GREAT LAKES FISHERY COMMISSION

1982 Project Completion Report[1]

Application of Decision Analysis to Sea Lamprey Control

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APPLICATION OF DECISION ANALYSIS
TO SEA LAMPREY CONTROL

Prepared for the
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Acknowledgements

We thank R. A. Braem, director of the Sea Lamprey Control Station, Marquette, Michigan, and J. J. Tibbles, director of the Sea Lamprey Control Centre, Sault Ste. Marie, Ontario, and their staffs for their openness and cooperation. Information provided by the control unit staffs during interviews and in supplementary documentation form the basis of this report.

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I. Selection of Streams for Treatment

INTRODUCTION

Our intention at the outset of this project was to examine, using tools from statistical decision theory, the decision rules of the sea lamprey control units. We realized the inappropriateness of statistical decision theory, which is based on statistical properties of sampling and estimation, in examining the selection of streams for treatment after completing the interviews with the staff of the two control units. Neither control unit uses statistically based estimates in their selection of streams for treatment. Data from sampling coupled with informed judgment form the basis of subjective synthesis that lead to the selections.

Nevertheless, the strategies employed by the control units in selecting streams for treatment can be characterized and examined, albeit at a coarser level. This characterization and examination of the strategies employed for selecting streams for treatment is the topic of this report section.

GENERAL STRUCTURE FOR DECISION PROBLEM

The first step in structuring the decision problem is to identify the alternative actions. Stream treatment with chemical lampricide presently is viewed as the only viable option by the control units. The use of barrier dams is not a real alternative for the control unit in the U.S. because the unit is limited to advising the states of appropriate locations for barrier dams. The actual decision to construct is one made by the states and not by the control unit. A similar situation exists for the Canadian control unit in that the province has the final word on construction of dams, leaving the control unit in an advisory capacity. The Canadian unit claims to have advised construction on many feasible sites with the province vetoing construction on all but the smallest streams. Another non-chemical approach, biological control, is not seen as a viable option because the methods and associated technologies are not believed to be sufficiently developed for effective control. Consequently, the list of alternative actions is a list of streams that might be treated with lampricide.

The next component of the decision problem that must be identified is the meter used to evaluate expected consequences. An appropriate meter, and one that is used at least implicitly by both control units, is the reduction in the number of transformers migrating into the lake. That reduction is one measure of the benefit from the control program and may be used directly in ranking alternatives, providing the reduction in numbers is monotonically related to the value of the fishery. Benefit alone is required if the selection of alternatives is based solely on effectiveness, i.e. on what is accomplished regardless of expense. Some measure of cost is required also if selection is based on efficiency which is a composite of both benefit and cost. Other attributes of value may be associated with the consequences of the control effort, however reduction in the number of transformers and cost of treatment seem to be overwhelmingly important in selecting streams for treatment. The problem of incidental mortality of non-target species is addressed directly in scheduling streams for treatment within a year and in the selection of lampricide concentration for treatment.

A framework for examining the decision rules relating to the selection of streams for treatment now can be constructed. Associated with each stream in each year are the expected reduction, due to treatment, in the number of transformers produced by the stream and the expected cost for that treatment. Thus each stream can be represented as a point on a plane, the coordinates of which are benefit (the expected reduction in transformers due to treatment) and the cost of treatment (Figure 1). The alternative actions facing the control units can be represented in a similar manner, with each point representing a particular group of streams rather than a single stream. For example, one point may represent treatment of twenty particular streams all in one year. The coordinates for that point are the expected total reduction in transformers and the total cost for treating those twenty streams (Figure 2). This representation allows for the characterization of decision rules in terms of the management criteria, effectiveness and efficiency.

