DECISION ANALYSIS APPLIED TO
GROUND WATER EXPLORATION

by

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B.Eng., Ahmadu Bello University, Zaria, 1972.

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(The Department of Civil Engineering)

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

January 1979

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Date February 14, 1979.

ABSTRACT

An outline of the essential steps needed in ground water exploration is given. Since drilling for ground water involves a lot of uncertainty, the main concepts of Bayesian decision theory are briefly reviewed. Three models for analyzing ground water decision problems are developed with an emphasis on the well-owner's utility or desirability to actually venture to invest on a water-drilling project. Finally, use of the decision models is illustrated by applications to a) Ryder Lake District (in British Columbia) - an area where water supply is a problem, with the only source being from underground; and to b) Inches Creek study area where approximately 4500 gallons per minute of ground water is needed for salmon enhancement facilities.

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ACKNOWLEDGEMENT

The author wishes to express his sincere gratitude to his supervisor Professor S.O. Russell for his invaluable guidance, assistance and constant encouragement throughout the preparation of this thesis. Special thanks are also extended to Mr. E.C. Halstead and Mr. H.M. Liebscher (both of the Hydrology Research Division, Vancouver, B.C.) for their advice and assistance in data collection; and to Mr. Ron Grigg for assistance in computer programming. And, finally, the author would also like to thank the Civil Engineering Department for financial assistance.

CHAPTER 1

INTRODUCTION

Human consumption of ground water has been increasing steadily over the years, especially in the past seventy-eight years. This has been as a result of increased use of irrigation, industry, and the rising standards of living. Today, ground water resources, which constitute more than ninety-five percent of the world's total fresh water supply, are generally uncontaminated in contrast to the increasingly polluted nature of many of its surface water sources. Though ground water generally averages out to be a little harder and more mineralized than surface water in the same locality, yet its quality is more uniform during the year. The temperature of ground water, like its chemical quality, is also relatively uniform throughout the year. This makes it preferable for many uses especially for the fishing industry, and also for cooling purposes in the summer, when surface water is warmer.

The importance of ground water does not mean that wells should be drilled just anywhere. There are many uncertainties involved; for one cannot say exactly what the outcome of a drilling project would be even after the hydrologist (the expert) has predicted a good aquifer. The outcome could be a dry hole or an undesirable yield. A systematic and formal analysis to take care of the risk and uncertainty is therefore very worthwhile.

Decision analysis, also known as statistical decision theory, management science, operations research, and Bayesian decision theory, is a discipline consisting of various methods, techniques, and attitudes to help the decision maker to choose wisely under these conditions of uncertainty. This analysis has already been applied to oil and gas exploration (Grayson, 1960 and Newendorp, 1975), forest management and geological investigations (Halter and Dean, 1971), water quality management (Hershmann, 1974) and also in the search for minerals. It requires that the explorer (expert) associate specific probabilities with the possible outcomes (dry hole, or various yields); and this is where the element of risk comes in. Where there are past records, statistical methods are used to calculate probabilities. Next, the owner of the project assesses his utility values or desirability of the various outcomes. Finally, expected utility values, which form the basis for decision, are computed.

The objective of this thesis, therefore, is to apply decision theory in the search for ground water. Different decision models have been developed and applied to Ryder Lake District, some fifty-five miles east of Vancouver in British Columbia; and also to Inches Creek where approximately 4500 gallons per minute of ground water is needed for salmon enhancement facilities. Ryder Lake District depends solely on ground water for its water supply. And so, people interested in settling there have always wanted to know how good the chances of obtaining water are before involving themselves in expensive drilling programs.

A summary of all the steps needed in ground water exploration is given in Chapter 2. Chapter 3 describes, in a nutshell, the procedures of carrying out a decision analysis, more especially as it applies to the search for ground water. This chapter also explains the use of utility theory which is one of the backbones of decision analysis. Three different models that can be used in analyzing ground water decision problems are developed and explained in Chapter 4. Chapter 5 illustrates how the above models can be applied to real-world situations such as in the Ryder Lake District and in Inches Creek study area. A description of the computer program used in the analysis is also given in this chapter, while the discussion of results and the conclusions are given in Chapter 6.

CHAPTER 2

SUMMARY OF GROUND WATER EXPLORATION

In the past, the only method of prospecting for ground water was "water witching" or "dowsing". But this method has proved most unreliable and a more scientific approach had to be found.

In 1963, the U.S. Geological Survey published a report[1] summarizing a general approach to ground water exploration. The following paragraphs are taken from that report.

2.1 Geologic Considerations

"Certain clues are helpful in locating ground water supplies. For instance, ground water is likely to occur in larger quantities under valleys than under hills. In arid regions, certain types of water-loving plants give the clue that there has to be ground water at shallow depths underneath to feed them. Any area where water shows up at the surface - in springs, seeps, swamps, or lakes - has to have some ground water, though not necessarily in large quantity or of usable quality.

"But the most valuable clues are the rocks. Hydrologists and geologists use the word rock to mean both hard, consolidated formations, such as sandstone, limestone, granite, or lava rocks, and loose unconsolidated sediments such as gravel, sand, and clay. They use the word aquifer for a layer of rock that carries a usable supply of water. Gravel, sandstone, and limestone are the best water carriers but they form only a fraction of the rocks in the earth's outer crust. Not all of them yield useful supplies of water. The bulk of the rocks consist of clay, shale, and crystalline rocks - a term used for the great variety of hard rocks that form most of the earth's crust. Clay, shale, and crystalline rocks are all poor producers, but they may yield enough water for domestic stock uses in areas where no better aquifers are present.

"The hydrologist or geologist first of all prepares a geological map and cross-sections showing where the different rocks come to the land surface and how they are arranged beneath the surface. He will observe how the rocks have been affected by earth pressures in the past. The geologic map and sections and the accompanying explorations show just which rocks are likely to carry water and where they are beneath the surface."

2.2. Past Records

"Next, he will gather all the information he can on existing wells - their location, depth, depth to water, and amount of water pumped, and what kind of rocks these wells penetrate. Much of what he is interested in is below the depth of ordinary excavations, and he cannot afford to drill a well or test hole in every place where he needs information.

"Records of wells where the driller has carefully logged the depth and types of different rock strata are helpful. A really useful well record will include the following: samples of the rock; information on which strata yield water and how freely; the static water level in each successively deeper stratum; and data from a pumping or bailing test of each water-bearing stratum showing how much water was yielded, and how much the water level lowers at the given rate of pumping or bailing."

2.3. Hydrologic Considerations

"The hydrologist will then make a contour map of the water table ...... he measures the depth from the land surface to the water table at wells. Next, he determines either from a topographic map or by surveying, how much the land is above sea level. Finally, he draws lines to connect all the points of equal elevations of the water table, so that the map shows the shape of the water table in the same way that a topographic map shows the shape of the land surface.

"The water-table map is especially important because it gives a clue not only to the depth below which ground water is stored, but also to the direction in which the water is moving. If there is any slope to the water table, the water moves in the direction of the slope."

2.4. Test Drilling and Sample Analysis

"Where there are no wells or not enough information on existing ones, the hydrologist may have to put down some test holes . . . The samples of the earth material brought up by drilling are examined and analyzed to determine which strata are water-bearing and how large an area they underlie.

"Thus, there is no magic about the hydrologist's work. It is based on common sense and scientific observation. He uses all the clues he can get - what he can see of the rocks as they are exposed at the land surface or in road cuts, quarries, tunnels or mines and what he can learn from wells.

"These ground water studies vary in completeness with the need for information. If the need is mostly for domestic supplies, an area the size of a county can be studied in a summer. The report and maps can be prepared the following winter.

"The hydrologist's report and maps will show where water can be obtained, what kind of water it is chemically, and in a very general way how much is available. If a large supply is needed or if there are problems with the present supply, more detailed studies must be made, either in the area where a large need exists or, in some cases, where a future need is anticipated. Whatever the scope of the study, the report is designed to provide a sound basis for whatever may follow it, whether it may be drilling home and farm wells, or large-scale water projects for a city, for industry, or for an irrigation project."

2.5 Surface and Subsurface Geophysical Methods

If the exploration project is economically important enough and if the geologic framework of the area is favourable, surface geophysical methods such as earth resistivity and seismic surveys could be used to locate aquifers. The earth resistivity method is useful for the detection and delineation of near-surface aquifers often outlining the courses of buried valleys, while seismic prospecting provides fair estimates of layer depth.

On the other hand, subsurface geophysical methods would also give more information about an aquifer. But before these methods are applied, an exploratory hole has to be drilled through the formations, obtaining samples while drilling, and recording a log of the borehole. Well logging consists of recording characteristic properties of the various strata in terms of depth. The next common well log is the driller's description of the geologic character of each stratum, the depth at which changes in character were observed, the thickness of the strata, and the depth to water.

2.6 Logging Techniques Used In Ground Water Exploration

Electric logging is the most common borehole geophysical operation. It verifies and supplements the descriptive logging of the hole which the driller records as drilling proceeds.

An electric log consists of a record of the apparent resistivities of the subsurface formations and the spontaneous potentials generated in the borehole, both plotted in terms of depth below the ground surface. These two properties are related indirectly to the character of the subsurface formations and to the quality of water contained in them. They can be measured only in mud-filled, uncased boreholes.

2.6.1. Spontaneous Potential

The spontaneous potential or self-potential (SP) curve is a record of natural voltages developed in most drilled wells between dissimilar fluids contained in the rocks penetrated and the borehole. The equipment used consists of two lead electrodes, one moving in the drill hole and the other stationary at the surface. The recorder plots millivolt changes in electric potential between these two electrodes as a function of depth. The source of spontaneous potential in a drill hole is generally accepted to be the sum of electro-chemical and electro-kinetic potentials.

The spontaneous potential curve may be used to calculate formation water resistivity, locate bed boundaries, distinguish between shales and sandstone or limestone in combination with other logs, and for stratigraphic correlation. The SP log is affected by hole diameter, bed thickness, water or mud resistivity, density, and chemical composition, mud cake thickness, mud filtrate invasion and well temperature. Although correction factors and curves are available to reduce or eliminate these effects, considerable information obviously must be available to make the necessary corrections. The SP log is rarely used quantitatively in groundwater hydrology, but it is widely run for qualitative lithological information. SP deflections are read from a shale baseline on the right to maximum negative deflections. The shale baseline is drawn through as many deflection minima as possible. A sand line may then be drawn through negative deflection maxima and if fluid salinity is constant, these lines will be parallel to each other and the zero baseline.

2.6.2. Resistivity

Theoretically the resistivity values recorded on a log are a measurement of the resistance of a cube of material measuring 1 meter along each edge, hence the units are ohms meter^2 per meter or simply ohm-meters. Since most rocks consist of nonconductive particles, the nature of the pore spaces and interstitial fluids determines the character of the resistivity curve. The numerous types of resistivity curves made by commercial logging companies are differentiated by the configuration of the electrodes and the resulting differences in the thickness of rock units measured and the depth of investigation. The single-point resistivity log, along with the SP, is the most widely used logging technique in water wells. It detects very thin beds and fracture zones (Davis, S.N. and DeWiest, R.J.M., 1966).

One principal use of the resistivity curve is that by merely glancing at it, the water-well driller can determine the depth and thickness of almost every bed penetrated except the thinnest ones.

When it is known that the quality of the water remains nearly the same for all the aquifers penetrated, changes in resistivity can generally be interpreted as being caused by changes in porosity, or by a clayey condition. But simultaneous use of the SP or gamma ray curve will assist in determining which of the two situations actually exists.

2.6.3. Other Logging Methods

Apart from electric logs, there are also radiation logs, acoustic logs, caliper logs, temperature logs, fluid conductivity logs, and fluid movement logs.

Like many geophysical logs, any radiation log may be used to determine the depth and thickness of beds, and for subsurface mapping. Other applications are: logging of cased holes (with the gamma ray and/or neutron curve); identification of clay and shale beds (with the gamma ray curve); identification of aquifers (with a combination of gamma ray and a neutron curve); and estimation of the porosity of aquifers (with any neutron curve or a gamma-gamma log). Radiation logs cannot be used to estimate the total dissolved solids (TDS) in aquifer waters unless the solids are primarily chlorides and exceed 40,000 parts per million (ppm).

