WATER RESOURCES RESEARCH, VOL. 17, NO. 6, PAGES 1585–1593, DECEMBER 1981

Nile Water for Sinai: Framework for Analysis

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The current plans of the Egyptian government call for a massive expansion of irrigated land, approximately 1.8 million additional hectares by the year 2000. The Egyptian Ministry of Irrigation presently intends to construct the Salaam, or Peace, Canal for the delivery of Nile water to the new reclamation areas in the Eastern Delta and Sinai. There are two primary objectives in transporting water to Sinai: (1) economic: to reclaim land to increase agricultural production and (2) political: to settle Sinai and establish a larger, permanent Egyptian presence. In this paper a multiobjective programing model is formulated and solved in order to examine the trade-offs between the economic and political objectives and to study their interrelationships with such variables as water quantity, water quality, water transport costs, crop rotations, and irrigation technology. The results illustrate that the high costs of water transport to Sinai will require the use of modern, water-efficient irrigation technologies, as well as entail substantial economic sacrifices if the political objectives associated with agricultural settlements in Sinai are to be achieved through the use of intensive, year-round cultivation such as that practiced in the Nile Valley. The analysis also shows that the entire array of decisions to be made regarding the reclamation efforts (e.g., routes for the canals, site selection, irrigation technology) may be sensitive to the value of water in the rest of the country, a point largely ignored in the official plans.

INTRODUCTION

Satellite photographs of the Sinai peninsula reveal a striking straight line dividing the vegetation east of the Egyptian-Israeli border and the desert to the west. This is no geophysical or climatic boundary; it is only the limits of the Israeli desert reclamation effort.

Egypt's population is pressing against the limits of its available resources. The present population has topped 40 million and is growing at approximately 2.5% per year. Even optimistic observers forecast a population of at least 65 million by the year 2000 [*Central Agency for Public Mobilization and Statistics*, 1972; *Waterbury*, 1978]. Throughout history, Egypt has produced agricultural surpluses which have enabled her to feed peoples around the Mediterranean, but in 1974 Egypt became a net importer of agricultural products for the first time.

The return of Sinai to Egyptian sovereignty thus presents Egypt with needed natural resources. Proponents of Egyptian land reclamation efforts feel that the most important of these resources are the several hundred thousand feddans (1 feddan = 1.04 acres = 4214 m^2) of potentially arable land in the northern Sinai. Any land reclamation efforts in Sinai will require careful planning and execution and the application of modern technology for water use. Egypt's recent experience with desert reclamation indicates how difficult this can be. About two thirds of the land Egypt has attempted to reclaim over the last thirty years is either out of cultivation or submarginal [*Hunting Technical Services, Ltd., et al.*, 1979]. In fact, the Nubaraya project west of the Nile Delta has become a case study cited throughout the world to demonstrate the hazards of installing irrigation systems without careful planning for drainage [*Schulze and DeRidder*, 1973; *El Gabaly*, 1981]. Water duties with surface irrigation methods in sandy soils have been enormous, and the application of sprinkler and drip irrigation systems will require farm water management skills unprecedented in Egypt. In brief, desert reclamation has presented technical, social, and administrative difficulties, and has not proved viable in terms of economic criteria.

Egypt is richly endowed with a water supply which is the envy of the rest of the Middle East. Since the construction of the Aswan High Dam, water has not been a limiting resource in Egypt's agricultural and economic development. Nevertheless, the Nile has a limited supply of water, and reclamation plans executed today will continue to operate past the present era of water abundance and will compete with future demands. A careful assessment of water supplies and demands in Egyptian agriculture is thus required.

This paper presents a framework for beginning this kind of analysis for the problem of transporting Nile water to Sinai and the Eastern Delta. A mathematical formulation of certain aspects of the problem is developed and solved. The purpose of the modeling approach is to offer insight into the interrelationships between water quantity, water quality, irrigation technology, and agricultural production. Our objective is not to argue for or against reclaiming areas of Sinai, but rather to indicate the need for a systematic evaluation of the available options.

SUMMARY OF RECLAMATION PLANS

The current plans of the Egyptian government call for a massive expansion of irrigated land, approximately 2.8 million additional feddans by the year 2000 [*Egyptian Ministry of Irrigation*, 1977]. More than half of this total is located in the Eastern Delta and Sinai and is estimated to require 8.76×10^9 m^3 of water annually, 6.72×10^9 from the Nile and 2.04×10^9 from the agricultural drains, and some municipal sewage effluent. The execution of this work is the joint responsibility of four ministries: Land Reclamation, Irrigation, Agriculture, and New Communities. As shown in Figure 1, twenty-one reclamation sites have been identified

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Paper number 1W1370.
0043-1397/81/001W-1370$01.00

