APPLICATION OF SEPARABLE PROGRAMMING TO REGIONAL WATER QUALITY MANAGEMENT

by

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TABLE OF CONTENTS

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Chapter Page

CHAPTER 1

INTRODUCTION

Often interrelated and competing uses of water give rise to complex water quality problems, especially in areas where the available water resources are hardly adequate enough to meet the growing demands. One such area is the Utah Lake drainage area, characterized by growing urbanization and also by extensive water uses for agricultural purposes. Water quality deterioration is caused by both urban and agricultural users. However, the nature of the water quality problems posed by urban and agricultural return flows, respectively, are quite distinct. Urban return flows contain large amounts of bacterial wastes and require treatment to reduce the biochemical oxygen demand (BOD). On the other hand, agricultural return flows contain large amounts of dissolved salts, and pose a salinity problem.

It is quite apparent that any efforts to maintain water quality in the area should aim at coordinating pollution abatement strategies among both types of users, the required water quality standards being met at minimum total costs. This involves setting up a mathematical model for the urban-agricultural water quality control system.

Huntzinger (1971) has carried out a comprehensive study on the future water usage models of Utah Valley to determine the shortages and surpluses of water under present conditions, and those resulting from changing future demands. A number of water management alternatives have been analyzed to determine their relative worth in efficiently utilizing water supply to satisfy present and future water demands. The mathematical model used in this study was originally proposed by Walker, et al., (1973a, 1973b). A number of researchers, (Smith, 1968, Michel, 1970), have developed cost functions for the components of the system. Details of the system flows as well as the associated salt concentrations are given by Walker, et al. (1973b). Walker, et al., (1973a) have solved the resulting optimization problem using the 'Jacobian differential algorithm'. Shojalashkari (1974) has used the generalized reduced gradient method in optimizing the same system. In this study, another simpler nonlinear optimization technique, separable programming, has been used in optimizing the system. The resulting optimal policies are discussed and compared with earlier solutions of Walker, et al., and Shojalashkari. A review of the report by Fuhriman, Merritt, et al. (1975) is also given.

The contents of the report will be briefly presented in the following few paragraphs. The Utah Lake drainage area has been divided into four districts. A brief description of the area and its characteristics is given in the first chapter. The water demands in the area are also presented.

A mathematical model proposed originally by Walker, et al., for coordinating pollution control activities in the urban and agricultural sectors, is discussed. The cost functions associated with the components of the system are also presented. The objective function for the optimization problem and the constraints are then developed. Optimal policies, assuming independent operation of the districts, are determined using separable programming. The results obtained are compared with those of Shojalashkari using the generalized reduced gradient method. A review of the report by Fuhriman, Merritt, et al. follows.

The next chapter explores the benefits resulting from coordinating pollution control strategies among the districts. The so called regional model is developed. The optimal policies are presented and discussed. Once again the results obtained are compared with earlier optimal policies obtained by Shojalashkari.

The following chapter deals with a discussion of the results presented by Walker, et al. (1974). The problem as presented by Walker, et al. was resolved using separable programming. The resulting optimal policies are presented and compared with those of Walker, et al.

Although the presentation of the model and its findings are carried out in the context of the Utah Lake drainage area, the approach is general enough to be applicable to other similar situations.

CHAPTER 2

THE UTAH LAKE DRAINAGE AREA

2.1. DESCRIPTION OF THE AREA

The Utah Lake drainage area is part of the Great Salt Lake drainage area, located in the north central part of Utah, as shown in Fig. 1. It encompasses about 3,356 square miles, and covers a major part of Utah County in addition to areas in four other counties, Sanpete, Juab, Wasatch, and Summit. The drainage area can be hydrologically divided into subareas, as shown in Fig. 2 (Huntzinger, 1971). This study concentrates on the Utah Valley.

As proposed by Walker, et al. (1973b) (see Fig. 3), the Utah Valley drainage area is divided into four districts, namely the Lehi-American Fork District, the Provo District, the Spanish Fork District, and the Elberta-Goshen District. They are being supplied by the American Fork River, Provo River, Spanish Fork River, and Currant Creek, respectively. It is noted that the return flows from Northern Juab Valley constitute the supply source for Currant Creek, and that the Elberta-Goshen District includes the western part of Goshen Valley, which is not supplied by the Spanish Fork River system.

The return flows from the four districts of the Utah Valley are eventually discharged into Utah Lake. Utah Lake is shallow (average depth about 8 ft., maximum depth about 20 ft.), has gently sloping shores, and is almost 19 miles long in the north-south direction, and about 10 miles wide (Huntzinger, 1971). To the east of the lake is

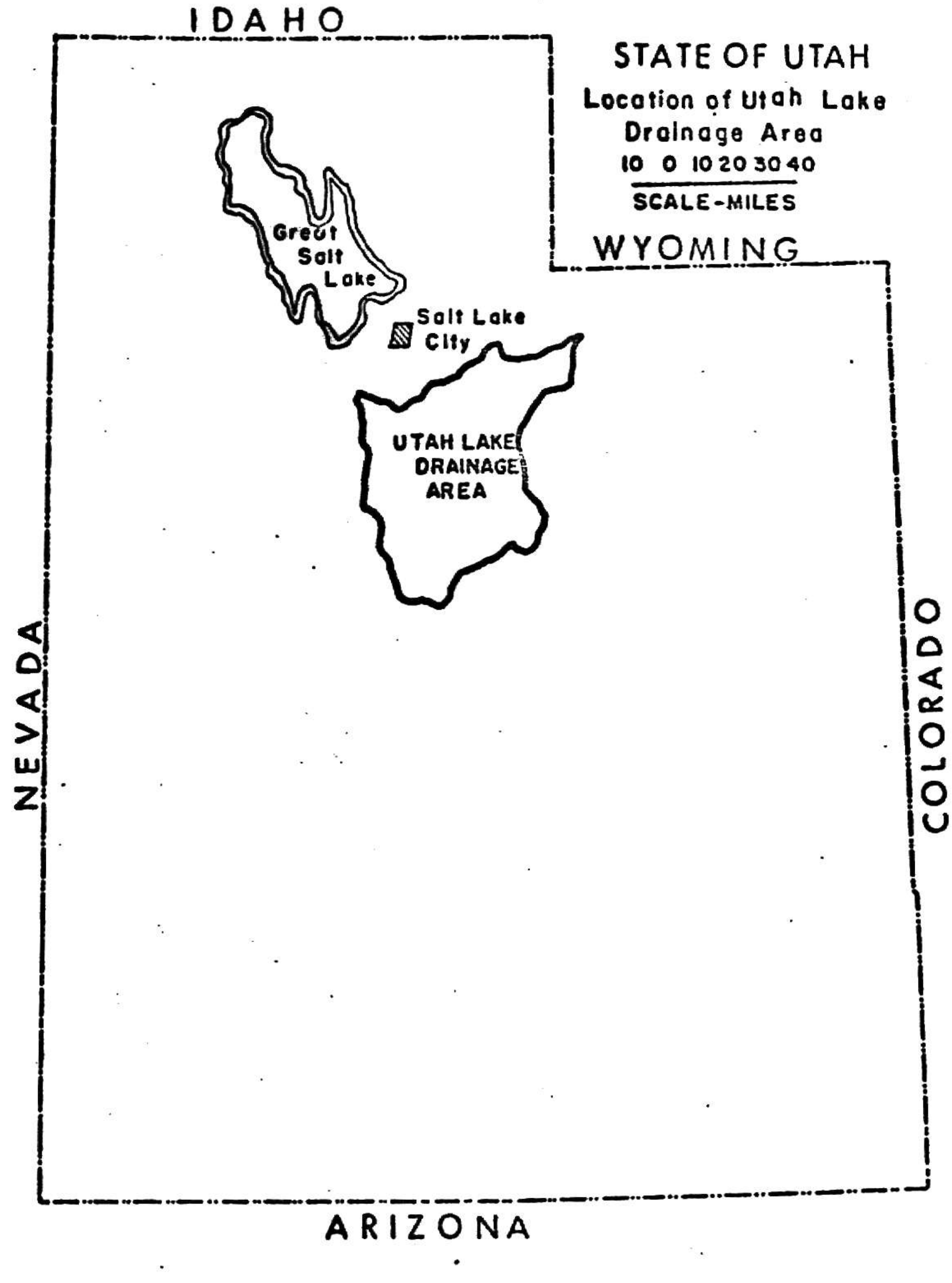

Fig · I · Location of the Utah Lake drainage area [Huntzinger, 1971]

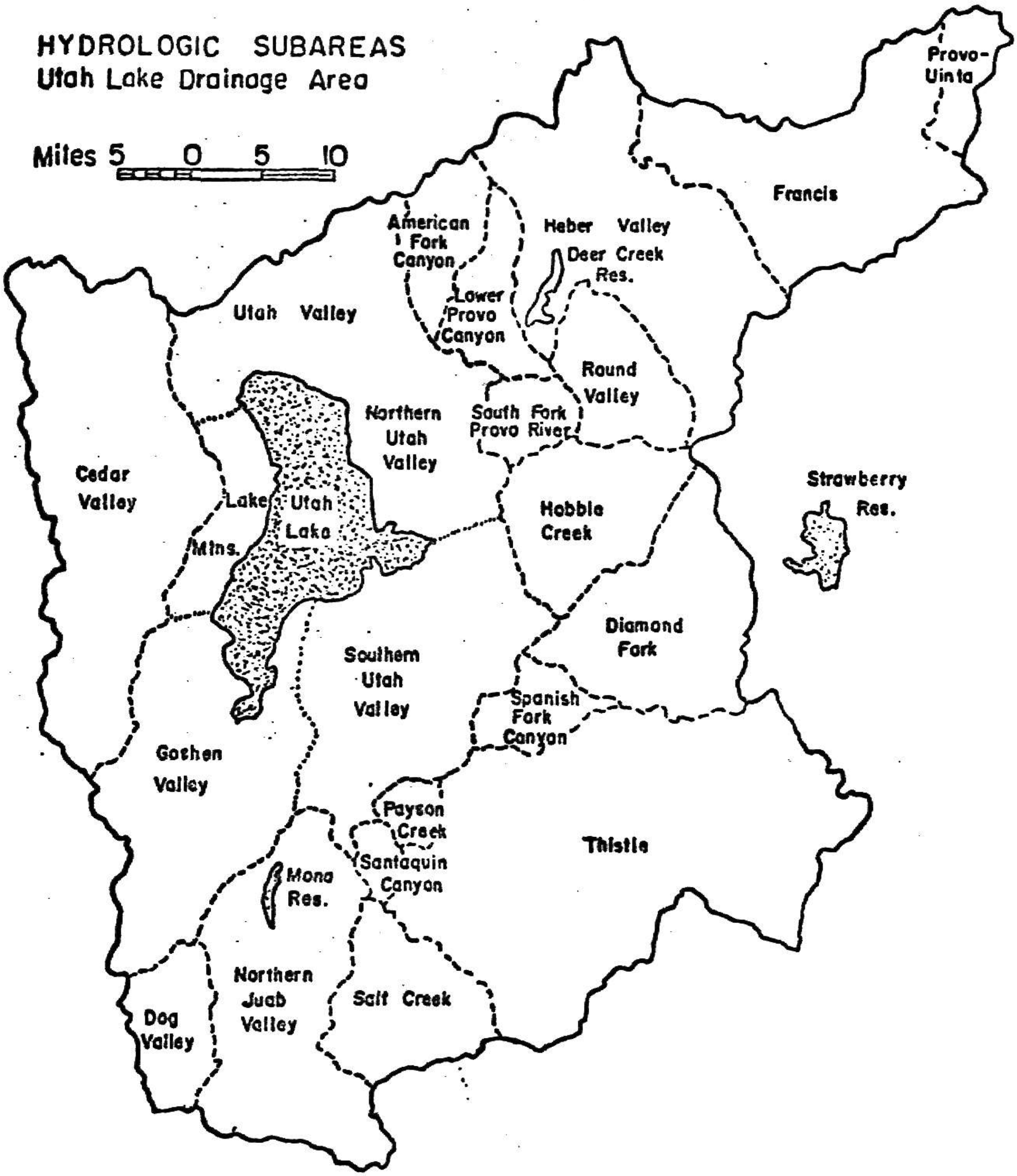

Fig. 2. Hydrologic subareas of the Utah Lake drainage area (Huntzinger, 1971).

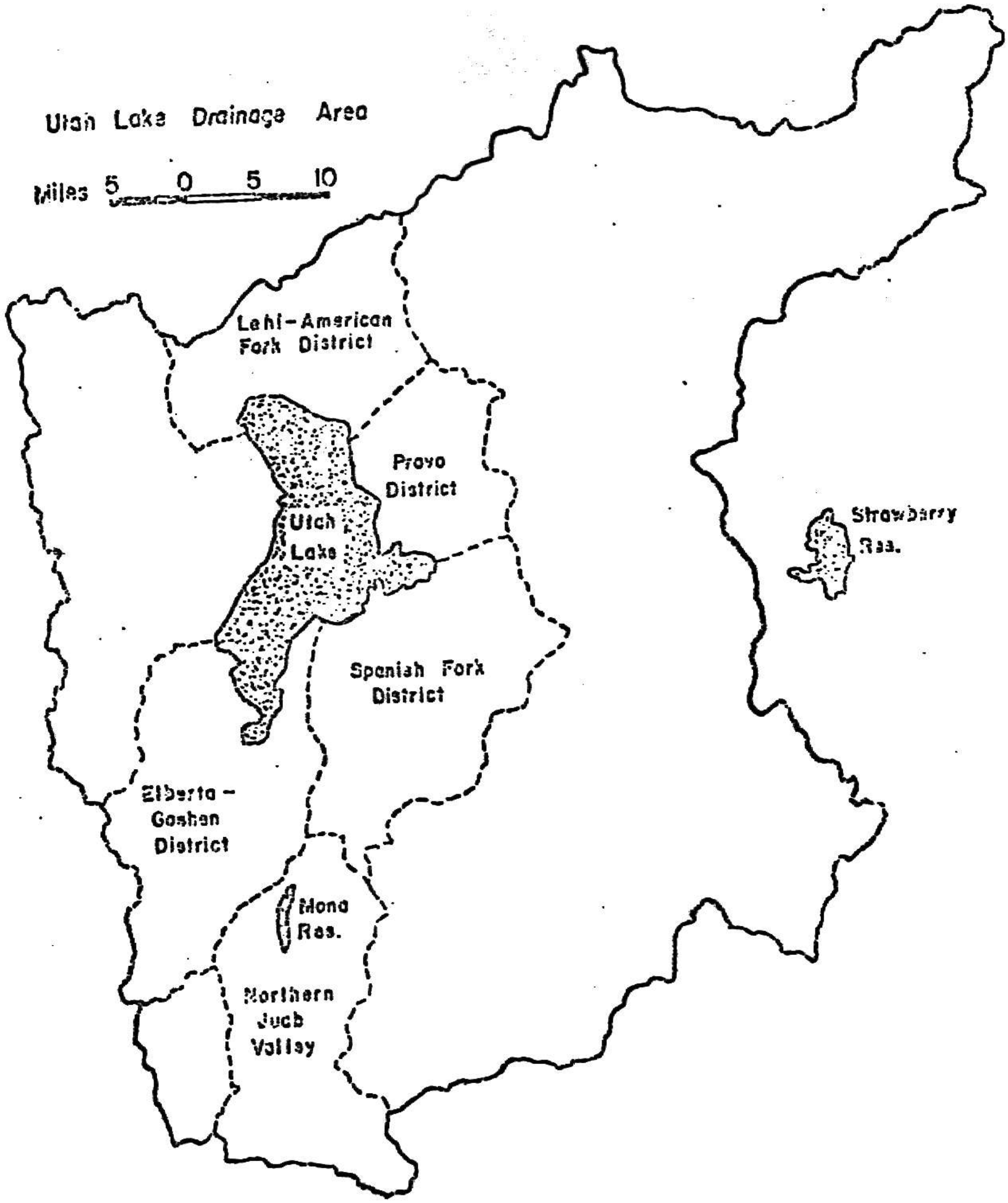

Fig. 3. General map of the Utah Lake drainage area (Huntzinger, 1971).

located a swampy area called Provo Bay which is connected to the Lake through a channel. Utah Lake drains into Great Salt Lake through its outlet, the Jordan River, which runs in a northerly direction.

The Utah Valley has a temperate and arid climate; low rainfall and humidity, high evaporation rate; mild summers and cold winters are also characteristics of the area (Huntzinger, 1971).

2.2. WATER RESOURCES AND DEMANDS IN THE UTAH VALLEY

The major portion of the available water resources in the Utah Lake drainage area are a number of streams and storage reservoirs. In Table 1 the major stream flows in the Utah Lake drainage area are listed. Two major streams of the area are the Provo River with a mean annual flow of 352,200 ac. ft., and the Spanish Fork River with a mean annual flow of 268,200 ac. ft.

The stream flow regulation in the area has been achieved through a number of small reservoirs, principal among them being:1) the Deer Creek Reservoir at the lower end of the Heber Valley. This reservoir supplies the municipal and industrial water demands in Salt Lake County, and discharges about 96,700 ac. ft. per year into the Provo River (Hyatt, et al., 1969); 2) the Strawberry Reservoir in the Uinta Basin which is the source of the interbasin water transfer into the Diamond Fork River through the Strawberry Tunnel; and 3) the Mona Reservoir at the northern edge of the Northern Juab Valley. It holds the return flows of the Northern Juab Valley and Currant Creek, and supplies the water needs of the Elberta-Goshen District. In addition to surface water resources, there are six major ground water sources in the Utah Lake drainage area

Table 1. Mean annual flow of major streams in the Utah Lake drainage area [Hyatt, et al., 1969].

River	Mean Annual Flow, acre-feet
Provo River	
near Kamas	34,300
Duchesne Tunnel	37,200*
Weber-Provo Diversion Canal	56,200*
at Hailstone	214,500
Ontario Tunnel	10,000*
Dry Creek and Fort Creek	20,000
American Fork River	38,200
Battle Creek	4,000
Grove Creek	3,000
Rock Creek	8,000
Hobble Creek	29,500
Spanish Fork River	
at Thistle	56,400
Strawberry Tunnel	60,800*
at Castilla	151,400
Payson Creek	9,400
Summit Creek	8,900
Salt Creek near Nephi	19,300
Currant Creek below Mona Reservoir	15,000
Jordan River	261,000

* Interbasin Transfer

(Walker, et al., 1973b). These are Kamas Valley, Heber Valley, Cedar Valley, Northern Juab Valley, Northern Utah Valley, and Southern Utah Valley, which includes Goshen Valley.

Agricultural activities in the Utah Valley are the single most important source of water use. Of a total of 219,658 acres of cultivated land in the area, about 74% is irrigated. The rest is dry farming. The estimated agricultural water demands under the 1970 conditions were 97,100 ac. ft. for the Lehi-American Fork District, 158,100 ac. ft. for the Provo District, 204,600 ac. ft. for the Spanish Fork District, and 35,600 ac. ft. for the Elberta-Goshen District. Table 2 lists the total agricultural water demands and supplies under the 1970 conditions (Walker, et al., 1973b).

Municipal and industrial water demands in the area, as of the present, constitute only about one-third of the agricultural demands. However, they are expected to increase in the future as urbanization and industrialization in the area increase, and agricultural activities decline. Table 3 shows the present and future urban water demands in the Utah Valley. The data are based on the projections made by the Economic Research Service of the U. S. Department of Agriculture (Huntzinger, 1971).

2.3. POLLUTION SOURCES IN THE UTAH VALLEY

As stated earlier, agricultural activities which are mostly concentrated in the Southern Utah Valley are the major sources of water use in the area. Urbanization in this area has been slow compared to the Northern Utah Valley where population concentration is high. This

Table 2. Annual agricultural water demands in the area under the 1970 conditions [Walker, et al., 1973b] Figures in ac. ft.

Districts	Supply Sources			Total Demand	Actual Agricultural Consumption	Agricultural Return Flows
	Canal Diversion	Precipitation	Pumped Water			
Lehi-American Fork	52,600	17,500	6,600 20,400*	97,100	39,800	57,300
Provo	131,100	19,000	8,000	158,100	74,300	83,800
Spanish Fork	135,400	51,400	17,800	204,600	100,300	104,300
Elberta-Goshen	13,500	10,100	1,200 10,800**	35,600	16,100	19,500

* Pumped water from the Provo District

**Pumped water from the Spanish Fork District

Table 3. Annual urban water demands in the Utah Valley area (Huntzinger, 1971), present and future. Figures in ac. ft.

District	1960		1980		2000		2020	
	Municipal	Industrial	Municipal	Industrial	Municipal	Industrial	Municipal	Industrial
Lehi-American Fork	6,500	1,000	10,700	1,500	17,000	2,200	23,000	3,000
Provo	18,000	64,000	29,800	106,000	48,000	130,000	65,600	144,000
Spanish Fork	2,000	6,000	5,000	7,500	6,700	10,000	7,800	15,000
Elberta-Goshen	250	---	350	---	500	---	750	---

gives rise to water quality problems that are mostly urban in nature in the northern part and agricultural in the southern part of the Valley. However, at the present time, the urban return flows pose a less serious pollution problem than the agricultural return flows with their high concentration of dissolved solids, which do represent a salinity control problem.

Utah Lake is the receiver of urban and agricultural return flows from all the districts. The Lake, in turn, drains into Great Salt Lake by passing through the Jordan River which is located in Utah County and which supplies most of the water needs of the Salt Lake City metropolitan area. Evaporation rate of the Lake being rather high, the salt concentration of the flows leaving the Lake are almost twice that of the inflows (Walker, et al., 1973b), posing a serious salinity problem in the Jordan River. The problem is only expected to become more acute in the future as water demands in the Salt Lake metropolitan area are expected to increase sharply. There is increasing possibility that additional water supplies from the Utah Lake drainage area will be utilized to meet growing demands. Any water quality control program must therefore necessarily address itself not only to the question of urban waste management, but also to the problem of salt concentration in the Utah Lake drainage area.

Water quality management in the Utah Valley can be achieved by any one of several possible approaches. One approach would be to impose quality standards on the Utah Lake or its outlets; another would be to set effluent standards on the return flows entering the Lake. Yet another alternative approach to agricultural salinity control can be initiated by imposing standards on the sources of agricultural water.

In this regard, it must be pointed out that as a result of the anticipated growth of urbanization in the Utah Valley and therefore the need for reallocation of the existing water resources among the competing demands, the state of Utah has devised the Central Utah Project (Walker, et al., 1973a, 1973b). The main features of the project are water transfers from the Colorado River Basin into the Utah Valley, and from the Utah Valley itself to Salt Lake County, and provisions for reducing the evaporation rate in Utah Lake by separating the Goshen and Provo Bays from the main body of the Lake, thus reducing the surface area of the Lake.

