THE EFFECT OF UNCERTAINTY IN IRRIGATION DEVELOPMENT

by

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A B S T R A C T

Uncertainty in irrigation development is of significant concern, more so now than before, because marginal projects are being developed. Piecemeal efforts to account for uncertainty do not indicate its relative importance in design decisions; its only when uncertainty in all the input functions to the system is properly accounted for that its significance can be realised. This thesis presents a method of analysing an irrigation project in which uncertainty was directly taken into account. The design decision problem involved the choice of the capacity of an irrigation system using regulated streamflow. The analysis showed that the optimal size of the irrigation project and the expected utility value decreases as the level of uncertainty increases, and it also depends on the ability of the owners to survive poor harvests.

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Chapter 1

INTRODUCTION

Many of the most favourable irrigation projects have already been developed. The remaining ones are obviously not favourable - perhaps because they are marginal at best, perhaps because of lack of information that would permit their effective evaluation. With irrigation projects uncertainty is a major factor: they are capital intensive and they have a long payoff period, therefore unsound decisions can be very costly; prices of products vary and cannot be predicted with certainty over the long life of the project; prices of inputs such as fertilisers, labour and maintenance costs vary; many past projects have not lived up to expectations, hence it is difficult to predict how new ones will be accepted. In addition there is the problem of the stochastic nature of water supply to the system; crop yields are subject to the water supply and to the other vagaries of weather; also estimates of future demands of water, future operating policies, technological developments and future political decisions cannot be predicted with certainty. The degree of uncertainty that can be accepted depends on the ability of the owners of the irrigation system to survive bad years; this ability also changes with time over the life of the project.
If uncertainty is not considered the analysis could either lead to overdesign, which can ruin the owner economically, or to

underdesign which is wasteful of scarce resources. Hence methods of analysing irrigation projects should directly take into account the uncertainty in the system.

Although it is generally recognised that there is some degree of uncertainty that must be taken into consideration in water resources project planning, design and operation, most engineering and economic analyses do not consider uncertainty directly. Sometimes uncertainty is taken into account indirectly - by design criteria such as designing for the flow that will be exceeded a certain percentage of the time, and by sensitivity analyses.

This thesis presents a method of analysing a project in which uncertainty was taken into account directly. The analysis was applied to a hypothetical project using simplified but realistic data. The problem in the project involved the choice of the capacity of an irrigation system using regulated stream flow.

Powers Creek Basin, a small water resources system in the Okanagan Basin, in the interior of British Columbia was chosen to provide the necessary data required in analysing the hypothetical irrigation project. Powers Creek Basin has a high agricultural potential, but this can only be realised with irrigation.

The essence of the method of analysis adopted is that uncertainties, represented by probabilities, can be combined together in a methodical manner which permits a proper decision of the size of the project to be made. The optimum size of the project was that which yields the maximum value of expected benefits.

The benefits from the system were measured in terms of net economic value, and in terms of utility value to the owner of the irrigation system. The probabilities were derived from available information, where possible, or they were subjective assessments derived on the basis of engineering judgement. Bayesian decision theory provides the mechanics of working with such probabilities and making a rational decision.

The specific characteristics of the data - cost capacity relationships, streamflow and crop yield - were not of concern in themselves so long as they are consistent with reality. The main emphasis was on the method of analysis, its applicability, and general conclusions derived from the trial analysis.

The analyses were first made on the basis of expected monetary benefits and then on the basis of expected utility. The latter showed that the optimal size of the project decreased as the level of uncertainty increases and as the owner's ability to survive a drought decreased.

The project is described in Chapter 2, and Chapter 3 presents the method of analysis. Chapters 4 and 5 present the results of the analyses using a decision criteria of expected monetary value and expected utility respectively. Chapter 6 demonstrates the effect of uncertainty on the optimal design. In Chapter 7 the results are discussed and conclusions drawn. The computer programs used in the analysis are given in the Appendix.

Chapter 2

DESCRIPTION OF THE PROBLEM

2.1. Types of Uncertainty in Water Resources Projects

Most data required in water resources system design and operation can be measured with a reasonable degree of accuracy. However, inspite of such accuracy, the magnitudes and timing of future flows cannot be predicted with a high degree of certainty. In addition our knowledge of the underlying hydrological processes is not adequate; also the mathematical models of the process have limited degree of suitability.
It is necessary to recognise the different types of uncertainty which should be dealt with in water resources system design and operation. There are three basic types - process uncertainty, statistical uncertainty and fundamental uncertainty, (Benjamin and Cornell, 1970), but there is a fourth type which results from circumstances external to the system.

(1) Process Uncertainty - this results from limited knowledge of the actual process, for example, the hydrological process. In an effort to predict such natural processes, mathematical models are often used, but, as a result of ignorance of the true processes involved, these predictions may be of questionable accuracy.

(ii) Statistical Uncertainty - even if the process was well understood and the appropriate models were used, the uncertainty of the likelihoods still remains.

because of limited statistical records. The data may be insufficient and relatively inaccurate; consequently when statistical parameters can be predicted, they still contain some uncertainty.

(iii) Fundamental Uncertainty - regardless of what data is available, future states of the process cannot be predicted with absolute certainty. For example, neither the magnitude nor the sequence of hydrological events can be predicted easily.

(iv) Uncertainty brought about by external circumstances - future operating policies of the water resources system are not known with certainty. Such policies are even more difficult to estimate if the project is a multipurpose one. Future political decisions, future technological developments and social changes, and overall economic conditions all affect the system. These conditions cannot be predicted with certainty over the long time period of most irrigation projects.

Most often these uncertainties are interrelated and there is no imdication as to which type of uncertainty is predominant. Usually the type of data will give a clue to which type of uncertainty governs the situation. If better information is required then it is important to recognise the type of uncertainty and how it can be reduced. More data will tend to reduce the magnitude of process and statistical uncertainty; fundamental uncertainty remains unchanged by the number of past experiments; the fourth type of uncertainty is more difficult to predict because it has elements of the former three.

The advantage of decision theory in accounting for uncertainty is the possibility of being able to assign probabilities to the uncertain events. Probabilities can be derived either from observations or from engineering judgement. The probabilities can then be incorporated in a decision process.

In the following problem the probabilities associated with the possible outcomes are derived partly from limited data and partly from the engineering judgement of experts in their respective fields.

2.2. Schematic Presentation of the Problem

The physical configuration to which decision theory is applied is described below and shown schematically on Fig. 2.1

A single reservoir supplies irrigation water D_i to an agricultural area A_i. The size of the area under irrigation is dependent on available water from the reservoir which in turn depends on the inflow I_i. The outflow O_i is the amount of water required to maintain normal flow conditions downstream of the reservoir. All quantities of flow are based on annual volumes.

The annual inflow I_i is known from stream flow records, however, the length of records is very limited, so that it has considerable uncertainty. The annual irrigation diversion requirement D_i is known once the area under irrigation is determined, but it also varies with weather conditions.

The costs of building the reservoir and all the attendant structures, the costs of land development for irrigation, the costs of conveying and distributing the water, and the maintenance costs, all can be estimated from previous projects in the area.

The crop yield from irrigated land depends on the available water. The crop yield can be estimated with some accuracy; these estimates are known from past yield figures and also from agricultural knowledge from other areas.

The selling price of agricultural products can be estimated within certain limits. It is known that prices will vary with the level of production in the area and will also vary from time to time as a result of external influences.

The main decision problem is to determine the level of investment (physical sizes of the components of the system) which will yield the maximum desired benefits. The costs of investment include the reservoir, land development and all auxiliary facilities. The dilemma is that, if the reservoir is small and the area under cultivation is also small, sufficient use of the possible water supply may not be fully realised. On the other hand, having a large reservoir and a large area under irrigation, the inflow volumes may not be sufficient to support such cultivation hence net returns will be reduced and the investment wasted. Within these two extremes there is a whole range of possible combinations of reservoir size and area under irrigation. The optimum design is that combination of reservoir size and area under irrigation which produces a maximum value of expected benefit:

Expected Benefit = Expected Revenue - Expected Cost.

$$E(B) = E(R(D_i)) - E(C(D_i))$$

where $R(D_i)$ represents the revenue obtained from using irrigation water D_i

$C(D_i)$ represents the costs of the system (Reservoir, Area under irrigation) associated with supplying D_i volume of water for irrigation.

The calculations of these quantities should take into account the 'imperfect' or uncertain knowledge of costs, prices, crop yield and stream flow.

2.3. Available Data

The pertinent information used in the analysis was obtained from Powers Creek Basin, a sub basin of the Okanagan Basin in the interior of British Columbia. The Okanagan Basin has 22 inches average annual precipitation; local variation in precipitation range from 10 to 15 inches in the valley bottoms to 35 to 40 inches in the mountain areas; summers are fairly warm with low humidity, and winters have occassionally very low temperatures. The basin is an important agricultural area, but it is heavily dependent on irrigation. However, there is sparse hydrometeorological data in most areas of the basin, and inspite of the important need for developing the area, decisions will still be based on this kind of data (Canada - Okanagan Basin Agreement 1974).

Powers Creek Basin is a small watershed (56 square miles) on the western side of the Okanagan Basin. Several upland lakes on the Creek have been harnessed to regulate water flow, primarily for agricultural purposes. This Basin has been chosen to provide data required in the analysis because it is typical of those basins earmarked for agricultural development inspite of the

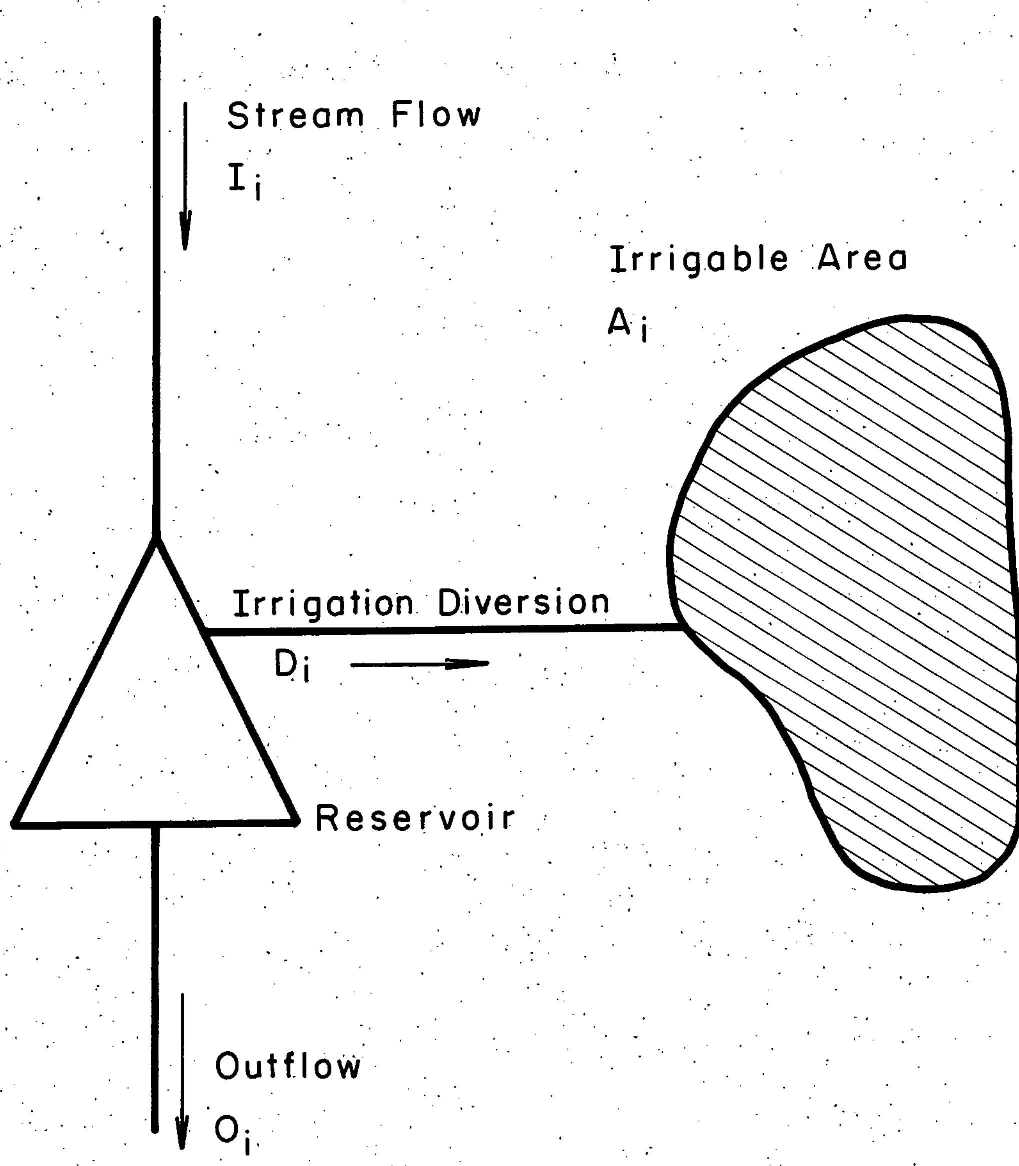

FIG. 2.1 SCHEMATIC REPRESENTATION OF THE SYSTEM.

inadequacy of hydrometeorological and agricultural data on it. One of the important forage crops grown with irrigation in the area is alfalfa. This crop is used to represent the agricultural yield from irrigation in the following analysis. The available data are given below.

2.3.1. Stream Flow Records

Continuous stream flow records of Powers Creek are available for the last eight years (up to 1974); prior to that the stream flow was measured only during freshet season (Water survey of Canada, 1973). Powers Creek and most creeks in the Okanagan Basin have less than fifteen years continuous stream flow record. The main river itself, the Okanagan River, has fifty years continuous stream flow record at two locations in the basin. The stream flow record for Powers Creek is shown in table 2.1 and 2.2. Fig. 2.2 shows the frequency distribution of the stream flow.

2.3.2. Crop Yield

The production relationship between water and crop yield is complex. Many variables (soil characteristics, moisture supply, air temperature, wind, crop diseases etc), some of which are difficult to control, affect the production. However an estimate of the production relationship was made after examining historic yield figures and water consumption. An agriculturalist who is very familiar with the area gave an estimate (Fig. 2.3.) of the relationship between crop yield and available irrigation water. The upper and lower limits

TABLE 2.1

POWERS CREEK ANNUAL STREAM FLOW
Station # 08NM 059 Below West Bank Diversion
Drainage Area = 53.6 sq. miles

YEAR	TOTAL ANNUAL DISCHARGE Acre-Feet
1966	7200
1967	13200
1968	17300
1969	16400
1970	7450
1971	20600
1972	26500
1973	7900

Mean Annual Flow = 14,570 Acre-feet

Standard deviation = 6,980 Acre-feet

TABLE 2.2

FREQUENCY ANALYSIS OF POWERS CREEK FLOW

FLOW Acre-feet	YEAR	RANK m	RETURN PERIOD $t_r = \frac{n+1}{m}$	% FLOW EQUALLED OR EXCEEDED
26,500	1972	1	9	11
20,600	1971	2	4.5	22
17,300	1968	3	3.0	33
16,400	1969	4	2.25	44
13,200	1967	5	1.80	56
7,900	1973	6	1.50	67
7,450	1970	7	1.29	78
7,200	1966	8	1.125	89

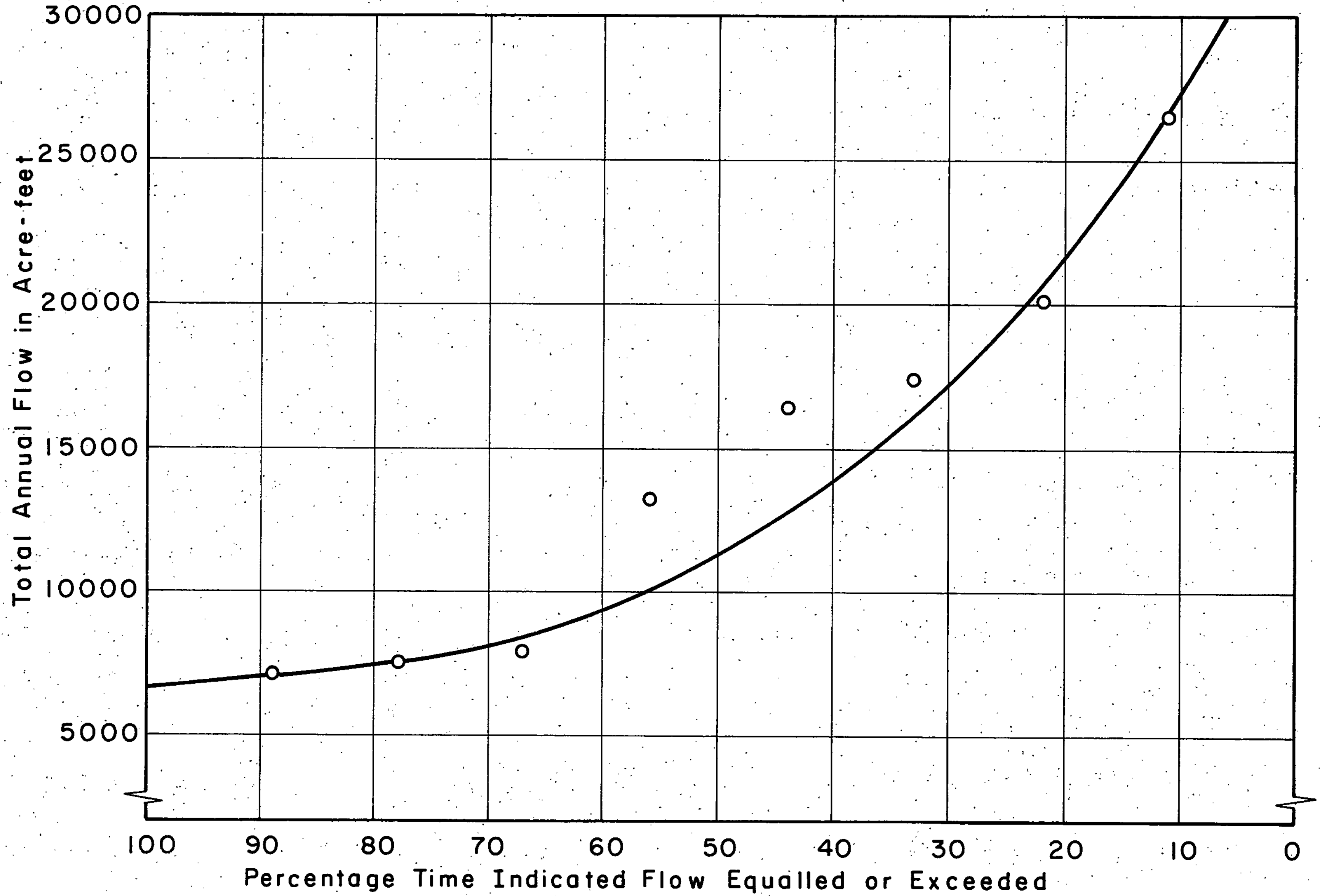

FIG. 2.2 STREAM FLOW FREQUENCY DISTRIBUTION.

bound the errors in the estimate. What Fig. 2.3 shows is that there is a minimum yield which can be obtained without irrigation - this corresponds to the natural yield. If more irrigation water is available the yield increases and there is a limiting value above which the yield will start to drop - usually when accumulation of water leads to ponding. The crop yield function used in the analysis is that which lies between the maximum and minimum values of yield.

2.3.3 Irrigation Water Requirement

The irrigation diversion requirement in the Okanagan Basin varies from 6.0 feet/year in the southern end of the basin to 1.75 feet/year in the north (Canada- British Columbia Okanagan Basin Agreement 1974). Local requirements in any area depend on local weather conditions, soil conditions, type of crop, topography and elevation of the land. The British Columbia Irrigation Guide suggests water requirements varying from 2.0 feet/year to 4.4 feet/year depending on the number of frost free days in an area. The same source also indicates that the total evapo-transpiration for pasture varies each year, and over a period of 11 years the mean is 1.6 feet/year, with minimum and maximum values of 75% and 115% of the mean respectively. The irrigation diversion requirement in Powers Creek has been estimated to be 3.03 feet/year (Canada- British Columbia Okanagan Basin Agreement). In the analysis the irrigation requirement of Powers Creek Basin was assumed to be 3.0 feet/year but several possible values in the range from a minimum value of 2.0 feet/year to a maximum value of 4.0 feet/year were

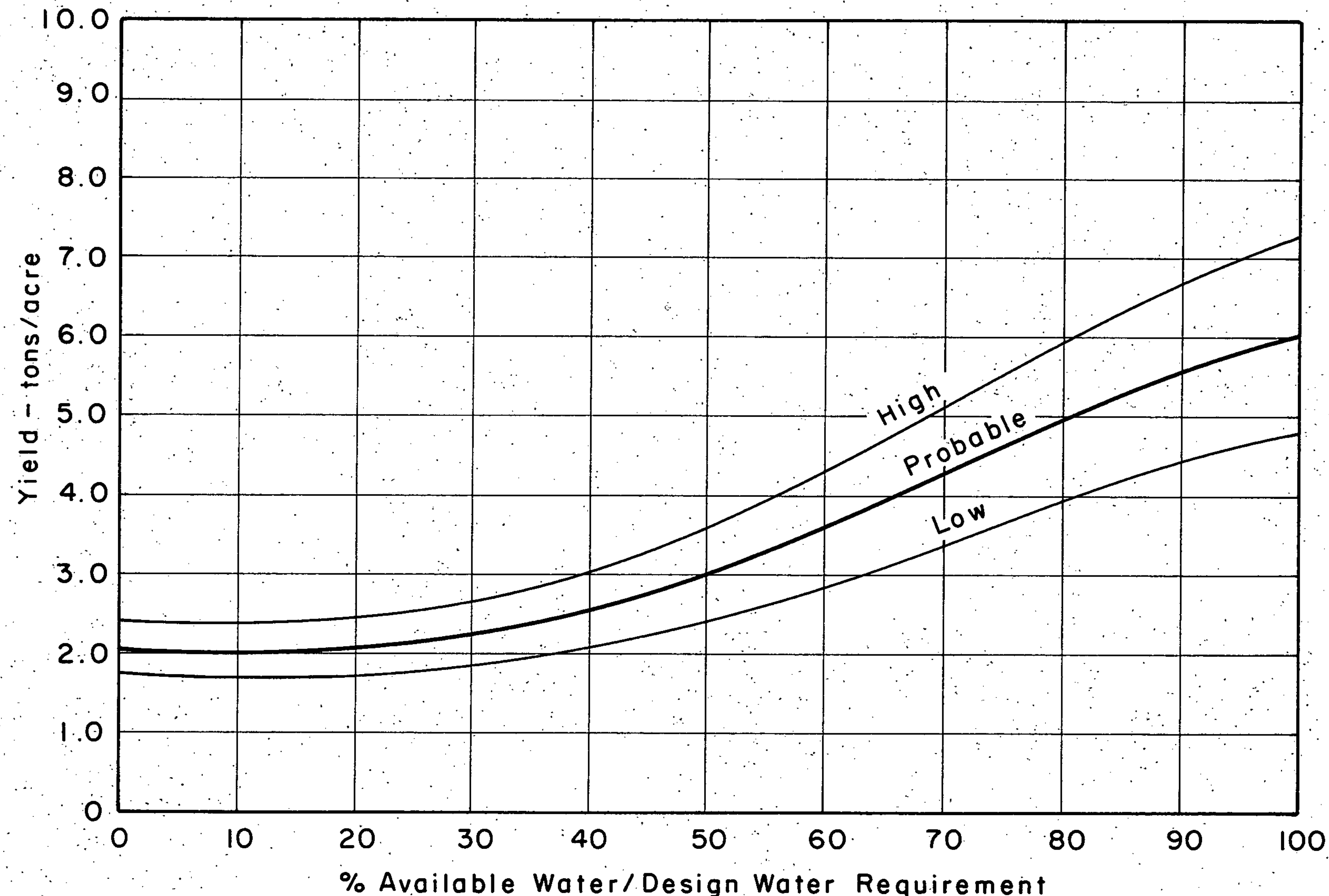

FIG.2.3 CROP YIELD AS A FUNCTION OF WATER.

also used for purpose of comparison.