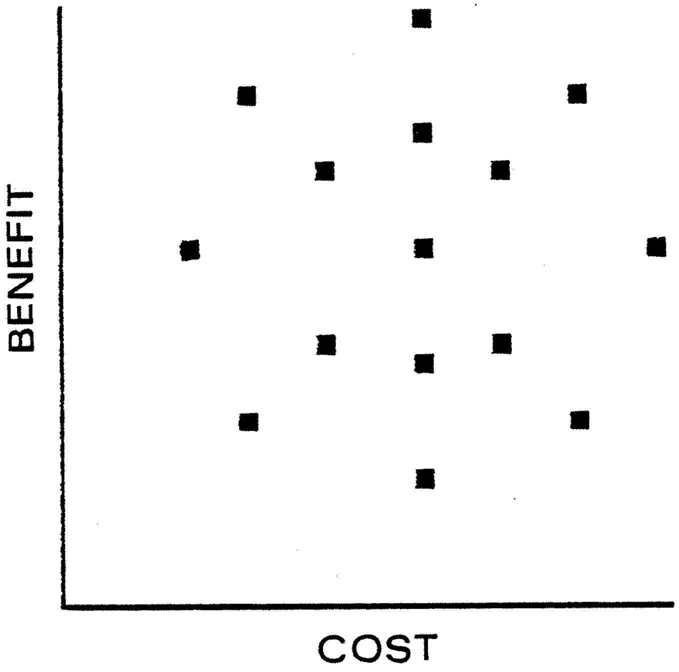


Figure 1. Representation of 15 hypothetical streams each characterized by a benefit from and a cost for treatment. The measure is the expected reduction in the transformer production due to treatment.

