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LEAST COST IRRIGATION SYSTEM SPECIFICATIONS FOR VARIOUS CONDITIONS

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SUMMARY: A methodology employing a dynamic-linear programming model was used to develop optimum rehabilitation plans for an irrigation district. The plans developed indicate the total irrigation system cost and configuration for various levels of efficiency and water cost.

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INTRODUCTION

Multi-objective irrigation system planning is a complex process when considering both water distribution and application systems. Planners must consider not only the objectives of irrigators but also other portions of the public that might be affected by a new irrigation system or the rehabilitation of an existing system. The system plan selected for implementation should effectively integrate distribution and application system components to provide the "best" system as specified by the various objectives.

Irrigation system plans are also subject to various constraining conditions. These conditions include physical, social and economic factors, and are necessary for specifying the relationships of individual components with one another. They are also necessary establishing boundary conditions around the entire system.

A methodology has been developed to enable the rapid evaluation of many different irrigation system alternatives (Busch, 1974, 1975). The methodology uses a two-stage dynamic-linear programming model to select optimal system configurations. Input to the model consists of economic and physical data for each component under consideration. Several alternative components may be specified for each portion of the system, and the model is used to select the optimal (least cost) combination of components that is subject to all specified constraints.

To test the model developed, an old irrigation district in eastern Idaho was selected, and least cost rehabilitation plans were developed. It is the purpose of this paper to describe the application of the model and present the optimum rehabilitation plans obtained.

STUDY AREA

The area selected for application of the optimization procedure is that served by the North Rigby Irrigation and Canal Company. It is located in Jefferson County, Idaho; and encompasses approximately 990 irrigated acres. The area served, shown in Figure 1, is less than one mile wide and approximately four miles long.

Irrigation water is supplied from the Great Feeder Canal through a distribution system that is relatively unchanged from when it was constructed during the 1880's. Approximately half of the diversion and drop structures are made of concrete with the other half being made of wood. No water measuring devices are installed in the system. Maintenance work is done by the water users using