The applications of acoustic logs in groundwater hydrology are: determination of porosity (from velocity measurements); location of fractured zones in dense rocks (from amplitude measurements); and determination in cased holes where cement makes good bond against casing and formation (from amplitude measurements). Neither the identification of rocks nor the estimation of TDS are possible from acoustic measurements.

Caliper logs have the following main applications to hydrology, namely: location of fractures, with a caliper having a single sharp feeler arm; location of washouts (hole enlargements) and other openings; guide to establish correction factors for measurements affected by hole size (in particular, resistivity and neutron); and guide to well construction.

Temperature logs are used in the following: determination of the temperature of aquifer waters in wells in thermal equilibrium; location of sources of waters and thieving beds; study of seasonal recharge to a groundwater system; and study of the distribution of waste during disposal projects.

The fluid conductivity log is a record as a function of depth of the conductivity - or its reciprical, the resistivity of the borehole fluid. Its main applications in hydrology are: location of the point(s) of entry of formation water(s) into a well; location of the point(s) of entry of injected water into permeable beds; and estimating the TDS of water in wells as a function of depth.

Fluid movement logging methods determine the direction and velocity of natural or artificially-induced flow within a well (Guyod, H., 1972).

2.7. Pump Tests

If, after all the above-mentioned exploratory methods have been applied, and groundwater is encountered during the test drilling, the driller can give a rough estimate of the yield of the well by bailing. But, if large quantities of water are needed and the funds are available, a pump test would be worthwhile in order to obtain an exact yield and the drawdown characteristics of the well. Before the pump test, however, the well is developed by screening. The test data can also be used to determine the coefficient of storage of the aquifer.

2.8 Observation Wells

Observation wells are used to monitor drawdown and pumpage characteristics of production wells. In order to obtain uniform distribution of drawdown, observation wells should not be located too close to the pumped well. They should be located about 100 feet to 300 feet from the pumped well (for unconfined aquifers) and about 300 feet to 700 feet (for confined squifers). A longer pumping duration is also required (Johnson, U.O.P., 1972).

The number of observation wells to be employed depends upon the amount of information that is desired and upon the funds available for the test program. The data obtained by measuring the drawdown at a single location outside the pumped well permit calculation of the average permeability and trarsmissibility of the aquifer and its coefficient of storage (Domenico, P.A. 1972). If two or more observation wells are placed at different distances, the test data can be analyzed in two ways by studying both the time-drawdown and the distance-drawdown relationships. Usually both these methods of analysis give a check on the results and enhance the dependability of the conclusions. It is always best to have as many observation wells as conditions allow.

2.9 Water Quality

Samples of the water encountered in the well should be analyzed in order to ensure that it meets the required standards for whatever purpose it is needed - whether for drinking, industrial use or for irrigation (Todd, 1959).

2.10 Ground Water Recharge

In order to avoid complete depletion of the aquifer, the various modes of recharge are of utmost importance. In many places, the major sources of recharge to aquifers are direct precipitation on intake areas and/or downward percolation of stream runoff. There are, however, artificial recharge techniques which in some circumstances can be employed if needed (Walton, 1970).

CHAPTER 3

DECISION ANALYSIS UNDER UNCERTAINTY IN GROUND WATER TERMS

Decision making under uncertainty implies that there are at least two possible outcomes that could occur if a particular course of action is chosen. Or, in other words, decision making under uncertainty occurs where the probabilities of the outcomes of any choice are not completely known. For example, when the decision to drill a water well is made, it is not known with certainty what the outcome would be. Even if water was encountered, it is not entirely certain what the yield of the well would be.

A summary of the steps used in solving decision analyses problems are as follows:

1. To define the possible outcomes that could occur for each of the available decision choices, or alternatives.
2. To evaluate profit or loss (or any other measure of value or worth) for each outcome.
3. To determine or estimate the probability of occurrence of each possible outome.
4. To calculate a weighted average profit (or measure of value) for each decision choice, where the weighting factors are the respective probabilities of occurrence of each outcome. This weighted average profit is called the expected value of the decision alternative, and is the comparative criterion used to accept or reject the alternative (Schlaifer, R., 1969).

Usually, the most difficult problem is obtaining the probabilities of occurrence of the various outcomes. Where no past statistical data are available, the geologist or hydrogeologist after studying the area concerned, gives his subjective probability estimates which will certainly be based on his personal biases, emotions, and past experience. Herein lie the elements of risk and uncertainty. For example, he could say that the probability of drilling and hitting water is 75% or even 20%.

If the owner of the drilling project is not satisfied with the geologist's probability estimate, he could purchase additional information in the way of drilling a test hole, collecting samples and analyzing them to obtain permeabilities of the materials or even running resistivity and spontaneous potential tests. Depending on the outcome of the additional information, the uncertainty involved would be reduced and new probability estimates could be obtained. These new estimates are obtained by updating the prior estimates using Bayesian Analysis (Benjamin and Cornell, 1970).

3.1. Utility Theory

The concept of mathematical expectation, or expected monetary value (EMV), is the traditional approach to decision making under conditions of uncertainty. Use of this criterion consists of multiplication of a probability of occurrence with the financial payoff for each possible outcome. For example, if p is the probability that a particular outcome will occur and v is the payoff (profit or loss) to be realized by the decision maker if the outcome occurs, then $p \times v$ is the "expected value" of the outcome. If there are two or more possible outcomes the expected values for each outcome are summed algebraically, with the decision being to accept the act if the sum is positive. If several decision alternatives are being considered, the criterion is to select the alternative which will maximize expected monetary value.

The expected monetary value concept implies that the decision maker is totally impartial to money. But this is not true because people are not impartial to money. Rather, they have specific attitudes and feelings about money which depend on the amounts of money, their personal risk preferences, and any immediate and/or longer term objectives they may have. A decision maker's attitudes and feelings about money may change from day to day, and may even be influenced by such factors as his business surroundings, and the overall business climate at a given time. The noted Swiss mathematician, Daniel Bernoulli (1700-1782) was one of the first to suggest that monetary values alone do not adequately represent a person's value system. He suggested that the utility (desirability, usefulness) of money is inversely proportional to the amount he already has (Newendorp, P. 1975).

The derivation of utility theory is based on eight axioms (von Neuman and Morgenstern). A person's utility curve is unique to him and increases with an increase in preferability. Utility values, or index numbers are dimensionless and the magnitude of the utility scale is arbitrary. Utility values are therefore used to replace monetary values and hence expected utilities are calculated as before.

The problem in implementing utility theory is that at present there are no effective methods to construct or determine the utility curve. Previous research on this problem has centred on the development and use of testing procedures to obtain the data needed to construct a utility curve. These procedures generally have been based on offering the decision maker a choice between a gamble having a desirable outcome (X) and a less desirable outcome (Z), or a no-risk alternative (Y) of intermediate desirability. The testing would seek to determine the decision maker's point of indifference between accepting the gamble (X occurring with probability p and Z occurring with probability 1 - p) or the no-risk alternative. The indifference point represents an equality of the decision maker's utility for the gamble and the no-risk alternative; that is

$$p \times U(X) + (1 - p) \times U(Z) = U(Y) \tag{3.1}$$

where U(X) = utility value of outcome X.

By arbitrarily assigning numerical values to two of the above utilities, the third could be computed. With careful design of the testing sequence, these three numerical utilities would be used to compute successive utilities. After determining a sufficient number of utilities, a utility curve would be drawn through the data points (Grayson, 1960).

In ground water terms, the utility curve would be that of the well-owner and not of the hydrogeologist or driller. This utility curve could show either the well-owner's preferability for obtaining various water yields or the desirability of having to drill to any depths.

The next chapter will show how this utility theory can be applied to the development of three models for analyzing ground water decision problems.

CHAPTER 4

MODELS FOR ANALYZING GROUND WATER DECISION PROBLEMS

4.1 Case I: Well Cost Known: Yield Not Known:

This case would involve a trade-off between the cost of drilling and the possible returns as regards the yield obtained from the well. And therefore, the utility of drilling and obtaining various yields and the utility of not drilling at all would be needed in order to be able to make a decision.

The utility curve is usually that of the owner of the well project and not that of the driller nor that of the hydrogeologist.

Figure 4.2 is an example of one such utility curve showing that beyond a particular yield, y(gpm), the well-owner's relative desirability (utility) to drill the well would be zero. But thereafter, his preference or utility for drilling would increase with an increase in the yield. Utility curves such as in fig. 4.2 are obtained by asking the well-owner questions such as: "Which alternative would you prefer - alternative (1) in which you would obtain say $y_1$gpm for certain, or alternative (2) - a gamble in which you have say a 75-25 chance of obtaining $y_2$gpm or nothing (a dry hole)?" y_2 is very much greater than y_1. If he replies that he feels the two alternatives are about equal, that is, he is "indifferent" between the two, then these alternatives would have the same utility to him.

If the utility of $y_2$gpm is set equal to say 100 utiles, and the utility of a dry hole is set equal to 0 utiles (or any arbitrary units could be chosen), then the utility of $y_1$gpm would be calculated using the following equation:

$$U(y_1) = 0.75[U(y_2)] + 0.25[U(0)] \qquad (4.1)$$

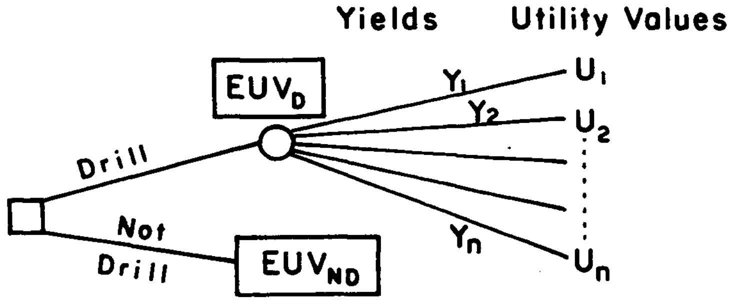

FIG.4.1: DECISION TREE SCHEMATIC.

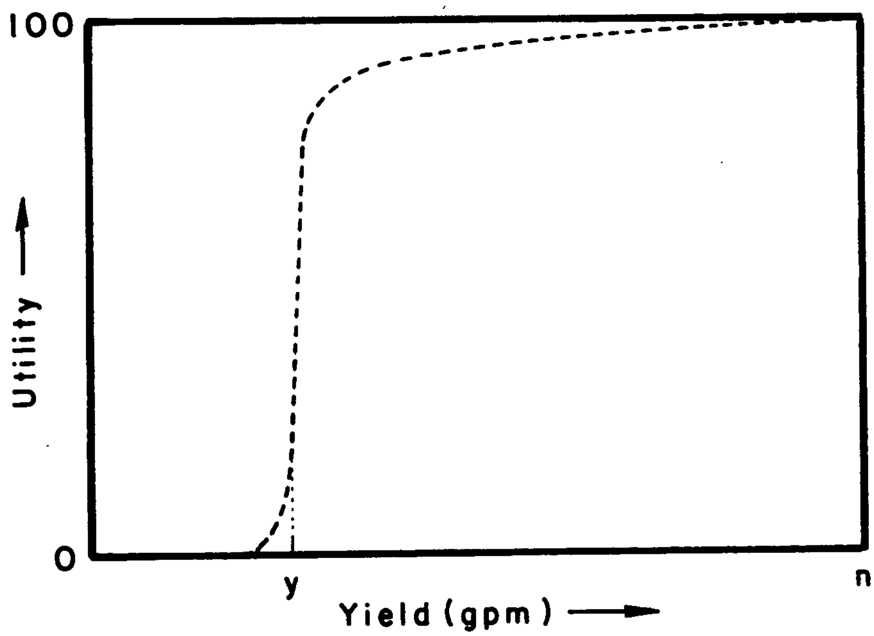

FIG. 4.2: UTILITY VERSUS YIELD.

By asking a series of such questions with different values of yields and probabilities, enough points could be obtained to plot his utility curve, which is entirely unique to him.

If the probabilities of obtaining the various yields are say p_1 for yield y_1, p_2 for yield y_2 etc, and the utilities of the same yields are U_1, U_2 etc. as in fig. 4.1, then the expected utility value of drilling would be given by:

$$EUV_D = \sum_{i=1}^{n} p_i \ U_i \qquad (4.2)$$

These probabilities of the various yields can be obtained in either of two ways:

1. By asking a hydrogeologist who knows about the area in question, and
2. By use of cumulative probability curves where data are available.

