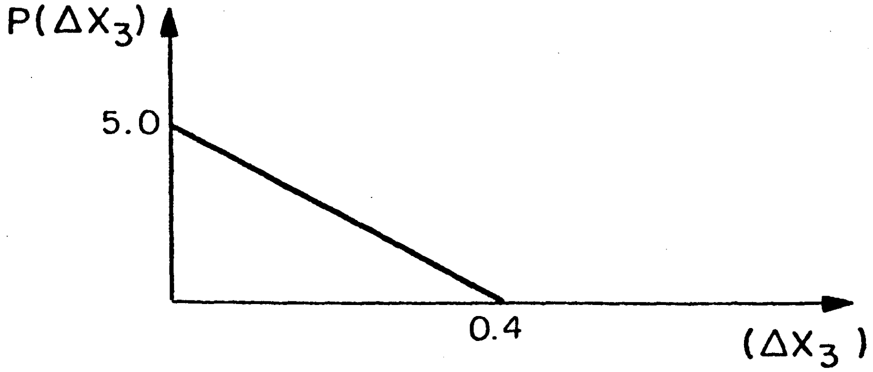
From Equation (6.31) the expected value and the variance of RI can be computed as



a. Probability Density Function of ΔX_1



b. Probability Density Function of ΔX_2



c. Probability Density Function of ΔX_3

Figure 6-5 Probability Distributions of the Changes in the Input Parameters

$$E[RI] = \sum_{j} \beta_j \, E[\frac{d\Delta P_j}{d\Delta X_j}] \qquad (6.34)$$

$$Var.[RI] = \sum_{j} \beta_j^2 \, Var.[\frac{d\Delta P_j}{d\Delta X_j}] \qquad (6.35)$$

The total derivatives of the system performance at the design values ($\Delta X = 0.0$) as well as their expected values are computed as shown in Table (6-6). These derivatives are used in computing the value of the resiliency index at the design values (Equation 6.31) and the expected resiliency index (Equation 6.34). The expected value of svstem resiliency (0.85) is found to be higher than the deterministic value (0.36). This is simply because the determinsitic value is based on measuring the total derivatives at ΔX=0.0, which are relatively small in comparison to the values at $\Delta X \leq 0.0$. On the other hand, the expected value takes into account all possible values of the gradients over the whole range of possible changes in the input parameters. Therefore, the expected value has to be larger than the deterministic one at the present conditions. As will be shown in the next chapter, the deterministic measure of the resiliency index at no changes in the planning parameters can be a misleading one, particularly in the systems which are resilient toward little surprises and very brittle toward the larger ones. The variance of the resiliency index is computed and is found equal to 0.009 which is really small compared to the expected value (0.85). The use of the two moments of the resiliency index ix comparing various alternatives will be shown in the next chapter

Table 6-5. Risk in the Input Parameters

Input Parameter	Risk (β)	Weight(w_j)
Irrigation water quantity	0.1	0.167
Irrigation water quality	0.4	0.666
Prices	0.1	0.167

Table 6-6. Total Derivatives and Resiliency of the case Study

Approach	$\frac{d\Delta P_1}{d\Delta X_1}$	$\frac{d\Delta P_2}{d\Delta X}$	$\frac{d\Delta P_3}{d\Delta X_3}$	RI
Measurements at the design values	0.2	0.01	1.577	0.36
Expected values	0.566	0.043	4.378	0.853

6.6 Resiliency Definition

After computing the deterministic or the expected value of the resiliency index, the next step is to judge the system design as a resilient or non-resilient one. Two values for the resiliency index can easily be interpreted. The first is when RI=0.0 which means that the system is perfectly resilient. The second one is when RI = $\propto$ which means that the system is perfectly brittle. Now the question is: How can we interpret the RI values which lie between these two limits? The resiliency index gives the ratio of the percentage degradation of a system performance to the percentage degradation of the planning parameters. Then, if this ratio is equal to one (RI=1.0) for a system design, the percentage degradation of the system performace is equal to the percentage degradation of the planning parameters. This system design can be thought of as neither resilient nor brittle. But if RI<1.0. the system design can be thought of as a resilient one. This is because the system has the redundancies to accommodate a part (or the whole) of the surprises in the planning parameter. In case of having RI>1.0, the system design can be judged as a brittle one. This is because the system degrades more rapidly than the planning parameters themselves. More classification to the system resilience (very resilient, fairly resilient, etc.) within the region of $0.0 \leq RI < 1$ is really dependent on the type of problem we are dealing with and type of alternate plans available. These interpretations of the resiliency index can lead us to a new and more precise definition of a system resiliency.

> "A resilient system design is the system whose percentage performance degradation due to unpleasant surprises in the planning parameters is less than the percentage degradation of the planning parameters themselves."

6.7 Summary

The performance of agricultural systems under the uncertainty inherent in the planning parameters is investigated through a multicriteria mathematical optimization model. Two criteria are used. The first is maximum net-benefit criterion. The second is income redistribution criterion in terms of maximum farmers' net-return from the investment. The model is used in measuring the performance of the case study under wide range of unpleasant surprises in the planning parameters. The output is used in deriving functional relationships between the performance of the case study and the unpleasant changes in the planning parameters. A resiliency index in terms of the total derivatives of these functions is derived in a probabilistic, as well as, deterministic, framework. This resiliency index leads to, for the first time, a unique definition of the resilient system design.

CHAPTER 7

THE RESILIENCY CRITERION AND ALTERNATIVE PLANNING SCHEMES

7.1 Introduction

The multi-criteria performance model presented in Chapter 6 is applied here to measure the performance of three alternate plans for the case study under various conditions of the input parameters (irrigation water quantity, irrigation water quality and prices of the various crops). These alternatives are the solution of the scheduling model to the hypothetical agricultrual expansion when using fresh water, saline water and recycled drainage water for irrigation, respectively. The resiliency of these plans are computed using the total derivative method in a deterministic and probabilistic framework. The deterministic index is found inefficient and misleading in distinguishing the most resilient designs. When using the probabilistic measure in terms of the first (mean) and second (variance) moments of the resiliency index, a conflict between the first and second alternatives is found. The first alternative has higher expected resilience but with larger variance than the second alternative. In order to investigate this conflict, the probability distributions of the resiliency indices of the two alternatives are generated. It is found that the first alternative is more resilient up to 90% confidence levels. For higher confidence levels, the second alternative is found to dominate the first one. More investigations on this conflict will be carried out in the next chapter.

7.2 Performance of the Planning Alternatives

The performance model is used here to measure the performance of three alternative plans for the case study. These plans are the solutions of the scheduling model for the case study under different conditions of irrigation water quality (Chapters 2 and 3). All of the alternatives achieve the same agricultural production level (Table (2-3)) from the various crops. They also achieve the same redistribution decisions of giving 10,000 farmers the opportunity to own the new land and gain a raise in income on the order of $600/farmer/year (Chapter 5). The first plan is the solution of the case study when fresh water is available for irrigation. The capacities of the irrigation and drainage canals are listed in Table (7-1) and (7-2), respectively. The distribution of land among the farmers and the per acre annual payments which achieve the redistribution decisions for this alternative are given in Table (5-3). Size of the developed land in this plan is introduced in Table (7-3).

The second alternative is the solution of the case study when using saline water for irrigation. The water salinity is taken as 1.6 mmhos in both the summer and the winter seasons. Irrigation water salinity, as shown in Chapter 3 causes an increase in the crop water requirements and a decrease in the yields of the crops. This results in an increase in the capacities of the irrigation and drainage canals compared to the first alternative as shown in Tables (7-1) and (7-2), respectively. Also an increase in the size of the cultivated areas to achieve the agricultural requirements is found (Table (7-3)). The size of land per farmer and per acre annual payment at the different

Table 7-1. Capacities of the Irrigation Canals

Canal	Capacities (m^3/sec) First Alternative	 Second Alternative	 Third Alternative
6-7	35.10	38.90	32.4
7-1	27.10	29.80	25.4
7-8	7.40	8.30	5.2
8-2	4.00	4.45	2.40
8-9	3.30	3.80	2.8
9-3	2.90	3.10	5.10
9-10	0.40	0.70	2.7
10-4	0.40	0.70	2.60
10-5	0.00	0.00	0.00
1-5	5.50	6.10	3.8
9*	--	--	7.2

*Mixing Pump Station

Table 7-2. Capacities of the Drainage Canals

Drain	Capacities (m^3/sec) First Alternative	Second Alternative	Third Alternative
2-9	1.20	1.32	0.70
1-9	6.40	7.02	6.40
3-9	0.90	0.91	1.50
4-10	0.10	0.20	0.80
5-10	1.60	1.80	1.10
9-10	8.60	9.34	1.50

Table 7-3. Size of the Developed Land

Area No.	Sizes (acres) First Alternative	Second Alternative	Third Alternative
1	18,000	18,000	18,000
2	18,000	18,000	11,194
3	10,000	10,000	9,980
4	12,000	12,000	12,000
5	1,380	2,368	8,206
Total	59,380	60,386	59,380

new areas are introduced in Table (5-3). In order to apply the performance model to this alternative, two constraint sets are added to account for the effect of the water salinity on the agricultural practices. The first set is to account for the salinity effect on crops' yields (Equation (7.1)). The second set is to compute the irrigation requirements of the crops from the saline water as shown in Equation (7.2).

$$Y^s_{i,p} = (100 - B(P,s)(1.5\ ECW^s_i - A(P,S))\overline{Y}^s_{i,p} \qquad \forall_{i,p,s} \qquad (7.1)$$

$$W^s_{i,p} = (1 + LR^s_i\ (ECW^s_i))\ \overline{W}^s_{i,p} \qquad \forall_{i,p,s} \qquad (7.2)$$

where,

$Y^s_{i,p}$ = yield of crop P during season s at area i

$B(P,s)$ = percent yield decrease of crop P during season s per unit salinity increase beyond threshold (Table (3-1))

$A(P,s)$ = salinity threshold of crop P during season s in mmhos/cm (Table (3-1)).

ECW^s_i = salinity of irrigation water at area i during season s

$\overline{Y}^s_{i,p}$ = yield of crop P during season s at area i when using fresh water for irrigation (Table (2-4))

$W^s_{i,p}$ = water requirements of crop P at area i during season s

LR^s_i = required leaching fraction at area i during season s

$\overline{W}^s_{i,p}$ = water requirements of crop P at area i during season s when using fresh water for irrigation (Table (2-4))

The third plan is the solution of the case study via the scheduling model when recycling the drainage water for irrigation is allowed (Chapter 3). The capacities of the irrigation and drainage canals in this plan are given in Tables (7-1) and (7-2), respectively. Land allocation among the farmers and land payments are listed in Table (5-3). Size of the developed areas are introduced in Table (7-3).