2.3.4 Costs of Development

Preliminary estimates of the reservoir and land development costs for irrigation were roughly estimated by a water resources engineer with experience in the area. These cost-size relationships are shown in Fig. 2.4 (Reservoir), Fig. 2.5 (Land Development) and Fig. 2.6 (Maintenance on irrigated area). The upper and lower limits bound the uncertainty in the estimates. The reservoir costs include all auxiliary structures - spillway, intake, etc. The land development costs include the cost of conveying and distribution structures (irrigation channels, laterals, piping, pumps, etc.) and also the cost of clearing and levelling the land for agricultural use.

The annual capital costs (repayment of loan, interest on capital etc) and the annual operating and maintenance costs of the fixed facilities (reservoir, irrigation networks) was assumed to be ten percent of the total capital cost. This is equivalent to assuming a 20 year life of the project with 7% interest on capital and 3% of total capital cost for the average annual operating and maintenance costs of the system. The total annual cost is the sum of the annual capital cost and the annual operating and maintenance costs given in Fig. 2.6.

2.3.5 Prices of Crops

Prices may vary each year depending on the laws of supply and demand constrained by external influences such as contractual agreements, and world economic conditions. A fixed price of $100 per ton was used in the analysis. The analysis was also done using two prices, $90 per ton and $110 per ton for purposes of comparison.

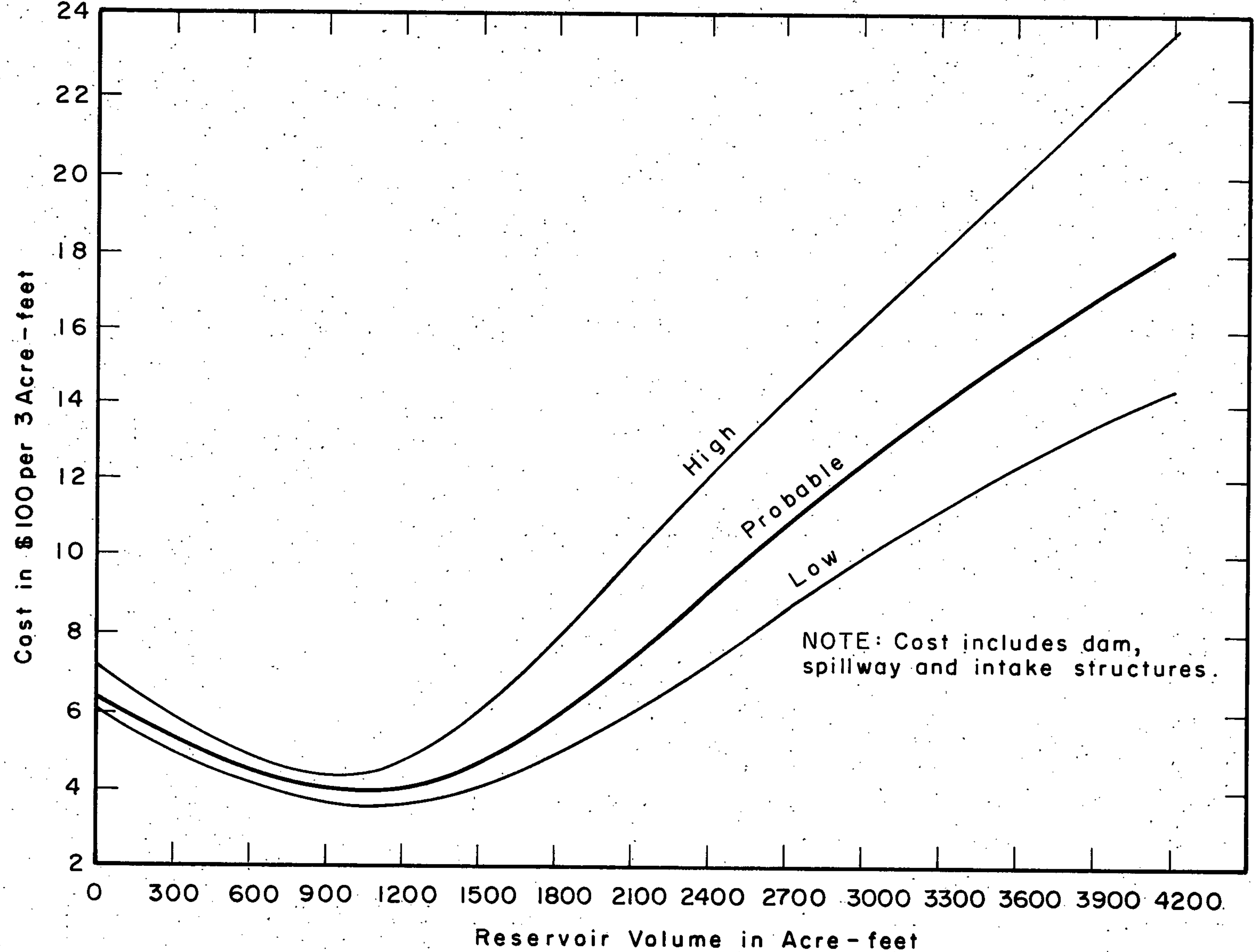

FIG. 2.4 RESERVOIR COST.

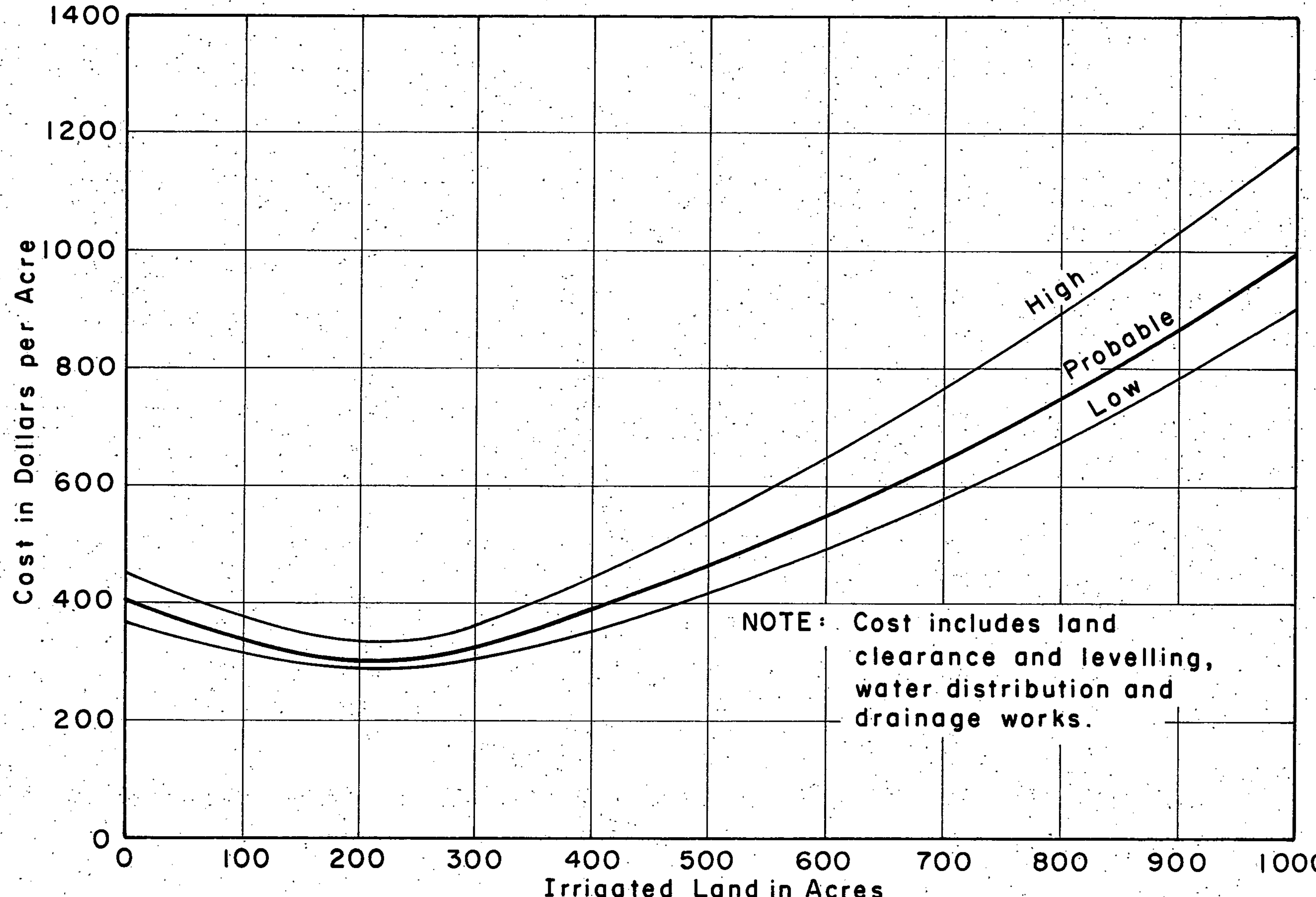

FIG. 2.5 LAND DEVELOPMENT COSTS.

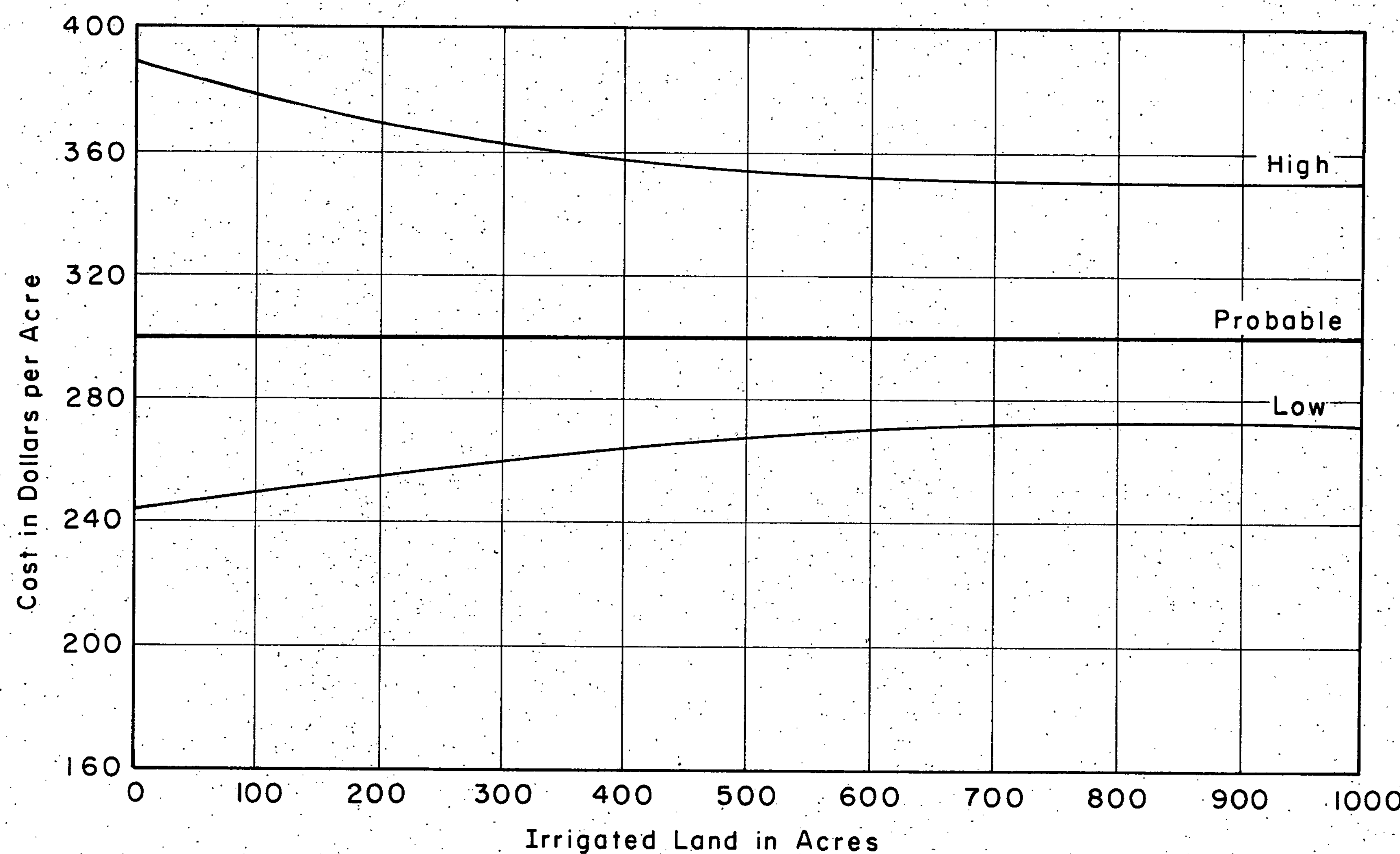

FIG. 2.6 ANNUAL FARM MAINTENANCE COST.

Chapter 3

METHOD OF SOLUTION

3.1 Basic Assumptions.

The following assumptions about the system were made.

3.1.1. Reservoir

(i) The reservoir is to be used primarily for storing irrigation water.

(ii) There is no carry over storage from season to season. All the water comes at the beginning of the season. Excess flow above the irrigation requirement is spilled as outflow.

(iii) The inflow into the reservoir is natural flow from the upstream basin. The effect of other storage reservoirs upstream is ignored.

(iv) Losses of water from the reservoir through evaporation, seepage into the embankment, and other secondary effects are assumed to have been deducted from the inflow. Therefore the reservoir size is the net size required to supply the necessary irrigation requirements.

3.1.2. Area Under Irrigation and Water Use

(i) The total irrigation requirement varies between 2.0 feet/year and 4.0 feet/year. This amount also includes the water losses incurred on the farm and the irrigation networks.

(ii) Only one crop under irrigation.

(iii) The maximum area under irrigation is assumed to be 1000 acres.

(iv) The maximum permissible withdrawal from the creek is set at one tenth of annual flow.

3.1.3. Crop Yield.

The crop yield varies with the available irrigation water. Without any irrigation the possible yield is around 2.0 Tons/acre. It is assumed that the farm water application rates will be controlled so as to avoid ponding and to obtain maximum yield possible with the available water.

3.1.4. Stream Flow

(i) Annual volumes of stream flow were used in the analysis.

(ii) Only 10% of the annual flow could be diverted for irrigation. The rest of the flow was assumed to be used to meet other requirements - for example to maintain normal flow conditions downstream for other water users.

3.2. Derivation of Basic Relationships

3.2.1. Probability of Costs and Yield.

The probability (equivalent to uncertainty) of each of the costs and the yield were derived as follows.

(i) A computer library program was used which approximates each function (cost, yield) by a cubic spline function and interpolates between given data points. Fig. 2.3. 2.4, 2.5, and 2.6 were drawn using the data derived by such a program.

(ii) With the functions derived as above the probability of the costs and the yield were derived by another computer program.

Fig. 3.1. shows a hypothetical function Y = f(X). For any value of X there is a set of possible values of Y bounded by the upper and lower limits. The true value of Y lies somewhere between the upper and lower limits. The uncertainty about the true value of Y can be described by a probability density function, and thus each value of Y has a probability attached to it. The values of Y were assumed to be distributed according to a "skew normal" distribution, see Fig.3.2, (Hershman 1974). A computer program has been derived (Higgins 1975) which calculates the probability associated with any value of Y by integrating over the probability density function bounded by the upper and lower limits of the function Y = f(X). This program is described in Appendix, Program A.

This procedure was used in deriving the probabilities of costs, crop yield and stream flow. The "skew normal" distribution was originally derived for hydrologic data but in this analysis it was used for economic data (costs) as well as crop yield. This is one manner of accounting for uncertainty in knowledge. Bogardi and Szidarovsky (1974) have used a normal probability density function to account for information uncertainty stemming from limited data in hydrologic design.

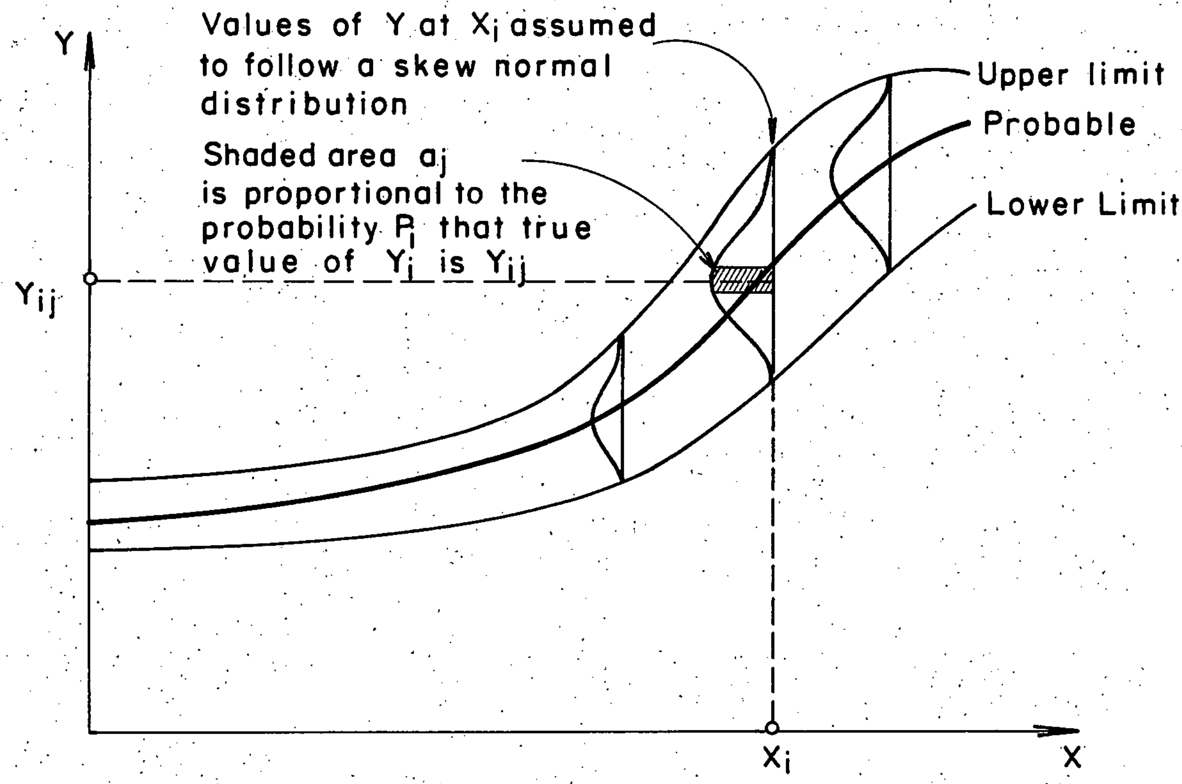

FIG. 3.1 HYPOTHETICAL FUNCTION $Y = f(x)$.

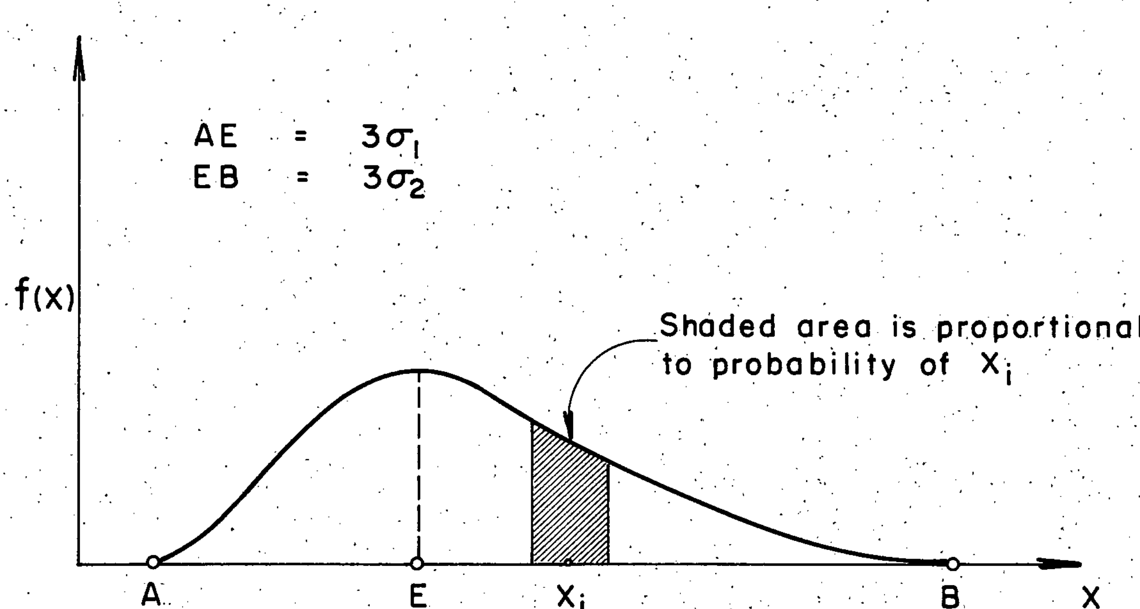

FIG. 3.2 "SKEW NORMAL" DISTRIBUTION.

However , the "skew normal" distribution seems to be an appropriate representation of most practical situations: variables are measured from a base (i.e. lower limit) and also possess an upper bound.

3.2.2. Probability of Stream flow.

The derivation of a stream flow distribution when there is only eight years data is, at best, a guess. The relatively short historic flow record does not clearly define the properties and parameters of the distribution; therefore errors could be made in selecting the underlying distribution. For the sake of keeping the analysis simple at this stage, it was assumed that the stream flow was distributed according to a "skew normal" distribution and the same program mentioned in the previous section was used to derive the probability of various magnitudes of stream flow.

For a theoretical "skew normal" distribution the lower limit is $-\infty$ and the upper limit is $+\infty$. However, in reality there exists the upper and lower limits, Q_u and Q_1, of stream flow possible in a given basin. The limiting values of flow have to be determined from the historic flow records.

With respect to Powers Creek, the only way to determine Q_u and Q_1 is to examine the stream flow records of some of the rivers in the same major basin (i.e. Okanagan Basin) and get a comparison of the limiting flows. However the other sub-basins in the Okanagan Basin have relatively short stream flow records, hence the only comparison possible is with the Okanagan River itself. Table 3.1 shows the stream flow records of the

Okanagan River at a hydrometric station where more than fifty years continuous record is available. The three driest years were 1929, 1930 and 1931; the three wettest years were 1928, 1948 and 1972:

Average minimum flow = (83,200 + 58,600 + 36,900)/3

= 59,567 acre-feet

Average maximum flow = (966,000 + 719,000 + 844,000)/3

= 843,000 acre-feet

Mean annual flow = 380,000 acre-feet

Therefore:

$$\frac{\text{minimum flow}}{\text{mean flow}} = \frac{59,567}{380,000} = 0.16$$

$$\frac{\text{maximum flow}}{\text{mean flow}} = \frac{843,000}{380,000} = 2.22$$

These same ratios of flow were used in estimating the limiting values of flow for Powers Creek.

