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A PROCEDURE FOR DETERMINING THE FEASIBILITY
OF PLANNED CONJUNCTIVE USE OF SURFACE
AND GROUND WATER

by

Barry C. Saunders

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Logan, Utah

1967

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Barry C. Saunders

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ABSTRACT

A Procedure for Determining the Feasibility
of Planned Conjunctive Use of Surface
and Ground Water

by

Barry C. Saunders, Master of Science

Utah State University, 1967

Major Professor: Dr. Calvin G. Clyde
Department: Civil Engineering

Improved management of water resources is one means for alleviating deficiencies in water supply. One promising management technique is integration of ground water and surface water supplies and storage units, or planned conjunctive use. In order to assess the value of this technique in relation to a particular area or basin, it is necessary to look at the economic, hydrologic, and legal system as a whole. A planning procedure is developed which will enable feasibility to be determined at a minimum cost.

The procedure consists of determining legal constraints, estimating benefits which will accrue to additional water, estimating the quantity of water which is physically available, and determining the costs of supply. Extension of the feasibility study is discussed in terms of systems analysis and linear programming. An example of the use of the procedure in the Little Lost River basin (Idaho) is given.

(84 pages)

INTRODUCTION

Need for planned conjunctive use

The dramatic growth of water resources planning in recent years has been brought about by increased pressures on a limited water supply, and a realization that organized planning of water utilization and distribution can produce significant economies. The Kerr Committee of the United States Senate (Select Committee on National Water Resources, 1961) has projected that between 1960 and 1980, demands on water resources in this country will have doubled, and demands will have tripled by the year 2000. Present usage, part of which is sequential, approximates 27 percent of mean annual stream-flow. For practical purposes, the total water resources available constitute a fixed quantity; it is obvious that if these demands are to be met, much more intensive management of the resources will be required.

Planned conjunctive use of surface and ground water is one management technique which is being developed to obtain maximum utilization of the water resources available to an area. Historically, surface water supplies in most areas have been developed first, and utilization of the ground water resource has begun only when the surface supply has proved inadequate to meet the demand. Ground water use has generally taken the form of drilling wells sufficient to

satisfy some expected deficiency. Further, conventional planning too frequently overlooks inefficiencies in the basic system, and responds to increased demands with hasty measures requiring a minimum change in existing facilities; the effect of such haphazard growth on ultimate costs is not considered. This pattern of water resources development is maintained by the large amounts of capital already invested in surface storage reservoirs, diversion structures, and surface distribution systems. Ground water continues to play a subordinate, supplementary role in many areas, but the proportion of the total water supply which it represents is becoming significant. The Select Committee on National Water Resources (1961) states that the ratio of withdrawals of underground water to withdrawals of surface water will increase from a present value of one-fourth to a value greater than one-half within the next 20 to 50 years. There is now growing recognition that ground water resources have many inherent advantages, some of which may not be realized without proper management.

The first and most obvious advantage of ground water is that it represents an additional water supply, which is limited only by the "safe yield" of the ground water reservoir. Part of this increased supply may take the form of return flow from irrigation on the upper parts of the basin, or water which would otherwise be lost to the area. A second important advantage is concerned with mal-distribution of

water with respect to time; fluctuations in ground water storage levels are relatively long-term as compared to streamflow fluctuations. Thus a ground water basin is a natural underground reservoir, and has the capability of smoothing out cyclical variations of supply. Thirdly, the aquifer itself is a pipeline, and may be used to a significant extent for more economical transmission of water to the areas of use. Todd (1959) has listed other advantages of planned utilization of ground water supplies, e. g., less land required for surface storage, generally better quality of ground water, smaller evapotranspiration losses, and potential for staged development.

It is apparent that full utilization of the water resources of an area requires that both surface and ground water supplies be considered. Because of the hydrologic interactions between the two supplies, the extent to which efficiency is attained is proportional to the degree of integrated planning. Planning for conjunctive use therefore should be one of the first steps in development of water resources in any region. Further, the planning effort must not be limited to an assurance of technical feasibility, but must place equal emphasis on economic aspects. J. R. Burton (1964), when speaking on water resources planning in Australia, made the important observation that engineering determines what can be done, and what it will cost, but economics must determine what is worth doing, and to what extent it is worth doing. Mitchell (1963) made a similar comment:

The development of plans to preserve, protect, and utilize, or in short to manage a ground water basin cannot be left to the devices of separate disciplines, but must from the beginning simultaneously recognize the physical and economic laws as well as the necessary social and legal considerations. (Mitchell, 1963, p. 1)

Planning for conjunctive use requires a high degree of knowledge and understanding of the technical-economic-social-legal interfaces.

Objectives of study

The major objective of the study is to develop a generalized procedure for determining the feasibility of planned conjunctive use in specific, limited, areas. Although this procedure might be applied by water management agencies of any size, it is intended to be most beneficial to those agencies which are large enough to have significant management options (such as several diversion points and/or numerous, scattered customers), but yet are too small to have developed formalized procedures and an associated staff which is continually seeking to improve efficiency. The procedure would, of course, not be applicable to those situations in which conjunctive use is patently impractical for financial or physical reasons. This type of agency would require a procedure that is simple, easily understandable, and relatively inexpensive to use. The proposed procedure provides a framework for investigations in particular areas to determine whether full-scale conjunctive use analyses are warranted.

A secondary objective is to define the kinds and types of data that are required in planning conjunctive use projects. This will

enable agencies contemplating such investigations to begin limited efforts to obtain the necessary data.

An additional secondary objective is to clarify the systems analysis approach, and indicate the applicability to planning for conjunctive use. One particular systems analysis technique, linear programming, can provide a useful extension to the initial feasibility study. The principles and application of this technique to the conjunctive use problem will be discussed.

Limits of the study

There is no real limit to the intensity with which water resources planning may be pursued. In order to increase the practical value of this study and make the results usable by agencies limited in budget and manpower, it was necessary to restrict the scope in five major areas. Although these restrictions are severe, they are in keeping with the major objective of developing a generalized conjunctive use feasibility procedure.

1. Irrigation will be the only beneficial use of water considered. It would not be difficult to extend the analysis to include beneficial uses whose value was proportional to the quantity of water supplied (or stored), such as municipal, industrial, flood control, navigation, or pollution control. However, beneficial uses whose value is related to the height of water in surface reservoirs, such as power and recreation, would introduce significant complexities.

2. Only direct benefits of irrigation will be considered. There is strong evidence to support the contention that water used for irrigation produces benefits in excess of those reflected in the increased crop income. However, a private water supplying agency would have difficulty in collecting from its customers for any of these indirect and often intangible benefits. Hence it was deemed desirable to omit them from the analysis.

3. Hydrologic processes will be considered deterministic, i. e., the feasibility of planned conjunctive use in a particular area will be assessed for "normal" or assumed hydrologic conditions over a certain time period. The estimated costs and benefits for a particular mode of operation will be single-valued rather than defined as a probability distribution.

4. Water quality problems will be ignored. The procedure will be aimed at areas with open-ended ground water basins. In these areas, water quality problems do not usually occur until efficiency of use (a measure of re-cycling) is very high.

5. Localized effects of ground water extraction or recharge will not be considered. It is assumed that this problem would be analyzed in the more detailed conjunctive use planning following a feasibility study.

Outline of study

The study is divided into two major parts: (1) the development of a generalized simplified procedure for quick and economical determination of the feasibility of planned conjunctive use, and (2) a means for extension of these results through the systems analysis technique of linear programming. The first part consists of a definition of the nature and requirements of a generalized procedure, presentation of the proposed procedure, and a discussion of means for obtaining and manipulating the data required. The second part includes a brief resumé of the systems analysis approach with emphasis on linear programming, the mechanics of creating a hydrologic linear programming model, discussion of the necessary equations, and the use of the results of the analysis. Appendix I presents the results of a trial use of the initial feasibility study procedure on a small stream/aquifer basin.

THE GENERAL PROCEDURE

Requirements

The cost of planning efforts must be a prime consideration in the development of any planning procedure. With regard to water resources planning, these costs may be extremely high due to the high costs of data collection. The most detailed planning efforts in the water resources field have been conducted by agencies of the federal government, and by the State of California, where operations of these groups are financed through a large tax base. In general, budgets for planning government projects are not included in the cost-benefit analysis of the projects; this can create situations in which planning is carried to an extent far in excess of the benefits which may be obtained from the additional planning. The small public or private water management agency is faced with much tighter budgetary control on planning. As a consequence, a planning procedure for use by these smaller agencies must be designed to permit the necessary decisions to be made at the least possible cost.

A minimum-cost planning procedure requires that the planning effort be terminated at the first indication of infeasibility. This may be accomplished through a judicious sequencing of tasks which results in natural decision-points. Critical, short-lead-time tasks should be completed early in the program; high-cost operations should be delayed

to the latest time commensurate with the scheduled planning completion date.

A second requirement of a general preliminary planning procedure is capability of expansion and/or refinement. Larger projects will usually require more intensive analysis, as will projects in which the cost-benefit ratio is marginal. Furthermore, planning efforts must often be tailored to the planning funds available, especially in the case of public agencies.

In basic form, application of the preliminary planning procedure to conjunctive use must provide the answer to one question, "Is planned conjunctive use of surface and ground water in this particular area worthy of a more detailed investigation?" To accomplish this end, legal, hydrologic, and economic feasibility must be investigated and assessed.

Literature describing general preliminary planning procedures is very limited. Formal government publications such as the "Green Book" (Federal Interagency Committee on Water Resources, 1958) and Senate Document No. 97 (The President's Water Resources Council, 1962) indicate general aspects and objectives of project planning, but are concerned with large-scale planning and national objectives. A review of the Bureau of Reclamation Instructions (1959) revealed no formalized procedures for the conduct of feasibility studies. Quite probably informally-described procedures are being

followed at the lower echelons. Preliminary planning for irrigation projects is discussed in various texts and handbooks of irrigation engineering. Again, this material is quite general. For example, Houk (1956) indicates that this phase is comprised of assembling and digesting of available data, securing additional data, and performing cursory analyses.

Available literature on planning specifically for conjunctive use of surface and ground water may be classed as either very general guidelines, or procedures followed on particular projects. Thomas (1957) gives an excellent presentation of the first classification by dividing the basin investigation into three categories: geologic, hydrologic, and economic. The California Department of Water Resources (1966) is an example of the second classification; Figure 1 is a flow chart of the planning procedure used. This procedure is predicated on the assumption that conjunctive use is feasible, and hence emphasizes final planning and the formulation and comparison of alternative plans. A generalization of the procedure used in this particular investigation is described by Chun, Mitchell, and Mido (1964).

