THE EFFECT OF UNCERTAINTY IN IRRIGATION DEVELOPMENT

by

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We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
March, 1976

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Date March 15, 1976
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, in spite 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 indication 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 $Q_i$ 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 occasionally 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  

<table>
<thead>
<tr>
<th>YEAR</th>
<th>TOTAL ANNUAL DISCHARGE Acre-Feet</th>
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<tbody>
<tr>
<td>1966</td>
<td>7200</td>
</tr>
<tr>
<td>1967</td>
<td>13200</td>
</tr>
<tr>
<td>1968</td>
<td>17300</td>
</tr>
<tr>
<td>1969</td>
<td>16400</td>
</tr>
<tr>
<td>1970</td>
<td>7450</td>
</tr>
<tr>
<td>1971</td>
<td>20600</td>
</tr>
<tr>
<td>1972</td>
<td>26500</td>
</tr>
<tr>
<td>1973</td>
<td>7900</td>
</tr>
</tbody>
</table>

Mean Annual Flow = 14,570 Acre-feet  
Standard deviation = 6,980 Acre-feet
<table>
<thead>
<tr>
<th>FLOW</th>
<th>YEAR</th>
<th>RANK</th>
<th>RETURN PERIOD</th>
<th>% FLOW EQUALLED OR EXCEEDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acre-feet</td>
<td></td>
<td></td>
<td>( r = \frac{n+1}{m} )</td>
<td></td>
</tr>
<tr>
<td>26,500</td>
<td>1972</td>
<td>1</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>20,600</td>
<td>1971</td>
<td>2</td>
<td>4.5</td>
<td>22</td>
</tr>
<tr>
<td>17,300</td>
<td>1968</td>
<td>3</td>
<td>3.0</td>
<td>33</td>
</tr>
<tr>
<td>16,400</td>
<td>1969</td>
<td>4</td>
<td>2.25</td>
<td>44</td>
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<tr>
<td>13,200</td>
<td>1967</td>
<td>5</td>
<td>1.80</td>
<td>56</td>
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<td>7,900</td>
<td>1973</td>
<td>6</td>
<td>1.50</td>
<td>67</td>
</tr>
<tr>
<td>7,450</td>
<td>1970</td>
<td>7</td>
<td>1.29</td>
<td>78</td>
</tr>
<tr>
<td>7,200</td>
<td>1966</td>
<td>8</td>
<td>1.125</td>
<td>89</td>
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</table>
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

NOTE: Cost includes dam, spillway and intake structures.
Cost includes land clearance and levelling, water distribution and drainage works.

FIG. 2.5 LAND DEVELOPMENT COSTS.
FIG. 2.6 ANNUAL FARM MAINTENANCE COST.
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.
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 $Y = f(x)$.

Values of $Y$ at $X_i$ assumed to follow a skew normal distribution.

Shaded area $a_j$ is proportional to the probability $P_j$ that true value of $Y_i$ is $Y_{ij}$.

Upper Limit
Probable
Lower Limit

$Y_{ij}$

$X_i$

FIG. 3.2 "SKEW NORMAL" DISTRIBUTION.

$AE = 3\sigma_1$
$EB = 3\sigma_2$

Shaded area is proportional to probability of $X_i$. 
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 $Q_l$, 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 $Q_l$ 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 = \( \frac{(83,200 + 58,600 + 36,900)}{3} \)
\[ = 59,567 \text{ acre-feet} \]

Average maximum flow = \( \frac{(966,000 + 719,000 + 844,000)}{3} \)
\[ = 843,000 \text{ acre-feet} \]

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 = \( 0.16 \times 14,570 = 2,330 \) acre-feet

maximum flow = \( 2.22 \times 14,570 = 32,345 \) acre feet

With \( Q_u \) and \( Q_l \) defined, the probabilities of other flow magnitudes were determined by the computer program referred 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**

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

<table>
<thead>
<tr>
<th>YEAR</th>
<th>MAXIMUM INSTANTANEOUS DISCHARGE</th>
<th>MAXIMUM DAILY DISCHARGE</th>
<th>MINIMUM DAILY DISCHARGE</th>
<th>TOTAL DISCHARGE</th>
<th>YEAR</th>
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<tr>
<td>1915</td>
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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 its 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 occurrence 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  
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<th>PROBABILITY</th>
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<tr>
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<tr>
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<th>VALUE</th>
<th>PROBABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>270</td>
<td>r</td>
</tr>
<tr>
<td>280</td>
<td>s</td>
</tr>
<tr>
<td>290</td>
<td>t</td>
</tr>
<tr>
<td>300</td>
<td>u</td>
</tr>
</tbody>
</table>