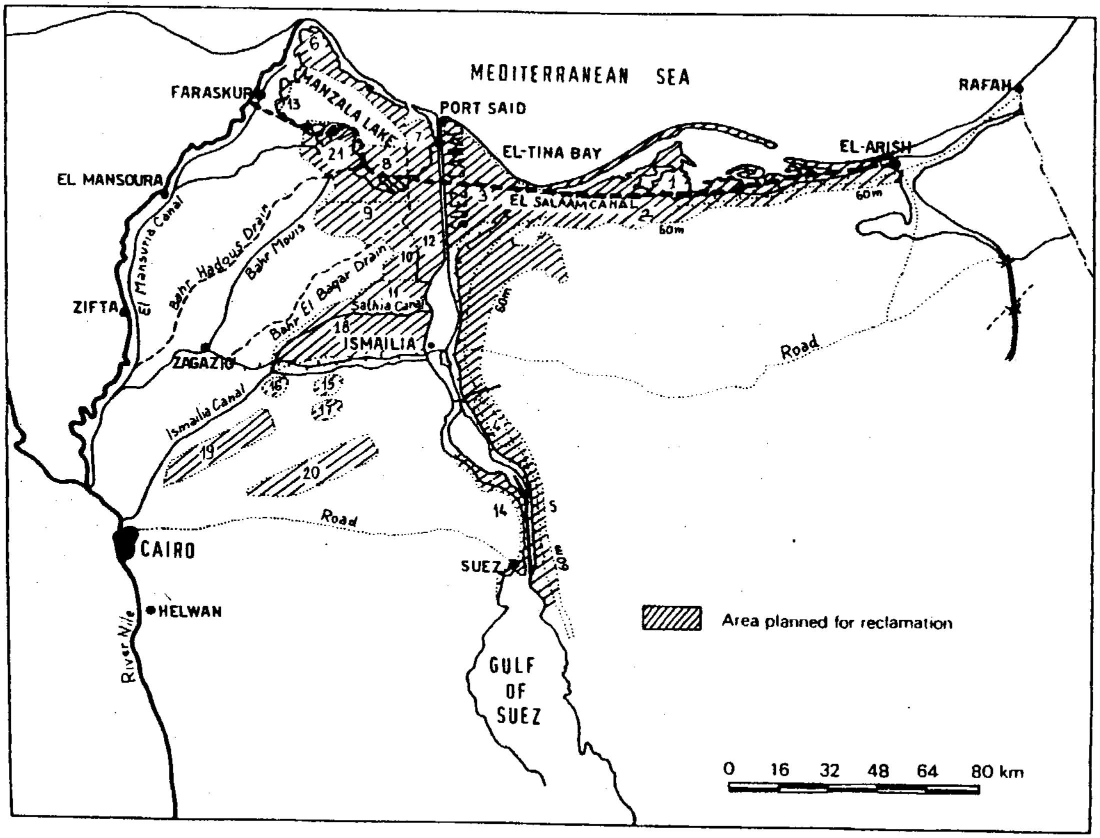

Fig. 1. Reclamation sites in the Eastern Delta and Sinai.

in the Eastern Delta and Sinai. Table 1 presents the source of the irrigation water and the proposed irrigation method for the sites in the reclamation plan.

The appropriate crop rotations and crop water requirements for both the old lands of the Nile Valley and the new reclamation areas have, however, been subjects of substantial controversy and uncertainty [*Waterbury*, 1979; *Kinawy*, 1977; *El Tobgy*, 1977; *Kramer*, 1978]. Crop rotations common in the old lands of the Nile Valley have generally not been successful in recent reclamation projects, and new crops such as soybeans and grapes have been grown.

The current annual mean water duty in Egyptian agriculture is on the order of 8000 m^3 per feddan. The Ministry of Irrigation estimates that this can be reduced to 7420 m^3 per

TABLE 1. Official Plan for Land Reclamation in the Eastern Delta and Sinai

Site Notation	Location	Area, hectares	Source of Irrigation	Type of Water	Method of Irrigation
1	Coastal Area between El Tina plain and El Arish	111,000	Salam Canal	Mixed	Surface
2	Coastal Area between contour line 5 and 60 meters	105,000	Salhia Canal	Fresh river water	Sprinkler
3	El Tina plain	57,000	Salam Canal	Mixed	Surface
4	East of Bitter Lakes	13,000	Suez irr. Canal	Fresh river water	Sprinkler
5	East of Suez Canal, contour line 40 m	23,000	Suez irr. Canal	Fresh river water	Sprinkler
6	Coastal belt between Port Said and Damietta.	20,000	Damietta Branch	Fresh river water	Sprinkler
7	South of Port Said	21,000	Salam Canal	Mixed	Surface
8	North of El Houssania plain	27,000	Salam Canal	Mixed	Surface
9	South of El Houssania plain	29,000	Salam Canal	Mixed	Surface
10	East of Bahr El Baqar area	13,000	Salhia Canal	Fresh river water	Surface
11	North of El Salhia	29,000	Salhia Canal	Fresh river water	Surface
12	South of Port Said plain	17,000	Pt. Said Canal	Fresh river water	Surface
13	Faraskur	2,000	Damietta Branch	Fresh river water	Surface
14	West of Suez Irrigation Canal to contour 20 m	17,000	Suez irr. Canal	Fresh river water	Surface
15	East of Delta and the extension of Adita area	6,000	Ismailia Canal	Fresh river water	Sprinkler
16	Adita Company	8,000	Ismailia Canal	Fresh river water	Sprinkler
17	El Mollak area	4,000	Ismailia Canal	Fresh river water	Sprinkler
18	El Salhia Desert	50,000	Salhia Canal	Fresh river water	Sprinkler
19	Moderiate El Shabab	42,000	Ismailia Canal	Fresh river water	Sprinkler
20	East Delta sewage water site	42,000	Cairo	Sewage effluent	Surface
21	El Mataria extension	12,000	Damietta Branch	Fresh river water	Surface

feddan for surface irrigation on clay soils without a reduction in crop yields. Sprinkler irrigation systems on sandy soils are expected to reduce this to 5250 m^3 per feddan. The use of more saline water would, however, increase these estimates due to the increased leaching requirements.