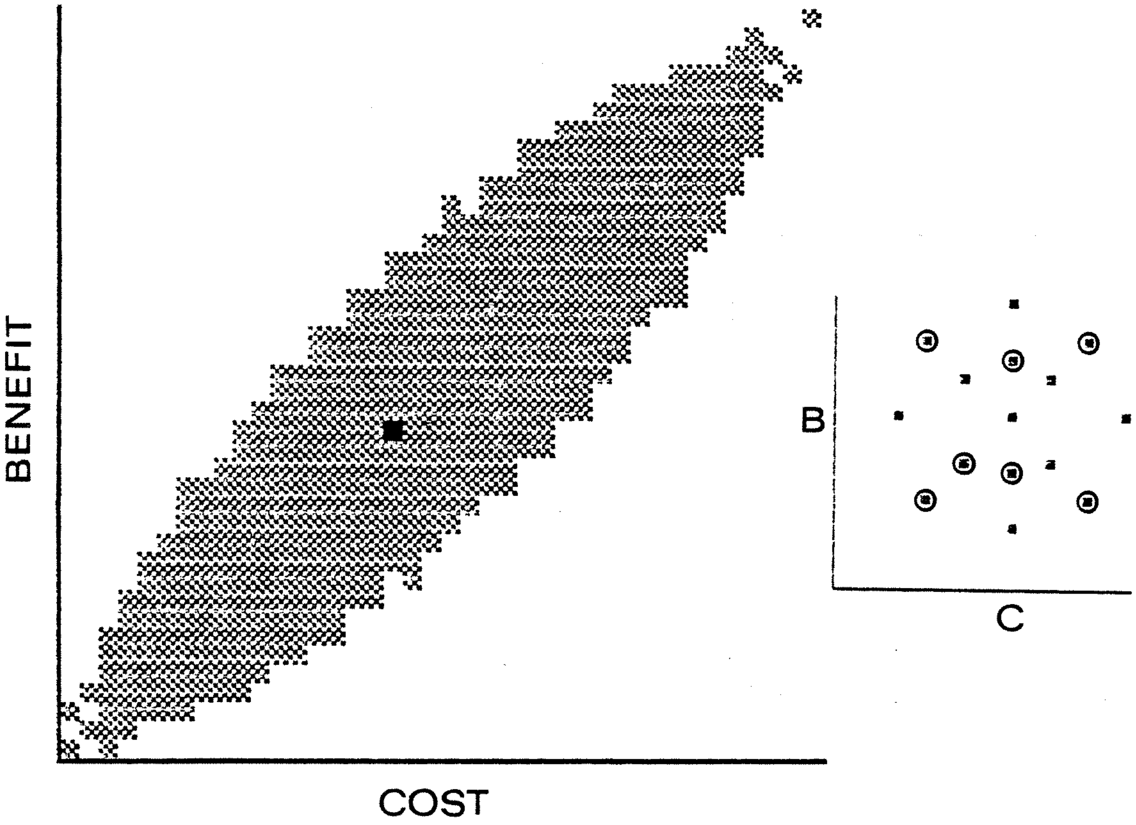


Figure 2. Representation of aggregate benefits and costs that result from considering groups of streams for treatment. This plot is a cluster of such points that include all possible combinations of the 15 hypothetical streams. (Note: the range of values on the two axes is much greater than that of Figure 1.) For example, the darkened square represents the aggregate benefits and costs of those streams depicted by the circled points of the inset figure.

Note: The aggregate benefits (and costs) were computed for illustrative purposes as the sum of individual benefits, i.e. $B(A,a_i) = B(A) + B(a_i)$ where

a_i is the action, treat stream i only,

A is the action, treat a particular group of streams not including i,

A,a_i is the action, treat the group of streams under A and stream i,

and B(.) is the benefit that results from an action.

However, the characteristic patterns that are addressed in this report pertain whenever $B(A,a_i)>B(A)$.

UNITED STATES CONTROL UNIT

The information that is generated by the U.S. control unit for use in selecting streams for treatment and the way in which that information is organized can be represented in the framework outlined above. The terminology that we are using may not be that used by the control unit, but the information is substantially the same. A conscious effort is made to assign expected benefits to the streams under U.S. jurisdiction. The level of expected benefit assigned to each stream is based primarily on the expected reduction in number of transformers produced by the stream. Assessment of expected reduction in transformers includes consideration of the abundance of ammocoetes, the proportion of ammocoetes greater than 120 mm, growth rate of ammocoetes, reliability of survey data, success of the last treatment, size of the adult runs and migration of ammocoetes into untreatable areas. A subjective synthesis of these factors, which have been qualitatively described, leads to a ranking of streams. In addition to the expected reduction in transformer production, the ranking for expected benefit for each stream is weighted by the level of activity of parasitic stage lamprey associated with the stream. Those streams associated with very active parasitic populations (high wounding rates near stream) are given a higher priority for treatment.

A detailed assessment of expected benefit is not made for every stream, rather the streams are classified first as either having significant potential for transformer production or not. Only those streams that are judged as having significant potential in a particular year are assessed for expected benefit. The effect of this first cut can be represented by dividing the plot of streams into two sections by a horizontal line (Figure 3). Only those streams above the line, i.e. those believed to have a significant potential for transformer production, are considered for treatment. Placement of a stream above or below the line depends largely on the date of last treatment, the effectiveness of the last treatment, recent survey results, the history of ammocoetes in the stream and the suitability of the stream habitat for lampey spawning and ammocoete survival. Again, these factors are dealt with qualitatively and assignment to a category is subjective. The effect of censoring the set of streams based solely on expected benefits is to reduce the alternatives to a subset of those originally available (Figure 4). Some streams that are not under active consideration for treatment in a particular year may be surveyed for ammocoetes. Such a stream may be considered for treatment in the following year depending on the results of the survey. An effort is made to survey all streams with a recent history of significant transformer production at least once every four years.

The total expected benefit and total cost of treatment for combinations of streams are computed after a level of expected benefit is assigned to each of the streams under active consideration for treatment. Not all possible combinations of streams are considered rather, attention is given to those combinations with a total cost close to the amount budgeted for the control effort. This is not an unreasonable approach in light of the total number of possible combinations, e.g. with 60 streams under active consideration over a billion billion combinations exist.