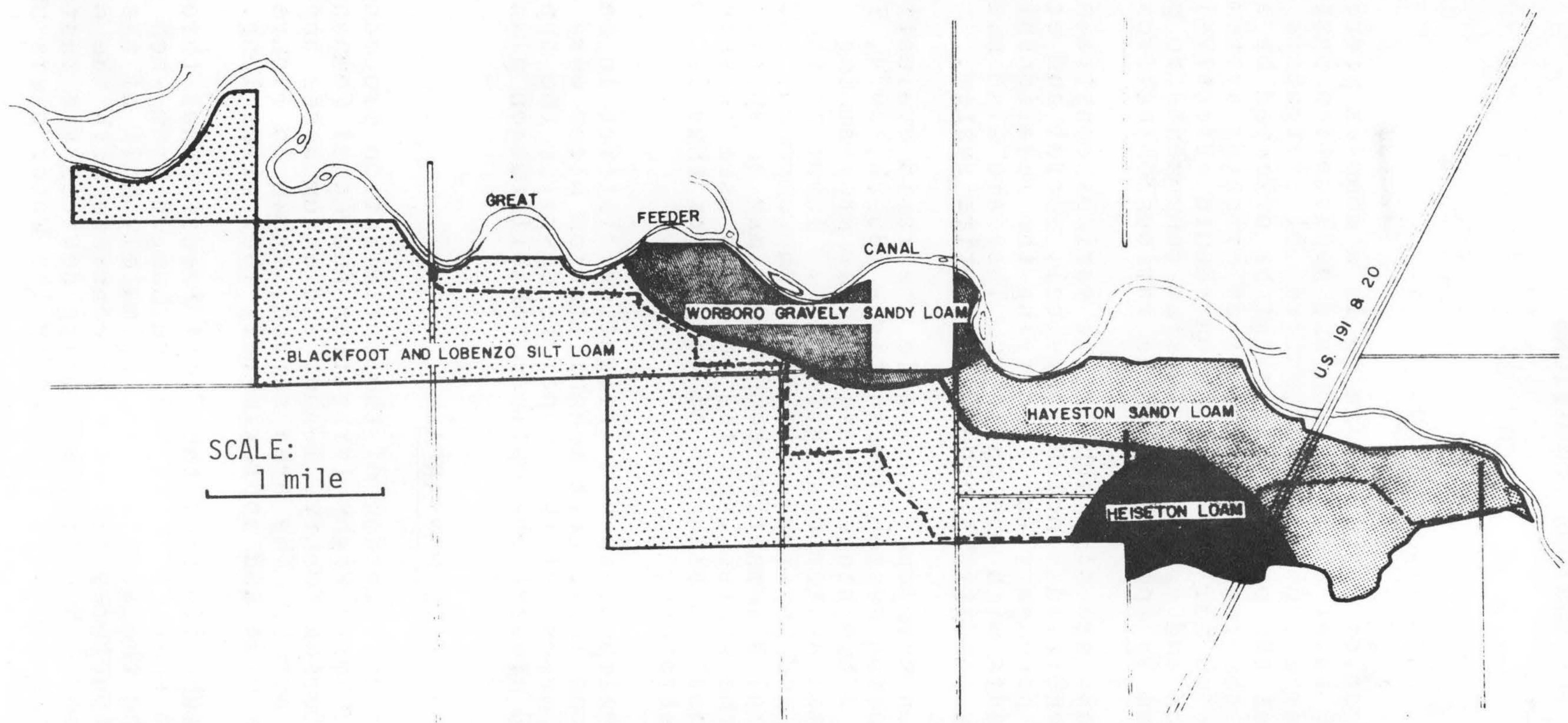

Figure 1. North Rigby Irrigation District.

farm equipment, and periodically a small bulldozer is used to clean and reshape sections of the main canal.

Soils present in the irrigation district are shown in Figure 1. All soils have medium to high intake rates and are underlain by sands and gravels. As a result, field irrigation efficiencies are quite low in the 20-50 percent range (Galinato, 1974). Canal sections often penetrate shallow soils and have gravel or sand bottoms. Brockway and de Sonneville (1973) report an average seepage rate 3.5 ft/day from canals in the area. High intake rates combined with a rather antiquated system make for an overall irrigation efficiency of less than 20 percent for the district.

PROCEDURE

Components within an irrigation system may be grouped into two main categories. First are those used to apply water to the land, application systems. The second, distribution systems, are used to convey and distribute water to the application systems. Physical and economic inputs are used to compute the cost and efficiency of each component functioning within a given irrigation district.

Application Systems

Input to the model requires annual costs of application systems on a per-acre basis.

$$\text{Annual Cost} = cN \qquad (1)$$

where

c = annual cost per acre
N = number of acres supplied

Also required is the application efficiency (percentage of water applied retained in the root zone) of each system under consideration. As the cost and application efficiency of application systems are dependent on several factors such as soil, slope, farm size, field size and crops grown, it is necessary to break the irrigation district into several units shown in Figure 2. The unit boundaries are influenced by soils, field size and crops grown, and coincide quite closely with the soils boundaries shown in Figure 1.