Four more constraint sets have to be included in the performance model to account for the possibility of drainage water recycling. The first set consists of salt conservation equations to the drainage network. This set is to determine the drainage water salinity at each node of the network. This constraint set can be written as:

$$\sum_{i=1}^{M+N-1} (ECWD_i^s\ fd_{i,j}^s + ECWLD_{i,j}^s\ LD_{i,j}^s(\ell d_{i,j})) + ECWdr_j^s\ dr_j^s(d_j^s)$$

$$- ECWD_j^s \sum_{\substack{\ell=1 \\ \ell\neq j}}^{M+N-1} fd_{j,\ell}^s = 0.0 \qquad \forall_{j,s} \qquad (7.3)$$

where

$ECWD_i^s$ = drainage water salinity at node i during season s

$LD_{i,j}^s$ = seepage water to drain (i,j) during season s

$ECWLD_{i,j}^s$ = salinity of seepage water to drain (i,j) during season s

$fd_{i,j}^s$ = amount of water flow in drain (i,j) during season s

dr_j^s = amount of drainage water at area i during season s

d_j^s = amount of irrigation water allocated to area i during season s

The second set is to compute the amount of recycled drainage water at each mixing station (one mixing station is only considered in the case study at node (9)). This set can be written as

$$\sum_{i=1}^{M+N-1} (ECWD_i^s\, rWD_{i,j}^s + ECW_{i,j}^s\, f_{i,j}^s(1-L_{i,j}^s(f_{i,j}^s, \ell_{i,j}))) - ECW_j^s \sum_{\substack{\ell=1\\ \ell\neq i}}^{M+N-1} f_{j,\ell}^s$$

$$- ECW_j\, d_j^s = 0.0 \qquad \forall_{j,s} \qquad (7.4)$$

where $rWD_{i,j}^s$ is the amount of recycled water from drain (i,J) during season s. In this case, the decision variables are the amount of recycled water, salinity of the mixed water (ECW_j^s) and the amount of mixed water ($f_{j,\ell}^s + d_j^s$). The third constraint set is to insure that the recycled drainage water from a drain is less than the available water at this drain as shown in Equation (7.5). The last set is to insure that at each mixing station the amount of recycled water is less than the existing capacity of pumping facility (Equation (7.6)).

$$rWD_{i,j}^s - fd_{i,j}^s \leq 0.0 \qquad \forall_{i,j,s} \qquad (7.5)$$

$$\sum_{i=1}^{M+N-1} rWD_{i,j}^s - CrWD_j \leq 0.0 \qquad \forall_{j,s} \qquad (7.6)$$

where $CrWD_j$ is the capacity of mixing station j.

In addition to the above constraints, the flow balance constraints for both irrigation and drainage networks (Equations (6.8) and (6.9)) have to modifed as shown in Equations (6.8') and (6.9'), and the non-negativity constraints set has to be expanded to insure the non-negativity of $rWD_{i,j}^s$ for all values of i, j, and s.

$$\sum_{i=1}^{N+M-1} f_{i,j}^{s} \left(1 - L_{i,j}^{s} \left(\ell_{i,j}, f_{i,j}^{s}\right)\right) + \sum_{i=1}^{N+M-1} rWD_{i,j}^{s} - \sum_{K=1}^{N+M-1} f_{j,K}^{s}$$

$$-d_{j}^{s} = 0.0 \qquad \forall_{j,s} \qquad (6.8')$$

$$\sum_{i=1}^{N+M=1} fd_{i,j}^{s} \left(1+LD_{i,j}^{s}(\ell d_{i,j}\right) - \sum_{i=1}^{N+M-1} rWD_{i,j}^{s} - \sum_{i=1}^{N+M-1} rWD_{i,j}^{s} - \sum_{\substack{K=1 \\ K \neq j}}^{N+M-1} fd_{j,K}^{s}$$

$$+dr_{j}^{s}\left(d_{j}^{s}\right) = 0.0 \qquad \forall_{j,s} \qquad (6.9')$$

Nonlinearity Problem

Linear programming can be used for solving the performance model to the first two planning alternatives where the objective function as well as the constraint sets are linear. Unfortunately this is not the case with the third alternative where two contraint sets are nonlinear. These nonlinearities are due to the multiplication of two decision sets (ECW_{j}^{s} and $f_{j,\ell}^{s}$ in Equation (7.4) and $ECWD_{j}^{s}$ and $fd_{j,\ell}^{s}$ in Equation 7.3)) in each other. As shown in Chapter 4, a simple enunmeration procedure can be used for solving this nonlinearity problem. This enumeration procedure along with a linear programming algorithm are used in solving the performance model for the third plan as will be shown next.

7.3 Solutions of the Performance Model for the Planning Alternatives

The linear programming package available at M.I.T. (the SESAME Code) is used for solving the model for the first and second alternate plans (120 constraints) for various conditions of the input parameters. The computation time (CPU) for each run was about 10 to

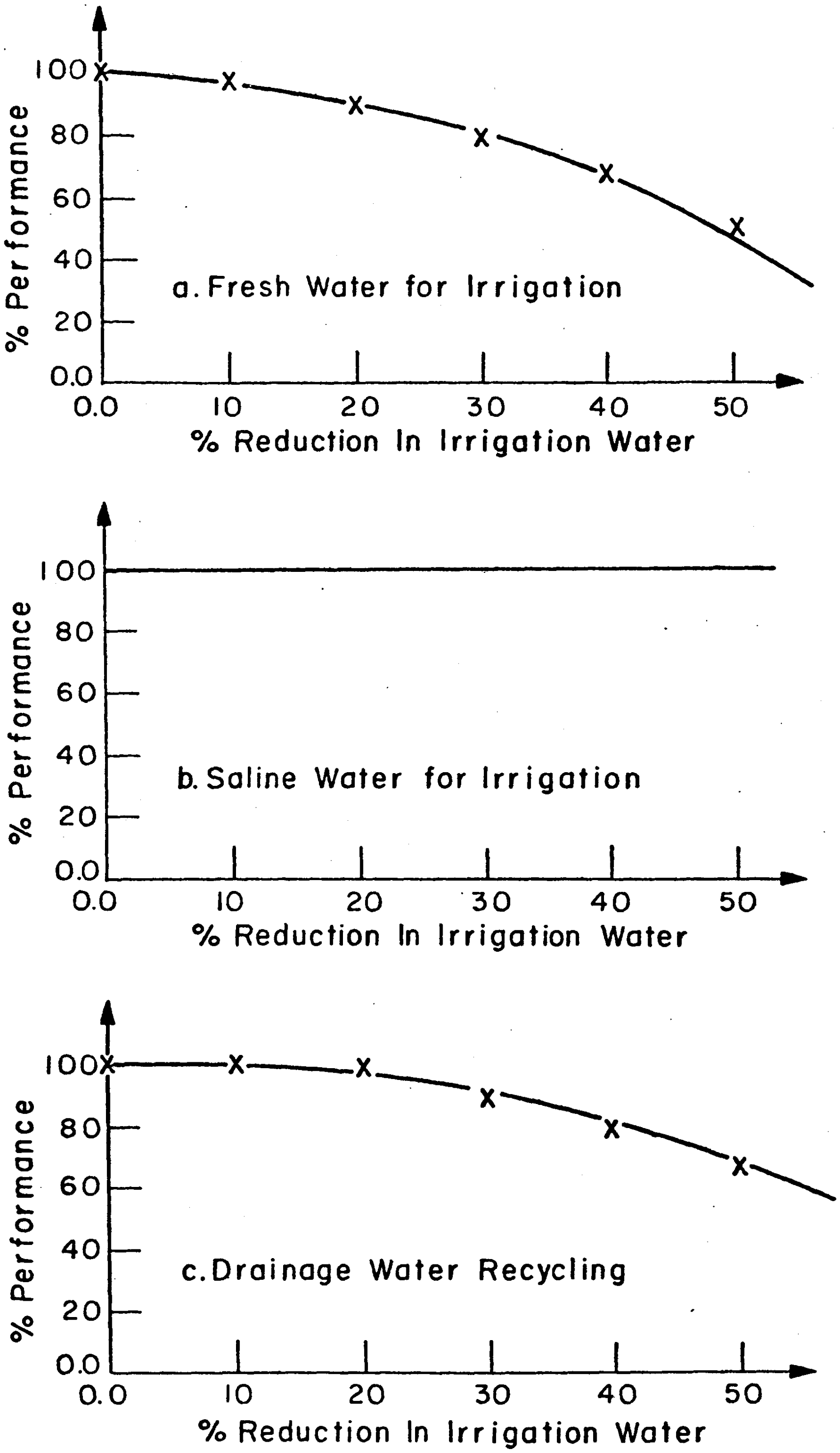


Figure 7-1 Performance of the Planning Alternatives vs. Irrigation Water Availability

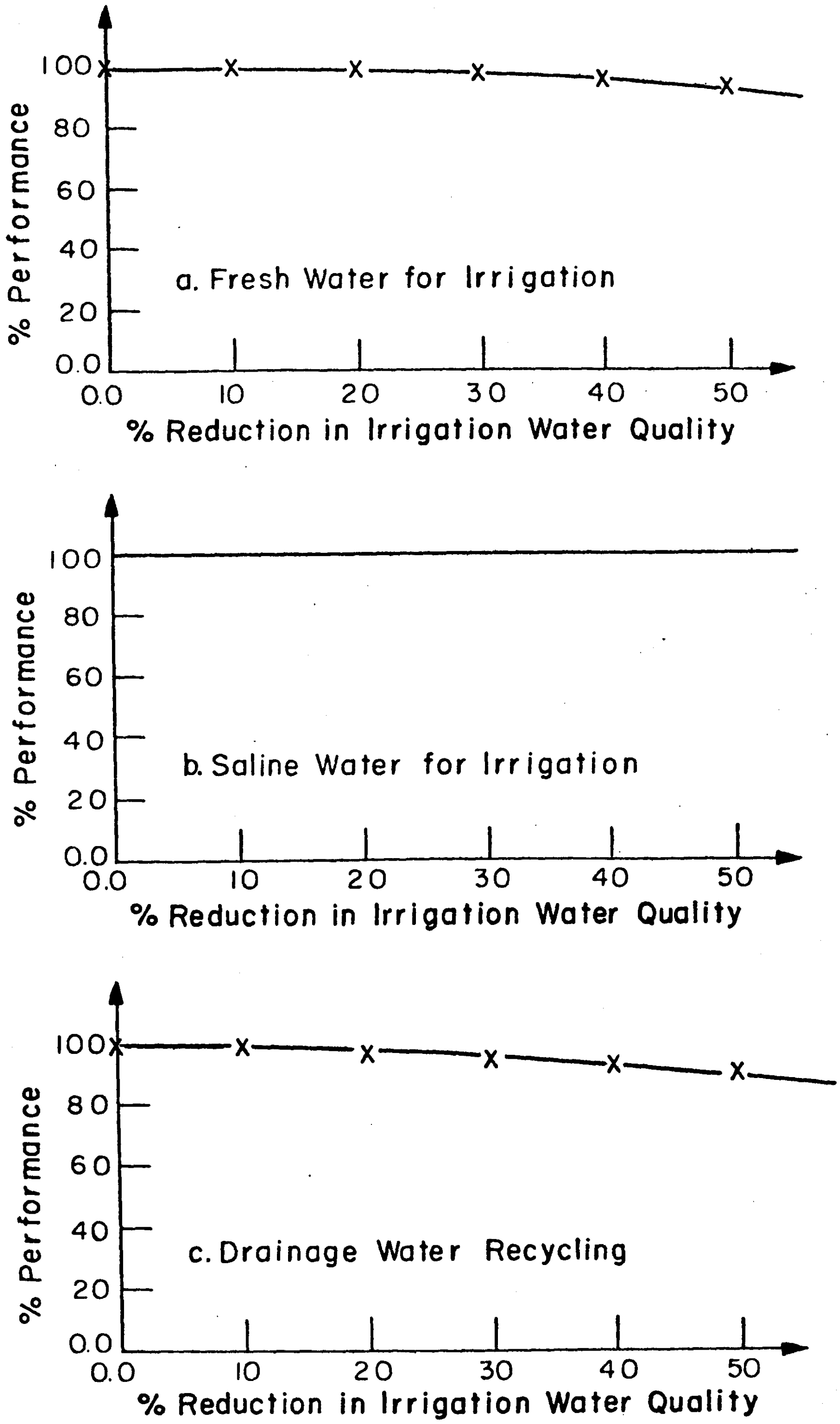


Figure 7-2 Performance of the Planning Alternatives vs. Degradation of Irrigation Water Quality

