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SYSTEMS ANALYSIS: A DECISION-MAKING TOOL FOR ARID LAND DEVELOPMENT

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SYSTEMS ANALYSIS: A DECISION-MAKING TOOL FOR ARID LAND DEVELOPMENT

INTRODUCTION

From the dawn of civilization man has been concerned with the management of the waters of the earth for subsistence, for protection against the elements and for transportation. In many instances, he went to great lengths to secure this essential ingredient in his fight for survival, as witness the kanats here in Iran, the Roman aqueducts, the bamboo-drilled wells of China, and many other such examples. The ancient worlds in both hemispheres were no strangers to the complex physical, economic and social problems which still characterize man's never-ending battle against aridity, flood, drouth, and pollution.

Water resources development is related to other national development needs and should be viewed as a complete system covering the many uses for which water is employed--domestic, agriculture, industrial, waste disposal, forests, wildlife, natural beauty and transportation. The planners and designers of water resource management systems must often choose among a number of alternative plans for the location and design of structures, land and water management systems, and institutional arrangements for effecting the acceptable plan. In a similar fashion, farmers must choose the right combination of water, fertilizer, labor, etc. for a variety of crops to maximize their returns. Much of the research and analysis applicable to such systems has dealt only with bits and pieces of the system. Lack of adequate data

and the laboriousness of methods of analysis have severely limited the number of alternatives that could be compared and prohibited a clear choice among a set of alternatives.

In our preoccupation with identifying problem areas in the broad and complex systems of water management, we sometimes fail to consider that adoption of a slight change may cause undue stress elsewhere in the entire system Too frequently our approach to problem solving is to accept the problem as it exists and work directly towards a solution. This can be a too narrow process and may lead to a workable but still unsatisfactory solution. We allow our conventional concepts to guide us. Instead, we should turn our attention more to an analysis of the problem itself to determine whether it can be broken down into component parts. We should consider the possibility that the end of a problem may come through the development of new means.

Systems analysis is a tool that can permit a view of the entire problem. It takes into account means and ends, choices and alternatives. It makes use of prediction and advanced testing to suggest objectives and courses of action. It provides a method for more thorough consideration of alternatives.

Systems analysis may be viewed as a formalization of interactions. It contains few new concepts; it makes use of newly developed tools. Its application is by no means restricted to the planning of large-scale water resource management schemes. It can have a significant role in the decision-making processes of individual farmers.

The development of better data, together with the development of high-speed computers, and the availability of newer analytical techniques have opened the way to more comprehensive analyses of relevant alternatives in

the design of water management systems and the benefits which can be derived from those systems.

There is no universally accepted definition of systems analysis nor is there any standardized method that can be presented as a general mathematical model for selecting the optimal alternative. It should be kept in mind that while systems analysis may be a powerful tool, the tools of operations research as applied to water resources systems can only assist the decision-making process. In addition, by itself systems analysis is useless; a knowledge of water resources systems is essential. The purpose of this discussion is to take a brief look at selected examples in which some form of systems analysis may be used to advantage.

THE SYSTEMS CONCEPT IN WATERSHED MANAGEMENT

Watershed Management is a relatively new science as evidenced by a lack of a large body of solidly established facts and well-proven relationships. There are several definitions of watershed management, one of which is the administration and regulation of all the available resources of a watershed for the production of water, control of erosion, regulation of streamflow and the control of floods. However, watersheds are generally of the multiple-use type in that they are used not only for the production of water but for timber, forage, wildlife habitat and for outdoor recreation purposes. While watersheds are flexible in that they may be managed to serve these various purposes, there is almost always some kind of trade-off in manipulating a watershed. That is, altering the vegetation to increase streamflow, for example, may result in erosion as well as reducing the benefits to be derived from the watershed's uses other than for water.

In water-short areas of the world, the management of water-source areas for the purpose of producing beneficial changes in the hydrologic regimen is a subject of increasing concern. The vegetative manipulation of forests to alter both the quantity and timing of streamflow has been under study in the United States for over 50 years. In studies of this type, attention is usually given to the harmful effects of a vegetative treatment such as erosion and sedimentation. However, no attention is given to the entire water system, from its source to its storage to its eventual use. For example, suppose a treatment produces water yield increases only in the very wet years and in those years the available storage facilities are not adequate to control the natural flows. This type of treatment would have no beneficial use as the storage facilities would simply be forced to spill the increased flow and hence the water would be wasted. Conversely, in the dry years when the added flow would be highly beneficial, the treatment may result in insignificant increases.