(b) Combined Value

<table>
<thead>
<tr>
<th>No.</th>
<th>TOTAL VALUE</th>
<th>POSSIBLE PAIRS OF VALUES TO GIVE TOTAL VALUE</th>
<th>PROBABILITY OF TOTAL VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>420</td>
<td>(150,270)</td>
<td>ar</td>
</tr>
<tr>
<td>2</td>
<td>430</td>
<td>(150,280),(160,270)</td>
<td>as + br</td>
</tr>
<tr>
<td>3</td>
<td>440</td>
<td>(150,290),(160,280), (170,270)</td>
<td>at+bs+cr</td>
</tr>
<tr>
<td>n</td>
<td>490</td>
<td>(190,300)</td>
<td>eu</td>
</tr>
</tbody>
</table>
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:

\[ \text{Expected Benefit} = \text{Expected Revenue} - \text{Expected Cost} \]

Where

\[ \text{Expected value} = \sum X_i P(X_i) \text{ for discrete variables} \]

\( X_i \) 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 reservoirs.
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 widely 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:

\[
\text{Expected Benefit} = \text{Expected Revenue} - \text{Expected Cost}
\]

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 calculations 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 = $A_k(c, \theta) + R_n(c, \theta) = TC(c, \theta)$

where $c$ = cost

$\theta$ = probability that true cost is $c$

Expected Cost = $c \times \theta$; $c$ and $\theta$ 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 = $P \times A \times Y_i$ $P$ = price, $A$ = Area

4. Net Benefits corresponding to the yields

$B_1 = P(Y_1) - C$

$B_2 = P(Y_2) - C$

$B_i = P(Y_i) - C$

$B_n = P(Y_n) - C$

5. Expected Benefit at Node 1

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

6. Total Expected Benefit at Node 1

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

7. Expected Expected Benefit given flow $Q_j$

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

8. Total Expected Expected Benefit for the chosen alternative

$EE(B) = \sum_{j=1}^{1} P(Q_j) \sum_{i=1}^{n} P(Y_i)(P(Y_i) - C)$

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
\[
\sum_{k} P(I_k) \sum_{j} P(Q_j) \sum_{i} P(Y_i)(PAY_i - C)
\]
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>
<thead>
<tr>
<th>ANNUAL IRRIGATION REQUIREMENT feet/year</th>
<th>OPTIMUM ACREAGE UNDER IRRIGATION acres</th>
<th>OPTIMUM RESERVOIR SIZE acre-feet</th>
<th>MAXIMUM EXPECTED BENEFITS $</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>600</td>
<td>1200</td>
<td>107,400</td>
</tr>
<tr>
<td>2.5</td>
<td>500</td>
<td>1200</td>
<td>78,300</td>
</tr>
<tr>
<td>3.0</td>
<td>400</td>
<td>1200</td>
<td>72,900</td>
</tr>
<tr>
<td>3.5</td>
<td>300</td>
<td>1200</td>
<td>54,900</td>
</tr>
<tr>
<td>4.0</td>
<td>300</td>
<td>1200</td>
<td>51,900</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Irrigated Land Acres</th>
<th>Optimum Reservoir Size Acre-Feet</th>
<th>Maximum Expected Dollar Benefits *</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>300</td>
<td>20,400</td>
</tr>
<tr>
<td>200</td>
<td>600</td>
<td>42,300</td>
</tr>
<tr>
<td>300</td>
<td>900</td>
<td>62,500</td>
</tr>
<tr>
<td>400</td>
<td>1200</td>
<td>72,900</td>
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<td>1500</td>
<td>64,200</td>
</tr>
<tr>
<td>600</td>
<td>1800</td>
<td>39,600</td>
</tr>
<tr>
<td>700</td>
<td>1800</td>
<td>-5,000</td>
</tr>
<tr>
<td>800</td>
<td>1800</td>
<td>-48,300</td>
</tr>
<tr>
<td>900</td>
<td>2100</td>
<td>-101,800</td>
</tr>
<tr>
<td>1000</td>
<td>1800</td>
<td>-149,300</td>
</tr>
</tbody>
</table>

* Taken to nearest $100
**Table 4.3**

**Uncertainty in Water Requirement**

<table>
<thead>
<tr>
<th>Total Water Requirement (Feet/acre per year)</th>
<th>Probability Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.05</td>
</tr>
<tr>
<td>2.5</td>
<td>0.10</td>
</tr>
<tr>
<td>3.0</td>
<td>0.60</td>
</tr>
<tr>
<td>3.5</td>
<td>0.20</td>
</tr>
<tr>
<td>4.0</td>
<td>0.05</td>
</tr>
</tbody>
</table>
### TABLE 4.4

INTERMEDIATE VALUES OF OPTIMUM CONDITIONS, INTEGRATED IRRIGATION WATER REQUIREMENT.