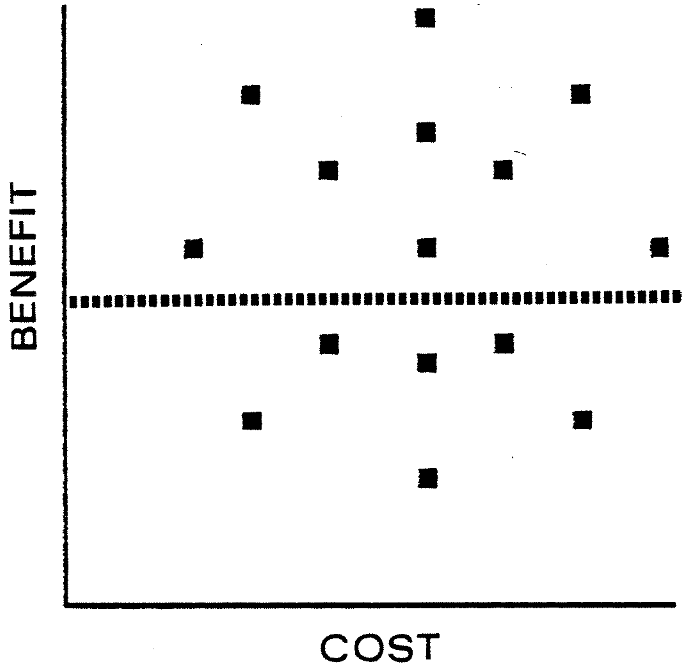


Figure 3. Representation of the set of all streams within the jurisdiction of one control unit divided into two categories based solely on benefit. Those streams above the line are believed to have a significant potential for transformer production.