4.1.1 Utility of Not Drilling

The expected utility value of not drilling, EUV_{ND}, is obtained by asking the well-owner a question such as: "If the only possible outcomes were the best (optimum yield) or the worst (dry hole), what would the chance of success have to be before you would accept to drill?" If he says 80%, for example, then EUV_{ND} would be equal to 80.

Whichever value is greater, EUV_D or EUV_{ND}, indicates the best decision, that is, either to drill or not to drill.

4.2 Case II: Well Cost Known; Well Depths Not Known; Yields Not Known; Stop Once an Aquifer is Encountered

4.2.1 Case II(a) - No Relationship Between Yield and Depth

Here, there are several depths the well could be drilled to. But, for each particular depth, (say d_1 with a probability p_{d1} of getting water), there would be yields $y_1 \ldots . y_n$ with probabilities $p_{y1} \ldots . p_{yn}$

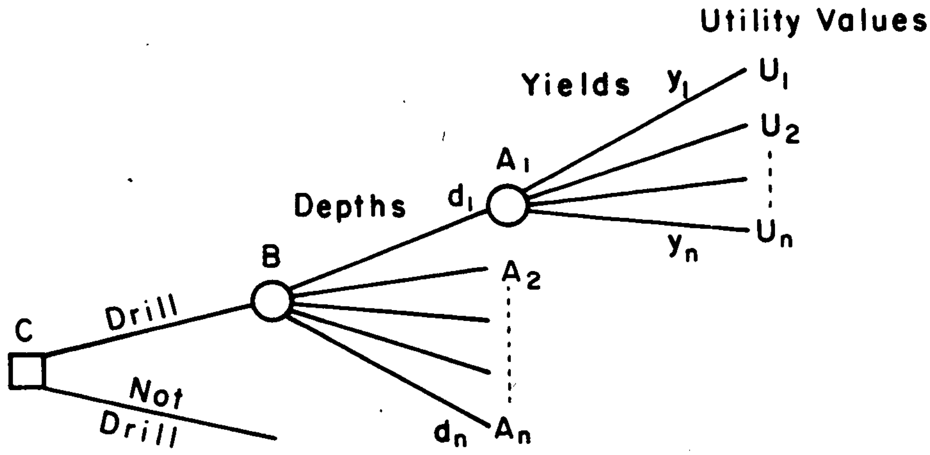

FIG. 4.3(a): DECISION TREE SCHEMATIC.

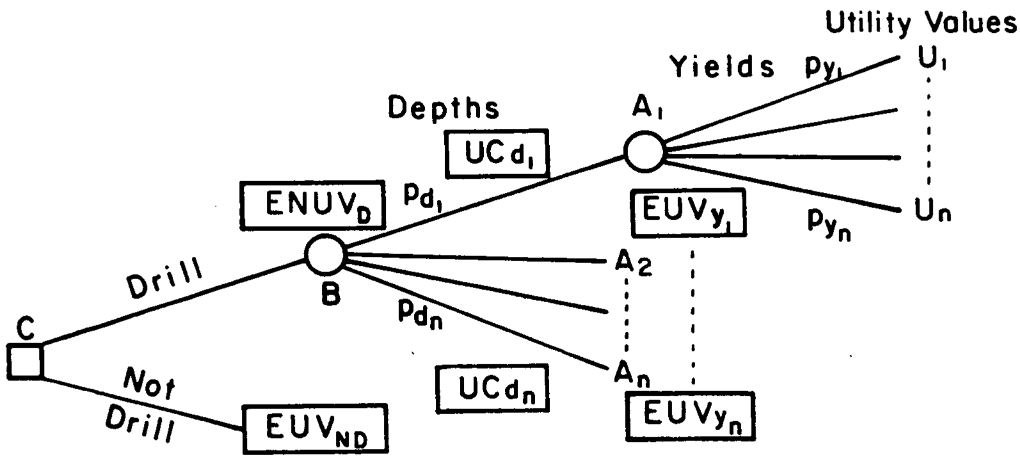

FIG. 4.3(b): DECISION TREE SHOWING EXPECTED VALUES.

and utility values $U_1 \ldots U_n$ associated with each yield value.

The utility versus yield curve would be obtained as in Case I (fig. 4.2).

The expected utility values ($EUV_{y1} \ldots EUV_{yn}$) at the chance nodes $A_1 \ldots A_n$ are again calculated as in Case I using equation (4.2). These expected utility values would be the same for the various depths if there were no relàtionahip between depth and yield.

Since the cost of drilling a hole is charged per foot drilled plus mobilization and demobilization, there would be a utility "cost" (UC_d) associated with drilling to any depth. This utility "cost" or relative desirability of drilling to any depth decreases with increase in depth. Figure 4.4, therefore, shows the well-owner's utility "cost" curve obtained by again asking him questions similar to those used in obtaining fig. 4.2 (Case I).

The expected utility value of drilling to all the different depths (EUV_d) (with probabilities of obtaining water $p_{d1} \ldots p_{dn}$ and corresponding utility "costs" $UC_{d1} \ldots UC_{dn}$) is again calculated using equation (4.2). The difference between the expected utility value of yield (EUV_y) and the expected utility value of depth, gives the expected net utility value of drilling decision ($ENUV_D$). Or,

$$ENUV_D = EUV_y - EUV_d$$

4.2.2. Case II(b): Probability Relationship Between Yield and Depth

Where there is a relationship between yield and depth in the form of a probability band with a mean, lower and upper limits such as in fig. 4.5, then the expected utility values ($EUV_{yi} \ldots EUV_{yn}$) at the chance nodes $A_1 \ldots A_n$ would be different because of the uncertainty involved. The probability of "yield" for a given value of "depth" is assumed to have a

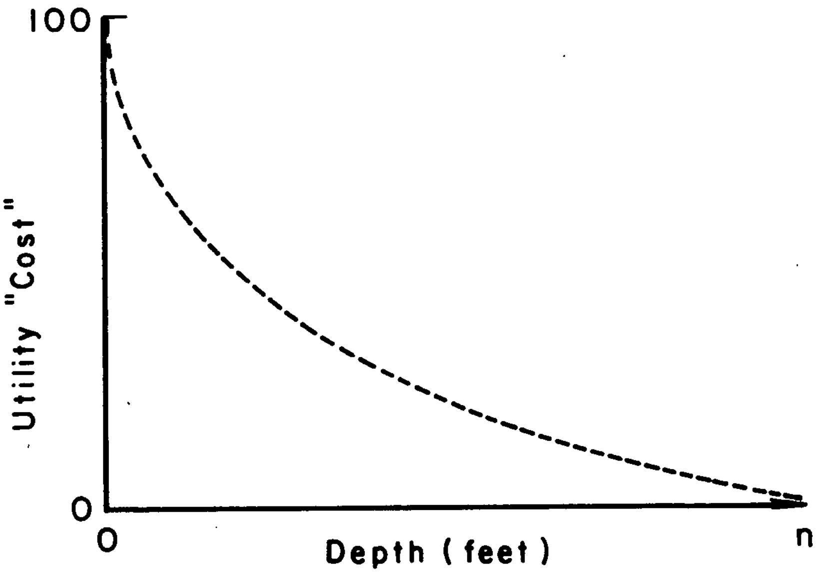

FIG.4.4: UTILITY "COST" VERSUS DEPTH.

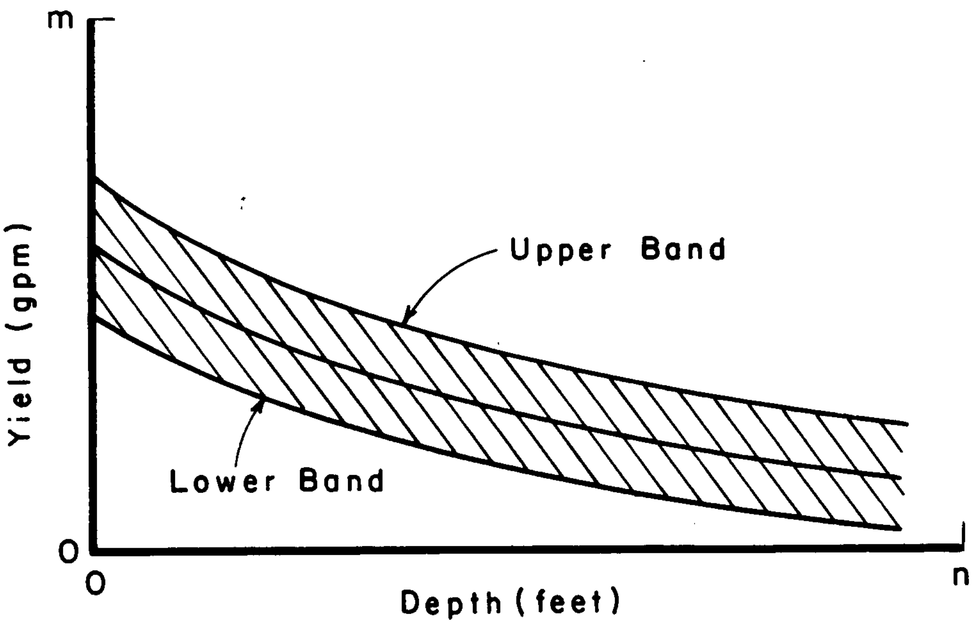

FIG. 4.5: YIELD VERSUS DEPTH PROBABILITY BAND.

skewed normal distribution between the upper and lower bounds.

Using the utility versus yield curve (fig. 4.2) and fig. 4.5, different values of expected utility of yields for all the various depths would be obtained. From each expected utility value for a particular depth is subtracted the utility "cost" for that particular depth, to obtain an expected net utility value $(ENUV_d)$ for that depth. This is done for all the different depths.

The expected net utility value of drilling decision $(ENUV_D)$ is obtained by multiplying each expected net utility value for a particular depth $(ENUV_{di})$ by the corresponding probability (p_{di}) of obtaining water at that depth, and summing over the entire range of depths. Or,

$$ENUV_D = \sum_{i=1}^{n} [p_{di}(ENUV_{di})] \tag{4.3}$$

4.2.3. Expected Utility of Not Drilling

To obtain the expected utility value of not drilling, the well-owner is asked a question such as: "You are offered two alternatives as follows:

Alternative A: You do not drill at all, but you obtain an outcome very close to the "best" - no risks involved.

Alternative B: A gamble in which you have a probability p of obtaining the "best" outcome and a probability (1 - p) of obtaining the "worst".

At what probability values would you be indifferent between accepting alternative A or B?"

In this particular case, the "best" outcome would be to drill to zero depth and still obtain the maximum yield. The utility associated with this would be 200 (100 + 100) - obtained by combining the utility curves of figs. 4.2 and 4.4. On the other hand, the "worst" outcome would be to

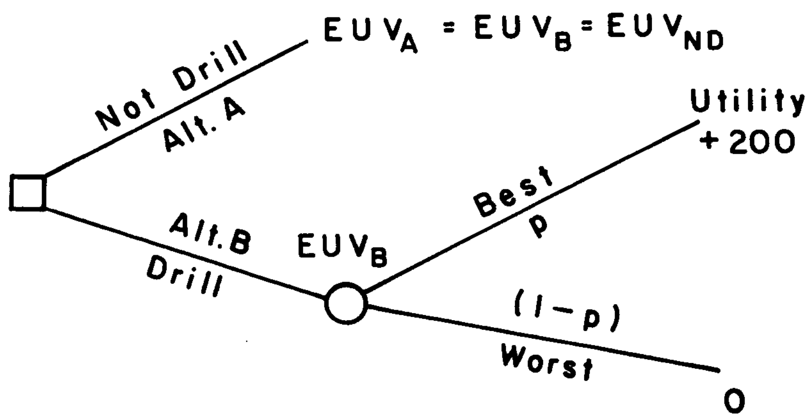

FIG. 4.6: SCHEMATIC DECISION TREE.

drill to the maximum depth only to obtain a zero yield. And again, combining figs. 4.2 and 4.4, the utility associated with this "worst" outcome would be zero (0+0).

If the well-owner's point of indifference were actually at p and (1 - p), then the expected utility value of not drilling (EUV_{ND}) would be given by the following equation:

$$EUV_{ND} = p \times 200 + (1-p) \times 0 \quad (4.4)$$

(See the decision tree of fig. 4.6).

Here again the decision to drill or not to drill would be made depending on which act has the greater expected net utility value (that is either $ENUV_D$ or EUV_{ND}).