<table>
<thead>
<tr>
<th>Irrigated Land</th>
<th>Optimum Reservoir Size</th>
<th>Maximum Expected Benefits *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acres</td>
<td>Acre-Feet</td>
<td>$</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>18300</td>
</tr>
<tr>
<td>200</td>
<td>900</td>
<td>39200</td>
</tr>
<tr>
<td>300</td>
<td>1200</td>
<td>57100</td>
</tr>
<tr>
<td>400</td>
<td>1200</td>
<td>65600</td>
</tr>
<tr>
<td>500</td>
<td>1500</td>
<td>57000</td>
</tr>
<tr>
<td>600</td>
<td>1800</td>
<td>32800</td>
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<td>-48300</td>
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<td>900</td>
<td>1800</td>
<td>-100000</td>
</tr>
<tr>
<td>1000</td>
<td>1800</td>
<td>-147200</td>
</tr>
</tbody>
</table>

* Nearest $100
FIG. 4.1 DECISION TREE: UNCERTAINTY IN WATER REQUIREMENT.
FIG. 4.2 EXPECTED ECONOMIC BENEFIT FROM IRRIGATED AREA.
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 interrelationships 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.
   \[ U(D) = p_1 U(D_1) + p_2 U(D_2) + p_3 U(D_3) \]
   \[ U(D), U(D_1), \text{etc are utility values.} \]
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.
   \[ i.e. \quad U(B) = pU(A) + (1-p)U(C) \]
   where $U(B)$, $U(A)$, $U(C)$ are utility values of A, B and C.
   \[ p = \text{probability of A} \]
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 in-depth 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 synonymous 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 agricultural 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 synonymous with monetary benefit, the expected benefit is the same as in Table 4.1, Chapter 4.
### TABLE 5.1

Maximum Expected Utilities

<table>
<thead>
<tr>
<th>Slope $S_2$ of Utility Function</th>
<th>Irrigated Water Requirement FT/yr</th>
<th>Optimum Irrigated Area Acres</th>
<th>Optimum Reservoir Size Acre-Feet</th>
<th>Maximum Expected Expected Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>600</td>
<td>1200</td>
<td>107,400</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>500</td>
<td>1200</td>
<td>78,300</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>400</td>
<td>1200</td>
<td>72,900</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>300</td>
<td>1200</td>
<td>54,900</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
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<td>1200</td>
<td>51,900</td>
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<td>79,200</td>
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<td>2.5</td>
<td>400</td>
<td>1200</td>
<td>60,900</td>
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<td>50,000</td>
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<td>400</td>
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</tr>
<tr>
<td></td>
<td>2.5</td>
<td>400</td>
<td>1200</td>
<td>56,100</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>300</td>
<td>900</td>
<td>38,700</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>300</td>
<td>1200</td>
<td>8,800</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>300</td>
<td>1200</td>
<td>-13,700</td>
</tr>
</tbody>
</table>
Table 5.2

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

<table>
<thead>
<tr>
<th>Irrigated Land</th>
<th>Utility Function Slope</th>
<th>( S_2 = 2 )</th>
<th>( S_2 = 3 )</th>
<th>( S_2 = 5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acres</td>
<td>Optimum Reservoir 300</td>
<td>Acre-feet</td>
<td>Acre-feet</td>
<td>Acre-feet</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>-19,500</td>
<td>300</td>
<td>-59,600</td>
</tr>
<tr>
<td>200</td>
<td>600</td>
<td>23,100</td>
<td>600</td>
<td>5,700</td>
</tr>
<tr>
<td>300</td>
<td>900</td>
<td>49,900</td>
<td>900</td>
<td>46,200</td>
</tr>
<tr>
<td>400</td>
<td>1200</td>
<td>42,200</td>
<td>1200</td>
<td>38,900</td>
</tr>
<tr>
<td>500</td>
<td>1500</td>
<td>-22,100</td>
<td>1500</td>
<td>-26,900</td>
</tr>
<tr>
<td>600</td>
<td>1500</td>
<td>-120,700</td>
<td>1500</td>
<td>-127,300</td>
</tr>
<tr>
<td>700</td>
<td>1800</td>
<td>-260,200</td>
<td>1800</td>
<td>-268,000</td>
</tr>
<tr>
<td>800</td>
<td>2100</td>
<td>-401,500</td>
<td>2100</td>
<td>-405,500</td>
</tr>
<tr>
<td>900</td>
<td>2100</td>
<td>-490,700</td>
<td>2100</td>
<td>-495,400</td>
</tr>
<tr>
<td>1000</td>
<td>2400</td>
<td>-557,200</td>
<td>2400</td>
<td>-560,000</td>
</tr>
</tbody>
</table>

* Nearest 100
Table 5.3

INTERMEDIATE VALUES OF EXPECTED UTILITY, INTEGRATED IRRIGATION WATER REQUIREMENT.