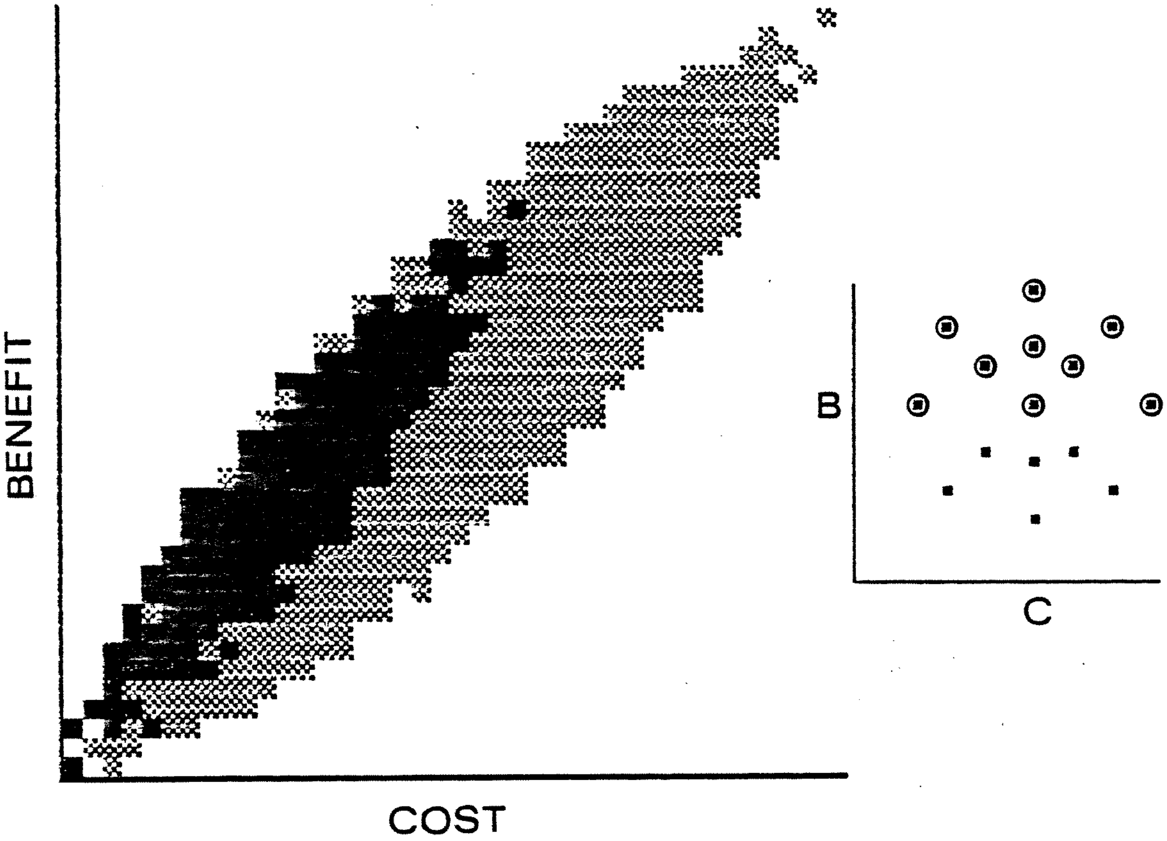


Figure 4. Representation of the effect that censoring the set of streams based on benefit has on the set of alternative actions. The darkened cluster represents those combinations that remain after censoring (circled points of the inset figure). The lightly shaded cluster represents the original set of alternatives.

Some strategy for reducing the number of combinations that constitute the alternative actions is required. The set of alternative actions that results from this culling of combinations can be represented on the plot of combinations of streams as a cluster of points about a vertical line located at a level of cost equal to the budget for the control effort (Figure 5).

The final step in selecting a particular group of streams to treat is to identify the combination with the greatest expected benefit within the constraint of the budget (Figure 6). The amount budgeted for the control effort is an independent constraint in that the request for funds is made prior to evaluating the alternative actions. Furthermore the level of funding that is requested is based primarily on the costs for retaining the treatment crews and the average quantity of lampricide applied annually over the past eight years.

CANADIAN CONTROL UNIT

The initial steps of the decision process employed by the Canadian control unit are the sequential deletion of streams from consideration for treatment. All streams within the jurisdiction of the Canadian unit have been classified according to the ability to produce transformers. This classification is based largely on habitat characteristics and historic evidence of lamprey production. Only those streams judged to have the potential for significant production of transformers are considered for treatment. The first cut reduces the number of streams under consideration