The flow chart

Figure 2 illustrates a flow chart of the proposed procedure for a feasibility study of planned conjunctive use. The sequence of operations proceeds from left to right, with the horizontal axis being a relative time base. An operation may not be completed until all the

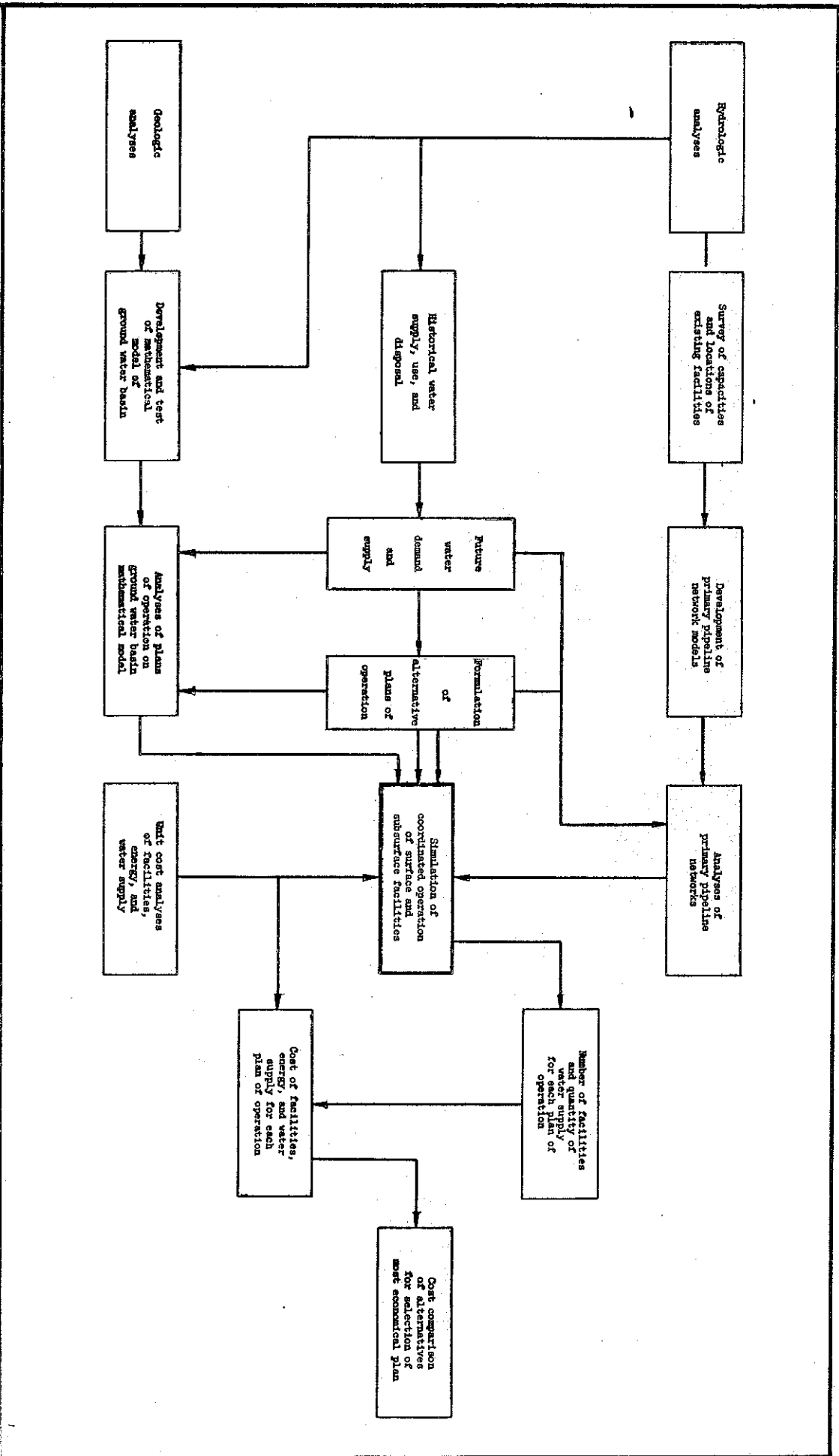


Figure 1. Simplified flow chart of investigation of planned utilization of ground water basins (California Department of Water Resources, 1966, p. 6).

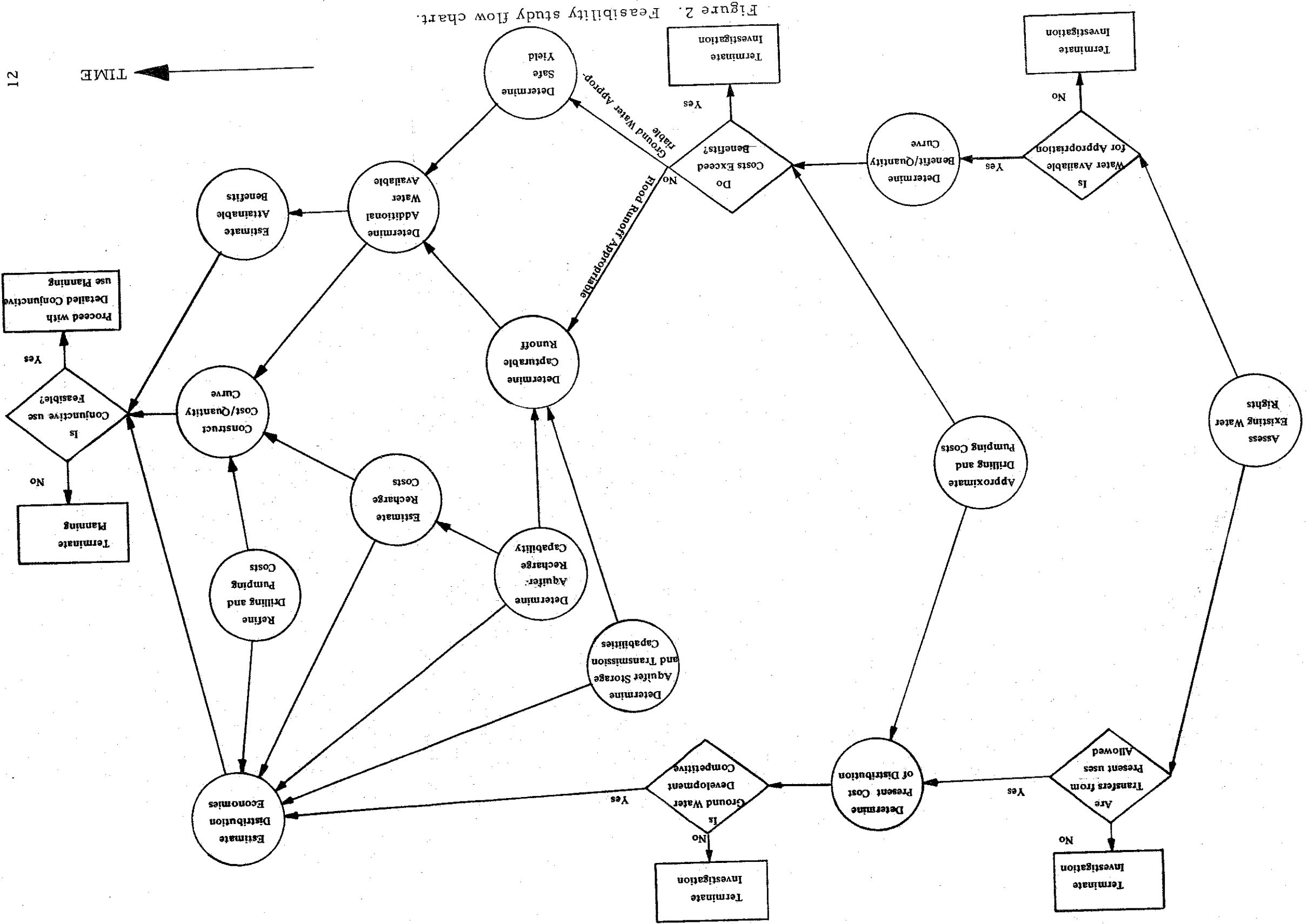


Figure 2. Feasibility study flow chart.

inputs have been received.

In keeping with the minimum planning cost philosophy, the initial operation is the determination of legal constraints. This task consists of determining whether and to what extent additional water is appropriable; the additional water may take the form of ground water, surface water, or both. An ancillary task is to assess the legal feasibility of water transfers or other exchanges; e. g., appropriating water from one location and replacing it with water from another location or source.

The knowledge of legal constraints permits a decision to be made between three alternatives. If no additional water is appropriable, and transfers or exchanges may not be made, conjunctive use is not feasible and the planning will be terminated. If additional water is appropriable, the estimation of costs and benefits of this additional water is initiated. If additional water is not appropriable, but transfers or exchanges might be allowed, there is a possibility for achieving distribution economies with conjunctive use, and this approach may be investigated.

In the event that additional water may be made available, the first task which should be accomplished is an estimation of gross benefits which might accrue to the water added to the system. This is a departure from the more common procedure of assuming a reasonable size of project, making a preliminary design of the project, and then

determining the cost/benefit ratio or net benefits for the particular project design. It is believed that creation of a curve of gross benefits versus quantity of water supplied will efficiently define the general size and type of possible projects. This curve, together with a rough estimate of well construction and pumping costs, leads to another decision point at which benefits and approximate costs may be compared to assess net benefits.

If it still appears possible that the benefits of the additional water supply may be sufficient to cover the costs, the study may continue along two alternative routes. This portion of the analysis is largely hydrologic, and the paths chosen are dependent on the previously determined legal constraints. If ground water is appropriable, the approximate safe yield of the aquifer must be determined. This would include recapture of water or reduction of losses. If flood water is appropriable, the amount that may be captured is determined; this must be calculated in conjunction with a study of the recharge capabilities in the area.

A summation of the additional water hydrologically available from the applicable legally feasible paths yields the maximum additional supply. This figure may be entered on the benefit/quantity curve, and a figure for maximum attainable benefits may be obtained.

Planning and costing of alternative projects enter the analysis at this point. The objective of this phase should be the creation of a

cost/quantity curve, showing the operational, maintenance, and capital amortization costs of supplying various quantities of water. This part of the investigation is usually the most costly and time-consuming, and hence is not initiated in the procedure until legal and hydrologic barriers have been assessed. Project formulation and cost analysis may be as extensive as deemed necessary, but it should be remembered that the entire study is designed to demonstrate feasibility, rather than to provide or select specific design criteria. Pursuant to this philosophy, only direct monetary costs should be considered. Although social costs and/or spillover effects may be significant, under the present day economic framework they are not relevant to practical decisions made by smaller water-resource agencies.

Returning to the first operation in the procedure, a condition may arise in which no additional water is appropriable or really required, but transfers or forms of exchanges are allowed. In this case, planned conjunctive use may still be advantageous by providing distribution economies. The first task on this path is to determine the present distribution costs for the given quantity of water. This together with the rough estimate of well construction and pumping costs is sufficient information on which to base a decision of economic feasibility of a change in distribution methods.

If ground water utilization costs appear competitive with those of surface water, the analysis may continue with an assessment of aquifer

storage capacity and recharge capabilities. This will define the limit to which surface storage and distribution facilities may be replaced by the natural capabilities of the aquifer, and will complete the hydrologic phase of this path. When costs of alternative distribution systems have been estimated, this path would rejoin the other path at the point of the final decision. Obviously, distribution economies should be investigated when additional water is appropriable as well, and the distribution economy path would be included in any analysis.

The conclusion to the feasibility study is the answer to the question, "Is planned conjunctive use feasible in this particular area?" The data made available during the study are a relationship between quantity of water supplied and gross benefits, and a relationship between quantity of water supplied and costs of supply. These may be combined to yield a general comment on feasibility of planned conjunctive use, and an estimate of the additional water which should be supplied to yield the maximum net benefits.

This section has outlined the proposed general procedure for investigating the potential of planned conjunctive use. The following section will expand on this procedure, indicating data which are required, and the means for obtaining and implementing these data.

DETAILED TASK ACCOMPLISHMENT

Legal feasibility

The purpose of this task is to determine the quantity of water in the basin, or area in question, which may legally be appropriated and/or used for beneficial purposes. In most western states, water rights are obtained by appropriation under the principle "first in time, first in right." Usually these rights are formally granted by an agency of the state (often the State Engineer) after determining that there are no other prior claims to the water. If a surface stream is over-appropriated, that is, streamflow is not sufficient to satisfy all the rights, those with the earliest rights are satisfied first. In states where the riparian doctrine of water rights is recognized, the land adjacent to a stream carries with it rights to reasonable use of the water. In most cases riparian rights may not be separated from the land. Ground water law has not been refined to a degree equivalent to surface water law, and acquisition procedures for rights to ground water may vary in different states from pure appropriation (Utah) to riparian (Texas). An excellent general description of ground water law is given by Wells A. Hutchins (1960). More detailed discussion of water laws in particular states may be found by consulting the bibliography prepared by Turney and Ellis (1962).