Estimates of the costs of land reclamation also vary widely [*Hunting Technical Services, Ltd., et al.*, 1979; *Hunting Technical Services, Ltd.*, 1980; *Voll*, 1978]. Indications are that drip irrigation may cost on the order of 2500 Egyptian Pounds (1 Egyptian Pound = 1 L.E. = $1.42 U.S.) per feddan (depending upon the type of equipment used), sprinkler irrigation 1500 L.E. per feddan, and surface irrigation 650 L.E. per feddan (Egyptian Water Master Plan, personal communication, 1979). *Hunting Technical Services* [1980] has recently argued that land reclamation costs for drip and sprinkler irrigation systems are likely to run as much as 7500 L.E. per feddan.

AVAILABLE WATER RESOURCES AND PROPOSED DELIVERY NETWORK

A complex network of irrigation and drainage canals currently exists in the Eastern Delta and will constitute the basis for future expansion of the water delivery system to serve any new reclamation areas. As shown in Figure 1, the Nile divides into two main branches 24 km north of Cairo: the Rosetta branch flows to the northwest and the Damietta to the northeast. Before the bifurcation the majority of the irrigation water for the Delta is withdrawn at the Delta barrage. The Damietta branch is closed at its mouth by the eastern Faraskor Dam, whih diverts approximately 0.2×10^9 m^3 of water annually to Manzala Lake.

Just north of Cairo is the junction of the main Nile and the Ismailia Canal, which carries water west to the entire Suez Canal Zone. The Ismailia Canal has suffered large seepage losses [*Shahin et al.*, 1979] and there have been proposals to both line the canal and expand its capacity. The Salhia Canal branches northward off the Ismailia Canal approximately midway between Cairo and Suez. Near the town of Ismailia, the Ismailia Canal again splits into two branches: (1) Port Said Canal turns north and (2) Suez Irrigation Canal flows south.

The Delta is crisscrossed with a dense network of agricultural drainage canals which empty into the Mediterranean. The flow rates and the salinity of the outlets of all the drains in the Delta were monitored by the River Nile–Lake Nasser Research Project of the Egyptian Academy of Scientific Research and Technology for the period November, 1978–November, 1979 and are reported in a project publication [*Zikri et al.*, 1979]. Two of these agricultural drains have often been discussed as possible sources of water for reclamation projects: Bahr Hadous and Bahr El Baqar. Their flow rates are about 2.4 and 1.4×10^9 m^3 annually, respectively. Both flow northeast toward Manzala Lake. The salinity of this drainage water varied from 922 to 1862 ppm for Bahr Hadous and from 666 to 960 ppm for Bahr El Baqar, with a weighted annual mean of 1428 and 757 ppm, respectively.

The salt content of drainage water is not, of course, a sufficient measure of its suitability as a source for reclamation projects. Nile water transported to Sinai will not only be used for agriculture but also for community water supplies. This raises particular concerns about the use of water from Bahr El Baqar, which receives both municipal and industrial effluents from Cairo. The present analysis, however, focuses upon agricultural reclamation issues, and both drains have been considered possible sources of water for Sinai.

The idea of bringing Nile water to Sinai is not new. In 1903, when the Sinai was in British hands, a small group of Englishmen and Zionists visited the northern Sinai coast with the idea that it might be a suitable Jewish homeland. Their 'feasibility study' concluded, however, that water was too difficult to obtain, and the idea was temporarily abandoned [*Bernstein*, 1979]. The British did subsequently bring water to the Sinai. As part of their logistical support for their campaign to retake Sinai from Turkey during World War I, the British generals Murray and Allenby laid a pipeline carrying Nile water through Sinai to Palestine. More recently, the Egyptian General Authority for Desert Reclamation began planning in 1957 for the transport of Nile water under the Suez Canal to Sinai. In 1980 a pipeline running under the Suez Canal (north of the town of Suez) was opened.

The Salaam, or 'Peace', Canal is the backbone of the Ministry of Irrigation's current plan for transporting water to new reclamation areas in the Eastern Delta and Sinai. The Salaam Canal will run from Faraskor eastward just south of Manzala Lake, under the Suez Canal, and then follow the Mediterranean coast to El Arish (Figure 1). It will pick up water from the agricultural drains, which will be mixed with the fresh water from Faraskor. The first phase of the project is scheduled to cost on the order of 250×10^6 L.E.

Numerous questions arise concerning the proposed Salaam Canal. What should its capacity be? Should it be lined to prevent excessive losses or saltwater intrusion? Should a pipeline be used in some areas instead of a canal? What should the ratio be of drainage to Nile water? The design details and cost estimates of the Salaam Canal project are obviously within the expertise of civil and irrigation engineers, but its careful assessment also requires the consideration of broader issues.

For example, the optimal capacity of the canal will depend upon the area to be reclaimed in Sinai, which will in turn be related to the costs of transporting water and its quality when it arrives. Similarly, the appropriate crop rotations and irrigation systems for the reclaimed areas will depend upon the cost of transporting water. The optimal mixture of drainage and Nile water depends not only on the crop yield to salinity relationships of different crops, but also on the different opportunity costs of Nile and drainage water in Egypt. The opportunity cost of diverting drainage water to the Salaam Canal would appear to be very low. Nile water at Faraskor, on the other hand, could have been used to generate more firm hydropower at Aswan or supply growing municipalities or industries. Another broad issue concerns the selection of the optimal route for taking water to Sinai; the proposed route of the Salaam Canal is only one of several.