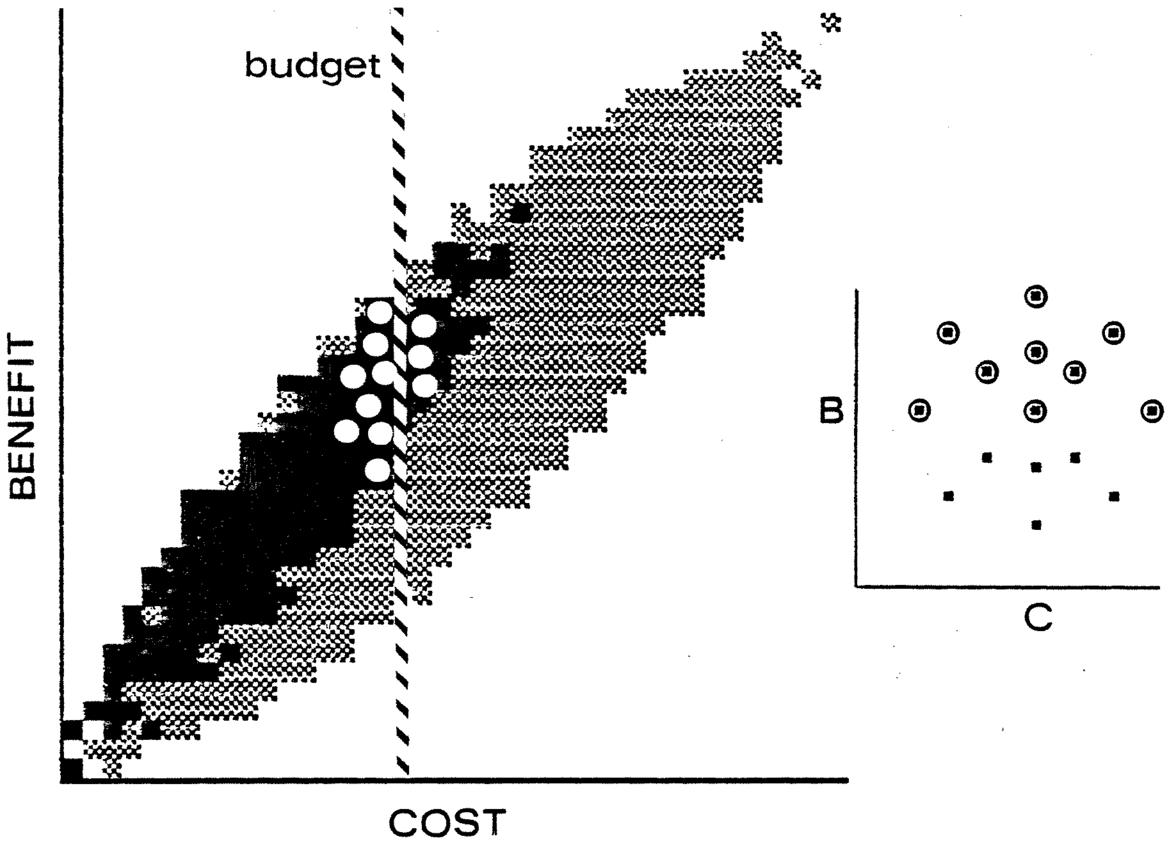


Figure 5. Representation of the budgeted amount for treatment relative to the total set of alternatives (light shading) and the censored subset (dark shading) as it would look for the U.S. control unit. The white dots close to the vertical budget line represent actions that are actively considered.