<table>
<thead>
<tr>
<th>Irrigated Land Acres</th>
<th>Utility Function with slope $S_2 = 2$</th>
<th>Slope $S_2 = 3$</th>
<th>Slope $S_2 = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimum Reservoir</td>
<td>Expected Utility</td>
<td>Optimum Reservoir</td>
</tr>
<tr>
<td></td>
<td>Acre-feet</td>
<td>*</td>
<td>Acre-feet</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>-24,000</td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>900</td>
<td>15,500</td>
<td>900</td>
</tr>
<tr>
<td>300</td>
<td>900</td>
<td>37,600</td>
<td>1200</td>
</tr>
<tr>
<td>400</td>
<td>1200</td>
<td>27,700</td>
<td>1200</td>
</tr>
<tr>
<td>500</td>
<td>1500</td>
<td>-35,600</td>
<td>1500</td>
</tr>
<tr>
<td>600</td>
<td>1800</td>
<td>-152,200</td>
<td>1800</td>
</tr>
<tr>
<td>700</td>
<td>1800</td>
<td>-268,300</td>
<td>1800</td>
</tr>
<tr>
<td>800</td>
<td>2100</td>
<td>-408,200</td>
<td>2100</td>
</tr>
<tr>
<td>900</td>
<td>2100</td>
<td>-487,300</td>
<td>2100</td>
</tr>
<tr>
<td>1000</td>
<td>2400</td>
<td>-544,900</td>
<td>2400</td>
</tr>
</tbody>
</table>

* Nearest 100
Choose Land  Choose Reservoir  Natural Stream Flow  Crop Yield

Utility

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 $\Sigma U(\theta_i) P(\theta_i)$, in which $U(\theta_i)$ is the utility associated with the best choice of action given that is known with certainty that $\theta_i$ 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:

\[
P(B_j|A) = \frac{P(A|B_j)P(B_j)}{\sum_{i} P(A|B_i)P(B_i)}
\]

Where \( B_i, i = 1,2,\ldots, n \) 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

\[
P(\theta_i|Z_k) = \frac{P(Z_k|\theta_i)P(\theta_i)}{\sum_{i} P(Z_k|\theta_i)P(\theta_i)}
\]

\( Z \) is the set of experimental outcomes
\( \theta \) is the set of states of nature
\( P(\theta_i) \) is prior probability of \( \theta_i \)
\[ P(Z_k | \theta_i) \] is sample likelihood of \( Z_k \) given the state \( \theta_i \).
\[ \Sigma P(Z_k | \theta_i)P(\theta_i) \] 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 in order to derive posterior probabilities. Besides, the interrelationships 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

<table>
<thead>
<tr>
<th>Set Number</th>
<th>Stream Flow</th>
<th>Irrigation Water Requirement</th>
<th>Costs of Development</th>
<th>Crop Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>C**</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>C</td>
<td>U</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>C</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>6</td>
<td>U</td>
<td>C</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

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
FIG. 6.1 FREQUENCY DISTRIBUTION OF POWERS CREEK ANNUAL FLOW; UNCERTAINTY 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

- $\Delta P_j$ = 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.
Probability Flow Equalled or Exceeded

$Q_{i1} \cdots Q_{i6}$ are possible flows at given probability $P_i$

$\alpha_1 \cdots \alpha_6$ probabilities that the true value of $Q_i$ is $Q_{i1}, Q_{i2} \cdots Q_{i6}$

FIG. 6.2 PROBABILITY MATRIX OF STREAM FLOW.
Table 6.2

MAXIMUM EXPECTED BENEFIT WITH BETTER INFORMATION.
IRRIGATION WATER REQUIREMENT = 3.0 feet/year

<table>
<thead>
<tr>
<th>Irrigated Land Acres</th>
<th>Expected Economic Benefit $</th>
<th>Expected Utility Slope $S_2 = 2$</th>
<th>Expected Utility Slope $S_2 = 3$</th>
<th>Expected Utility Slope $S_2 = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>21,300</td>
<td>17,500</td>
<td>-56,200</td>
<td>-133,700</td>
</tr>
<tr>
<td>200</td>
<td>44,400</td>
<td>28,300</td>
<td>12,800</td>
<td>- 18,200</td>
</tr>
<tr>
<td>300</td>
<td>65,000</td>
<td>58,300</td>
<td>56,600</td>
<td>53,400</td>
</tr>
<tr>
<td>400</td>
<td>76,800</td>
<td>54,700</td>
<td>51,800</td>
<td>45,800</td>
</tr>
<tr>
<td>500</td>
<td>70,400</td>
<td>13,400</td>
<td>6,700</td>
<td>- 6,900</td>
</tr>
<tr>
<td>600</td>
<td>45,200</td>
<td>-72,000</td>
<td>-80,200</td>
<td>- 96,400</td>
</tr>
<tr>
<td>700</td>
<td>4,000</td>
<td>-214,400</td>
<td>-241,700</td>
<td>-274,900</td>
</tr>
<tr>
<td>800</td>
<td>-36,300</td>
<td>-367,500</td>
<td>-371,600</td>
<td>-379,800</td>
</tr>
<tr>
<td>900</td>
<td>-85,500</td>
<td>-457,500</td>
<td>-462,800</td>
<td>-473,400</td>
</tr>
<tr>
<td>1000</td>
<td>-131,300</td>
<td>-524,100</td>
<td>-531,000</td>
<td>-544,900</td>
</tr>
</tbody>
</table>
Table 6.3
SUMMARY OF RESULTS