Therefore:-

minimum flow = 0.16 x 14,570 = 2,330 acre-feet

maximum flow = 2.22 x 14,570 = 32,345 acre feet

With Q_u and Q_l defined, the probabilities of other flow magnitudes were determined by the computer program refered to previously.

3.2.3. Matrix Format

After determining the probabilities of various values of Y for each given value of X (See Fig. 3.1), discrete pieces

Table 3.1

OKANAGAN RIVER, STREAMFLOW RECORD

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OKANAGAN RIVER AT OKANAGAN FALLS - STATION NO. 08NM002

ANNUAL EXTREMES OF DISCHARGE IN CFS AND ANNUAL TOTAL DISCHARGE IN AC-FT FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE	MAXIMUM DAILY DISCHARGE	MINIMUM DAILY DISCHARGE	TOTAL DISCHARGE	YEAR
1915	---	1160 CFS ON MAY 29	400 CFS ON MAR 23	434000 AC-FT	1915
1916	---	1300 CFS ON JUL 2	---	---	1916
1917	---	1140 CFS ON JUN 29	190 CFS ON NOV 24	330000 AC-FT	1917
1918	---	1100 CFS ON JUN 10	160 CFS ON MAR 6	278000 AC-FT	1918
1919	---	1200 CFS ON JUN 5	150 CFS ON JAN 7	303000 AC-FT	1919
1920	---	1100 CFS ON JUL 10	100 CFS ON APR 19	201000 AC-FT	1920
1921	---	2500 CFS ON JUN 10	105 CFS ON MAR 4	412000 AC-FT	1921
1922	---	950 CFS ON MAY 19	130 CFS ON SEP 19	335000 AC-FT	1922
1923	---	1150 CFS ON JUN 22	390 CFS ON DEC 2	437000 AC-FT	1923
1924	---	558 CFS ON FEB 2	53.0 CFS ON NOV 28	170000 AC-FT	1924
1925	---	1160 CFS ON MAY 20	45.0 CFS ON JAN 27	205000 AC-FT	1925
1926	---	705 CFS ON MAR 16	30.0 CFS ON OCT 1	145000 AC-FT	1926
1927	---	1030 CFS ON DEC 28	30.0 CFS ON JAN 3	323000 AC-FT	1927
1928	---	2680 CFS ON JUN 10 *	43.0 CFS ON DEC 28	966000 AC-FT	1928
1929	---	713 CFS ON MAY 31	8.1 CFS ON DEC 4	83200 AC-FT	1929
1930	---	402 CFS ON MAY 14	5.3 CFS ON JAN 31	58600 AC-FT	1930
1931	---	146 CFS ON MAY 7	4.6 CFS ON MAR 14 *	36900 AC-FT	1931
1932	---	970 CFS ON MAY 7	7.7 CFS ON JAN 9	309000 AC-FT	1932
1933	---	1300 CFS ON MAY 30	118 CFS ON FEB 25	514000 AC-FT	1933
1934	---	1160 CFS ON APR 24	208 CFS ON SEP 7	470000 AC-FT	1934
1935	---	1110 CFS ON MAY 24	457 CFS ON JAN 2	545000 AC-FT	1935
1936	1000 CFS AT 1400 PST ON JUN 18	1000 CFS ON JUN 18	178 CFS ON APR 13	387000 AC-FT	1936
1937	1080 CFS AT 1430 PST ON JUN 3	1040 CFS ON JUN 3	96.0 CFS ON JAN 5	330000 AC-FT	1937
1938	1270 CFS AT 0900 PST ON MAY 28	1240 CFS ON MAY 28	150 CFS ON DEC 30	337000 AC-FT	1938
1939	543 CFS AT 1500 PST ON MAY 8	532 CFS ON MAY 4	117 CFS ON FEB 18	216000 AC-FT	1939
1940	304 CFS AT 2000 PST ON JUN 11	263 CFS ON JUN 12	52.0 CFS ON FEB 24	122000 AC-FT	1940
1941	824 CFS AT 1300 PST ON DEC 23	798 CFS ON DEC 20	83.0 CFS ON MAY 27	288000 AC-FT	1941
1942	1310 CFS AT 1900 PST ON JUL 4	1280 CFS ON JUL 1	123 CFS ON MAR 29	560000 AC-FT	1942
1943	865 CFS AT 0900 PST ON MAY 9	798 CFS ON MAY 9	134 CFS ON OCT 19	288000 AC-FT	1943
1944	802 CFS AT 1300 PST ON JUN 4	795 CFS ON JUN 3	70.0 CFS ON MAY 4	194000 AC-FT	1944
1945	1250 CFS AT 1400 PST ON JUN 7	1240 CFS ON JUN 7	257 CFS ON SEP 14	457000 AC-FT	1945
1946	1360 CFS AT 1800 PST ON MAY 13	1360 CFS ON MAY 14	492 CFS ON FEB 16	624000 AC-FT	1946
1947	696 CFS AT 1130 PST ON JAN 1	689 CFS ON JAN 1	114 CFS ON MAR 1	212000 AC-FT	1947
1948	1550 CFS AT 1200 PST ON JUN 18	1530 CFS ON JUN 18	140 CFS ON MAR 21	719000 AC-FT	1948
1949	1350 CFS AT 1040 PST ON MAY 16	1330 CFS ON MAY 16	355 CFS ON DEC 22	516000 AC-FT	1949
1950	1310 CFS AT 1300 PST ON JUN 15	1300 CFS ON JUN 6	321 CFS ON JAN 30	491000 AC-FT	1950
1951	1440 CFS AT 1230 PST ON MAY 13	1440 CFS ON MAY 13	590 CFS ON JAN 31	647000 AC-FT	1951
1952	1410 CFS AT 1700 PST ON MAY 20	1410 CFS ON MAY 20	164 CFS ON NOV 29	507000 AC-FT	1952
1953	1040 CFS AT 1730 PST ON MAY 22	944 CFS ON MAY 23	152 CFS ON JAN 16	331000 AC-FT	1953
1954	---	1190 CFS ON JUL 11	45.0 CFS ON OCT 19	520000 AC-FT	1954
1955	---	1030 CFS ON JUN 10	276 CFS ON DEC 19	473000 AC-FT	1955
1956	1540 CFS AT 1015 PST ON JUL 15	1540 CFS ON JUL 15	282 CFS ON JAN 1	537000 AC-FT	1956
1957	1670 CFS AT 2130 PST ON AUG 27	1480 CFS ON AUG 28	223 CFS ON APR 13	433000 AC-FT	1957
1958	2790 CFS AT 0800 PST ON APR 25 *	2560 CFS ON APR 26	315 CFS ON OCT 3	385000 AC-FT	1958
1959	2150 CFS AT 0945 PST ON MAY 25	2120 CFS ON MAY 26	326 CFS ON JAN 13	648000 AC-FT	1959
1960	1160 CFS AT 0010 PST ON JAN 1	1150 CFS ON JAN 1	315 CFS ON JUN 4	384000 AC-FT	1960
1961	1970 CFS AT 1230 PST ON JUN 7	1790 CFS ON JUN 6	242 CFS ON FEB 15	344000 AC-FT	1961
1962	1310 CFS AT 1445 PST ON APR 30	1250 CFS ON APR 28	229 CFS ON JAN 28	309000 AC-FT	1962
1963	581 CFS AT 1400 PST ON AUG 16	348 CFS ON AUG 16	141 CFS ON MAY 15	165000 AC-FT	1963
1964	1380 CFS AT 0915 PST ON JUN 16	1360 CFS ON JUN 17	163 CFS ON JAN 1	410000 AC-FT	1964
1965	1640 CFS AT 0930 PST ON JUN 6	1620 CFS ON JUN 6	216 CFS ON NOV 9	478000 AC-FT	1965
1966	462 CFS AT 1500 PST ON APR 12	455 CFS ON APR 10	153 CFS ON OCT 18	226000 AC-FT	1966
1967	---	1360 CFS ON JUN 5	---	---	1967
1968	1760 CFS AT 1030 PST ON JUN 12	1730 CFS ON JUN 12	---	---	1968
1969	1680 CFS AT 1556 PST ON MAY 31	1660 CFS ON MAY 31	269 CFS ON DEC 12	496000 AC-FT	1969
1970	1030 CFS AT 0930 PST ON MAY 13	1020 CFS ON MAY 13	97.1 CFS ON DEC 13	211000 AC-FT	1970
1971	1970 CFS AT 0900 PST ON JUN 5	1930 CFS ON JUN 6	60.7 CFS ON FEB 19	357000 AC-FT	1971
1972	2700 CFS AT 2130 PST ON MAY 10	2680 CFS ON MAY 11	203 CFS ON OCT 17	894000 AC-FT	1972
1973	1240 CFS AT 0730 PST ON JUN 2	680 CFS ON AUG 7	44.6 CFS ON NOV 21	186000 AC-FT	1973
				380000 AC-FT	MEAN

* - EXTREME RECORDED FOR THE PERIOD OF RECORD

of data are obtained - discrete probabilities for discrete values of Y and X. Therefore the entire function can be broken into discrete quantities. A very useful method of handling this data is to store it in a matrix format. For example, a matrix of reservoir costs, a matrix of land development costs and a matrix of crop yield. With respect to the function in Fig. 3.1, the first row of matrix would represent discrete levels of X, the first column would represent discrete levels of Y, and the other elements of the matrix represent the probabilities of values of Y at specific levels of X. This method of representing data has two advantages: firstly, the entire function (cost, yield, etc.) can be broken down into discrete levels and the function can be used in it's normal mode without recourse to mathematical approximation; secondly, addition, multiplication (or any other operation) of matrices can be easily carried out using computer programs that are available in most computer libraries. The number of discrete levels of each function depends on the desired accuracy.

This method of data representation was used in the analysis given below.

3.3 The Method of Analysis

3.3.1 Combining Two Functions.

The premise for combining any two cost functions is that they are independent events i.e. the costs of the reservoir are not related at all with the costs of land development and the costs on the farm. Therefore the basic axioms of probability can be applied in combining the probabilities (uncertainty) associated with each of the costs. Accordingly, the probability of the joint occurence of two independent events A and B is the product of their probabilities, and the probability of the union of two mutually exclusive events C and D is the sum of their probabilities.

Assume that two cost estimates have to be combined, and that the costs have already been presented in a matrix format. There are then two independent sets of data as shown in Table 3.2; each cost estimate has a probability associated with it. Set A may represent the cost of a reservoir of a particular size, and Set B represents the cost of developing land of a certain acreage. Any cost in Set A can combine with any cost in Set B and the probability of the combined value is the product of the individual probabilities. This may look like a very large number of combinations, but it is not necessarily so; some of the combined values are not unique. Consider the minimum and maximum values of total cost:

$$\text{Minimum total cost} = 150 + 270 = 420$$

$$\text{Maximum total cost} = 190 + 300 = 490$$

The interval between the minimum and maximum values is divided into intervals of 10 just like the cost items of Sets A and B. The number of cost combinations required to produce a total cost of 420, for example, is limited - only the sum of 150 and 270 can give a value of 420. Two sets of costs can produce a value of 430, a sum of 150 and 280, and a sum of 160 and 270. The probability of 430 is the sum of the products of the individual

TABLE 3.2

COMBINING TWO SETS OF COSTS

(a)

SET A		SET B	
VALUE	PROBABILITY	VALUE	PROBABILITY
150	a	270	r
160	b	280	s
170	c	290	t
180	d	300	u
190	e		

(b) Combined Value

No.	TOTAL VALUE	POSSIBLE PAIRS OF VALUES TO GIVE TOTAL VALUE	PROBABILITY OF TOTAL VALUE
1	420	(150,270)	ar
2	430	(150,280),(160,270)	as + br
3	440	(150,290),(160,280), (170,270)	at+bs+cr
. .	. .	. .	. .
n	490	(190,300)	eu

probabilities. The procedure is illustrated in Table 3.2 (b).

This method can be applied to any number of sets of data, even if the sizes of sets are different, provided only two sets of data are combined at a time. The cost intervals between the elements of the sets (e.g. 10 in Sets A and B) need not be the same. However the combination is easier and more accurate if the intervals are equal. Where the two intervals are not equal an average value could be used. The combination need not be addition only, other operations could be used as well.

By representing the functions in a matrix format the above operations are easier to do by computer, and the combined function is also represented as a matrix.

3.3.2. Expected Benefits.

The preceding activities prepared the data for use in the decision process. The decision problem is to determine the combination of reservoir size and land under irrigation which yields the maximum expected benefit:

Expected Benefit = Expected Revenue - Expected Cost

Where

Expected value = $\sum X_i P(X_i)$ for discrete variables

X_i is discrete variable

$P(X_i)$ is the probability of variable X_i

The decision problem can be represented in the form of a decision tree, as indicated in Fig. 3.3, and the probabilities shown indicate the uncertainty associated with the data. There are two types of events shown on the decision tree. Those events over which the decision maker has choice of action (for example, choice of reservoir size and choice of acreage to irrigate) are called decision events; those events which depend on chance or natural circumstances (for example, stream flow) are called chance events. The main decision problem is how to choose between alternative levels of investment when there is uncertainty about each outcome. The use of expected values - costs benefits, yield - reduces the dissimilar magnitudes to a common denominator from which they can all be compared. The procedure is then to calculate the expected values at each branch. The optimum decision is the one which has the maximum expected benefit. The benefit can be measured either by monetary value or by utility value.

The decision procedure is summarised below; also refer to Fig. 3.3.

For a value of Total Irrigation Water requirement

1. Choose area to irrigate.
2. Choose Reservoir size to supply water.
3. Determine costs associated with the choice
   - Annual Capital Cost
   - Maintenance Cost
   - Total Annual Cost

   and the expected cost.
4. Determine available quantity of water from stream flow records.
5. Determine possible crop yields and Revenues.
6. Determine net benefit and expected benefit.
7. Repeat 4 to 6 for all possible flows.

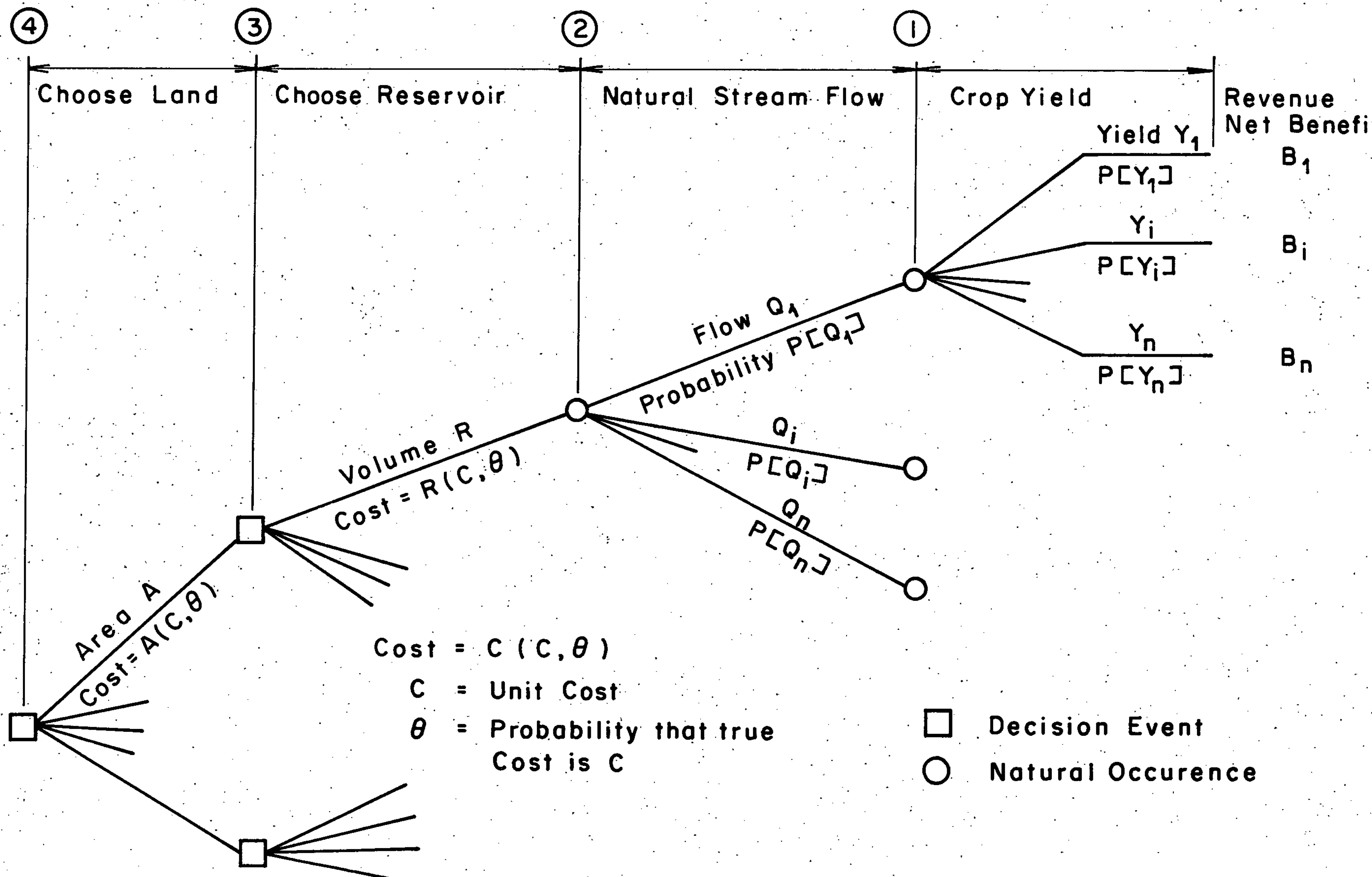


FIG. 3.3 DECISION TREE .

8. Repeat 2 to 7 for all possible resevoirs.

9. Repeat 2 to 8 for all possible acreages.

10. Calculate the maximum option.

Repeat for other values of irrigation water requirement and choose the optimum decision.

Chapter 4

DECISION CRITERION BASED ON MONETARY VALUE

4.1 Definition of Benefits

The determination of benefits from an irrigation system must, of necessity, first of all define the beneficiary, the costs to such beneficiary and the benefits accruing. If the beneficiary involves the whole society or a large community both the costs of the system and the benefits from it are wide spread into the community; also these costs and benefits may be direct (e.g. capital costs of building the system) or they may be indirect, and to a large degree, difficult to quantify. Besides, a monetary measure of benefit (or costs) may not necessarily reflect the net worth to society. If the beneficiary is reduced to a single farmer, though some of the costs and benefits from an irrigation system may affect third parties, nevertheless the costs and benefits to the farmer are localised and relatively easier to measure. The latter approach was adopted in the analysis, the beneficiary was assumed to be a single farmer, who was also assumed to bear all costs and to receive all benefits. Another way to look at the problem of a beneficiary is to consider society or a community as an entity (instead of a conglomerate) and hence costs and benefits are considered with respect to one body instead of spreading them among individuals. This avoids the controversy of who actually bears the cost and who receives the benefits.

The benefits were measured in terms of economic values -

that is, the increase in profits obtained by direct use of the water. Indirect benefits to the farmer such as enhanced land values and efficient utilization of resources were not considered at this juncture. Nonetheless indirect benefits can be incorporated in the utility value a farmer attaches to the investment alternatives. This aspect of decision making is considered in Chapter 5.

4.2. Derivation of Benefits

The basic equation for determining expected monetary benefit is:-

Expected Benefit = Expected Revenue - Expected Cost

Hence knowing the cost-capacity relationships, the stream flow and the crop yield, the optimum capacity of the project is one which produces the maximum net value. Costs are proportional to the land under irrigation and the reservoir volume; each cost item has a probability (uncertainty) associated with it. Revenues are proportional to the level of development (i.e. Reservoir and land), the stream flow, the consumptive use, the crop yield and the price; also each quantity has probability (uncertainty) associated with it. Since there is a whole range of possible combinations of reservoir sizes with land under irrigation, each combination yields a unique set of benefits. It is easier to follow the sequence of actions to be taken by examining Fig. 3.3. The caculations are illustrated below and are shown in detail in computer Program B-1 in the Appendix.

1. Choose land area to irrigate, A_k, and reservoir size R_m.

Total Cost = $A_k(c,\theta) + R_m(c,\theta) = TC(c,\theta)$

where c = cost

θ = probability that true cost is c

Expected Cost = c x θ; c and θ are determined as in Table 3.2 (b).

Total Expected Cost = $\sum c\theta$

2. For flow Q_j with probability $P(Q_j)$ there is a set of crop yields possible, Y_i, with probability $P(Y_i)$, where i = 1,2,....n

3. Revenue = P x A x Y_i P = price, A = Area

4. Net Benefits corresponding to the yields

$$B_1 = PAY_1 - C$$
$$B_2 = PAY_2 - C$$
$$B_i = PAY_i - C$$
$$B_n = PAY_n - C$$

5. Expected Benefit at Node 1

$$E(B_i) = P(Y_i)(PAY_i - C)$$

6. Total Expected Benefit at Node 1

$$= \sum_{i}^{n} P(Y_i)(PAY_i - C)$$

7. Expected Expected Benefit given flow Q_j

$$= P(Q_j) \sum_{1}^{n} P(Y_i)(PAY_i - C)$$

8. Total Expected Expected Benefit for the chosen alternative

$$EE(B) = \sum_{j}^{l} P(Q_j) \sum_{i}^{n} P(Y_i)(PAY_i - C)$$

This is the expected expected benefit for one choice of Land and Reservoir size. Several combinations are tried and the maximum of these values gives the optimum design conditions subject to uncertainty in costs, yield, and stream flow.

4.3. Computed Values Of Monetary Benefits.

The results of the computations are summarised in Table 4.1. The maximum expected benefits vary with the value of total water requirement; the lowest water demand yields the maximum benefits from the system. The values of maximum benefit obtainable from each irrigated area is shown in Fig. 4.2. The maximum benefit progressively decreases with an increase in water requirement. The optimum reservoir volume corresponding to each area is directly proportional to the total water requirement for smaller acreages, see Table 4.2, however for larger acreages it seems economically better to provide smaller reservoirs rather than to have those large enough to provide all the water. As an example, for an area of 700 acres, with total water requirement of 3.0 feet/acre, it is more profitable to provide a smaller reservoir (1800 acre-feet) than a larger one (2100 acre-feet) that may seem appropriate.

4.4. Effect of Uncertainty in Irrigation Water Requirement

In the previous analysis different values of water requirement were used to demonstrate how the expected benefits are affected by the water requirement. However it is better to take into account the uncertainty associated with the water requirement. The uncertainty about the true value of water requirement is represented by associating (subjectively) a probability to each value as shown in Table 4.3.