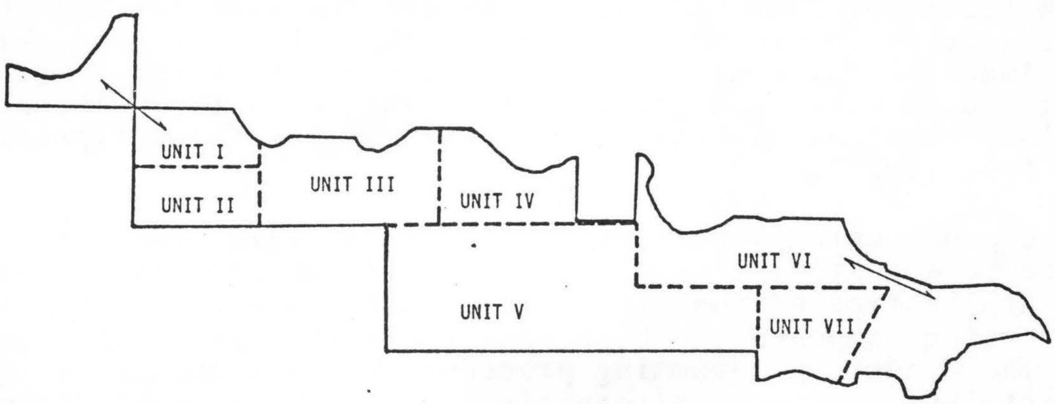

Figure 2. Units within North Rigby Irrigation District.

Alternative application systems considered include both gravity and sprinkler systems listed in Tables 1 and 2. Annual costs for the different sizes of systems listed were obtained for every crop grown on each of the different soils. The costs include the total annual costs of applying water and conveying water from the point of diversion to the point or points of application.

Distribution Systems

The annual cost of each distribution system component is specified as a function of the maximum flow rate conveyed, controlled or pumped by that component. Also, for any component there is a minimum cost associated with construction, operation and maintenance, the fixed specified cost. Therefore, the total annual cost of the component is:

$$\text{Annual Cost} = cQ + d \qquad (2)$$

where

c = annual cost per unit volume flow rate
Q = maximum volume flow rate
d = annual fixed specified cost

The conveyance efficiency of each component is also computed.

Four main distribution system alternatives were considered for the irrigation district; gravity, pressure-pipe, wells with high head pumps and wells with low head pumps. The gravity system is designed to supply water from the Great Feeder Canal and deliver it to farms at zero pressure. The pressure pipe system is also supplied from the Great Feeder Canal by a pumping plant with sufficient head to supply a sprinkler system without need of a booster pump. Wells with low head pumps are designed to deliver water at zero pressure, and those with high head pumps to deliver water at sprinkler operating pressure. Maximum static lift for all pumps is considered to be 110 feet or less based upon the findings of Brockway and de Sonneville (1973).

Three types of conveyance, unlined canal, lined canal and gravity pipeline, were considered for each section of the gravity distribution system. Sections A through H of the unlined canal route are shown in Figure 3. Junction locations are the same for all three types of gravity conveyance, and the pressure head is near zero at each junction. Therefore, combinations of the three types may be specified to make up a gravity distribution system. The number of possible combinations considering each of the three types for each of N sections is 3^N.

A dynamic programming procedure (Busch, 1974, 1975) was used to eliminate more costly, less efficient dustribution system combinations. Application of the procedure results in a reduction of gravity system component combinations to 54 for the irrigation district. The dynamic programming procedure was not applied to the other distribution system alternatives. There are no different types of components for any section of the pressure-pipe system, and the same is true for the well-pump combinations.

Table 1. Surface application systems considered for the North Rigby Irrigation District

System Type	Symbol	General Description
Unimproved gravity	UG	The system consists of poorly maintained earthen ditches with earthen and wooden structures and portable canvas dams used for water control. Maximum allowable length of irrigation run is 1300 feet.
Improved gravity	IG	The system consists of well maintained earthen ditches with concrete and metal structures used for water control. Maximum allowable length or irrigation run is 650 feet. A cross ditch is specified if the irrigation run is in excess of the 650 foot length.

Table 2. Sprinkler application systems considered for the North Rigby Irrigation District

System Type	Symbol	General Description
Hand-line sprinkler	HS	The layout of the system consists of hand-carried laterals supplied by a permanent or semi-permanent mainline.
Hand-line sprinkler with pump	HSP	Same as hand-line sprinkler but equipped with a pump to supply pressure.
Side-roll sprinkler	RS	The layout of the system consists of mechanically moved laterals supplied by a permanent or semi-permanent mainline.
Side-roll sprinkler with pump	RSP	Same as side-roll system, but equipped with a pump to supply pressure.