Legal constraints on water resources of undeveloped areas are usually not critical; generally the water which is available hydrologically is available legally. The opposite is often true in developed basins. In Utah, a water deficient state, a ground water appropriator may not withdraw water from an artesian aquifer to such an extent that it decreases the pressure at the well of a senior ground water appropriator. Or, in basins where the American Rule of ground water rights is in effect, ground water levels may not be lowered to an extent that other appropriators in the basin are unable to pump water, despite the fact that such lowering of the water table might well increase the inflow to the basin.

The water rights investigation can best be handled by an attorney, but in preliminary investigations the task might well be delegated to an engineer. As guidelines, it should be remembered that the successful operation of a conjunctive use project requires that the storage capacity of the aquifer be utilized, and that water be withdrawn from the stream/aquifer system at the most efficient locations. These actions are dependent on the legal feasibility of appropriating seasonal and cyclical runoff, and performing intra-basin transfers. The legal investigation will seldom yield a clear-cut definition of the quantity of water available for appropriation. The actual appropriability can be determined only by the outcome of a formal application for water rights, since only after an application has been filed are other appropriators

required to state and define their presumed rights. However, the investigation should determine whether there are legalities to consider, and should indicate the practical maximum of various kinds of water which could reasonably be considered appropriable.

Estimation of gross benefit limits

The estimation of maximum possible gross benefits of additional water is critical for providing an upper limit to the costs which may be incurred. Mr. B. D. Gardner (1966, p. 13) states with regard to water planning, that ". . . what is required for optimal planning decisions is a demand curve for all uses and users of water." This demand curve would indicate the quantity of water which would be purchased at any price level, or conversely, the price level which would prevail in a free water market for any given quantity of water supplied to the market.

The construction of such a demand curve presents many practical difficulties, and the value (for planning) of a particular demand curve is dependent on the degree to which these difficulties are surmounted. One problem is that a demand curve represents the situation at a particular instant of time, while a project is intended to operate for many years. Planning for an optimal project then should take into account demand curves projected for various times throughout the life of the project. This degree of sophistication should not be required for a feasibility study. However, the demand curve constructed for this type of study should reflect reasonable estimates of near-future conditions.

A major problem in the construction of demand curves for water is that there is seldom a free market condition prevailing which would provide historical data on the response of water users to changes in price. Fullerton (1966) has noted an approximation of a water market existing in the Delta area of the Sevier River basin of Utah, in which transfers of water rights are effected by outright sale, sale of irrigation company stocks, and rental of water or of irrigation company stocks. Unfortunately, the data concerning this or similar isolated water markets would be peculiar to the areas in which the data were generated, and could not be readily utilized in the analyses of other areas.

Because of the paucity of historical data relating to demand curves for water, many investigators have chosen to attack the problem of valuation of water from other directions. Gardner (1966) briefly describes several of these approaches, the most important of which are marginal productivity analysis and the value-added concept.

Marginal productivity analysis. In general, marginal productivity analysis is concerned with establishing relationships between variations in the quantities of various inputs to the resulting changes in outputs. The marginal productivity of an input is defined as the amount by which the output will change with a one unit change in input. If the value of the output is measurable, the value of an input can be expressed in the same units. Thus when the marginal productivity of

water is known at every level of water supply, the total value of any quantity of water can be computed.

An alternative method of viewing marginal productivity analysis is through the concept of the production function. The end result of the analysis is to define the output in terms of the inputs, or

$$O = f(x_1, x_2 \dots x_n);$$

this is defined as the production function. When this function is estimated, the value of any input can be expressed in terms of its effect on output.

There is considerable work in progress directed towards the determination of production functions for irrigation water. V. W. Ruttan (1965) has published the results of an extremely comprehensive study in which regional production functions were developed, using as variables the acreage of irrigated land and current operating expenses. A. I. McCutchan (1964) commented on the production function concept and presented a curve relating the crop yield of sugar beets versus the quantity of water applied. A similar relationship was determined for alfalfa production response to water application in Arizona (Underground Water Commission, 1953, p. 88). Both of these studies exhibited diminishing marginal productivity as more water was applied to the land.

C. Beringer (1961) raised a strong objection to static production function studies in which water quantity was the independent variable and crop output was the dependent variable. The basis of his critique was twofold; such an approach failed to consider time distribution of water application over the irrigation cycle as an important variable,¹ and the results from such analyses could not be extended to cover areas not included in the original studies. He set forth, and supported with experimental data, the thesis that plant growth should first be related to moisture tension in the soil, and then later and indirectly to quantity of water applied. His contention was that the law of diminishing returns with respect to water should be viewed as a relationship in which output is a non-linear function of the inverse of various moisture stress conditions which are allowed to occur between irrigations.

The production function, or marginal productivity, approach is potentially a valuable tool for estimating benefits of irrigation. At the present state of refinement, however, it appears an impractical approach for use in a feasibility study.

Value-added approach. Value-added is defined as the amount by which the market value of the outputs of a production process exceed the cost of goods and services put into the process. For the case of irrigation, the value-added by irrigation water is assumed to be equal

¹It is conceivable that this factor could be included by a more sophisticated expression of the production function.

to the value of the total crop production minus costs of all factors of production except the water. An excellent example of this approach is the University of New Mexico investigation of the San Juan and Rio Grande basins (Wollman, 1962).

Practical problems encountered when applying the value-added approach usually lie in the areas of data collection and extrapolation. Stewart (1964) has discussed these problems in a critique of the U. S. Department of Agriculture investigations in the Upper Colorado River basin. One noteworthy point which was emphasized is that the approach to valuation of water is a residual one; returns to other factors of production are assumed equivalent to their market prices, and any "excess profit" from these factors accrues to the irrigation water. Flack (1965) reports on the variability of data due to economies of scale. It was determined that in the San Joaquin Valley of California, the average 1280-acre farm operator could break even at a water cost of \$17/acre-foot; for an 80-acre farm, the break-even cost dropped to \$7.50/acre-foot.

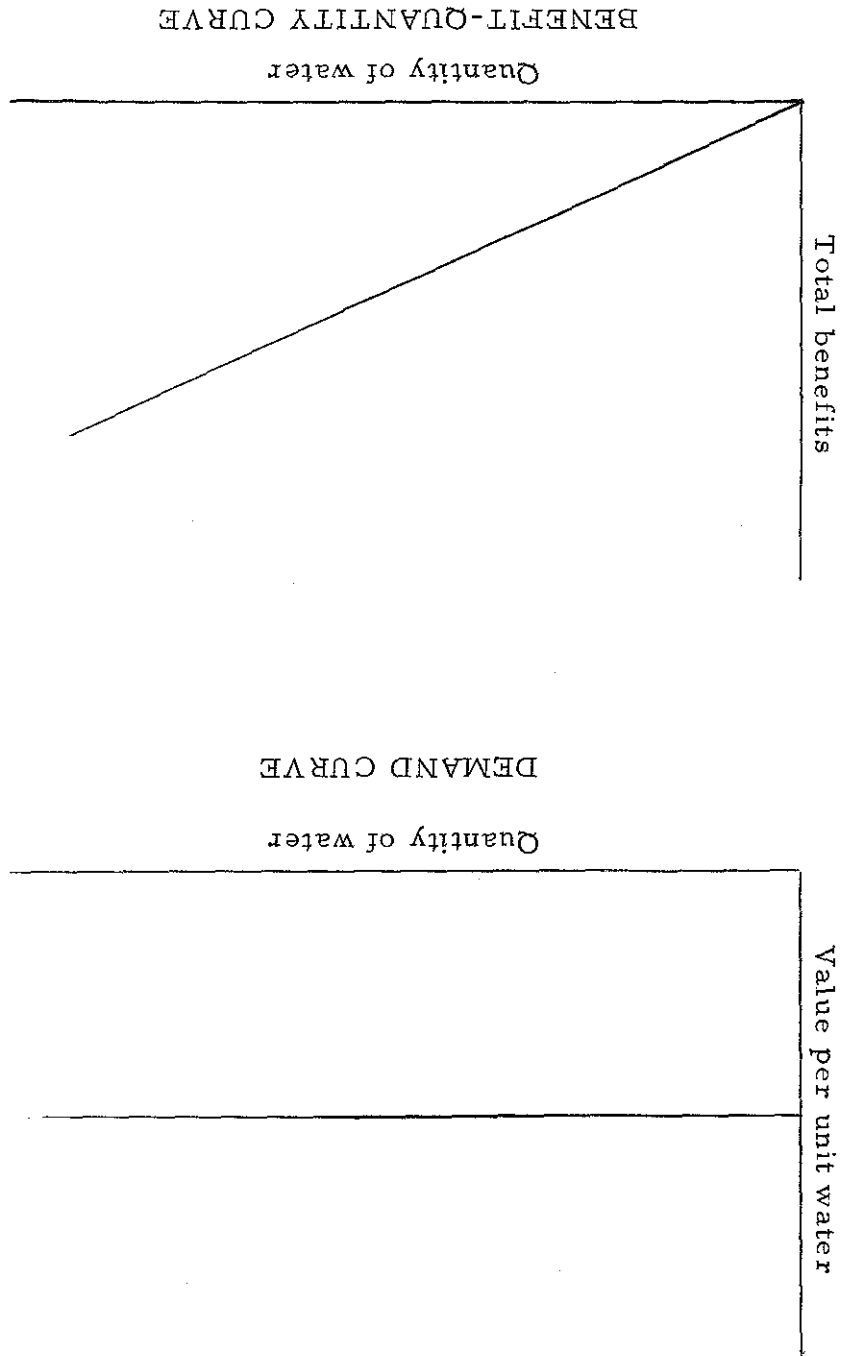
Although the value-added concept has proven very useful in water resources planning, it is not generally applied to the problem of constructing a demand curve for water. The analysis is dependent on historical data, or projections of historical data. Since this is the case, the end result of a value-added analysis is usually a figure representing the total value-added by a particular quantity of water to

a particular production process. The underlying assumption is that the production process, or particular irrigated farm, "requires" this quantity of water; the effects of lesser or greater quantities of water on the same land are not determined.

It is doubtful that the average value of a given volume of water (obtained by dividing total value-added by the quantity of water added) is especially meaningful, since this would yield a horizontal demand curve. In other words, any increment of water supplied to the area has a value identical to that of any other increment of water supplied. The total benefit curve (the integral of the demand curve) for this situation would be a straight line with slope equal to the average value-added (see Figure 3). If, as Wollman (1962, p. 118) states, "The objective in developing a new project should be to irrigate the highest grade of land," then a straight-line benefit curve is unrealistic and inadequate to attain this objective.

Land classification. One means of circumventing this problem is through a classification of land and/or other factors within the basin, and a determination of the value-added by water on each of the various classes. This produces a discontinuous demand curve (see Figure 4). Each horizontal segment of the curve represents the average value-added on a particular area class; individuals farming the best area thus should be willing to pay the highest price for water. The number and extent of the discontinuities are determined by the number of

Figure 3. Valuation of irrigation water--one land class.