The following briefly illustrates a procedure for evaluating the effects of a watershed treatment designed to increase the water yield by looking at the entire water system, from its source to its use.

The planning for most water resources management systems normally starts with an analysis of precipitation to determine among other things, its distribution in time with respect to the probable occurrence of drouth periods. In our particular example, a study would be made on how a watershed transforms precipitation into streamflow. The results should be sufficiently sensitive to determine the effects of a watershed treatment on streamflow. Finally, an investigation is needed to obtain the required storage to meet the downstream needs for water.

Available precipitation records are analyzed for the purpose of predicting what might happen in the future. Too often our analysis implies that the historical records will repeat itself. If hundreds of years of records are available, we may very well rely completely on historical records to predict the future. However, since this is not too frequently the case, some means of generating sequences of precipitation is needed. Stochastic models of precipitation, with all degrees of sophistication are currently available which will produce a synthetic time series that preserves the statistics (mean, standard deviation, etc.) of the available historical records. Hopefully, this simulated record can account for all the variability found in these historical records.

To convert precipitation into streamflow, computerized, mathematical watershed models are used. This simulated hydrologic response of a watershed coupled with a stochastic precipitation model results in a synthetic streamflow record. Then, using this simulated streamflow as inflow into a reservoir, a storage-draft analysis can be made for any kind of demand scheduale, such as water for irrigation, municipal use, power, etc.

The storage-draft relationship is simply a means for determining the size of the reservoir or storage needed to produce a firm outflow from the reservoir to meet specific downstream water requirements. Looking at this another way, the relationship can be used to determine the <u>dependable</u> supply of water that can be obtained from a given river system with its storage facilities. The supply can also be determined for those cases where users are willing to accept a certain amount of risk in receiving a greater quantity of water.

With the system thus defined, various watershed treatments under a variety of site conditions can now be evaluated to determine their potential usefulness to the ultimate consumer. The use of operations research or systems analysis is practically a necessity to determine both the optimal combination of treatments and their scheduling within the many constraints confronted land managers. The physical constraints are only one aspect of the problem. Consideration must also be given to the budgetary, legal, social political factors involved in water resources management.

SYSTEMS ANALYSIS IN AGRICULTURE

In this section two examples will be presented to illustrate the use of operations research techniques to select from a number of alternatives that particular course of action which will best accomplish the overall objectives.

Let us assume that a farmer wants to raise two crops. From past experience, he knows that his net profits are 4 and 3 units of money per unit of land. Naturally, he wants to maximize his profits. However, he has only 200 units of water and crop A requires two per land unit while crop B needs only one per land unit. An additional constraint is placed on the farmer in that he only has 150 land units.

The above problem could be solved quite easily to determine the number of acres that should be planted to each crop in order to maximize profits. Stated mathematically, the optimization problem is to maximize

$$V = 4A + 3B \quad \text{(objective function)}$$

subject to the constraints

$$2A + B \leq 200$$

$$A + B \leq 150$$

$$A \geq 0, \; B \geq 0$$

If we replace the inequality signs by equal signs it is apparant that A should be planted on 50 land units and B on 150 units to maximize profits.

However, with as few as four crops and three constraints, the solution is far from obvious. If the objective function in this case is a simple linear algebraic equation and if the constraints also can be expressed as linear algebraic equations or inequalities involving nonnegative decision variables, the result is a particular type of optimization problem known as the linear-programming problem.

A possible four crop problem that can be solved by linear programming is presented in the following table.

Requirement	Crop				Total Availabilities
	A	B	C	D	
Labor	1	1	1	1	≤ 15
Water	7	5	3	2	≤ 120
Fertilizer	3	5	10	15	≤ 100
Unit Profit	4	5	9	11	Maximize
Acreage Planted	x_1	x_2	x_3	x_4	