CHAPTER 3

THE DISTRICT SALINITY - BOD CONTROL MODEL

This section deals with the development of a mathematical model for representing the salinity-BOD control system. A description of the various system components is given, followed by a discussion of the cost functions for the components. The objective function and the constraints imposed on the model are then defined. The optional policies obtained under the assumptions of individual operation of the districts are presented, followed by a comparison with earlier solutions obtained by Shojalashkari (1974). The report by Fuhriman, Merritt, et al., (1975) is reviewed.

For the purposes of this study, the water quality criteria to be controlled are the total dissolved solids (TDS) and the biochemical oxygen demand (BOD) concentrations. Although the waste treatment facilities remove such pollutants as suspended solids, phosphate, etc., the water quality standards here are limited to TDS and BOD as the two parameters that best characterize the quality (Walker and Skogerboe, 1973), and that are commonly measured and used in the design and monitoring of water quality schemes.

3.1. THE SYSTEM COMPONENTS

Figure 4 shows the schematic diagram of the urban-agricultural salinity-BOD control system for a district (Walker, et al., 1973b). In any district an urban sector and an agricultural sector are distinguished. The urban sector waste water flows, Q_u in million gallons per day (mgd),

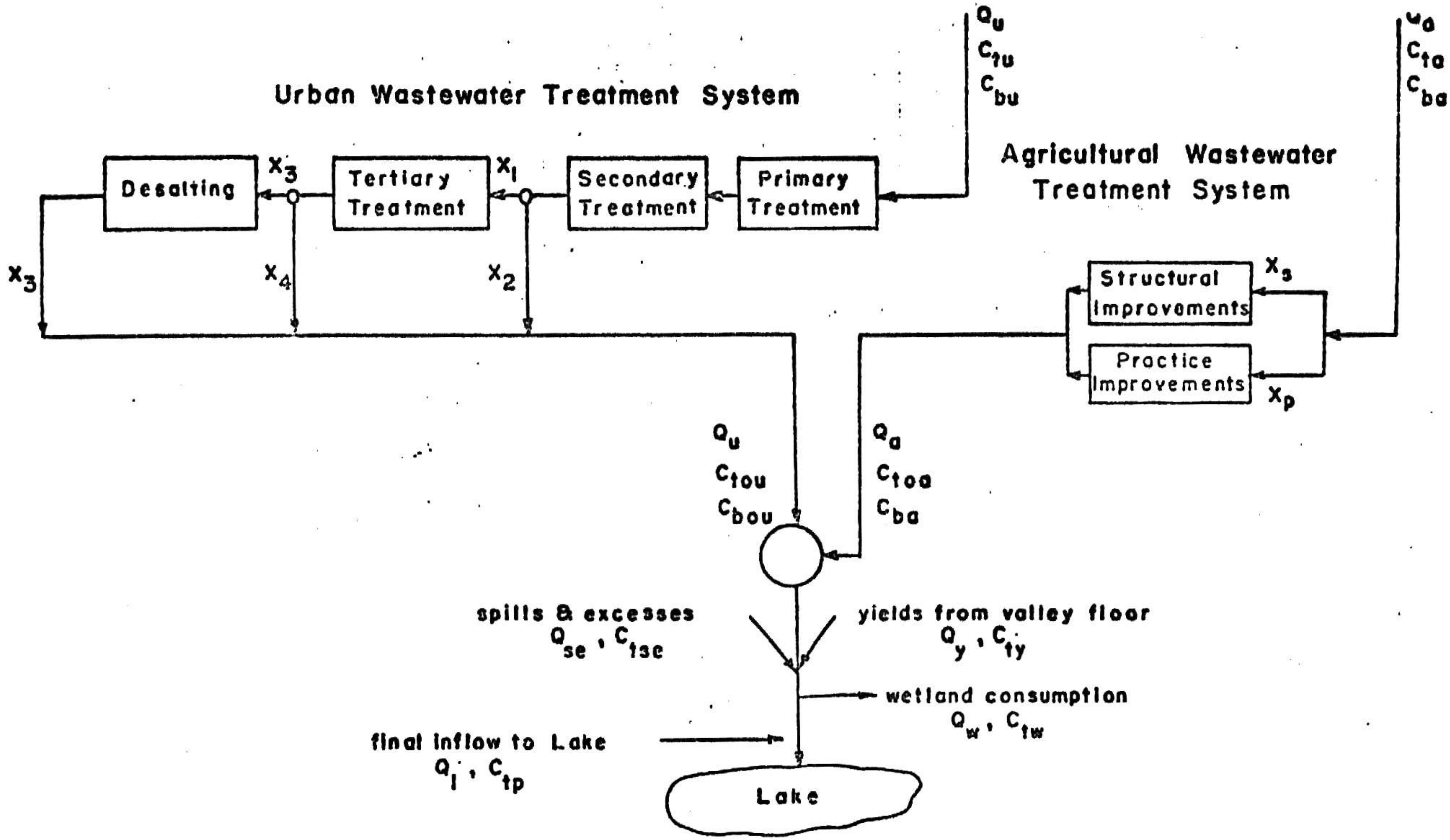

Fig. 4. Schematic diagram of the return flows in a district [Walker, et al., 1973b].

are collected and directed to the primary-secondary treatment unit. These flows have a TDS content of C_{tu} mg/l and a BOD content of C_{bu} mg/l.

At the outlet of the primary-secondary treatment unit, the outflows are divided into two streams, of which X_1 mgd are sent into tertiary treatment for further BOD removal, and X_2 mgd are directed to the effluent channel of the sector. At the outlet of the tertiary unit, of X_1 mgd, X_3 mgd are fed into the desalting plant, and X_4 mgd are directed to the effluent channel. As a result of the various treatments, the effluents from the urban sector have a lower TDS concentration of C_{tou} and a lower BOD content of C_{bou}.

In the agricultural sector it is assumed that BOD concentration of the irrigation flows, C_{ba}, are low enough so that no BOD reduction would be required. On the other hand, the salt content of the agricultural return flows is normally high. Hence salt reduction is required. Salt reduction in the agricultural sector does not involve physical removal of salts in a desalting plant. This would be very expensive as the water has to undergo tertiary treatment before it can be treated in the desalting plant. Otherwise, it fouls up operation of the plant. Irrigation flows are prevented from picking up salt through two kinds of practices (Walker and Skogerboe, 1973):

i) Structural improvements, that is, physical improvements of the irrigation system which reduce the amount of salt picked up by the irrigation flows, employing such measures as canal lining, land leveling, measuring and control structures, delivery of water to the fields only when needed, and in amounts to the demands, even distribution of water into the soil, etc.

ii) Practice improvements, that is, correcting the effects of poor water management. Included under this category are such practices as minimization of surface areas by eliminating unnecessary ponds and marshes, reduction of salt leaching from the soil and granular aquifers by adopting different methods of irrigation in different areas, and reducing the seepage and dumping of surplus flows into natural waste-ways through tighter control of water in the conveyance system.

As a result of the two salinity-control practices described above, the salt content of the agricultural return flows is reduced to C_{toa} mg/l.

The urban and agricultural return flows are then directed into Utah Lake along with three other flows. Spills and excess flows, Q_{se}, in a district are those flows that are not diverted to urban and agricultural uses. Associated with the spills and excesses is a salt content of C_{tse} mg/l. Yields from the valley floor, Q_y, are those flows that originate as surface runoff and deep percolation from precipitation on non-agricultural lands. A TDS concentration of C_{ty} mg/l is associated with these flows. Finally, the wetland consumptive uses are the potential wetland demands less the precipitations in the concerned district. The sum of the agricultural and urban return flows, yields from the valley floor, and spills and excesses minus the wetland consumptive use constitute the total inflow to the Lake, Q_I, from a district.

Figure 5 represents the water and salt balances in the Utah Valley under the 1970 conditions (Walker, et al., 1973b). Table 4 summarizes these data. The data have been compiled and in some cases estimated by Walker and his associates, based on a number of sources including the U. S. Bureau of Reclamation (1964a, 1964b, 1964c), Hyatt, et al., (1969), and Huntzinger (1971). The reader is referred to Walker, et al., (1973b) for details on the methods of analysis and estimation of data as well as the assumptions made to construct the water and salt budget diagram of Fig. 5.

3.2. COST FUNCTIONS FOR THE SYSTEM COMPONENTS

The objective of the district model is to achieve a desired level of salinity-BOD concentration in the return flows from the district at a minimum total annual cost. This section deals with the cost functions used in setting up the objective function.

Beginning with the urban sector, the waste treatment cost information is reported by several researchers (for example, Smith, 1968; Michel, 1970; Shah and Reid, 1970). The cost figures represent the capital costs of equipment as well as operating and maintenance costs.

In what follows, Y_c represents the total capital costs for the equipment in question, in terms of millions of dollars, Y_{om} the operating and maintenance costs in terms of ¢/1000 gallons of water treated, and Z the plant capacity in million of gallons per day (mgd).

For the primary treatment unit, Smith (1968) suggests the following cost functions in terms of 1967 dollars:

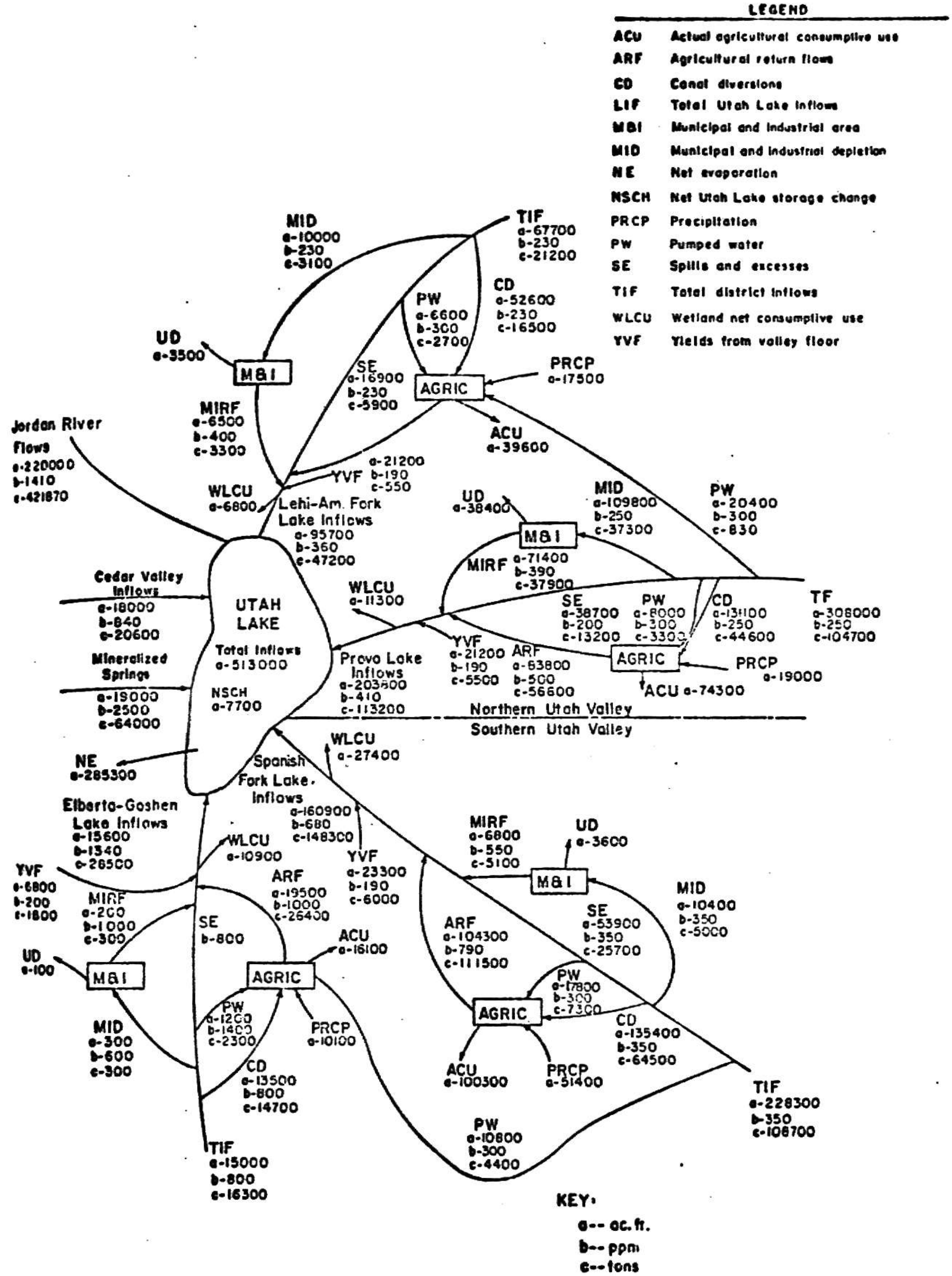

Fig. 5. Water and salt balance diagram for Utah Valley under 1970 conditions [Walker, et al., 1973b].

Table 4. Water and Salt Budget for Utah Valley under 1970 Conditions

Districts	Flows*						Salt Contents, mg/ℓ					BOD Contents, mg/ℓ	
	Urban Sector Q_u	Agricultural Sector Q_a	Yields Q_y	Spills & Excesses Q_{se}	Wetland Consumption Q_w	Total Inflow Q_I	Urban C_{tu}	Agric. C_{ta}	Yields C_{ty}	Spills & Excesses C_{tse}	Present Values C_{tp}	Urban C_{bu}	Agric. C_{ba}
Lehi-American Fork	6,500.0 6.42	57,300.0 56.58	21,200.0 20.93	17,500.0 17.28	6,800.0 6.71	95,700.0 94.50	400	420	190	230	362	180	15
Prove	71,400.0 70.51	83,800.0 82.75	21,200.0 20.93	38,700.0 38.22	11,300.0 11.16	203,800.0 201.25	390	500	190	200	400	180	15
Spanish Fork	6,800.0 6.71	104,300.0 103.0	23,300.0 23.01	53.900.0 53.23	27,400.0 27.06	160,900.0 158.89	550	790	190	350	680	180	15
Elberta-Goshen	200.0 0.20	19,500.0 19.26	6800.0 6.71	0.0 0.0	10900.0 10.76	15,600.0 15.40	1000	1000	200	0.0	1350	185	15

*Figures in the first row are flows in terms of ac. ft., and in the second row in terms of mgd.

**Assumed figures based on information provided by the Utah State Health Division (1974).

$$Y_c = 0.316\ Z^{0.71} \tag{1}$$

$$Y_{om} = 4.47\ Z^{-0.17} \tag{2}$$

For the secondary treatment unit, the following capital cost function in terms of 1967 dollars, is given by Smith (1968):

$$Y_c = 0.58\ Z^{0.80} \tag{3}$$

For the same unit the operating and maintenance cost function, again in 1967 dollars, is given by Michel (1970):

$$Y_{om} = 9.02\ Z^{-0.107} \tag{4}$$

The tertiary treatment unit consists of three components each: flocculation, line treatment, and sedimentation; granular carbon adsorption; and finally ammonia stripping. Each component has capital costs, and operating and maintenance cost functions. Smith (1968) has suggested the following cost functions in terms of 1967 dollars:

$$Y_c = 0.05\ Z^{0.89} \tag{5}$$

$$Y_{om} = 2.99\ Z^{-0.038} \tag{6}$$

for flocculation, lime treatment, and sedimentation;

$$Y_c = 0.398\ Z^{0.65} \tag{7}$$

$$Y_{om} = 10\ Z^{-0.28} \tag{8}$$

for granular adsorption; and

$$Y_c = 0.0398\ Z^{0.90} \tag{9}$$

$$Y_{om} = \begin{cases} 11.58\ Z^{-0.30} & Z \leq 3 \text{ mgd} \quad (10) \\ 1.20\ Z^{-0.04} & Z > 3 \text{ mgd} \quad (11) \end{cases}$$

for ammonia stripping.

The desalting plant is assumed to be of an electrodialysis type for which the following cost functions, in 1967 dollars, are suggested by Smith (1968):

$$Y_c = 0.51\ Z^{0.67} \tag{12}$$

$$Y_{om} = 47.94\ Z^{-0.21} \tag{13}$$

which are for a 4-stage demineralization system with a removal efficiency of 90% (Walker and Skogerboe, 1973).

In the agricultural sector, the costs are of a different nature. As mentioned earlier, the salt pick-up by the irrigation flows is minimized through structural improvements and practice improvements. Walker and Skogerboe (1973) have estimated the relationship between the percentage of salt that can be reduced through the above-mentioned practices, and the percentage of area treated. These relationships are represented in Fig. 6. For example, if 50% of the entire district were to be rehabilitated by both structural improvements and improved irrigation practices, 30% of the salt can be removed through structural improvements and 44% through practice improvements, for a total TDS removal of 74%. If the entire area were to be rehabilitated by both

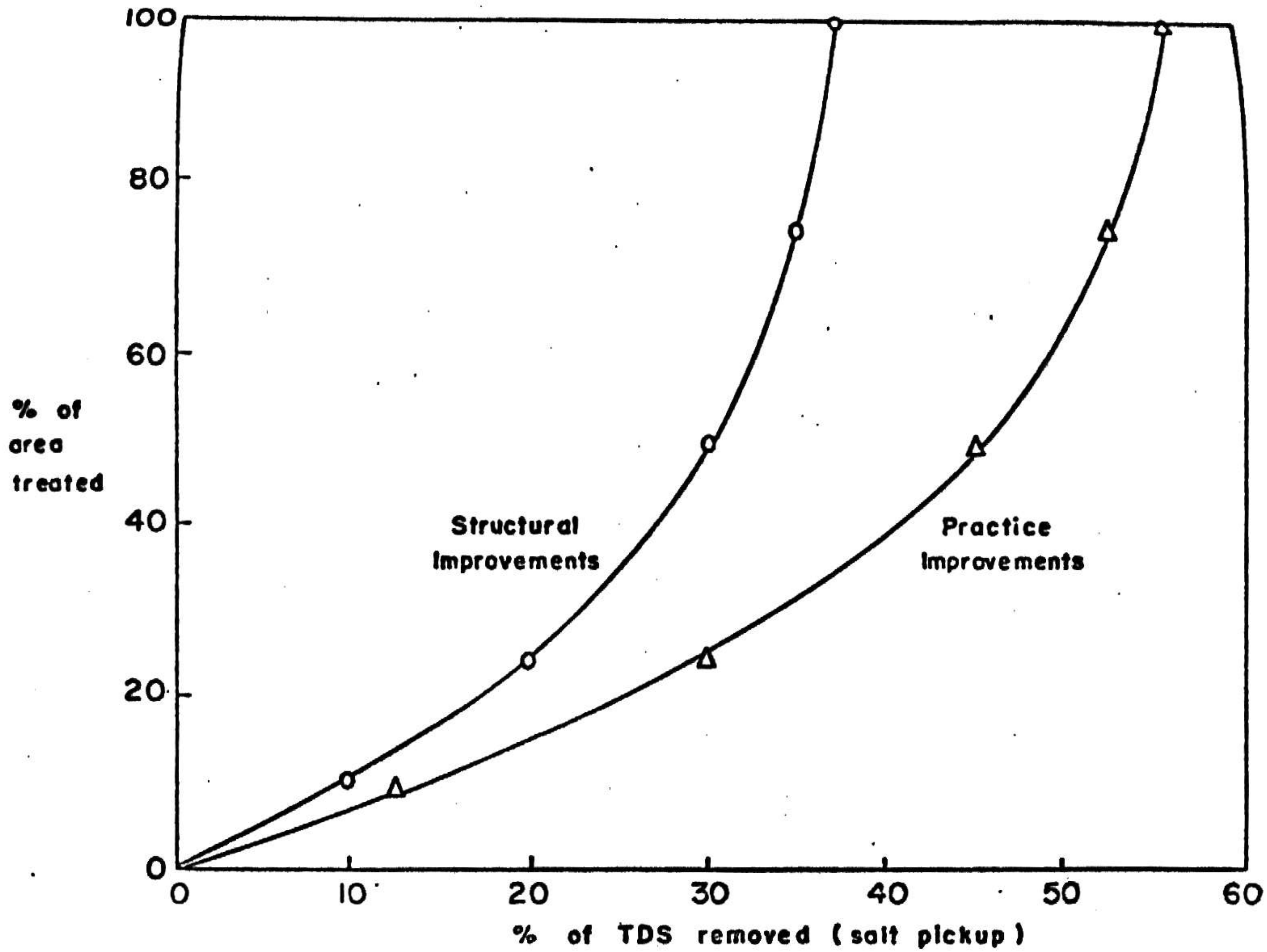

Fig. 6. Cost-effectiveness distributions for agricultural salinity control [Walker, et al., 1973b].

methods, the percentages of salt removed are 37.5% and 56.5% through structural and practice improvements, respectively, and total TDS removed is 94%. Walker, et al., (1973b) have estimated the total annual costs when the entire area in each district is to be rehabilitated through each of the two practices. The salt removal cost through each practice is proportional to the percentage of the area treated.

Let C_s and C_p be the total annual cost of rehabilitating the entire area of a district through structural and practice improvements, respectively. Also, let X_s represent the percentage of the TDS removed through structural improvements. This requires that $f_s(X_s)$ percent of the area be rehabilitated by this method. Similarly, X_p percent removal of TDS by improved practices requires that $f_p(X_p)$ percent of the area be treated by this method. The relationships between $f_s(X_s)$ and X_s, and between $f_p(X_p)$ and X_p are given in Fig. 6. If the percentages of salt reduction through structural and practice improvements are chosen as X_s^* and X_p^* respectively, the percentages of the area treated through each method would be $f_s(X_s^*)$ and $f_p(X_p^*)$, respectively, and the total annual costs of agricultural salinity control in that district is

$$Y_A = C_s f_s(X_s^*)/100 + C_p\ f_p(X_p^*)/100\ . \tag{14}$$

The functional forms of the relations $f_s(X_s)$ and $f_p(X_p)$ are estimated as follows:

$$f_s(X_s) = 34.42\left[3.68135 - \ln\ (39.70 - X_s)\right],\quad X_s \leq 37.50 \tag{15}$$

$$f_p(X_p) = 37.60\left[4.11087 - \ln\ (56.50 - X_p)\right],\quad X_p \leq 56.0 \tag{16}$$

The total annual costs of agricultural rehabilitation, C_s and C_p, are given in the Walker, et al. Report (1973b) and summarized in Table 5.

3.3. FORMULATION OF THE OBJECTIVE FUNCTION

This section and the following one deal with the formulations of the objective function and constraints respectively.

It is noted that in the preceding section the capital costs of the waste treatment facilities were expressed in terms of million dollars, the operating and maintenance costs in terms of ¢/1000 gallons of water treated. In both cases the costs were in 1967 dollars.