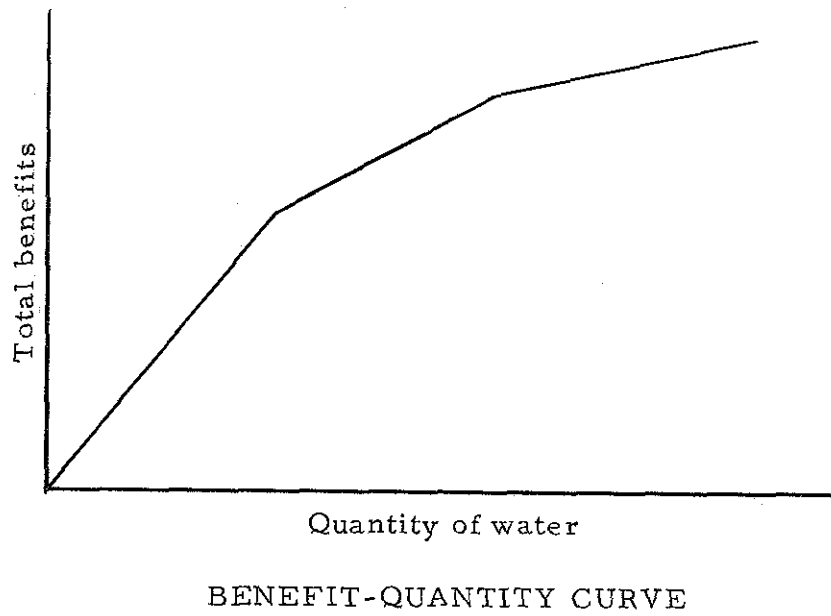
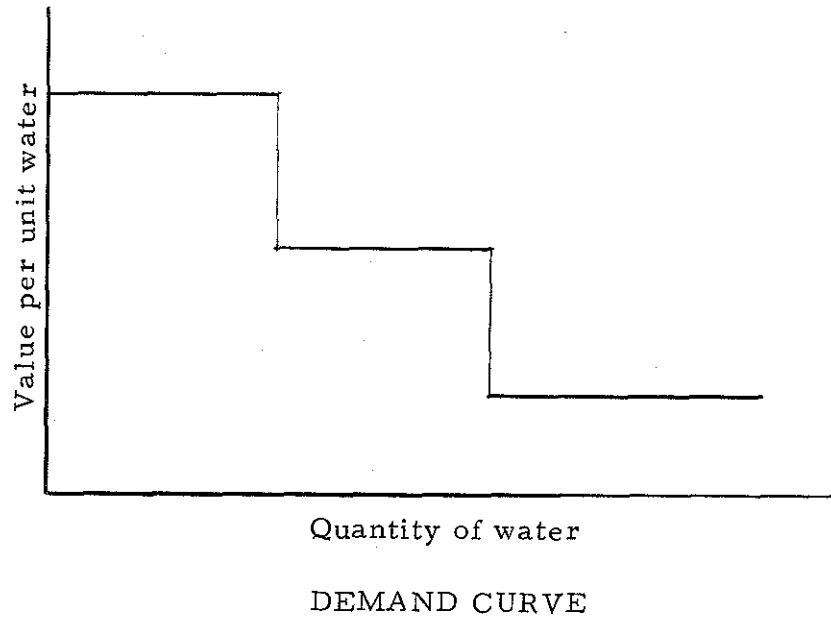


Figure 4. Valuation of irrigation water--multiple land classes.

classes chosen. Figure 4 also shows the benefit/quantity curve resulting from this type of demand curve. Since the slope of this curve at any point is equal to the value-added at that point, changes in slope occur at each discontinuity in the demand curve.

Physical properties of the land are probably the most important determinant of maximum attainable benefits from irrigation. Consequently, there have been numerous attempts to define and measure the important properties, determine relative importance, and assign weighted values so that the productive value of a particular parcel of land could be objectively estimated. Although agricultural specialists may be available to perform the task of land classification, a general understanding of the concepts and procedures is necessary for engineers and planners attempting to estimate attainable gross benefits of conjunctive use projects.

The major determinants of land productivity (excluding irrigation supply), are (1) soil conditions, including texture, permeability, depth, and salt and/or alkali problems; (2) topographic characteristics; and (3) climatic conditions, principally precipitation and length of growing season. Houk (1956) presents a good general description of the use of these factors in developing land classification systems. Christensen and Hansen (1961) have prepared a circular on land classification illustrating how an individual proceeds to classify a certain parcel of land. This system is based on the assignment of point values to various

conditions of selected parameters; the overall land rating is obtained as the product of the point values of each parameter. Under this system, lands are not divided into separate classes, but this may be easily accomplished by setting upper and lower class limits. The procedure has been refined by Christensen and Hutchings (1966) but remains the same general approach.

The complexity of land classification naturally increases as the number of classes increases. Houk (1956) indicates that the Bureau of Reclamation used three classes of irrigable acreage in planning the Columbia Basin Project: (1) most desirable land, suitable for diversified crops, (2) land suitable for most crops, and (3) land suitable for special crops such as rice, pasture, or forage. This would appear to be an adequate breakdown for a preliminary feasibility study.

Determination of monetary benefits. Although the classification of land is a major accomplishment in the estimation of potential benefits, difficult tasks remain in the assumptions of how the land will be farmed, and what prices the resulting crops will command in the market. This is undoubtedly the most subjective portion of the feasibility study, and there are relatively few guidelines that can be suggested. It would not be too difficult to determine how the various classes of land should be farmed, but experience has shown that historical farming patterns are slow to change. Castle has indicated logical reasons for discrepancies between optimal and actual irrigation practices, and warns that,

If theoretical water requirements are used in watershed planning and if they deviate substantially from the use farmers are actually making of the water, they may lead to a considerable over-valuation of water. (Castle, 1962, p. 121)

Probably the best projections of future patterns would be based on present practices on local existing irrigated farms. Projections of agricultural prices would be mandatory in detailed planning of irrigation projects; fortunately, long-range projections should not be required for a feasibility study. Although it would be wise to consider obvious future price patterns, in general present price levels will provide sufficient accuracy for the intended purposes.

The Bureau of Reclamation (1959) has developed comprehensive procedures for the estimation of direct irrigation benefits. The basis for these procedures is a modification of the value-added approach in which all costs of production except water are estimated and subtracted from the monetary worth of the crop and other outputs. The residual is termed the farmer's "ability to pay," and is in effect the amount which he would be able to pay for the necessary irrigation water. Figure 5 is taken from the Reclamation Manual (Bureau of Reclamation, 1959) and indicates the required data. Although this specific analysis is much too detailed for a preliminary feasibility study, it illustrates the types of data that would be required for any value-added analysis. An excellent example of data which would be valuable in this type of analysis is that presented by Rogers and Neely (1966) concerning upland

**SUMMARY OF FARM INCOME AND EXPENSES
FOR SUMMARIZING IRRIGATION PAYMENT CAPACITY**

Item	Farm Budgets - Without Project					Farm Budgets - With Project					Difference
	Budget No.		Budget No.		Total	Budget No.		Budget No.		Total	
	Farm	Area	Farm	Area		Farm	Area	Farm	Area		
Weight - number of farms											
Acres, total											
Acres, irrigable											
Farm investment											
Farm sales											
Farm perquisites											
Gross farm income											
Interest (4% of investment)											
Taxes											
Livestock purchases											
Hired labor											
All other expenses											
Total farm expenses											
Net farm income											
One percent of farm investment											
Remaining net farm income											
Method A											
Family living allowance											
Payment capacity, total											
Payment capacity, per acre											
Method B											
Hours of family labor											
Value of family labor											
Return to management											
Payment capacity, total											
Payment capacity, per acre											

See Subparagraph 116.4.12A

Figure 5. Irrigation payment capacity form (Bureau of Reclamation, 1959, Para. 116.6.4c).

desert valleys in Nevada.

Alternative approach--supplemental concept. A possible alternative method for the determination of a benefit-quantity curve can be developed when the water added by conjunctive operation is supplemental to the normal (usually surface water) supply. This concept was illustrated by L. M. Hartman (1963), using an irrigated area along the Arkansas River as an example. With an irrigation level established on the basis of the mean annual flow from 1940-1961, water deficiencies resulted during eight of the twenty-two years. The value of the supplemental supply, then, was the value of the crops that should have been produced during those eight years of deficiency but were not. Since deficiencies cannot be predicted with a high degree of accuracy, large amounts of irrigation water are often expended during the early part of a season on acreage which is not destined to produce after deficiencies occur. A supplemental irrigation supply for these situations would have extremely high value.

Domenico, Schulke, and Maxey (1966) have reported on an investigation of physical and economic aspects of conjunctive use in a basin in Nevada, and have utilized this supplemental concept in estimating benefits. They state,

For years characterized by normal streamflow, it is profitable to consider the cost of supplemental water as an 'insurance' premium that is due and payable each and every year. (Domenico, Schulke, and Maxey, 1966, p. 32)

The use of this method of valuation of benefits of supplemental water is relatively simple if streamflow records are available. The benefits accruing to irrigated agriculture may be readily determined (since the farms are presently in operation and no changes in use patterns are envisioned), the decrease in crop production due to streamflow deficiencies may be obtained from historical data, and the frequency and magnitude of expected deficiencies may be calculated by statistical methods.

The high benefits accruing to a supplemental irrigation supply may appear to contradict the law of diminishing returns, but it must be remembered that there does exist a somewhat firm minimum water requirement for plant growth. Also, these benefits of planned conjunctive use are those due to storage aspects; "safe yield" ground water used to irrigate new areas must be valued in the same manner as the base (usually surface water) supply.

Initial estimation of ground
water extraction costs

Referring to the flow chart in Figure 2, the next task to be accomplished after the determination of the benefit/quantity curve is a preliminary estimate of the costs of utilizing the ground water supply. The objective of the task is to obtain rough cost/quantity data which, in conjunction with benefit/quantity data, will provide the basis for a decision on whether to continue the investigation. For example, if

the benefit/quantity curve shows that the maximum benefit level is \$20/acre-foot, but the minimum ground water extraction costs would probably be \$25/acre-foot, the feasibility study may be terminated at that point.

The two parameters required in this task are well construction costs and pumping costs. Since a high level of accuracy is not required, historical data on wells already operating in certain portions of the area could be presumed to be relevant elsewhere in the basin. When no such data exist, approximate depth to ground water should be determined, and cost data from surrounding areas may be adjusted to provide the necessary information. (Means for determining depth to ground water will be discussed in a later section.)

Geologic and hydrologic investigations

At this point in the study, legal feasibility and economic potential of planned conjunctive use have been demonstrated. The problem of determining physical, or hydrologic, feasibility remains. Again referring to the flow chart in Figure 2, it is evident that the conduct of this phase is dependent on the findings of the legal investigation. Each alternate path represents a different means of obtaining water; (1) from the ground water supply itself, and (2) from planned utilization of the storage capabilities of the aquifer.

Determination of safe yield. Safe yield of an aquifer has been concisely defined as, ". . . the amount of water which can be

withdrawn from (the ground water basin) without producing an undesired result." (Todd, 1959, p. 200). However, this definition is not universally accepted. Mann (1963) reviews many of the existing definitions, and concludes that safe yield is a function of the assumptions made in particular studies. Kazmann (1956) questions the validity of basic concepts, and cites the variability of safe yield for particular basins under changing conditions. Although there does appear to be confusion and disagreement concerning precise definitions, the practical necessity for evaluating safe yield (or sustained or perennial yield) remains. The review of conflicting opinions serves merely to impress upon the engineer the need for caution in the application of safe yield values.