The decision sequence is shown in Fig. 4.1, and the total expected expected benefit is

$$\sum_{k}^{K} P(I_k) \sum_{j}^{l} P(Q_j) \sum_{i}^{n} P(Y_i)(PAY_i - C)$$

The results are summarised in Table 4.4 and the optimum design is

Irrigated Land = 400 acres

Optimum Reservoir = 1200 acre-feet

Maximum Benefit = $65,600

The results summarised in Table 4.4 were plotted on the same figure in Fig. 4.2 - shown as "Integrated Curve". Comparison of the benefit curve for 3.0 feet/year water requirement and that of the integrated curve shows that while the optimum size of the project is unaffected (i.e. irrigated land = 400 acres, reservoir size = 1200 acres) by accounting for uncertainty in water requirement, the expected benefit is reduced by 10%.

TABLE 4.1

OPTIMUM DESIGN CONDITIONS

ANNUAL IRRIGATION REQUIREMENT feet/year	OPTIMUM ACREAGE UNDER IRRIGATION acres	OPTIMUM RESERVOIR SIZE acre-feet	MAXIMUM EXPECTED BENEFITS $
2.0	600	1200	107,400
2.5	500	1200	78,300
3.0	400	1200	72,900
3.5	300	1200	54,900
4.0	300	1200	51,900

Optimum Reservoir Size = 1200 acre-feet

Optimum Acreage = 600 acres

Optimum Water Requirement = 2.0 feet/year

Maximum Expected benefits = $107,400

TABLE 4.2

INTERMEDIATE VALUES OF OPTIMUM CONDITIONS ON BASIS OF DOLLAR BENEFITS, TOTAL IRRIGATION REQUIREMENT = 3 FT/YR

Irrigated Land Acres	Optimum Reservoir Size Acre-Feet	Maximum Expected Dollar Benefits * [illegible] $[illegible]
100	300	20,400
200	600	42,300
300	900	62,500
400	1200	72,900
500	1500	64,200
600	1800	39,600
700	1800	- 5,000
800	1800	-48,300
900	2100	-101,800
1000	1800	-149,300

* Taken to nearest $100

TABLE 4.3

UNCERTAINTY IN WATER REQUIREMENT

Total Water Requirement Feet/acre per year	Probability Assessment
2.0	0.05
2.5	0.10
3.0	0.60
3.5	0.20
4.0	0.05

TABLE 4.4

INTERMEDIATE VALUES OF OPTIMUM CONDITIONS, INTEGRATED IRRIGATION WATER REQUIREMENT.

Irrigated Land Acres	Optimum Reservoir Size Acre-Feet	Maximum Expected Benefits * $
100	300	18300
200	900	39200
300	1200	57100
400	1200	65600
500	1500	57000
600	1800	32800
700	1800	- 6400
800	1800	- 48300
900	1800	-100000
1000	1800	-147200

* Nearest $100

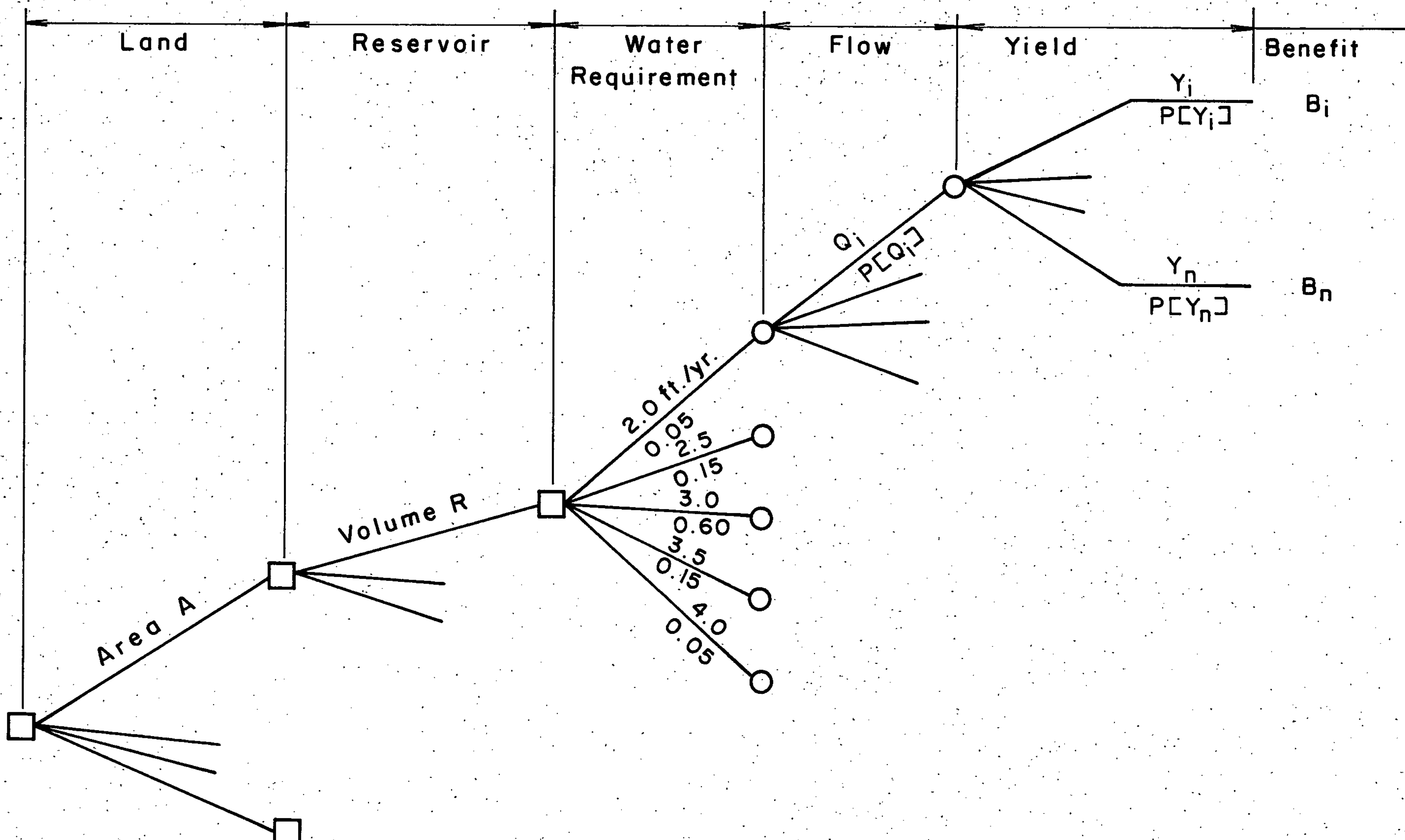


FIG. 4.1 DECISION TREE: UNCERTAINTY IN WATER REQUIREMENT.

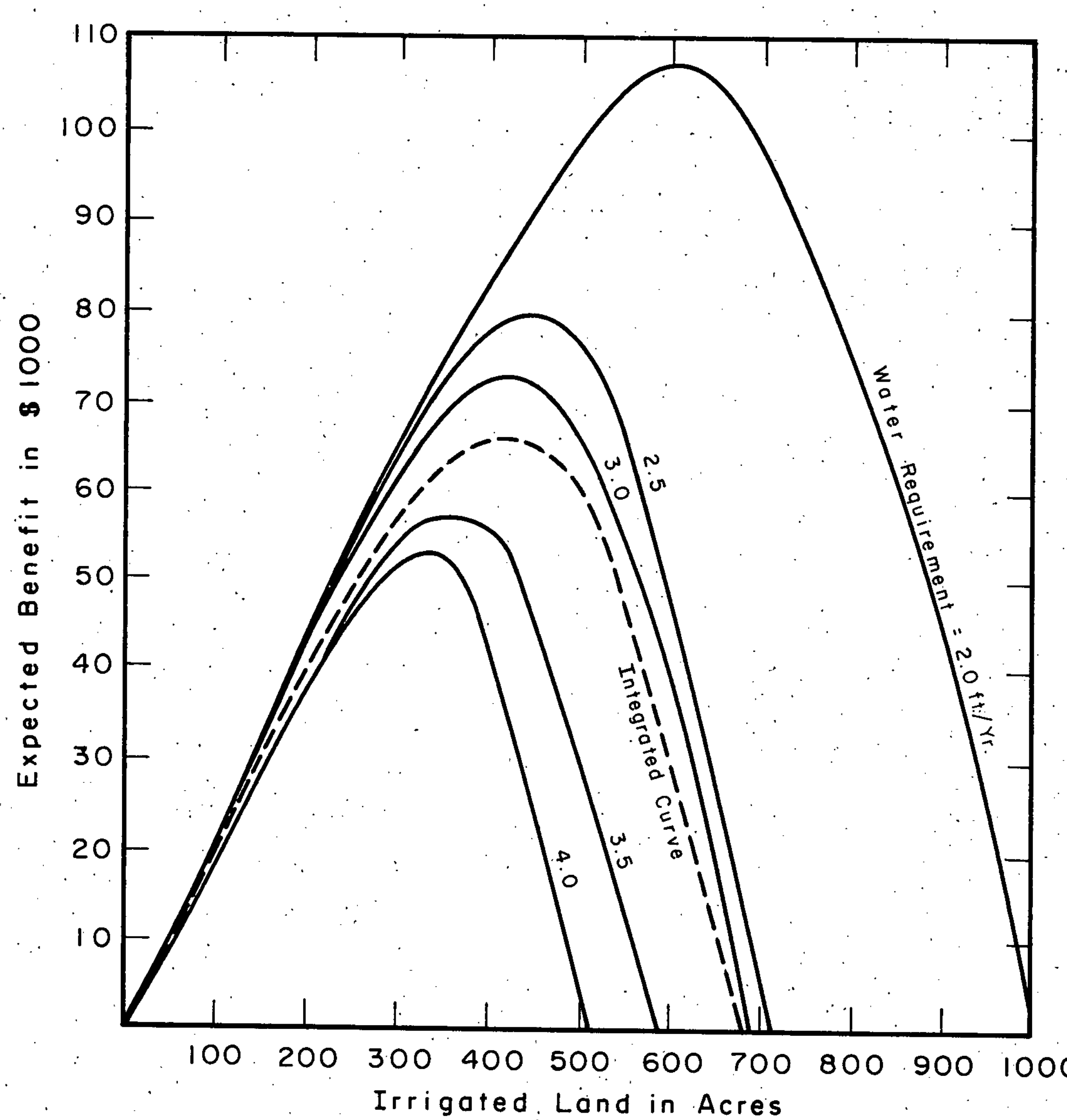


FIG. 4.2 EXPECTED ECONOMIC BENEFIT FROM IRRIGATED AREA.

Chapter 5

DECISION CRITERION BASED ON UTILITY VALUE

5.1 Introduction of Utility Value

In the previous Chapter the benefit accruing from an irrigation system were measured in terms of monetary values. It was assumed, for example, that as long as there was excess revenue over cost, the investment was justified and it was beneficial. This economic consideration hides the underlying principle that benefits and costs are derivatives of social and cultural values of a particular society - in other words, the true worth of benefits and costs varies from one group of people to another. In as much as water resources development is a means of enhancing social welfare, then the social values and attitudes a society holds regarding desirable development must be considered in decision making. The question whether a higher benefit - cost ratio indicates a good project can only be examined in the context of a unique set of social and cultural conditions.

For a farmer, in the western societies, concerned with payment of loans, interest, taxes and depreciation of machinery, a higher benefit - cost ratio is not only desirable, it is a necessity. For a rural villager, in a developing country where farming is labour intensive, the actual cost is a minor consideration compared to his desire to produce more food for the immediate family.

These two points of view serve to emphasize the need to tie the scale of costs and benefits to some form of intrinsic values to the people for which the investment is made. The degree to which these values are incorporated in decision making is a determining factor of the acceptance of the project.

The "true" value of a project varies from one individual to another even in one cultural group. It will also vary with time and circumstances when the project is undertaken. For most situations an investment is considered worthwhile if its yield is above a threshold value. This value is influenced by several factors such as relative wealth of the investor, the timing of the investment, the degree of risk (undesirable consequence) and the attitude of the investor towards risk. It will also depend on how the investor views his role to society - i.e. whether he is more concerned with direct personal gain, or with the value of investment to his society.

These factors are important and it is proper that the measure of benefits and costs should be an assessment that takes such factors into consideration. The complex interelationships and values involved can only be assessed in a subjective manner. Thus it is necessary to relate the desired benefits to another scale that measures the subjective value that a decision maker attaches to the different levels of investment. A "utility value" or intrinsic worth provides such facility (Halter and Dean 1971). The numerical assessment of utility value of each outcome is done via a utility function.

5.2. Expected Utility Decisions

When a decision maker prefers one outcome to another he has, implicitly or explicitly, attached a utility value to each outcome. Usually the utility value is relative to other desirable and undesirable outcomes. The concept of the utility function and of rational choice is based on axioms of coherence (Luce and Raiffa,1957) which can be summarised as follows:-

1. Faced with two alternatives A and B a decision maker either prefers A to B, B to A,or is indifferent.
2. If A is preferred to B and B to C then A is preferred to C.
3. If a decision maker is indifferent between alternatives A and B, they can be substituted for each other.
4. An alternative D which has a set of possible outcomes D_1, D_2 and D_3 with probabilities p_1, p_2 and p_3 respectively is equivalent to the sum of their expected values.

   $$U(D) = p_1U(D_1) + p_2U(D_2) + p_3U(D_3)$$

   $U(D)$,$U(D_1)$ etc are utility values.
5. If two alternatives lead to the same consequence the alternative in which the preferred outcome has the greater probability will be chosen.
6. If A is preferred to B and B to C then there must be some set of odds on A and C such that a decision maker is indifferent between choosing B with certainty and a "lottery" with odds on A and C.

   i.e. $U(B) = pU(A) + (1-p)U(C)$

   where $U(B)$, $U(A)$, $U(C)$ are utility values of A, B and C.

   p = probability of A

However there are two basic problems in the process: how to assess utility value (i.e. to determine utility function), and whose decision value to use in a decision situation - the utility value of one individual does not necessarily represent the utilities of all people who will be affected by a particular outcome. Assessing utility value is a subjective process in which the decision maker is forced to consider explicitly the factors involved in a problem and the consequences of the decision. This indepth analysis of a situation is an important ingredient of the overall decision process.

Once the utilities have been assigned to outcomes in the above manner then maximizing expected utility will be consistent with the decision maker's preference; therefore it is a valid criterion for choosing between competing alternatives (Benjamin and Cornell 1970).

5.3. Derivation of Utility Function for Irrigation Investment

The utility function of a farmer was used to measure the benefits from an irrigation system. The derivation of the utility function was based on the following conditions.

1. Objective:

   To maximize the crop yield and the net economic benefit from the irrigation system.

2. Assumptions:

   (i) The investment is undertaken solely by the farmer.

   (ii) The farmer grows only one crop.

   (iii) The farmer has to make a minimum return necessary to support himself - meet his financial obligations, cost of production, and for the welfare of his family.

Below this minimum return on investment the farmer will begin to face hardships.

The most favourable outcome to the farmer is an annual bumper yield, and the worst consequence is when the yield is zero. Hence assuming that the maximum available acreage is 1000 acres and the maximum yield is 6.0 Tons/acre

Most favourable outcome = 1000 x 6 = 6000 Tons

Maximum revenue = 6000 x 100 = $600,000

Least favourable outcome = 1000 x 0 = 0 Tons

Minimum Revenue = 0 x 100 = $0

While the likelihood of the above outcomes is very very small, they serve to highlight the limiting conditions. Obviously the outcome which yields $600,000 has the highest utility value.

The farmer's expected utility value for any decision will vary between these two basic alternatives depending on the probabilities and utility value of the outcome. Thus it is possible to attach an expected utility value to each branch of the decision tree in Fig. 5.2. The optimum decision choice is the one which yields the maximum expected utility.

5.4 Utility Function

A simplified utility function of the farmer is shown in Fig 5.1. The function is assumed to be a function of net economic benefit. This utility function will vary from one decision maker to another, it will also vary with different circumstances surrounding the decision. The actual shape is not

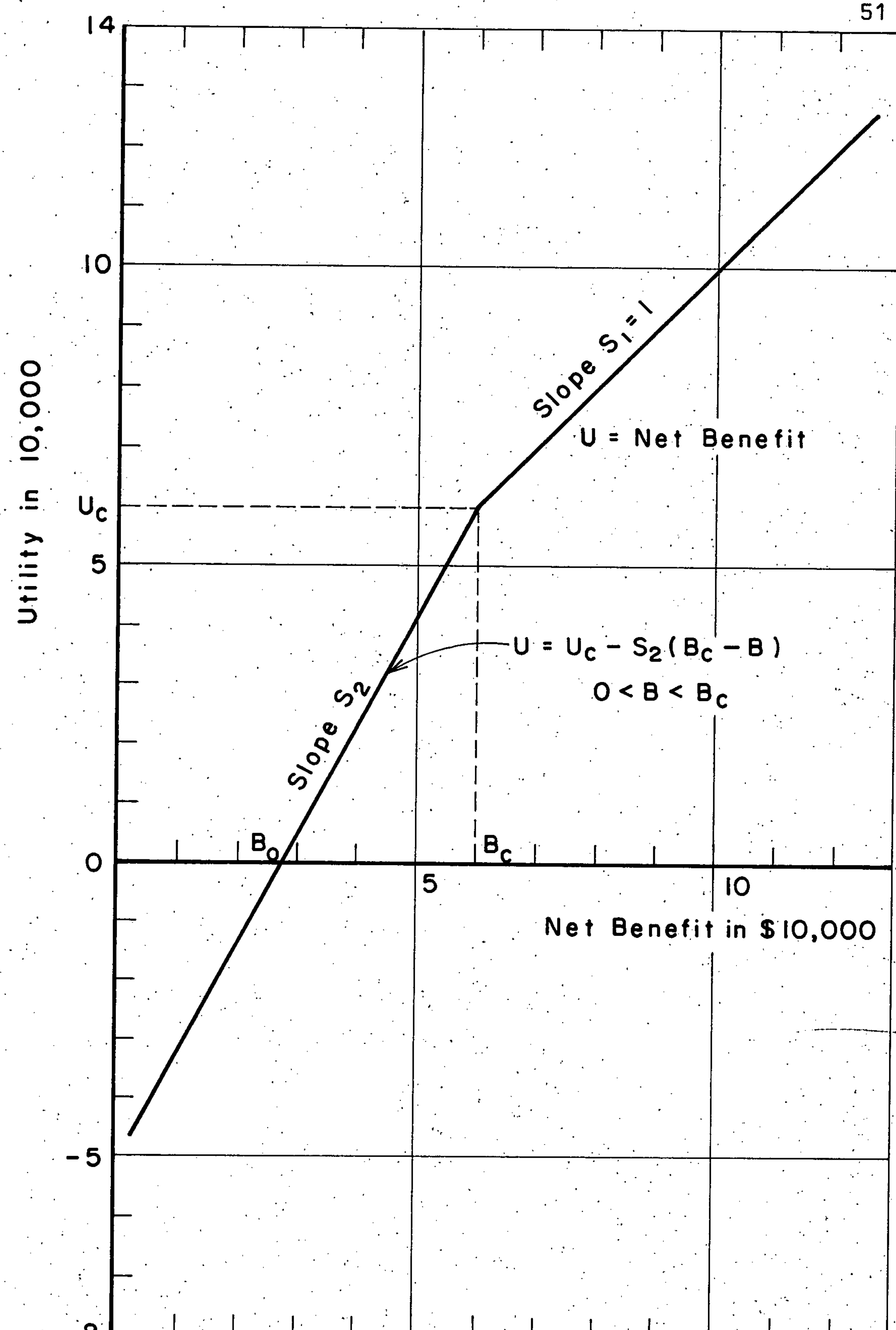


FIG.5.1 HYPOTHETICAL UTILITY FUNCTION OF A FARMER.

critical to the methodology presented here. The general principle depicted in Fig. 5.1 is that there is a minimum utility value U_c below which the utility is diminishing more rapidly than the expected value, and above which the farmer's utility is synonmous with monetary value. The value of B_c corresponds to the minimum return the farmer needs to carry on his operation. The slope S_2 of the utility function represents the farmer's circumstances and attitude towards risk. If the return is B_0 the farmer has to use his reserve of wealth or borrow money inorder to meet his operating expenses.

This utility function can be likened to that of a decision maker responsible for food production in a developing country. An agricutural project should not only produce enough food but it must also be economically viable inorder to pay back loans on capital. Hence the utility value is a function of net economic benefit. The value of U_c represents the utility attached to the minimum comfortable level of food production. Food production levels below B_c cause increasing hardships in the society, and for values below $B = 0$ the situation is hopeless - there is less food and not enough money to sustain loan payments. Hence the utility corresponding to values less than $B = 0$ have very high negative values. It is reasonable to assume that the decision maker's utility function would be improved by some form of charitable guarantee or support in case of bad harvest, for example food relief aid from the United Nations Organisation.

5.5 Computation of Expected Utility

Reference to Fig. 5.2 indicates that there is a utility value associated with each decision branch. These utilities were calculated by associating each net benefit value with a utility via the utility function in Fig 5.1. Net benefits were calculated in the same manner as in Chapter 4. Thus each value of yield and consequent benefit has a unique utility value. The decision procedure then was to calculate the expected utility at each decision alternative.

For flow Q_j with probability $P(Q_j)$, expected utility at Node 2.

$$EU_j = P(Q_j) \sum_{i}^{n} P(Y_i)U(Y_i)$$

Where $U(Y_i)$ = utility associated with each yield obtainable with flow Q_j

$P(Y_i)$ = Probability of yield Y_i

For a given choice of land and reservoir, the expected expected utility

$$EEU = \sum_{j}^{m} P(Q_j) \sum_{i}^{n} P(Y_i)U(Y_i)$$

Taking into account the uncertainty in irrigation water requirement, then

$$EEU = \sum_{k}^{K} P(I_k) \sum_{j}^{m} P(Q_j) \sum_{i}^{n} P(Y_i)U(Y_i)$$

The land and reservoir sizes associated with the maximum expected expected utility are the optimum design values. The working procedure is given in detail in Program B-2 in the Appendix.

5.6. Values of Expected Utility

The maximum values of expected expected utility for different demand levels of water requirement are shown in Table 5.1. The utilities vary with the utility function, hence the computed values are shown for different utility functions. Fig 5.3, 5.4 and 5.5 show this variation graphically. The integrated water demand curve is also superimposed on each graph. Tables 5.2 and 5.3 show a summary of intermediate values of maximum utility both for a total water requirement of 3.0 feet/year and for the condition when uncertainty in water demand is taken into consideration.

The decision maker will usually assign very high disutility values to those options which yield negative benefits. In this analysis it was assumed that for all negative net benefits the utility is - 600,000 whatever the shape of the function. Note that because of the preponderance of high disutility values with steeply sloping utility functions the expected utility values are progressively lower going down Table 5.1. In particular the high disutility value of -600,000 weighed down heavily on the expected values. When the utility function is synonmous with monetary benefit, the expected benefit is the same as in Table 4.1, Chapter 4.