In order to convert all the costs into annual costs expressed in 1974 dollars it was assumed that the waste treatment facilities had a useful life of 30 years, that the interest rate for the purpose of capital recovery was 6% per year, and that a load-factor of 330 on-stream days per year would suffice. The costs were then increased by 44% to account for the rate of inflation since 1967 (Business Week, 1974). Under these assumptions the cost functions for the waste treatment equipment are:

i) Primary Treatment Unit

$$Y_c = 1.44 \times (0.316\ Z^{0.71}) \times 10^6 \times 0.07265$$

$$= 3.31 \times 10^4\ Z^{0.71} \tag{17}$$

where the capital recovery rate factor for a life of 30 years and an interest rate of 6% per year is .07265;

Table 5. Total Annual Agricultural Salinity Control Costs

District	C_s	C_p
Lehi-American Fork	$704,840	$2,544,270
Provo	914,510	2,984,570
Spanish Fork	1,302,060	7,855,670
Elberta-Goshen	527,260	1,698,070

$$Y_{om} = 1.44 \times (4.47\ Z^{-0.17})(\frac{1}{100}\ \frac{\$}{¢})\ (Z\ \frac{\text{million gallons}}{\text{day}})$$

$$(10^6\ \frac{\text{gallons}}{\text{mgd}})(\frac{1}{1000} \times \frac{1}{\text{gallons}}) \times 330\ \frac{\text{days}}{\text{year}}$$

$$= 1.44 \times 330 \times 10 \times (4.47\ Z^{-0.17 + 1})$$

$$= 2.12 \times 10^4\ Z^{0.83} \qquad (18)$$

ii) Secondary Treatment Unit

$$Y_c = 1.44 \times 0.58\ Z^{0.80} \times 10^6 \times 0.07265$$

$$= 6.07 \times 10^4\ Z^{0.80} \qquad (19)$$

$$Y_{om} = 1.44 \times 9.02\ Z^{-0.107} \times 330 \times 10\ Z$$

$$= 4.29 \times 10^4\ Z^{0.893} \qquad (20)$$

iii) Tertiary Treatment Unit

$$Y_c = 1.44 \times 10^6 \times (0.07265 \quad 0.05\ Z^{0.89} + 0.398\ Z^{0.65} + 0.0398\ Z^{0.90})$$

$$= 5.23 \times 10^3\ Z^{0.89} + 4.16 \times 10^4\ Z^{0.65} + 4.16 \times 10^3\ Z^{0.90} \qquad (21)$$

$$Y_{om} = (1.44 \times 330 \times 10\ Z)\left\{ 2.99\ Z^{-0.038} + 10\ Z^{-0.28} + \begin{Bmatrix} 11.58\ Z^{-0.30} & Z \leq 3 \text{ mgd} \\ 1.20\ Z^{-0.04} & Z > 3 \text{ mgd} \end{Bmatrix} \right\}$$

$$= 1.42 \times 10^4 Z^{0.962} + 4.75 \times 10^4 Z^{0.72}$$

$$+ \begin{cases} 5.50 \times 10^4 Z^{0.70}, & Z \leq 3 \text{ mgd} \\ 5.70 \times 10^3 Z^{0.96}, & Z > 3 \text{ mgd} \end{cases} \quad (22)$$

iv) Desalting Unit

$$Y_c = 1.44 \times 0.51 Z^{0.67} \times 10^6 \times .07265$$

$$= 5.34 \times 10^4 Z^{0.67} \quad (23)$$

$$Y_{om} = 1.44 \times 47.94 Z^{-0.21} \times 330 \times 10 Z$$

$$= 22.76 \times 10^4 Z^{0.79} \quad (24)$$

Referring to Fig. 4, the objective function for any district i can now be written as:

$$\begin{aligned} Y_{D,i} = {} & 3.31 \times 10^4 (X_{1,i} + X_{2,i})^{0.71} + 2.12 \times 10^4 (X_{1,i} + X_{2,i})^{0.83} \\ & + 6.07 \times 10^4 (X_{1,i} + X_{2,i})^{0.80} + 4.29 \times 10^4 (X_{1,i} + X_{2,i})^{0.893} \\ & + 5.23 \times 10^3 X_{1,i}^{0.89} + 4.16 \times 10^4 X_{1,i}^{0.65} + 4.16 \times 10^3 X_{1,i}^{0.90} \\ & + 1.42 \times 10^4 X_{1,i}^{0.962} + 4.75 \times 10^4 X_{1,i}^{0.72} \\ & + \begin{cases} 5.50 \times 10^4 X_{1,i}^{0.70}, & X_{1,i} \leq 3 \text{ mgd} \\ 5.70 \times 10^3 X_{1,i}^{0.96}, & X_{1,i} > 3 \text{ mgd} \end{cases} \end{aligned}$$

$$+ 5.34 \times 10^4 X_{3,i}^{0.67} + 22.76 \times 10^4 X_{3,i}^{0.79}$$

$$+ C_{s,i} \times 34.42 \left[3.68135 - n\,(39.70 - X_{s,i})\right]/100$$

$$+ C_{p,i} \times 37.60 \left[4.11087 - n\,(56.50 - X_{p,i})\right]/100$$

$$i = 1,2,3,4. \tag{25}$$

3.4. CONSTRAINTS IMPOSED ON THE SYSTEM

The constraints on the system may be classified into two types: constraints on the physical flows in the system, and constraints on the BOD and TDS concentrations of the district effluents. Referring to Fig. 4, the following constraints on the physical flows are evident:

$$g_{1,i}(\bar{X}) = X_{1,i} + X_{2,i} - Q_{u,i} = 0 \tag{26}$$

$$g_{2,i}(\bar{X}) = X_{2,i} + X_{3,i} + X_{4,i} - Q_{u,i} = 0 \tag{27}$$

$$i = 1,2,3,4.$$

In the formulation of the BOD and TDS constraints, the salt content C_{tou} and the BOD content C_{bou} can be calculated as follows:

$$C_{tou,i} = \frac{(X_{2,i} + X_{4,i})C_{tu,i} + (1-e_d)\,C_{tu,i}\,X_{3,i}}{X_{2,i} + X_{3,i} + X_{4,i}}$$

$$= \frac{(X_{2,i} + X_{4,i})C_{tu,i} + (1-e_d)\,C_{tu,i}\,X_{3,i}}{Q_{u,i}} \tag{28}$$

$$C_{bou,i} = \frac{X_{2,i}\,(1-e_{ps})C_{bu,i} + (X_{3,i} + X_{4,i})(1-e_t)(1-e_{ps})C_{bu,i}}{X_{2,i} + X_{3,i} + X_{4,i}}$$

$$= \frac{X_{2,i}\,(1-e_{ps})C_{bu,i} + (X_{3,i} + X_{4,i})(1-e_t)(1-e_{ps})C_{bu,i}}{Q_{u,i}} \tag{29}$$

where

e_d = salt removal efficiency of the desalting unit = 0.90

e_{ps} = BOD removal efficiency of the primary-secondary units combined = 0.85

e_t = BOD removal efficiency of the tertiary unit = 0.99.

In the agricultural sector, the salt content of the return flows C_{toa}, is related to the percentages of salt removal by structural and practice improvements, $X_{s,i}$ and $X_{p,i}$, through the following relationship (Walker and Skogerboe, 1973):

$$X_{s,i} + X_{p,i} = 100 \times \frac{C_{ta,i} - C_{toa,i}}{C_{ta,i} - C_{tmin,i}} \tag{30}$$

where $C_{ta,i}$ is the salt content of the irrigation flows before the rehabilitation, and $C_{tmin,i}$ is the minimum salt content that can be achieved in district i. It may be recalled that the maximum possible salt reduction through structural and practice improvements is 94% of the salt picked up, $C_{tmin,i}$ would, therefore, be equal to 6% of $C_{ta,i}$. Hence, the value of $C_{toa,i}$ from eq. (30) is:

$$C_{toa,i} = C_{ta,i} - \frac{.94}{100} C_{ta,i} (X_{s,i} + X_{p,i}) \tag{31}$$

As no BOD treatment is assumed in the agricultural sector in this model, the original BOD concentration $C_{ba,i}$ remains unchanged.

The balance equations can now be written for the BOD and TDS concentrations at the point of entry into the Lake, to represent the BOD and TDS constraints:

$$Q_{u,i} C_{bou,i} + Q_{a,i} C_{ba,i} \leq (Q_{u,i} + Q_{a,i}) \times BOD_{std}, \qquad i = 1,2,3,4 \tag{32}$$

$$Q_{u,i} C_{tou,i} + Q_{a,i} C_{toa,i} + Q_{se,i} C_{tse,i} + Q_{y,i} C_{ty,i} \leq Q_{I,i} \times (C_{tp,i} - TDS_{std}), \qquad i = 1,2,3,4 \tag{33}$$

where BOD_{std} is the BOD standard imposed on the system outflows, $C_{tp,i}$ is the present concentration of salt in the district's effluents, TDS_{std} is the salt reduction standard imposed on the district's effluents, and $Q_{I,i}$ is the total inflow into the Lake from district i (see Table 4) and is defined as:

$$Q_{I,i} = Q_{u,i} + Q_{a,i} + Q_{se,i} + Q_{y,i} - Q_{w,i} \tag{34}$$

Substituting eqs. (28), (29), and (31) into eqs. (32) and (33) gives:

$$g_{3,i}(\bar{X}) = X_{2,i} (1-e_{ps}) C_{bu,i} + (X_{3,i} + X_{4,i})(1-e_t)(1-e_{ps}) C_{bu,i} + Q_{a,i} C_{ba,i} - (Q_{u,i} + Q_{a,i}) \times BOD_{std} \leq 0 \tag{35}$$

$$g_{4,i}(\bar{X}) = (X_{2,i} + X_{4,i})\, C_{tu,i} + (1-e_d)\, C_{tu,i}\, X_{3,i}$$

$$+ Q_{a,i}\; C_{ta,i} - \frac{.94}{100}\, C_{ta,i}(X_{s,i} + X_{p,i})$$

$$+ Q_{se,i}\, C_{tse,i} + Q_{y,i}\, C_{ty,i} - Q_{I,i} \times (C_{tp,i} - TDS_{std}) \leq 0$$

$$i = 1,2,3,4 \qquad (36)$$

The optimization problem for a district, therefore, is to minimize the total annual costs $Y_{D,i}$, as given by eq. (25), subject to the constraints, $g_{1,i}(\bar{X})$ through $g_{4,i}(\bar{X})$ as represented by eqs. (26), (27), (35), and (36).

3.5. APPLICATION OF SEPARABLE PROGRAMMING TO THE DISTRICT MODEL

Separable programming is a special class of nonlinear programming that can be adapted to linear programming. Separable programming problems must be of the form:

maximize or minimize

$$C(\bar{X}) = \sum_{i=1}^{m} f_i(X_i) \qquad (37)$$

subject to

$$\sum_{i=1}^{m} g_{ki}\,(X_i) \leq b_k \quad , k = 1,2...P \qquad (38)$$

and

$$X_i \geq 0 \quad , i = 1,2...\, m \qquad (39)$$

It is noted that the objective function and the constraints are constructed of separable functions. Approximation of the nonlinear separable functions by piecewise linear functions yields a restricted linear programming problem which can be solved by a revised simplex method. MPS/360 has the necessary revision. For more details the reader is referred to Hadley (1964) and Williams (1972).

Often the nonlinear programming problem has some terms that are not separable functions. However, simple mathematical manipulations like taking logarithms or substitutions, yield separable functions. Once again the reader is referred to Hadley (1964) for more details.

It may be pointed out that in the optimization problem under discussion, the objective function, $Y_{D,i}$, represented by eq. (25) is not entirely made up of separable functions. However, it may be easily converted to the required form if we substitute

$$X_{7,i} = X_{1,i} + X_{2,i} \tag{40}$$

The separable programming problem is then:

Minimize

$$\begin{aligned} Y_{D,i} = {} & 3.31 \times 10^4 X_{7,i}^{0.71} + 2.12 \times 10^4 X_{7,i}^{0.83} + 6.07 \times 10^4 X_{7,i}^{0.80} \\ & + 4.29 \times 10^4 X_{7,i}^{0.893} + 5.23 \times 10^3 X_{1,i}^{0.89} + 4.16 \times 10^4 X_{1,i}^{0.65} \\ & + 4.16 \times 10^3 X_{1,i}^{0.90} + 1.42 \times 10^4 X_{1,i}^{0.962} + 4.75 \times 10^4 X_{1,i}^{0.72} \\ & + \begin{cases} 5.50 \times 10^4 X_{1,i}^{0.70} & \text{, if } X_{1,i} \leq 3 \text{ mgd} \\ 5.70 \times 10^3 X_{1,i}^{0.96} & \text{, if } X_{1,i} > 3 \text{ mgd} \end{cases} \end{aligned}$$

$$+ 5.34 \times 10^4 X_{3,i}^{0.67} + 22.76 \times 10^4 X_{3,i}^{0.79}$$

$$+ C_{s,i} \times 34.42 \left[3.68135 - \ln (39.70 - X_{s,i})\right]/100$$

$$+ C_{p,i} \times 37.60 \left[4.11087 - \ln (56.50 - X_{p,i})\right]/100$$

$$i = 1,2,3,4 \tag{41}$$

subject to the constraints

$$X_{1,i} + X_{2,i} = Q_{u,i} \tag{42}$$

$$X_{2,i} + X_{3,i} + X_{4,i} = Q_{u,i} \tag{43}$$

$$X_{2,i} (1-e_{ps}) X_{bu,i} + X_{3,i} (1-e_t)(1-e_{ps}) X_{bu,i}$$

$$+ X_{4,i}(1-e_t)(1-e_{ps}) X_{bu,i} \leq (Q_{u,i} + Q_{a,i}) \times BOD_{std}$$

$$- Q_{a,i} C_{ba,i} \tag{44}$$

$$X_{2,i} C_{tu,i} + X_{4,i} C_{tu,i} + (1-e_d) C_{tu,i} X_{3,i}$$

$$- \frac{0.94}{100} Q_{a,i} C_{ta,i} X_{s,i} - \frac{0.94}{100} Q_{a,i} C_{ta,i} X_{p,i} \tag{45}$$

$$\leq Q_{I,i} (C_{tp,i} - TDS_{std}) - Q_{a,i} C_{ta,i} - Q_{se,i} C_{tse,i} - Q_{Y,i} C_{ty,i}$$

$$X_{1,i} + X_{2,i} - X_{7,i} = 0 \qquad i = 1,2,3,4 \tag{46}$$

The computer output of a problem typical of those solved in this report is presented in the appendix. It is apparent that the arithmetic involved in setting up a separable programming problem for the revised simplex method is very cumbersome. For this reason, a

FORTRAN program that was developed by Williams (1972) has been used. The program does all the necessary calculations to linearize the nonlinear separable functions of the problem, and produces punched input data in MPS/360 format. To this punched output are added the following cards:

1) Cards defining the objective functions and the constraints.
2) Cards for the linear portions of the separable programming problem.
3) Cards defining the right hand sides of the constraints.
4) The necessary control cards.

In solving the problems all the nonlinear separable functions were linearized over 10 partitions.

3.6. OPTIMAL POLICIES FOR THE DISTRICT MODEL

In this section the water quality control policies in each district in the Utah Lake drainage area are considered. At present the high concentration of TDS poses the most serious water quality problem in the area. However with increasing urbanization in the area, the question of municipal and industrial wastes is sure to cause some concern, if not now, in the near future. Thus, in regions like the Utah Lake drainage area, where both urban and agricultural activities prevail side by side, comprehensive water quality management programs must be developed that focus on coordination between urban and agricultural pollution control on a large scale.

In this section, coordinated salinity-BOD control policies for each district are determined under present conditions. In the solutions obtained, it has been assumed that each district is to satisfy the water quality standards individually. Such a policy will be referred to as a 'district policy' in further considerations.

It may be recalled that the optimization problem in separable programming form is to minimize the objective function, $Y_{D,i}$, represented by eq. (41) subject to the constraints as given by eqs. (42) through (46) respectively.

The values of the parameters in these equations, $C_{s,i}$ $C_{p,i}$, the various flow rates, and the influent salt and BOD concentrations are given in Tables 4 and 5.

At the present time, a BOD standard of 25 mg/l in the district's effluents is in force (Utah State Health Division, 1974), therefore this standard is used in each district. Since there are no specific salt concentration standards as of now, the value of the salt reduction standard (TDS), was artificially varied over a wide range to investigate the resulting changes in optimal policies.

Separable programming is used as the method of optimization in each district. The reader is referred to Williams (1972) for details about the computational procedures for the method. A typical computer output is attached in Appendix A.

In Figs. 7 through 10, the total annual costs as well as the sector costs of salinity-BOD control are presented for districts 1 through 4, respectively. It might be observed that all the districts

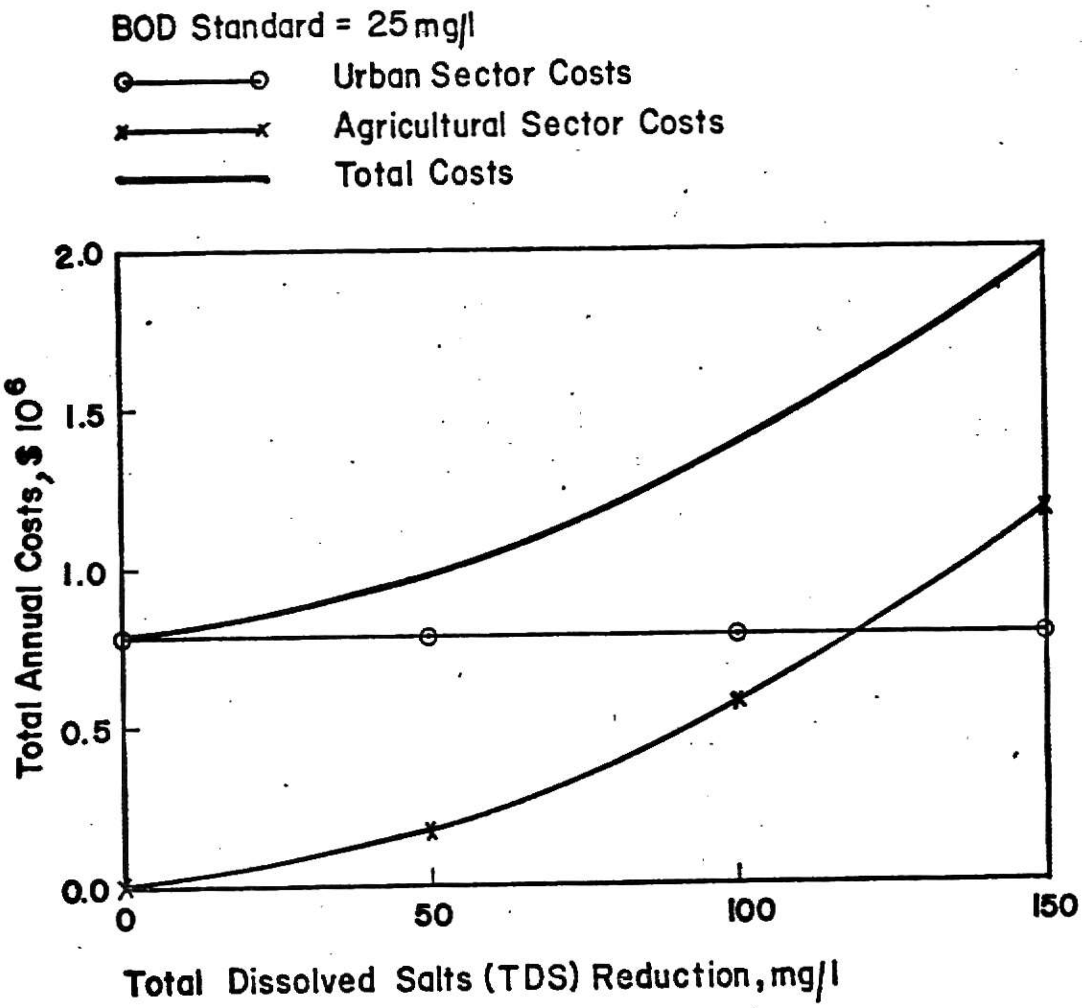

Fig. 7. Total annual costs vs. TDS reduction in the Lehi-American Fork District.

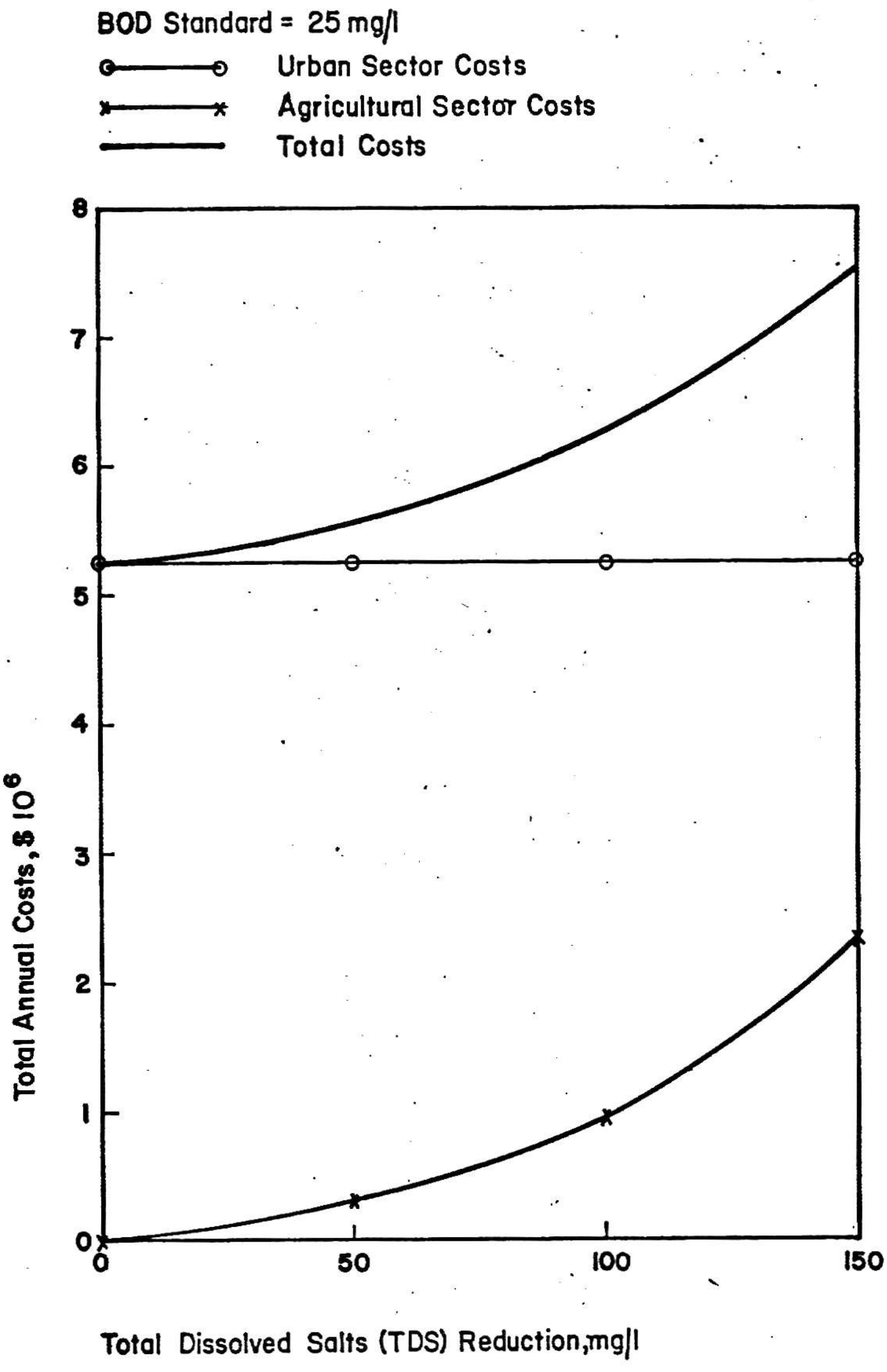

Fig. 8. Total annual costs vs. TDS reduction in the Provo District.