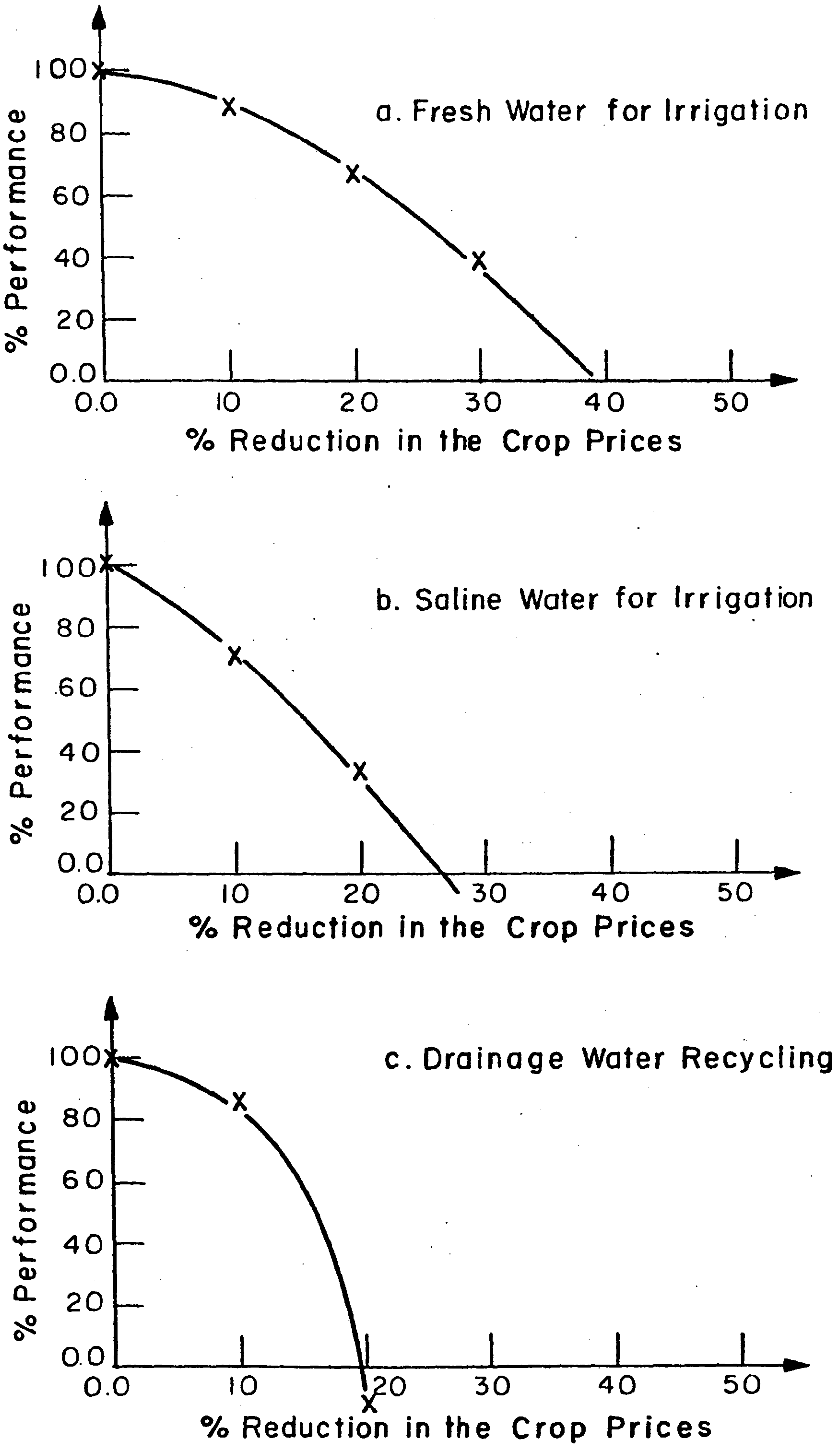


Figure 7-3 Performance of the Planning Alternatives vs. Reduction in Crop Prices

15 seconds on an IBM 370, But when using the enumerations procedure along with the linear programming algorithm for solving the model to the third alternative (140 constraints), the CPU time was about 70 seconds for each run. The solutions are presented in Figures (7-1), (7-2) and (7-3).

As shown in Figure (7-1), the second design is the most resilient one toward the unpleasant surprises in irrigation water availability (100% resiliency). This is due to the overbuilding to use the available saline water for irrigation and to be to a high degree independent of fresh water availability. The third design is like the second alternative where the recycled drainage water gives the system a capability of accommodating to some degree the shortage in water supply. On the other hand, the first alternative, in which only fresh water is used for irrigation, is found to be the least resilient design. This is due to the absence of any redundancy in the design rather than the reallocation of the irrigation water among the crops to accommodate surprise in irrigation water quantity.

Figure (7-2) indicates that the agricultural systems are not that sensitive to the degradation of irrigation water quality. The second alternative which is designed on the basis of using a low-quality water for irrigation, naturally is found insensitive at all levels to the water quality degradation. The first design is found as the second resilient alternative. The third design which allows the reuse of the drainage water in the irrigation practices, is the most sensitive alternative to water quality degradation. This is because the degradation in irrigation water quality causes a degradation in drainage water quality and their combined effect on agricultural production is more severe than the separate effect of the low-quality irrigation water in the first design alternative.

All of the three alternatives are found to be brittle to the reductions in crops' prices (Figure (7-3)). The third alternative performs reasonably well only when price reductions are small (10%). With more reduction in the prices, the system performance degrades very rapidly. This is mainly due to the failure of the redistribution objectives, particularly in the areas where drainage water is recycled for irrigation. In these areas, the agricultural return is relatively low and the reduction in prices then causes the agricultural revenues to be less than the annual payments. This results in subsidizing the farmers in these areas from the government return which consequently greatly reduces the economic efficiency of the investment. The second alternative is also found non resilient to the reductions in crops' prices. This is due to the same reason of low agricultural return of the land. However, it performs little better than the third design because the whole land is subjected to the same water quality conditions, and the income of the land is then more equally distributed among the farmers than in the case of the third design. The first design has the advantage on the second one of a higher land return. Therefore, it is found to be the best of the three alternatives in accommodating surprises in the crop prices.

7.4 Resiliency of the Planning Alternatives

The RLFOR algorithm available in the International Mathematical and Statistical Libraries (IMSL) is used to determine functional relationships between performance of the three alternatives (P_1, P_2 and P_3, respectively) and the changes in the input parameters (irrigation water quantity (ΔX_1), irrigation water quality (ΔX_2) and Prices (ΔX_3)). These functions are listed in Table (7-4). The total derivatives of these functions with respect to changes in the input parameters are computed as shown in the table. The probability distribution of the changes in the input parameters and the occurence probabilities of these changes are assumed as presented in Table (7-5). The values of the total derivatives at the design values ($\underline{\Delta X} = \underline{0.0}$), and expected values of the total derivatives and their variances are introduced in Table (7-6). The deterministic resiliency index as well as the expected resiliency and its variance for the various alternatives are computed (Table (7-7)).

The deterministic measure of the resiliency index indicates that the first alternative is the most resilient design, the third alternative is the second resilient design and the second alternative is the least resilient one. On the other hand, when the resiliency index is taken as a random variable, the expected value measure gives the same conclusion that the first alternative is the most resilient one. But it indicates that the second alternative is the second resilient system while the third alternative is an inferior one. This conflict between the deterministic and expected values of

Table 7-4. Performance of the Alternate Plans in Terms of Changes in the Input Parameters

Alternative	Performance (ΔX_1, ΔX_2, and $\Delta X_3 \leq 0.0$)	Total Derivatives
First alternative (using only fresh water for irrigation)	$\Delta P_{11} = 0.32\Delta X_1 - 0.9\Delta X_1^2 + 0.93\Delta X_1^3$	$\frac{d\Delta P_{11}}{d\Delta X_1} = 0.32 - 1.8\Delta X_1 + 2.79\Delta X_1^2$
	$\Delta P_{12} = 0.024\Delta X_2 - 0.10\Delta X_2^2$	$\frac{d\Delta P_{12}}{d\Delta X_2} = 0.024 - 0.2\Delta X_2$
	$\Delta P_{13} = 1.03\Delta X_3 - 3.38\Delta X_3^2$	$\frac{d\Delta P_{13}}{d\Delta X_3} = 1.03 - 6.76\Delta X_3$
Second alternative (using only saline water for irrigation)		$\frac{d\Delta P_{21}}{d\Delta X_1} = \frac{d\Delta P_{22}}{d\Delta X_2} = 0.0$
	$\Delta P_{23} = 2.79\Delta X_3 - 2.23\Delta X_3^2$	$\frac{d\Delta P_{23}}{d\Delta X_3} = 2.79 - 4.46\Delta X_3$
Third alternative (recylcing drainage water for irrigation)	$\Delta P_{31} = -0.18\Delta X_1 - 1.68\Delta X_1^2$	$\frac{d\Delta P_{31}}{d\Delta X_0} = -0.18 - 2.36\Delta X_1$
	$\Delta P_{32} = 0.082\Delta X_2 - 0.04\Delta X_2^2$	$\frac{d\Delta P_{32}}{d\Delta X_2} = 0.082 - 0.08\Delta X_2$
	$\Delta P_{33} = 2.08\Delta X_3 - 14.08\Delta X_3^2$	$\frac{d\Delta P_{33}}{d\Delta X_3} = 2.08 - 28.16\Delta X_3$

Table 7-5. Probability Distribution of Changes in the Input Parameters and Probability of Occurrence