The problem can be stated as follows:

$$\text{Maximize profit} = \text{maximize } (4x_1 + 5x_2 + 9x_3 + 11x_4)$$

subject to the constraints

$$1x_1 + 1x_2 + 1x_3 + 1x_4 \leq 15$$

$$7x_1 + 5x_2 + 3x_3 + 2x_4 \leq 120$$

$$3x_1 + 5x_2 + 10x_3 + 15x_4 \leq 100$$

$$x_1 \geq 0,\ x_2 \geq 0,\ x_3 \geq 0,\ x_4 \geq 0$$

The solution to the above problem turns out to be

$$\bar{x}_1 = 50/7 \qquad \bar{x}_3 = 55/7$$

$$\bar{x}_2 = 0 \qquad \bar{x}_4 = 0$$

In addition to wanting optimal values, farmers may also want to know how profit would be affected by increasing each input (labor, water, fertilizer, etc.) or by a change in the cost of the raw materials--and consequently a change in the unit profit. In many real applications of linear programming models, these considerations are even more important than finding exact optimal values.

In many instances, time is an important consideration such as in dealing with sequential-decision processes. The farmer's concern about when to irrigate--at what soil moisture level? or at what stage of growth?--is such a process.

Certain semi-arid regions are continually faced with water shortages, especially for irrigation. Farmers should be advised not only on the most efficient methods for applying water but also on those practices that will result in the greatest return per unit of water.

Suppose experiments on a given crop were conducted to determine the effect that a given moisture stress at a particular stage of growth had on crop yield. Let us assume that these effects can be indicated by the use of yield coefficients, and that the following table is a result of these experiments:

YIELD COEFFICIENTS

Deficiency, Moisture units	Stage of growth			
	A	B	C	D
0	0.9	1.0	1.1	1.0
1	.8	.7	.8	.9
2	.7	.5	.7	.8
3	.5	.3	.2	.6
4	.3	.2	.1	.3

If an additional assumption is made that these yield coefficients are additive, then it is readily seen that the total seasonal coefficient for no soil moisture deficiency is 4.0. This would represent the maximum yield obtainable for a given climate and no other limiting factors.

To illustrate a particular example, suppose a farmer is faced with a 25 percent shortage in irrigation water, and that he has the option of using the water at any time throughout the growing season. The question is, then, when should he choose to short his crop to have the least effect on crop yield.

The problem can be simplified by choosing the stages of growth such that they all require the same amount of water, say 4 moisture units each. This particular type of problem is readily solved through the use of dynamic programming techniques.

The usual procedure in such problems is to work backwards. For growth stage D, the yield coefficients are shown in the last column of the above table. That is, if we arrive at this stage with a given deficiency, the choice is obvious.

Now, let us look at stage C. If we arrive in time at this stage with no deficiency, the required 4 deficient units will have to be selected from some combination of those occurring in both stages C and D. For example, the farmer may choose to have the entire deficiency in stage C and none in D, or 3 in C and 1 in D, or 2 in each and so on. It turns out, that for this situation, the best choice as indicated by the highest combined yield coefficient would to hold back 2 moisture units in each stage.

Still looking at stage C, a similar calculation is made assuming that a deficiency of 3 moisture units has to be allocated to both stages C and D. This is repeated for 1 and 2 deficient units. The following illustrates the procedure:

If 4 units are to be allocated to stages C and D:

Combined yield coefficients	Selection
1.1 + 0.3 = 1.4	
0.8 + 0.6 = 1.4	
0.7 + 0.8 = 1.5	use 2 units in C
0.2 + 0.9 = 1.1	
0.1 + 1.0 = 1.1	

If 5 units (3 deficient) are to be allocated:

Combined yield coefficients	Selection
1.0 + 1.7 = 2.7	use 0 units in C
0.7 + 1.9 = 2.6	
0.5 + 2.0 = 2.5	
0.3 + 2.1 = 2.4	

If 6 units (2 deficient) are to be allocated:

Combined yield coefficients	Selection
1.0 + 1.9 = 2.9	use 0 units in C
0.7 + 2.0 = 2.7	
0.5 + 2.1 = 2.6	

If 7 units (1 deficient) are to be allocated:

Combined yield coefficients	Selection
1.0 + 2.0 = 3.0	use 0 units in C
0.7 + 2.1 = 2.8	

The same process is repeated at stage B with the same result. Stages B and C should have no moisture deficiency.

Thus, the final result of this particular analysis indicates that for the situation here 75 percent of the required water is available for irrigation (4 units deficient out of 16 required), the highest yield would be obtained by supplying stages A and D with 50 percent (2 moisture units) of their requirement and 100 percent for stages B and C.