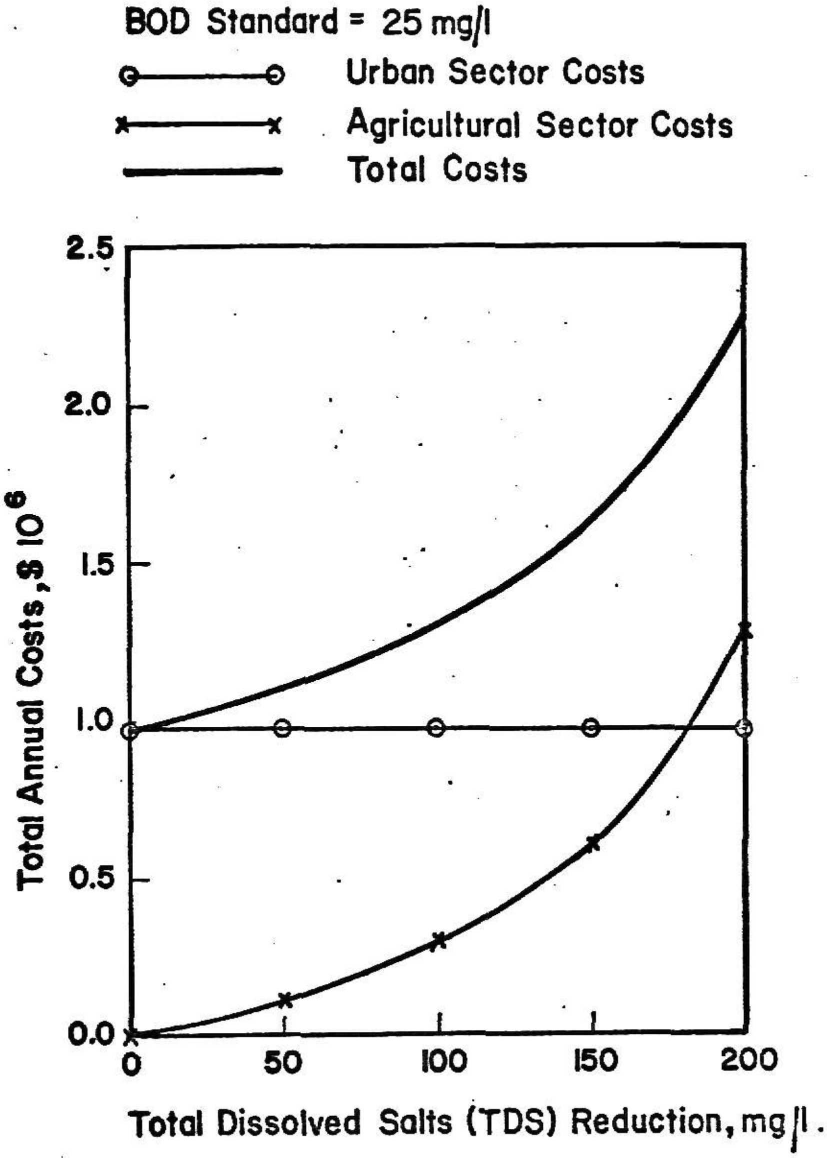

Fig. 9. Total annual costs vs. TDS reduction in the Spanish Fork District.

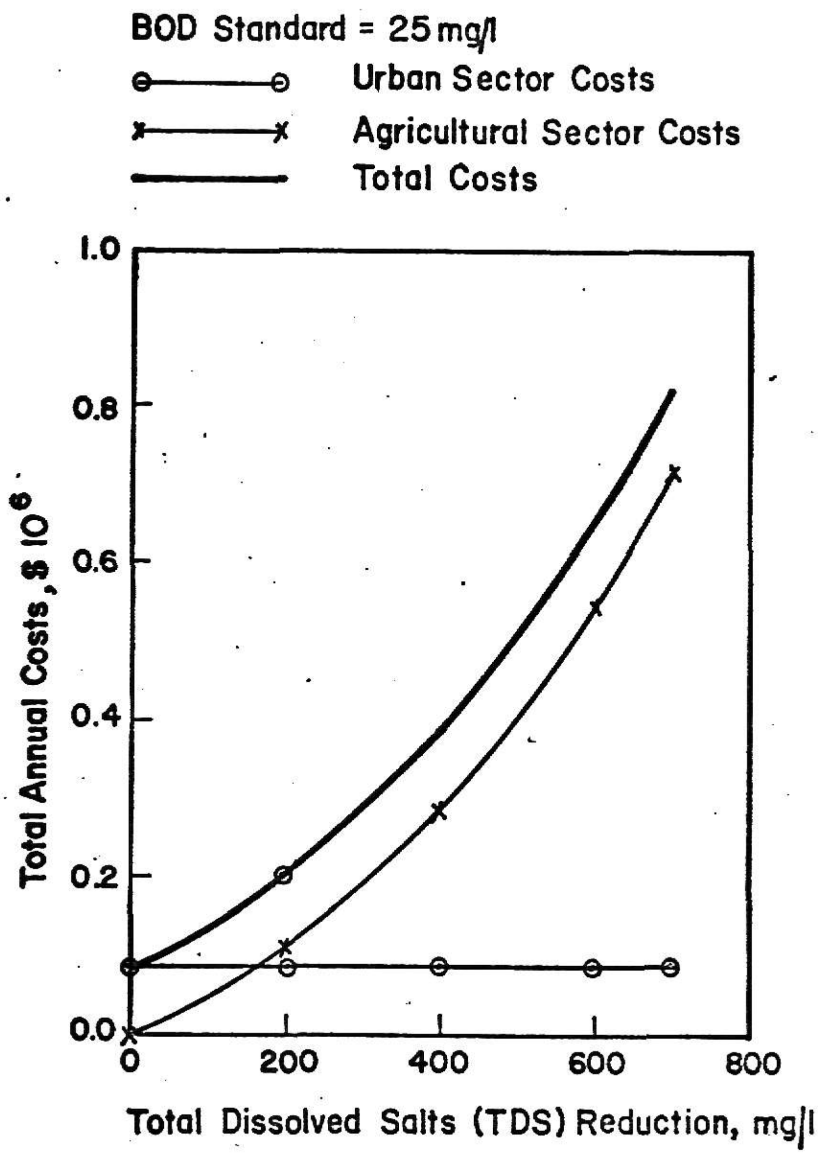

Fig. 10. Total annual costs vs. TDS reduction in the Elberta-Goshen District.

exhibit an increasing marginal cost, implying that low levels of pollution control are cheaper to achieve than higher levels. As an illustration, the cost of increasing the salt reduction level in the district's effluents from 0 mg/l to 50 mg/l is $0.19 million per year, in the Lehi-American Fork district. On the other hand, the cost for a 50 mg/l increase in salt reduction from 100 mg/l to 150 mg/l is $0.60 million. There is also a significant difference in water quality control costs between the Lehi-American Fork district and the Provo district. It costs $1.981 million in the Lehi-American Fork district to maintain a BOD level of 25 mg/l and a TDS reduction standard of 150 mg/l. For the same quality levels, the annual cost in the Provo district is $7.526 millions. This is attributed to the fact that both urban and agricultural return flows in the Provo district are considerably larger than those of the Lehi-American Fork district. The Spanish Fork district is characterized by a high level of agricultural activity with a low level of urbanization. A BOD standard of 25 mg/l and a salt reduction of 200 mg/l is achieved at a cost of $2.265 millions, of which $0.971 million is for the urban sector, and $1.294 millions is for the agricultural sector. The agricultural return flows in the Elberta-Goshen district while being modest in comparison with those in the other districts, are almost 100 times larger than the urban return flows in the district. The salt content of these return flows is relatively high, and hence a more stringent salt reduction standard should be imposed on the district's effluents. The total annual cost of achieving a BOD standard of 25 mg/l and a salt reduction of 700 mg/l is $0.823 million.

Tables 6 through 9 give the optimal flows, X_1,X_2, X_3 and X_4 in the urban sector, and the agricultural control measures, X_s and X_p, and also the total annual cost of maintaining the water quality level. The figures correspond to a BOD standard of 25 mg/l. The salt reduction standard is varied over a suitable range for each district.

At this stage, referring back to Fig. 4, it may be noted that the urban return flows are treated in the primary and secondary units, regardless of the BOD standard imposed on the system. If treatment in the primary and secondary units is not sufficient to satisfy the BOD standard in the district, as much of the urban return flows as necessary may undergo tertiary treatment. However, as is evident from the urban sector flow mixture in Tables 6 through 9, primary and secondary treatment of the urban return flows is quite sufficient to reduce the BOD content to such a level, that the BOD standard in the district's effluents is met; hence no tertiary treatment is required in any district.

A second feature of the district policies, as is evident from Tables 6 through 9, is that in all the districts the salt reduction is carried out entirely in the agricultural sector. The implication is that, physical removal of salt through the desalting plant is quite expensive, especially as any flow passing into the desalting plant must undergo tertiary treatment first. Besides, as was mentioned earlier, costs of salinity control in the agricultural sector are lower at low levels of control than corresponding costs in the urban sector, thus making investment in the agricultural sector more effective.

Table 6. Optimal policies for the Lehi-American District, corresponding to a BOD standard of 25 mg/1.

TDS Reduction Standard (mg/1)	Urban Sector Flow Mixture				Agricultural Sector's Control Measures		Total Annual Costs
	X_1 mgd	X_2 mgd	X_3 mgd	X_4 mgd	X_s %	X_p %	$\$10^6$
0	0	6.42	0	0	0	0	0.791
50	0	6.42	0	0	21.48	0	0.980
100	0	6.42	0	0	30.00	12.63	1.376
150	0	6.42	0	0	33.75	30.04	1.981

Table 7. Optimal Policies for the Provo District, corresponding to a BOD standard of 25 mg/1.

TDS Reduction Standard (mg/1)	Urban Sector Flow Mixture				Agricultural Sector's Control Measures		Total Annual Costs
	X_1 mgd	X_2 mgd	X_3 mgd	X_4 mgd	X_s %	X_p %	$\$10^6$
0	0	70.51	0	0	0	0	5.236
50	0	70.51	0	0	25.86	0	5.569
100	0	70.51	0	0	30.00	21.73	6.226
150	0	70.51	0	0	33.75	43.85	7.526

Table 8. Optimal Policies for the Spanish Fork District, corresponding to a BOD standard of 25 mg/1.

TDS Reduction Standard (mg/1)	Urban Sector Flow Mixture				Agricultural Sector's Control Measures		Total Annual Costs
	X_1 mgd	X_2 mgd	X_3 mgd	X_4 mgd	X_s %	X_p %	$\$10^6$
0	0	6.71	0	0	0	0	0.971
50	0	6.71	0	0	10.41	0	1.107
100	0	6.71	0	0	20.79	0	1.305
150	0	6.71	0	0	30.00	1.18	1.667
200	0	6.71	0	0	33.75	7.82	2.265

Table 9. Optimal Policies for the Elberta-Goshen District, corresponding to a BOD standard of 25 mg/l.

TDS Reduction Standard (mg/l)	Urban Sector Flow Mixture				Agricultural Sector's Control Measures		Total Annual Costs
	X_1 mgd	X_2 mgd	X_3 mgs	X_4 mgd	X_s %	X_p %	$\$10^6$
0	0	0.20	0	0	0	0	0.092
150	0	0.20	0	0	14.70	0	0.176
200	0	0.20	0	0	17.08	0	0.209
400	0	0.20	0	0	26.50	7.84	0.385
600	0	0.20	0	0	30.00	21.10	0.648
700	0	0.20	0	0	31.61	28.00	0.823

In the discussion in this section, it has been assumed that the cost of zero mg/l salt reduction is zero. Referring back to the objective function, represented by eq. (25), it is noted that the term

$$C_{p,i} \times 37.60\left[4.11087 - n\,(56.50 - X_{p,i})\right]/100$$

does not reduce to zero when $X_{p,i}$ is zero. For the Lehi-American Fork district, the above expression reduces to \$0.073 million when $X_{p,i} = 0$. Corresponding values for the other districts are \$0.086 million, \$0.226 million and \$0.049 million, for the Provo, Spanish Fork and Elberta-Goshen districts, respectively. These values have been added to the urban sector costs in presenting the results.

3.7. COMPARISON OF THE SEPARABLE PROGRAMMING SOLUTION WITH THE GENERALIZED REDUCED GRADIENT METHOD SOLUTION

The same problem for the Utah Lake drainage area has been solved by Shojalashkari (1974). In this section, some of the results obtained using separable programming are compared with the results obtained using the G.R.G. method. Table 10 presents such a comparison, for a BOD standard of 25 mg/l and a TDS reduction standard of 150 mg/l. Referring to Table 10, it is observed that the two solutions are quite close to each other. The slight differences may be attributed to the fact that separable programming does involve some approximation in linearizing the nonlinear separable functions.

Table 10. Comparison of the Separable Programming solution with the G.R.G. solution.

For all districts BOD standard = 25 mg/1
TDS reduction standard = 150 mg/1

District	Method of Solution	Urban Sector Flow Mixture (mgd)				Agricultural Sector Control Measures %		Total Annual Costs
		X_1	X_2	X_3	X_4	X_s	X_p	$\$10^6$
1	Separable Prog.	0	6.42	0	0	33.75	30.04	1.981
	G.R.G.	0	6.42	0	0	33.10	30.40	1.950
2	Separable Prog.	0	70.51	0	0	30.00	21.73	7.526
	G.R.G.	0	70.51	0	0	35.70	42.10	7.440
3	Separable Prog.	0	6.71	0	0	30.00	1.18	1.667
	G.R.G.	0	6.71	0	0	29.20	1.50	1.700
4	Separable Prog.	0	0.20	0	0	14.70	0	0.176
	G.R.G.	0	0.20	0	0	13.00	0	0.160

3.8. REVIEW OF A REPORT BY FUHRIMAN, MERRITT, ET AL. (1975)

In this section a brief review of a report by Fuhriman, Merritt, et al., (1975) is given. In their work, the inflows, outflows, and in-lake water quality and quantity of the Utah Lake were studied over a 36 month period in order to determine the effect of a proposed diking project on the quality and quantity of the water in the Lake. Also, a methodology was developed to determine the effects of diking, or for that matter, any other water management practice on the quality of water in a lake system.

The report also presents a computer simulation model that analyzes the effects of a water management program on the water quality of the Lake, particularly as related to the 'conservative salts' present. The simulation model was also used to evaluate water evaporation from the Lake by use of a salt balance technique. The results obtained in the study confirmed that diking of the Utah Lake would have positive beneficial effects on the water quality in the Lake. Diking will also result in considerable saving of water, and reclamation of valuable land.

As was mentioned earlier, the work involved measuring inflows and outflows into the Lake, as well as water quality of the flows. A comparison of some of the results obtained in this study with those of the report was attempted. In fact, the report does mention that quality and quantity measurements on the effluents from the Lehi-American Fork and Provo sewage treatment plants were taken. But the computer listing that followed did not contain any information on these effluents.

CHAPTER 4

THE REGIONAL SALINITY-BOD CONTROL MODEL

In the previous chapter, optimal policies were developed under the assumption that each district operates independently. Each district is required to satisfy the BOD and TDS reduction standards in its effluents. It is worth investigating whether it would be more economical for the districts to coordinate their salinity-BOD control activities, and operate on a regional basis. Under this mode of operation the BOD and TDS reduction standards would be met in the aggregated effluents into the Lake, though they may be violated in some individual district's effluents.

Advantages of a regional approach also stem from the economies of operating on a larger scale. Problems faced by local governments, which lack the necessary economic and manpower resources, can be alleviated (Clayton and Huie, 1973).

In this chapter, an attempt is made to explore the potentials for regionalization and coordination of the water control strategies among the four districts of the Utah Valley.

4.1. FORMULATION OF THE REGIONAL SALINITY-BOD CONTROL MODEL

The objective in the formulation of the Utah Valley salinity-BOD model, is to minimize the aggregated costs of urban wastewater treatment as well as the costs of salinity control in the districts, such that the BOD and TDS reduction standards in the aggregated inflows into the Utah Lake are met.

It must be stressed, that in the regional model, there are still four waste water treatment facilities in operation, one in each district. One might wonder, why not have a single waste water treatment facility for the entire Utah Valley drainage area. Consolidation of the smaller waste water treatment plants into a regional facility might be supported by arguments based on the economies of operating on a larger scale, that were mentioned earlier. However, the cost reduction achieved by operating and maintaining such a facility, should be weighed against the cost of transporting the waste water to this central facility. Optimal location of the centralized facility itself would be a problem in operations research. As information on the cost of waste water transportation in the Utah Valley drainage area was not available the existing structure of urban waste water treatment was left unchanged. In considerations that follow, each district still operates its own waste water treatment facility.

Under the above assumption, the objective function of the Utah Valley model can be written as follows:

Minimize

$$Y_T = \sum_{i=1}^{4} Y_{D,i}$$

where

Y_T represents the total annual cost of salinity-BOD control in the Utah Valley area.

$Y_{D,i}$ is the total annual cost of salinity-BOD control in the i district, as given by eq. (25).

As before the constraints on the system may be classified into flow constraints, and BOD and TDS reduction constraints. It might be recalled, that each district still operates its own urban waste water treatment facility. Hence the flow constraints must be satisfied in each district individually. The flow constraints may be stated as follows:

$$g_{1,i}\ (\overline{X}) = 0 \qquad\qquad i = 1,2,3,4 \tag{47}$$

$$g_{2,i}\ (\overline{X}) = 0 \qquad\qquad i = 1,2,3,4 \tag{48}$$

where $g_{1,i}\ (\overline{X})$ and $g_{2,i}\ (\overline{X})$ are given by eqs. (26) and (27), respectively.

The BOD constraints on the urban and agricultural return flows are imposed on each district effluent, individually. It might seem to the reader, that this is contradictory to the purpose of coordinating water quality control strategies among the districts. But legal requirements about the minimum amount of BOD reduction that must be carried out by the pollutors, force imposing the BOD constraints on each district individually. Therefore the BOD constraints can be written as follows:

$$g_{3,i}\ (\overline{X}) \leq 0 \qquad\qquad , \ i = 1,2,3,4 \tag{49}$$

where $g_{3,i}\ (\overline{X})$ is given by eq. (35).

The TDS reduction standard can be imposed on the aggregated return flows into the Lake. The constraint can be written as:

$$g_6\,(\bar{X}):\ \sum_{i=1}^{4}\left\{(X_{2,i}+X_{4,i})\,C_{tu,i}+(1-e_d)\,C_{tu,i}\,X_{3,i}\right.$$

$$+\,Q_{a,i}\;C_{ta,i}-\frac{0.94}{100}\,C_{ta,i}\,(X_{s,i}+X_{p,i})$$

$$\left.+\,Q_{se,i}C_{tse,i}+Q_{Y,i}C_{ty,i}\right\}$$

$$-\left\{\sum_{i=1}^{4}(Q_{u,i}+Q_{a,i}+Q_{se,i}+Q_{y,i}-Q_{w,i})\right\}$$

$$\times\,(C_{tpe}-TDS_{rtd})\leq 0 \qquad (50)$$

where C_{tpe} is the present salt content of the aggregated return flows, computed as follows:

$$\frac{\sum_{i=1}^{4}(Q_{u,i}\;C_{tu,i}+Q_{a,i}\;C_{ta,i}+Q_{y,i}\;C_{ty,i}+Q_{se,i}\;C_{tse,i})}{\sum_{i=1}^{4}(Q_{u,i}+Q_{a,i}+Q_{y,i}+Q_{se,i}-Q_{w,i})} \qquad (51)$$

TDS_{std} is the salt reduction standard.

The optimization problem may be summarized as:

Minimize

$$Y_T=\sum_{i=1}^{4}Y_{D,i} \qquad (52)$$

subject to

$$g_{1,i}\,(\bar{X})=0 \qquad i=1,2,3,4$$

$$g_{2,i}\,(\bar{X})=0 \qquad i=1,2,3,4$$

$$g_{3,i}\,(\bar{X})\leq 0 \qquad i=1,2,3,4$$

$$g_6\,(\bar{X})\leq 0$$

where

$Y_{D,i}$ is defined by eq. (25), $g_{1,i}(\bar{X})$, $g_{2,i}(\bar{X})$, $g_{3,i}(\bar{X})$ and $g_6(\bar{X})$ are defined by eqs. (26), (27), (35) and (50), respectively.

4.2. ADAPTING THE REGIONAL MODEL TO SEPARABLE PROGRAMMING

Referring back to the mathematical representation of the Regional Model, it is observed that only the objective function contains nonlinear terms that are not separable.