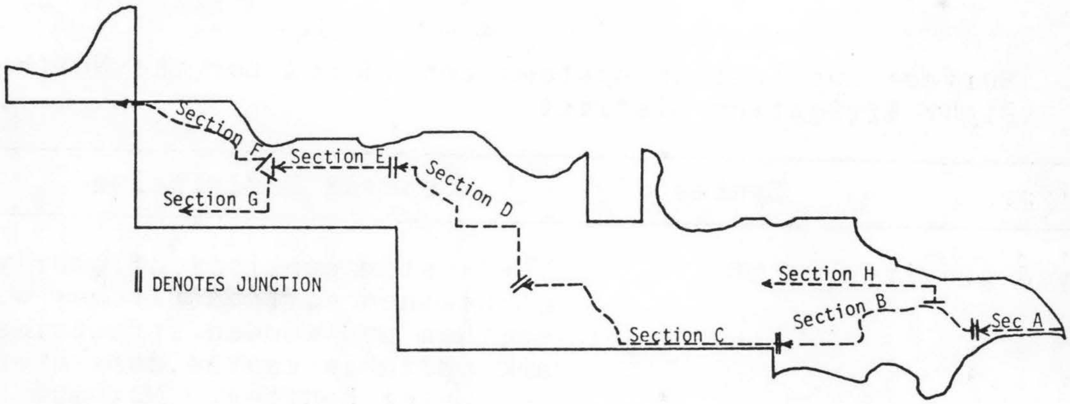

Figure 3. Unlined canal route and sections for North Rigby Irrigation District.

Cost-discharge relationships for all distribution system components are estimated quite well by the linear Equation 2. The correlation coefficients relating estimated and computed values are greater than 0.90 for all components considered.

Linear-Programming Problem Formulation

The linear cost functions for alternative application systems and distribution system components, and operation and maintenance costs are combined in a linear-programming model. Model constraints assure that all crops within the district receive an adequate supply of water to meet maximum consumptive use requirements. The model is revised for each different distribution system combination alternative.

Least cost system specifications are obtained as optimal solutions from the linear-programming model. The total system cost and all individual component costs are obtained. In addition, water flow rates through each distribution system component and acreages covered by each type of application system are specified. Post optimal analyses may be performed to vary costs and constraining parameters and to determine the sensitivity of any optimal solution to individual parameter changes.

RESULTS

Optimum rehabilitation plans for the North Rigby Irrigation District were obtained to meet different specified conditions. Various levels of overall system efficiency (percentage of water diverted to consumptive use) were specified, and the price of water entering the system was allowed to vary over a specified range. The effects of these parameter changes were computed separately, and the results will be described separately.

Effects of Changes in System Efficiency

The results of optimal solutions for different distribution system alternatives are summarized in Tables 3, 4 and 5. The range of efficiencies shown for each alternative is the attainable range for optimal solutions.

For the gravity distribution system, solutions were obtained for a range in efficiency from the present 17.1 percent to 70 percent as shown in Table 3. Corresponding system costs vary from $67,523 to $93,179. The maximum flow rates required are given as are the annual losses to deep percolation and surface runoff. These losses can be used to determine the system contribution to subsurface and surface drainage in the area.

Component configuration for the distribution and application systems is specified for each efficiency level. Up to and including a specified efficiency of 60 percent, the greatest change in components occurs with the application systems changing from unimproved gravity to sprinkler. Very little change is present in the distribution system at specified efficiencies less than 70 percent. These results indicate that for a gravity distribution system it would be more economical for water users to improve overall system efficiency by using sprinkler application systems rather than by undertaking a major rehabilitation of the distribution system.