A similar analysis can be made for any other deficiency. The farmer can then go one step further. He may find out that the greatest return can be obtained by applying less than the total amount of water required.

While the above methodology is correct, there are several drawbacks to this procedure. Little or no data is available to determine the yield coefficients. The additive nature of these coefficients which implies that a moisture stress at one stage has no affect on another stage of growth may not be true. There are other problems, too, such as the interrelationship between water and other crop variables. Nonetheless, more and more research efforts are being directed along these lines because of the importance of the problem.

DISCUSSION AND SUMMARY

Since arid land development is intimately associated with water resources systems, procedures that aid in the management of such systems is of relevant concern to all seminar participants. From the examples presented, systems analysis may be defined as the art and science of selecting from a large number of feasible alternatives that particular set of actions which will best accomplish the overall objectives within the constraints of law, economics, resources and political and social pressures. Perhaps a more appropriate term would be decision analysis.

The intent of using examples in this paper is not to discuss the procedures themselves but rather to illustrate the type of problems that can be dealt with using these techniques. In the first example, the idea of a system was presented in that plans for treating a watershed to induce more runoff should be looked at from the standpoint of both the damaging effects resulting from such an action and the ultimate recipient of such action. Thus, if the watershed treatment produces reservoir-filling sediment or increased water supplies comes only at times when there is no available storage space then this action would have little or no economic value.

The use of an important systems analysis tool, simulation, was used in this example. To account for the variable nature of streamflow, a stochastic precipitation model was coupled with a deterministic watershed model to generate a synthetic series of streamflow both for the treated and untreated watersheds. Other systems analysis techniques would have to follow to determine a detailed course of action--what type, where and when the treatments should be applied.

To emphasize the point that systems analysis can be used not only for large-scale water resources systems, two types of optimization problems of concern to individual farmers were illustrated. In the first case, the aim was to maximize profits by selecting the area to be planted to each crop. Crops have different requirements for labor, water and fertilizer and each yields a different return to the farmer. Since there are obvious limitations to the land, water and finances that are available, the selection has constraints as well as many alternatives. This first instance is an example of linear programming.

However, since all objective functions or constraints do not have linear relationships, other techniques have to be used in these cases. Also, the time element is difficult to introduce into a linear programming problem. Many water resources problems concern the optimization of a sequential-decision process. For example, scheduling irrigation water applications for the sake of water conservation or for maximizing net profits are problems that can be solved using the techniques of dynamic programming.

Farmers are continually confronted with such questions as--How much fertilizer should I use?--When should I apply it?--When should I irrigate considering that I have a limited water supply?--How much land can I irrigate with an occassionally cient supply? Questions such as these can apply either at the farmer or project level. The procedures used to obtain solutions to these problems are not necessarily difficult. However, they be impractical or even impossible to attain because of the type of data they may require. In the optimal irrigation timing example, the yield coefficients are simply

not available for most crops. Research, however, is currently being directed to obtain the necessary data and relationships.

In summary, the techniques of operations research, systems analysis, or decision analysis are relatively new and hence are usually a mixture of art and science. Attaining improved decision-making still involves a considerable amount of ingenuity on the part of the manager. Not all parts of the problem can be solved with mathematical models and high-speed computers. Man's experience is still an essential ingredient in decision-making processes. Systems analysis has, on the other hand, demonstrated an important principle. An action program, whether or not instituted by systems analysis, cannot be undertaken in isolation from the surrounding managerial environment. It is readily apparent, for example, that intensifying the agricultural development upstream will affect the quality and quantity of water available to a downstream irrigation project. Other action programs, however, may result in much more subtle changes to another aspect of the environment. Thus, a systems analysis or operations research project should be regarded, at least in part, as a systems effort.

REFERENCES

Fiering, Myron B., Streamflow Synthesis, Harvard University Press, Cambridge, Massachusetts, 138 pp., 1967.

Hall, Warren A. and John A. Dracup, Water Resources Systems Engineering, Mc-Graw Hill, New York, 372 pp. 1970.

Pakistan Forest Institute, Proceedings First West Pakistan Watershed Management Conference, Pakistan Forest Institute, Peshawar, 577 pp., 1968.

Sopper, William E. and Howard W. Lull (editors) International Symposium on Forest Hydrology, Pergamon Press, Oxford, 813 pp., 1967.