<table>
<thead>
<tr>
<th>Uncertainty in Data shown</th>
<th>Decision Criterion</th>
<th>Optimum Area</th>
<th>% Change Over Perfect Data</th>
<th>Range of Irrigated Area</th>
<th>% Change Over Perfect Data</th>
<th>Expected Benefit, Dollars, and Utility</th>
<th>% Change Over Perfect Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Acres</td>
<td>Acres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certainty in all Money</td>
<td></td>
<td>425</td>
<td>710</td>
<td>77,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Utility; $S_2 = 2$</td>
<td>350</td>
<td>410</td>
<td>60,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>350</td>
<td>335</td>
<td>59,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>340</td>
<td>265</td>
<td>57,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs Money</td>
<td></td>
<td>410</td>
<td>-3</td>
<td>710</td>
<td>0</td>
<td>76,000</td>
<td>- 2</td>
</tr>
<tr>
<td></td>
<td>Utility; $S_2 = 2$</td>
<td>340</td>
<td>-3</td>
<td>380</td>
<td>-7.0</td>
<td>59,500</td>
<td>- 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325</td>
<td>-4</td>
<td>245</td>
<td>-8</td>
<td>54,000</td>
<td>- 5</td>
</tr>
<tr>
<td>Crop Money</td>
<td></td>
<td>410</td>
<td>-3</td>
<td>690</td>
<td>-3</td>
<td>73,000</td>
<td>- 6</td>
</tr>
<tr>
<td></td>
<td>Utility; $S_2 = 2$</td>
<td>325</td>
<td>-7</td>
<td>330</td>
<td>-19</td>
<td>50,500</td>
<td>-17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325</td>
<td>-4</td>
<td>220</td>
<td>-17</td>
<td>39,000</td>
<td>-32</td>
</tr>
<tr>
<td>Costs Crop Yield Money</td>
<td></td>
<td>410</td>
<td>-3</td>
<td>690</td>
<td>-3</td>
<td>73,000</td>
<td>- 6</td>
</tr>
<tr>
<td></td>
<td>Utility; $S_2 = 2$</td>
<td>325</td>
<td>-7</td>
<td>320</td>
<td>-22</td>
<td>51,000</td>
<td>-16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325</td>
<td>-7</td>
<td>270</td>
<td>-19</td>
<td>46,500</td>
<td>-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>320</td>
<td>-6</td>
<td>205</td>
<td>-23</td>
<td>40,500</td>
<td>-29</td>
</tr>
<tr>
<td>Costs Crop Yield Money</td>
<td></td>
<td>405</td>
<td>-5</td>
<td>680</td>
<td>-4</td>
<td>66,000</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>Utility; $S_2 = 2$</td>
<td>325</td>
<td>-7</td>
<td>315</td>
<td>-23</td>
<td>39,000</td>
<td>-36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325</td>
<td>-7</td>
<td>230</td>
<td>-31</td>
<td>32,000</td>
<td>-46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>315</td>
<td>-7</td>
<td>165</td>
<td>-38</td>
<td>22,500</td>
<td>-60</td>
</tr>
<tr>
<td>Costs Crop Yield Money</td>
<td></td>
<td>405</td>
<td>-18</td>
<td>625</td>
<td>-12</td>
<td>58,700</td>
<td>-24</td>
</tr>
<tr>
<td>Stream Flow Utility $S_2 = 2$</td>
<td></td>
<td>250</td>
<td>-28</td>
<td>223</td>
<td>-46</td>
<td>25,000</td>
<td>-59</td>
</tr>
</tbody>
</table>
FIG. 6.3 CUMULATIVE PROBABILITY OF ANNUAL FLOWS OF POWERS CREEK.
Choose to Gather more Data
Choose Land
Choose Reservoir
Natural Stream Flow
Crop Yield
Net Benefit and Utility Value

Volume R
Cost

Area A
Cost

More Data
Existing Data

This branch of the Tree is similar to that in FIG. 5.2

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.