PROBLEM FORMULATION

This section presents a mathematical formulation of the problem of planning for the cultivation of new areas in the Eastern Delta and in Sinai in order to provide a broad framework for the analysis of some of the questions presented above. There are two primary objectives in transporting Nile water to Sinai: (1) economic: to reclaim land to increase agricultural production and (2) political: to settle Sinai and establish a larger, permanent Egyptian presence. There are many ways in which this general political objective could be formulated for representation in a model. For example, Egyptian decision makers may simply desire to maximize the total area of land reclaimed in the reclamation sites. Alternatively, decision makers may prefer a plan with a few large settlements to another plan with the same total land irrigated but with many small settlements. Similarly, the government may prefer the development of certain areas of the Sinai to others for political or military reasons. The political objective might include a desire that every reclamation site should at least break even economically. Such a constraint may, however, preclude any reclamation in the Sinai itself because the most economically attractive sites are in the Eastern Delta near existing cultivated areas.

Another aspect of the political objective may be a concern for equity: the distribution of the costs and benefits of the reclamation process. The impact of the reclamation efforts on income distribution in Egypt will, however, be largely determined by the financing arrangements negotiated with international lending agencies, the pricing policy for agricultural products, and the form of economic ventures which will be permitted to undertake reclamation efforts. These considerations are beyond the scope of the present analysis.

We do not know which of the many possible formulations of the political objective most accurately characterizes the actual preferences of the Egyptian government. To illustrate the application of the model framework and to reduce the dimensionality of the problem, the political objective has been assumed to be the maximization of the minimum percentage of land reclaimed among the regions. This representation of the political objective does guarantee a fairly equitable distribution of reclaimed land among the reclamation sites [*Cohon and Marks*, 1973].

In this analysis we will use

X_{ijk}	area used to grow crop rotation i in region j with irrigation system k;
Y_{sj}	amount of water shipped annually from source s to region j;
Q_s, Q_j	quality of water at source s and quality of water delivered to region j, respectively (in terms of total dissolved solids);
$P_i(Q_j)$	net revenue from cropping one feddan with crop rotation i as a function of the quality of the irrigation water;
L_k	annualized land reclamation cost per feddan for irrigation system k (assuming a 10-year life for the irrigation equipment and 10% discount rate);
$C_{sj}(Y_{sj})$	annualized cost of transporting water from source s to region j (assuming a 20-year life and 10% discount rate);
$E_{sj}(Y_{sj})$	conveyance losses incurred in transporting water from source s to region j;
R_{ik}	water requirements per feddan for crop rotation i with irrigation system k;
V_s	total annual available supply of water at source s;
A_j	land available for reclamation in region j;
W_s	opportunity cost to the rest of the country of using a unit of water at source s for reclamation projects in the Eastern Delta and Sinai.

Given the objectives of maximizing the annual economic profits from cultivation of the reclaimed lands and maximizing the minimum fraction of the arable area to be cultivated among the reclamation sites, the problem of planning for agricultural development in the Eastern Delta and Sinai can be formulated as follows:

$$\mathrm{Max}_{\{X_{ijk},Y_{sj}\}} \sum_i \sum_j \sum_k [P_i(Q_j)X_{ijk} - L_k X_{ijk} - \sum_s Y_{sj}(C_{sj}(Y_{sj}) + W_s)] \qquad (1a)$$

where Q_j is defined as

$$Q_j = \frac{\Sigma_s(Y_{sj} - E_{sj}(Y_{sj}))Q_s}{\Sigma_s(Y_{sj} - E_{sj}(Y_{sj}))} \qquad \forall j \qquad i, j, k, s \in F \qquad (1b)$$

$$\mathrm{Max}_{\{X_{ijk},Y_{sj}\}}\alpha \qquad (2a)$$

where α is the minimum percentage of land reclaimed among the j regions:

$$\alpha \le \frac{\Sigma_i\Sigma_k X_{ijk}}{A_j} \qquad \forall j \qquad i, j, k \in F \qquad (2b)$$

subject to the following constraints:
Water supply is greater than or equal to water demand:

$$\Sigma_s (Y_{sj} - E_{sj}(Y_{sj})) - \Sigma_i\Sigma_k R_{ik}X_{ijk} \ge 0 \qquad (3)$$

$$\forall j \qquad i, j, k, s \in F$$

Availability of water at each source:

$$\Sigma_j Y_{sj} \le V_s \qquad \forall s \qquad j, s \in F \qquad (4)$$

Availability of land in each region:

$$\Sigma_i \Sigma_k X_{ijk} \le A_j \qquad \forall j \qquad i, j, k \in F \qquad (5)$$

Nonnegativity of the decision variables:

$$X_{ijk}, Y_{sj} \ge 0 \qquad i, j, k, s \in F \qquad (6)$$

The feasibility set F contains all the combinations of i, j, k, s which were considered viable for the purposes of this analysis. In particular, it has been used to ensure that water delivery was from sources at higher elevation than recipient reclamation sites (with the exception of a portion of region 1, discussed later) and that the crop rotation, irrigation method and soil type were compatible for a given reclamation site.

The solution of the model yields values for the decision variables X_{ijk}, the area used to grow crop rotation i in region j with irrigation system k, and Y_{sj}, the annual quantity of water shipped from source s to region j. The use of an annual crop rotation instead of a single crop avoids the additional complexity associated with seasonal variations in crop water requirements and in water opportunity costs [*Thomas and ReVelle*, 1966; *Guariso et al.*, 1979]. The alternative crop rotations considered in the analysis and their respective water requirements are presented in Table 2 and include the major rotations in the Nile Delta plus the possibility of a clover-soybean rotation. The possibility of a two- or three-year crop rotation was not incorporated in this formulation (this would, however, only require the minor modification of a larger time increment). Surface, sprinkler, and drip irrigation systems were considered viable alternatives in the analysis. Surface irrigation was not, however, permitted in reclamation areas with sandy soils.