The determination of safe yield should begin with the formulation of the equation of hydrologic equilibrium for the basin; this is a listing of all the inflows and outflows of water. This hydrologic budget approach to safe yield is discussed at length by the ASCE Committee on Ground Water (1961). Figure 6 indicates the hydrologic factors involved. Safe yield would be represented by the average annual pumping rate that could be maintained without causing a permanent decrease in the water level of the ground water reservoir. Referring to Figure 6, safe yield may be increased by reducing the outflows from the reservoir; i. e., evapotranspiration, base flow, and subsurface outflow. Safe yield may also be increased by increasing the

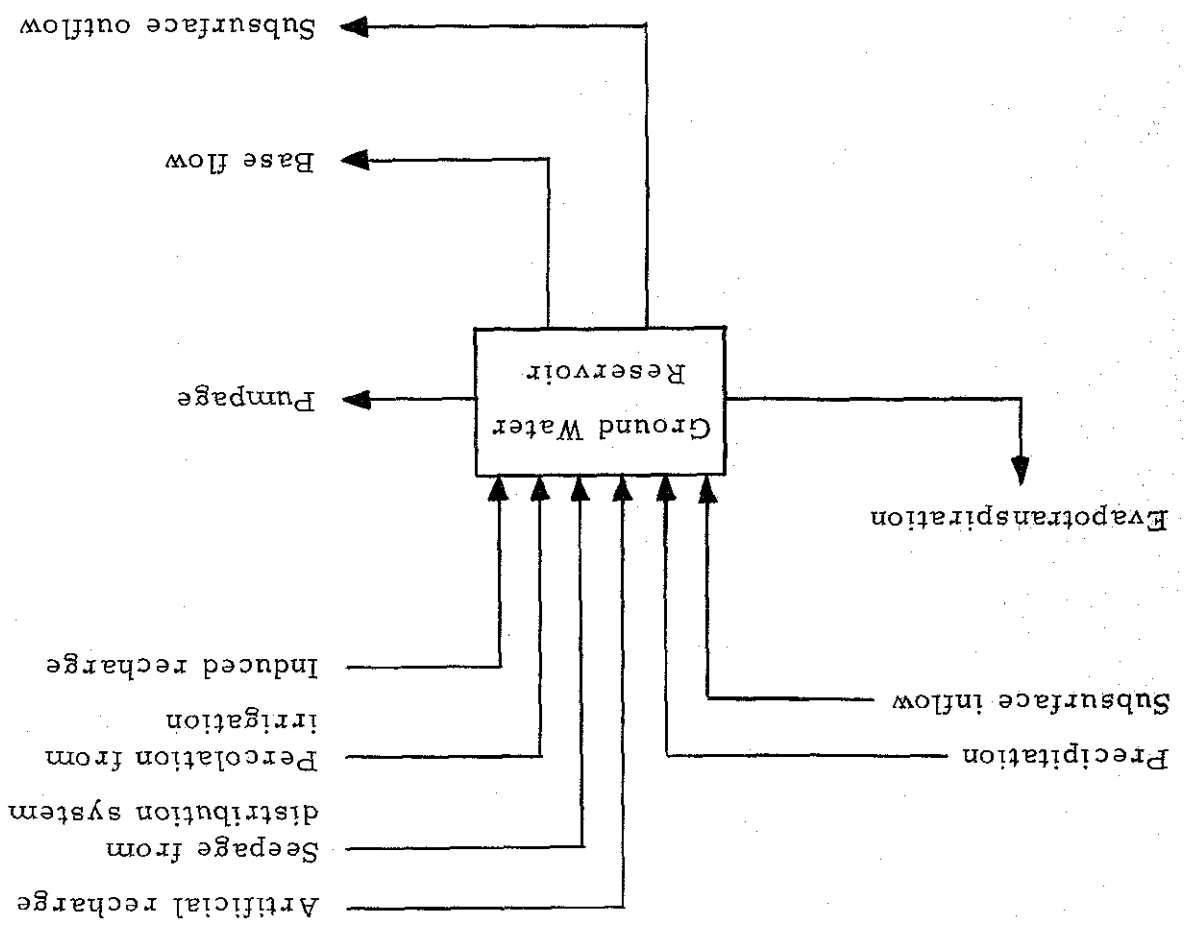


Figure 6. Inflow-outflow components of ground water reservoir.

inflows; Mann (1963) emphasized the point that return flows from irrigation, which allow recirculation of water, should be included in the safe yield analysis.

A significant increase in the effective ground water supply in areas of high water table may be attained by the reduction of evapotranspiration losses. These losses are in large part due to phreatophytes, or vegetation with root structures especially suited to obtain water from relatively deep levels. The Select Committee on National Water Resources (1960) has estimated phreatophytic losses in the five southwestern states (California, Arizona, Nevada, New Mexico, and Utah) at 10 - 12 million acre-feet/year. Although eradication of phreatophytes by destructive means has been proposed and occasionally attempted, the most effective method of reducing these losses is through pumping and utilization of the ground water; by lowering the water table, increasing percentages of the useless vegetation are unable to tap the ground water supply.

For purposes of preliminary estimates of safe yield, savings due to evapotranspiration reduction may be approximated by the following procedure. First estimate the present evapotranspiration by multiplying the phreatophytic area involved by a consumptive use factor; publications by Young and Blaney (1942) and Muckel (1966) will be helpful in determining the appropriate factors. Then assume a maximum depth of root penetration for the species of phreatophytes. Finally, assume that the quantity of water transpired is directly

proportional to the depth of water; water savings can then be calculated for any desired change in water level. Muckel (1966, p. 29) indicates that the relationship between evapotranspiration and water level is actually convex towards the origin, hence the assumption of linearity should be conservative.

Safe yield is also influenced strongly by the efficiency of irrigation practices. Gravity systems in particular can lose large percentages of irrigation water to the underlying aquifer through deep percolation. Jensen (1967) discusses the subject of irrigation efficiency at length, and indicates that deep percolation losses amounting to 30% of the water delivered to the farm are not uncommon. Conveyance losses in unlined canals may also approach this figure; a large percentage of this water serves to recharge the aquifer.

Separation of irrigation losses into evapotranspiration and deep percolation is feasible (Willardson and Pope, 1963) but would probably be uneconomic for use in a feasibility study. When possible, irrigation efficiency data from similar projects and areas should be used to approximate aquifer recharge. The Bureau of Reclamation (1965) has compiled data concerning distribution losses on all BuRec projects. Careful transposition of data selected from this list should result in usable estimates for the design area.

Several methods exist for the indirect determination of safe yield of well-developed basins (Todd, 1959), but for a virgin basin,

practical methods are few, and attainable accuracy is low (Charles, 1946). This is due to lack of data and the difficulty of estimating some of the major inflow-outflow components; e. g., subsurface inflow and outflow, and recharge from or discharge to streamflow. Todd (1959) describes two methods which may be applicable to certain undeveloped basins. The first is based on Darcy's law, and requires knowledge of the average hydraulic gradient, aquifer permeability, and cross-sectional area at the outflow section of the aquifer. The second method is based on the assumption that annual recharge to the ground water basin is equal to the product of the annual rise in water table, the area of the aquifer, and the specific yield. Kazmann (1946) describes the use of both these methods in relation to a study of the Miami River Valley in Ohio. Mundorff, Broom, and Kilburn (1963) used the former method for the determination of perennial yield in the Little Lost River basin of Idaho.

In specific situations, the method of estimating safe yield will be largely dependent on the nature of the basin and the types of data that are available. Excluding mining of the resource, withdrawal of water from a ground water basin is normally effected by the reduction of some outflow component. This indicates that the most direct approach to estimating safe yield would be to estimate the largest potentially capturable outflows. For example, if subsurface outflow were considered the major contributor to potential safe yield, the

method based on Darcy's Law would be indicated. If the necessary data were not available, the alternatives would be to obtain the required data, or to use an alternative method, such as a hydrologic budget.

Determination of capturable runoff. The second means of obtaining additional water through planned conjunctive use is through the capture and storage of cyclical (rather than seasonal) runoff; this is applicable only to unconfined aquifers. The quantity of water obtainable in this manner is limited by: (1) the amount of runoff appropriable and physically available, (2) the infiltration capacity and size of artificial recharging facilities (to be discussed in a later section), and (3) the storage capacity of the aquifer.

The amount of available runoff is determined from the initial legal investigation plus an analysis of streamflow records. Usually, appropriability is given in terms of that quantity presently appropriated; this will give a figure of stream discharge above which flow may be legally captured. The probability of occurrence of flows above this value may be determined by statistical methods (Beard, 1962); the accuracy of these estimates is proportional to the length of the streamflow record. Accuracy may be increased by the synthetic generation of records, but it is doubtful that this procedure would be employed during a feasibility study.

The storage capacity of a ground water basin is determined through a geological investigation. Simply, the storage capacity is the gross volume of the saturable rock multiplied by the specific yield. Davis and DeWiest (1966) and Madson and Jensen (1963) discuss the determination of ground water basin boundaries by geological, geophysical, and physical means. Even for preliminary surveys, it is essential that cores or cuttings from one or more test holes be available for estimation of specific yield. Where wells already exist in the area, driller's logs can be reviewed to provide this information. Morris and Johnson (1967) list hydrologic properties of selected rock and soil materials which might be used when no other data is available.

The areal extent of the ground water basin and transmissibility (or hydraulic conductivity) of the aquifer affect a related aspect of the storage potential of the basin. If the basin is small and transmissibility is high, runoff during a season of exceptionally high precipitation may well leave the basin within the next few seasons. Though storage capacity may be relatively great in this instance; the water captured cannot be utilized quickly enough. Hence transmissibility is an additional parameter which should be estimated; this is generally accomplished with well tests (Bentall, 1963; DeWiest, 1965).

Estimation of attainable gross benefits

The hydrologic and geologic phase of the feasibility study has now defined the quantity of additional water that could be made available by utilizing the safe yield and/or storage capacity of the aquifer. The earlier economic phase of the study yielded a benefit/quantity curve that indicated the economic value of any particular quantity of additional water supplied to the area. The maximum attainable gross benefits can be obtained by entering the amount of hydrologically available water on the benefit/quantity curve, and reading the value of the ordinate.

Cost analysis

The remaining tasks in the feasibility study are the estimation of cost savings possible with changes in the distribution system (assuming no new water is appropriable), and the estimation of costs of supplying additional water (when legally and hydrologically feasible).

Determination of existing distribution costs. The objective of this task is to define the capital and O & M (operating and maintenance) costs of supplying various expected levels of water demand with the existing distribution system. When these costs differ significantly within the region (as caused by differences in topography and distance from the source of supply), it is necessary to subclassify the costs into those applicable to the different areas. This task may be

accomplished by the analysis of historical cost data, and will provide a base against which to compare the costs of supplying selected portions of the region with pumped water.

Determination of recharge capabilities and costs. It was previously noted that the achievement of distribution economies by planned conjunctive use might be possible even in the event that no additional water was appropriable. This would require that water pumped from the ground water basin be replaced with locally-supplied surface water or importations, and indicates the necessity for evaluating the costs of artificial recharge. This transfer or exchange situation exists in several large ground water basins in California, and has prompted much economic and hydrologic research (Todd, 1965; Richter and Chun, 1959; Skinner, 1966).

While pumping from ground water is largely limited by the quantity of water available and the depth to the saturated aquifer, artificial recharge is constrained by the infiltration and percolation rates of the material overlying the aquifer. This restraint is effectively economic, since larger recharge area can compensate for lower infiltration rates. For this reason, it is more meaningful to combine the studies of recharge capabilities and recharge costs.

There are numerous methods of artificial recharge; these have been succinctly described by Todd (1959). For use in agricultural areas, the most promising would be: (1) the flooding method, in

which water is diverted over relatively flat land, (2) the basin method, in which shallow basins are constructed and filled with water, and (3) natural channel method, in which check dams are built on the stream to spread flow over a larger area, and thus utilize the natural infiltration capacity of the stream bed. Artificial recharge by flooding may be accomplished at a minimum cost in an irrigated area by off-season or over-irrigation.

In order to determine quantity of water delivered to the aquifer, and thus measure cost effectiveness, it is necessary to measure or estimate infiltration rates. Unfortunately, infiltration rates determined in conjunction with precipitation studies are of limited value; when a soil surface is inundated, infiltration decreases more sharply with time due to increased clogging of the soil pores. If existing infiltration data related to the area in question are not sufficient for a reasonable estimate of infiltration rate, a relatively inexpensive test of recharge capacity might be conducted by flooding a small area and measuring infiltration over time.

Todd (1965) lists infiltration rates, O & M costs, and total costs of selected artificial recharge projects in California. O & M costs, which vary from \$1.33 to \$17.63 per acre-foot, are more meaningful than total costs, which include cost of land. A study of these projects might reveal similarities to a proposed project which would allow transposition of some cost components.