Total Irrigation Water Requirement = 3.0 ft./Yr.

- Slope $S_2 = 2$
- Slope $S_2 = 5$

Uncertainty in Costs of Development
Uncertainty Crop Yield
Uncertainty in Costs, Yield, and Stream Flow
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 16% 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 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.
NOTE: Utility Function used has Slope \( S_2 = 2 \)

Expected Benefits in $; All Input Data known with Certainty

Expected Benefits in $, Uncertainty in Costs and Crop Yield

Expected Benefits in $, Uncertainty in Costs, Yield and Streamflow

Expected Utility; All Input Data known with Certainty

Expected Utility; Uncertainty in Costs and Yield

Expected Utility; Uncertainty in Costs, Crop Yield, Irrigation Water Requirement

Expected Utility; Uncertainty in Costs, Crop Yield and Streamflow

FIG. 7.1 SUMMARY OF BENEFIT FUNCTIONS.
REFERENCES


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
   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.
PROGRAM B--2

THIS PROGRAM CALCULATES THE EXPECTED BENEFITS FROM A SINGLE PURPOSE RESERVOIR BUILT TO SUPPLY IRRIGATION WATER TO AN AGRICULTURAL AREA. BENEFITS ARE CALCULATED IN 'UTILITY VALUE'. UTILITY IS A FUNCTION OF NET ECONOMIC VALUE.

SEVERAL VALUES OF IRRIGATION WATER REQUIREMENTS ARE TRIED: 2.0, 2.5, 3.0, 3.5, 4.0 FEET/YEAR.

REZCST = THE MATRIX OF RESERVOIR COSTS
LNDCST = THE MATRIX OF COSTS OF LAND DEVELOPMENT
MAIN  = MATRIX OF MAINTENANCE AND OPERATING COST
YIELD = MATRIX OF CROP YIELD
STFL  = MATRIX OF STREAM FLOW PROBABILITY
FLPRB = MATRIX OF STREAM FLOW PROBABILITY
REVN  = MATRIX OF TOTAL REVENUE FROM SALE OF CROPS
EEY  = EXPECTED YIELD OF CROPS
BNFT  = EXPECTED BENEFITS
YCRP = CROP YIELD (TONS/ACRE)
YAXIS = PERCENT AVAILABLE WATER OVER DESIGN WATER REQUIREMENT

NRR = NUMBER OF ROWS OF MATRIX 'REZCST'
NCR = NUMBER OF COLUMNS OF MATRIX 'REZCST'
LRL = NUMBER OF ROWS OF 'LNDCST'
LCL = NUMBER OF COLUMNS OF 'LNDCST'
MRM = NUMBER OF ROWS OF 'MAIN'
MCM = NUMBER OF COLUMNS OF 'MAIN'
KRY = NUMBER OF ROWS OF 'YIELD'
KCY = NUMBER OF COLUMNS OF 'YIELD'

PRICE OF CROPS IS ASSUMED TO BE $100.00 PER TON.

REAL REZCST(60,30),LNDCST(60,30),MAIN(60,30),
1 YIELD(60,30)
2 DIMENSION WREQD(5),SPB(60),REVN(20),BNFT(20),EXP(20)
3 DIMENSION CST(60),FST(60),SCCST(60),SCND(60),SUM(60),
1 SMPB(60)
4 DIMENSION AREA(20),XLAKE(20),VALUE(20),XLND(20),
1 RZV(10),RETN(10)
5 DIMENSION STFL(60),FLPRB(60),YAXIS(25),YCRP(25)
6 DIMENSION XX(60,30),AB(30),XPC(30),EXPNS(60),UNCT(60)
7 DIMENSION PRUT(20),TRUE(20)
8 INTEGER LRZ(20),HRZ(20),LLD(20),HLD(20)
9 INTEGER LYE(30),HYD(30),LMN(30),HMN(30)
10 INTEGER SML(30),BIG(30)
11 INTEGER COLM,ROW

COMMON XX,SML,BIG
13 COMMON EXPNS,UNCT
14 COMMON STFL,FLPRB,YAXIS,YCRP
15 COMMON/BLK1/SUM,SMPB
16 COMMON/BLK2/CST,FST,SCCST,SCND/BLK3/N1,N2,NCOMB,DELTA
17 COMMON/BLK4/LRZ,HRZ,LLD,HLD,LMN,HMN
18 COMMON/BLK5/EEY,REVN,BNFT,EXP