Input Parameters	Probability Distribution of Surprises	Probability of Occurrence (β)
Quantity of Irrigation Water	$P(\Delta X_1)=4.0 + 8\Delta X_1$ $-0.5\leq\Delta X_1\leq 0.0$	0.1
Quality of Irrigation Water	$P(\Delta X_2)=2.0$ $-0.5 \leq X_2\leq 0.0$	0.4
Prices of Crops	$P(\Delta X_3) = 5.0+12.5\Delta X_3$ $-0.4\leq X_3\leq 0.0$	0.1

Table 7-6. The Design Values, Expected Values and Variances of the Total Derivatives of the Performance of the Planning Alternatives

Approach	$\frac{d\Delta P_{11}}{d\Delta X_1}$	$\frac{d\Delta P_{21}}{d\Delta X_1}$	$\frac{d\Delta P_{31}}{d\Delta X_1}$	$\frac{d\Delta P_{12}}{d\Delta X_2}$	$\frac{d\Delta P_{22}}{d\Delta X_2}$	$\frac{d\Delta P_{32}}{d\Delta X_2}$	$\frac{d\Delta P_{13}}{d\Delta X_3}$	$\frac{d\Delta P_{23}}{d\Delta X_3}$	$\frac{d\Delta P_{33}}{d\Delta X_3}$
Value at $\underline{\Delta X}=\underline{0.0}$	.32	0.0	-0.18	.024	0.0	.082	1.03	2.79	2.08
Expected Value	.738	0.0	0.214	.074	0.0	.102	1.936	3.388	5.853
Variance	.126	0.0	.079	.0008	0.0	.00013	.398	.173	6.899

Table 7-7. Deterministic Values, Expected Values and Variances of the Resiliency Index of the Planning Alternatives

Alternative	Deterministic RI ($\Delta \underline{X} = \underline{0.0}$)	Expected RI	Variance of RI
1	0.145	0.297	.0054
2	0.279	0.339	.0017
3	0.223	0.648	.070

the resiliency index is mainly due to the behavior of the third alternative toward the unpleasant surprises in the crop prices. For a little reduction in the prices, the system performance is fairly resilient. when the size of the price reduction increases, the performance very rapidly decreases as shown in Figure (7-3-C). Therefore when measuring the total derivative of the performance with respect to changes in the prices at design values ($\underline{\Delta X} = \underline{0.0}$), a relatively small value is obtained (Table (7-6)). This result in preferring the third alternative to the second one ($\frac{d\Delta P_{33}}{d\Delta X_3} = 2.08$ and $\frac{d\Delta P_{23}}{d\Delta X_3} = 2.79$). On the other hand, the expected value measure which is more realistic in reflecting the system behavior toward all possible sizes of the unpleasant surprises in the prices provides a larger value for the gradient of the third alternative. It prefers the second design to the third one ($E(\frac{dP_{33}}{d\Delta X_3})=5.853$, $E(\frac{dP_{23}}{d\Delta X_3}) = 3.388$). This result can lead us to the conclusion that the deterministic measure of the resiliency index is inadequate and probably misleading in such cases.

By using the first and second moments of the probability distributions of the resiliency index, the third design as shown in Table (7-7) can be distinguished as an inferior alternative. A conflict between the first and second alternatives is found. The first alternative has a smaller expected value of the resiliency index (higher resiliency) but with larger variance than the second alternative (Table (7-7)). The first two moments of the resiliency index distribution are not enough in this case to dominate one of these two alternatives as the most resilient design. More information about the probability density functions of the resiliency index of the second alternatives is needed. One way of solving this conflict is to generate the probability density functions of the resiliency indices. Then for a specified confidence level, the most resilient design can be distinguished. The density function of the first alternative is equal to the multiplication of the three distributions of ΔX_1,ΔX_2 and ΔX_3. This density function can only be generated numerically via a Monte Carlo simulation model. This procedure is carried out and the probability density function of the resiliency index of the first alternative is obtained as shown in Figure (7-4). On the other hand, the probability density function of the resiliency index of the second design can mathematically be derived in terms of the distribution of ΔX_3. From Table (7-4) and Table (7-5), the resiliency index of the second alternative (RI_2) can be written as

$$RI_2 = 0.279 - 0.446\, \Delta X_3 \qquad (7.7)$$

Then we have

$$f(RI_2) = f(\Delta X_3(RI_2)) \left| \frac{d\Delta X_3}{dRI_2} \right| \qquad (7.8)$$

where

$$f(\Delta X_3) = 5.0 + 12.5\, \Delta X_3 \qquad -0.4 \le \Delta X_3 \le 0.0 \qquad (7.9)$$

Then the probability density function of the resiliency index of the second alternative can be computed as

$$f(RI_2) = 28.74 - 62.832 RI_2 \qquad 0.279 \le RI_2 \le .4574 \qquad (7\text{-}10)$$

Table 7-8. A Resiliency Comparison Between the Planning Alternatives

	Resiliency Index (RI)		
Confidence Level	First Alternative	Second Alternative	Third Alternative
99%	0.497	0.439	0.988
95%	0.45	0.4175	0.9394
90%	0.3978	0.4006	0.8788
85%	0.3825	0.3879	0.8182
80%	0.3671	0.3722	0.7576

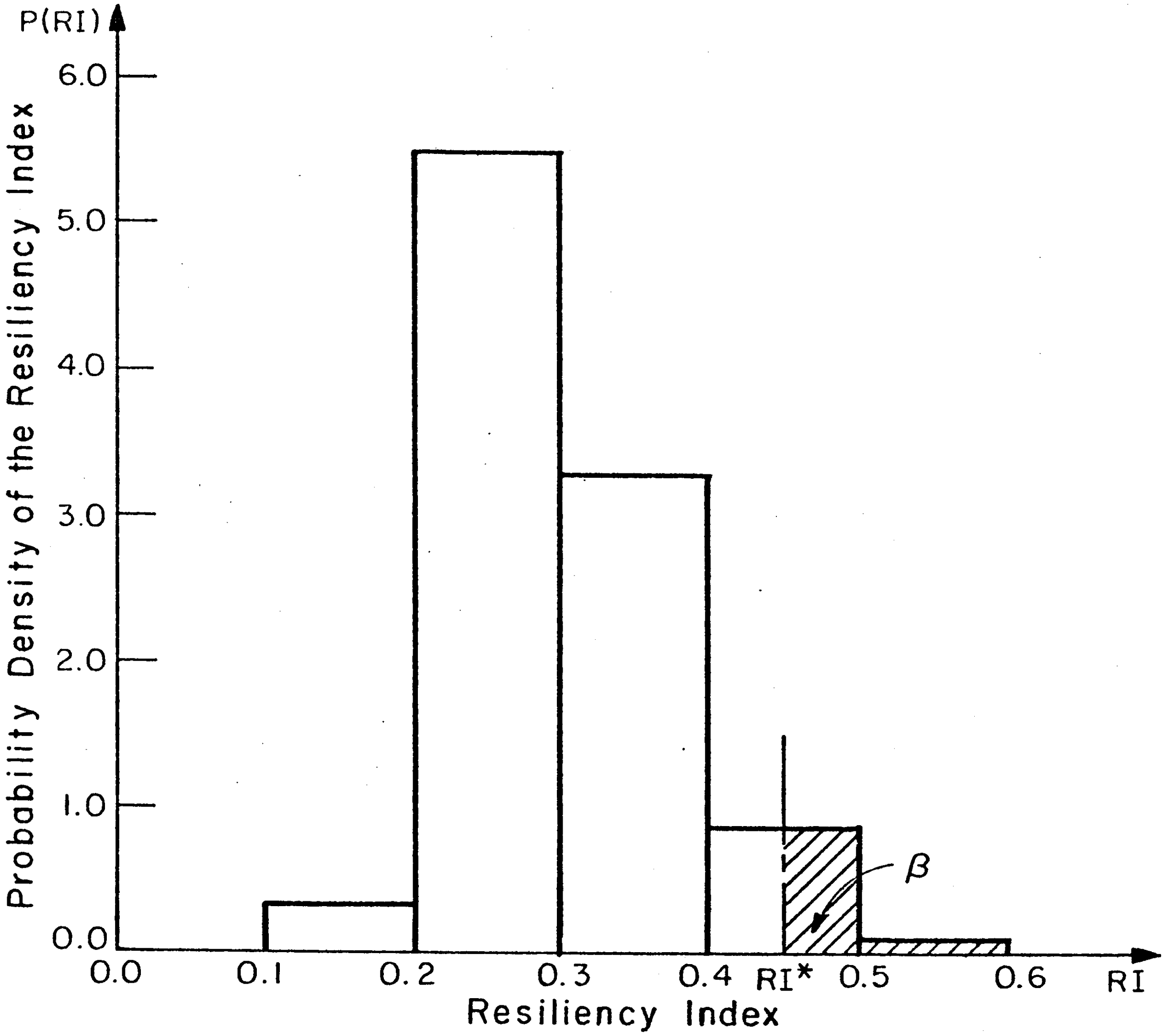


Figure 7-4 Probability Distribution of the Resiliency Index of the First Planning Alternative