TABLE 2. Data Input for the Analysis

Crop Rotations		Water Requirements, m³ per feddan	Profits L.E. per feddan
Number	Components		
$i = 1$	Clover-rice	12,442	298
$i = 2$	Clover-cotton	8,701	374
$i = 3$	Clover-maize	7,989	152
$i = 4$	Clover-soybean	8,312	158
$i = 5$	Wheat-maize	8,362	184
Irrigation Systems		Installation Costs, L.E. per feddan	
Number	Type		
$k = 1$	Surface	650.00	
$k = 2$	Sprinkler	1500.00	
$k = 3$	Drip	2500.00	
Reclamation Regions			
Number	Name	Soil Texture	
$j = 1$	Sinai Northern coast	sandy and sandy clay	
$j = 2$	El Tina Plain	sandy and sandy calcareous	
$j = 3$	West of Suez Canal	saline clay	
$j = 4$	North of Salhia Canal	sandy and sandy clay	
$j = 5$	South of Ismailia Canal	sandy and sandy calcareous	
$j = 6$	Area between Salhia and Ismailia Canals	sandy and sandy calcareous	
$j = 7$	South of Manzala Lake	saline clay	
Sources			
Number	Name		
$s = 1$	Ismailia Canal		
$s = 2$	Salhia Canal		
$s = 3$	Port Said Canal		
$s = 4$	Damietta Branch		
$s = 5$	Bahr Hadous		
$s = 6$	Bahr El Baqar		

Six possible sources of water were considered: Ismailia Canal, Salhia Canal, Port Said Irrigation Canal, the Damietta Branch at Faraskor, Bahr Hadous Drain, and Bahr El Baqar Drain. Not all of the twenty-one regions in Figure 1 were included in the analysis. Reasonable alternative water supplies did not seem to exist for reclamation areas 4, 5, 6, 13, 14, 19, and 20. The remaining fourteen reclamation regions were combined into seven areas for purposes of the analysis, as indicated in Table 2.

Several points should be noted about this model formulation. First, large-scale water transport may not be the best technology for meeting the economic objective of settlement of the Sinai. Smaller-scale technology which makes efficient use of the scant winter rains and underground water resources might provide an attractive alternative to the type of intensive agriculture practiced in the Nile Valley. These water resources were not utilized by irrigated agriculture in this analysis because data for the various reclamation sites were not available. However, if the decision is made to extend the intensive, year-round agricultural practices which exist in the Nile Valley into the desert reclamation sites, the minimal rainfall would constitute a trivial percentage of the annual water requirements and thus would have an insignificant effect on the value of the objective function.

Second, the explicit water delivery network is not represented by this model formulation. Water is assumed to be shipped directly from each source to each region. This is an appropriate approximation only if the costs of transporting water are a linear function of the quantity of water shipped and the distance between the source and the reclamation site, which we have assumed in order to simplify the solution of the model. Economies of scale will certainly dictate, however, that water transported to the northern Sinai will only be shipped along one route. In order to partially reflect this fact, the two regions in the northern Sinai are assumed to receive the same quality of water.

Third, all of the water shipped from source s was assumed to be delivered to the center of the reclamation region j, rather than to one of its boundaries, and then distributed. This means that the cost of the delivery network within each region was assumed to be independent of the overall solution.

Fourth, the costs of transporting water do not include any pumping costs for raising water to the reclamation region along the Sinai coast, where 250,000 feddans lie between 5 and 60 m above mean sea level. Adequate data on pumping costs and topography of the region were not available. This omission will make land reclamation in the Sinai look more attractive than it really is likely to be. Recent increases in the price of petroleum may make significant lifts of water for agricultural purposes prohibitively expensive [*Pacific Consultants*, 1980]. Although the introduction of these additional costs will change the value of the economic objective, it will not alter the values of the decision variables. This region along the northern Sinai coast already has the highest water costs because it is the farthest from all the water sources.

Numerous other assumptions have been made to solve the model with the available data. The water quality to crop yield relationships incorporated in the objective function are illustrated in Figure 2 and were obtained by interpolation of experimental data [*Ayers and Westcot*, 1976]. A given crop rotation is assumed to have the same water requirement in all regions and soil types, i.e., R_{ik} is assumed to be the same for all j. The water losses from s to j, $E_{sj}(Y_{sj})$, are assumed in (1b) and (3) to represent seepage, and thus the water lost removes a certain percentage of the salts shipped from the source. Calculations for Upper Egypt have, in fact, shown that total evaporation losses from the irrigation distribution system constitute only a small percentage of the water requirements for irrigated agriculture. Conjunctive use of ground and surface water may be an option in some of the reclamation sites, in which case seepage losses from canals may be partially utilized. Little is presently known, however, about the extent of such possibilities, and they are not considered in the present analysis (or in the government's official plans).

Investment planning evaluations of reclamation projects in the Eastern Delta and Sinai should charge these projects for the water they use on the basis of the opportunities foregone by the rest of the economy: for example, in reduced water available for agriculture in Upper Egypt, for hydropower generation, or for municipal or industrial use. The value of water within Egypt will increase as more water is withdrawn for reclamation because higher-value water users are excluded and will also increase over time due to growth in municipal and industrial water use.

This will be true even assuming the current allocation of water between Egypt and the Sudan as specified in the 1959 Nile Waters Agreement is maintained in the future. The Sudan will, however, utilize its entire allocation of 18.5 ×

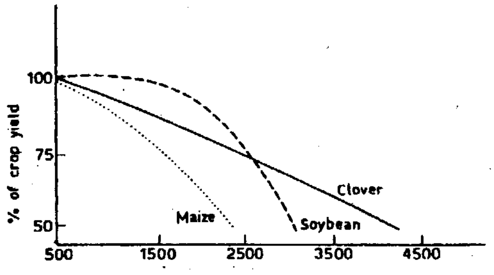

Fig. 2. Sensitivity of maize, soybean, and clover to different salt concentrations of irrigation water.