C:::READ IN DIMENSIONS OF MATRICES
19 READ 10,NRR,NCR,LRL,LCL,MRM,MCM,KRY,KCY
C:::INITIALISE 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)
   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)
   FORMAT(F10.3,11F9.3)
50 CONTINUE
DO 60  I=1,MRM
   READ(8,55) (MAIN(I,J),J=1,MCM)
   FORMAT(F10.3,11F9.3)
60 CONTINUE
DO 65  I=1,KRY
   READ(7,64) (YIELD(I,J),J=1,KCY)
   FORMAT(F10.3,11F9.3/F10.3,9F9.3)
65 CONTINUE
DO 2 K=1,40
   READ(2,67) STFL(K),FLPRB(K)
   FORMAT(F10.2,F15.5)
   FLOW=STFL(K)/10.0
   STFL(K)=FLOW
2 CONTINUE

C:::READ IRRIGATION WATER REQUIREMENT
READ 70, (WREGDUR(IR),IR=1,5)
FORMAT(5F10.2)
PRINT 71
PRINT 72
FORMAT('1'9X,'CONSUMPTIVE USE',9X,'IRRIGATED LAND
1'10X,'OPTIMUM RESERVOIR SIZE',8X,'EXPECTED
1BENEFITS')
72 FORMAT('1'9X,'FEET PER YEAR',13X,'ACRE ',20X,
1'ACRE-FEET',21X,'UTILITY')

C:::FOR EACH OF THE MATRICES DETERMINE THE ROWS
C CONTAINING NON-ZERO VALUES
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)

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)
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)

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:::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,i,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)
N0RM=N1
100 CONTINUE

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=N0RM
N8=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
START COST COMBINATIONS
CALL A PROGRAMME TO COMBINE TWO MATRICES
CALL CBMINE(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)
ANNUAL OPERATING COST=10% OF TOTAL CAPITAL COST
DO 150 J=1,NCOMB
CST(J)=SUM(J)/10.0
FST(J)=SMPB(J)
CALL GSET (SUM,60,1,60,0.0)
CALL GSET (SMPB,60,1,60,0.0)
COMBINE ANNUAL OPERATING COST WITH MAINTENANCE AND
OPERATING COST OF IRRIGATION SYSTEM
DELL=CST(2)-CST(1)
N1=NCOMB
MIN=LMN(L)
LARGE=HMN(L)
DEL2=MAX((MIN+1),1)-MAX(MIN,1)*MAX(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=(DELL+DEL2)/2.0
CALL CBMINE(CST,FST,SCCST,SCND,N1,N2,DELTA,
4NCOMB,SUM,SMPB)
DETERMINE THE EXPECTED ANNUAL COST
COST=EXPCST(NCOMB,SUM,SMPB)
CALL A SUBROUTINE TO MATCH STREAM INFLOW WITH
IRRIGATION WATER REQUIREMENT AND TO CALCULATE THE
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
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
CALCULATE THE MAXIMUM BENEFIT
CALL MXBNFT(TRUE,NB,NL,XMAX)
LM=L-2
AREA(LM)=LNDGST(1,L)
XLAKE(LM)=REZGST(1,(NL+1))
VALUE(LM)=XMAX
PRINT 750,DEW,AREA(LM),XLAKE(LM),VALUE(LM)
750 FORMAT(' ',10X,12.2,4X,12.2,6X,20.2)
800 CONTINUE
C:::CALCULATE THE MAXIMUM OF MAXIMUM BENEFITS FROM EACH QUANTITY OF IRRIGATION WATER USE

160 CALL MXBNFT(VALUE,LM,NL,XMAX)
161 XLND(IR)=AREA(NL)
162 RZV(IR)=XLAKE(NL)
163 RETN(IR)=XMAX

164 900 CONTINUE

C:::CALCULATE THE MAXIMUM OF ALL THE MAXIMUMS

165 CALL MXBNFT(RETN,5,NL,XMAX)
166 CULT=XLND(NL)
167 DAM=RZV(NL)
168 GRT=XMAX

C:::PRINT OUT MAXIMUM VALUES

169 DO 905 IR=1,5
170 PRINT 903,WREQD(IR),XLND(IR),RZV(IR),RETN(IR)
172 905 CONTINUE

173 PRINT 910,WREQD(NL)
174 910 FORMAT('- ',10X,'OPTIMUM CONSUMPTIVE USE = ',F5.2,4X,
175 6'FEET PER YEAR')
176 PRINT 920,CULT
177 920 FORMAT('- ',10X,'OPTIMUM ACREAGE = ',F12.2,4X,'ACRES')
178 PRINT 930,DAM
179 930 FORMAT('- ',10X,'OPTIMUM RESERVOIR SIZE = ',F12.2,4X,
180 'ACRE-FEET')
181 PRINT 940,GRT
182 940 FORMAT('- ',1GX,'EXPECTED BENEFIT = ',F15.2,
183 'UTILITY')
184 STOP
185 END