Refinement of drilling and pumping costs. At this stage of the feasibility study, geologic and hydrologic data should be available in quantities sufficient to refine the initial estimates of ground water extraction costs. Measured and/or estimated water table elevations, hydraulic conductivity, and subsurface geologic properties will permit the estimation of well construction costs, probable yields, and power consumption for pumping. As with surface distribution systems, different costs may prevail over different areas of the basin.

Estimation of distribution economies. After existing distribution costs, probable ground water extraction costs, and probable recharge costs have been determined, an estimate of the feasible distribution economies may be made. This task would consist of very preliminary design of alternative distribution systems at various historic levels of supply, calculation of total cost of the alternatives, and comparison with the existing system cost.

Determination of cost/quantity curve. Returning to the flow chart (Figure 2), it is seen that completion of the alternative path of additional water available requires the construction of a cost/quantity curve. It has been previously determined that additional water is available from the safe yield of the aquifer and/or the capture of unappropriated flood runoff. During this task, alternative projects for obtaining and distributing this water must be formulated (in an approximate manner) and priced. Possible cost reductions due to

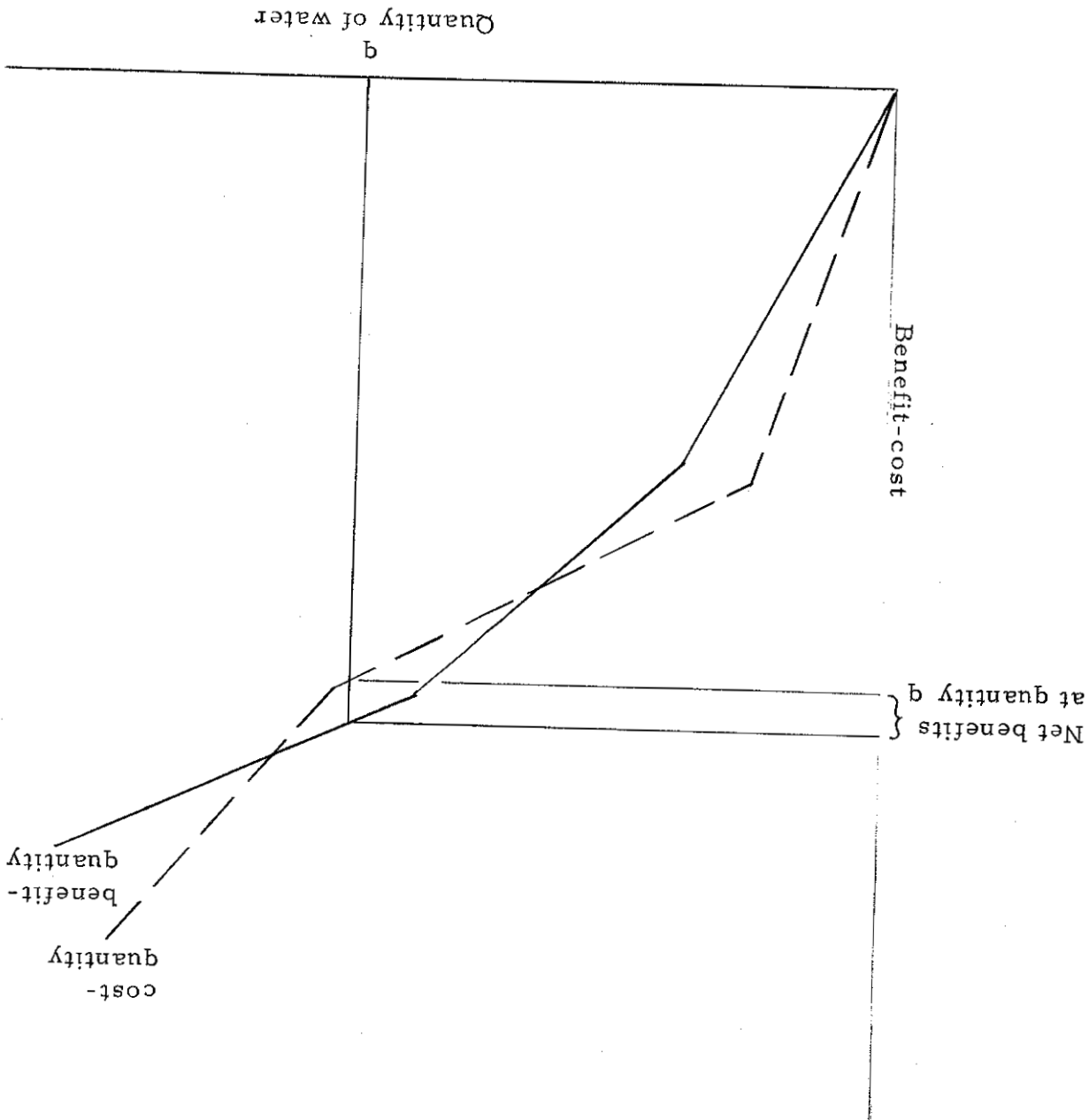
direct or indirect subsidies or other political factors should also be considered and included in the final cost curve.

Generally accepted procedures for preliminary engineering design may be used at this point, and require little elaboration. During this design phase, it should be remembered that the objective is to determine the costs of utilization of various quantities of the additional water. It is not necessary or desirable to refine the designs to any great degree, since this work would be included in a future detailed planning effort. The alternatives examined need not necessarily include the best or optimum design. What is important is that an adverse decision concerning conjunctive use feasibility should not be reached merely because an efficient design was overlooked.

Final decision

The final decision may be made on the basis of net benefits. These are represented by the estimate of attainable distribution economies and/or a comparison of the cost quantity curve to the benefit/quantity curve (limited by the maximum attainable gross benefits). Figure 7 shows how the net benefits would be estimated from such a comparison. Reiterating, the objective of the feasibility study is to assess the probable worth of planned conjunctive use in a particular area with specific legal, hydrologic, and economic constraints. The final decision, which may be

Figure 7. Net benefit determination.



affected by subjective social, political, or financial considerations,
represents a choice between abandonment of the concept and
continuation of planning in the form of detailed project analysis.

EXTENSION OF THE INITIAL STUDY

Systems analysis approach

The feasibility study is an initial, expedient step in the more inclusive systems analysis process. This total process may be viewed as a methodical scientific approach to formulating the best possible means of dealing with a given problem. The applicability of the systems approach to water resources planning and management can be illustrated by a more complete definition of systems analysis as:

. . . a method of analysis which considers all the possible variables simultaneously, because the dependencies and interrelationships among the variables are such that the combination of maximum utility cannot be reached by maximizing the value of each variable independently.
(Bower, 1965, p. 36)

The growing importance of multiple-purpose and multiple-unit projects, and integrated river basin planning, has introduced economic and physical complexities into water resource system design which cannot be handled adequately by the more conventional methods. While applications of full-scale systems analyses are presently restricted to regional planning, the small agency should be aware of the basic concepts and potentialities.

The use of systems analysis requires that the project be viewed in terms of relationships to the existing environment. Maass et al. (1962) have divided the process into four steps involving the

identification of objectives, translation of objectives into design criteria, design of alternative plans that satisfy the criteria, and evaluation of the consequences of the plans. To these tasks may be added that of formulation of the physical, economic, legal, social, institutional, and financial constraints under which the system must operate, although Maass emphasizes the danger of rigid acceptance of constraints without determination of the economic consequences. Reviewing the feasibility study in terms of systems analysis, it can be seen that the preliminary objective was to prove the existence of attainable net benefits, the design criterion chosen was the value of direct irrigation benefits minus monetary costs, and the constraints were legal and hydrologic. When feasibility has been demonstrated, the analysis of the system may continue, culminating in the selection of an optimum plan.

The practical application of systems analysis to complex water resource problems has become feasible through the development of operations research techniques and high-speed computers. Chow (1964, Section 26-II) presents a concise summary of these techniques. Two main categories are represented; (1) analysis by simulation, in which the water resource system is modeled on the computer, and the response of the system to various hydrologic, economic, or other inputs is observed, and (2) analysis by mathematical models, which requires somewhat more simplified system simulation, but in which

the optimum design may be determined directly. Detailed information on these procedures may be obtained from the work of Maass et al. (1962) and in literature referenced by Chow (1964, p. 26-44). More recent information on the subject is contained in publications by Crawford and Linsley (1966), Dracup (1966), Eshett and Bittinger (1965), Halter and Miller (1966), Riley, Chadwick, and Bagley (1966), and Tyson and Weber (1964).

Linear programming

General. One operations research approach that appears to hold considerable promise for the design of conjunctive use systems is linear programming. Linear programming is concerned with the allocation of scarce (or economically valuable) resources, among alternative ends subject to various constraints. The procedure is designed to maximize or minimize some previously-defined objective function. The conjunctive use problem is amenable to a linear programming approach, since it consists of allocating water (a scarce resource) from alternative sources to alternative uses, subject to legal, economic, hydrologic, and other constraints, in order to maximize net benefits (or other similar objective function).

The mechanics of solving the linear programming problem are complex (see Gass, 1958; or Hadley, 1962), but standardized computer programs will permit linear programming to be used by many of more capable small water management agencies. Moreover,

benefit can be derived through a knowledge of the potential of the method and procedures for setting up the problem and using the results, since these tasks can best be handled by the persons most directly involved with the water management problem.

The application of linear programming to a conjunctive use problem requires the accomplishment of three main tasks. First, a schematic model of the system should be developed to assist in visualization of the interrelationships between parameters. Secondly, the objective function must be formulated; this specifies the quantity to be maximized or minimized (e. g. , net benefits) and the effect of each parameter on this quantity (e. g. , each unit of irrigation produces z dollars of benefits). Last, the constraints must be developed to delineate boundaries of the area of feasible solutions to the problem.

Creation of the model. When the feasibility study has been conducted according to the proposed procedure, a preliminary model of the ground water system will have been developed for the determination of safe yield (Figure 6); this could be expanded to include all the other parameters pertinent to the hydrologic system. General considerations in construction of the model are the degree of hydrologic simulation, inclusion of proper physical features, and decisions as to the number of time periods which should be used.