4.3 Case III: Decision to Purchase Imperfect Information

The importance of purchasing additional information is to better define (or reduce) the uncertainty associated with the decisions to be made. For example, the decision to drill a 700 foot water well could be deferred until say, a seismic and/or resistivity survey is run to better define the structure and its physical dimensions. Other examples of information purchased to better reduce uncertainty are logging surveys, analysis of samples, and pump tests in order to decide how many more wells have to be drilled to meet a specific water demand.

If the additional information is perfect (that is, there is no error in the interpretation and it will tell precisely the true state of nature), a relatively straightforward analysis will suggest whether it is feasible to purchase the information. But, if the information is imperfect, the analysis of whether to purchase the information becomes more complex.

Figure 4.7 is a schematic decision tree for the analysis of decisions to purchase imperfect information.

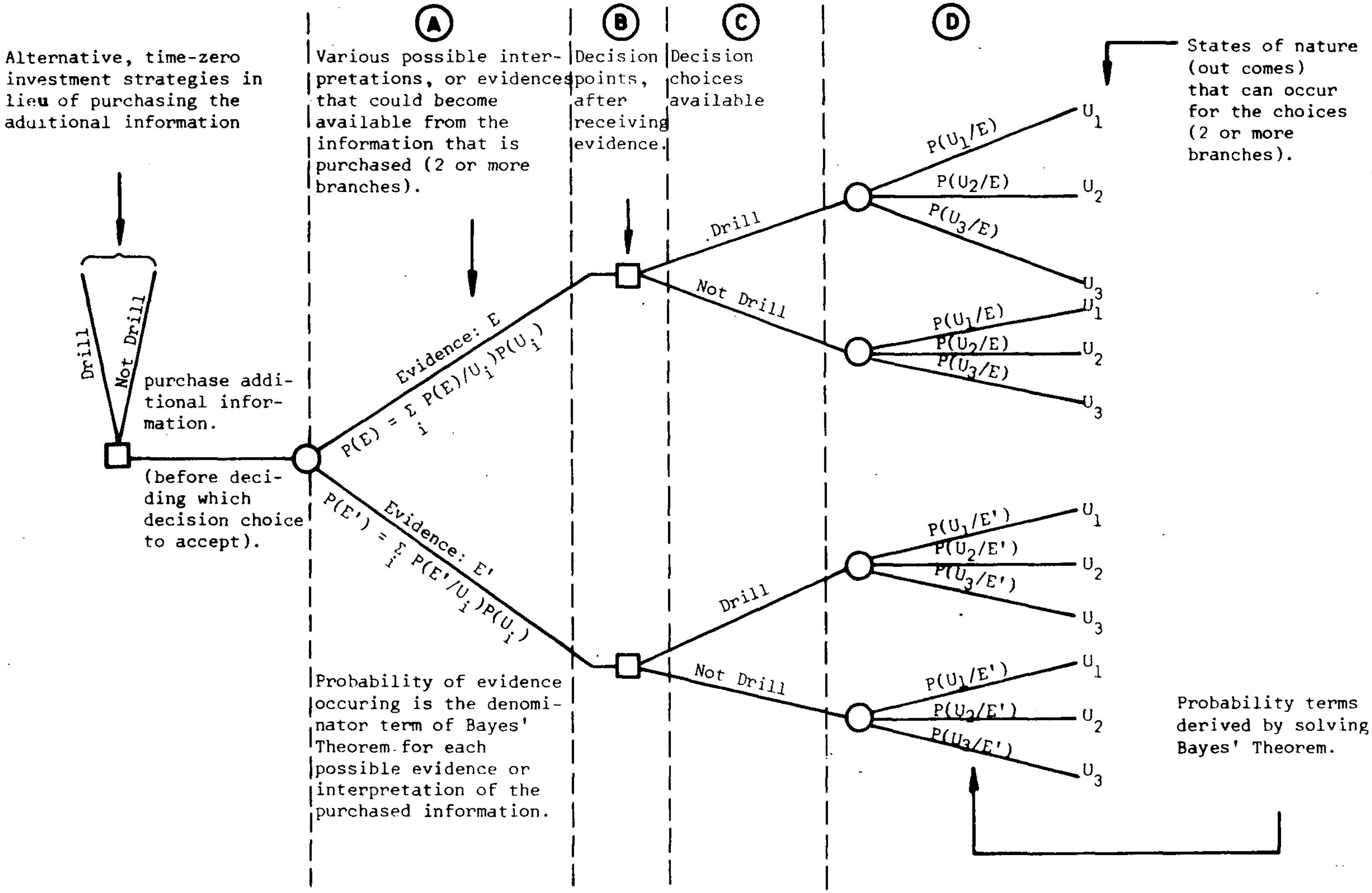

FIG.4.7: DECISION TREE USED TO DETERMINE THE FEASIBILITY OF PURCHASING ADDITIONAL INFORMATION.

If there were more than two possible interpretations of the information (E), the number of branches in Section (A) would be increased accordingly. Similarly, for Sections (C) and (D) if there were more choices and more possible states of nature $(U_1 \ldots U_n)$.

The probabilities on the chance node branches in Section (D) are obtained by solving Bayes' Theorem. The probability terms represent the revised perceptions of the likelihoods of the various states of nature, given the new evidence or interpretation. The probability terms in Section (A) represent the denominator terms of Bayes' Theorem.

Case III could be combined with either Case I or Case II, and the analysis carried out as before.

CHAPTER 5

APPLICATIONS

5.1 Ryder Lake District

5.1.1 Introduction

Since the only source of water in the Ryder Lake District is from underground, prospective settlers in the area have always wanted to know what are the chances of obtaining the quantity of water they need before investing in drilling water wells. Obviously, this is a big problem having to do with uncertainty. Therefore, a formal analysis using decision theory, will throw more light on the decision to be made instead of the dependence on sheer intuition as in the past.

5.1.2 Location

Ryder Lake District is a rolling hilly area with elevations that rise to more than 2,700 feet above sea-level. It is located within Chilliwack District Municipality, and lies between longitudes 121° 51' and 121° 56'30" and latitudes 49° 05'30" and 49° 07'30". It is bounded on the south by the Chilliwack River and on the east by the Skagit Range of the Cascade Mountains, and is about 55 miles east of Vancouver.

It has an area of approximately 26 square kilometers and a population of roughly 1,000.

It is partly a residential and partly farming community.

5.1.3 Climate

The Ryder Lake area is characterized by a heavy winter rainfall and a dry summer. About two-thirds of the annual average total precipitation of about 56 inches occurs from October to March inclusive. Rainfall during the growing season - April to September - is inadequate in most years for the maximum development and yield of crops. The heavy sustained rains from October to March replenish the groundwater reservoirs. During this period, little water, apart from runoff, is lost by evaporation and transpiration. The soil and the unconsolidated surface deposits above the water-tables are kept wet and maximum infiltration results.

5.1.4 Surficial Geology

The oldest known unconsolidated deposits in the Ryder Lake area are the Huntingdon gravels. They appear to be stream deposits laid down during the retreat of the Cordilleran Ice (Vashon) Sheet and prior to the advance of the Sumas Ice. These gravels are overlain by sediments transported by the Sumas Ice Sheet which originated in the Cascades some 11,000 years ago.

Sumas till, composed mainly of sand till, boulders, gravel and clay is formed in layers up to 50 or 60 feet thick, and in places stratified, overlying bedrock. A mechanical analysis of a fine fraction of this Sumas till gave an average result of 63 percent sand, 33 percent silt and 4 percent clay (Halstead, E.C., 1961).

The bedrock consists of shales and argillites that may yield some ground water from joints and fracture zones.

5.1.5 Water Supply

Groundwater is the only source of water in this area. And in order to tap this water, wells had to be dug or drilled. The type of well depends partly on the depth to water but more on the financial resources of the well owner.

About 60 percent of the inhabitants have dug wells to a maximum depth of about 20 feet in unconfined or perched aquifers in Sumas till. These dug wells are commonly lined with concrete tiles or wood curbing, but those dug in till may not require lining as the compact till will stand without caving or slumping. Most of these wells do not yield sufficient supplies and often go dry in summer.

Those of the inhabitants who could afford the bill, have drilled wells, (See Table 5.1 and fig. 5.1). Drilled wells are the most effective type for the recovery of groundwater and are required especially where large yields are needed, such as for municipal or irrigation use. Drilled wells are lined with a casing commonly more than six inches in diameter, and may be completed as open-end, screened, or gravel-packed wells. Cable-tool and rotary drilling rigs are used, commonly the former because of the following advantages:

1) Economics:
   a) Lower initial equipment cost, and hence lower depreciation.
   b) Lower daily operating cost, including maintenance, personnel, and water requirements.
   c) Lower transportation costs.
   d) Lower rig-up time and expense.
   e) Drilling rates comparable to rotary in hard rocks at shallow depths.
2) Better cutting samples.
3) Easy identification of water-bearing strata.
4) No circulating system.
5) Minimum contamination of producing zones. (Campbell, M.D., and Lehr, J.H., 1973).

There are, however, two groups of people in the area that have constituted themselves into Water Users Communities. They are the Uplands Water Users Community and the Southside Water Users Community. The former obtains its water directly by channelling all the flows from a group of springs known as Eden Banks Springs. These springs produce nothing less than about 10,000 gallons of water per day which is more than sufficient for the eighteen homes (lots) and one slaughter house they are supposed

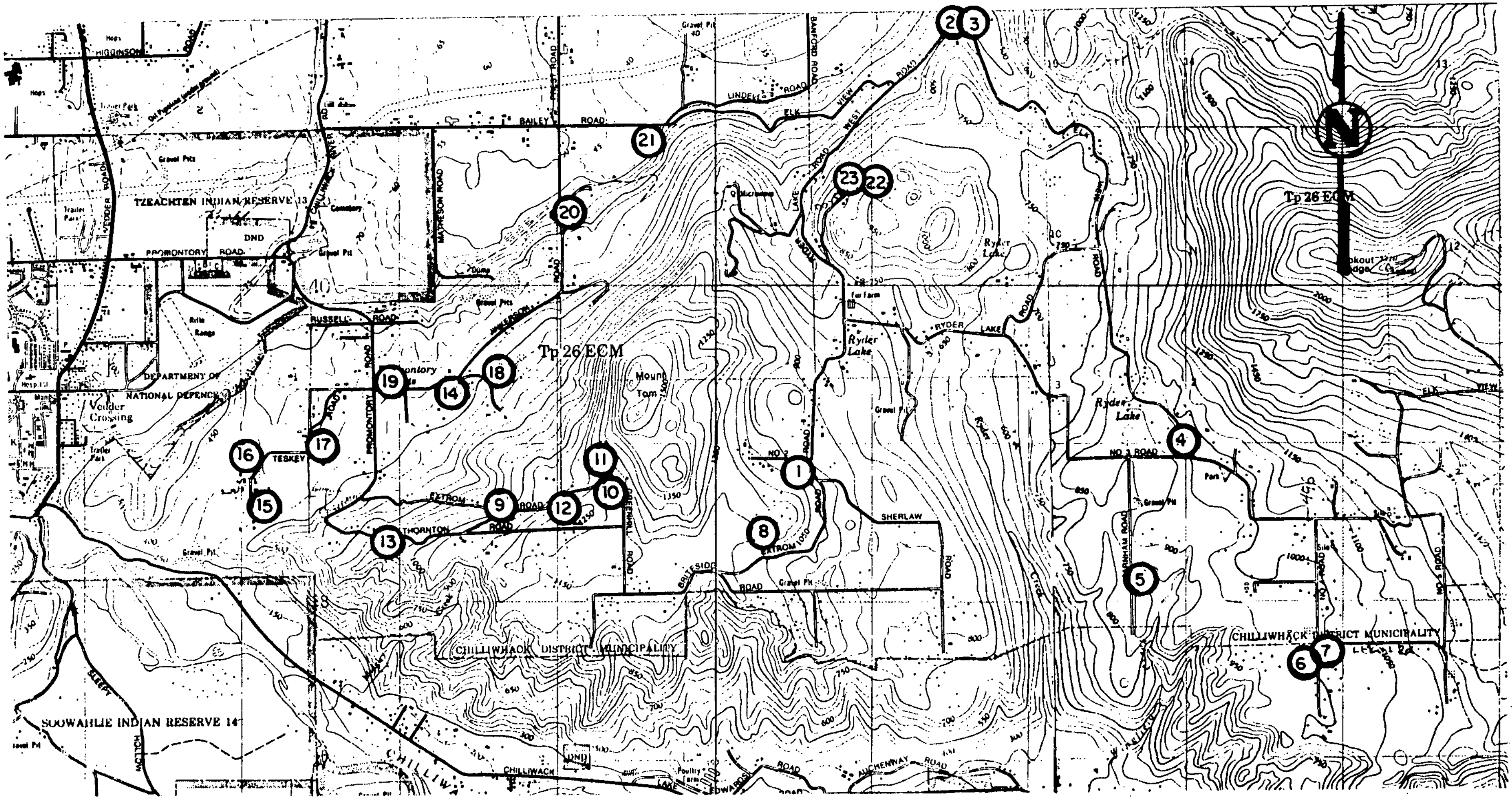

FIG. 5.1: MAP SHOWING DRILLED WELL LOCATIONS.