The summary for low head well supply in Table 4 shows least cost solutions for efficiencies from 38.4 to 70 percent. At efficiencies less than 38.4 percent, the cost of pumping water is greater than the cost of improving application systems. The small variation in total annual cost over the entire efficiency range is due to the fact that pumping costs decrease as application systems are upgraded and efficiency increases.

Efficiencies of 70 percent only are shown for the pressure pipeline and high head well supplies as these alternatives supply only sprinkler systems designed to operate at 70 percent efficiency. A comparison of the total costs shows that the cost of wells with high head pumps supplying sprinkler systems at 70 percent efficiency is less than any other alternative except for the gravity distribution system operating at 17.1 percent.

It should be emphasized that costs associated with different systems are somewhat of a different nature. For example, much of the annual cost associated with an unimproved gravity type distribution and application system is paid out for manual labor, management, and machine hire furnished by farmer irrigators. However, much of the annual cost associated with a side-roll sprinkler system supplied by a well with a high head pump is money required to repay a high initial capital investment.

Effects of Changes in Water Costs

Charges for water are often assessed for surface water delivered to an irrigation district by a feeder canal. The basis for charges

Table 3. Total annual system costs for varying efficiencies for a gravity distribution system

System efficiency (%)	17.1	20	30	40	50	60	70
Total annual cost ($)	67,523	68,931	73,329	76,826	79,586	81,851	93,179
Max. flow rate (cfs)	56.9	48.7	32.4	24.3	19.5	16.2	13.9
Volume to DP (AF)	3326	2563	1409	944	844	721	399
Volume to SR (AF)	3554	3048	1816	1097	445	65	0
Distribution system							
Section A	UC[a]	UC	UC	UC	UC	UC	LC
B	UC	UC	UC	UC	UC	UC	GP
C	UC	UC	UC	UC	UC	UC	GP
D	UC	LC	LC	LC	LC	LC	GP
E	UC	UC	UC	GP	GP	GP	GP
F	UC	UC	UC	UC	UC	UC	GP
G	UC	UC	UC	UC	UC	UC	LC
H	UC	UC	UC	UC	UC	UC	GP
Application system							
Unit I	UG[b]	UG	UG	RSP	RSP	RSP	RSP
II	UG	RSP	RSP	RSP	RSP	RSP	RSP
III	UG	UG	HSP	HSP	HSP	HSP	HSP
IV	UG	IG	HSP(30%) IG(70%)	HSP	HSP	HSP	HSP
V	UG	UG	UG	RSP(17%) UG(83%)	RSP(79%) UG(11%)	RSP	RSP
VI	UG	RSP(15%) UG(85%)	RSP	RSP	RSP	RSP	RSP
VII	UG	UG	UG	UG	UG	RSP(70%) UG(30%)	RSP

[a]UC = unlined canal, LC = lined canal, and GP = gravity pipeline

[b]Application system symbols in Tables 1 and 2

Table 4. Total annual system costs for varying efficiencies for a low head well supply

System efficiency (%)	38.4	40	50	60	70
Total annual cost ($)	86,738	86,785	87,007	87,165	87,739
Max. flow rate (cfs)	25.3	24.3	19.5	16.2	13.9
Volume to DP (AF)	523	520	505	501	399
Volume to SR (AF)	1618	1467	739	256	0
Application system					
Unit I	UG[a]	UG	UG	RSP(89%), UG(11%)	RSP
II	RSP	RSP	RSP	RSP	RSP
III	HSP	HSP	HSP	HSP	HSP
IV	HSP	HSP	HSP	HSP	HSP
V	UG	RSP(14%), UG(86%)	RSP(83%), UG(17%)	RSP	RSP
VI	RSP	RSP	RSP	RSP	RSP
VII	UG	UG	UG	UG	RSP

[a]Application system symbols in Tables 1 and 2

Table 5. Total annual system costs for varying efficiencies for high pressure pipeline and high head well supplies

	Pressure pipeline	Wells with high head pumps
System efficiency (%)	70	70
Total annual cost ($)	75,121	68,769
Max. flow rate (cfs)	13.9	13.9
Volume to DP (AF)	399	399
Volume to SR (AF)	0	0
Application system		
Unit I	RS[a]	RS
II	RS	RS
III	HS	HS
IV	HS	HS
V	RS	RS
VI	RS	RS
VII	RS	RS

[a]Application system symbols in Table 2

can vary. A common basis is cost per unit volume, usually dollars per acre-foot.