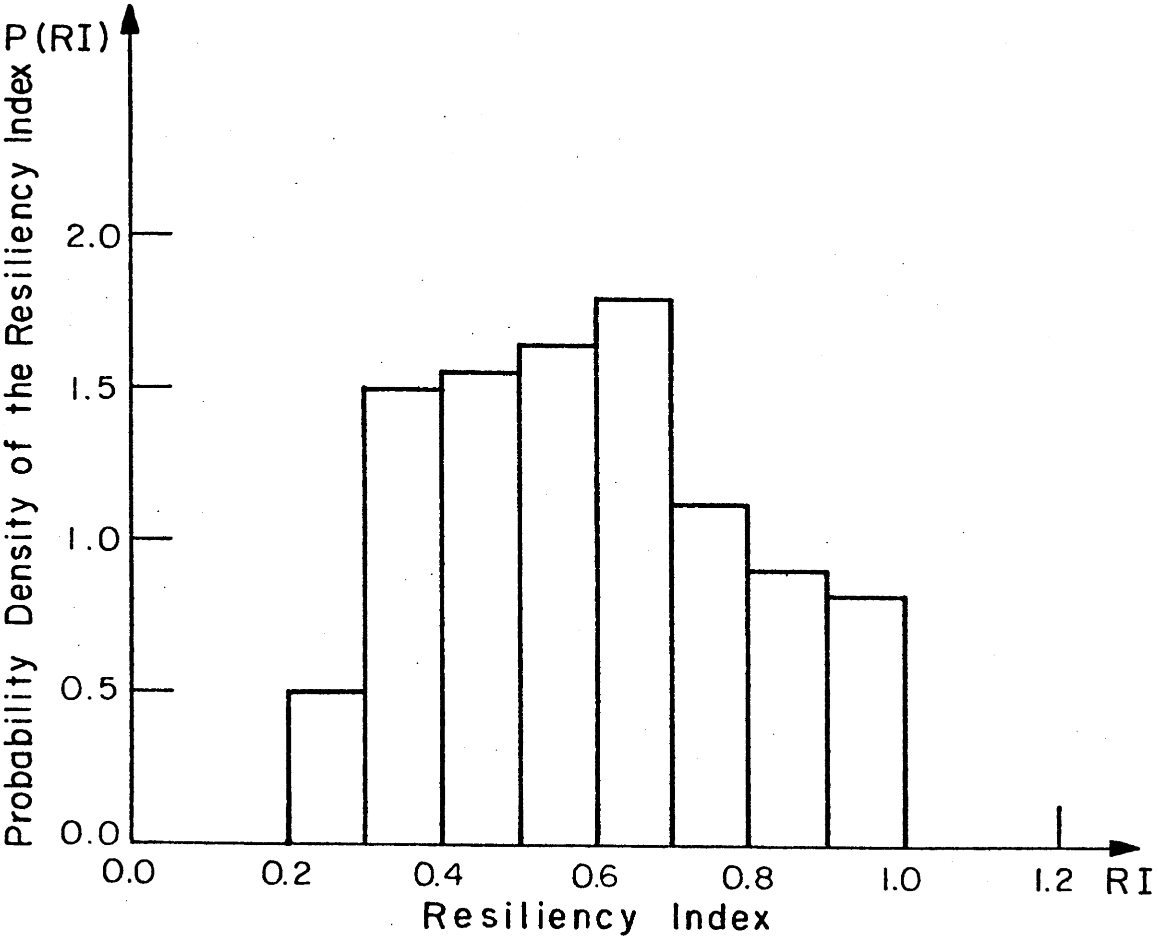


Figure 7-5 Probability Distribution of the Resiliency Index of the Third Planning Alternative

and the cumulative distribution can be determined as

$$F(RI_2) = -31.416\ RI_2^2 + 28.74\ RI_2 - 5.573 \qquad 0.279 \leq RI_2 \leq .4574 \qquad (7.11)$$

From Figure (7-4) and Equation (7.11), the most resilient design at a specified confidence level can be distinguished. The resiliency index for the three alternatives at different confidence levels is computed (Table (7-8)). It is found that the second design is the most resilient one ($RI_2 = 0.4175$) at 95% confidence level. However for lower confidence levels (90%, 85%, 80%, etc.) the first alternative dominates the second one. The selection procedure in such conflict is very difficult and it cannot be carried out without looking to the other design criteria (least cost and redistribution efficiency). It is the subject of the next chapter along with the conflict between the planning criteria.

CHAPTER 8

A COMPARISON BETWEEN AGRICULTURAL EXPANSION PLANNING ALTERNATIVES VIA THE ECONOMIC EFFICIENCY, INCOME REDISTRIBUTION AND RESILIENCY CRITERIA

8.1 Performance of Agricultural Expansion Planning Alternatives

As shown in Chapter 5, the return of agricultural expansion investment is allocated between the government for more beneficial investments to the society and the lower income people (landless farmers) for improving their income conditions. The allocated benefits to each party, as explained in Chapter 4, should be according to the tradeoff of the society between consumption and investment. If the investment is more valuable than consumption, then the government should get a higher portion from the investment return. On the other hand, if the consumption is more valuable than the investment, then the farmers should have a higher priority than the government when allocating the investment return among them. However, in this research, it is assumed, as shown in Chapter 5, that the decision makers have decided to give the opportunity to 10,000 landless farmers to own the new lands and gain an income increase on the order of \$600/farmer/year. This decision has resulted in giving up 34.74 million dolars from the investment return to the farmers. The remainder from the investment net-return is gained by the government.

The three planning alternatives developed for the case study in Chapters 2 and 3 are achieving the same agricultural production level and hence the same gross return. But they have different expansion and farming costs as shown in Table (8.1). Therefore, the three

Table 8.1 Performance of the Planning Alternatives

Criteria	Issues	Alternatives			Best Alternatives
		1	2	3	
Economic Efficiency	Expansion Cost (10^6dollars)	84.1	85.4	83.1	3
	Government's Return (10^6dollars)	90	88.60	90	1,3
	Government's Net-Return (10^6dollars)	5.9	3.2	6.9	3
Income Redistribution	Farming Cost (10^6dollars)	58	59.40	58	1,3
	Farmers' Net Return (10^6dollars)	31.71	31.71	31.71	1,2,3
Economic Efficiency and Income Redistribution	Total Cost (10^6dollars)	142.1	144.8	141.1	3
	Total Return (10^6dollars)	179.71	179.71	179.71	1,3
	Total Net Return (10^6dollars)	37.61	34.91	38.61	3
	Regret (10^6dollars)	1.0	3.70	-	3

planning alternatives are achieving different levels of net-return for the agricultural expansion investment. The third alternative in which the drainage water of the new land is reused for irrigation after being mixed with a fresh water is achieving the highest net-return to the government (6.9 million dollars). The first planning alternative which is based on using only fresh water for irrigation is achieving less return to the government (5.9 million dollars). The least return to the government (3.2 million dollars) is obtained when the second planning alternative, in which only a saline water is used for irrigation. By summing up the shares of the farmers (31.71 million dollars) and the government from the investment net-return, performance of the investment in terms of its total output (net return) can be determined under the three planning alternatives as shown in Table (8-1). The third alternative achieves the best performance for the investment (38.61 million dollars), the first alternative achieves the second best performance (37.61 million dollars) and the least performance (34.91 million dollars) for the investment is obtained when using the second planning alternative.

8.2 Resilience vs Performance in Agricultural Expansion Planning

As shown above, the least cost planning alternatives are achieving the best performance for the investment. Unfortunately, these alternatives are not the most resilient ones. As shown in Chapter 7, the least cost design (third alternative) is also the least resilient one. With a high reliability (95% or more) the second planning alternative which has the highest expansion as well as

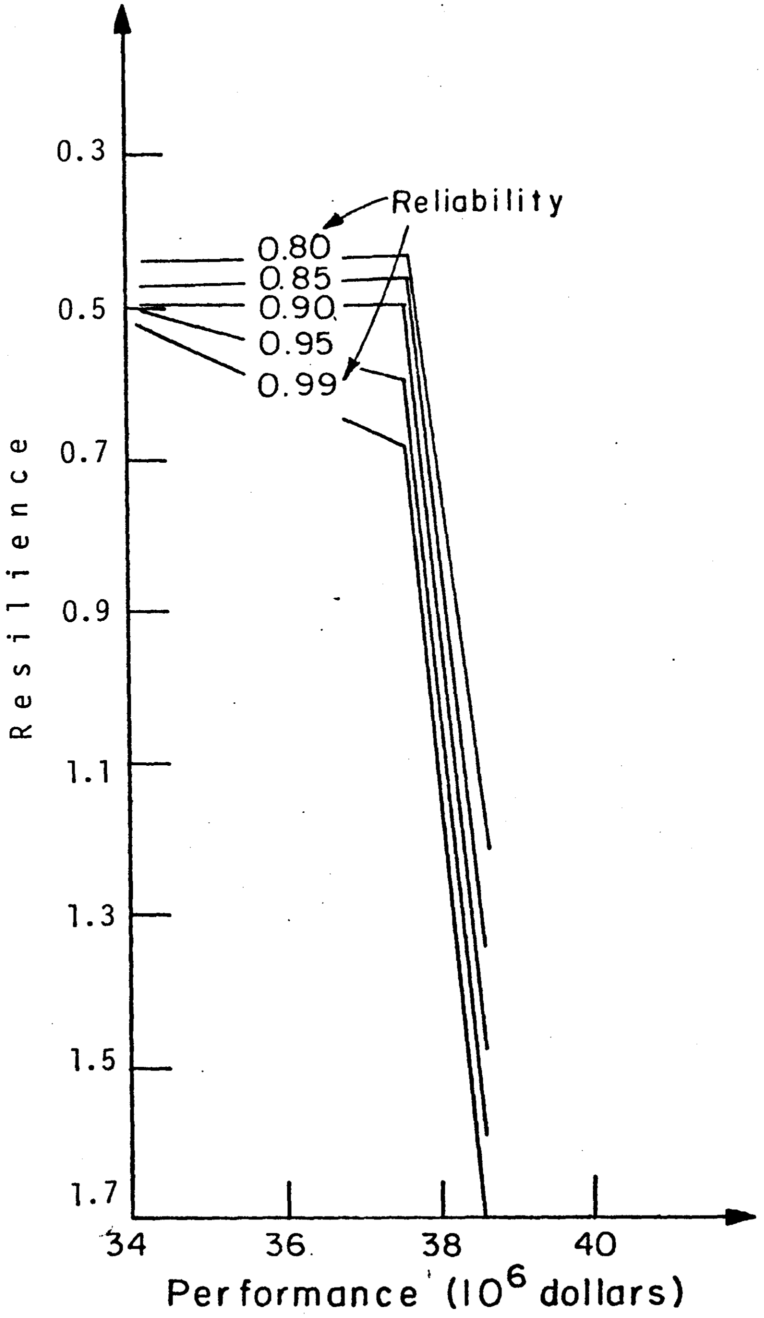


Figure 8-1 Resilience vs. Performance In Agricultural Expansion Planning

farming cost is found to be the most resilient design. However, with less reliability (90% or less), the first alternative is found to be more resilient than the second one. This, as explained in the last chapter, is due to the conflict between the mean and variance of the resiliency index of these two planning alternatives.

By using the information provided in Table (8-1) about the performance of the planning alternatives and the resiliency computations (Table 7-8) in Chapter 7, the relationship between the performance and resilience of agricultural expansion investment (the case study) is determined, as shown in Figure (8-1). From this figure, it can clearly be seen, particularly for high reliability levels, that a trade-off between the resilience and performance of the investment exists. By overbuilding a system design, which will result in more cost and less return, more resilient performance toward future surprises will be obtained. The selection of the best planning alternative is a decision-making process.

CHAPTER 9

SUMMARY, CONCLUSIONS and FUTURE RESEARCH

9.1 Summary

Agricultural expansion planning has been defined in a two-level hierarchy. At the first level, a strategic planning on the agricultural sector level is to be performed. At this level the feasibility of the various agricultural investments is to be examined and the role of each investment in achieving the strategic goals of the sector is to be determined. The strategic decisions at this level, considering the agricultural expansion investment, may include the agricultural production targets of the new land; allocated budget, foreign exchange and resource inputs to the investment; and income redistribution objectives. At the second level, solutions to the planning issues of the expansion are to be provided. The solutions should be developed in such a way that the strategic decisions from the first level can be implemented. This research has focussed only on the second level of the planning process.

This study has addressed three issues in planning of large-scale irrigated agricultural expansion investment. First is the investment scheduling in such a way that the growing agricultural demands can be satisfied and the budget as well as resource constraints are not violated. The second issue is the use of such a large-scale public investment in improving the income redistribution conditions in a society. The third issue is the uncertainty and its effect on the performance of agricultural systems.