–RYDER LAKE AREA–

to serve. The Southside Water Users Community, made up of 20 homes (lots), also obtain their supply from a spring which flows into a dug well about 15 feet deep. Surprisingly, none of the supplies has gone dry so far.

5.1.6 Quality of Water

The hardness of the groundwater in this area ranges between 43 and 135 parts per million (ppm) (Halstead, 1961). The water is generally medium to soft, but there are some exceptions. Where hard water is found, its total hardness is not excessive and does not limit the use of the water.

The water also falls within safe limits for irrigation use. Some might be rejected because of its high iron content and the probable damage it could cause to the distribution system.

5.1.7 Decision Model Applications To Ryder Lake Area

The only available well data for the study area as shown in Table 5.1 was used in all the calcuations and graphs.

A Probability Matrix Program (set up in the Civil Engineering Department for manipulating probability matrices and vectors with options for multiplication, addition, subtraction, updating and rescaling) was used for the expected value computations.

5.1.7.1 Case I of Model

First, a cumulative probability versus yield curve was produced using data from Table 5.1. Secondly, a utility (of drilling) versus yield curve (fig. 5.2) was obtained as in fig. 4.2 and using equation (4.1). The optimum domestic water requirement was taken as 1 gpm; and 5 gpm (a value below which no drilling licence would be issued) was assigned a utility value of 100, that is U(5 gpm) = 100, and U(0 gpm) = 0. Shown below is a sample calculation of points plotted to obtain the utility (of drilling) curve.

TABLE 5.1 DRILLED WELL RECORDS - RYDER LAKE DISTRICT

Address	Depth (ft)	Dia. (in)	Yield gpm	Comments
1. Ryder Lake Rd. & No 2 Rd (February 1977)	132	6	1½	Quartz Lenses, Fractures @ 132'
2. 48455 Elk View Road	744	6	1½	9 - 284 Bedrock
3. 48470 Elk View Road (October 1975)	104	6	2	0 - 10 till; 10 - 104, bedrock
4. 49185 Elk View Road (November 1972)	47	6	Dry	0 - 8 gravel; 8 - 17 till; 17 - 47, gravel
5. 5014 Farnham Road (May 1976)	249		Dry	0 - 42 sand, gravel 240 - 249, clay hardpan
6. 49612 Atkins Road (December 1974)	110		Dry	0 - 41 gravel; 50 - 110 packed sand and gravel
7. Extrom Road (Location?) (December 1974)	365		Dry	345 - 365 gravel, sand some shale, 0 - 17 find sand
8. 47320 Extrom Road (July 1971)	500		3½	0 - 8 loam 340 - 500 shale
9. 46925 Extrom Road (1970)	269	6	1	0 - 30 hard packed sand and clay; 263 - 269 gray clay
10. 47200 Extrom Road (May 1975)	740	6	Dry	0 - 37 till; 281 - 740 bedrock
11. 46650 Thornton Road (July 1975)	443	6	Dry	Sand and gravel (0 - 443)
12. 46880 Jinkesson Road (July 1958)	63		Dry	0 - 17 silted gravel and till; 53 - 63 dry sand
13. 5296 Tesky Road (September 1971)	61		Dry static 106	Sand
14. 5392 Tesky Road (September 1975)	343	6	2	0 - 26 till; 94 - 343 bedrock, shale
15. 47005 Russell Road (June 1977)			Dry static 198'	0 - 60 till and boulders 245 - 265 gravel, sand
16. 46655 Russell Road (December 1974)	343	6	1½ static 101'	0 - 6 loam
17. 6180 Promontory Rd (1959)	127	6	3	0-20 dug well 112 - 118 w.b. sand
18. 588 Bailey Road	123		Dry	0 - 22 peaty loam 121 - 123 coarser sand
19. End of Parsons Road (September 1974)	380	6	Dry	0 - 155 sand, gravel 300 - 380 silty sand & clay

continued overleaf

TABLE 5.1 (Continued)

20. 6235 Parsons Road (September 1974)	320	6	1	0 - 6 Dirt 6 - 320 shale
21. Lindel Road (May 1976)	455	6	½	0 - 21 broken shale 21 - 445 shale
22. Lindel Road (August 1976)	85	6	3	0 - 9 overburden 9 - 85 shale

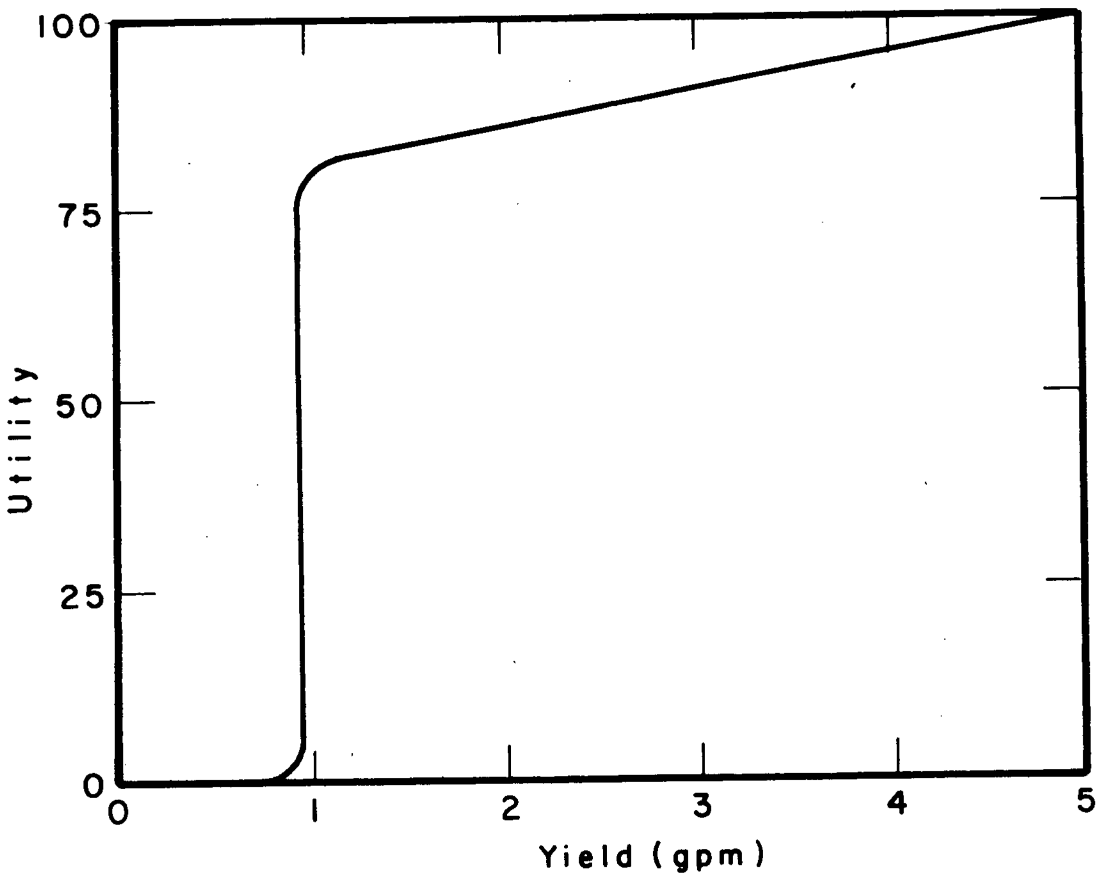

FIG.5.2: UTILITY VERSUS YIELD (RYDER LAKE AREA).

1st Question; posed to one of the well-owners, gave the following result:

Alternative 1: Obtain 1 gpm for certain, or

Alternative 2: A gamble in which there is an 80-20 chance of obtaining 5 gpm or a dry hole (0 gpm).

Using equation (4.1),

$$U(1\text{ gpm}) = 0.8[U(5\text{ gpm}] + 0.2[U(0\text{ gpm})]$$
$$= 0.8 \times 100 + 0.2 \times 0 = 80$$

2nd Question; gave the following result:

Alternative 1: Obtain 3 gpm for certain, or

Alternative 2: A gamble in which there is a 50-50 chance of obtaining 5 gpm or 1 gpm.

Again using equation (4.1),

$$U(3\text{ gpm}) = 0.5[U(5\text{ gpm})] + 0.5[U(1\text{ gpm})]$$
$$= 0.5 \times 100 + 0.5 \times 80 = 90$$

By inputting the curves in figs. 5.2 and 5.3 into the computer program, and multiplying, the expected utility value of drilling, EUV_D was found to be 33.66.

On the other hand, the expected utility value of not drilling, EUV_{ND}, was obtained as 85 using the method of asking questions outlined in the preceding chapter.

Comparing both expected utility values, the ultimate decision for this case would be <u>not to drill</u>.

5.1.7.2 Case II(a) of Model: No Relationship Between Yield and Depth

First, the utility versus yield curve (fig. 5.2) and the yield versus cumulative probability curve (fig. 5.3) were fed into the computer program and multipled to obtain an expected utility value (EUV_y as regards to yield)

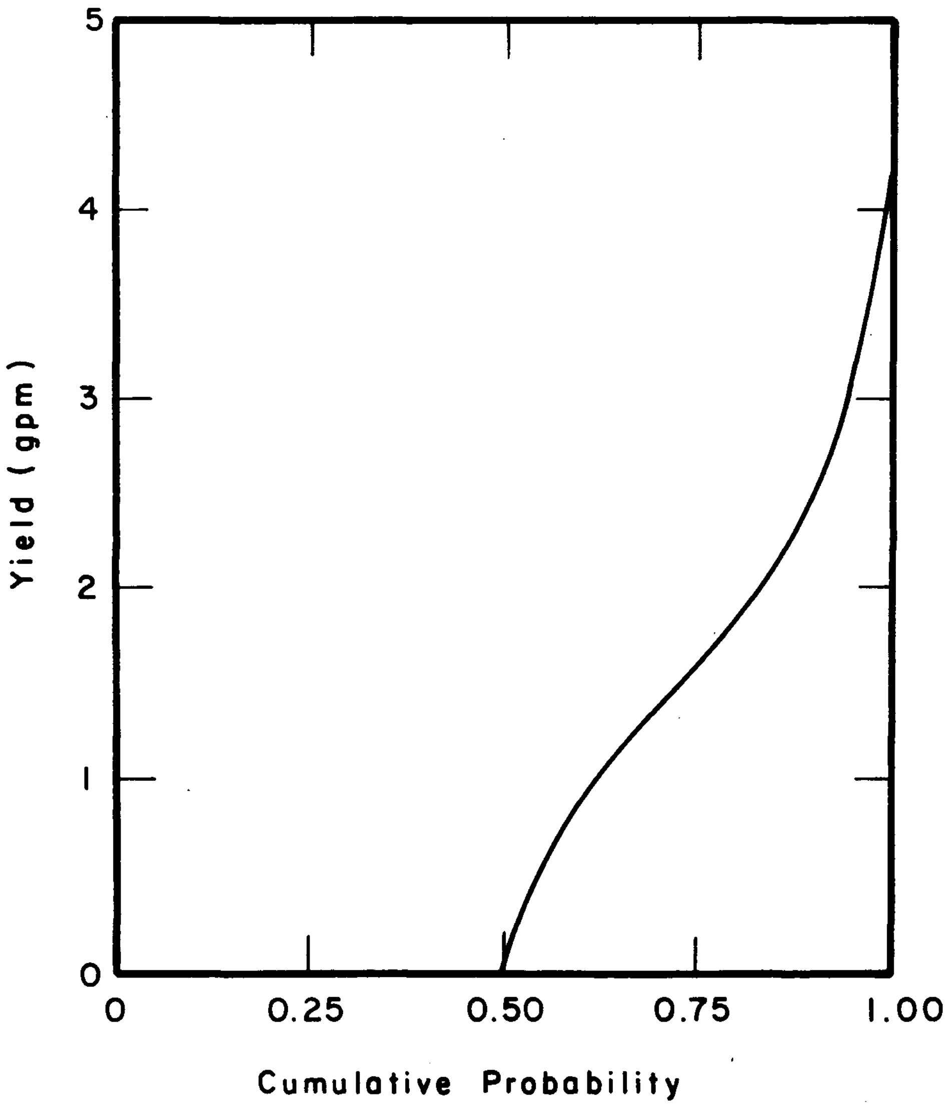

FIG. 5.3: YIELD VERSUS CUMULATIVE PROBABILITY.