TABLE 5.1

Maximum Expected Utilities

Slope S_2 of Utility Function	Irrigation Water Requirement FT/YR	Optimum Irrigated Area Acres	Optimum Reservoir Size Acre-Feet	Maximum Expected Expected Utility
1	2.0	600	1200	107,400
	2.5	500	1200	78,300
	3.0	400	1200	72,900
	3.5	300	1200	54,900
	4.0	300	1200	51,900
2	2.0	400	900	79,200
	2.5	400	1200	60,900
	3.0	300	900	50,000
	3.5	300	1200	28,500
	4.0	200	900	12,300
3	2.0	400	900	78,400
	2.5	400	1200	59,300
	3.0	300	900	46,200
	3.5	300	1200	22,000
	4.0	300	1200	400
5	2.0	400	900	76,700
	2.5	400	1200	56,100
	3.0	300	900	38,700
	3.5	300	1200	8,800
	4.0	300	1200	-13,700

Table 5.2

INTERMEDIATE VALUES OF MAXIMUM EXPECTED UTILITY, USING DIFFERENT UTILITY FUNCTIONS: IRRIGATION WATER REQUIREMENT = 3.0 feet/year

Irrigated Land	Utility Function Slope $S_2 = 2$		$S_2 = 3$		$S_2 = 5$	
Acres	Optimum Reservoir Acre-feet	Expected Utility *	Optimum Reservoir Acre-feet	Expected Utility *	Optimum Reservoir Acre-feet	Expected Utility *
100	300	-19,500	300	-59,600	300	-138,100
200	600	23,100	600	5,700	600	- 29,200
300	900	49,900	900	46,200	900	38,700
400	1200	42,200	1200	38,900	1200	32,200
500	1500	-22,100	1500	-26,900	1500	- 36,500
600	1500	-120,700	1500	-127,300	1500	-140,400
700	1800	-260,200	1800	-268,000	1800	-283,700
800	2100	-401,500	2100	-405,500	2100	-413,600
900	2100	-490,700	2100	-495,400	2100	-504,700
1000	2400	-557,200	2400	-560,000	2400	-565,900

* Nearest 100

Table 5.3

INTERMEDIATE VALUES OF EXPECTED UTILITY, INTEGRATED IRRIGATION WATER REQUIREMENT.

Irrigated Land	Utility Function with slope $S_2 = 2$		Slope $S_2 = 3$		Slope $S_2 = 5$	
	Optimum Reservoir	Expected Utility *	Optimum Reservoir	Expected Utility *	Optimum Reservoir	Expected Utility *
Acres	Acre-feet		Acre-feet		Acre-feet	
100	300	- 24,000	300	- 65,700	300	-148,900
200	900	15,500	900	- 4,900	900	- 45,600
300	900	37,600	1200	31,500	1200	20,300
400	1200	27,700	1200	22,100	1200	10,700
500	1500	- 35,600	1500	- 42,100	1500	- 55,100
600	1800	-152,200	1800	-157,700	1800	-168,800
700	1800	-268,300	1800	-276,400	1800	-292,800
800	2100	-408,200	2100	-411,900	2100	-419,400
900	2100	-487,300	2100	-490,700	2100	-497,600
1000	2400	-544,900	2400	-547,300	2400	-552,200

* Nearest 100

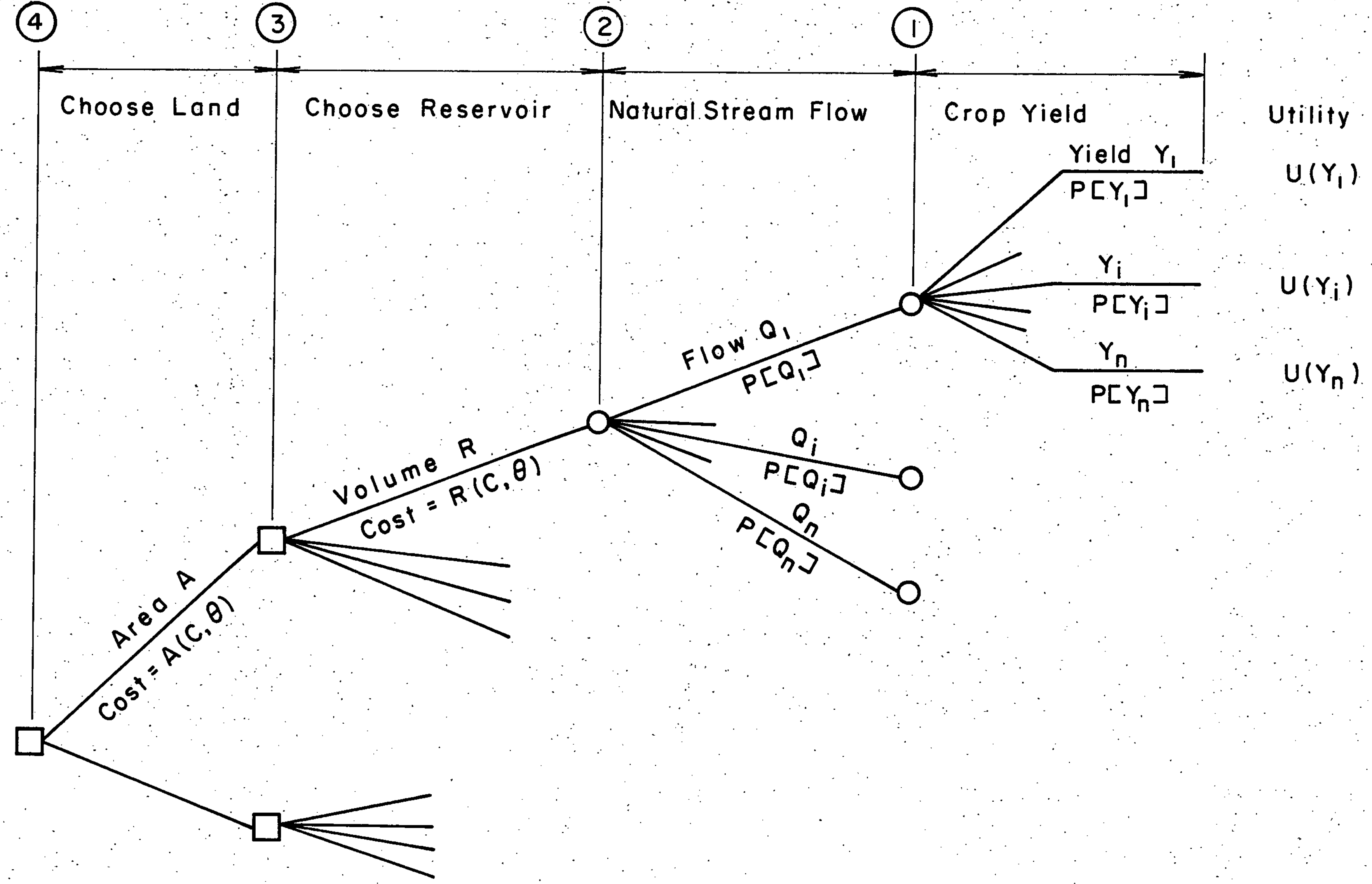


FIG. 5.2 DECISION TREE WITH UTILITY VALUES.

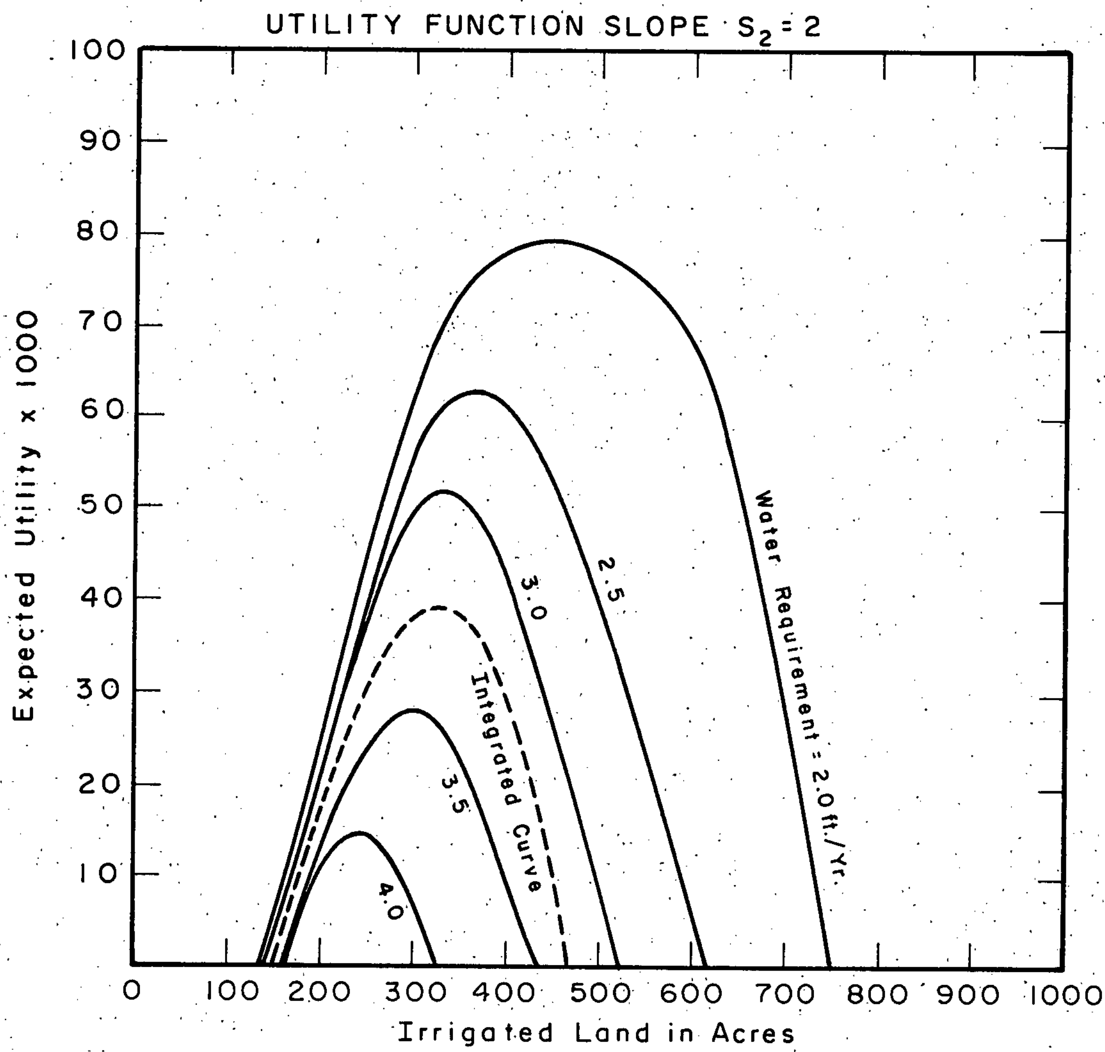


FIG. 5.3 EXPECTED UTILITY AS FUNCTION OF IRRIGATED AREA.

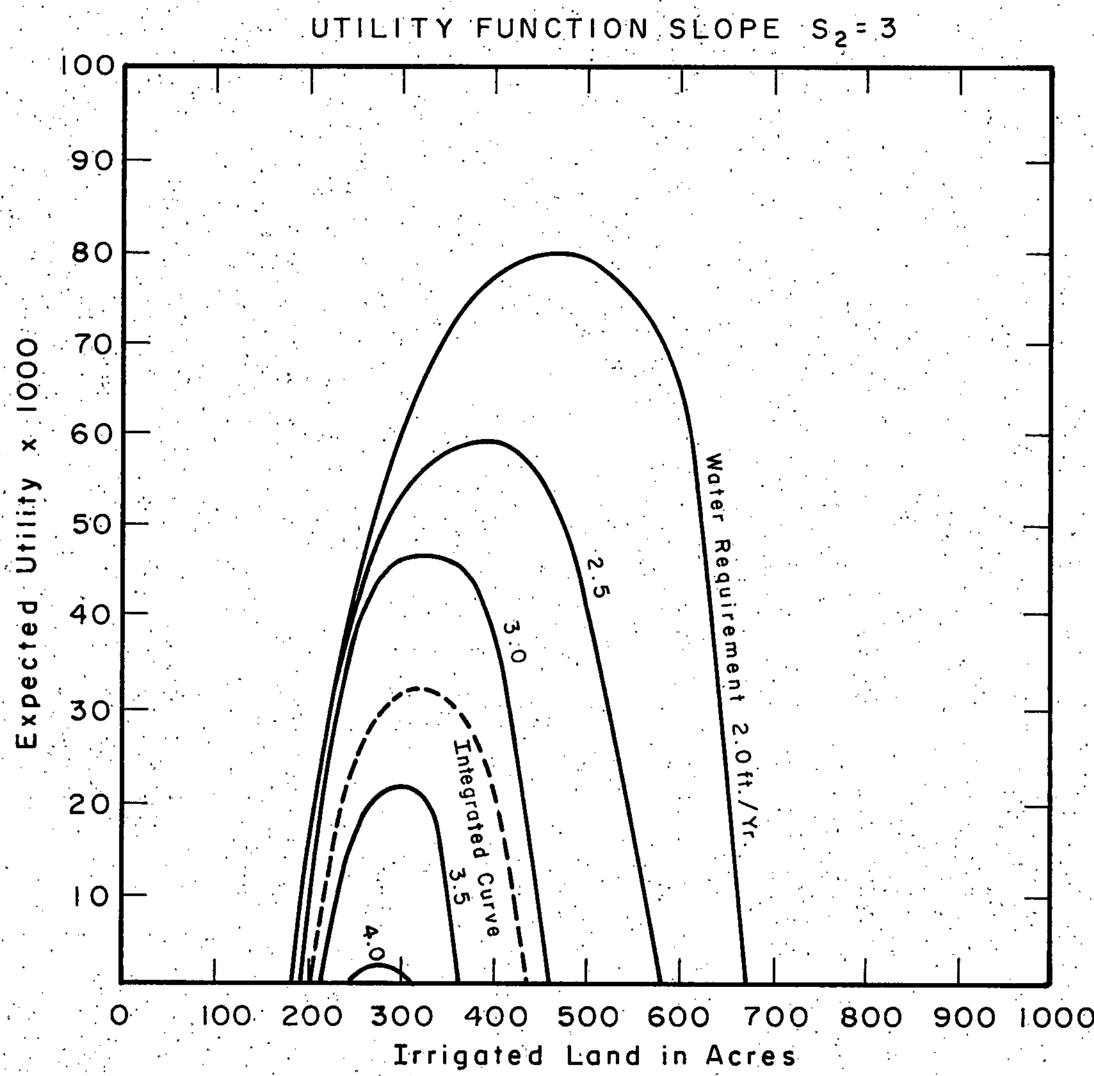


FIG. 5.4 EXPECTED UTILITY AS FUNCTION OF IRRIGATED AREA.

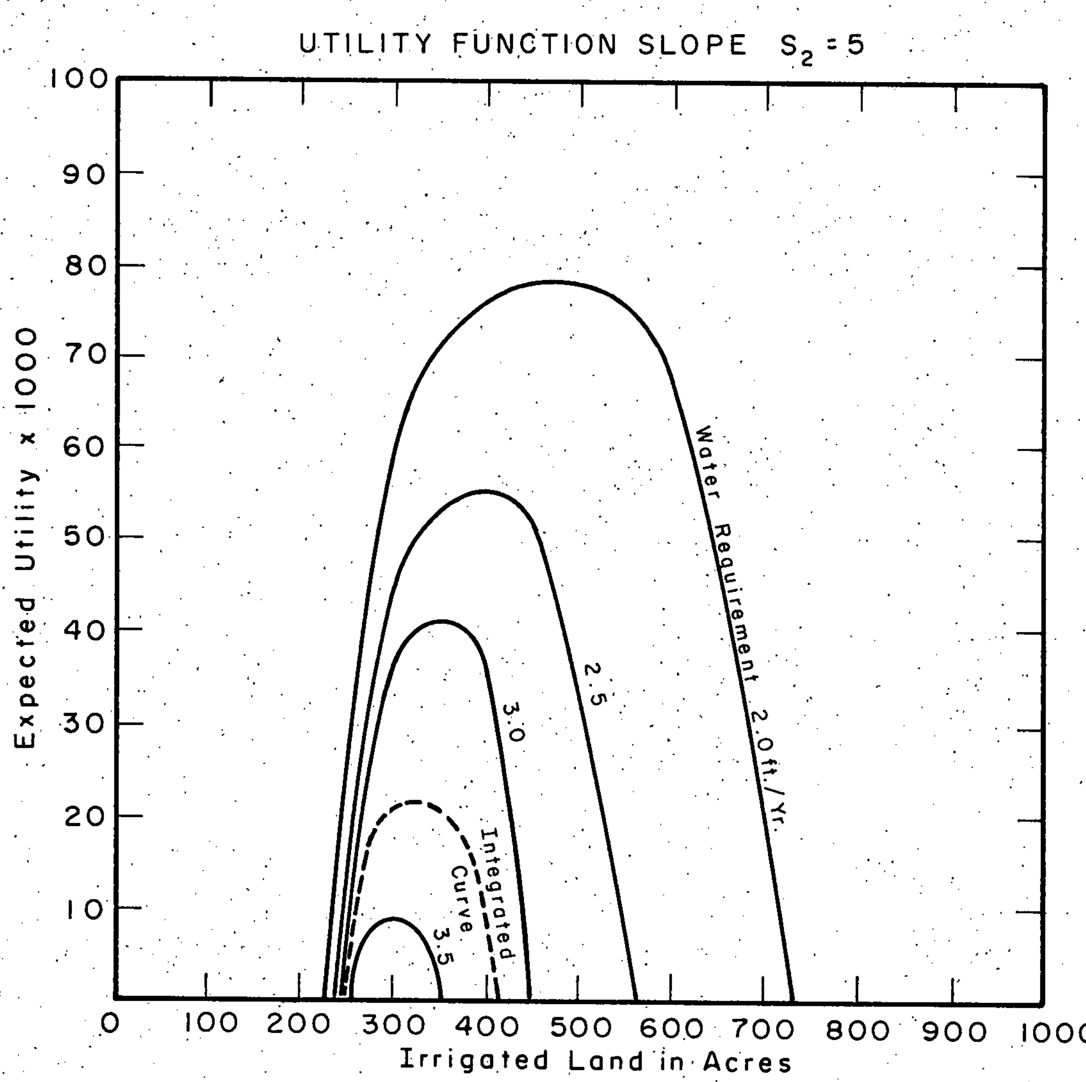


FIG. 5.5 EXPECTED UTILITY AS FUNCTION OF IRRIGATED AREA.

Chapter 6

THE EFFECT OF UNCERTAINTY ON OPTIMAL DESIGN

6.1 Introduction

While the value of observed factual information is undeniable only time can provide the lengths of records required for adequate probability analysis of information necessary for planning and design of water resources systems. Starting from a state of no information, as more data becomes available the greater the certainty we can attach to the gathered information. The more data needed the higher the costs of obtaining the data. At a certain point in time we have to ask ourselves the question: "What is the value of better information?" or "What is the potential benefit for reducing uncertainty?" This means that no data gathering process should be considered if it costs more than the potential savings gained from use of better information.

It is necessary at this point to define what is meant by "Value of Perfect Information." It is defined to be "the difference between (1) the prior expectation $\sum U(\theta_i)\ P(\theta_i)$, in which $U(\theta_i)$ is the utility associated with the best choice of action given that is known with certainty that θ_i is the true state, and (2) the expected utility associated with no experiment" (Benjamin and Cornell, 1970).

There are several methods available to a decision maker for obtaining better information: observation over long periods of time; field experiments, e.g. controlled experimentation in an agricultural station may yield better estimates of yield of a crop; computer modelling, e.g. simulation of natural stream flow. Whichever method is adopted, the resulting data will have some degree of uncertainty associated with it. Hence before a decision can be made, it is necessary to update the prior probability of each piece of information in the light of the newly available information.

6.2. Revision of Probabilities

The process of combining new information with prior probabilities to derive posterior probabilities is done through Bayes' Theorem:

$$P(B_j|A) = \frac{P(A|B_j)P(B_j)}{\sum_{i}^{n} P(A|B_i)P(B_i)}$$

Where B_i, i = 1,2,...........n is a set of mutually exclusive and collectively exhaustive events.

A is a set of events that is also defined over the same sample space as B_i.

This theorem can be applied to yield the conditional probabilities of events given the existence of experiments to estimate those events. The equation can then be written as

$$P(\theta_i|Z_k) = \frac{P(Z_k|\theta_i)P(\theta_i)}{\sum_{i}^{n} P(Z_k|\theta_i)P(\theta_i)}$$

Z is the set of experimental outcomes

θ is the set of states of nature

$P(\theta_i)$ is prior probability of θ_i

$P(Z_k|\theta_i)$ is sample likelihood of Z_k given the state θ_i

$\Sigma P(Z_k|\theta_i)P(\theta_i)$ is a normalizing factor.

A decision analysis in which only the prior probabilities are used is called a prior analysis; whereas a terminal analysis uses the new posterior probability obtained by incorporating new information about the states. The decision analyses done in Chapter 4 and 5 are examples of prior analysis, they used prior estimates and probabilities. A posterior analysis involves making a terminal analysis of each experimental outcome to obtain the utility associated with each outcome. Consequently an experiment is chosen if its expected value of better information is more than the cost of obtaining such information.

In practice it may not be necessary to apply Bayes' theorem rigorously inorder to derive posterior probabilities. Besides, the interelationships between events are usually so complex that it is difficult to derive conditional probabilities. Thus the posterior probabilities are derived directly from new (and also cumulative) data that is available. Once the posterior probability has been derived, the decision analysis proceeds in a similar manner as in prior analysis. The same utility function as in prior analysis can be used because the decision maker's preference is not altered by the probability assignments to each piece of information.

6.3 Application to Problem of Irrigation Development

As more information accumulates and as more knowledge about the system grows the overall uncertainty in the input functions will be reduced. If the cost-capacity relationships were known with certainty, the functions could be represented by the "probable" curves only in Fig. 2.4, 2.5 and 2.6. Similarly if the physical conditions affecting the crop yield could be ascertained the crop yield obtained from use of any amount of water could be known exactly. Longer and more reliable stream flow records would enable the derivation of a more accurate flow distribution.

The effect of uncertainty on the design decision was investigated by analysing the irrigation system with data of varying degrees of uncertainty. The main decision model was run using the data represented in Table 6.1. The uncertainty in the data was "removed" by using only the middle or "probable" curve of each function instead of working within a set of levels bounded by the upper and lower curves. Where stream flow was assumed to be known with certainty, the flow distribution derived in section 3.3.2 was used. The uncertainty in stream flow was accounted for as given in Section 6.3.1 below.