Figure 8 illustrates a deterministic hydrologic model developed for a hypothetical stream-aquifer basin in which irrigation is the

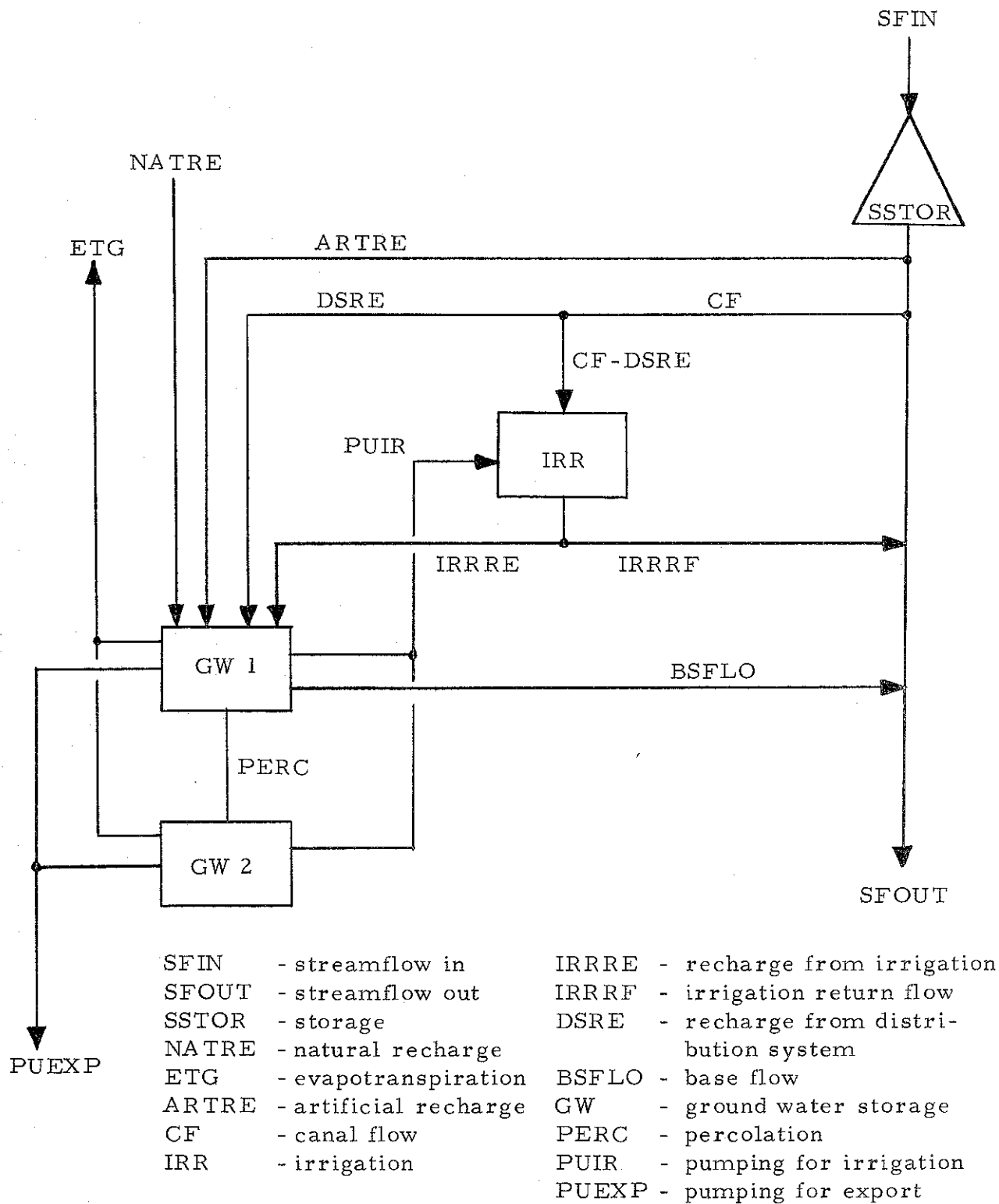


Figure 8. Hydrologic model.

only beneficial use. (This model was created in part by the writer during the initial phase of a conjunctive use project at the Utah Water Research Laboratory.) Important operational features of the model include the following: (1) irrigation water can be obtained through canal flow from the reservoir or pumping from ground water; (2) ground water recharge is comprised of interbasin subsurface flow and precipitation, seepage from canal flow and irrigation, and artificial recharge; (3) streamflow out of the basin consists of runoff from irrigation, baseflow from the ground water, and surface inflow not held in storage. The model could be expanded by the addition of other beneficial uses (e. g. municipal and industrial), additional reservoirs, or additional hydraulically unconnected aquifers.

The time period chosen for this particular model was one year consisting of a wet season and a dry season. Using two seasons effectively doubles the number of variables in the analysis, since wet season values are independent of the dry season values (except through the constraint equations). The inclusion of additional time periods in the optimization would have a similar multiplying effect.

Objective function. The objective function may be constructed after an appropriate objective has been assumed and after all the parameters affecting this objective have been defined (usually in the model). For the problem of conjunctive use, a valid objective is

the maximization of net benefits; this may be expressed as the summation of "benefit" variables times their respective unit values, minus the summation of "cost" variables times their respective unit costs. This objective function would be written

$$\max z = \sum_{i=1}^n B_i p_i - \sum_{i=1}^n C_i p_i$$

For example, in the model (Figure 8) canal flow is a cost item having a fixed price for each acre-foot delivered; water delivered for irrigation is a benefit item having a fixed return for each acre-foot used.

One rather annoying limitation of linear programming can be ascertained from an inspection of the required form of the objective function; the total cost or benefit due to any parameter must vary linearly with the quantity of that parameter. If this assumption is not in agreement with the physical situation, modification of the model may be required. For instance, ground water pumping costs are not only proportional to the quantity of water pumped, but are also directly related to the pumping lift; the cost of pumping an acre-foot of water from a fifty-foot depth is considerably less than that of pumping a similar quantity from a hundred-foot depth. The impact of the linearity requirement can be reduced by dividing the parameter in question into increments, and placing values on each

increment. This was done on the ground water storage component (GW), of the model, where a second lower level was associated with a higher pumping cost. Dorfman (Maass and others, 1962, p. 501) presents other more complex methods of dealing with non-linearities.

The principal effort in the construction of the objective function will usually be related to data collection. Each parameter in the objective function must be assigned a unit value or cost, which hopefully can be based on historical economic data. In some cases value or cost may be difficult or impossible to obtain objectively (e. g. , value of water in ground water storage), and assumptions must be made. Fortunately, much of the economic information collected earlier during the feasibility study should be directly applicable.

Constraints. The third requirement of the linear programming method is a set of constraints; these may be in the form of equations or inequalities. Each constraint limits the permissible values of certain variables and thus indirectly places a boundary on the composition of feasible solutions. Obviously, each non-redundant constraint added to the system reduces the range of the set over which feasible solutions can be found.

In the conjunctive use problem, most of the constraints will be in the form of hydrologic continuity equations. For instance, the first ground water level (GW1) can be isolated as a free body, and the constraint would consist of equating the inputs to the outputs. Legal constraints might also be introduced in the form of inequalities

limiting pumping and/or streamflow out to values less than a specified amount. Considerable care should be exercised in the construction of constraints to insure that the model adequately represents the physical situation.

The same limitation applying to the objective function applies to the constraint equations or inequalities; they must be linear. This introduces problems when attempting to develop hydrologic relationships to reduce the number of variables, such as defining base flow or subsurface outflow in terms of ground water in storage. Pertaining to this relationship, Darcy's law states that the ground water discharge is proportional to the product of: (1) the hydraulic conductivity, (2) the area of flow (which is roughly proportional to the quantity of water in storage), and (3) the slope of the hydraulic gradient (which is also roughly proportional to the quantity of water in storage). Thus subsurface outflow could be better approximated by a quadratic relationship, but this form is unacceptable in linear programming. Some problems of this type can be handled by incremental methods as indicated in the preceding discussion on the objective function. In other cases it may be necessary to assume linear relationships even though they are known to be unrealistic, and then assess the impact of these assumptions when the results of the optimization have been obtained.

After the objective function and constraints have been formulated, a specialist is required to translate this information into a

form compatible with one of the many computer programs designed to accomplish the linear programming task. (Usually such programs are written specifically for use with a particular computer.)

Use of results. Although the final objective of the linear programming analysis is to provide specifications for the design and/or operation of conjunctive use facilities, the initial results will be used to check and refine the operation of the model. Careful study of the "primal" output, which consists of the maximum (or minimum) attainable value of the objective function and the quantity of each variable required to produce this value, will often reveal unrealistic assumptions or omitted or inadequate constraints. This work requires close cooperation between individuals well-versed in the intricacies of linear programming, and those knowledgeable of the hydrologic and economic factors and processes relative to the area under study.

When the model is operating as desired, all outputs of the linear programming analysis may be used, and the full capabilities of the method become apparent. The primal output presents values of the system parameters to be used for attainment of optimum output under the assumed conditions. This would include such items as quantity of water which should be supplied through canals (which indirectly specifies the size of the canal system), quantity of water to be supplied by pumping, and size of the surface storage reservoir. The "dual" output presents the "shadow price" of the right hand side

of each constraint, or the value by which the objective function would be changed by a one unit change in the right-hand side of any constraint. For instance, the shadow price concerning the streamflow into the system would represent the increase in benefits that would be attained if one additional unit of streamflow were available. Shadow prices may also be viewed as the marginal value of each resource in the optimal solution.

The reduced cost output is particularly valuable in assessing the response of the system to price changes or inaccuracies in economic data. This output assigns to each parameter not included in the optimal solution a value of reduced cost; this represents the parameter price level which would have to exist for that parameter to enter the optimal solution. As an example, assume that canal flow for the wet season does not enter the optimal solution at a price of \$10/acre-foot. If the reduced cost output listed a value of \$6.50 for this parameter, this would imply that wet season canal flow would enter into the solution if the cost dropped to \$6.50/acre-foot. Obviously, in this case, a fairly large error in the original cost estimate for wet season canal flow would have had no serious effect on the composition of the optimal solution.

The "primal range" and "dual range" outputs contain the results of the sensitivity analysis. The former is designed to indicate the range of prices, for any parameter in the optimal

solution, which may occur without changing the composition of the optimal solution. This data is analogous to that of the reduced cost output, which is relevant to parameters not contained in the optimal solution. The dual range output presents the range of values over which the right-hand-side elements of the constraints may vary without producing infeasibility. This would be useful in assessing the optimality of the system with respect to possible legal or hydrologic changes.

The preceding brief discussion of the normal output of a linear programming analysis should illustrate the quantity and diversity of information that may be obtained. It cannot be overemphasized, however, that the results of the analysis can be no more reliable or accurate than the input data used.

SUMMARY AND CONCLUSIONS

Planning conjunctive use of surface and ground water can result in increased efficiency of water resource utilization in many areas. The value of this management technique has been recognized by some of the larger water management agencies, but planning procedures have not been formalized or defined sufficiently to result in widespread understanding and implementation. Since smaller water agencies are not capable of applying the more sophisticated methods of planning conjunctive use, simplified methods must be developed if efficiency of water resource utilization at the lower levels of management is to be improved.

The flow chart presented in this study is one such tool which will assist an agency in making the first necessary decision relative to planned conjunctive use, which is the answer to the question of feasibility. The determination of feasibility has been shown to be dependent on the assessment of legal, hydrologic, and economic factors. This study did not produce any new or improved means of analyzing or assessing these factors, but rather did attempt to define required tasks and types of information, to indicate present acceptable means for accomplishing the tasks, and to relegate to each a place in an integrated efficient procedure.

It is the opinion of the writer that the major obstacle to a feasibility estimate concerning planned conjunctive use lies in the assessment of economic factors, namely anticipated gross benefits. There is at present no truly adequate means of determining the value of water in irrigation, and this is one of the more easily analyzed beneficial uses. Hopefully, future research will remedy this situation.

The brief review of the systems analysis approach and linear programming has given some insight into the means by which conjunctive use might be planned in the relatively near future. To one familiar with water management practices currently followed in many agencies and small river basins (such as was investigated and discussed in the Appendix), the contrast between these practices and those which are now theoretically feasible is striking. It is hoped that this study will be of value in decreasing this gap between theoretical and practical management of water resources.

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APPENDIX

Conjunctive Use Feasibility Study--Little Lost River Basin

General

The Little Lost River watershed is located in central Idaho, 80 miles northwest of Pocatello. The basin extends for approximately 50 miles northwest of the margin of the Snake River Plain, and is bounded on the southwest by the Little River Range, and on the northeast by the Lemhi Range (see Figure 9). The average height of the mountain peaks is 10,000 feet, while that of the basin proper is from 4800 to 6500 feet.

Inflow to the basin is made up entirely of precipitation. Surface runoff from the surrounding mountains is concentrated into numerous creeks (many of which are intermittent), which feed the Little Lost River. The river itself has been defined as starting at the confluence of Sawmill and Summit Creeks, at the northwest end of the basin. Although the mean annual discharge of the Little Lost River at Howe (in the lower end of the basin) is significant (50,680 acre-feet), much of this is used to irrigate the Lower Valley. None of the discharge reaches the Snake River as overland flow. All surface flow infiltrates into the alluvium underlying the valley floor; this is discharged into the basaltic aquifer underlying the Snake River Plain.