Once again the following simple substitutions yield an objective function that is made up of separable functions:

$$X_{1,i} + X_{2,i} = X_{7,i} \qquad , i = 1,2,3,4$$

The optimization problem in separable programming form may be written as follows:

Minimize

$$Y_T = \sum_{i=1}^{4} \Big\{ 3.31 \times 10^4 X_{7,i}^{0.71} + 2.12 \times 10^4 X_{7,i}^{0.83} + 6.07 \times 10^4 X_{7,i}^{0.80}$$

$$+ 4.29 \times 10^4 X_{7,i}^{0.893} + 5.23 \times 10^3 X_{1,i}^{0.89} + 4.16 \times 10^4 X_{1,i}^{0.65}$$

$$+ 4.16 \times 10^3 X_{1,i}^{0.90} + 1.42 \times 10^4 X_{1,i}^{0.962} + 4.75 \times 10^4 X_{1,i}^{0.72}$$

$$+ \begin{cases} 5.50 \times 10^4 X_{1,i}^{0.70} & , X_{1,i} \leq 3 \text{ mgd} \\ 5.70 \times 10^3 X_{1,i}^{0.96} & , X_{1,i} > 3 \text{ mgd} \end{cases}$$

$$+ 5.34 \times 10^4 \times X_{3,i}^{0.67} + 22.76 \times 10^4 X_{3,i}^{0.79}$$

$$+ C_{s,i} \times 34.42 \left[3.68135 - \ln (39.70 - X_{s,i})\right]/100$$

$$+ C_{p,i} \times 37.60 \left[4.11087 - \ln (56.50 - X_{p,i})\right]/100 \Big\} \qquad (53)$$

subject to

$$X_{1,i} + X_{2,i} = Q_{u,i} \qquad , i = 1,2,3,4 \qquad (54)$$

$$X_{2,i} + X_{3,i} + X_{4,i} = Q_{u,i} \qquad , i = 1,2,3,4 \qquad (55)$$

$$X_{2,i} (1-e_{ps}) C_{bu,i} + X_{3,i} (1-e_t)(1-e_{ps}) C_{bu,i}$$

$$+ X_{4,i} (1-e_t)(1-e_{ps}) C_{bu,i}$$

$$\leq (Q_{u,i} + Q_{a,i}) \times BOD_{std} - Q_{a,i} C_{ba,i} \qquad , i = 1,2,3,4 \qquad (56)$$

$$\sum_{i=1}^{4} \Big\{ (X_{2,i} + X_{4,i}) C_{tu,i} + (1-e_d) C_{tu,i} X_{3,i}$$

$$- \frac{0.94}{100} Q_{a,i} C_{ta,i} X_{s,i} - \frac{0.94}{100} Q_{a,i} C_{ta,i} X_{p,i} \Big\}$$

$$\leq - \sum_{i=1}^{4} \Big\{ Q_{a,i} C_{ta,i} + Q_{se,i} C_{tse,i} + Q_{y,i} C_{ty,i} \Big\}$$

$$- \Big\{ \sum_{i=1}^{4} (Q_{u,i} + Q_{a,i} + Q_{se,i} + Q_{y,i} - Q_{w,i}) \Big\}$$

$$\times (C_{tpe} - TDS_{std}) \qquad (57)$$

$$X_{1,i} + X_{2,i} - X_{7,i} = 0 \qquad , i = 1,2,3,4 \qquad (58)$$

The computer solution of the problem has already been dealt with in a previous chapter and will not be dealt with here.

4.3. OPTIMAL COSTS AND POLICIES FOR THE REGIONAL MODEL

The optimization problem for Utah Valley in separable programming form, as represented by the objective function, eq. (53), and the constraint, eqs. (54) through (58), has 28 variables, 4 of which are dummy variables introduced to adapt the problem to separable programming. The problem has 17 constraints, all of which are linear. The separable programming option in MPS/360 is once again used to solve the problem. A BOD standard of 25 mg/l and a TDS reduction standard of 150 mg/l are assumed. The resulting optimal policies are presented in Table 10.

The urban sector flow mixtures in Table 10, indicate that the urban return flows, after undergoing primary and secondary treatment, are entirely diverted to the urban effluent channels. The implication is that no tertiary treatment is required to meet the BOD standard. In fact, substitution of the results in the BOD constraints would reveal that the BOD constraints are far from active. They are very easily satisfied by primary and secondary treatment of the urban return flows. Once again, as in the case of independent or individual operation, salt reduction is carried out entirely in the agricultural sector. However, the agricultural control measures, $X_{s,i}$ and $X_{p,i}$, are distributed among the districts in a different fashion from when the districts were operating independently. For the regional model, structural improvements and practice improvements in the Lehi-American Fork district are 26.25% and zero % (see Table 11), respectively, as against 33.75% and 30.04% (see Table 10) for independent operation of the districts. For the Provo district, the corresponding values of X_s and X_p are 30.00% and 16.80% (see Table 11) for the regional model, as against 33.75% and 43.85% (see Table 10) for independent operation; for the Spanish Fork district, the values for the regional model are 30.00% and 5.60% (see Table 11) as against 30.00% and 1.18% (see Table 10) for independent operation; for the Elberta-Goshen district, the values are 26.25% and 11.20% (see Table 11) for the regional model, as against 14.70% and zero % (see Table 10) for independent operation. It is noted that for regional operation, control measures in the agricultural sector are reduced for the Lehi-American Fork and Provo districts, while they are augmented in the other two districts.

The economic advantages of a regional strategy in comparison with individual operation, will now be dealt with. In Table 11, the total annual cost for the Utah Valley, as well as the cost breakdown for the districts are given. For a BOD standard of 25 mg/l and a TDS reduction standard of 150 mg/l, the total annual cost for regional operation is $\$9.522 \times 10^6$, the breakdown among the districts being as follows:

$\$1.054 \times 10^6$ for the Lehi-American Fork district,

$\$6.076 \times 10^6$ for the Provo district,

$\$1.963 \times 10^6$ for the Spanish Fork district,

$\$0.429 \times 10^6$ for the Elberta-Goshen district.

The total annual cost under the assumption of individual operation are $\$11.346 \times 10^6$, obtained by summing up the following:

Table 11. Optimal policies for the Utah Valley Drainage Area, corresponding to a BOD standard of 25 mg/1 and a salt reduction standard of 150 mg/1

District	Urban Sector Flow Mixture				Agricultural Sector Control Measures		Total Annual Cost
	X_1 mgd	X_2 mgd	X_3 mgd	X_4 mgd	X_s %	X_p %	$\$10^6$
Lehi-American Fork District	0 (0)*	6.42 (6.42)	0 (0)	0 (0)	26.25 (26.3)	0 (14.6)	
Provo District	0 (0)	70.51(70.51)	0 (0)	0 (0)	30.00 (31.9)	16.8(20.6)	9.522
Spanish Fork District	0 (0)	6.71 (6.71)	0 (0)	0 (0)	30.90 (33.0)	5.60(14.2)	(10.465)
Elberta-Goshen District	0 (0)	0.20 (0.20)	0 (0)	0 (0)	26.25 (26.3)	11.20 (0)	

* Figures in parentheses indicate optimal policies obtained using the Generalized Reduced Gradient Method by Shojalashkari.

Table 12. Cost breakdown for the Utah Valley Model. Figures in $\$10^6$

Cost Breakdown	Districts			
	Lehi-American Fork	Provo	Spanish Fork	Elberta-Goshen
1) Urban Sector	0.791	5.236	0.971	0.092
2) Agricultural Sector				
Structural Improvements	0.263	0.444	0.684	0.196
Practice Improvements	0.000	0.396	0.308	0.141
Total Agricultural Sector	0.263	0.840	0.992	0.337
3) Total Cost for District	1.054	6.076	1.963	0.429
4) Total Cost for Utah Valley		9.522		

1.981×10^6 for the Lehi-American Fork district,

7.526×10^6 for the Provo district,

1.667×10^6 for the Spanish Fork district,

0.176×10^6 for the Elberta-Goshen district.

Thus regional operation results in a cost reduction of 1.824×10^6 per year as compared with independent operation.

In summary, it may be pointed out that the significant savings resulting from adopting a regional approach, stems from the fact that each district does not have to meet the salt reduction standards individually. There is reallocation of salt reduction measures among the agricultural sectors of the four districts. In case of the Lehi-American Fork district and the Provo district, agricultural control measures and consequently, costs, are less under a regional mode of operation. On the other hand, agricultural salinity control measures are augmented in case of the Spanish Fork district and the Elberta-Goshen district. Costs in these two districts are correspondingly higher than under the assumption of independent operation. The urban waste water treatment costs remain the same for both regional and independent operation. This is because even under the assumption of regional operation, the BOD constraints are imposed individually on the return flows of each district. Besides, the construction of the model requires that, in each district the urban return flows undergo primary and secondary treatment in any case.

4.4. COMPARISON OF THE SEPARABLE PROGRAMMING SOLUTION WITH THE GENERALIZED REDUCED GRADIENT METHOD SOLUTION

The figures indicated within parentheses in Table 11 are the results obtained by Shojalashkari for the same problem using the Generalized Reduced Gradient method. It is noted that the two methods yield identical urban sector policies. There are some differences in the optimal policies for salinity control in the agricultural sectors. The most significant differences are the following:

The optimal policy obtained using separable programming suggests a control measure of $X_{p,i}$ = zero, in practice improvements in the Lehi-American Fork district, and 11.2% in practice improvements in the Elberta-Goshen district. The corresponding values in the G.R.G. solution obtained by Shojalashkari are 14.6% in the Lehi-American Fork district, and zero % in the Elberta-Goshen district. Practice improvement control measures are 16.8% and 5.60% in the Provo and Spanish Fork districts, respectively, for the separable programming solution. Corresponding values for the G.R.G. solution are 20.6% and 14.2%, respectively. There is also some difference in the total annual cost figures for the two methods of solution; $9.522 millions for the separable programming solution, as against $10.465 millions for the G.R.G. solution.

These differences are to be expected in view of the fact that separable programming is a technique that involves approximating nonlinear separable functions by piecewise linear approximations. The closeness of the approximated piecewise linearization to the nonlinear separable function depends on the shape of the nonlinear curve, as also on the number of partitions used in the above said approximation. Better approximations may be obtained with more flat curves. Increasing the number of partitions also yields a better approximation. However, it must be kept in mind that increasing the number of partitions also increases the number of variables in the problem. Consequently the computer time required in the solution of the problem is also increased.

CHAPTER 5

VERIFICATION OF THE OPTIMAL POLICIES OBTAINED BY WALKER, ET AL. (1973a, 1973b, 1974)

This chapter deals with the discussion of the problem as solved by Walker, et al. (1973b) in their report, and also the results obtained by them. The method of optimization used by Walker, et al. (1973a) has been described as the Jacobian Differential Algorithm.

5.1. PROBLEM AS SOLVED BY WALKER, ET AL. (1973a, 1973b, 1974)

The essentials of the model used by Walker, et al., are the same as that of Shojalashkari (1972). However, Walker, et al., have not included $Q_{y,i}$ (yields from the valley floor), $Q_{se,i}$ (spills and excesses) and $Q_{w,i}$ (wetland consumption), in the final inflow into the Lake. There is a significant salt content associated with these flows. Referring back to Table 7, it is noted that the Lehi-American Fork district has a salt content of 190 mg/1, and the Spanish Fork district has a salt content of 350 mg/1. Besides, the net flow $Q_y + Q_{se} - Q_w$ does contribute a sizable portion of the total inflow into the Lake. For example, in the Lehi-American Fork district, $Q_y + Q_{se} - Q_w$ amounts to 31.5 mgd; total inflow from the district into the Lake is 94.50 mgd. In the Spanish Fork district, it amounts to 49.18 mgd out of a total inflow into the Lake of 158.89 mgd. The situation is somewhat different in the Elberta-Goshen district. $Q_y + Q_{se} - Q_w$ is a negative quantity, -4.05 mgd; total inflow into the Lake is 15.40 mgd. This is because of the rather large magnitude of Q_w.

The optimization problem considered by Walker, et al., can be represented as:

Minimize

$$Y_{D,i}$$

subject to the constraints,

$$g_{1,i}(\bar{X}) = 0$$

$$g_{2,i}(\bar{X}) = 0$$

$$g_{3,i}(\bar{X}) \leq 0$$

$$\begin{aligned} g_{7,i}(\bar{X}) = {} & (X_{2,i} + X_{4,i})\, C_{tu,i} + (1-e_d)\, C_{tu,i}\, X_{3,i} \\ & + Q_{a,i}\, C_{tu,i} - \frac{0.94}{100}\, C_{ta,i}\, (X_{s,i} + X_{p,i}) \\ & - (Q_{u,i} + Q_{a,i}) \times (C_{tp,i} - TDS_{rtd}) \leq 0 \qquad (59) \\ & \qquad i = 1,2,3,4 \end{aligned}$$

where

$$C_{tp,i} = \frac{(Q_{u,i} \times C_{tu,i} + Q_{a,i}\, C_{ta,i})}{(Q_{u,i} + Q_{a,i})} \qquad (60)$$

and, $Y_{D,i}$, $g_{1,i}(\bar{X})$, $g_{2,i}(\bar{X})$ and $g_{3,i}(\bar{X})$ are given by eqs. (25), (26), (27) and (35).

The regional model for the Utah Valley is formulated as before. The optimization problem is to minimize the aggregated costs, subject to the flow constraints in each district, the BOD constraints in each district, and the salt reduction constraint on the aggregated return flows into the Lake. In mathematical notation the problem may be defined as:

Minimize

$$Y_T = \sum_{i=1}^{4} Y_{D,i}$$

subject to

$$g_{1,i}\ (\bar{X}) = 0 \qquad , \ i = 1,2,3,4$$

$$g_{2,i}\ (\bar{X}) = 0 \qquad , \ i = 1,2,3,4$$

$$g_{3,i}\ (\bar{X}) \leq 0 \qquad , \ i = 1,2,3,4$$

$$\sum_{i=1}^{4} g_{7,i}\ (\bar{X}) \leq 0$$

The last constraint may be expanded as:

$$\sum_{i=1}^{4} g_{7,i}\ (\bar{X}) = \sum_{i=1}^{4} \Big\{ (X_{2,i} + X_{4,i})\ C_{tu,i} + (1-e_d)\ C_{tu,i}\ X_{3,i} + Q_{a,i}\ C_{ta,i} - \frac{0.94}{100}\ C_{ta,i}\ (X_{s,i} + X_{p,i}) \Big\} - \sum_{i=1}^{4} (Q_{u,i} + Q_{a,i})\ (C_{tpe} - TDS_{rtd}) \leq 0 \qquad (61)$$

where

$$C_{tpe} = \frac{\sum_{i=1}^{4} (Q_{u,i}\ C_{tu,i} + Q_{a,i}\ C_{ta,i})}{\sum_{i=1}^{4} (Q_{u,i} + Q_{a,i})} \qquad (62)$$

5.2. A DISCUSSION OF THE OPTIMAL POLICIES OBTAINED BY WALKER, ET AL.

Walker, et al., (1973b) have used the Jacobian Differential Algorithm in the solution of the above optimization problem. The TDS reduction standard was artificially varied over a suitable range, keeping the BOD standard fixed, to study the resulting effect on the optimal policies. In each case, salinity control costs (salinity control cost for a TDS reduction standard of zero mg/l was assumed to be $0), were plotted against the corresponding TDS reduction standard in mg/l. Plots of TDS reduction in the urban and agricultural sector effluents against TDS reduction in the district's effluents were also constructed. The plots obtained by Walker, et al., have been reproduced in Figs. 11 through 14.

A brief discussion of the results, as presented by Walker, et al., follows. The Provo district is the only one of the four, which, under present conditions, has urban water demands of a magnitude comparable with that of the agricultural water demands. This district contributes about 40% of the return flows in the basin, and 27% of the salts. Referring to Fig. 11, it is observed that, for TDS reductions less than 10 mg/l in the district's effluents, salinity control is primarily an agricultural policy. However, as the necessity for more stringent TDS reduction standards arises, agricultural control measures remain essentially fixed, while urban policies are implemented. Finally, beyond a TDS reduction of 130 mg/l, the balance again tilts in favor of agricultural control measures. The cost curve reflects the alternating policies, which indicate increasing and then decreasing

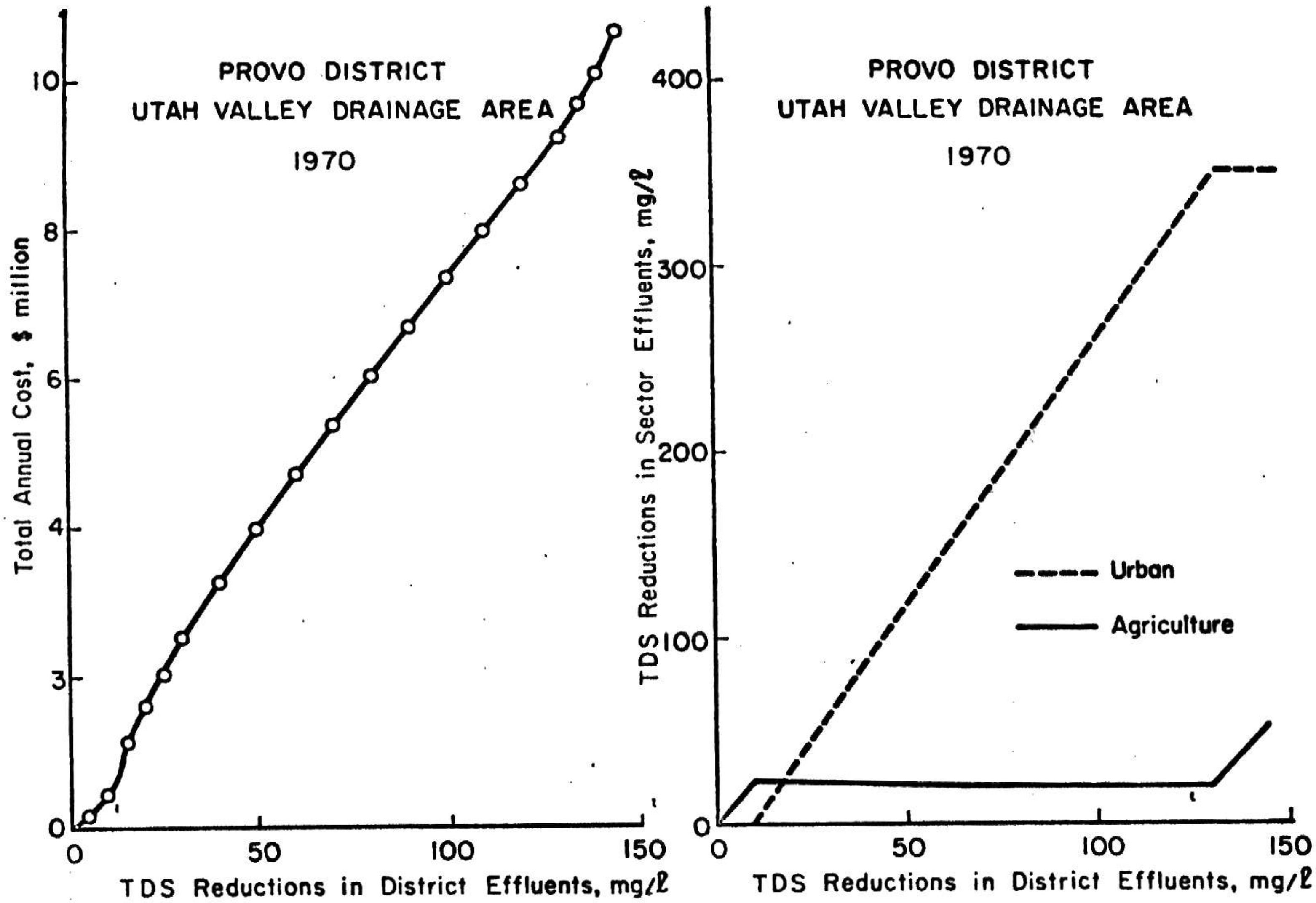

Fig. 11. Optimal policies for salinity control in the Provo District (Walker, et al., 1973b).

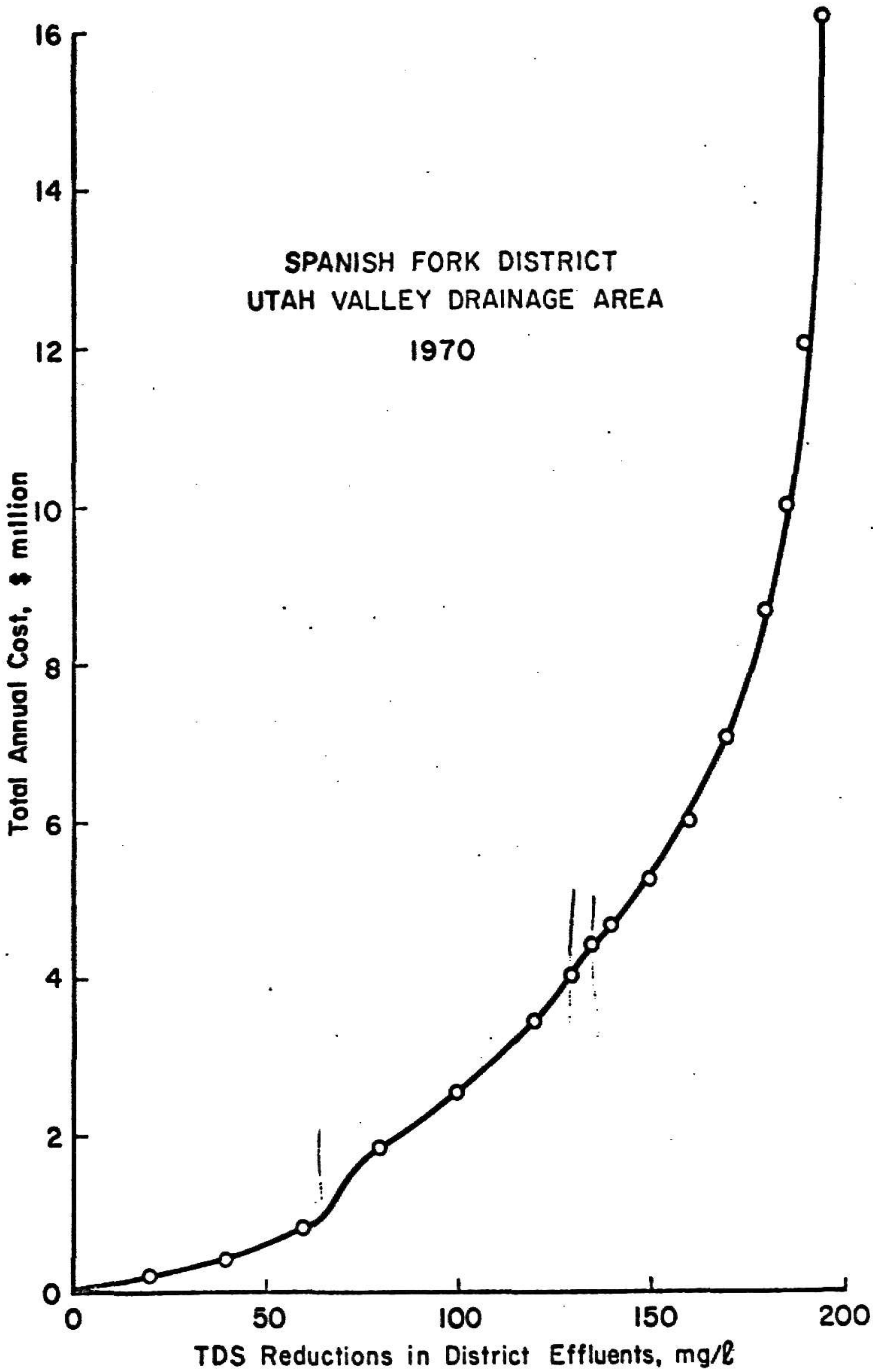

Fig. 12. Total annual costs for salinity control in the Spanish Fork District (Walker, et al., 1973b).