10^9 m^3 (as measured at Aswan) in the near future, and its share of the benefits of the Upper Nile water conservation projects is already allocated to new irrigation schemes which are scheduled to come on line as the additional water supplies become available. The Sudan will probably face severe water scarcity problems before Egypt, particularly in the Blue Nile region [*Coyne and Bellier et al.*, 1978]. It is likely that the opportunity cost of water in the Sudan and Egypt will be markedly different by the end of the century. At the same time Egypt is likely to be still attempting reclamation of marginal desert lands, the Sudan will have to forego profitable irrigation schemes in areas with good soils. Such a situation will clearly highlight the economic inefficiencies of the current and proposed allocation of water between Egypt and the Sudan and increase the pressure on Egypt for a change in the framework of the 1959 Nile Waters Agreement [*Whittington and Haynes*, 1981].

Unfortunately, data on the opportunity costs of water over time and in different locations, which would permit the incorporation of such issues into this analysis, are not presently available. On the basis of available estimates [*Fitch et al.*, 1981], the opportunity cost of water (W_s) is assumed to be in the range 5–15 L.E. per 1000 m^3 for Nile water ($s = 1, 2, 3, 4$) and constant at all fresh water sources. The opportunity cost of using drainage water from Bahr Hadous and Bahr El Baqar ($s = 5, 6$) is assumed to be zero in the present analysis. This drainage water, which is currently pumped into some of the lakes along the Mediterranean, such as Lake Manzala, may in fact have a small positive value because it helps maintain existing fisheries.

The use of an opportunity cost of water to the rest of the country, W_s, in conjunction with a constraint on the availability of water at each source (4) requires additional explanation. Suppose the constraint on water availability at a source is tight and W_s, the value of water at source s in the next best alternative use in the rest of the economy (i.e., outside the planning region), is zero. In this case the shadow value of water associated with that constraint, call it λ_s^0, is the opportunity cost within the planning region of doing without an additional unit of water from that source. If W_s is positive, the shadow value of water associated with a tight constraint on a fresh water source, call it λ_s^*, is still equal to the opportunity cost of doing without an additional unit of water within the reclamation region, but in this case it is assumed that the reclamation project is charged W_s for each unit of water it receives; thus, $\lambda_s^* = \lambda_s^0 - W_s$. Although W_s is defined as independent of the quantity of water used in the reclamation process, the presence of the canals with finite capacities separates the present system of Egyptian agriculture from the reclamation planning region, placing different opportunity costs on the use of water within the two economic systems.

The final two-objective problem was solved using the well-known constraint method for generating the set of noninferior solutions [*Cohon and Marks*, 1975]. The mathematical model is nonlinear because of the relationship $P_i(Q_j)$ between agricultural profits and water salinity. Taking advantage of the particular model structure, the following two-level procedure was used to efficiently compute each solution. Suppose a certain value of the water quality $\bar{Q}_j$ is set for each region j. Then a linear program can be obtained by substituting $\bar{P}_{ij} = P_i(\bar{Q}_j)$ in (1*a*) and by transforming (1*b*) into the following set of linear constraints:

$$Q_j \Sigma_s (Y_{sj} - E_{sj}(Y_{sj})) - \sum_s [(Y_{sj} - E_{sj}(Y_{sj})) Q_s] = 0 \qquad \forall j \tag{7}$$

This linear program is easily solved for the values of the decision variables X_{ijk} and Y_{sj}. A search over the dimension of the independent variable Q_j can thus solve the overall problem. The computation was performed using an adaptive random search method of the type proposed by *Karnapp* [1963], which in turn utilizes a standard linear programing algorithm as a subroutine.

RESULTS OF THE ANALYSIS

The solution of the model is illustrated graphically in Figure 3, assuming an opportunity cost of Nile water equal to 10 L.E. per 1000 m^3. Each point on this Pareto optimal boundary represents a 'noninferior' reclamation plan with respect to the two objectives of achieving the highest economic benefit and of maximizing the minimum percentage of land reclaimed among the reclamation sites. Any point to the right of the curve is infeasible; any point to the left is suboptimal in the sense that one objective can be increased without decreasing the other. In order to show the nature of the results obtained, Table 3 presents the two extreme solutions for this case: (1) the one which yields the maximum economic benefit and (2) the one which yields the maximum area reclaimed.

Given the highly approximate nature of the data and the assumptions mentioned above, the maximum economic benefit (Table 3, on the left) is obtained with the cultivation of only 447,000 feddans, about one third of the land available for reclamation. If more land is reclaimed, the total economic benefit from reclamation efforts decreases. The net benefits reach zero when about one million feddans are cultivated. This trade-off arises because increases in land

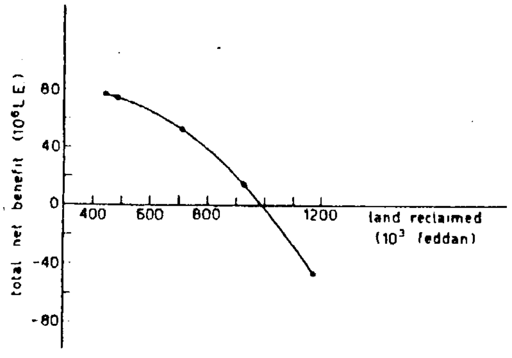

Fig. 3. Tradeoffs between economic benefits and area reclaimed.