A mathematical optimization model has been built to aid analyzing the scheduling problems of land development, crop selection, and capacity expansion of the irrigation and drainage network. The model has been applied to a medium-sized case study on the order of 70,000 acres and a solution was obtained. The possibility of drainage water reuse in agricultural practices has been introduced. The effects of this low-quality water on the yields and water requirements of the various crops have been discussed. These effects have been added to the constraint sets of the scheduling model to determine the impacts of drainage water reuse on the scheduling decisions. It has been found that with a proper crop selection in the new areas, recycling of the drainage water for irrigating the new land will cause only slight economic losses (less than 2% increase in the expansion cost). Moreover, when using a mixed drainage water with a fresh water, an economic gain has been obtained (about 1% decrease in the expansion cost).

The role of agricultural expansion investment in improving the income redistribution conditions in a society has been investigated. Land distribution approach to a poorer sector (landless farmers) of the society to gain the agricultural revenues and improve their income has been selected. A mathematical model (redistribution model) has been built to determine the optimum land distribution among the farmers which achieves a specified (by the government) income increase to them and maintains a high agricultural efficiency in the new land. In addition, the model has been formulated in such a way that the land payment policy which insures the recovery of the expansion cost can be determined.

The use of the marginal and average cost approaches in estimating the prices of the new land has been illustrated. It has been found that the income redistribution objectives (income increase to the farmers and equity between them) cannot be insured and the expansion cost cannot be recovered (land payments have been estimated higher than the agricultural revenues of some areas) when using either approaches in estimating land prices. On the other hand, the redistribution as well as the cost recovery objectives have been achieved when the redistribution model has been used.

The trade-off between the number of the new owners and their income increase under different conditions of cost recovery and pay-back periods has been generated via the redistribution model. The limiting factors to this trade-off have been introduced and a solution approach has been discussed.

No conflict has been found between the net-return of the investment and the farmers' return from the investment. For a specified cost recovery condition, it has been found that the alternative expansion planning scheme which has the highest net return (least cost) gives the opportunity for the largest number of farmers to own the new land and gain a specified income increase. But a conflict between the government return from the investment and the redistribution benefits (farmers' return) has been found. This conflict has been addressed and the trade-off between the two objectives has been illustrated.

The performance of the agricultural expansion planning alternatives under the uncertainty inherent in the planning parameters has been investigated. This has been done through a multicriteria mathematical optimization model. Two criteria have been used to express the performance of such public investment. The first is maximum net-benefit criterion. The second is income redistribution criterion in terms of maximum farmers' net-return from the investment. This maximization procedure has been constrained with the physical components of the agricultural systems (capacities of the canals, size of developed areas, land distribution among the farmers, etc.). The operating decisions which have been considered are the cropping pattern in the new areas, and the flows in the canals. This model has been used in measuring the performance of the planning alternatives under wide range of unpleasant surprises in the planning parameters. The outputs have been used in deriving frunctional relationships between the performance of the planning alternatives and the unpleasant changes in the planning parameters. A resiliency index in terms of the total derivatives of these functions has been derived in a probabilistic, as well as, a deterministic, framework. This index has been used in comparing the various planning alternatives in terms of their resiliency toward future surprises. It has been found that the most costly (due to overinvesting) planning alternatives are the most resilient ones and the least expensive alternative is the least resilient design.

9.2 Findings and Conclusions

The main contributions of this work are related to the field of agricultural expansion planning. The thesis provides a comprehensive planning framework through which the best agricultural expansion planning alternatives can be distinguished. In this framework, the interactions between agricultural expansion investment and the other investments on the agricultural sector level have been recognized and identified. Within this framework, the most important planning issues of agricultural expansion investment have been addressed and modeling approches for analyzing these issues have been developed.

The main findings and conclusions can be summarized as follows:

1. The decomposition procedure of agricultural expansion planning process into a two-level hierarchy. This decomposition procedure allowed us to look at the planning of agricultural expansion investment from a wide spectrum on the agricultural sector level. It allowed the planning of agricultural expansion investment to be in parallel with the other agricultural investments to minimize the conflict between the various investments, to optimally allocate the budget as well as scarce resources among them and to determine the optimum rule of each investment in achieving the strategic goals of the agricultural sector. In addition, this decomposition procedure allowed the main issues of agricultural expansion planning to be identified and sophisticated tools for analyzing them to be developed.
2. The deterministic dynamic model which has been used in analyzing the scheduling issue of agricultural expansion investment. It has been developed in such a way that for every year of the scheduling horizon, the sites of land to be developed, cropping

pattern in these sites and correct timing of capacity expansion of irrigation and drainage networks which achieve the strategic goals of the investment can be simultaneously determined. Moreover, the model has given us a good insight on the possibility of drainage water reuse in agricultural practices and how it may be a powerful solution to the problem of fresh water scarcity. Nothing similar has been previously developed in such a planning context.

3. The income redistribution model which has been successfully used in estimating prices of the new land which insure the equity between the farmers, recovery of the expansion cost, and better income conditions to the new owners (landless farmers). As shown in Chapters (4) and (5), the redistribution model can be used for other purposes like deriving the trade-off between the number of poor people who will get an increase in their income from the investment return and the value of this income increase; and in determining the new land prices as well as land distribution among the landless farmers which maximize the government return from the investment. This modeling approach represents the first attempt toward analyzing and formulating the redistribution issue in an agricultural expansion planning context in a practical way.
4. The use of the marginal and average cost approaches in estimating the land prices for such a complicated large-scale investment. It has been analytically explained how these

classic economic approaches can be used in allocating the expansion cost among the new owners of the various new areas which have different agricultural revenues. It has been found that when using either approach in land pricing, the equity between the farmers (in achieving the same income level) cannot be achieved and the expansion cost cannot be recovered (the allocated costs to some areas have been found higher than the agricultural revenues at these areas).

5. The exploration of the existing conflict between the government return and the benefits of the lower income people (landless farmers) from the agricultural expansion investment. The trade-off between the two objectives in this agricultural public investment has been derived and the limiting factors to this trade-off have been addressed.

6. The multiobjective performance model which has been developed to measure the performance of agricultural systems under uncertainties. It has been shown that using either the maximum net-benefit criterion or income redistribution criterion alone in measuring the performance of agricultural public investments is inadequate. Also, it has been shown that no conflict between the income redistribution and the economic efficiency criteria exists in the case of having fixed benefits from the investment. The performance model has shown that large-scale agricultural systems have many redundant design components (even if they are optimally designed) which

can be used -- if the system operated properly -- to accommodate or to minimize the unpleasant effects of future surprises on system performance.

7. The resiliency index which represents a major finding in this research. Via this index and, for the first time, an agricultural system design can be judged as a resilient or a brittle one. This index opens the doors for the scientists as well as the engineers to a systematic consistent framework for overcoming the uncertainty problems in the design of large-scale systems.
8. The resiliency definition. It represents a first unique meaningful definition to the resiliency of a large-scale system to be developed on a theoretical basis.
9. The exploration of the potential conflict between the cost of system designs and their resiliency. It has been found that the overbuilt designs (the most expensive designs) are the most resilient ones. The trade-off between the cost and the resiliency of agricultural systems has been derived and investigated.

9.3 Future Research

As shown throughout the thesis there are some topics where further research could enhance the approaches presented. As shown in Chapters 2 and 3, solutions to the scheduling model via mixed integer programming is computationally inefficient. Fortunately, the scheduling problem can be decomposed into three sub-problems: Land development and crop selection, irrigation network expansion, and drainage network expansion. The sub-problems are interactive but a decomposition method (goal coordination or model coordination methods) can be used to decouple them. An algorithm based on this decomposition procedure may be developed. It should be more efficient than the mixed integer programming insolving the scheduling problem.

The possible confilct between the income redistribution objectives and agricultural efficiency represents a potential area for future research. More experimental research is needed to determine the effect of farm size on agricultural efficiency in the developing countries. The output of such experiments should be included in the analysis of the redistribution issue, and the trade-off between income redistribution and agricultural efficiency objectives should be evaluated.

As shown in Chapter 4, the income redistribution model can be used to determine the prices of the new land which achieve the income redistribution objectives and insure the recovery of the expansion cost. A modification to the income redistribution model to account for a pricing scheme to the irrigation water in the new areas represents a potential area for future research. Water pricing will lead to a higher efficiency of water use, as the farmers will be more careful not to waste water.

Development of an analysis tool of the potential conflict between the mean and variance of the resiliency index of the various planning alternatives is another important area for future research. As shown in Chapter 7, because of this conflict it was impossible for us to distinguish the most resilient design. In addition, this conflict, as shown in Chapter 8, has increased the difficulty of the decision makers' rule in analyzing the trade-off between the resiliency and the performance of agricultural expansion planning to distinguish the best planning alternative. A solution to the trade-off between the mean and variance of the resiliency index should enhance the resiliency concept presented in the thesis.

An integrated modeling approach for analyzing the issues of scheduling, income redistribution and uncertainty, simultaneously, should be the second phase of this research. With the sophisticated analysis provided in this work for each of the planning issues, this modeling approach should be a straightforward exercise. The main problem which may face such an approach is the one of dimensionality. However, a decomposition procedure, as explained above, may be useful in overcoming this problem.

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APPENDIX A

Table A-1. The Twenty Years Payment Policy

Income Increase (dollars/farmer/year)

Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	410	10	340	10	-	-	-	-	-	-	-	-	-	-	-	-
	2	215	5	229	7	-	-	-	-	-	-	-	-	-	-	-	-
1.2	3	291	8	293	10	-	-	-	-	-	-	-	-	-	-	-	-
	4	248	10	238	10	-	-	-	-	-	-	-	-	-	-	-	-
	5	202	5	235	9	-	-	-	-	-	-	-	-	-	-	-	-
	1	376	6	360	6	390	10	380	10	269	10	-	-	-	-	-	-
	2	215	5	195	5	175	5	200	7	225	10	-	-	-	-	-	-
1.1	3	270	6	286	9	283	10	264	9	263	10	-	-	-	-	-	-
	4	198	5	238	10	221	9	218	10	208	10	-	-	-	-	-	-
	5	202	5	202	5	202	7	188	7	122	5	-	-	-	-	-	-

Table A-1 The Twenty Years Payment Policy (Cont.)

Income Increase (dollars/farmer/year)

Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	.	.	340	5	360	7	346	7	359	10	349	10	-	-	-	-
	2	.	.	195	5	175	5	155	5	172	7	193	9	-	-	-	-
1	3	.	.	252	6	275	9	264	9	253	10	231	9	-	-	-	-
	4	.	.	178	5	158	5	218	10	187	9	188	10	-	-	-	-
	5	.	.	182	5	162	5	142	5	102	5	145	7	-	-	-	-
	1	.	.	.	.	320	5	326	6	359	9	349	9	350	10	326	9
	2	.	.	.	.	175	5	155	5	135	5	115	5	95	5	144	7
.9	3	.	.	.	.	213	5	253	8	253	9	210	7	243	10	233	10
	4	.	.	.	.	152	5	138	5	118	5	198	10	188	10	178	10
	5	.	.	.	.	162	5	142	5	122	5	102	5	192	10	62	5

Table A-1 The Twenty Years Payment Policy (Cont.)