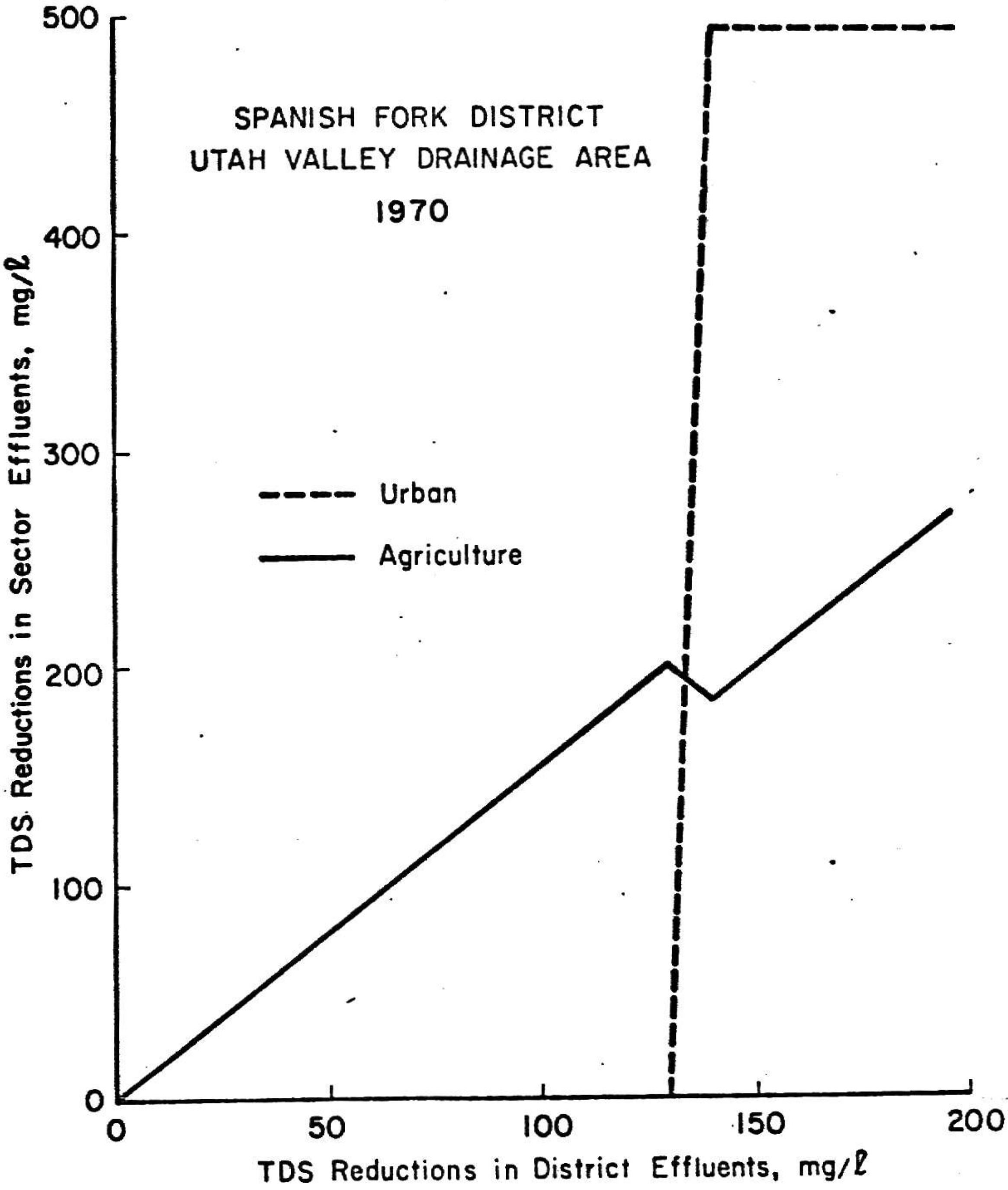

Fig. 13. Optimal policy for reducing the concentrations of TDS in the return flows of the Spanish Fork District (Walker, et al., 1973b).

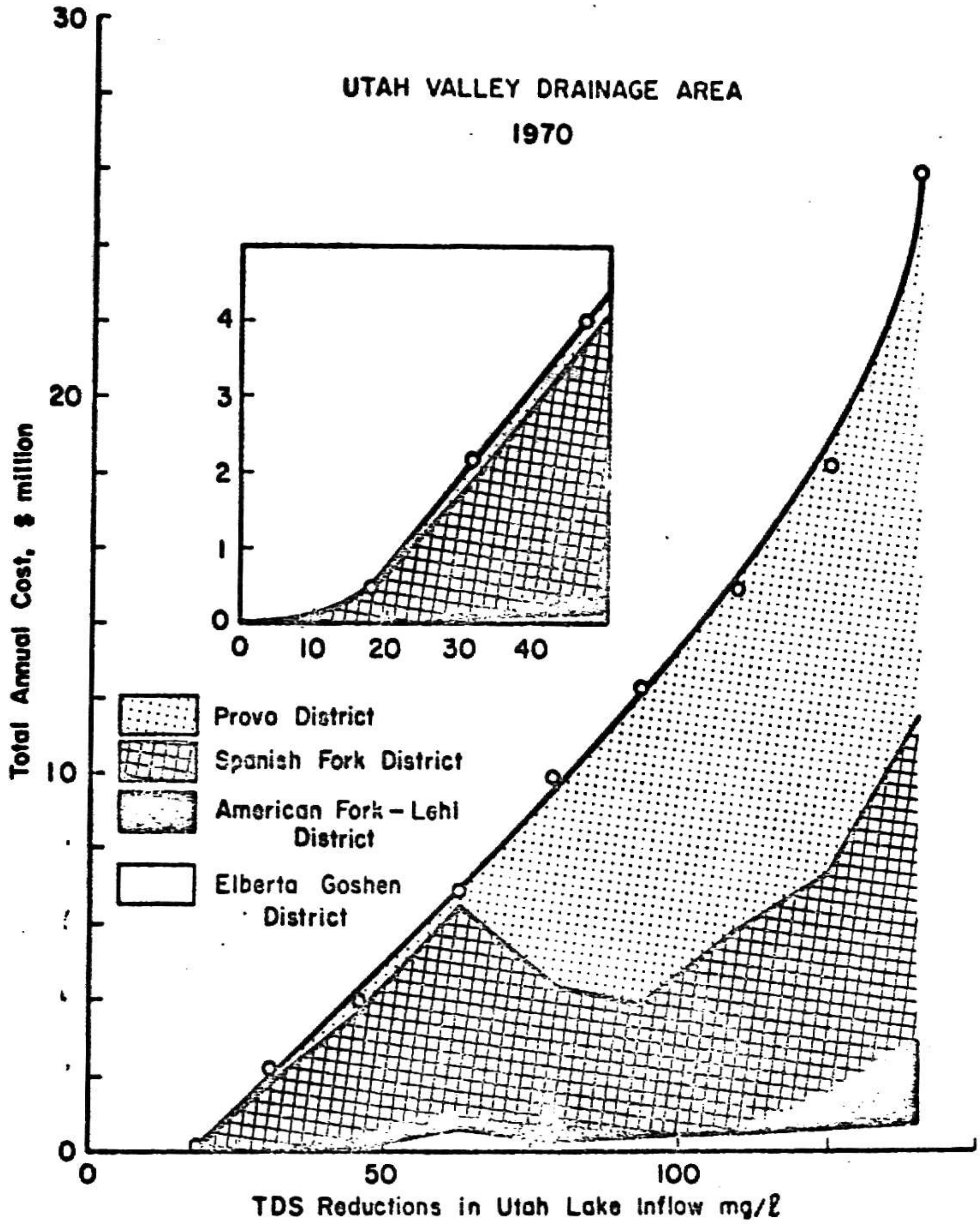

Fig. 14. Optimal water quality management policies in the Utah Valley area (Walker, et al., 1973b).

marginal cost characteristics of the urban and agricultural control measures.

The Spanish Fork district accounts for 31% of the flows in the basin, and 34% of the salts. The district is predominantly agricultural in nature. It is quite apparent, therefore, that water quality management in the district should concentrate primarily on the agricultural sector. A study of Figs. 12 and 13 substantiates this conclusion. Figure 12 is a plot of the total annual salinity control costs in the district, versus the TDS reduction standard; Fig. 13 is a plot of TDS reduction in the sector effluents versus TDS reduction in the district's effluents. Referring to Fig. 12, it is observed that the curve has two points where it changes slope. At a TDS reduction of about 75 mg/l, the noticeable break in the curve indicates a shift from control measure alternatives in the agricultural sector to a combination of structural and practice improvements. The undulation at around a TDS reduction of 130 mg/l indicates that, at this point urban desalting measures are undertaken. In fact, implementation of desalting is almost immediate for all of the urban effluent flows. Beyond this point, agricultural control measures are once again resorted to, as all of the urban effluents have already been desalted.

A comparison of the results for the Provo and the Spanish Fork districts emphasizes the need to determine optimal policies for each district. Conclusions drawn from one district are not uniformly applicable to the conditions of other districts. However, it might be tentatively stated that, for low TDS reduction in the district's effluents, the best investment is likely to be in the agricultural sector. It is also quite obvious that if complete control is desired, both urban and agricultural salinity control measures should be undertaken in their entirety. In the middle ground, the optimal decisions are less apparent, and must be evaluated for each set of conditions.

Having optimized the individual districts policies, for a specified set of effluent standards, the next major issue is to determine an optimal policy for water quality management, under the assumption of regional operation. The development of the Regional Model has been dealt with in the preceding section. Referring to Fig. 14, it is observed that low levels of TDS reduction, up to about 70 mg/l, the bulk of the control measures are undertaken in the Spanish Fork district. It is recalled, that when the TDS reductions required are low, low marginal costs in the agricultural sector direct efforts in that direction. Beyond a TDS reduction of about 60 mg/l, it becomes more economical to employ control procedures in the Provo district, which contributes a sizeable urban effluent. It is also of interest to note that contributions to salt reduction, from the Lehi-American Fork and Elberta-Goshen districts, are insignificant. Hence, it is to be concluded that, primarily, larger areas are to be attended to first.

5.3. OPTIMAL POLICIES USING SEPARABLE PROGRAMMING

Referring to Figs. 11 through 14, it is observed that the total annual costs obtained by Walker, et al., are very much higher than the values obtained earlier in this report for the same problem considering the three additional flows, Q_y, Q_{se}, and Q_w. This does not seem intuitively appealing. Some difference is to be expected in view of the fact that Q_y, Q_{se}, and Q_w have been ignored, as also because of the fact that the cost figures obtained by Walker, et al., are in terms of 1970 dollars. The cost figures obtained by Shojalashkari and the author are in terms of 1974 dollars.

The problem as solved by Walker, et al., was optimized using separable programming. A BOD standard of 25 mg/l was assumed, and the TDS reduction standard was artificially varied. The total annual cost figures (obtained by assuming salinity control cost for a TDS reduction of zero mg/l is zero dollars) were plotted against TDS reduction in the district's effluents (Figs. 15, 17 and 19). Figures 16 and 18 are plots of TDS reduction in the urban and agricultural sectors, against TDS reduction in the district, for the Provo and Spanish Fork districts, respectively. Suspicions about the unusually high cost figures obtained by Walker, et al., were confirmed. For example, the annual salinity control cost figure obtained by Walker, et al., for a TDS reduction of 150 mg/l in the Provo district was \$10.40 x 10^6 (see Fig. 11), as against \$1.26 x 10^6 for the separable programming solution (see Fig. 15). Corresponding cost figures for the Spanish Fork district for the same TDS reduction were \$5.25 x 10^6 for the solution of Walker, et al. (see Fig. 12), and \$0.35 x 10^6 for the separable programming solution (see Fig. 17). For the regional model, for a TDS reduction standard of 100 mg/l, Walker, et al., obtained an annual cost figure of \$13.5 x 10^6 (see Fig. 13), as against \$0.93 x 10^6 for the separable programming solution (see Fig. 19). Reference to Figs.

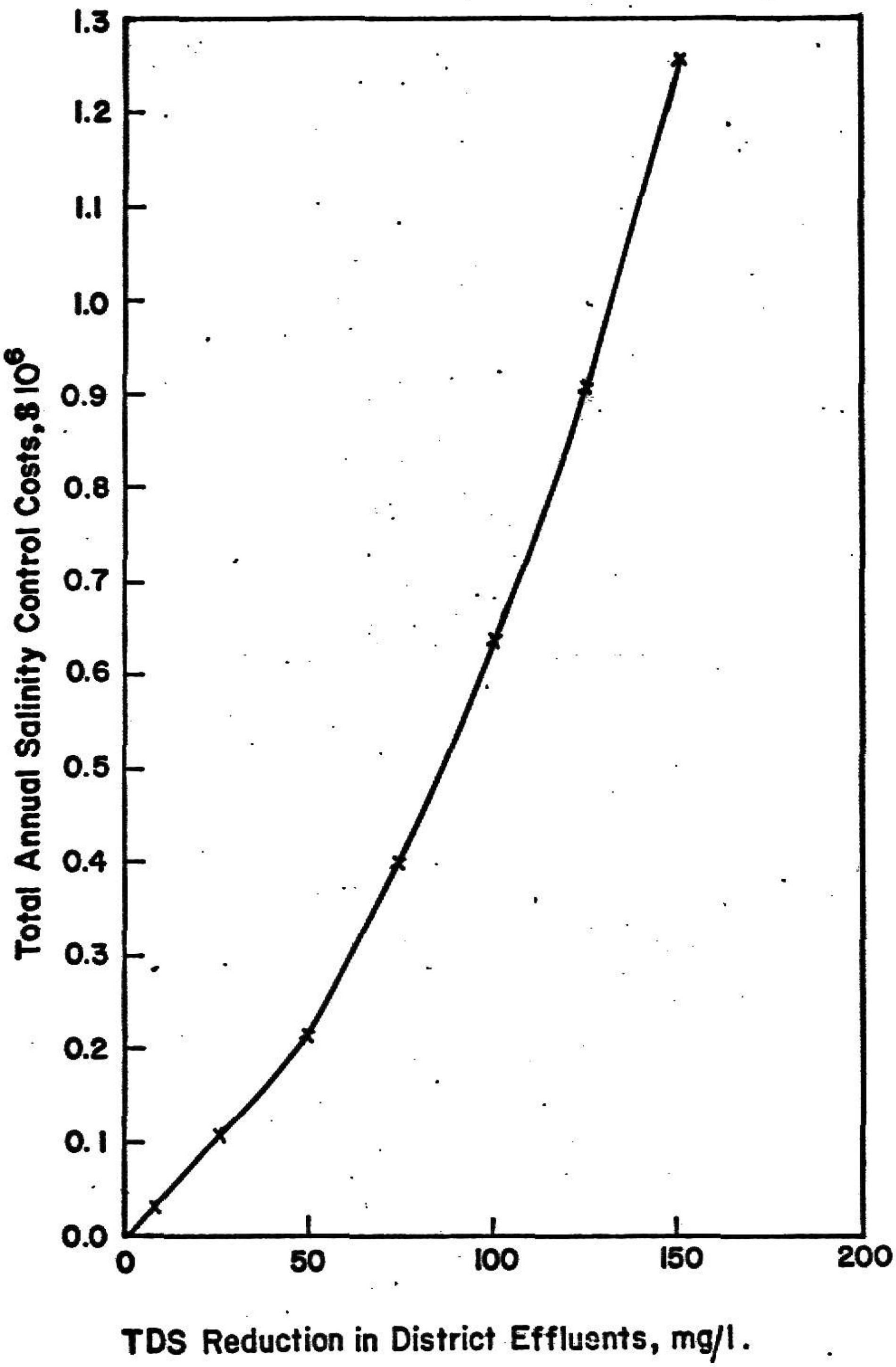

Fig. 15. Salinity control costs vs TDS reduction for the Provo District (Separable Programming Solution of Walker's version).

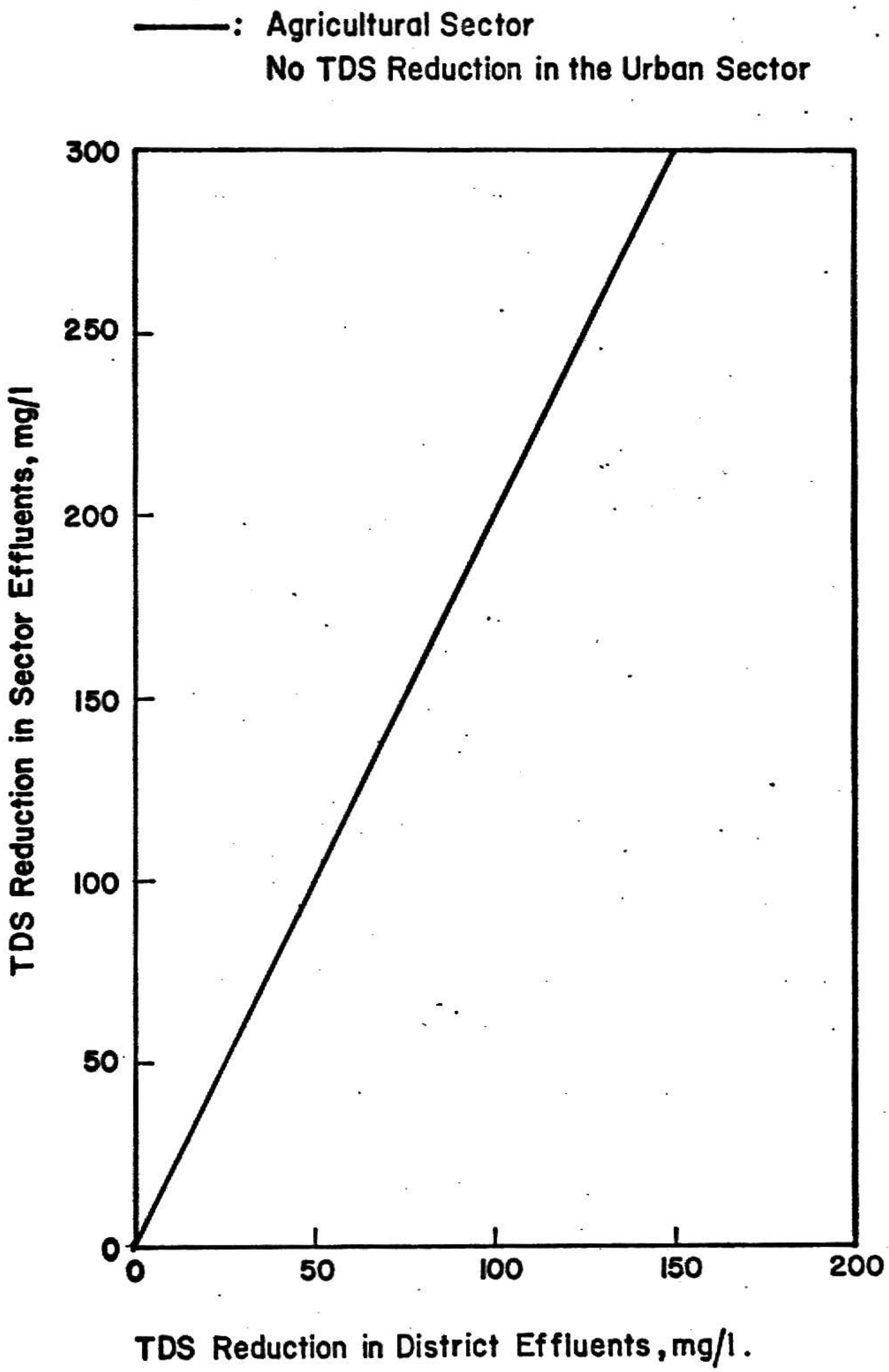

Fig. 16. TDS reduction in sectors vs TDS reduction in district effluents for the Provo District (Separable Programming Solution of Walker's version).

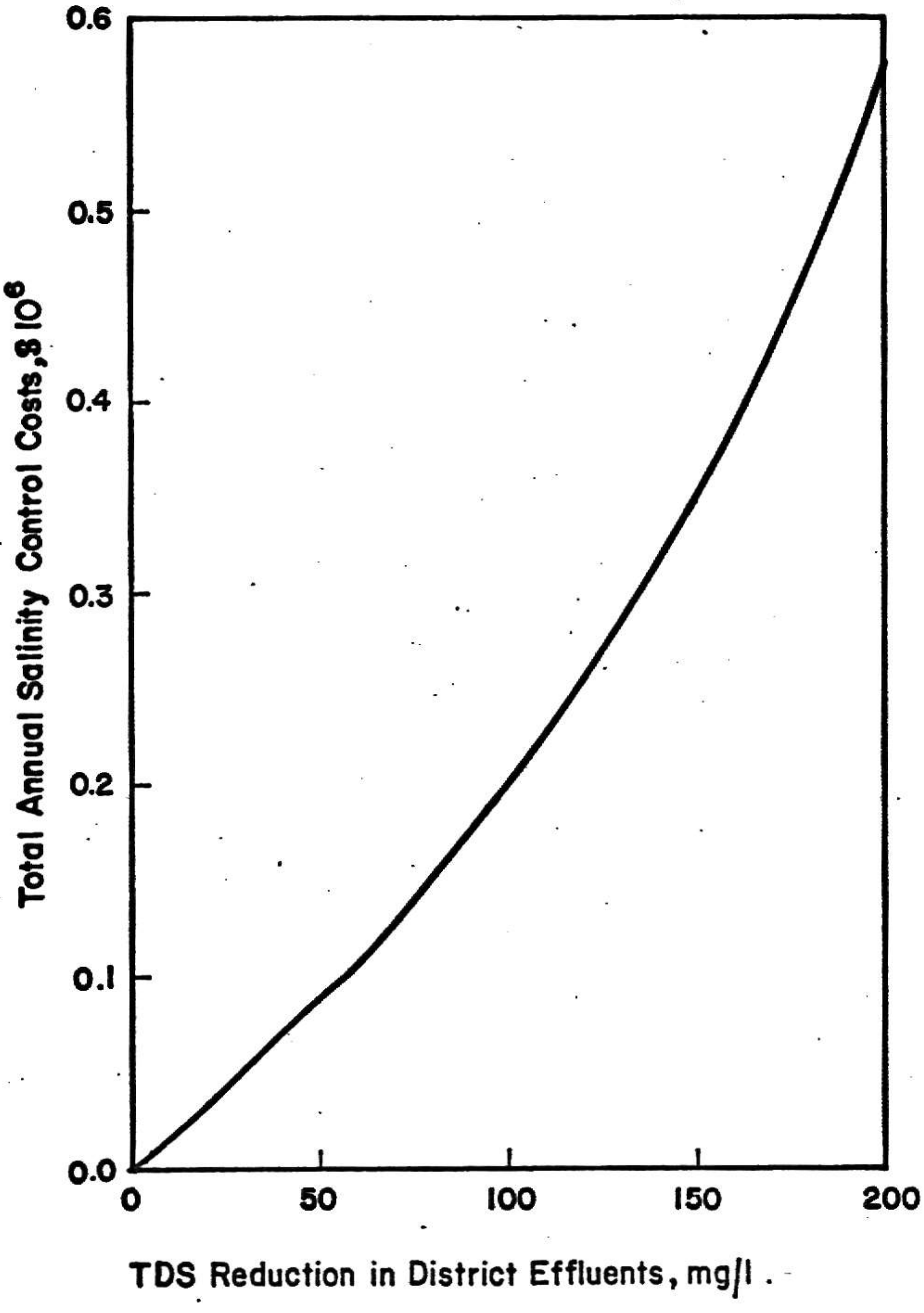

Fig. 17. Salinity control costs vs TDS reduction for the Spanish Fork District (Separable Programming Solution of Walker's version).