The charge for surface water entering the North Rigby Irrigation District was allowed to vary from $0 per acre-foot to $12 per acre-foot. These charges were considered for both gravity and pressure distribution systems but not for wells as charges are seldom assessed against pumped groundwater. Results related to the various water costs are summarized in Tables 6 and 7.

The data in Table 6 indicate that system configuration does not change for water costs of $8 per acre-foot or greater. Also, application system components are the first to change with increasing water cost as they were with increasing specified system efficiency. This fact indicates that the amount of water saved versus cost is generally greater for application system components than for distribution system components.

Table 6. Total annual system costs for varying water costs for a gravity gravity distribution system

Water cost ($/AF)	0	2	4	6	8	10	12
System cost ($)	67,523	84,318	92,718	98,394	103,537	108,509	113,480
System efficiency (%)	17.1	26.0	54.8	62.5	67.0	67.0	67.0
Max. flow rate (cfs)	56.9	37.0	17.8	15.6	14.5	14.5	14.5
Volume to DP (AF)	3326	1599	809	685	505	505	505
Volume to SR (AF)	3554	2294	219	0	0	0	0
Distribution system							
Section A	UC[a]	UC	UC	UC	LC	LC	LC
B	UC	UC	UC	UC	LC	LC	LC
C	UC	UC	UC	UC	UC	UC	UC
D	UC	LC	LC	LC	LC	LC	LC
E	UC	UC	GP	GP	GP	GP	GP
F	UC	UC	UC	UC	UC	UC	UC
G	UC	UC	UC	UC	LC	LC	LC
H	UC	UC	UC	UC	GP	GP	GP
Application system							
Unit I	UG[b]	UG	RSP	RSP	RSP	RSP	RSP
II	UG	RSP	RSP	RSP	RSP	RSP	RSP
III	UG	UG	HSP	HSP	HSP	HSP	HSP
IV	UG	IG	HSP	HSP	HSP	HSP	HSP
V	UG	UG	RSP	RSP	RSP	RSP	RSP
VI	UG	RSP	RSP	RSP	RSP	RSP	RSP
VII	UG	UG	UG	RSP	RSP	RSP	RSP

[a]UC = unlined canal, LC = lined canal, GP = gravity pipeline

[b]Application system symbols in Tables 1 and 2

Table 7. Total annual system costs for varying water costs for a high pressure pipeline system

Water cost ($/AF)	Overall annual system cost[a] Pressure pipeline ($)
0	75,121
2	79,881
4	84,641
6	89,401
8	94,161
10	98,921
12	103,681

[a]System configuration is identical to those in Table 5

Based upon the results obtained and considering only the total annual cost, the most economical way to increase the overall irrigation efficiency of the given district is to abandon all present systems and to install wells from which water could be pumped to supply sprinkler systems. System costs increase quite drastically if a charge for water entering the system from a surface source is considered. However, an increasing water charge would also force a marked increase in system efficiency. Charging for water would add a cost requiring money to be spent outside the district.

Various other plans and incentives for rehabilitation could easily be considered as changes in the linear-programming model require minimal modification of the modeled problem. Specific planning needs would dictate which relationships and constraining conditions would be most meaningful for the district considered.

Results obtained from the model can be used to develop specific designs for system components. The cost of the resultant design for the entire system would be nearly the same as the optimum cost obtained from the modeled problem.

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