6.3.1 Accounting for Uncertainty in Stream Flow

Statistical model parameters derived from historic records have a considerable degree of uncertainty. According to Benson (1960) the frequency distribution of 40 samples (drawn from a finite population of 1,000 flood discharges) each of a 25 year size of the maximum flood discharges showed a very wide scatter especially for long (more than 200 years) return periods. This scatter indicates the error in estimating population characteristics from a sample. The process uncertainty, statistical uncertainty and fundamental uncertainty are all quite significant

TABLE 6.1

DATA USED IN INVESTIGATING THE EFFECT OF UNCERTAINTY

Set Number	Stream Flow	Irrigation Water Requirement	Costs of Development	Crop Yield	
1	C	C**	C	C	
2	C	C	C	U	
3	C	C	U	C	
4	C	C	U	U	*
5	C	U	U	U	*
6	U	C	U	U	

C = Data assumed to be known with certainty

U = Uncertainty in Data

* Analysis done in Chapter 4 and 5

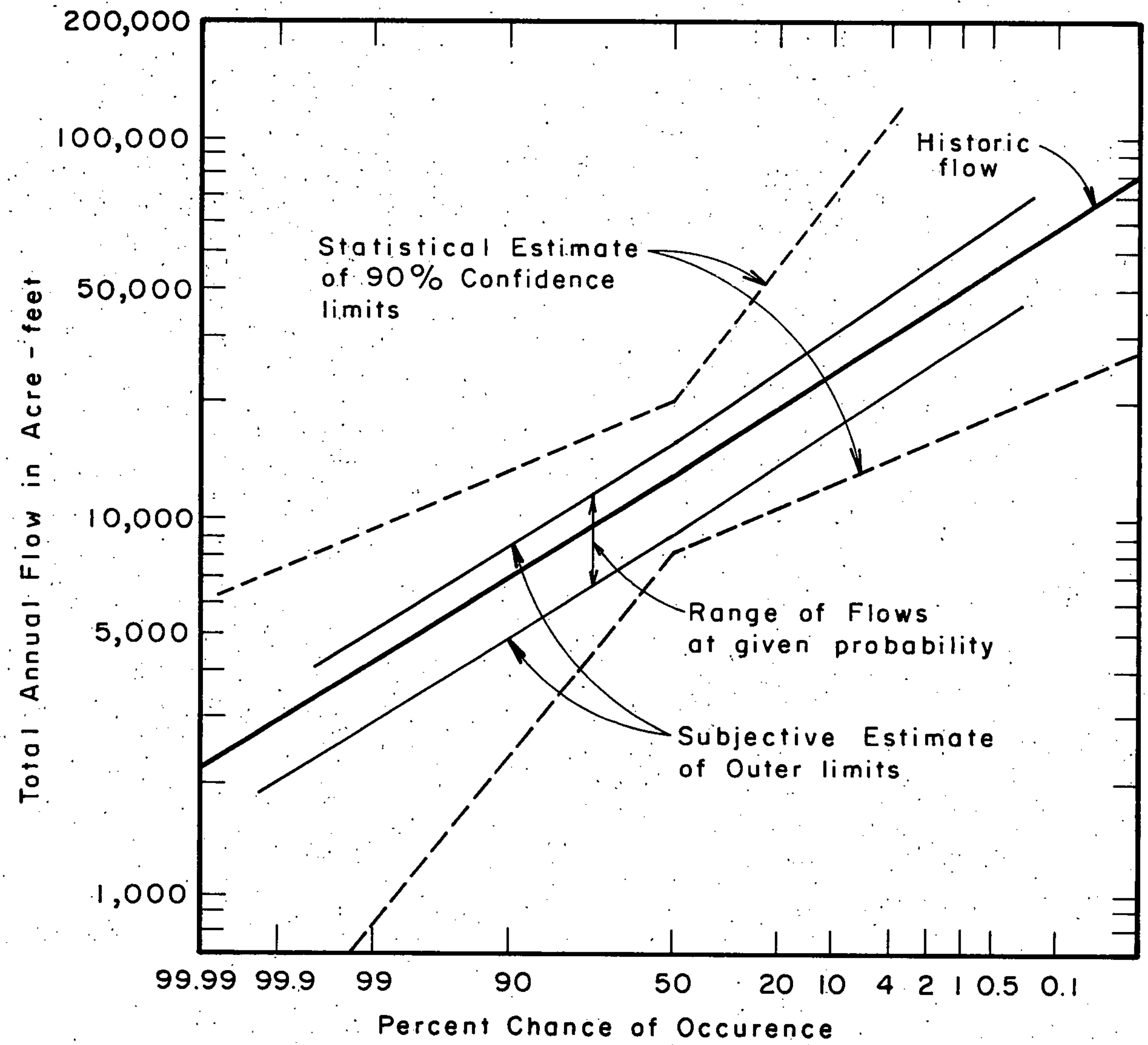
** Irrigation Water Requirement assumed to be 3.0 feet/year.

where short historic records are involved. The uncertainty about the true values can be incorporated by defining confidence limits on the model parameters and on the data, or by a subjective estimate of the limiting values of the data.

A frequency distribution of Powers Creek annual flow was obtained by fitting a Log Pearson Type III distribution to the data. Confidence limits to the distribution were then estimated statistically. A graphical estimation of the statistical procedure (Yevjevich, 1972) was used to put 90% confidence limits on the distribution. The subjective estimate of limits of flow was based on the assumption that the true value of maximum flows were 20 to 30% higher, and the minimum flows were 30% lower than the historic record shows. These figures were derived from analysis of the streamflow records of river basins of comparable size to Powers Creek in the Okanagan Basin. In any practical situation the subjective estimates will be based on the decision maker's knowledge of the area he is working with. Fig. 6.1 shows the frequency distribution of Powers Creek annual flow with statistical and subjective estimate of the uncertainty limits.

Once uncertainty limits have been derived, the uncertainty about the true value of the flow at a given probability can be defined by a probability distribution bounded by the limits of flow in Fig. 6.1. The probability distribution was assumed to be a "skew normal" defined previously. A probability matrix of stream flow, Fig.6.2, was determined in the same manner outlined in previous chapters.

A probability density function can be derived from the



NOTE:
Flow Probability Analysis log Pearson Type III Dist.

FIG. 6.1 FREQUENCY DISTRIBUTION OF POWERS CREEK ANNUAL FLOW; UNCERTAINITY LIMITS FITTED STATISTICALLY AND SUBJECTIVELY.

matrix of Fig 6.2. The probability of flow Q_{ij} is

$$P(Q_{ij}) = \Sigma \Delta p_j \, a_{ij}$$

where Δp_j = probability interval on horizontal axis

a_{ij} = probability that the true value of flow Q_i is Q_{ij}, defined with respect to p_j

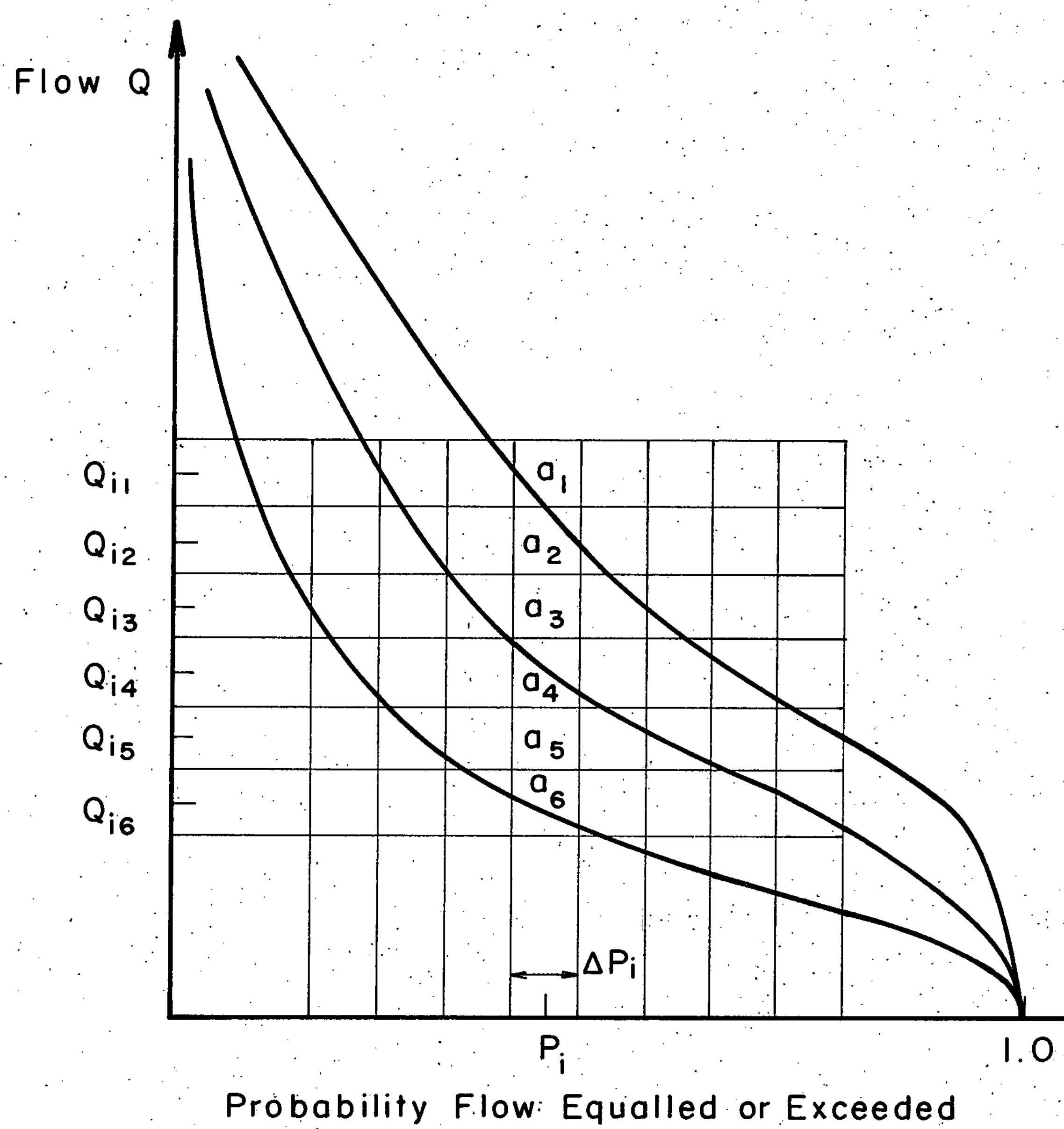
The probability density function of flow derived above was used in the main decision model. Fig 6.3 shows a graphical representation of the cumulative probability function of flow obtained from statistical and subjective estimates of uncertainty limits.

6.4. Results

Fig. 6.4. shows the decision tree for the situation when all input functions are known with certainty. The total cost of the system is now a simple summation of the costs of the individual components of the system; there is only one value of crop yield obtainable with a given flow.

Table 6.2 gives a summary of results obtained from analysing the system with better information; and Fig. 6.5 is a graphical representation of the results for a water requirement of 3.0 feet/year. Fig 6.6 and 6.7 show the values of expected economic benefit and expected utility respectively for varying degrees of uncertainty in the input functions. All the results are summarised in Table 6.3.

The results show a definite increase in expected benefits with better information. The potential benefit of reducing uncertainty can then be compared to the cost incurred in obtaining better information and a decision can be made of the relative importance of each input function.



Q_{i1} .... Q_{i6} are possible flows at given probability P_i

a_1 .... a_6 probabilities that the true value of Q_i is Q_{i1}, Q_{i2} .... Q_{i6}

FIG. 6.2 PROBABILITY MATRIX OF STREAM FLOW.

Table 6.2

MAXIMUM EXPECTED BENEFIT WITH BETTER INFORMATION.

IRRIGATION WATER REQUIREMENT = 3.0 feet/year

Irrigated Land Acres	Expected Economic Benefit $	Expected Utility Slope $S_2 = 2$	Expected Utility Slope $S_2 = 3$	Expected Utility Slope $S_2 = 5$
100	21,300	17,500	- 56,200	-133,700
200	44,400	28,300	12,800	- 18,200
300	65,000	58,300	56,600	53,400
400	76,800	54,700	51,800	45,800
500	70,400	13,400	6,700	- 6,900
600	45,200	- 72,000	- 80,200	- 96,400
700	4,000	-214,400	-241,700	-274,900
800	-36,300	-367,500	-371,600	-379,800
900	-85,500	-457,500	-462,800	-473,400
1000	-131,300	-524,100	-531,000	-544,900

Table 6.3

SUMMARY OF RESULTS

Uncertainty in Data shown	Decision Criterion	Optimum Area	% Change Over Perfect Data	Range of Irrigated Area	% Change Over Perfect Data	Expected Benefit, Dollars, and Utility	% Change Over Perfect Data
		Acres		Acres			
Certainty in all	Money	425		710		77,500	
	Utility; $S_2 = 2$	350		410		60,500	
	$S_2 = 3$	350		335		59,500	
	$S_2 = 5$	340		265		57,000	
Costs	Money	410	-3	710	0	76,000	- 2
	Utility; $S_2 = 2$	340	-3	380	- 7.0	59,500	- 2
	$S_2 = 3$						
	$S_2 = 5$	325	-4	245	- 8	54,000	- 5
Crop Yield	Money	410	-3	690	- 3	73,000	- 6
	Utility; $S_2 = 2$	325	-7	330	-19	50,500	-17
	$S_2 = 3$						
	$S_2 = 5$	325	-4	220	-17	39,000	-32
Costs Crop Yield	Money	410	-3	690	- 3	73,000	- 6
	Utility; $S_2 = 2$	325	-7	320	-22	51,000	-16
	$S_2 = 3$	325	-7	270	-19	46,500	-22
	$S_2 = 5$	320	-6	205	-23	40,500	-29
Costs Crop Yield Irrigation Demand	Money	405	-5	680	- 4	66,000	-15
	Utility; $S_2 = 2$	325	-7	315	-23	39,000	-36
	$S_2 = 3$	325	-7	230	-31	32,000	-46
	$S_2 = 5$	315	-7	165	-38	22,500	-60
Costs Crop Yield Stream Flow	Money	405	-18	625	-12	58,700	-24
	Utility $S_2 = 2$	250	-28	223	-46	25,000	-59

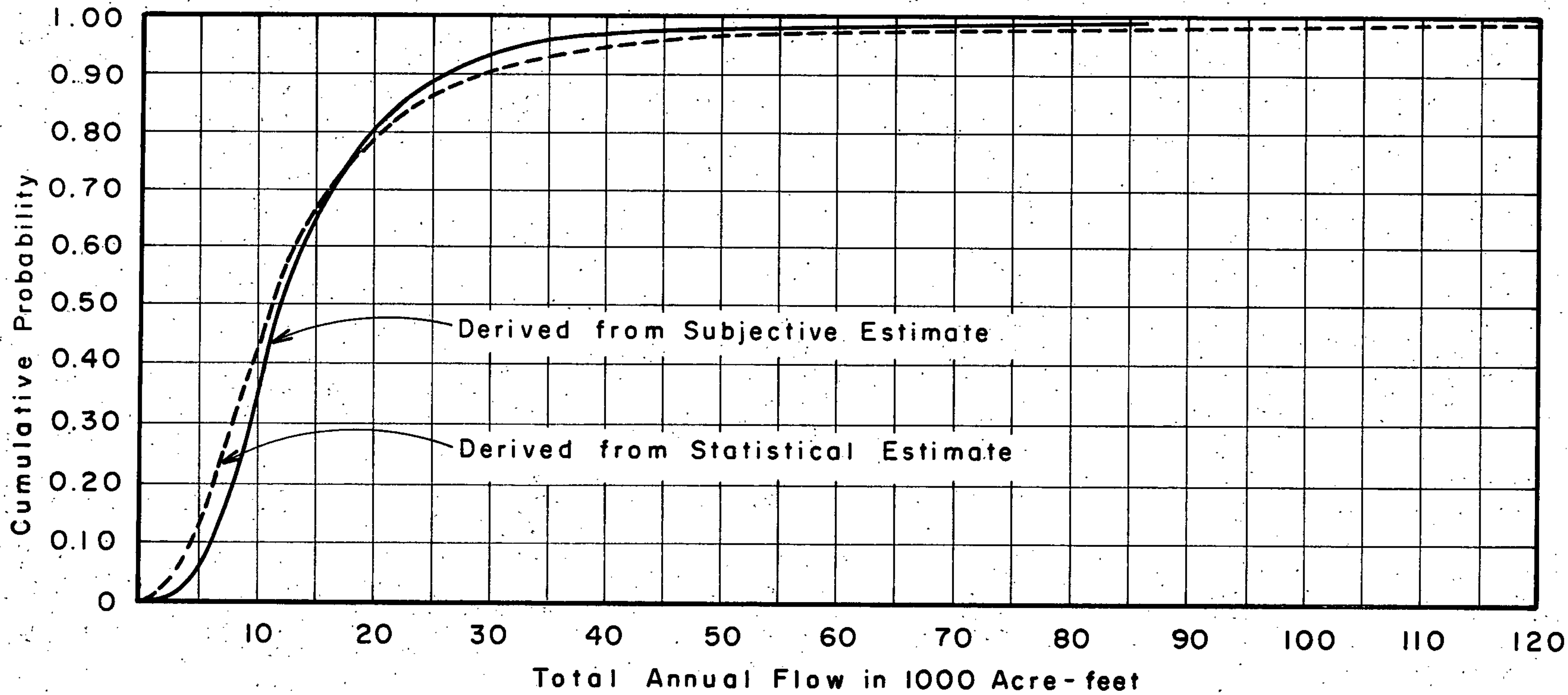


FIG. 6.3 CUMULATIVE PROBABILITY OF ANNUAL FLOWS OF POWERS CREEK.

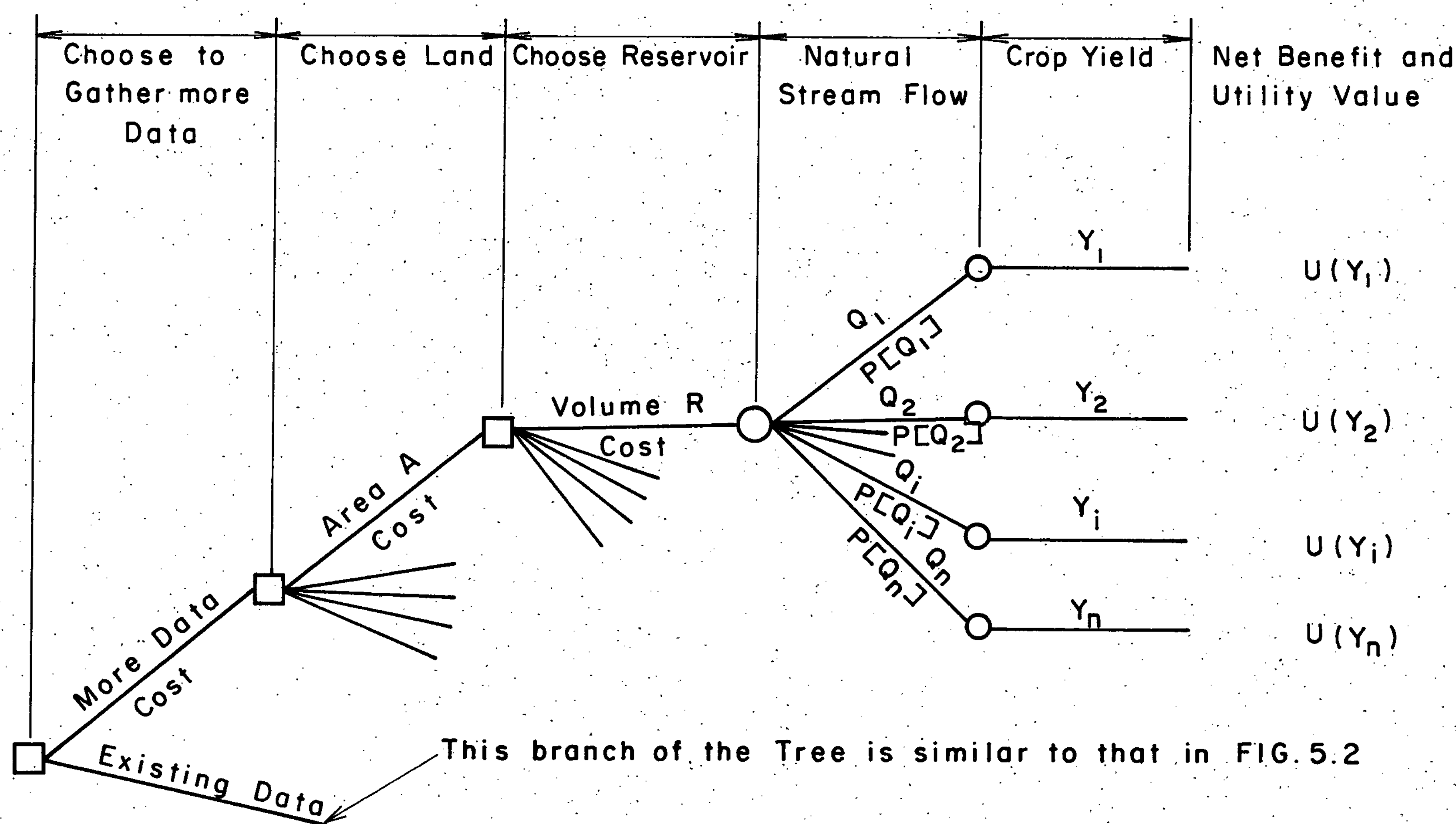


FIG. 6.4 DECISION TREE WITH BETTER INFORMATION.

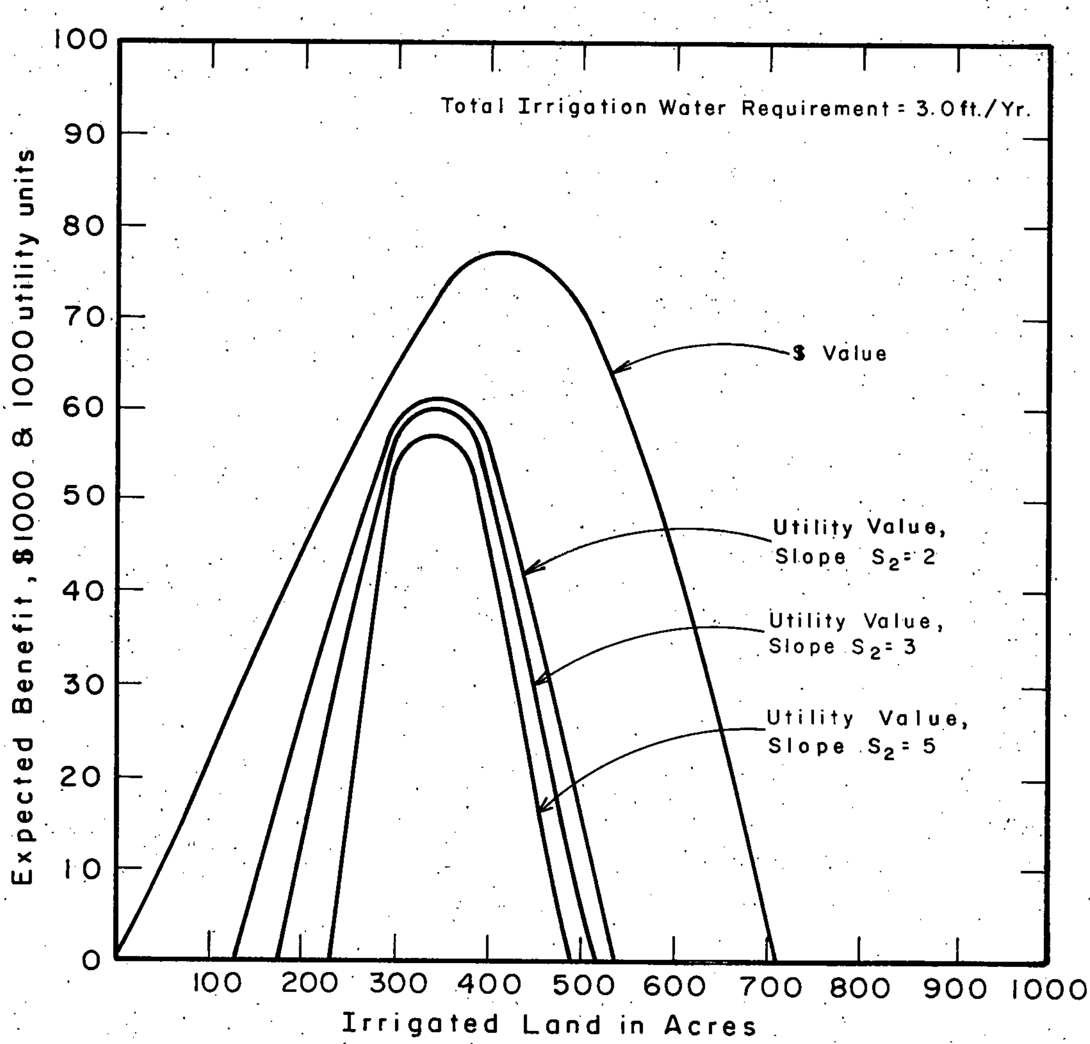


FIG. 6.5 EXPECTED BENEFITS, DOLLARS AND UTILITIES : BETTER INFORMATION.