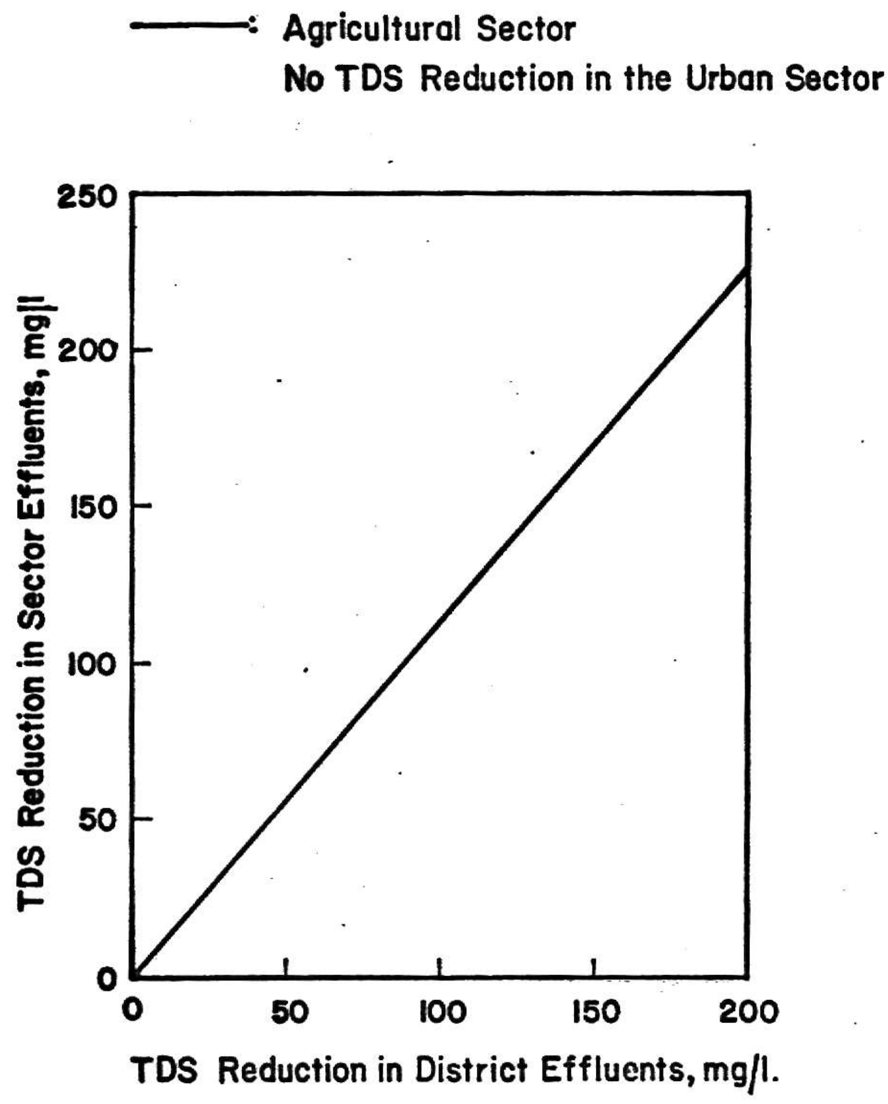

Fig. 18. TDS reduction in sectors vs TDS reduction in district effluents for the Spanish Fork District (Separable Programming Solution of Walker's version).

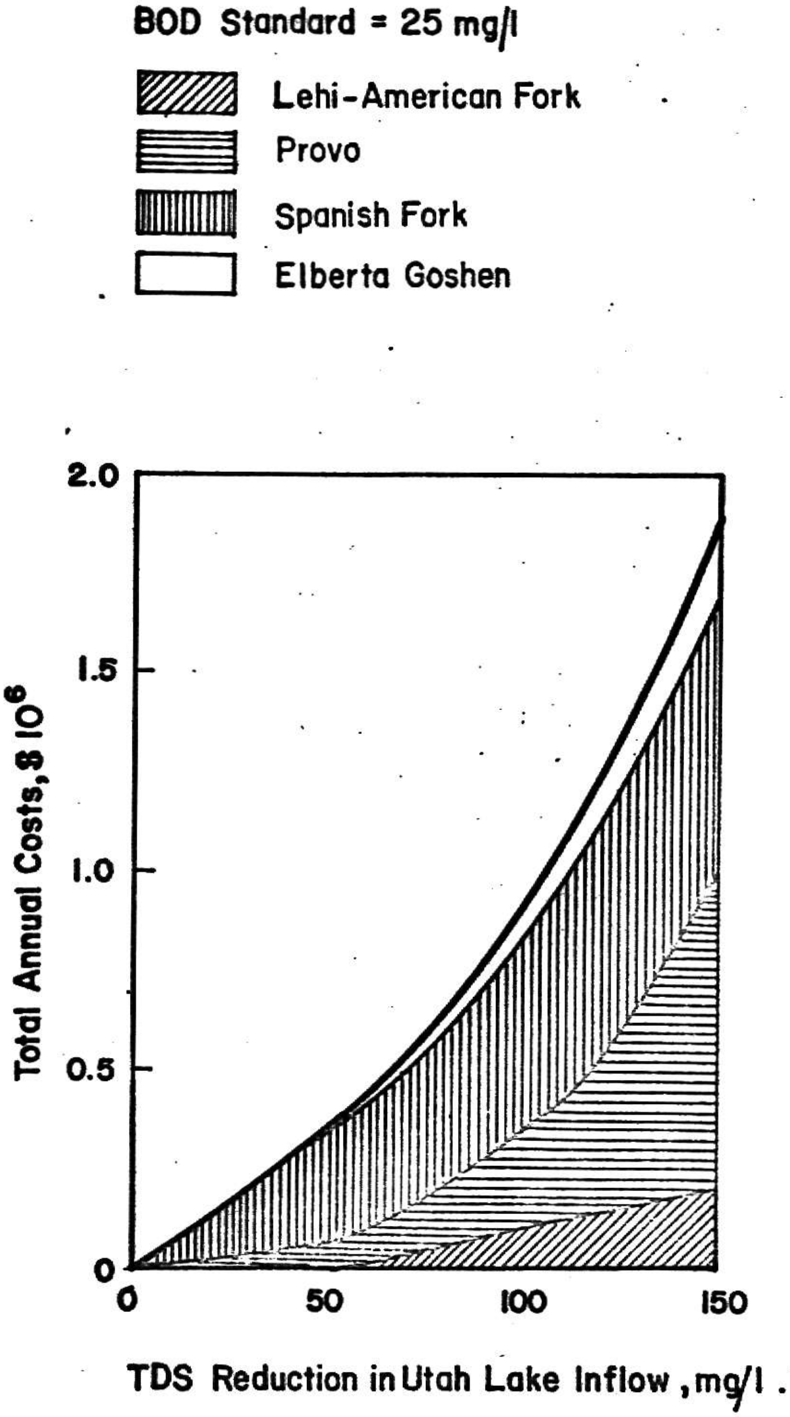

Fig. 19. Optimal water quality management policies in the Utah Valley area (Separable Programming Solution of Walker's version).

15 and 17 (separable programming solution), also reveals that for all the TDS reduction standards considered, agricultural salinity control measures are sufficient to meet the standards in both the districts. In the solution obtained by Walker, et al., in the Provo district urban salinity control measures begin at salt reduction levels as low as 25 mg/l (see Fig. 11), in the Spanish Fork district all the urban waste water is desalted for TDS reductions of 130 mg/l or higher in the district's effluents. Examining Figs. 14 and 19, it may also be inferred that there are significant differences in the ratio of cost breakdown among the four districts for the two methods of solution. As further details of the optimal policies obtained by Walker, et al., were not available, a more detailed comparison of the two solutions could not be made.

The following arguments also tend to confirm that Walker's policies are far from optimal. Referring to Table 4, it may be shown that a TDS reduction of 200 mg/l in the Spanish Fork district can be achieved by structural improvements alone (though this is not the most efficient way), at a cost of less than $\$1.3 \times 10^6$ (see Table 5). Walker's cost figure of over $\$16.0 \times 10^6$ is obviously not optimal. Similarly, in the Provo district 100% structural and practice improvements can achieve more than a TDS reduction of 150 mg/l at a cost of $\$3.9 \times 10^6$, whereas Walker's cost figure for a TDS reduction of 150 mg/l is nearly $\$11.0 \times 10^6$ (see Tables 4 and 5).

CHAPTER 6

DISCUSSION AND CONCLUDING REMARKS

This report was primarily concerned with the optimization of a water quality model, in which both urban and agricultural return flows are considered. The Utah Lake drainage area served as a source for the numerical data required. Hydrologically, the area was divided into four districts, in each of which, urban and agricultural activities exist. The Spanish Fork and the Elberta-Goshen districts are primarily agricultural in nature. The Lehi-American Fork district and the Provo district are characterized by a rapid rate of urbanization.

It was also stressed that, in areas such as the Utah Valley, where a number of pollutors contribute to deterioration of water quality, water quality management strategies should aim at coordination of pollution control strategies among all the users.

Optimal policies were first determined under the assumption that each district was to meet certain BOD and TDS reduction standards. The optimal policies obtained indicated that, without exception, under present conditions, primary and secondary treatment of urban waste waters is more than adequate to meet the BOD standards. BOD reduction in the tertiary treatment unit, or BOD reduction of agricultural flows (for which the model considered in this report has no provision), was not necessary. From the point of view of salinity control, it was determined that agricultural control measures were more economical.

In the next chapter, optimal policies were determined for the situation where the salinity-BOD control activities of the districts are coordinated. The explicit purpose was to take advantage of the economies of operating on a large scale. Salt reduction standards were imposed on the aggregated return flows into the Lake, instead of on the individual districts return flows. The same could not be done with the BOD standard because existing regulations require primary and secondary treatment of all urban and industrial wastes. The total annual cost figures, under the assumption of regional operation, were $1.824 million less per year than when the districts operated separately. Urban waste treatment costs, being the same in both cases, the savings realized are in the agricultural sector. The results obtained were compared with those of Shojalashkari (1974), using the Generalized Reduced Gradient Method.

Finally, the problem as solved by Walker, et al., (1973b), was optimized using Separable Programming. The essential difference between the problems as treated by Walker, et al., and Shojalashkari, is that the former have not considered the flows Q_y, Q_{se} and Q_w, and the associated salt concentrations. Comparison of the results obtained with those of Walker, et al., showed drastic differences in both cost figures and optimal policies.

REFERENCES

1. Business Week, June 15, 1974.
2. Hadley, G., Nonlinear and Dynamic Programming, Addison-Wesley, Reading, Mass., 1964.
3. Huntzinger, T. L., Future water use models of Utah Valley, Master's Thesis, Colorado State University, Fort Collins, Colorado, December, 1971.
4. Fuhriman, D. K., Merritt, L. B., Bradshaw, J. S. and Barton, J. R., Water quality effect of diking a shallow arid-region lake, Report No. EPA-660/2-75-007, April, 1975.
5. Hyatt, M. L., Skogerboe, G. V., Haws, F. W., and Austin, L. H., Hydrologic inventory of the Utah Lake drainage area, Report W G40-3, Utah Water Research Laboratory, Utah State University, Logan, Utah, Nov., 1969.
6. Mathematical Programming System 360, Version 2, Linear and Separable Programming-, User's Manual, GH20-0476-2, International Business Machines Corp., 1968.
7. Michel, R. L., "Costs and manpower for municipal wastewater treatment plant operation and maintenance, 1965-1968," Journal Water Pollution Control Federation, Vol. 42, No. 5, Part 1, pp. 1883-1910, Nov., 1970.
8. Shah, K. L., and Reid, G. W., "Techniques for estimating construction costs of waste treatment plants," Journal Water Pollution Control Federation, Vol. 42, No. 5, Part 1, pp. 776-793, May, 1970.

9. Shojalashkari, R., Application of Systems Analysis to Regional Water Quality Management Models, Ph.D. dissertation, Kansas State University, Manhattan, Kansas, 1974.

10. Smith, R., "Costs of conventional and advanced treatment of wastewater," Journal Water Pollution Control Federation, Vol. 40, No. 9, pp. 1546-1574, September, 1968.

11. U. S. Bureau of Reclamation, Central Utah Project Initial Phase, Bonneville Unit, Definite Plan Report, Region 4, Salt Lake City, Utah, August, 1964a.

12. U. S. Bureau of Reclamation, Central Utah Project Initial Phase, Bonneville Unit, Definite Plan Report, Appendix B Water Supply, Vols. 1 and 2, Region 4, Salt Lake City, Utah, August, 1964b.

13. U. S. Bureau of Reclamation, Central Utah Project Initial Phase, Bonneville Unit, Definite Plan Report, Appendix C Project Lands, Region 4, Salt Lake City, Utah, 1964c.

14. Utah State Health Division, private communication, June, 1974.

15. Walker, W. R., and G. V. Skogerboe, Mathematical modelling of water management strategies in urbanizing river basins, Report No. 45, Environmental Resources Center, Colorado State University, Fort Collins, Colorado, June, 1973a, pp. 119.

16. ________, T. L. Huntzinger, and G. V. Skogerboe, Coordination of agricultural and urban water quality management in the Utah Lake drainage area, Report No. 47, Environmental Resources Center, Colorado State University, Fort Collins, Colorado, June, 1973b.

17. ________, G. V. Skogerboe, and T. L. Huntzinger, "Optimal allocation of water quality controls in urbanizing river basins," Water Resources Bulletin, American Water Resources Association, Oct., 1974, Vol. 10, No. 5, pp. 845-859.

18. Williams, J., Optimization of industrial systems with the Separable Programming and the Generalized Reduced Gradient Methods, Master's Thesis, Kansas State University, Manhattan, Kansas, 1972.

APPENDIX 1. COMPUTER PROGRAM FOR GENERATING SEPARABLE PROGRAMMING DATA IN MPS/360 FORMAT.

```
      C........JEREL WILLIAMS..........................JULY,1971......................
      C
      C....THIS ROUTINE IS DESIGNED TO GENERATE THE LINEAR APPROXIMATION VALUES
      C     AND TO PUNCH DATA CARDS WITHIN THE SPECIFICATIONS OF MPS/360
      C     LINEAR AND SEPARABLE PROGRAMMING.
      C
      C....A USER DESIGNED SUBROUTINE FUNC MUST ACCOMPANY THIS ROUTINE.
      C
      C....THE USER MUST SUPPLY DATA FOR SIX VARIABLES.  ALL DATA IS ECHO CHECKED.
      C          NFUN=THE NUMBER OF VARIABLES
      C          NROWS=THE NUMBER OF CONSTRAINTS+1
      C          START=THE INITIAL STARTING POINT FOR EACH VARIABLE
      C          INTER=THE NUMBER OF UNIFORM PARTITIONS DESIRED BETWEEN ALOW& UPPER
      C          ALOW=THE LOWER BOUND OF THE UNIFORM REGION
      C          UPPER=THE UPPER BOUND OF THE UNIFORM REGION
      C
      C....THE DATA CARD FORMAT IS AS FOLLOWS.
      C          FIRST CARD
      C                READ NFUN & NROWS, FORMAT 2I5
      C          THERE NOW OCCURS ONE DATA CARD FOR EACH VARIABLE CONTAINING
      C          START, INTER, ALOW, & UPPER, FORMAT F10.0, I10, 2F10.0
      C
0001   900 FORMAT(5X,5HERROR/5X,30HALOW EQUALS UPPER FOR VARIABLE,I5)
0002   901 FORMAT(5X,5HERROR/5X,31HINVALID VALUE FOR NFUN OR NROWS)
0003   902 FORMAT(5X,5HERROR/5X,27HINTER EQUALS 0 FOR VARIABLE,I5)
0004  1000 FORMAT(2I5)
0005  2000 FORMAT(4X,1HP,I4,5X,3HROW,I3,4X,F12.3,3X,3HROW,I3,4X,F12.3)
0006  3000 FORMAT(4X,1HP,I4,5X,4HGRID,I3,3X,F12.3)
0007  3001 FORMAT(4X,1HP,I4,5X,3HROW,I3,4X,F12.3,3X,4HGRID,I3,3X,F12.3)
0008  4000 FORMAT(4X,3HSET,I3,4X,8H'MARKER',17X,8H'SEPORG')
0009  5000 FORMAT(F10.0,I10,2F10.0)
0010  6000 FORMAT(5X,23HECHO CHECK FOR VARIABLE,I5/5X,6HSTART=,F10.2/
          15X,6HINTER=,I10  /5X,6HALOW =,F10.2/5X,6HUPPER=,F10.2/)
0011  7000 FORMAT(4X,6HENDSET,4X,8H'MARKER',17X,8H'SEPEND'/80(1H*))
0012  8000 FORMAT(1X,14HUP SEPBOUND  P,I4, 9X,3H1.0)
0013  9000 FORMAT(5X,27HECHO CHECK FOR NFUN & NROWS/
          15X,6HNFUN =,I5/5X,6HNROWS=,I5/)
      C
      C.....UNIT NUMBERS
      C
0014        NREAD=5
0015        NPRNT=6
0016        NPNCH=7
      C
      C.....NREAD=CARD INPUT,NPRNT=PRINT OUTPUT,NPNCH=PUNCH OUTPUT
      C
0017        DIMENSION ROW(50),F(50,50)
0018        READ(NREAD,1000) NFUN,NROWS
0019        WRITE(NPRNT,9000) NFUN,NROWS
0020        IF(NFUN.LT.1.OR.NROWS.LT.1) GO TO 96
0021        NKK=0
0022        KKK=1000
      C
      C.....DO CALCULATIONS FOR EACH VARIABLE
      C
0023        DO40KK=1,NFUN
0024        IAN=1
0025        READ(NREAD,5000) START,INTER,ALOW,UPPER
```

```
      WRITE(NPRNT,6000) KK,START,INTER,ALOW,UPPER
C
C.....CHECK DATA FOR ERRORS.  PROGRAM DOES NOT ALLOW INTER .GT. 50.
C
      IF(INTER.GT.50) INTER=50
      IF(INTER.EQ.0) GO TO 97
      IF(ALOW.EQ.UPPER) GO TO 98
C
C.....DETERMINE UNIFORM PARTITION STEP-SIZE
C
      AN=INTER
      DELTA=(UPPER-ALOW)/AN
      LL=KK+100
      WRITE(NPNCH,4000) LL
      KKK=NROWS+KK
C
C.....CHECK ALOW.NE.START.  CREATE ANOTHER PARTITION IF TRUE
C
      IJ=0
      IF(ALOW-START)2,3,2
    2 X=START
      AX=ALOW
      IJ=1
      INTER=INTER+1
      IAX=2
      DO11IK=1,NROWS
   11 ROW(IK)=0.0
      GO TO 8
C
C.....CALCULATE PARTITION VALUES
C
    3 IJ=IJ+1
      DO10IK=1,NROWS
   10 ROW(IK)=0.0
      XK=IJ-IAX
      X=XK*DELTA+ALOW
      AX=X+DELTA
C
C.....CALCULATE FUNCTION DIFFERENCES
C
    8 DO100J=1,NROWS
      CALL FUNC(J,KK,AX,F,NFUN,NROWS)
      ROW(J)=F(J,KK)
      CALL FUNC(J,KK,X,F,NFUN,NROWS)
  100 ROW(J)=ROW(J)-F(J,KK)
C
C.....CREATE GRID VALUE
C
      GRID=X-AX
      II=IJ+KKK
C
C.....START PUNCH LOOP
C
      IR=0
   16 IR=IR+1
      IF(IR.GT.NROWS) GO TO 90
      IF(ROW(IR))17,200,17
   17 IR3R=IR+1
```

```
      GO TO 20
   19 IPRR=IPRR+1
   20 IF(IPRR.GT.NROWS) GO TO 89
      IF(ROW(IPRR))75,19,75
   89 IRR=IR+100
      WRITE(NPNCH,3001) II,IRR,ROW(IR),LL,GRID
      IR=NN
      GO TO 200
   90 IR=NN
      WRITE(NPNCH,3000) II,LL,GRID
      GO TO 200
   75 IRR=IR+100
      IMM=IPRR+100
      WRITE(NPNCH,2000) II,IRR,ROW(IR),IMM,ROW(IRRR)
  199 IR=IPRR
  200 IF(IR.LT.NN) GO TO 16
      IF(IJ.LT.INTER) GO TO 3
      KKK=KKK+INTER
      NKK=NKK+INTER
  400 CONTINUE
      WRITE(NPNCH,7000)
C
C.....CREATE BOUNDS SECTION
C
      DO 1 I=1,NKK
      II=I+1000
    1 WRITE(NPNCH,8000) II
      STOP
   96 WRITE(NPRNT,901)
      STOP
   97 WRITE(NPRNT,902) KK
      STOP
   98 WRITE(NPRNT,900) KK
      STOP
      END
```

```
FORTRAN IV G LEVEL  21              FUNC              DATE = 76016          15/58/21              PAGE 0001

0001              SUBROUTINE FUNC(I,J,X,F,NFUN,NROWS)
0002              DIMENSION F(50,50)
0003              MM=(J-1)*NROWS+I
0004              GO TO(1,2,3,4,5),MM
0005            1 F(1,1)=-1*(5.23*1000*(X)**0.89+4.16*10000*(X)**0.65+
                 14.16*1000*(X)**0.90+1.42*10000*(X)**0.962+4.75*10000*(X)**0.72
                 1+5.70*1000*(X)**0.96)
0006              RETURN
0007            2 F(1,2)=-1*(5.34*10000*(X)**0.67+22.76*10000*(X)**0.79)
0008              RETURN
0009            3 F(1,3)=-1*704840=34.42*(3.68135-ALOG(39.70-(X)))/100.00
0010              RETURN
0011            4 F(1,4)=-1*2544270*37.60*(4.11087-ALOG(56.50-(X)))/100.00
0012              RETURN
0013            5 F(1,5)=-1*(3.31*10000*(X)**0.71+2.12*10000*(X)**0.83+
                 16.07*10000*(X)**0.80+4.29*10000*(X)**0.893)
0014              RETURN
0015              END
```

APPENDIX 2. COMPUTER OUTPUT OF A TYPICAL SEPARABLE PROGRAMMING PROBLEM.