Income Increase (dollars/farmer/year)

Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
.8	1	.	.	.	.	.	.	300	5	275	5	349	9	338	9	310	8
	2	.	.	.	.	.	.	155	5	135	5	114	5	94	5	75	5
	3	.	.	.	.	.	.	193	5	263	10	187	6	170	6	233	10
	4	.	.	.	.	.	.	122	5	118	5	98	5	161	8	178	10
	5	.	.	.	.	.	.	0	5	122	5	135	6	82	5	62	5
.7	1	.	.	.	.	.	.	.	.	.	.	258	5	240	5	310	8
	2	.	.	.	.	.	.	.	.	.	.	115	5	95	5	75	5
	3	.	.	.	.	.	.	.	.	.	.	210	7	170	6	153	6
	4	.	.	.	.	.	.	.	.	.	.	98	5	188	10	127	7
	5	.	.	.	.	.	.	.	.	.	.	102	5	82	5	62	5

Table A-1. The Twenty Years Payment Policy (Cont.)

		Income Increase (dollars/farmer/year)															
Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
.6	1	.	.	.	.	.	.	.	.	.	.	.	.	235	5	220	5
	2	.	.	.	.	.	.	.	.	.	.	.	.	95	5	75	5
	3	.	.	.	.	.	.	.	.	.	.	.	.	170	6	203	8
	4	.	.	.	.	.	.	.	.	.	.	.	.	78	5	98	6
	5	.	.	.	.	.	.	.	.	.	.	.	.	82	5	102	6
.5	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

. Inferior Solution

\- Infeasiable Solution

Table A-2 The Fifteen Years Payment Policy

Income Increase (dollars/farmer/year)

Cost Recovery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	410	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	232	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.1	3	303	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	248	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	247	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	360	5	394	9	390	10	380	10	-	-	-	-	-	-	-	-
	2	215	5	195	5	199	6	215	8	-	-	-	-	-	-	-	-
1.0	3	282	7	252	6	266	8	273	10	-	-	-	-	-	-	-	-
	4	236	8	238	10	228	10	218	10	-	-	-	-	-	-	-	-
	5	202	5	182	6	186	6	142	5	-	-	-	-	-	-	-	-

Table A-2. The Fifteen Years Payment Policy (Cont.)

Cost Recovery	Area	Income Increase (dollars/farmer/year)															
		500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	.	.	340	5	320	5	371	9	370	10	349	9	350	10	-	-
	2	.	.	195	5	175	5	155	5	203	8	190	8	205	10	-	-
0.9	3	.	.	233	5	283	10	239	7	173	5	253	10	243	10	-	-
	4	.	.	198	6	220	9	210	9	198	9	187	9	176	9	-	-
	5	.	.	236	9	162	5	142	5	174	7	102	5	82	5	-	-
	1	.	.	.	.	320	5	300	5	360	9	360	10	349	10	340	10
	2	.	.	.	.	175	5	155	5	135	5	115	5	95	5	144	7
0.8	3	.	.	.	.	213	5	239	7	203	6	210	7	243	10	233	10
	4	.	.	.	.	158	5	184	7	148	6	173	8	188	10	148	8
	5	.	.	.	.	35	5	142	5	174	7	136	6	145	7	102	6

Table A-2. The Fifteen Years Payment Policy (Cont.)

		<u>Income Increase</u> (dollars/farmer/year)															
Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	.	.	.	.	.	.	.	.	310	6	335	8	338	9	327	9
	2	.	.	.	.	.	.	.	.	135	5	115	5	95	5	75	5
0.7	3	.	.	.	.	.	.	.	.	173	5	187	6	196	7	233	10
	4	.	.	.	.	.	.	.	.	118	5	98	5	115	6	127	7
	5	.	.	.	.	.	.	.	.	152	6	135	6	119	6	131	7
	1	.	.	.	.	.	.	.	.	.	.	249	5	277	6	289	7
	2	.	.	.	.	.	.	.	.	.	.	115	5	95	5	75	5
0.6	3	.	.	.	.	.	.	.	.	.	.	187	6	196	7	233	10
	4	.	.	.	.	.	.	.	.	.	.	98	5	78	5	58	5
	5	.	.	.	.	.	.	.	.	.	.	102	5	82	5	62	5

Table A-2. The Fifteen Years Payment Policy (Cont.)

Income Increase (dollars/farmer/year)

Cost Re-covery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
.5	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	220	5
	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	74	5
	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	113	5
	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	127	7
	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	102	6
.4	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Table A-3. The Ten Years Payment Policy

Income Increase (dollars/farmer/year)

Cost Recovery	Area	500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
.9	1	410	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	253	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	303	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	243	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	202	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
.8	1	360	5	340	5	390	10	380	10	370	10	-	-	-	-	-	-
	2	215	5	249	9	175	5	201	7	225	10	-	-	-	-	-	-
	3	253	5	293	10	283	10	273	10	263	10	-	-	-	-	-	-
	4	243	9	198	6	228	10	218	10	208	10	-	-	-	-	-	-
	5	240	8	202	6	232	10	214	9	211	10	-	-	-	-	-	-

Table A-3. The Ten Years Payment Policy (Cont.)

Cost Recovery	Area	Income Increase (dollars/farmer/year)															
		500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	.	.	.	.	319	5	370	9	370	10	360	10	350	10	340	10
	2	.	.	.	.	175	5	155	5	135	5	149	6	158	7	182	9
.7	3	.	.	.	.	276	9	273	10	225	7	242	9	243	10	233	10
	4	.	.	.	.	182	6	138	5	208	10	187	9	188	10	178	10
	5	.	.	.	.	186	6	142	5	122	5	160	7	165	8	169	9
	1	.	.	.	.	.	.	300	5	310	6	349	9	303	7	340	10
	2	.	.	.	.	.	.	145	5	135	5	115	5	95	5	75	5
.6	3	.	.	.	.	.	.	220	6	240	8	187	6	243	10	220	9
	4	.	.	.	.	.	.	138	5	118	5	132	6	188	10	178	10
	5	.	.	.	.	.	.	142	5	152	6	160	7	82	5	102	6

Table A-3. The Ten Years Payment Policy (Cont.)

Cost Re-covery	Area	Income Increase (dollars/farmer/year) 500		600		700		800		900		1000		1100		1200	
		P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j	P_j	n_j
	1	.	.	.	.	.	.	.	.	.	.	260	5	303	7	260	6
	2	.	.	.	.	.	.	.	.	.	.	115	5	95	5	75	5
.5	3	.	.	.	.	.	.	.	.	.	.	153	5	170	6	233	10
	4	.	.	.	.	.	.	.	.	.	.	132	6	78	5	127	7
	5	.	.	.	.	.	.	.	.	.	.	136	6	165	8	62	5
	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	219	5
	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	75	5
.4	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	182	7
	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	58	5
	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	152	8

APPENDIX B

B-1. The Operating Rules of the Case Study when Using the Multi-criteria Performance Model

Table B-1. Cropping Pattern in the New Land Under Surprises in Irrigation Water Quality (Crop-Acres)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
	1	3,483	7,000	7,517	3,483	--	14,517
	2	8,936	--	--	8,936	8,997	67
10%	3	1,973	--	8,027	1,973	5,980	2,047
	4	4,319	--	4,445	4,319	4,407	510
	5	669	--	--	669	616	--
Total		19,380	7,000	19,989	19,380	20,000	17,141
	1	3,021	7,107	7,872	3,021	--	14,979
	2	8,887	--	--	8,887	9,093	20
20%	3	2,455	--	7,545	2,455	3,508	2,525
	4	3,927	--	4,583	3,927	6,791	--
	5	667	--	--	667	609	--
Total		18,957	7,107	20,000	18,957	20,001	17,524
	1	2,324	7,447	8,229	2,324	--	15,676
	2	8,810	--	--	8,810	9,182	8
30%	3	2,435	--	7,565	2,435	3,552	2,481
	4	4,036	--	4,206	4,036	6,656	--
	5	662	--	--	662	611	--
Total		18,267	7,447	20,000	18,267	20,001	18,165

(Continued on next page)

Table B-1 (Continued)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
	1	3,210	5,980	8,809	3,211	--	14,789
	2	8,844	--	--	8,844	8,994	--
40%	3	2,339	--	7,661	2,339	4,114	2,330
	4	4,321	--	3,531	4,321	6,293	--
	5	664	--	--	664	597	--
Total		19,378	5,980	20,001	19,378	20,000	17,119
	1	3,143	5,828	9,028	3,143	--	14,857
	2	8,841	--	--	8,841	8,920	--
50%	3	2,308	--	7,692	2,308	4,360	2,239
	4	4,424	--	3,280	4,424	6,128	--
	5	664	--	--	664	592	--
Total		19,380	5,828	20,000	19,380	20,000	17,096

Table B-2. Seasonal Flows in the Irrigation Canals Under Surprises in Irrigation Water Quality (m^3/sec)

		Canal								
Reduction	Season	6-7	7-1	1-5	7-8	8-2	8-9	9-3	9-10	10-4
10%	Winter	9.91	6.4	2.69	3.3	1.33	1.94	1.72	.2	.2
	Summer	32.0	24.0	5.51	7.39	4.0	3.31	2.90	.39	.38
20%	Winter	9.92	6.4	2.7	3.3	1.4	1.87	1.65	.2	.2
	Summer	32.60	24.56	5.51	7.39	4.0	3.32	2.90	.39	.38
30%	Winter	9.92	6.43	2.7	3.3	1.4	1.86	1.64	.2	.2
	Summer	33.47	25.4	5.51	7.39	4.0	3.32	2.90	.382	.38
40%	Winter	9.92	6.43	2.75	3.28	1.4	1.86	1.64	.2	.2
	Summer	32.72	24.68	5.51	7.39	4.0	3.32	2.90	.39	.382
50%	Winter	9.92	6.44	2.75	3.28	1.39	1.85	1.63	.21	.2
	Summer	32.94	24.9	5.51	7.39	4.0	3.32	2.90	.39	.382

Table B-3. Seasonal Flows in the Drainage Canals Under Surprises in Irrigation Water Quality (m^3/sec)

Reduction	Season	Drain 1-9	2-9	3-9	9-10	4-10	5-10
10%	Winter	1.1	0.4	0.51	2.03	0.06	0.80
	Summer	5.47	1.19	0.86	7.60	0.11	1.62
20%	Winter	1.1	0.41	0.49	2.03	0.06	0.8
	Summer	5.65	1.19	0.86	7.78	0.11	1.62
30%	Winter	1.1	0.42	0.49	2.02	0.06	0.80
	Summer	5.9	1.19	0.86	8.04	0.11	1.62
40%	Winter	1.09	0.41	0.49	2.01	0.06	0.81
	Summer	5.68	1.19	0.86	7.82	0.11	1.62
50%	Winter	1.09	0.41	0.49	2.01	0.06	0.81
	Summer	5.75	1.19	0.86	7.88	0.11	1.62