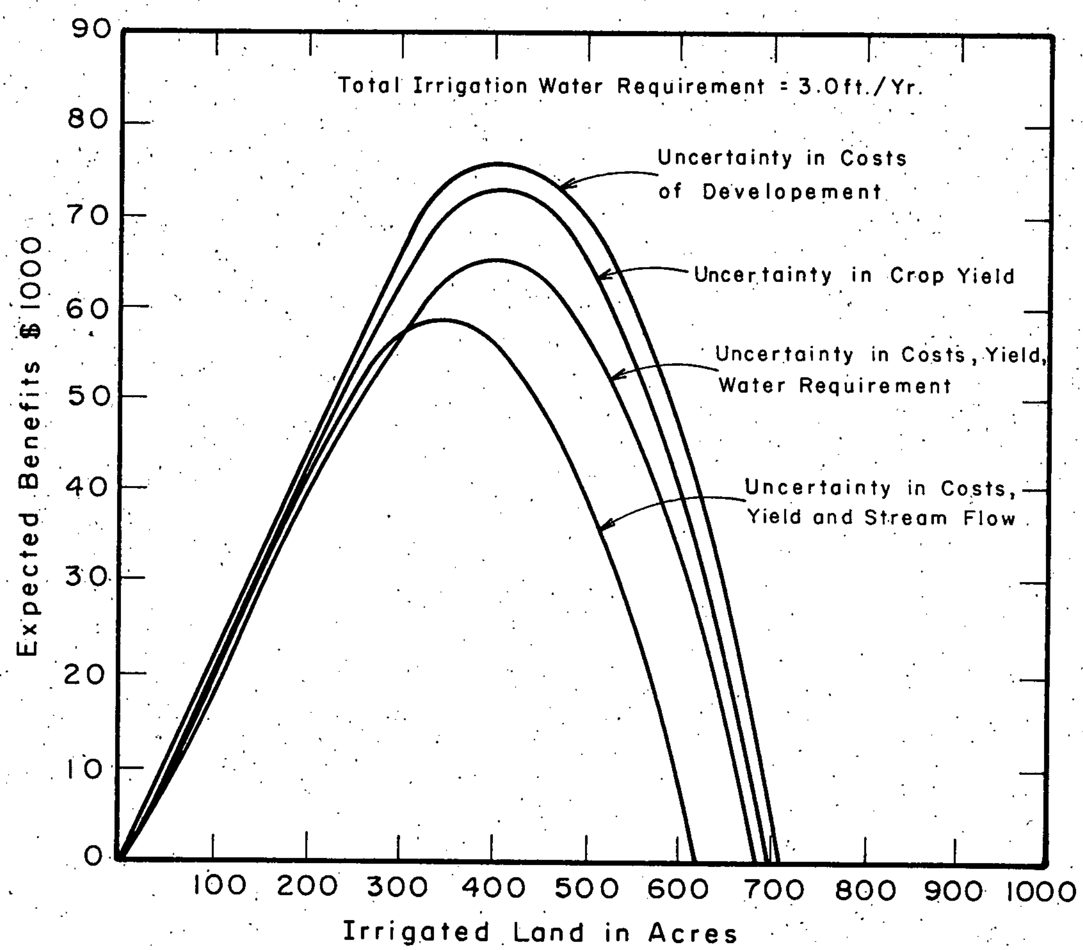


FIG. 6.6 EXPECTED ECONOMIC BENEFIT, VARYING DEGREES OF UNCERTAINTY.

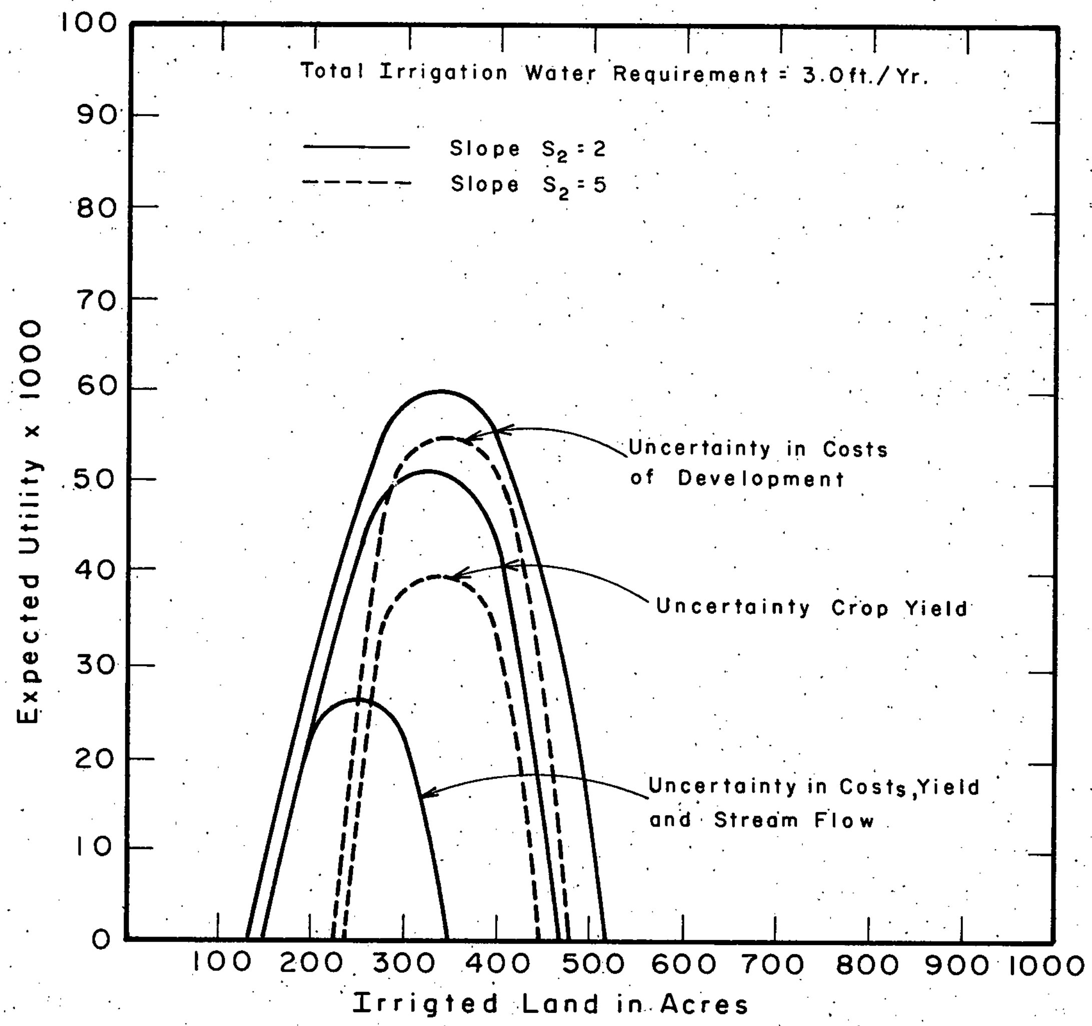


FIG. 6.7 EXPECTED UTILITY, VARYING DEGREES OF UNCERTAINTY.

Chapter 7

DISCUSSION AND CONCLUSIONS

7.1 Discussion of Method of Analysis

The probability model used to present uncertainty in the data is not necessarily unique to the system; other models could have been used and the analysis would have yielded slightly different decisions. Wood and Rodriguez-Iturbe (1975) have shown that different flood frequency models lead to different benefit functions. Therefore the conclusions given below should be viewed in the light of the underlying assumptions and the model used. The effect of model uncertainty on the decision was not investigated in this analysis.

The manner of attaching uncertainty bounds to the data was a subjective process. While it could be criticised on statistical grounds, it is, nonetheless, a practical process; variances are not always symmetrically distributed about the mean, as is the usual assumption in statistical derivation of confidence limits. Besides most data in practice is measured from a lower bound to an upper bound, and determining these limiting values statistically from a short historic record is not always easy. The subjective uncertainty bounds allow the decision maker to pool together all the available information, be it historical or subjective.

Expected values are long term averages of the functions, therefore it can be inferred that the decision chosen is the optimum over a long time provided that the underlying assumptions are valid over the same time horizon. The uncertainty about future conditions is still present. The method of analysis does not indicate the decision situation in the face of short term trends, for example, a three year drought. It is possible to analyse flow sequences which can include such events, but this would have complicated the analysis and was not considered in the present study.

When two functions are combined together in the manner outlined in Chapter 3, some accuracy can be lost if there is a large difference in magnitudes of the discrete intervals of the functions. Therefore judicious choice of the discrete intervals as well as the size of the matrices is essential in order to preserve the desired accuracy and also to save computation time and costs.

7.2 Comparison of Results

All the comparison of results, whether of decision criteria, magnitude of benefits, or optimum design conditions were made using 3.0 feet/year as the irrigation water requirement. With respect to the results, the "optimum" size or capacity is the size of the system which yields the maximum returns - given any particular decision criterion. The "total irrigable area" refers to the area under irrigation which yields positive returns. This is a measure of the total preferred area that can be developed at the prevailing conditions.

For both decision criteria - maximizing expected economic benefit,maximizing the expected utility - the optimum decision was sensitive to the irrigation water requirements. The results of Chapter 4 and 5 showed that low water demands led to the highest expected returns, and high water demands produced the lowest expected returns. For example reducing the water demand by 30% from 3.0 feet/year to 2.0 feet/year, the optimum irrigated area increased by 40% and the expected returns went up by 50% for both decision criteria; increasing the water requirement by 15% to 3.5 feet/year reduced the optimum irrigated area and expected returns by more than 20%.

These figures serve to indicate the importance of accounting for uncertainty in water requirements as well as other inputs to the system. If an error is made in estimating the water requirement, the expected benefits will be altered by quite a high order of magnitude.

7.2.1 Criterion of Maximizing Expected Economic Benefit

The decision choice was not significantly affected by the uncertainty in the input data. The maximum expected benefit and the optimum capacity were obtained from using data that was known with certainty. When uncertainty was introduced into the data, the optimum decision did not change significantly (see Table 6.3) for uncertainty in costs of development, crop yield and water requirement; however the expected benefit was reduced slightly with more uncertainty in the system. When uncertainty in stream flow was considered as well, the optimum capacity was reduced by 18% and the maximum benefit was reduced by 24%.

7.2.2 Criterion of Maximizing Expected Utility Value

The decision choice was more sensitive to uncertainty when utility value was used as a decision criterion. The analysis yielded the maximum expected utility and the largest optimum size when all the input data to the system were known with certainty.

When there was uncertainty in the costs of development but all other data were known with certainty, the optimum capacity and the derived benefits were marginally reduced. This result is probably due to the fact that expected values of costs were used in the analysis, and these were not significantly different from the cost function defined by the "probable" curve on the graphs of unit costs.

Uncertainty in the crop yield alone (all other data known with certainty) had a more significant effect on the decision. The optimum irrigated area was reduced by 5%, the total irrigable area by 18% and the expected utility by 24%, on an average of the utility functions used. Usually the steeper the utility function, the larger the reduction in expected values, i.e. the more conservative the decision maker the more sensitive he is to uncertainty.

Uncertainty in both the costs of development and the crop yield led to almost the same decision as when only uncertainty in crop yield was considered; however the total irrigable area was reduced by 19 to 23% and the expected utility by 16 to 29%. The more conservative the decision maker (i.e. steeper utility function) the higher the reduction.

By considering uncertainty in water requirement as well as in costs of development and crop yield, the reduction in optimum capacity was 7%. However the greatest change was in the maximum expected utility and the total irrigable area - it was reduced by 23 to 38%, while the expected utility value was reduced by 36 to 60% depending on the utility function.

Uncertainty in stream flow had the greatest effect on the decision. The optimal capacity and the maximum expected utility value were reduced significantly when stream flow uncertainty was accounted for. Using a utility function with slope $S_2 = 2$, the optimal capacity was reduced by 28% and the maximum expected utility value was reduced by 59%.

The effect of variation in price of crops was investigated by using two prices which were 10% higher and lower than the standard price. It was found that the optimum size of the system and the expected returns increased with increase in price and decreased with decrease in price.

7.3 Contrast between Expected Monetary Value and Expected Utility

The effect of uncertainty in input data on the decision was more noticeable when utility value was used as a decision criterion. Table 6.3 shows the different decision choices obtained by using the two decision criteria. Whatever level of uncertainty was considered, the criterion of maximizing expected utility value was more sensitive to the level of uncertainty. With increase in uncertainty in the system the optimum area chosen on the basis of maximizing economic benefit was reduced by 3, to 18% while the expected benefit was reduced by 2 to 24%. For the criterion of maximizing expected utility value the reduction in area was 3 to 28%, while the expected utility was reduced by 2 to 60%. At each level of uncertainty which was considered the optimum area chosen on the basis of maximizing expected utility value was at least 20% less than the area chosen on the basis of maximizing economic benefit.

The criterion of maximizing expected economic benefit is not sensitive to the risks involved in each outcome. The process of maximizing expected monetary values does not discriminate between high losses which the decision maker cannot absorb, and high benefits which are obviously desirable and can be easily absorbed by the decision maker. This criterion is often equated to the gambler's ruin situation (Hall and Dracup, 1970). This is clearly noticeable by examining the limiting values of irrigable land. On the basis of economic value the lowest limit of development is zero acreage and the maximum limit is near the available acreage. A more careful observation indicates that marginal benefits from very large areas were very small in comparison to the cost incurred; also smaller developments are just not worthwhile.

Agricultural development is usually considered to be a high risk undertaking because of the uncertainties involved. Consequently decision making in this field must take into account these factors, and also the initial circumstances (or wealth) of the decision maker as well as his attitude towards risk. The utility value has the advantage of being able to take into consideration such relevant factors. A steeper utility function indicates a more conservative attitude towards risk. Poor returns are assigned very high negative utility values, and the minimum irrigable area is far greater than zero; the magnitude increases, the more conservative the decision maker. The total irrigable area decreases with increasing uncertainty in the data, and with more conservative utility functions.

It is natural for people to act in a conservative manner when faced with uncertainty in outcomes. In engineering analysis this conservatism is displayed by use of liberal factors of safety. However the overall effect of uncertainty cannot be adequately estimated by factors of safety inspite of their usefulness and simplicity in use. It is only by a direct comprehensive consideration of uncertainty in a decision that the effect of uncertainty can be effectively evaluated. Knowledge of these effects can then lead to corrective measures. The criterion used in decision making should be such that as to bring out the fundamental attitudes of the decision maker towards the desired development.

The importance of this human attribute of conservatism should not be overlooked in development studies. People usually desire to work within the framework of a system that they are comfortable with. As such they will resist development plans which they intuitively feel are loaded with uncertainty. This is particularly important in developing countries. Long time proven traditional methods of farming are hard to change, people are slow to accept expansive development programs if they consider the costs and the risks to be too high, or if they place low utility value on the products. Failure to recognise this aspect of human nature usually leads to frustration in attempting to persuade developing countries to adopt certain modes of agricultural development. As Franceschi (1972) pointed out, one of the basic problems of development in developing countries is one of changing human attitudes from a passive acceptance of traditional events to an active struggle against challenging circumstances.

While utility value criterion is a better principle, it is not always easy to determine the utility function. For an irrigation project to be readily acceptable it must maximize the utility values of the farmers; however only the utility value of the main decision maker is used in the analysis. The advantage of this type of analysis is that the decision maker has the opportunity to synthesize his utility value from knowledge of the utility value of the people for whom the project is planned.

7.4. CONCLUSIONS.

This thesis has shown the importance of directly accounting for uncertainty in water resources projects. This approach has the advantage of focussing the attention of the decision maker on the important inputs to the system. The analysis has shown that if uncertainty is directly taken into consideration, the analysis would yield lower optimum design conditions than when than when the analysis is carried out without considering uncertainty. The greater the uncertainty the less the optimum conditions obtained. The analysis has shown that hydrological uncertainty is the most important consideration to the system, it tends to reduce the optimum capacity and the expected benefits from the system. The uncertainty in economic inputs and in crop yield will significantly reduce the expected returns from the system. The results of the analysis are summarised in Fig. 7.1. The realisation of the relative importance of each of the inputs helps to define the areas of concentrated activity in any effort to improve the system. In this respect, the comprehensive analysis of uncertainty is far superior to the use of mere factors of safety or factors of ignorance.

The analysis has shown quantitatively the effects of a conservative attitude on decision making under uncertainty. In the face of uncertainty people will tend to make decisions which minimize the undesirable consequences. The nature of such decisions depends on the prevailing circumstances at the time the decision is made - i.e. the degree of risk involved, the likelihood of such risk, and the decision maker's relative wealth or ability to survive undesirable consequences. With respect to irrigation development, the more uncertainty in the system the smaller the desired development. The importance of these attitudes especially in agricultural development explains some of the problems encountered in implementing development schemes in the developing countries.

The degree to which the intrinsic values and attitudes which the decision maker attaches to the project can be incorporated in a decision process depends on the decision criterion used. A utility value, can, to a large extent, reflect the true worth a decision maker attaches to the project. Its measurement is not always easy but through the use of subjective probability theory it is possible to pool together all relevant information into one useful form. Once the utility value has been determined, the decision criterion of maximizing expected utility value will be consistent with the decision maker's preferences. This is the essence of development - to maximize the utility value.

The method used to account for uncertainty in stream flow is a useful analysis which is often ignored. Unless it can be proved that the model parameters estimated from a short historic sample are known with a desirable degree of certainty, the parameters should have uncertainty limits on them to reflect lack of knowledge of the true values. Most historic records are so short that the uncertainty about the true parameters is quite high, therefore they should be analysed with uncertainty limits on them.

The method of analysis given in this thesis is useful in comparing, selecting and ranking different projects necessary to meet a given demand. Each project has its own problems and its own uncertainty. By analysing the projects as given in this thesis, the desirability of each project will be influenced by the magnitude of its output as well as the likelihood of attaining such an output.

Some improvements on the method of analysis are possible. The probability model used to represent uncertainty need not be the "skew normal" distribution alone, other models such as normal distribution could be investigated. What is needed is to determine which is the most suitable model to use in a particular situation. The analysis should also be carried out using stream flow sequences that include the most adverse short term flow conditions, for example using 5-year or 10-year sequences of flows obtained by stream flow generation, provided model parameters have been analysed for uncertainty.

In the end, this method of analysis has one subtle advantage, the designer can know with some degree of certainty that the effect of uncertainty in the system has been accounted for.

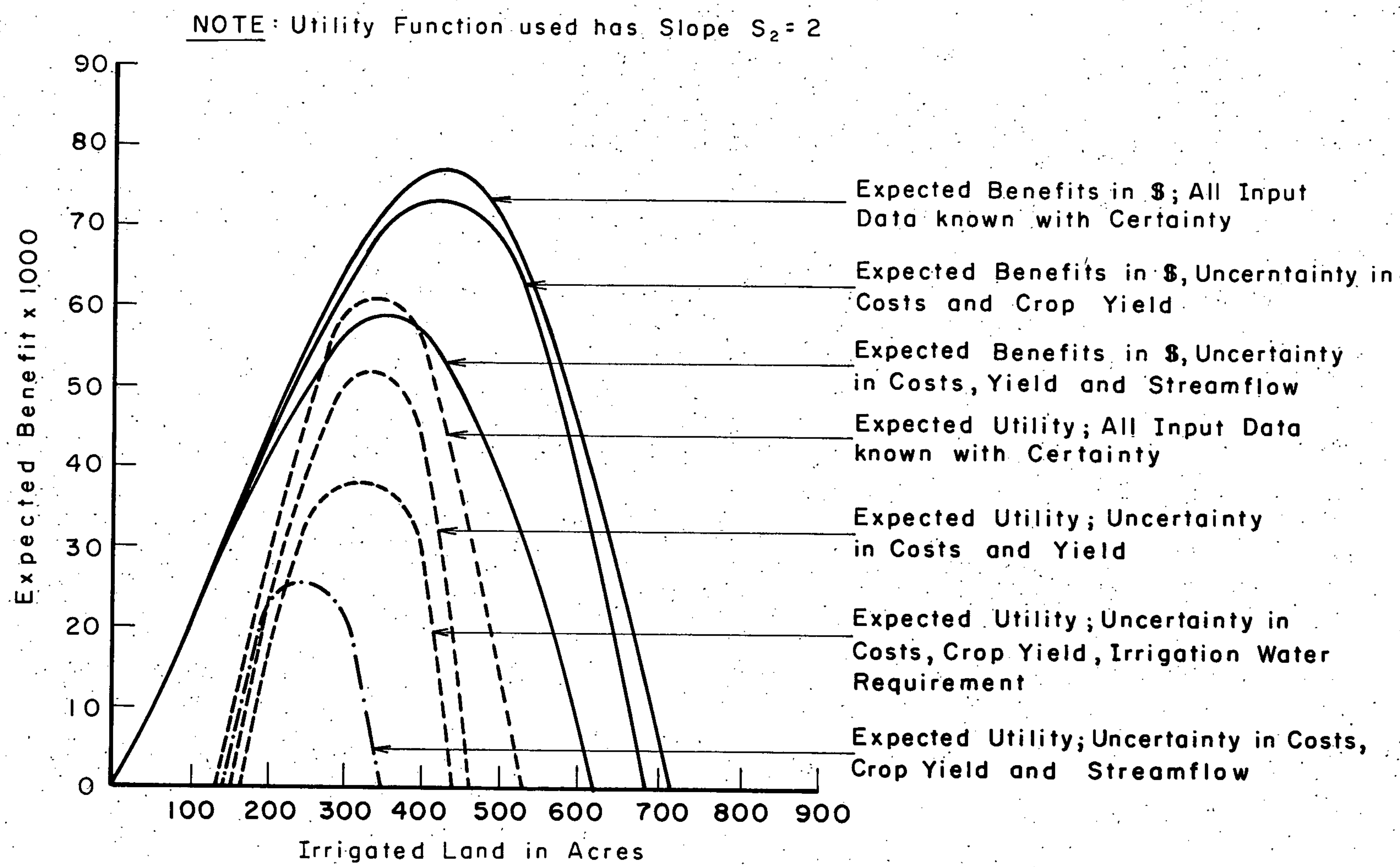


FIG. 7.1 SUMMARY OF BENEFIT FUNCTIONS.

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APPENDIX

There are two basic computer programs necessary in the analysis. The first program, designated as Program A prepares all the data for the main program, called Program B, which has variants B-1, B-2 and B-3.

Program A

It has two complementary functions which together prepare the data and stores it in a Matrix Format ready for use in the main program.