— RYDER LAKE AREA —

of 33.66, as in Case I. Secondly, the utility "cost" versus depth curve (fig. 5.4) and the depth versus cumulative probability curve (fig. 5.5) were fed in and again multiplied to obtain an expected utility value (EUV_d) as regards to depth) of 32.39. The difference of 1.27 between both values was found to be the expected net utility value of the act "to drill".

5.1.7.3 Case II(b) of Model: Probability Relationship Between Yield and Depth

For this case, the utility versus yield curve (fig. 5.2) and the yield versus depth curve (fig. 5.6) in the form of a probability band were fed into the program and multiplied to obtain an expected utility value in the form of a matrix. From this matrix was subtracted the utility "cost" versus depth curve (fig. 5.4) (in matrix form) to obtain expected net utility values for all the various depths (also in matrix form). The depth versus cumulative probability curve (fig. 5.5) was finally fed in. The matrix of the expected net utility values for the different depths was multiplied by the cumulative probability matrix to obtain the overall expected net utility of drilling decision of 43.17.

Using equation (4.4) with $p = 0.7$, the expected utility value of not drilling (EUV_{ND}) was calculated to be 140.

Comparing the expected net utility values of the act "to drill", namely, 1.27 for Case II(a), 43.17 for Case II(b) and the expected utility value of the act "not to drill" (140), the decision to be made would then be "not to drill".

5.2 Inches Creek

5.2.1 Location

Inches Creek study area is part of the alluvial fan and flood plain deposits at the mouth of Norrish Creek on the north of the Fraser River about 80 kilometres east of Vancouver (British Columbia) (fig. 5.7). Because

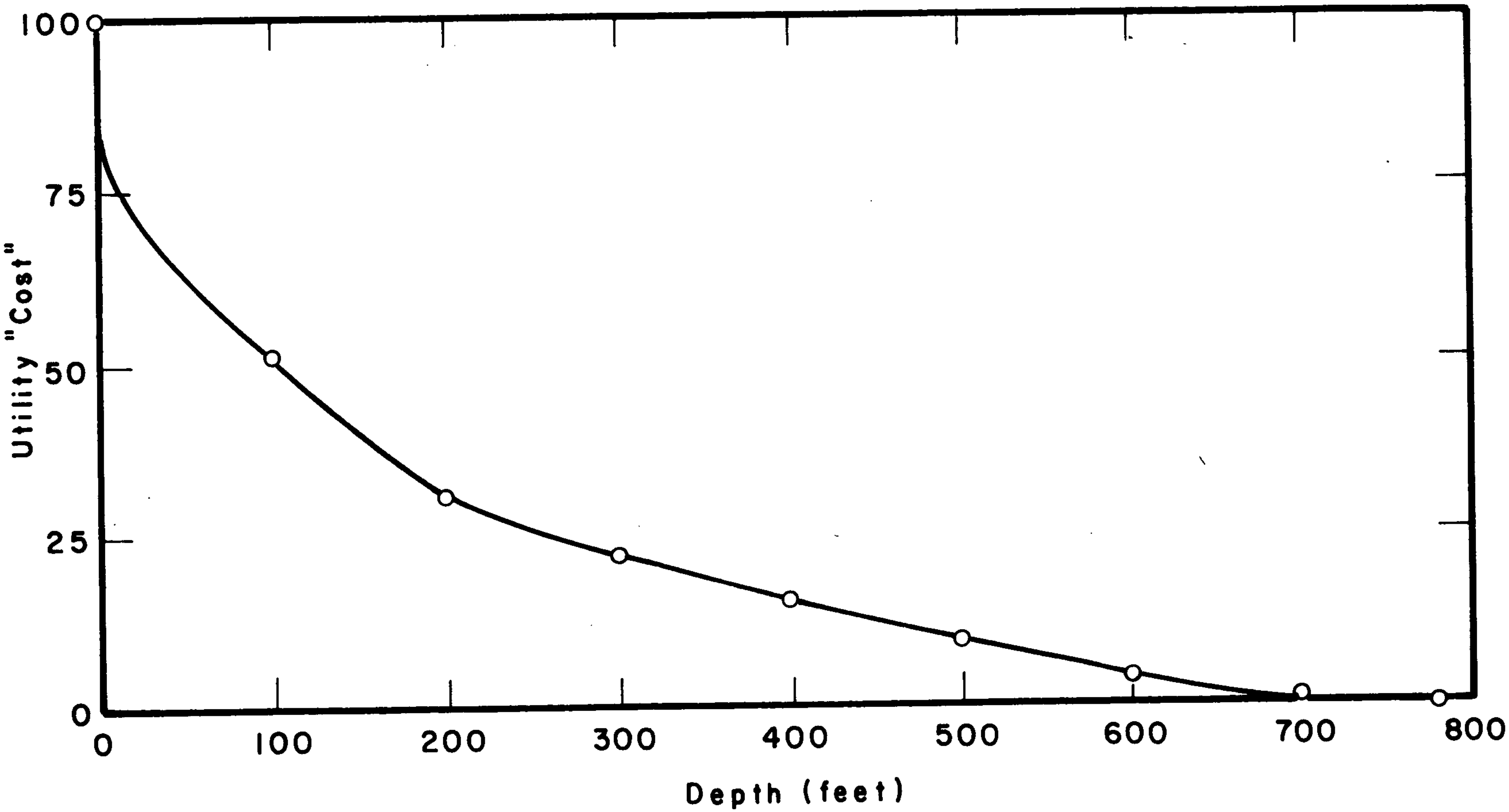

FIG. 5.4: UTILITY "COST" VERSUS DEPTH (RYDER LAKE AREA).

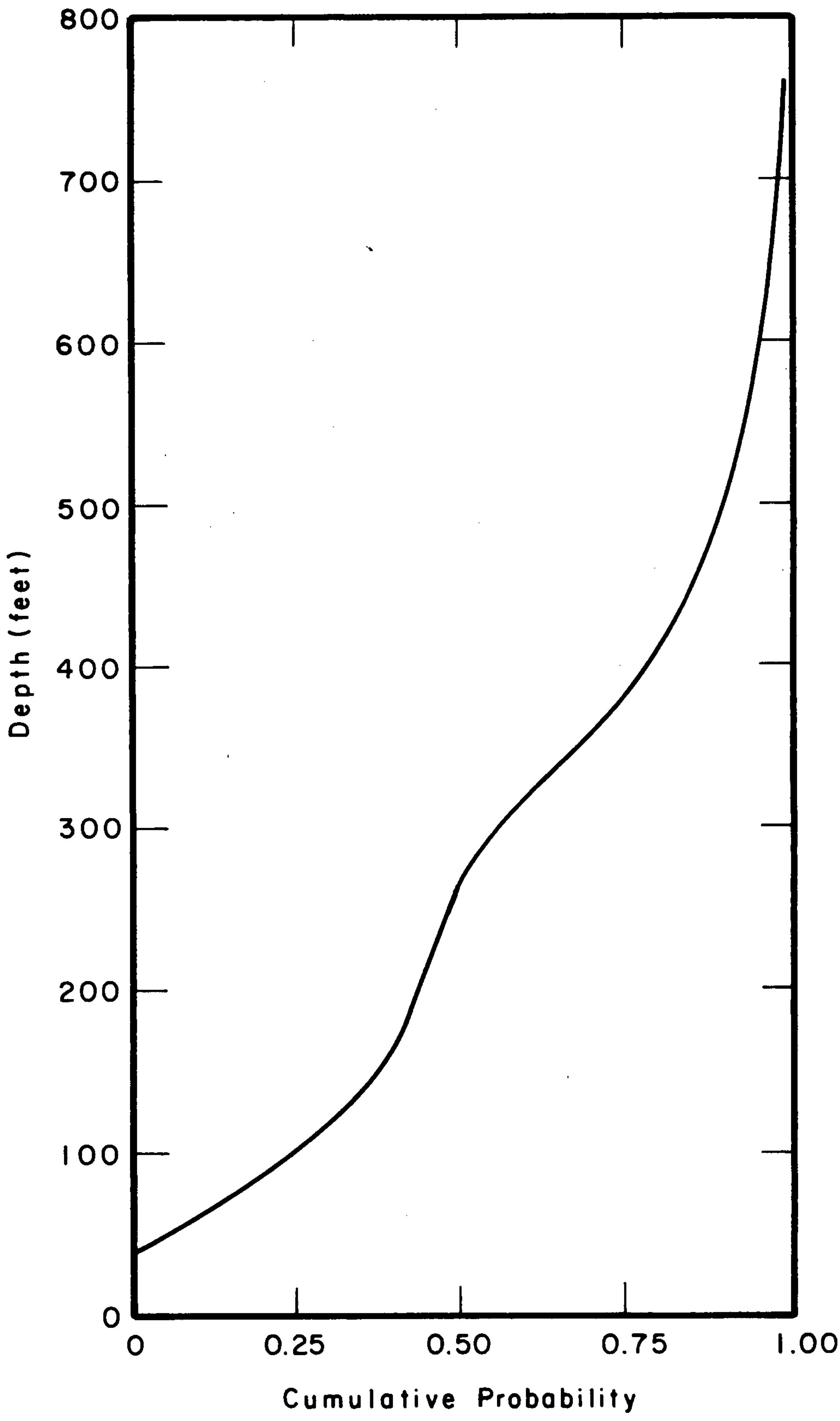

FIG. 5.5: DEPTH VERSUS CUMULATIVE PROBABILITY.

— RYDER LAKE AREA —

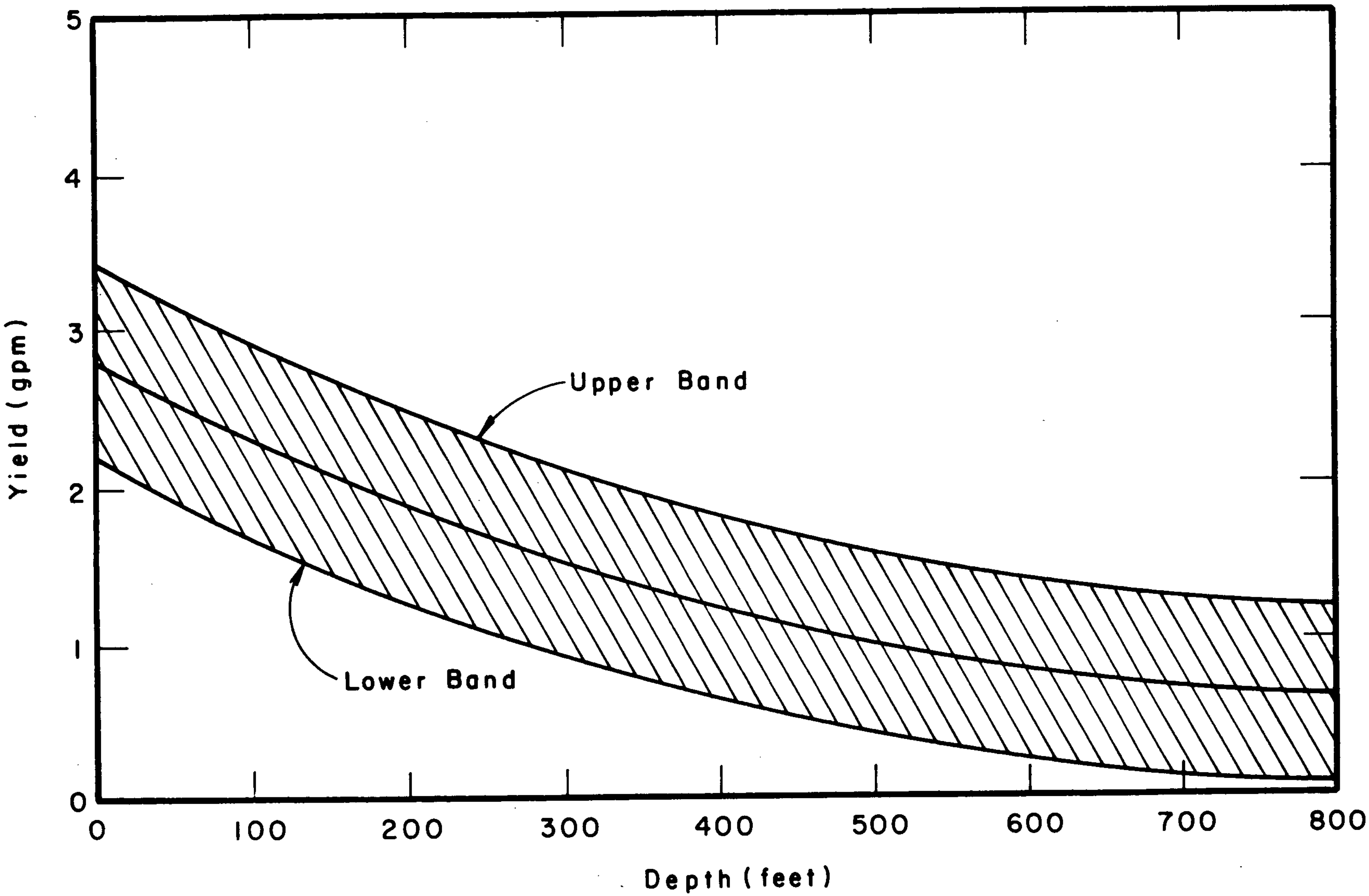

FIG.5.6: YIELD VERSUS DEPTH PROBABILITY BAND (RYDER LAKE AREA).