Table B-4 Cropping Pattern in the New Land Under Surprises in Irrigation Water Quantity (Crop-Acres)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
10%	1	3,519	2,479	12,002	3,519	--	14,481
	2	8,411	--	--	8,411	9,589	--
	3	1,921	1,190	6,888	1,921	3,588	2,658
	4	4,902	--	--	626	660	--
Total		19,379	3,699	20,000	19,379	20,000	17,139
20%	1	5.150	--	11,960	5,150	1,869	10,784
	2	7,106	--	--	7,106	10,894	--
	3	2,086	--	7,914	2,086	--	3,469
	4	4,505	--	--	4,505	6,497	--
	4	532	--	--	532	740	--
Total		19,379	--	19,874	19,379	20,000	14,253
30%	1	8,601	--	3,994	8,601	--	7,722
	2	5,600	--	--	5,600	12,201	--
	3	1,157	--	8,843	1,157	--	3,653
	4	3,605	--	--	3,605	6,963	--
	5	417	--	--	417	836	--
Total		19,380	--	--	19,380	20,000	11,375

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Table B-4 (Continued)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
	1	10,188	--	--	10,188	--	4,947
	2	4,085	--	--	4,085	13,475	--
40%	3	1,647	--	5,596	1,647	--	3,556
	4	3,160	--	--	3,160	5,591	--
	5	301	--	--	301	934	--
Total		19,381	--	5,596	19,381	20,000	8,503

Table B-5. Seasonal Flows in the Irrigation Canals Under Surprises in Irrigation Water Quantity (m^3/sec)

		Canal								
Reduction	Season	6-7	7-1	1-5	7-8	8-2	8-9	9-3	9-10	10-4
10%	Winter	8.93	5.65	2.51	3.1	1.45	1.63	1.43	0.19	0.18
	Summer	31.73	23.7	5.43	7.39	4.0	3.32	2.9	0.39	0.38
20%	Winter	7.94	5.06	2.12	2.72	1.34	1.35	1.18	0.16	0.16
	Summer	28.2	20.25	5.50	7.39	4.00	3.32	2.9	0.39	0.38
30%	Winter	6.94	4.47	1.67	2.34	1.24	1.08	0.94	.13	0.12
	Summer	24.68	16.88	5.51	7.30	4.00	3.24	2.82	.39	0.38
40%	Winter	5.95	3.9	1.22	1.93	0.99	0.93	0.83	0.09	0.09
	Summer	21.15	13.93	5.51	6.8	4.00	2.74	2.33	0.39	0.38

Table B-6. Seasonal Flows in the Drainage Canals Under Surprises in Irrigation Water Quantity (m^3/sec)

		Drain					
Reduction	Season	1-9	2-9	3-9	9-10	4-10	5-10
10%	Winter	0.93	0.43	0.43	1.80	0.06	0.74
	Summer	5.42	1.19	0.86	7.55	0.11	1.60
20%	Winter	0.87	0.40	0.35	1.64	0.05	0.62
	Summer	4.37	1.19	0.86	6.49	0.11	1.62
30%	Winter	0.83	0.37	0.28	1.49	0.04	0.49
	Summer	3.37	1.19	0.84	5.45	0.11	1.62
40%	Winter	0.79	0.29	0.25	1.35	0.03	0.36
	Summer	2.49	1.19	0.69	4.42	0.11	1.62

Table B-7. Cropping Pattern in the New Land Under Surprises in Crop Prices (Crop-Acres)

			Winter Crops			Summer Crops	
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
10%	1	5,087	7,000	5,913	5,087	--	12,913
	2	8,526	--	--	8,526	6,814	689
	3	3,999	--	3,173	3,999	3,806	2,195
	4	1,086	--	10,914	1,086	9,380	--
	5	683	--	--	683	--	144
Total		19,381	7,000	20,000	19,381	20,000	15,941
20%	1	7,108	7,000	3,892	7,108	--	10,892
	2	7,646	--	--	7,646	5,875	1,084
	3	3,712	--	4,437	3,712	4,107	2,181
	4	329	--	11,671	329	10,018	--
	5	585	--	--	585	--	163
Total		19,380	7,000	20,000	19,380	20,000	14,320
30%	1	9,837	7,000	1,162	9,837	--	8,162
	2	6,218	--	254	6,218	4,004	1,807
	3	3,323	--	6,677	3,323	4,515	2,162
	4	--	--	10,609	--	10,294	--
	5	--	--	1,298	--	1,187	--
Total		19,378	7,000	20,000	10,378	20,000	12,131

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Table B-7 (Continued)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
	1	11,000	7,000	--	11,000	--	7,000
	2	1,000	--	8,735	1,111	15,975	--
40%	3	3,730	--	6,270	3,730	--	3,144
	4	--	--	4,333	--	2,838	1,754
	5	--	--	663	--	1,187	--
Total		15,841	7,000	19,338	15,841	20,000	11,898

Table B-8. Seasonal Flows in the Irrigation Canals Under Surprises in Crop Prices (m^3/sec)

		Canal								
Reduction	Season	6-7	7-1	1-5	7-8	8-2	8-9	9-3	9-10	10-4
10%	Winter	9.81	6.41	2.54	3.2	1.24	1.93	1.71	0.20	0.20
	Summer	30.27	22.28	5.51	7.39	4.0	3.32	2.90	0.39	0.38
20%	Winter	9.76	6.42	2.28	3.15	1.32	1.8	1.61	0.18	0.17
	Summer	28.28	20.33	5.51	7.39	4.00	3.32	2.9	0.39	0.38
30%	Winter	9.69	6.38	1.89	3.11	1.48	1.60	1.39	0.2	0.2
	Summer	25.6	17.7	5.51	7.39	4.00	3.32	2.9	0.39	0.38
40%	Winter	8.70	6.3	1.67	2.22	1.53	0.67	0.57	0.1	0.1
	Summer	24.46	16.59	5.51	7.39	4.00	3.32	2.9	0.39	0.38

Table B-9. Seasonal Flows in the Drainage Canals Under Surprises in Crop Prices (m^3/sec)

		Drain					
Reduction	Season	1-9	2-9	3-9	9-10	4-10	5-10
10%	Winter	1.14	0.37	0.51	2.04	0.06	0.75
	Summer	4.97	1.19	0.86	7.1	0.11	1.62
20%	Winter	1.22	0.39	0.48	2.11	0.05	0.67
	Summer	4.39	1.19	0.86	6.51	0.11	1.62
30%	Winter	1.33	0.44	0.41	2.21	0.06	0.56
	Summer	3.61	1.19	0.86	5.72	0.11	1.62
40%	Winter	1.37	0.45	0.17	2.02	0.03	0.49
	Summer	3.28	1.19	0.86	5.39	0.11	1.62

B-2. The Operating Rules of the Case Study When Using the Economic Efficiency Performance Model

Table B-10. Cropping Pattern in the New Land Under Surprises in Irrigation Water Quantity (Crop-Acres)

		Winter Crops			Summer Crops		
Reduction	Area	Clover	Beans	Wheat	Cotton	Maize	Rice
10%	1	1,578	2,720	13,702	1,578	1,608	14,814
	2	--	--	4,472	--	16,672	--
	3	7,628	2,372	--	7,628	--	2,372
	4	10,174	--	1,826	10,174	1,720	--
	5	--	--	--	--	--	--
Total		19,380	5,092	20,000	19,380	20,000	17,186
20%	1	1,578	--	16,422	1,578	4,378	12,044
	2	--	--	840	--	13,902	--
	3	7,628	1,460	912	7,628	--	2,372
	4	10,174	--	1,826	10,174	1,720	--
	5	--	--	--	--	--	--
Total		19,380	1,460	20,000	19,380	20,000	14,416
30%	1	8,768	--	9,232	8,768	--	9,232
	2	--	--	--	--	12,220	--
	3	7,628	--	2,372	7,628	--	2,372
	4	2,984	--	3,924	2,984	7,780	--
	5	--	--	--	--	--	--
Total		19,380	--	15,528	19,380	20,000	11,604

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Table B-10 (Continued)

Reduction	Area	Winter Crops			Summer Crops		
		Clover	Beans	Wheat	Cotton	Maize	Rice
	1	11,554	--	5,889	11,554	--	6,446
	2	--	--	--	--	9,871	--
40%	3	7,628	--	2,372	7,628	--	2,372
	4	198	--	--	198	10,129	--
	5	--	--	--	--	--	--
Total		19,380	--	8,261	19,380	20,000	8,818
	1	10,428	--	--	10,428	2,711	4,861
	2	--	--	--	--	6,994	--
50%	3	8,952	--	1,048	8,952	--	1,048
	4	--	--	--	--	10,295	--
	5	--	--	--	--	--	--
Total		19,380	--	1,048	19,380	20,000	5,909

Table B-11. The Net Return of the Various Agricultural Crops (dollars/acre)

Crop	Yield (ton/acre)	Price (dollars/acre)	Farming Cost (dollars/acre)	Net Return (NR) (dollars/acre)
Clover	12	8.5	38.1	63.9
Beans	240	1.0	50.9	189.1
Wheat	171	1.5	111.4	145.1
Cotton	583	1.032	187.9	413.76
Maize	143	1.7	121.5	121.6
Rice	172	2.3	126.1	269.5

Table B-12. Spatial Income Redistribution in the New Land Under Surprises in Irrigation Water Quantity

Reduction	Area	NR (dollars)	NR/acre (dollars/acre)	AP (dollars/acres)	n (acres)	ΔI (dollars/farmer/year)
	1	7,444,165	413.6	340	5	378
	2	2,676,202	148.7	195	5	*
10%	3	4,731,390	473.1	252	6	1327
	4	5,333,817	444.5	178	5	1332.5
	5	--	--	182	5	*
	1	6,914,802	384	340	5	220
	2	1,812,367	101	195	5	*
20%	3	4,691,262	469	252	6	1302
	4	5,333,817	444.5	178	5	1332.5
	5	--	--	182	5	*
	1	8,015,710	445	340	5	526.5
	2	1,485,952	82.6	195	5	*
30%	3	4,627,022	462.7	252	6	1264.2
	4	4,091,420	341	178	5	815
	5	--	--	182	5	*
	1	8,110,575	450.5	340	5	553
	2	1,200,314	66.7	195	5	*
40%	3	4,627,022	462.7	252	6	1264.2
	4	1,326,263	110.5	178	5	*
	5	--	--	182	5	*

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Table B-12 (Continued)

Reduction	Area	NR (dollars)	NR/acre (dollars) acre)	AP (dollars/ acres)	n (acres)	ΔI (dollars/ farmer/year)
	1	6,683,304	371.3	340	5	156.5
	2	850,470	47.2	195	5	*
50%	3	4,710,513	471	252	6	1314
	4	1,251,872	104.3	178	5	*
	5	--	--	182	5	*

*Annual payment is greater than the agricultural return.