1. For a given function such as Crop yield versus Percentage Available Water, the program approximates the function by a piecewise cubic polynomial. It also supplies interpolated data between the given data points.
   This curve fitting and interpolation is done for upper, mid and lower curves of the relationship, representing the upper, probable and lower estimates.
2. For any value of the abscissa it is assumed that the ordinates between the upper and lower limits follow a "skew normal" distribution. The program then calculates the probabilities of values of ordinates by integrating the assumed probability density function. This leads to values of ordinates each with a probability associated with it.
   The results are stored as a matrix with the first row and first column representing the abscissa and ordinate axes of the function, and the other elements of the matrix the probabilities of values of ordinates at given values of the abscissa.

The basic procedure in the program is summarised in subsequent sections of this Appendix.

Program B

This is the main program used in the decision model, it computes the expected economic benefit and expected utilities. Most of the input functions (cost, yield etc) are supplied in a matrix format. The variants of the program are

Program B-1: Calculates the Expected Benefits using monetary values as a measure of benefits.

Program B-2: Calculates the Benefits in terms of utility value.

Program B-3: This is slightly similar to B-2, here the uncertainty attached to the input function has been eliminated.

These three programs are quite similar, but Program B-2 is more general because it contains subprograms to determine the utilities associated with each outcome. Only Program B-2 will be described in detail.

PROGRAM A
(By Richard Higgins)

TO DETERMINE THE PROBABILITY MATRICES OF INPUT FUNCTIONS

1. Start the Program
2. Read in the Data

   Reservoir Cost versus Size

   Land Development Cost

   Annual Farm Maintenance Cost

   Crop yield versus Percentage Available/Design water Requirement.

The Data for each input function consists of the ordinates and abscissae of the upper, probable and lower estimates of each relationship.

3. Enter Data of Reservoir Cost versus Size.
4. Call a Cubic Spline Program to Approximate the function and to Interpolate extra data points on graphs.
5. Choose One Level of Size e.g. Reservoir Volume
6. Call a Program to Fit a "Skew Normal" probability density function between the Upper and Lower limits of graph
7. Call a Program to Integrate the "Skew Normal" Distribution and to Compute the Probability of chosen levels of unit costs between Upper and Lower limits
8. Repeat Steps 4,5,6 and 7 for other Reservoir Sizes.
9. Enter the Results as Elements of a Matrix; First Row gives the Size of Reservoir, First Column gives the Unit Costs, and All other Elements are Probabilities of Costs at various Reservoir Sizes.
10. Store Matrix of Reservoir Costs
11. Repeat 3 to 10 for other Data
12. Stop.

```
$COMPILE
C
C               PROGRAM  B--2
C
C    THIS PROGRAM CALCULATES THE EXPECTED BENEFITS FROM A
C    SINGLE PURPOSE RESERVOIR BUILT TO SUPPLY IRRIGATION
C    WATER TO AN AGRICULTURAL AREA
C    BENEFITS ARE CALCULATED IN 'UTILITY VALUE'
C    UTILITY IS A FUNCTION OF NET ECONOMIC VALUE
C    SEVERAL VALUES OF IRRIGATION WATER REQUIREMENTS ARE
C    TRIED ---    2.0, 2.5, 3.0, 3.5, 4.0 FEET/YEAR
C      REZCST=THE MATRIX OF RESERVOIR COSTS
C      LNDCST=THE MATRIX OF COSTS OF LAND DEVELOPMENT
C      MAIN=MATRIX OF MAINTENANCE AND OPERATING COST
C      YIELD=MATRIX OF CROP YIELD
C      STFL=MATRIX OF STREAM FLOW
C      FLPRB=MATRIX OF STREAM FLOW PROBABILITY
C      REVN=MATRIX OF TOTAL REVENUE FROM SALE OF CROPS
C      EEY=EXPECTED YIELD OF CROPS
C      BNFT=EXPECTED BENEFITS
C      YCRP=CROP YIELD (TONS/ACRE)
C      YAXIS= PERCENT AVAILABLE WATER OVER DESIGN WATER
C            REQUIREMENT
C
C      NRR=NUMBER OF ROWS OF MATRIX 'REZCST'
C      NCR=NUMBER OF COLUMNS OF MATRIX 'REZCST'
C      LRL=NO. OF ROWS OF 'LNDCST'
C      LCL=NO. OF COLUMNS OF 'LNDCST'
C      MRM=NO. OF ROWS OF 'MAIN'
C      MCM=NO. OF COLUMNS OF 'MAIN'
C      KRY=NO. OF ROWS OF 'YIELD'
C      KCY=NO. OF COLUMNS OF 'YIELD'
C
C      PRICE OF CROPS IS ASSUMED TO BE $100.00 PER TON
C
      REAL REZCST(60,30),LNDCST(60,30),MAIN(60,30),
     1YIELD(60,30)
      DIMENSION WREQD(5),SPB(60),REVN(20),BNFT(20),EXP(20)
      DIMENSION CST(60),FST(60),SCCST(60),SCND(60),SUM(60),
     1SMPB(60)
      DIMENSION AREA(20),XLAKE(20),VALUE(20),XLND(20),
     1RZV(10),RETN(10)
      DIMENSION STFL(60),FLPRB(60),YAXIS(25),YCRP(25)
      DIMENSION XX(60,30),AB(30),XPC(30),EXPNS(60),UNCT(60)
      DIMENSION PRUT(20),TRUE(20)
      INTEGER LRZ(20),HRZ(20),LLD(20),HLD(20)
      INTEGER LYD(30),HYD(30),LMN(30),HMN(30)
      INTEGER SML(30),BIG(30)
      INTEGER COLM,ROW
C
      COMMON XX,SML,BIG
      COMMON EXPNS,UNCT
      COMMON STFL,FLPRB,YAXIS,YCRP
      COMMON/BLK1/SUM,SMPB
      COMMON/BLK2/CST,FST,SCCST,SCND/BLK3/N1,N2,NCOMB,DELTA
      COMMON/BLK4/LRZ,HRZ,LLD,HLD,LMN,HMN
      COMMON/BLK5/EEY,REVN,BNFT,EXP
C
C:::READ IN DIMENSIONS OF MATRICES
      READ 10,NRR,NCR,LRL,LCL,MRM,MCM,KRY,KCY
```

```
10    FORMAT(8I8)
      READ 15,BMAX,BC,YC,SLP
15    FORMAT(4F10.2)
      READ 20,PRC
20    FORMAT(F10.2)
      NCOMB=0
C:::INITIALSE THE MATRICES TO ZERO
      CALL GSET (REZCST,60,30,60,0.0)
      CALL GSET (LNDCST,60,30,60,0.0)
      CALL GSET (MAIN,60,30,60,0.0)
      CALL GSET (YIELD,60,30,60,0.0)
C:::READ FROM FILES AND STORE IN MATRICES SPECIFIED
      DO 40 I=1,NRR
       READ(4,35) (REZCST(I,J),J=1,NCR)
35     FORMAT(F10.3,11F9.3/F10.3,3F9.3)
40    CONTINUE
      DO 50 I=1,LRL
      READ(3,45) (LNDCST(I,J),J=1,LCL)
45     FORMAT(F10.3,11F9.3)
50    CONTINUE
      DO 60 I=1,MRM
      READ(8,55) (MAIN(I,J),J=1,MCM)
55     FORMAT(F10.3,11F9.3)
60    CONTINUE
      DO 65 I=1,KRY
       READ(7,64) (YIELD(I,J),J=1,KCY)
64     FORMAT(F10.3,11F9.3/F10.3,9F9.3)
65    CONTINUE
      DO 2 K=1,40
      READ(2,67) STFL(K),FLPRB(K)
67    FORMAT(F10.2,F15.5)
      FLOW=STFL(K)/10.0
      STFL(K)=FLOW
2     CONTINUE
C
C:::READ IRRIGATION WATER REQUIREMENT
      READ 70,(WREQD(IR),IR=1,5)
70    FORMAT(5F10.2)
      PRINT 71
      PRINT 72
71     FORMAT('1',9X,'CONSUMPTIVE USE',9X,'IRRIGATED LAND
     1',10X,'OPTIMUM RESERVOIR SIZE',8X,'EXPECTED
     1BENEFITS')
72     FORMAT(' ',9X,'FEET PER YEAR',13X,'ACRE ',20X,
     1'ACRE-FEET',21X,'UTILITY')
C
C:::FOR EACH OF THE MATRICES DETERMINE THE ROWS
C    CONTAINING NON-ZERO VALUES
C
      CALL GCOPY(REZCST,XX,NRR,NCR,60,60)
      CALL PREP(XX,NRR,NCR,SML,BIG)
      CALL GCOPY(SML,LRZ,NCR,1,30,20)
      CALL GCOPY(BIG,HRZ,NCR,1,30,20)
      CALL GSET (XX,60,30,60,0.0)
C
      CALL GCOPY(LNDCST,XX,LRL,LCL,60,60)
      CALL PREP(XX,LRL,LCL,SML,BIG)
      CALL GCOPY(SML,LLD,LCL,1,30,20)
      CALL GCOPY(BIG,HLD,LCL,1,30,20)
      CALL GSET (XX,60,30,60,0.0)
```

```
C
      CALL GCOPY(MAIN,XX,MRM,MCM,60,60)
      CALL PREP(XX,MRM,MCM,SML,BIG)
      CALL GCOPY(SML,LMN,MCM,1,30,20)
      CALL GCOPY(BIG,HMN,MCM,1,30,20)
      CALL GSET (XX,60,30,60,0.0)
C
      KKL=KCY-1
      CALL GCOPY(YIELD,XX,KRY,KCY,60,60)
      CALL EXPECT(XX,KRY,KCY,AB,XPC)
      CALL PREP(XX,KRY,KCY,SML,BIG)
      CALL GCOPY(AB,YAXIS,KKL,1,30,25)
      CALL GCOPY(SML,LYD,KCY,1,30,30)
      CALL GCOPY(BIG,HYD,KCY,1,30,30)
      CALL GSET (XX,60,30,60,0.0)
C
C:::CHOOSE ONE VALUE OF IRRIGATION WATER REQUIREMENT
      DO 900 IR=1,5
      PRINT 701
701   FORMAT('-',10X,'NEW CONSUMPTIVE USE')
      DEW=WREQD(IR)
C:::CHOOSE ACREAGE TO BE IRRIGATED
       DO 800 L=3,LCL
        CALL GSET (EXPNS,60,1,60,0.0)
        CALL GSET (UNCT,60,1,60,0.0)
        SOIL=LNDCST(1,L)
        VOLM=LNDCST(1,L)*WREQD(IR)
        MIN=LLD(L)
        LARGE=HLD(L)
        DEL1=(LNDCST((MIN+1),1)-LNDCST(MIN,1))*LNDCST(1,L)
        TEMP=DEL1
C:::DEL1 IS THE COST INTERVAL FOR LAND COSTS
       N1=0
        DO 100 I=MIN,LARGE
         N1=N1+1
         EXPNS(N1)=LNDCST(I,1)*LNDCST(1,L)
         UNCT(N1)=LNDCST(I,L)
         NORM=N1
100     CONTINUE
C
C:::CHOOSE THE RESERVOIR SIZE
        DO 700 N=2,NCR
         CALL GCOPY(EXPNS,CST,NORM,1,60,60)
         CALL GCOPY(UNCT,FST,NORM,1,60,60)
         N1=NORM
         NB=N-1
         DEL1=TEMP
         QA=REZCST(1,N)
         MIN=LRZ(N)
         LARGE=HRZ(N)
         DDD=REZCST((MIN+1),1)-REZCST(MIN,1)
         DEL2=DDD*REZCST(1,N)/3.0
         N2=0
         DO 120 I=MIN,LARGE
          N2=N2+1
          SCCST(N2)=(REZCST(I,1)*REZCST(1,N))/3.0
          SCND(N2)=REZCST(I,N)
120      CONTINUE
C:::CHOOSE COST COMBINATION INTERVAL
         DELTA=(DEL1+DEL2)/2.0
```

```
C
C:::START COST COMBINATIONS
C:::CALL A PROGRAMME TO COMBINE TWO MATRICES '
            CALL CMBINE(CST,FST,SCCST,SCND,N1,N2,DELTA,
     4NCOMB,SUM,SMPB)
            CALL GSET (CST,60,1,60,0.0)
            CALL GSET (FST,60,1,60,0.0)
            CALL GSET (SCCST,60,1,60,0.0)
            CALL GSET (SCND,60,1,60,0.0)
C:::ANNUAL OPERATING COST=10% OF TOTAL CAPITAL COST
            DO 150 J=1,NCOMB
             CST(J)=SUM(J)/10.0
150          FST(J)=SMPB(J)
            CALL GSET (SUM,60,1,60,0.0)
            CALL GSET (SMPB,60,1,60,0.0)
C:::COMBINE ANNUAL OPERATING COST WITH MAINTENANCE AND
C    OPERATING COST OF IRRIGATION SYSTEM
            DEL1=CST(2)-CST(1)
            N1=NCOMB
            MIN=LMN(L)
            LARGE=HMN(L)
            DEL2=(MAIN((MIN+1),1)-MAIN(MIN,1))*MAIN(1,L)
            N2=0
            DO 220 I=MIN,LARGE
             N2=N2+1
            SCCST(N2)=MAIN(I,1)*MAIN(1,L)
             SCND(N2)=MAIN(I,L)
220         CONTINUE
             DELTA=(DEL1+DEL2)/2.0
C
            CALL CMBINE(CST,FST,SCCST,SCND,N1,N2,DELTA,
     4NCOMB,SUM,SMPB)
C:::DETERMINE THE EXPECTED ANNUAL COST
            COST=EXPCST(NCOMB,SUM,SMPB)
C
C::: CALL A SUBROUTINE TO MATCH STREAM INFLOW WITH
C    IRRIGATION WATER REQUIREMENT AND TO CALCULATE THE
C    EXPECTED CROP YIELD AND EXPECTED UTILITY
            CALL WATER(YIELD,STFL,FLPRB,YAXIS,LYD,HYD,SOIL,
     6PRC,VOLM,QA,COST,SLP,YC,BC,EEU)
            TRUE(NB)=EEU
C
            CALL GSET (CST,60,1,60,0.0)
            CALL GSET (FST,60,1,60,0.0)
            CALL GSET (SCCST,60,1,60,0.0)
            CALL GSET (SCND,60,1,60,0.0)
            CALL GSET (SUM,60,1,60,0.0)
            CALL GSET (SMPB,60,1,60,0.0)
700       CONTINUE
C
C:::CALCULATE THE MAXIMUM BENEFIT
          CALL MXBNFT(TRUE,NB,NL,XMAX)
          LM=L-2
          AREA(LM)=LNDCST(1,L)
          XLAKE(LM)=REZCST(1,(NL+1))
          VALUE(LM)=XMAX
        PRINT 750,DEW,AREA(LM),XLAKE(LM),VALUE(LM)
750     FORMAT(' ',10X,F12.2,4X,F12.2,6X,F12.2,8X,F20.2)
800       CONTINUE
C
```

```
C:::CALCULATE THE MAXIMUM OF MAXIMUM BENEFITS FROM EACH
C    QUANTITY OF IRRIGATION WATER USE
C
           CALL MXBNFT(VALUE,LM,NL,XMAX)
           XLND(IR)=AREA(NL)
           RZV(IR)=XLAKE(NL)
           RETN(IR)=XMAX
C
  900   CONTINUE
C
C:::CALCULATE THE MAXIMUM OF ALL THE MAXIMUMS
        CALL MXBNFT(RETN,5,NL,XMAX)
        CULT=XLND(NL)
        DAM=RZV(NL)
        GRT=XMAX
C:::PRINT OUT MAXIMUM VALUES
        DO 905 IR=1,5
         PRINT 903,WREQD(IR),XLND(IR),RZV(IR),RETN(IR)
  903    FORMAT('-',9X,F10.2,13X,F10.2,18X,F10.2,16X,F12.2)
  905   CONTINUE
        PRINT 910,WREQD(NL)
  910   FORMAT('-',10X,'OPTIMUM CONSUMPTIVE USE =',F5.2,4X,
       1'FEET PER YEAR')
        PRINT 920,CULT
  920   FORMAT('-',10X,'OPTIMUM ACREAGE =',F12.2,4X,'ACRES')
        PRINT 930,DAM
  930   FORMAT('-',10X,'OPTIMUM RESERVOIR SIZE =',F12.2,4X
       6,'ACRE-FEET')
        PRINT 940,GRT
  940   FORMAT('-',10X,'EXPECTED BENEFIT =',F15.2,4X,
       6'UTILITY')
        STOP
        END
C

        SUBROUTINE PREP(XX,ROW,COLM,SML,BIG)
        REAL XX(60,30)
        INTEGER SML(30),BIG(30)
        INTEGER COLM,ROW
        SML(1)=0
        BIG(1)=0
        DO 200 J=2,COLM
         DO 100 I=2,ROW
         IF(XX(I,J).GT.0.0) GO TO 120
  100    CONTINUE
  120    SML(J)=I
         LF=I+1
         DO 130 I=LF,ROW
         IF(XX(I,J).EQ.0.0) GO TO 140
  130    CONTINUE
  140    BIG(J)=I-1
  200   CONTINUE
        RETURN
        END
C

        SUBROUTINE EXPECT(XX,NROW,KOL,AB,XPC)
        REAL XX(60,30),AB(30),XPC(30)
        KKL=KOL-1
        DO 100 JJ=1,KKL
```

```
         I=JJ+1
  100   AB(JJ)=XX(1,I)
        KS=1
        DO 400 K=2,KOL
         DO 200 I=2,NROW
          LL=I
          IF(XX(I,K).GT.0.0) GO TO 210
  200    CONTINUE
  210    SUM=0.0
         DO 300 L=LL,NROW
          TEMP=XX(L,K)*XX(L,1)
          SUM=SUM+TEMP
          IF(TEMP.EQ.0.0) GO TO 350
  300    CONTINUE
  350    XPC(KS)=SUM
         KS=KS+1
  400   CONTINUE
        RETURN
        END
C
C    SUBROUTINE TO COMBINE TWO MATRICES

        SUBROUTINE CMBINE(CST,FST,SCCST,SCND,N1,N2,DELTA,
       6NCOMB,SUM,SMPB)
        DIMENSION CST(60),FST(60),SCCST(60),SCND(60)
        DIMENSION SUM(60),SMPB(60)
        STAT=(CST(1)+SCCST(1))-DELTA
        TOP=CST(N1)+SCCST(N2)
        PRL=CST(1)+SCCST(1)
        IF(PRL.EQ.CST(1)) GO TO 100
        GO TO 140
  100   DO 120 K=1,N1
        SUM(K)=CST(K)
  120   SMPB(K)=FST(K)
        NCOMB=N1
        GO TO 500
  140   DO 400 I=1,60
         PROB=0.0
         SMCST=0.0
         PP=0.0
         SUM(I)=STAT+(DELTA*I)
        IF((SUM(I)-TOP).GE.DELTA) GO TO 410
         DO 300 J=1,N1
          DO 200 M=1,N2
           SMCST=CST(J)+SCCST(M)
           PP=FST(J)*SCND(M)
         IF(SMCST.LE.(SUM(I)-DELTA)) GO TO 200
         IF(SMCST.LE.SUM(I)) GO TO 160
         IF(SMCST.GT.SUM(I)) GO TO 300
           PRINT 150
  150      FORMAT('HELP I AM LOST')
  160      PROB=PROB+PP
  200     CONTINUE
  300    CONTINUE
         SMPB(I)=PROB
  400   CONTINUE
  410   NCOMB=I-1
  500   RETURN
        END
C
```

```
C***SUBROUTINE TO MATCH STREAM INFLOW WITH IRRIGATION
C    WATER REQUIREMENTS

           SUBROUTINE WATER(YIELD,STFL,FLPRB,YAXIS,LYD,HYD,
          6SOIL,PRC,VOLM,QA,COST,SLP,YC,BC,EEU)
           REAL YIELD(60,30),STFL(60),FLPRB(60),YAXIS(25)
           INTEGER LYD(30),HYD(30)
           MAX=21
           SS=0.0
           IF(VOLM.EQ.0.0) GO TO 710
           DO 700 J=1,40
            M=21
            IF(STFL(J).GE.QA) GO TO 500
            PECNT=100.0*STFL(J)/VOLM
            GO TO 540
    500     PECNT=100.0*QA/VOLM
    540     IF(PECNT.GT.100.0) GO TO 645
            DO 600 K=1,21
             IF((YAXIS(M)-PECNT).GE.5.0) GO TO 550
             IF((YAXIS(M)-PECNT).LE.2.5) GO TO 650
    550      M=21-K
    600     CONTINUE
    645     M=MAX
    650     KOL=M+1
C$$CALL A SUBROUTINE TO LOOK UP YIELD AND TO COMPUTE
C   NET ECONOMIC BENEFIT AND EXPECTED UTILITY
            CALL PRODCE(YIELD,LYD,HYD,SOIL,PRC,SLP,YC,BC,KOL,
          6COST,EU)
            SS=SS+EU*FLPRB(J)
    700    CONTINUE
    710    EEU=SS
           RETURN
           END
C
C
C    SUBROUTINE TO DETERMINE EXPECTED UTILITY

           SUBROUTINE PRODCE(YIELD,LYD,HYD,SOIL,PRC,SLP,YC,BC
          6KOL,COST,EU)
           REAL YIELD(60,30),BNFT(20),REVN(20),PRUT(20)
           INTEGER LYD(30),HYD(30)
           MIN=LYD(KOL)
           LAGE=HYD(KOL)
           NZ=0
           DO 100 I=MIN,LAGE
            NZ=NZ+1
            REVN(NZ)=YIELD(I,1)*SOIL*PRC
            BNFT(NZ)=REVN(NZ)-COST
    100    CONTINUE
C***CALL A SUBROUTINE TO DETERMINE UTILITIES ASSOCIATED
C    WITH ABOVE ECONOMIC BENEFITS
           CALL UTILIT(BNFT,NZ,SLP,YC,BC,PRUT)
           L=0
           EU=0.0
           DO 200 IN=MIN,LAGE
            L=L+1
            EU=EU+PRUT(L)*YIELD(IN,KOL)
    200    CONTINUE
           RETURN
           END
```

```
      C
      C***SUBROUTINE TO CALCULATE EXPECTED UTILITIES

            SUBROUTINE UTILIT(BNFT,N,SLP,YC,BC,PRUT)
            REAL BNFT(50),PRUT(50)
            DO 600 I=1,N
             IF(BNFT(I).LE.0.0) GO TO 400
             IF(BNFT(I).GT.BC) GO TO 500
             Y=YC-SLP*(BC-BNFT(I))
             GO TO 550
        400  Y=-600000.0
             GO TO 550
        500  Y=BNFT(I)
        550  PRUT(I)=Y
        600 CONTINUE
            RETURN
            END
      C
      C   SUBROUTINE TO CALCULATE THE EXPECTED COST

            FUNCTION EXPCST(NCOMB,SUM,SMPB)
            REAL SUM(60),SMPB(60)
            EXPCST=0.0
            DO 100 I=1,NCOMB
        100 EXPCST=EXPCST+(SUM(I)*SMPB(I))
            RETURN
            END
      C
      C   SUBROUTINE TO CALCULATE MAXIMUM VALUES

            SUBROUTINE MXBNFT(BNFT,NUM,NL,XMAX)
            REAL BNFT(20)
            NL=1
            XMAX=-1.0E 8
            DO 100 I=1,NUM
             IF(BNFT(I).LE.XMAX) GO TO 100
             XMAX=BNFT(I)
            NL=I
        100 CONTINUE
            RETURN
            END
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C
      C

      $DATA
```