C

183 SUBROUTINE PREP(XX,ROW,COLM,SML,BIG)
184 REAL XX(60,30)
185 INTEGER SML(30),BIG(30)
186 INTEGER COLM,ROW
187 SML(1)=0
188 BIG(1)=0
189 DO 200 J=2,COLM
190 DO 100 I=2,ROW
191 IF(XX(I,J).GT.0.0) GO TO 120
192 100 CONTINUE
193 120 SML(J)=I
194 LF=I+1
195 DO 130 I=LF,ROW
196 IF(XX(I,J).EQ.0.0) GO TO 140
197 130 CONTINUE
198 140 BIG(J)=I-1
199 200 CONTINUE
200 RETURN
201 END

C

202 SUBROUTINE EXPECT(XX,NROW,KOL,AB,XPC)
203 REAL XX(60,30),AB(30),XPC(30)
204 KKL=KOL-1
205 DO 100 JJ=1,KKL
I=JJ+1
207 100 AB(JJ)=XX(1,I)
208 KS=1
209 DO 400 K=2,KOL
210 DO 200 I=2,NROW
211 LL=I
212 IF(XX(I,K).GT.0.0) GO TO 210
213 200 CONTINUE
214 210 SUM=0.0
215 DO 300 L=LL,NROW
216 TEMP=XX(L,K)*XX(L,1)
217 SUM=SUM-TEMP
218 IF(TEMP.EQ.0.0) GO TO 350
219 300 CONTINUE
220 350 XPC(KS)=SUM
221 KS=KS+1
222 400 CONTINUE
223 RETURN
224 END

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(l1)+SCCST(1))-DELTA
TOP=CST(N1)+SCCST(N2)
PRL=CST(1) + SCCST(1)
IF(PRLOEQ.CST(1)) GO TO 100
GO TO 140
100 DO 120  K=1,N1
  120 SUM(K) = CST(K )
  120 SMPB(K)=FST(K)
  NC0MB=N1
  GO TO 500
140 DO 400  I=1,60
  PROB=0.0
  SM CST=0.0
  PP=0.0
  SUM(I)=STAT+(DELTA*I)
  IF((SUM(I)-TOP).GE. DELTA) GO TO 410
  DO 300 J=1,N1
    300 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
   400 CONTINUE
410 NC0MB=I-1
500 RETURN

END
SUBROUTINE WATER(YIELD,STFL,FLPRB,YAXIS,LYD,HYD,SOIL,PRC,VOLM,QA,C0ST,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 K0L=M+1

CALL A SUBROUTINE TO LOOK UP YIELD AND TO COMPUTE NET ECONOMIC BENEFIT AND EXPECTED UTILITY

CALL PRODCE(YIELD,LYD,HYD,SOIL,PRC,SLP,YC,BC,KOL,C0ST,EU)

SS=SS+EU*FLPRB(J)

700 CONTINUE

710 EEU=SS

RETURN

END

SUBROUTINE PRODCE(YIELD,LYD,HYD,SOIL,PRC,SLP,YC,BC,KOL,C0ST,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)-C0ST

100 CONTINUE

CALL A SUBROUTINE TO DETERMINE UTILITIES ASSOCIATED 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
**SUBROUTINE TO CALCULATE EXPECTED UTILITIES**

```fortran
307 SUBROUTINE UTILIT(BNFT,N,SLP,YC,BC,PRUT)
308 REAL BNFT(50),PRUT(50)
309 DO 600 I=1,N
310 IF(BNFT(I).LE.0.0) GO TO 400
311 IF(BNFT(I).GT.BC) GO TO 500
312 Y=YC-SLP*(BC-BNFT(I))
313 GO TO 550
314 400 Y=-600000.0
315 GO TO 550
316 500 Y=BNFT(I)
317 550 PRUT(I)=Y
318 600 CONTINUE
319 RETURN
320 END
```

**SUBROUTINE TO CALCULATE THE EXPECTED COST**

```fortran
321 FUNCTION EXPCST(NCOMB,SUM,SMPB)
322 REAL SUM(60),SMPB(60)
323 EXPCST=0.0
324 DO 100 I=1,NCOMB
325 100 EXPCST=EXPCST+(SUM(I)*SMPB(I))
326 RETURN
327 END
```

**SUBROUTINE TO CALCULATE MAXIMUM VALUES**

```fortran
328 SUBROUTINE MXBNFT(BNFT,NUM,NL,XMAX)
329 REAL BNFT(20)
330 NL=1
331 XMAX=-1.0E 8
332 DO 100 I=1,NUM
333 IF(BNFT(I).LE.XMAX) GO TO 100
334 XMAX=BNFT(I)
335 NL=I
336 100 CONTINUE
337 RETURN
338 END
```