The optimization problem solved is for the Lehi-American Fork district.

BOD standard = 25 mg/1

TDS reduction standard = 150 mg/1

```
CONTROL PROGRAM COMPILER - MPS/360 V2-M11                                  PAGE    1 - 76/016

0001            PROGRAM
0002            INITIALZ
0055            MOVE(XDATA,'DATA-SET')
0056            MOVE(XPBNAME,'EXAMPLE')
0057            CONVERT
0068            BCDOUT
0069            MOVE(XOBJ,'ROW101')
0070            MOVE(XRHS,'LIMITS')
0071            TITLE('PRIMAL-LOCAL OPTIMUM')
0072            XSETLB=-1    $* BOUNDED VARIABLES AT LOWER LIMIT
0074            SETUP('BOUND','SEPBOUND','MAX')
0075            PRIMAL
0076            SOLUTION     $* LOCAL OPTIMUM
0078            TITLE('PRIMAL-GLOBAL OPTIMUM')
0079            XSETLB=+1     $* BOUNDED VARIABLES AT UPPER LIMIT
0081            SETUP('BOUND','SEPBOUND','MAX')
0082            PRIMAL
0083            SOLUTION     $* GLOBAL OPTIMUM
0085            TITLE('DUAL-GLOBAL OPTIMUM')
0086            SETUP('BOUND','SEPBOUND','MAX')
0087            DUAL
0089            SOLUTION     $* GLOBAL OPTIMUM DUAL
0090            EXIT
0091            PEND
```

```
CONVERT DATA-SET TO EXAMPLE

TIME =    0.01

1- ROWS SECTION.

   0 MINOR ERROR(S) -    0 MAJOR ERROR(S).
2- COLUMNS SECTION.

   0 MINOR ERROR(S) -    0 MAJOR ERROR(S).
3- RHS'S SECTION.
  LIMITS
   0 MINOR ERROR(S) -    0 MAJOR ERROR(S).
5- BOUNDS SECTION.
  BOUND
  SEPBOUND
   0 MINOR ERROR(S) -    0 MAJOR ERROR(S).
 PROBLEM STATISTICS -    11 ROWS,      68 VARIABLES,     132 ELEMENTS, DENSITY =  17.64
 THESE STATISTICS INCLUDE ONE SLACK VARIABLE FOR EACH ROW.
     0 MINOR ERRORS,     0 MAJOR ERRORS.
```

```
NAME           DATA-SET
ROWS.
 N  ROW101
 E  ROW102
 E  ROW103
 L  ROW104
 L  ROW105
 E  ROW106
 E  GRID101
 E  GRID102
 E  GRID103
 E  GRID104
 E  GRID105
COLUMNS
    X1        ROW102         1.00000   ROW106         1.00000
    X1        GRID101        1.00000
    X2        ROW102         1.00000   ROW103         1.00000
    X2        ROW104        27.00000   ROW105       400.00000
    X2        ROW106         1.00000
    X3        ROW103         1.00000   ROW104          .27000
    X3        ROW105        40.00000   GRID102        1.00000
    X4        ROW103         1.00000   ROW104          .27000
    X4        ROW105       400.00000
    X5        ROW105     -  223.37784   GRID103        1.00000
    X6        ROW105     -  223.37784   GRID104        1.00000
    X7        ROW106     -    1.00000   GRID105        1.00000
    SET101    'MARKER'                 'SEPORG'
    P1001     ROW101    -121631.1980   GRID101   -      .64200
    P1002     ROW101     -79496.0000   GRID101   -      .64200
    P1003     ROW101     -69238.6750   GRID101   -      .64200
    P1004     ROW101     -63492.5630   GRID101   -      .64200
    P1005     ROW101     -59552.3130   GRID101   -      .64200
    P1006     ROW101     -56618.6880   GRID101   -      .64200
    P1007     ROW101     -54308.7500   GRID101   -      .64200
    P1008     ROW101     -52420.2500   GRID101   -      .64200
    P1009     ROW101     -50833.5630   GRID101   -      .64200
    P1010     ROW101     -49472.2500   GRID101   -      .64200
    SET102    'MARKER'                 'SEPORG'
    P1011     ROW101    -200052.1880   GRID102   -      .64200
    P1012     ROW101    -140376.6880   GRID102   -      .64200
    P1013     ROW101    -124403.5000   GRID102   -      .64200
    P1014     ROW101    -115091.5000   GRID102   -      .64200
    P1015     ROW101    -108627.5000   GRID102   -      .64200
    P1016     ROW101    -103755.2500   GRID102   -      .64200
    P1017     ROW101     -99877.5000   GRID102   -      .64200
    P1018     ROW101     -96676.1880   GRID102   -      .64200
    P1019     ROW101     -93964.7500   GRID102   -      .64200
    P1020     ROW101     -91625.0000   GRID102   -      .64200
    SET103    'MARKER'                 'SEPORG'
    P1021     ROW101     -24071.8670   GRID103   -     3.75000
    P1022     ROW101     -26726.1130   GRID103   -     3.75000
    P1023     ROW101     -30038.8130   GRID103   -     3.75000
    P1024     ROW101     -34291.1250   GRID103   -     3.75000
    P1025     ROW101     -39548.6880   GRID103   -     3.75000
```

```
    P1026    ROW101   -47848.875CC   GRID103   -     3.75CCC
    P1027    ROW101   -59664.00000   GRID103   -     3.75CCC
    P1028    ROW101   -79256.625CC   GRID103   -     3.75000
    P1029    ROW101  -118569.938CC   GRID103   -     3.75CCC
    P1030    ROW101  -241376.5000    GRID103   -     3.75000
    SET104   'MARKER'                'SEPORG'
    P1031    ROW101   -99852.43900   GRID104   -     5.60000
    P1032    ROW101  -111507.8750    GRID104   -     5.60000
    P1033    ROW101  -120234.250C    GRID104   -     5.60CCC
    P1034    ROW101  -145461.5630    GRID104   -     5.60CCC
    P1035    ROW101  -171516.188C    GRID104   -     5.60000
    P1036    ROW101  -209281.750C    GRID104   -     5.60CCO
    P1037    ROW101  -268271.5630    GRID104   -     5.60000
    P1038    ROW101  -374159.CCCO    GRID104   -     5.60000
    P1039    ROW101  -623061.000C    GRID104   -     5.60CCO
    P1040    ROW101 -2392957.000     GRID104   -     5.60000
    SET105   'MARKER'                'SEPORG'
    P1041    ROW101  -110300.1980    GRID105   -      .64200
    P1042    ROW101   -92084.CCCOC   GRID105   -      .64200
    P1043    ROW101   -75430.43300   GRID105   -      .64200
    P1044    ROW101   -70896.43900   GRID105   -      .64200
    P1045    ROW101   -67725.18900   GRID105   -      .64200
    P1046    ROW101   -65212.59300   GRID105   -      .64200
    P1047    ROW101   -63379.97800   GRID105   -      .64200
    P1048    ROW101   -61775.539CC   GRID105   -      .64200
    P1049    ROW101   -60411.00000   GRID105   -      .64200
    P1050    ROW101   -59227.813CC   GRID105   -      .64200
    ENDSET   'MARKER'                'SEPEND'
RHS
    LIMITS   ROW102       6.420CC    ROW103      6.42000
    LIMITS   ROW104     726.20000    ROW105 -11690.700CO
BOUNDS
 UP BOUND    X5          37.50000
 LO BOUND    X6          56.00000
 UP SEPABOUND P1001       1.00000
 UP SEPABOUND P1002       1.00000
 UP SEPABOUND P1003       1.00000
 UP SEPABOUND P1004       1.CCCOC
 UP SEPABOUND P1005       1.00000
 UP SEPABOUND P1006       1.00000
 UP SEPABOUND P1007       1.CCCCC
 UP SEPABOUND P1008       1.00000
 UP SEPABOUND P1009       1.00000
 UP SEPABOUND P1010       1.CCCCC
 UP SEPABOUND P1011       1.00000
 UP SEPABOUND P1012       1.CCCCC
 UP SEPABOUND P1013       1.00000
 UP SEPABOUND P1014       1.00000
 UP SEPABOUND P1015       1.CCCCC
 UP SEPABOUND P1016       1.00000
 UP SEPABOUND P1017       1.CCCOO
 UP SEPABOUND P1018       1.CCOCC
 UP SEPABOUND P1019       1.00000
 UP SEPABOUND P1020       1.CCCCC
```

```
 UP SEPBOUND  P1021          1.00000
 LO SEPBOUND  P1022          1.00000
 UP SEPBOUND  P1023          1.00000
 LO SEPBOUND  P1024          1.00000
 UP SEPBOUND  P1025          1.00000
 UP SEPBOUND  P1026          1.00000
 LO SEPBOUND  P1027          1.00000
 UP SEPBOUND  P1028          1.00000
 LO SEPBOUND  P1029          1.00000
 UP SEPBOUND  P1030          1.00000
 UP SEPBOUND  P1031          1.00000
 LO SEPBOUND  P1032          1.00000
 LO SEPBOUND  P1033          1.00000
 LO SEPBOUND  P1034          1.00000
 LO SEPBOUND  P1035          1.00000
 UP SEPBOUND  P1036          1.00000
 LO SEPBOUND  P1037          1.00000
 LO SEPBOUND  P1038          1.00000
 UP SEPBOUND  P1039          1.00000
 LO SEPBOUND  P1040          1.00000
 LO SEPBOUND  P1041          1.00000
 UP SEPBOUND  P1042          1.00000
 LO SEPBOUND  P1043          1.00000
 UP SEPBOUND  P1044          1.00000
 LO SEPBOUND  P1045          1.00000
 LO SEPBOUND  P1046          1.00000
 LO SEPBOUND  P1047          1.00000
 LO SEPBOUND  P1048          1.00000
 LO SEPBOUND  P1049          1.00000
 LO SEPBOUND  P1050          1.00000
ENDATA
```

PRIMAL-LOCAL OPTIMUM

SOLUTION (OPTIMAL)

TIME = 0.24 MINS. ITERATION NUMBER = 61

...NAME...	...ACTIVITY...	DEFINED AS
FUNCTIONAL	1909809.44738-	ROW101
RESTRAINTS		LIMITS
BOUNDS....		SEPBOUND

SECTION 1 - ROWS

NUMBER	...ROW..	AT	...ACTIVITY...	SLACK ACTIVITY	..LOWER LIMIT.	..UPPER LIMIT.	.DUAL ACTIVITY
1	ROW101	BS	19C8809.44738-	19C8809.44738	NONE	NONE	1.00000
2	ROW102	EC	6.42000	.	6.42000	6.42000	92255.16044
3	ROW103	EC	6.42000	.	6.42000	6.42000	66921.12534
4	ROW104	BS	173.34000	552.96000	NONE	726.30000	.
5	ROW105	UL	11680.70000-	.	NONE	11680.70000-	167.30291-
6	ROW106	EC	.	.	.	.	92255.16044-
7	GRID101	BS	.	.	.	.	.
8	GRID102	EQ	.	.	.	.	60229.01281-
9	GRID103	EC	.	.	.	.	37371.74107-
10	GRID104	EQ	.	.	.	.	37371.74107-
11	GRID105	EQ	.	.	.	.	92255.16044-

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
12	X1	LL	.	.	.	NONE	.
13	X2	BS	6.42000	.	.	NONE	.
14	X3	BS	.	.	.	NONE	.
15	X4	BS	.	.	.	NONE	.
16	X5	BS	33.75000	.	.	NONE	.
17	X6	BS	30.03744	.	.	NONE	.
18	X7	BS	6.42000	.	.	NONE	.
19	P1001	LL	.	121631.18800-	.	1.00000	121631.18800-
20	P1002	LL	.	79496.00000-	.	1.00000	79496.00000-
21	P1003	LL	.	69289.62500-	.	1.00000	69238.62500-
22	P1004	LL	.	63492.56300-	.	1.00000	63492.56300-
23	P1005	LL	.	59552.31300-	.	1.00000	59552.31300-
24	P1006	LL	.	56618.68800-	.	1.00000	56618.68800-
25	P1007	LL	.	54308.75000-	.	1.00000	54308.75000-
26	P1008	LL	.	52420.25000-	.	1.00000	52420.25000-
27	P1009	LL	.	50833.56300-	.	1.00000	50933.56300-
28	P1010	LL	.	49472.25000-	.	1.00000	49472.25000-
29	P1011	LL	.	200052.18800-	.	1.00000	161365.16178-
30	P1012	LL	.	140376.68800-	.	1.00000	101709.66178-
31	P1013	LL	.	124403.50000-	.	1.00000	85736.47378-
32	P1014	LL	.	115081.50000-	.	1.00000	76414.47378-
33	P1015	LL	.	108627.50000-	.	1.00000	69960.47378-
34	P1016	LL	.	103755.25000-	.	1.00000	65088.22378-
35	P1017	LL	.	99877.50000-	.	1.00000	61210.47378-
36	P1018	LL	.	96676.18800-	.	1.00000	58009.16178-
37	P1019	LL	.	93964.75000-	.	1.00000	55297.72378-
38	P1020	LL	.	91625.00000-	.	1.00000	52957.97378-
39	P1021	UL	1.00000	24071.26700-	.	1.00000	116072.16202
40	P1022	UL	1.00000	26726.11300-	.	1.00000	113417.31602
41	P1023	UL	1.00000	30039.41300-	.	1.00000	110105.21602
42	P1024	UL	1.00000	34291.12500-	.	1.00000	105852.90402
43	P1025	UL	1.00000	39948.68800-	.	1.00000	100195.34102
44	P1026	UL	1.00000	47849.87500-	.	1.00000	92295.15402
45	P1027	UL	1.00000	59664.00000-	.	1.00000	80480.02402
46	P1028	UL	1.00000	79296.62500-	.	1.00000	60847.40402
47	P1029	UL	1.00000	118569.93800-	.	1.00000	21574.09102
48	P1030	LL	.	241376.50000-	.	1.00000	101232.47098-
49	P1031	UL	1.00000	99852.43800-	.	1.00000	109429.31200
50	P1032	UL	1.00000	111502.87500-	.	1.00000	97778.37500
51	P1033	UL	1.00000	126234.25000-	.	1.00000	83047.50000
52	P1034	UL	1.00000	145461.56300-	.	1.00000	63820.18700
53	P1035	UL	1.00000	171616.18800-	.	1.00000	37665.56200
54	P1036	BS	.36383	209281.75000-	.	1.00000	.
55	P1037	LL	.	268271.56300-	.	1.00000	58989.81300-
56	P1038	LL	.	374159.00000-	.	1.00000	164877.25000-
57	P1039	LL	.	623061.00000-	.	1.00000	413779.25000-
58	P1040	LL	.	2392557.00000-	.	1.00000	2183275.25000-
59	P1041	UL	1.00000	110700.18800-	.	1.00000	51072.37500-
60	P1042	UL	1.00000	83084.00000-	.	1.00000	23956.18700-

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
61	P1043	UL	1.00000	75430.43800-	.	1.00000	16202.62500-
62	P1044	UL	1.00000	70896.43800-	.	1.00000	11668.62500-
63	P1045	UL	1.00000	67725.18800-	.	1.00000	8497.37500-
64	P1046	UL	1.00000	65312.56300-	.	1.00000	6084.75000-
65	P1047	UL	1.00000	63379.93800-	.	1.00000	4152.12500-
66	P1048	UL	1.00000	61775.93800-	.	1.00000	2548.12500-
67	P1049	UL	1.00000	60411.00000-	.	1.00000	1183.18700-
68	P1050	BS	1.00000	59227.81300-	.	1.00000	.

PRIMAL-GLOBAL OPTIMUM

SOLUTION (OPTIMAL)

TIME = 0.36 MINS. ITERATION NUMBER = 45

...NAME...	...ACTIVITY...	DEFINED AS
FUNCTIONAL	1908809.44738-	ROW1C1
RESTRAINTS		LIMITS
BOUNDS....		SEPBOUND

SECTION 1 - ROWS

NUMBER	...ROW..	AT	...ACTIVITY...	SLACK ACTIVITY	..LOWER LIMIT.	..UPPER LIMIT.	.DUAL ACTIVITY
1	ROW101	BS	1908809.44738-	1908809.44738	NONE	NONE	1.00000
2	ROW102	EQ	6.42000	.	6.42000	6.42000	92255.16044
3	ROW103	EQ	6.42000	.	6.42000	6.42000	66921.12534
4	ROW104	BS	173.34000	552.96000	NONE	726.30000	.
5	ROW105	UL	11680.70000-	.	NONE	11680.70000-	167.30281-
6	ROW106	EQ	.	.	.	.	92255.16044-
7	GRID101	BS	.	.	.	.	.
8	GRID102	EQ	.	.	.	.	60229.01281-
9	GRID103	EQ	.	.	.	.	37371.74107-
10	GRID104	EQ	.	.	.	.	37371.74107-
11	GRID105	EQ	.	.	.	.	92255.16044-

SECTION 2 - COLUMNS

	NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
A	12	X1	LL	.	.	.	NONE	.
	13	X2	BS	6.42000	.	.	NONE	.
	14	X3	BS	.	.	.	NONE	.
	15	X4	BS	.	.	.	NONE	.
	16	X5	BS	33.15000	.	.	NONE	.
	17	X6	BS	30.03744	.	.	NONE	.
	18	X7	BS	6.42000	.	.	NONE	.
	19	P1001	LL	.	121431.18800-	.	1.00000	121431.18800-
	20	P1002	LL	.	79496.90000-	.	1.00000	79495.90000-
	21	P1003	LL	.	69289.62500-	.	1.00000	69289.62500-
	22	P1004	LL	.	63492.56300-	.	1.00000	63492.56300-
	23	P1005	LL	.	59552.31300-	.	1.00000	59552.31300-
	24	P1006	LL	.	56618.68800-	.	1.00000	56618.68800-
	25	P1007	LL	.	54303.75000-	.	1.00000	54300.75000-
	26	P1008	LL	.	52470.25000-	.	1.00000	52470.25000-
	27	P1009	LL	.	50933.56300-	.	1.00000	50933.56300-
	28	P1010	LL	.	49472.25000-	.	1.00000	49472.25000-
	29	P1011	LL	.	200052.18800-	.	1.00000	161385.16178-
	30	P1012	LL	.	140376.68800-	.	1.00000	101709.66178-
	31	P1013	LL	.	124403.50000-	.	1.00000	85736.47378-
	32	P1014	LL	.	115081.50000-	.	1.00000	76414.47378-
	33	P1015	LL	.	108677.50000-	.	1.00000	69960.47378-
	34	P1016	LL	.	103755.25000-	.	1.00000	65088.22378-
	35	P1017	LL	.	99877.50000-	.	1.00000	61210.47378-
	36	P1018	LL	.	96676.18800-	.	1.00000	58009.16178-
	37	P1019	LL	.	93964.75000-	.	1.00000	55297.72378-
	38	P1020	LL	.	91625.00000-	.	1.00000	52957.97373-
	39	P1021	UL	1.00000	24071.86700-	.	1.00000	116072.16202
	40	P1022	UL	1.00000	26726.11300-	.	1.00000	113417.91602
	41	P1023	UL	1.00000	30034.81300-	.	1.00000	110105.21602
	42	P1024	UL	1.00000	34291.12500-	.	1.00000	105852.90402
	43	P1025	UL	1.00000	39949.68800-	.	1.00000	100195.34102
	44	P1026	UL	1.00000	47844.87500-	.	1.00000	92295.15402
	45	P1027	UL	1.00000	59664.00000-	.	1.00000	80480.02902
	46	P1028	UL	1.00000	79296.62500-	.	1.00000	60847.40402
	47	P1029	UL	1.00000	118569.93800-	.	1.00000	21574.09102
	48	P1030	LL	.	241376.50000-	.	1.00000	101232.47098-
	49	P1031	UL	1.00000	99952.43800-	.	1.00000	109429.31200
	50	P1032	UL	1.00000	111502.87500-	.	1.00000	97779.37500
	51	P1033	UL	1.00000	126234.25000-	.	1.00000	83047.50000
	52	P1034	UL	1.00000	145461.56300-	.	1.00000	63920.13700
	53	P1035	UL	1.00000	171616.18800-	.	1.00000	37665.56200
	54	P1036	BS	.36383	209241.75000-	.	1.00000	.
	55	P1037	LL	.	269271.56300-	.	1.00000	59949.81300-
	56	P1038	LL	.	374159.00000-	.	1.00000	164877.25000-
	57	P1039	LL	.	623061.00000-	.	1.00000	413779.25000-
	58	P1040	LL	.	2392957.00000-	.	1.00000	2183675.25000-
	59	P1041	UL	1.00000	110300.18800-	.	1.00000	51072.37500-
	60	P1042	UL	1.00000	33084.00000-	.	1.00000	23856.18700-

PRIMAL-GLOBAL OPTIMUM

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
61	P1043	UL	1.00000	75433.43800-	.	1.00000	16202.62500-
62	P1044	UL	1.00000	70896.43800-	.	1.00000	11664.62500-
63	P1045	UL	1.00000	67725.18800-	.	1.00000	3497.37500-
64	P1046	UL	1.00000	65312.56300-	.	1.00000	6084.75000-
65	P1047	UL	1.00000	63379.93100-	.	1.00000	4152.12500-
66	P1048	UL	1.00000	61775.93800-	.	1.00000	2548.12500-
67	P1049	UL	1.00000	60411.00000-	.	1.00000	1183.18700-
68	P1050	BS	1.00000	59227.81300-	.	1.00000	.

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APPLICATION OF SEPARABLE PROGRAMMING TO REGIONAL WATER QUALITY MANAGEMENT

by

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AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

Walker, et al., have developed a mathematical model of water quality management that optimizes allocation of water pollution control strategies in an area where both urban and agricultural activities exist side by side. The model was applied to the Utah Lake drainage area which was subdivided into four districts, each of which discharges urban and agricultural return flows into the Lake. Optimal policies that minimize the cost of maintaining specific BOD and salinity standards were first determined under the assumption of independent operation among the districts. Next it was assumed that the salinity-BOD control efforts of the districts could be regionally coordinated to take advantage of the economies of operating on a larger scale. As before BOD standards were imposed on the effluents from each district, but TDS reduction standards were imposed on the aggregated return flows. The method of optimization used by Walker, et al., was the 'Jacobian differential algorithm'. Shojalashkari used the generalized reduced gradient method to optimize a slightly different version of the same system.

This study was undertaken because of serious discrepancies among the solutions to the two versions mentioned above. Separable programming which is a comparatively simpler nonlinear programming technique, was used as the method of optimization in this study. A simple mathematical manipulation was used to convert the objective function to a form amenable to separable programming. The separable programming option in MPS/360 was used to resolve the problem as solved by Walker, et al., and Shojalashkari. The optimal policies obtained in this study agree well with those determined by Shojalashkari. However, there was total disagreement with the optimal policies proposed by Walker, et al.