of the hydrogeological setting of Inches Creek, it has become an important natural spawning ground for coho and chum salmon.

5.2.2 Objective of Study

The objective of the study is to provide approximately 4500 gpm of groundwater needed for salmon enhancement facilities (spawning, hatchery, and incubation) for the Fisheries Department.

5.2.3 Aquifer Recharge

The recharge to the aquifer in Inches Creek area is partly from precipitation and partly from inflow from Norrish Creek.

5.2.4 Application Of Decision Model Case III

The initial problem in Inches Creek study area was the lack of past drilled well data from which probabilities of occurrence of the various well yields could be obtained. The hydrogeologists, therefore, had to carry out preliminary geologic investigations and were able to give the following aquifer yield estimates:

Minimum yield	=	1000 gpm
Most probable yield	=	2500 gpm
Maximum yield	=	5000 gpm

Applying a triangular distribution to the above, a yield versus cumulative probability (prior) curve (fig. 5.8) was obtained.

In order to obtain some more information about the yield of the aquifer and hence the number of production wells that would be needed, a test hole was drilled and pump-tested at a total cost of approximately $2,500. Based on the new test yields, the hydrogeologist, from past experience, was able to predict corresponding production well yields and hence the probability band shown in fig. 5.9.

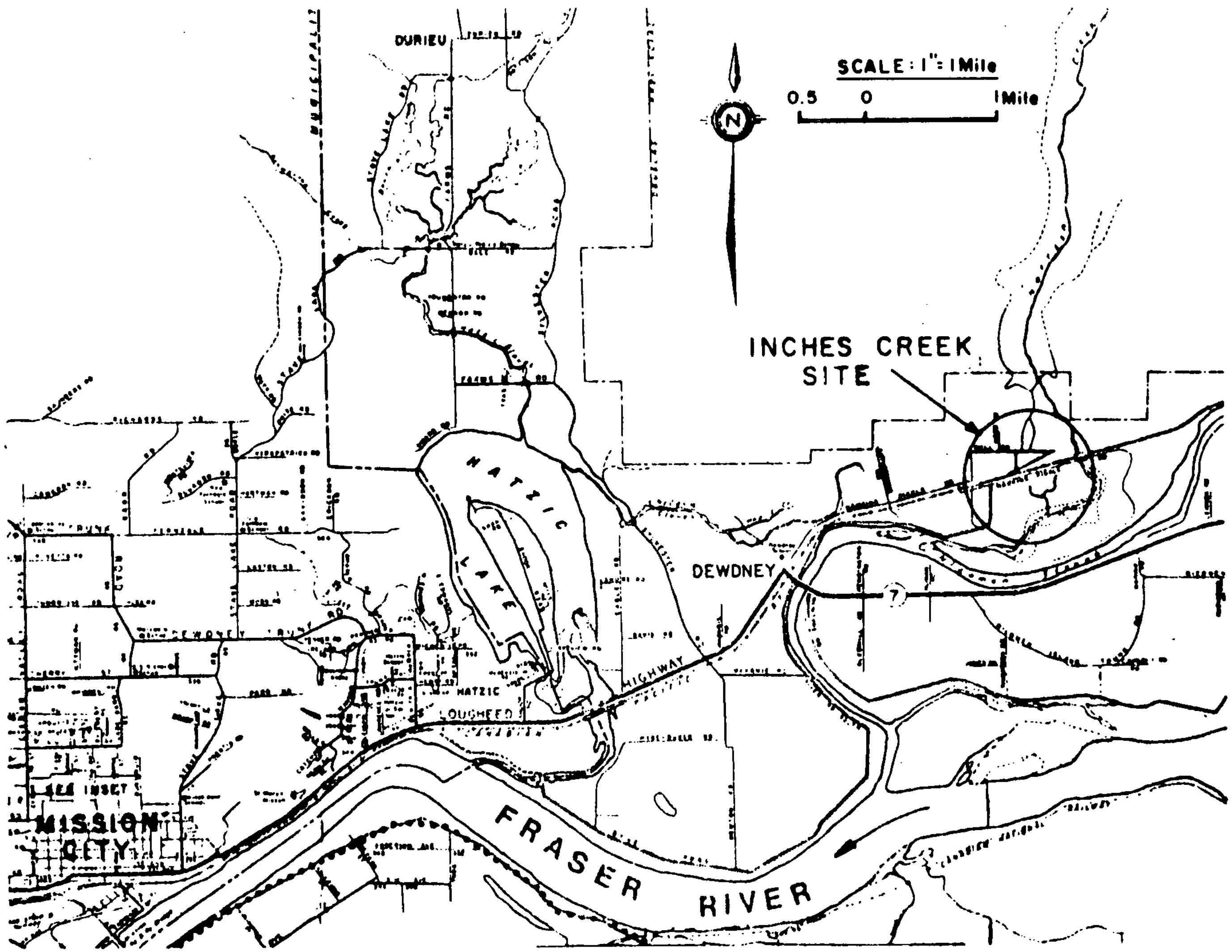

FIG. 5.7: INCHES CREEK LOCATION MAP.