The principal aquifer in the basin is the alluvial valley fill. The aquifer is highly permeable, and the normal water table is quite

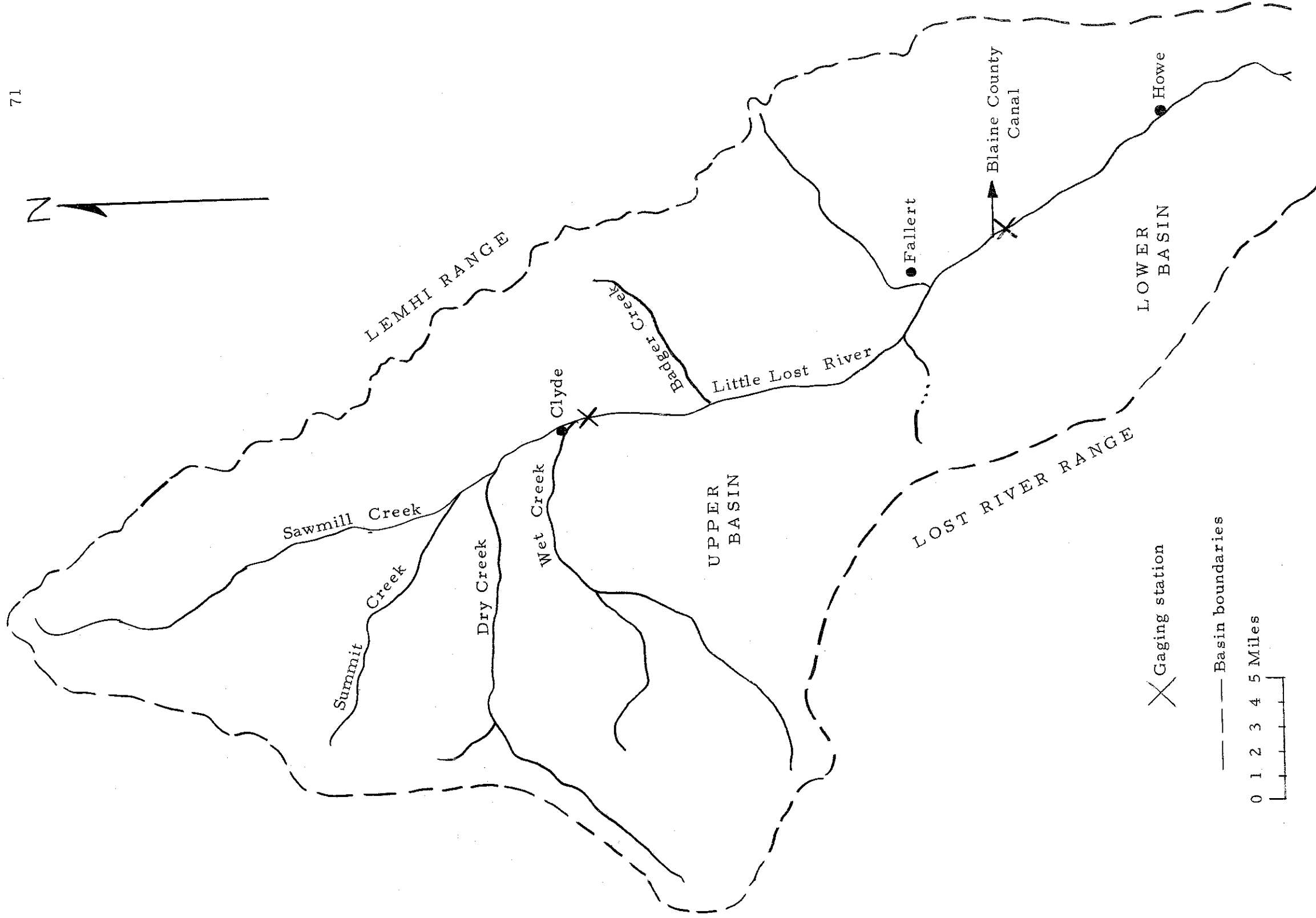


Figure 9. Little Lost River Basin.

close to the ground surface. The Little Lost River and tributary creeks vary between influent and effluent conditions along their lengths and with respect to time. The combination of high permeability and relatively shallow depth to ground water has resulted in a very close hydrologic relationship between the stream and the aquifer.

The principal industry in the basin is irrigated agriculture; grain and alfalfa hay are the major crops. The mean annual precipitation over the watershed is 14.8 inches, but at Howe, in the Lower Valley, it is 8.2 inches. Prior to 1954 essentially all the water for irrigation was diverted from the river itself. Since that time, ground water utilization for irrigation has been increasing. The single beneficial use, high degree of hydrologic connection between the stream and aquifer, and closed nature of the system, would make conjunctive use planning relatively simple in this basin.

The required hydrologic and geologic data for this basin were obtained from publications by Hendricks (1963) and Mundorff, Broom, and Kilburn (1963). Economic, agricultural, and legal information was obtained from personal conversations with individuals in the Little Lost River area.

Legal assessment

Oscar Johnson (1967), watermaster for the Little Lost River, indicated that the streamflow was more than fully appropriated. Water

rights in the area take the form of decrees which allow the diversion of specified flows. At the beginning of the normal irrigation season (April 1), streamflow is sufficient to satisfy all rights (except flood rights); flow is usually insufficient beginning the early part of July. The normal irrigation season extends to late October. Mr. Nephi Hansen (1967), who was watermaster for the basin until 1964, substantiated the over-appropriation. He stated that the appropriations totaled approximately 400 cfs, while mean annual discharge near Howe is 70.0 cfs, and mean July discharge is 90.4 cfs (Hendricks, 1963, p. 100).

There appears to be no restriction on appropriation of ground water in the basin (York, 1967). Individuals desiring to drill wells and install pumps need only file their intentions with the State Reclamation Engineer.

Mr. Johnson indicated that water exchanges are permitted. One limitation to this practice is that water removed downstream in exchange for an upstream right is assessed a 10% transportation fee. This was said to be required by the extremely high percolation losses in the streambed. Mr. Johnson could foresee no difficulties with a diversion of streamflow if the quantity of water diverted were replaced by pumped water.

The legal assessment should result in a decision to continue the investigation.

Estimation of ground water
extraction costs

The use of pumped ground water for irrigation is a common practice in the Little Lost River basin. Although several farming operations are conducted with ground water as the only source of supply (notably the 2400-acre Ruby Farms in the lower valley), ground water is generally supplemental to surface supplies. The Soil Conservation Service agent (Stallnaker, 1967) estimated that nearly all landowners in the basin have one or more wells on their property to insure against crop losses when surface supplies are inadequate.

Pumpage from ground water is not metered in this area, and per unit pumpage costs can only be estimated. Individuals within the basin estimated the pumping costs in the Lower Valley at \$1.62 - \$3.75/acre-foot. Average pumping lifts are 60 feet in the Upper Valley, and 94 feet in the Lower Valley.

Due to time limitations, reliable data concerning fixed costs and maintenance costs of pump irrigation systems in the basin were not obtained. This could be accomplished in a normal study by careful review of farm records. Davis and Price (1967) have performed such a review in the Milford, Utah, area, a basin with similar pumping lift (85-foot average) and similar aquifers (valley fill). There, average fixed cost plus maintenance cost for pumped water was calculated to be \$1.66/acre-foot. Using this figure as

approximate for the Little Lost River basin, total per unit costs for pumped water would be on the order of \$4/acre-foot.

Determination of benefit-quantity curve

A relatively short analysis of the water supply in the Little Lost River basin reveals that a benefit-quantity curve is not necessary to make the next decision in the feasibility study. There is no physical water shortage in the basin; Mundorff, Broom, and Kilburn (1963, p. Q43) estimate an additional 50,000 acre-feet/year could be pumped without harmful effects. Most water-users in the basin have wells, and are free to pump water at any time, but are constrained economically. Although Mr. Stallnaker estimates there are 50,000 additional acres of a quality equivalent to those now under irrigation (except for water supply), this land has not been developed. The logical conclusion is that the returns from the water are not sufficient to cover the pumping costs. In this particular area, planned conjunctive use cannot result in significantly decreasing the pumping lifts (and consequently decreasing the pumping costs), since these lifts are low at the present time. Hence additional water made available would not be utilized.

This phase results in a decision to terminate this path.

Determination of present
distribution costs

Although planned conjunctive use appears infeasible for providing additional water to users in the Little Lost River basin, feasibility with regard to provision of distribution economies must also be investigated. This requires the determination of ground water extraction costs (already accomplished), the determination of present distribution costs, and inspection of the system for points of possible cost reduction.

Present distribution costs may be divided into the costs of providing the surface supply, and the costs of the supplemental ground water supply normally required. The Blaine County Irrigation Company supplies a large share of the surface water to individual irrigators, and distribution costs incurred by this company should be indicative of the average distribution costs throughout the basin. The total distribution costs are covered by the irrigators belonging to the company; assessments are made to each according to the size of his irrigated acreage. In 1967, the assessment was \$1.10/acre, or approximately 15¢/acre-foot (Pope, 1967). (Surface irrigation efficiencies are seldom greater than 40%--Stallnaker, 1967.) It will be recalled that costs of pumped water were in the neighborhood of \$4.00/acre-foot.

Reiterating, surface water (at 15¢/acre-foot) is used according to water rights until the supply becomes deficient. Pumped water (at

\$4.00/acre-foot) is then used to complete the necessary crop requirements. Mundorff indicates that the Little Lost River during the latter part of the irrigation season is influent to the ground water reservoir in the Upper Basin; from a point approximately eight miles north of Howe, the stream is influent during all seasons. Mr. Hansen approximates the average stream losses during low water at 40 - 50% of streamflow. He further states that early water rights amounting to 72 cfs are held by Lower Basin landowners; these rights must be filled prior to the diversion of any significant quantity in the Upper Basin.

It can be concluded from the above information that a surface-water diversion in the Upper Basin would effectively reduce Lower Basin streamflow by a quantity less than the amount of the actual diversion. For example, assuming 40% losses in the stream and Upper Basin streamflow of 100 cfs, Lower Basin streamflow will be 60 cfs. A 50 cfs diversion in the Upper Basin will leave 50 cfs in the stream, or 30 cfs in the Lower Basin. Thus 20 cfs has been lost to Lower Basin users, but 50 cfs has been gained by Upper Basin users.

The distribution economies possible with planned conjunctive use now become apparent. From the system viewpoint, it is much more efficient for the Upper Basin irrigators to use surface water whenever physically possible. With this operation, the total quantity of water which must be pumped will be minimized.

A rough estimate of the cost savings may be obtained in the following manner. Mundorff approximates 1959 pumpage in the Upper Basin at 12,000 acre-feet, and in the Lower Basin, 25,000 acre-feet. There are no farms in the Upper Basin which utilize only pumped water, so the 12,000 acre-feet can be assumed to be a supplemental supply for approximately ninety days beginning July 1. Average streamflow (at the Howe gaging station) during this period was 76.6 cfs, or a total of 12,600 acre-feet. It would not be unreasonable to assume that 8,000 acre-feet of this streamflow could have been used in the Upper Basin for irrigation. With a conservative estimate of 20% streamflow loss, the amount of surface water saving is calculated to be 1600 acre-feet. Since the difference between cost of pumped water and cost of surface water is \$4.00 minus \$0.15 or \$3.85, the potential saving from this method of operation is over \$6,000 for the year.

It is reemphasized that this conjunctive use operation is feasible under the present legal framework. There are administrative difficulties which would have to be resolved; these would concern arrangements for payments from Upper Basin users to Lower Basin users to divide the costs of Lower Basin pumpage. Probably the most efficient organizational form would be one in which the irrigation company owned and operated the wells and pumping equipment as well as the surface distribution system.

The outcome of the feasibility study is a decision to proceed with detailed conjunctive use planning for maximum distribution economies.