TABLE 3. Sample Results from Two Model Solutions

	Maximum Economic Benefit			Maximum Land Reclamation Area		
Region *j*	Source of Irrigation Water	Crop Rotation	Irrigation System	Source of Irrigation Water	Crop Rotation	Irrigation System
1	*			Pt. Said 24† B. Hadous 33 B. Baqar 91	Clover-soybean	Drip
2	Pt. Said 5† B. Baqar 63	Wheat-maize	Sprinkler	B. Hadous 12 B. Baqar 3 Pt. Said 76	Wheat-maize	Drip
3	B. Hadous 85 B. Baqar 10	Clover-cotton	Surface	B. Hadous 51 B. Baqar 6 Damietta 63	Clover-cotton Clover-soybean	Surface Drip
4				Salhia 25	Clover-soybean	Sprinkler
5				Ismailia 11	Wheat-maize	Sprinkler
6	B. Baqar 27	Wheat-maize	Sprinkler	Salhia 29	Wheat-maize	Sprinkler
7	Damietta 16 B. Hadous 8	Clover-cotton	Surface	B. Hadous 4 Damietta 37	Clover-cotton	Surface

*Not used, i.e., no reclamation undertaken in this area.

†Numbers beside the sources of irrigation water represent the percentage of the water available at that source (V_s) used in the specified reclamation area.

reclamation occur farther and farther from the sources of water, which necessitates increased water transport costs. If all the land available is cultivated (Table 3, on the right) Egyptian society will incur a substantial annual economic loss.

Only three of the five possible crop rotations were used in the noninferior reclamation plans. The clover-rice rotation was always excluded because of its high water requirements; the clover-maize was excluded because of its low profitability. Moreover, both rotations are relatively sensitive to the salinity of the irrigation water. All the other crops will be grown in different percentages depending upon the scale of the reclamation effort.

When water is relatively inexpensive, the clover-cotton rotation is selected for reclamation areas with saline, clay soils, and surface irrigation is used. As the area reclaimed increases, however, there is a gradual shift from clover-cotton to a clover-soybean rotation with sprinkler or drip irrigation because the increased costs of transporting water dictate the use of more water-efficient but expensive irrigation systems [*Gisser et al.*, 1979] and crop rotations with lower water requirements. In this analysis, drip irrigation is not used until at least 40% of the land in each site is cultivated. As the minimum percentage of land reclaimed increases to 50% and then 100%, the use of drip irrigation increases to 13% and 65%, respectively. These results emphasize the need for careful planning of the reclamation effort, because if the objective of the Egyptian government is to expand cultivation throughout the potential sites despite the economic losses, then water-efficient irrigation systems may be required even in the reclamation sites close to the sources, where surface irrigation would initially appear to be more suitable.

The decision to use a certain mixture of drainage and fresh water depends on the one hand on the opportunity cost of using fresh Nile water elsewhere in the Nile Valley and its transport costs, versus on the other hand the transport costs of saline water and the reduction in crop yield entailed by its use. All of the noninferior plans presented in Figure 3 use large amounts of drainage water, which with our assumptions reduces crop yields in different percentages depending on the type of crop and the quality of water delivered to a specific region. This analysis suggests that the water delivered to regions 1, 2, and 3 will be relatively saline, resulting in a reduction in crop yield of the order of 5–7%. The salinity of the water delivered to regions 6 and 7, on the other hand, will only marginally impact crop production. In all cases the highest yield reductions are suffered by clover. Regions 4 and 5 are always irrigated with Nile water and are thus not confronted with salinity problems.

As the opportunity cost of using fresh water increases over time, more and more drainage water will be used in the reclamation plans. This implies that mean profits per feddan will decrease because crop yields will decline as a result of the use of more saline irrigation water. A related situation arises if the amount of Nile water available at the source is a binding constraint on the problem (due, for example, to capacity constraints on some canals). In this case, expanding the area to be reclaimed will result in increased use of more saline water. This creates an interesting divergence of interests between the individual farmer in the reclamation area and the central government. If the landholding is fixed, it is not in the interests of the individual farmer for land reclamation efforts in the area to increase because the salinity of his irrigation water will increase. The total collective benefits may, however, increase with the use of this drainage water. Land reclamation efforts must proceed in stages, and the ministries responsible for planning and execution should be careful as to the quality of water they initially promise to deliver to the farmer because the water quality may change substantially as reclamation efforts continue.

The sensitivity of the final result to variations in the value used for the opportunity cost of fresh water is illustrated in Figure 4. The tradeoffs between economic benefits and the area of land reclaimed were calculated for three different opportunity costs of water: 5, 10, and 15 L.E. per 10^3 m^3. The impact of the variation is small in the early stages of reclamation. The values of the objective function in the three solutions differ more and more, however, as the reclamation effort increases. When all the land available is reclaimed, an increase of 5 L.E. in the cost of fresh water results in about a 25% increase in the costs associated with the total reclama-

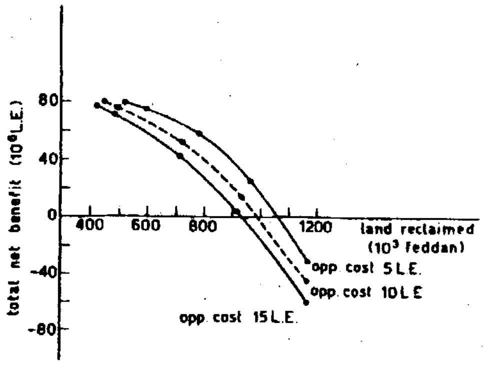

Fig. 4. Sensitivity of trade-offs between economic benefits and area reclaimed to different opportunity costs of water.

tion plan. The values of the decision variables, on the other hand, are relatively insensitive to the variation in the opportunity cost of the Nile water. Regions 2, 3, 6, and 7 are always selected as the most economically profitable locations. In all the noninferior reclamation plans the percentage of land reclaimed in each of these regions was greater than the minimum percentage of land cultivated in the other reclamation sites. For example, assuming an opportunity cost of fresh water of 5 L.E. per 1000 m^3, the highest economic benefit is attained when regions 2, 3, 6, and 7 (which represent about 43% of the total) are completely cultivated.