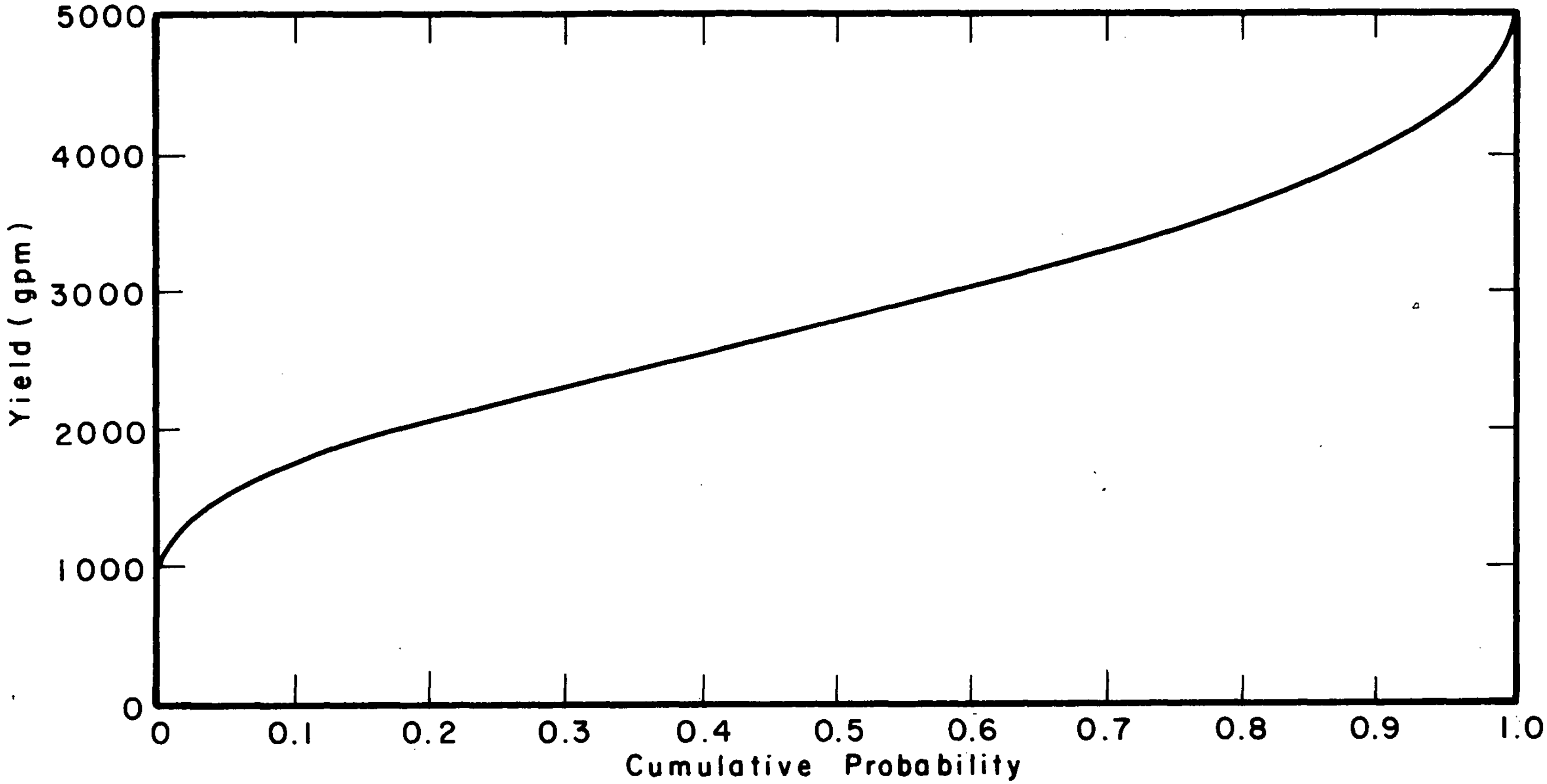

FIG. 5.8 : YIELD VERSUS CUMULATIVE PROBABILITY (PRIOR).
— INCHES CREEK —

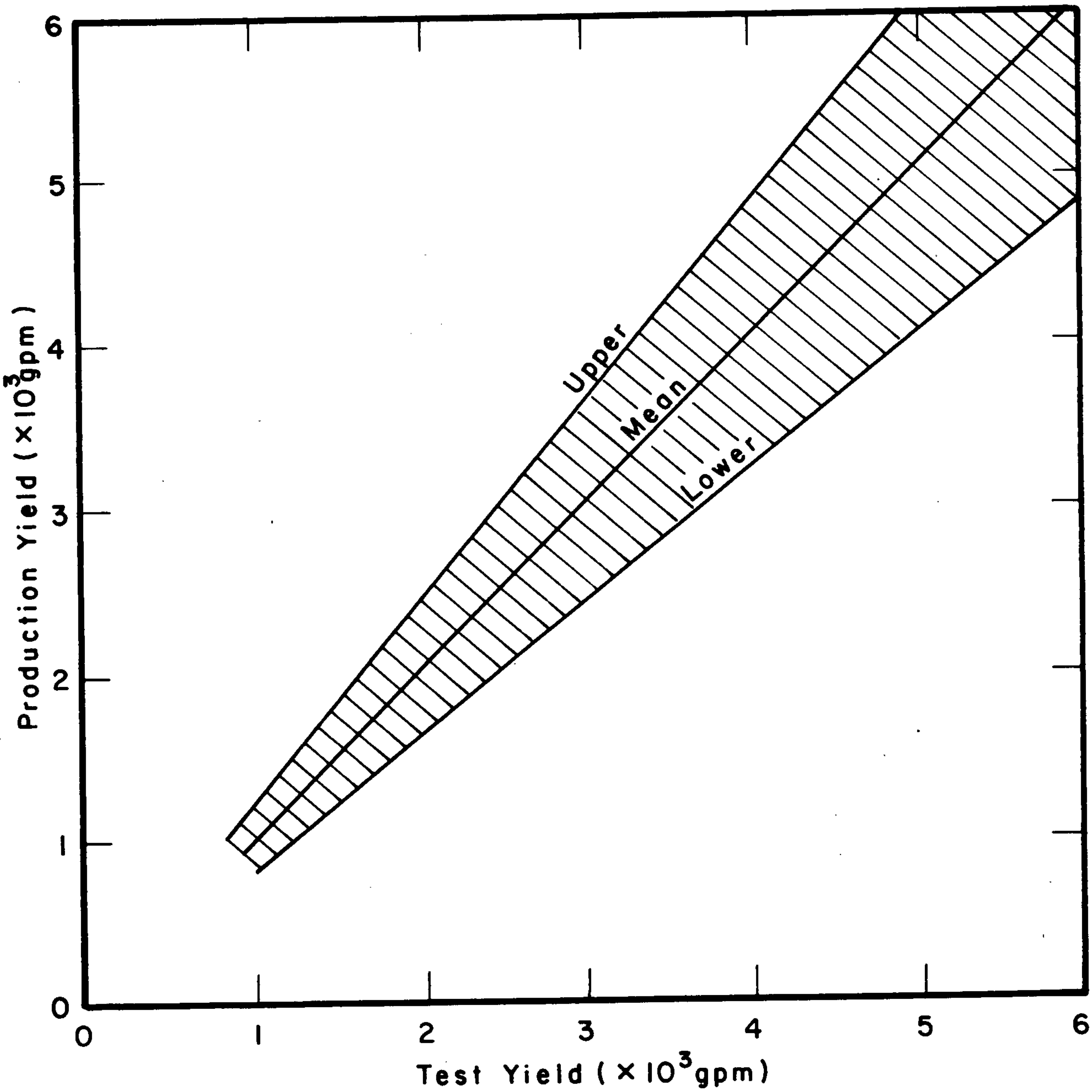

FIG. 5.9: PRODUCTION YIELD VS. TEST YIELD PROBABILITY BAND.

— INCHES CREEK —

To obtain a monetary value versus yield curve such as in fig. 5.10, the owner of the project was asked how much he would be prepared to pay for various yields, for certain, if he were buying ready-made wells.

Figure 5.11 shows the decision tree layout. At the terminal H, the outcome of the various yields would be the dollar values C_1, C_2, ...C_5, obtained from fig. 5.10. But at G, the corresponding outcomes would be $(C_1 + C_T)$, ... $(C_5 + C_T)$, where C_T is the cost of the test well. Figure 5.9, when applied to the computer program (used in Ryder Lake Analysis) produces probabilities [$(\bar{p}_{p/t})$ of production yields given the various test yields] in the form of a matrix. Multiplying the row matrix produced from fig. 5.10 (after adding C_T) by the above matrix gives another row matrix of test expected monetary values $TEMV_1$ .... $TEMV_5$. The probabilities $(p_{t1} \ldots p_{t5})$ of obtaining the various test well yields are found by using Bayes' Theorem. These probabilities multiplied by their corresponding (TEMV) values and summed gave the net test expected monetary value (NTEMV) of $1,162.

By using figs. 5.8 and 5.10, an expected monetary value (EMV) of $1,662 was obtained for the decision node C. And hence the decision to drill a test hole has been proved to be justifiable.

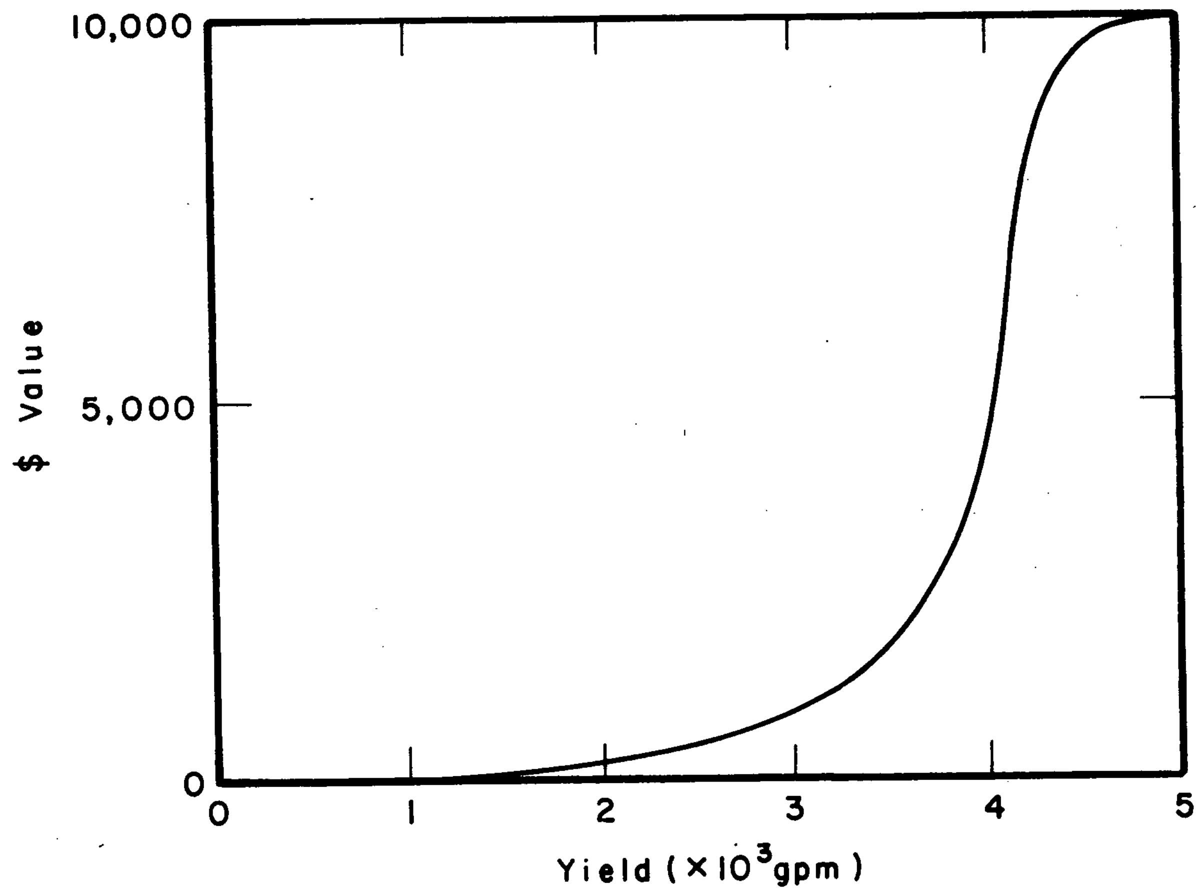

FIG.5.10: PRODUCTION WELL COST VERSUS YIELD.
—INCHES CREEK—

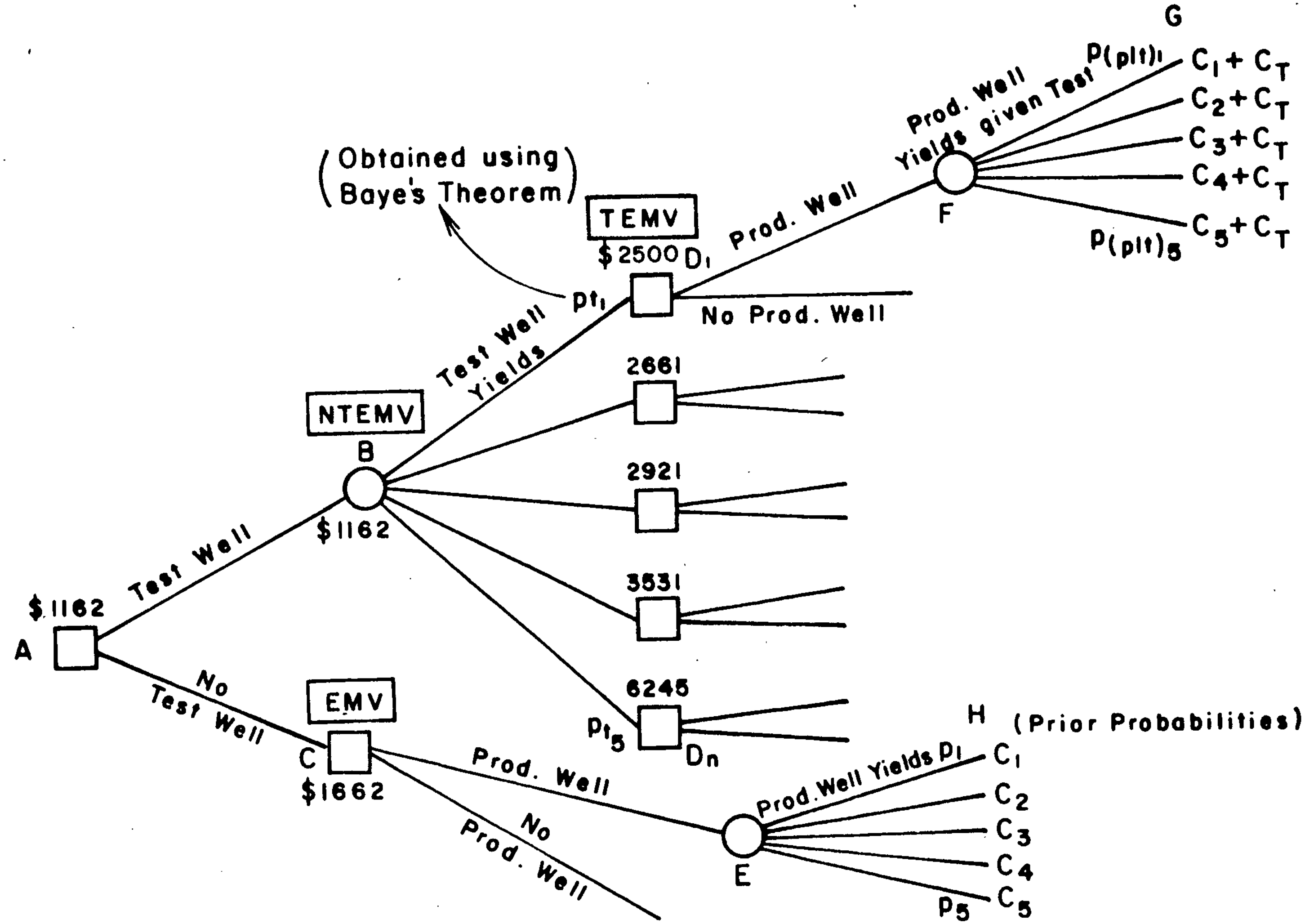

FIG. 5.11: DECISION TREE SHOWING PURCHASE OF IMPERFECT INFORMATION.
— INCHES CREEK —

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The decision models developed in this thesis are to enable prospective water well owners to make the right decisions under condition of uncertainty, that is, whether to invest in drilling or not; or whether to first of all spend extra money in drilling test holes in order to gain more information about an aquifer before actually embarking on drilling the required production well(s). The decision criterion, however, is based on expected utility which is a summation of the products of probabilities of obtaining the various yields and utility values.

The utility values are those of the decision maker and entirely represent his preferences. One major problem, therefore, lies in obtaining a fairly accurate utility curve. And so far, there has not been a set-down procedure for achieving this.

Where there are no past well records as in the Inches Creek area, the probabilities of obtaining various yields will certainly be those of the expert hydrogeologist. And, of course, these probabilities will vary from one hydrogeologist to another. There is no doubt, then, that the accuracy of the results will be very much affected by these two parameters - utility and probability (the source of uncertainty).

The results for the Ryder Lake District indicate the decision of not to drill any water wells at all while in the Inches Creek area, the decision to drill two production wells in order to meet the 4500 gallons per minute requirement was made only after drilling a test hole. The above decisions could have been made without going through a formal, systematic analysis as outlined in the thesis. But what if the decision maker has made a wrong decision. How would he exonerate himself? What would be his criterion for the decision he has made? Hence, in order to protect himself, he definitely will need to follow a rational process, considering all risks involved before arriving at a final decision.

Finally, use of the techniques in this thesis will enable the justification of major decisions especially those dealing with public resources such as the Fisheries.

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