Finally, Figure 5 compares the original solution (Figure 3) with the one obtained by assuming zero seepage losses along the canals. This sets an upper bound on the benefits which can be achieved by completely lining the main irrigation network. Canal lining could, in fact, be incorporated in the model with another set of decision variables [*Walker et al.*, 1979]. The difference in the two solutions presented shows that costless canal lining causes a 10% improvement in the total net benefit when 500,000 feddans are reclaimed. However, if all the land available is reclaimed, costless canal lining reduces the losses from reclamation to about zero. This situation arises because seepage losses are low when the cultivated regions are close to the sources of water but then increase as the distance of water transport increases. Of course, this is also true for the costs of lining the canals, which depend on the length and the capacity of the canals. Here again the solution in terms of decision variables is not significantly affected, except for reduction in the use of drip irrigation.

CONCLUDING REMARKS

A thoughtful reader will logically wonder whether the distortions introduced into this model from the numerous simplifications and data limitations are too large for there to be any confidence in the solution set generated. We certainly would not argue that this model should be used to make actual investment planning decisions. Reclamation of Sinai and the Eastern Delta on the scale currently envisioned would be a multibillion dollar program which would consume a substantial portion of Egypt's GNP (as well as funds from international donors) for many years, and would have far-reaching implications for the management of the entire Nile basin. To expect solutions from such a modest modeling effort to provide 'answers' to problems this complex would be to misunderstand the use of extremal methods in the planning process.

The value of the analysis presented in this paper does not lie in its ability to identify an 'optimal' reclamation plan or a set of optimal plans for land reclamation in the Eastern Delta and Sinai. Neither the available data nor the model formulation can support such an objective. This model does, however, illustrate some of the complexity of the decisions with regard to water transport and land reclamation in the Eastern Delta and Sinai, and this in itself is of particular value in the existing Egyptian institutional context. The multitude of interrelated questions are not amenable to intuitive answers but require thorough, systematic examination. This will necessitate the development in Egypt of a planning process which can assess the technical and policy options involved in water transfers, land reclamation, and agricultural production.

The model provides a conceptual framework for thinking about the necessary planning and research efforts. For example, the results of the analysis clearly identify several priorities for future work. First, a better understanding of the possibilities for the future canal network is required. The analysis presented in this paper serves to emphasize that the optimal routing and capacity of these canals are dependent upon the opportunity costs of fresh and drainage water and upon the crop rotation and irrigation system selected for each reclamation site.

Second, the analysis should be expanded to address the question of the optimal scheduling of investment for reclamation. The results discussed here raise several interesting issues concerning the timing of project development, which can only be properly explored within the context of a multiperiod model. Third, there has to date been little consideration of the social opportunity costs of using water for the reclamation effort in the Eastern Delta and Sinai. The Egyptian Ministry of Irrigation has yet to address the problem of how limited water supplies should be rationally allocated among competing users. This analysis shows that the entire array of decisions to be made regarding the reclamation effort is sensitive to the value of water in the rest of the economy and that the issue of valuing water cannot be ignored when planning reclamation efforts.

Fourth, all the solutions are obviously dependent upon the assumed crop yields, crop water requirements, irrigation system performance, and land reclamation costs. The magnitude of the investment being contemplated would appear to justify large-scale demonstration projects in order to test

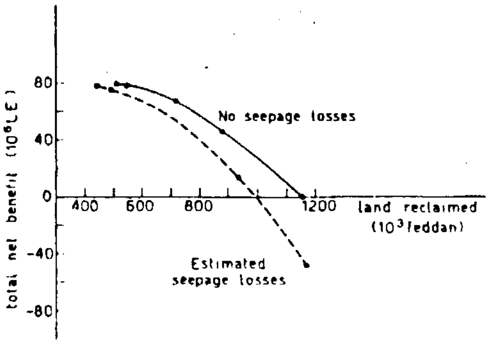

Fig. 5. Sensitivity of trade-offs between economic benefits and area reclaimed to seepage losses in canals.

some of these assumptions before commitments are made to implement a full-scale development plan.

Finally, the model explicitly addresses the fact that there are tradeoffs between the economic and political objectives of land reclamation. The results illustrate that the high costs of water transport to Sinai will entail substantial economic sacrifices if the political objectives are achieved through the use of intensive, year-round agricultural practices such as those in the Nile Valley. This emphasizes the importance of additional research on the possibilities for limited cultivation in Sinai based on small-scale irrigation technology and the use of underground water supplies in order to achieve the political objectives associated with agricultural settlements.

Acknowledgments. We wish to express our appreciation to the International Division, United States Environmental Protection Agency, to the Ford Foundation, and to the Egyptian Academy of Scientific Research and Technology for their support during this research. The authors also appreciate the thoughtful comments of Abe Charnes, Abel Wolman, and Sergio Rinaldi, as well as the valuable criticism provided by the anonymous referees.

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(Received August 4, 1980;
revised March 27, 1981;
accepted July 10, 1981.)