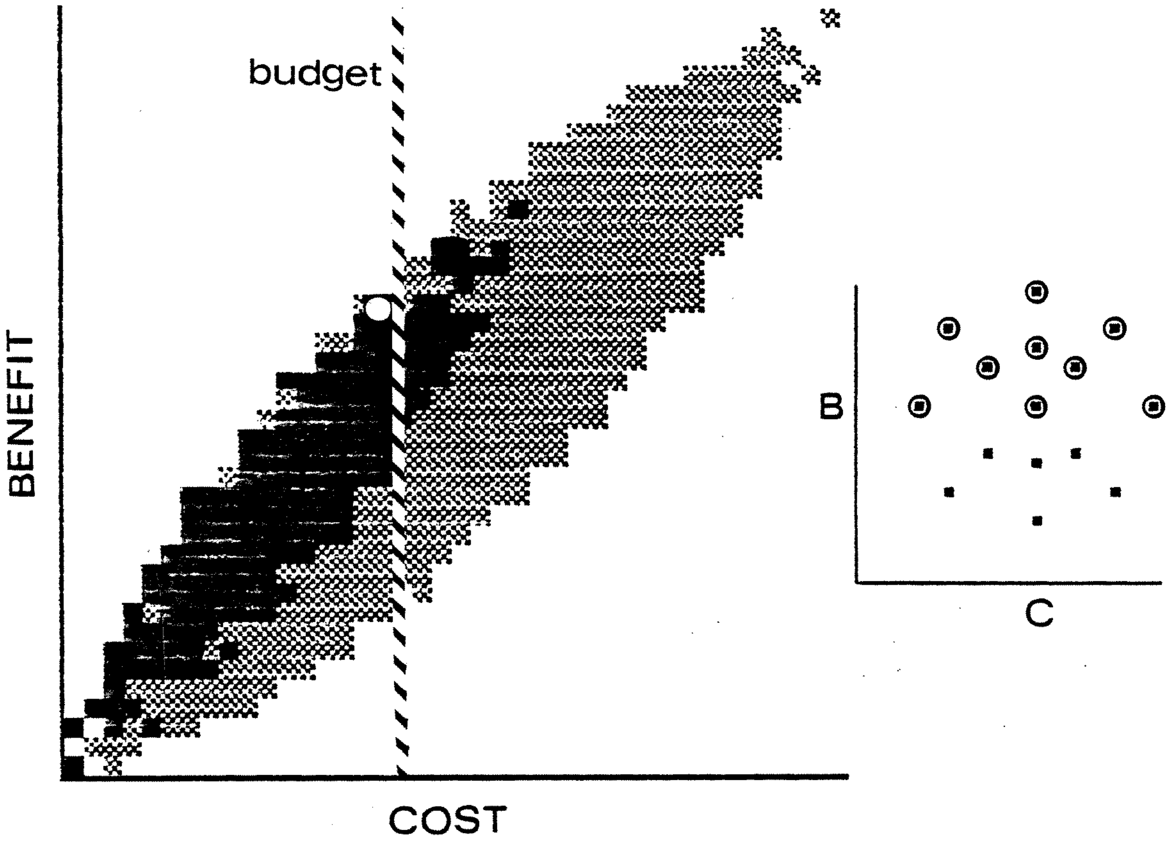


Figure 6. Representation of the action finally selected (white dot) under the approach employed by the U.S. control unit. That action is characterized by the greatest expected benefit within budget for the censored set of alternatives.

to about 80. Some 35 to 40 streams of those 80 might be actively considered for treatment in a particular year. That second cut is based largely on the last date of treatment, the effectiveness of that treatment and the results from post-treatment surveys. The decision to include or exclude streams from consideration at these two junctures derives from a subjective synthesis of information and informed judgment.

The final culling of streams for active consideration is made on the basis of results of distribution surveys. The rationale for inclusion at this juncture is fairly well defined, if any ammocoetes that would likely transform (110 to 160 mm individuals depending on environmental conditions) in the next year are found in the samples, the stream remains a candidate for treatment. Roughly 20 streams meet the criteria for final consideration each year. Treatment of all 20 generally is possible within the limitations of budget. If re-establishment of an ammocoete population occurs in a stream the year following treatment, the stream is likely to be considered for treatment four years later (the time typically expected for transformation). This means that each of the 80 or so streams judged to have significant potential for transformer production can be treated anytime it meets the final criteria for consideration, on the average once every four years.

The decision strategy of the Canadian control unit can be described within the outlined framework as censoring the set of streams under consideration for treatment based on the expected benefit that would accrue from treatment. The effect of this censoring on the set of alternative actions is to limit the alternatives to a subset of those available within

Canadian jurisdiction. The characteristics of this censored subset relative to the complete jurisdictional set is similar to that of the U.S. censored subset relative to its complete jurisdictional set of alternatives (Figure 7). Any of these remaining alternatives typically is a financially viable option because all fall within budget (Figure 8). Treatment of all streams that remain after censoring is the alternative that maximizes expected benefit within budget for the censored set (Figure 9).

JURISDICTIONAL EFFICIENCY

Both costs and benefits are considered in evaluating efficiency. Commonly, the ratio of marginal benefits to marginal costs or net return (the difference between benefits and costs) is used as an index of efficiency. These indices require that both benefit and cost be measured on cardinal scales, i.e. magnitude rather than a rank ordering is represented. The expected benefits from treatment are represented ordinally by both control units, which precludes the use of B/C ratios or net return. However, efficiency can be addressed in terms of dominance in this case.

An action, i, is said to dominate the action, j, if the benefit from i is greater than the benefit from j and the cost for i is no greater than the cost for j, or if the cost for i is less than the cost for j and the benefit from i is no less than the benefit from j (Figure 10). The subset of actions that is not dominated by any other action within the set of

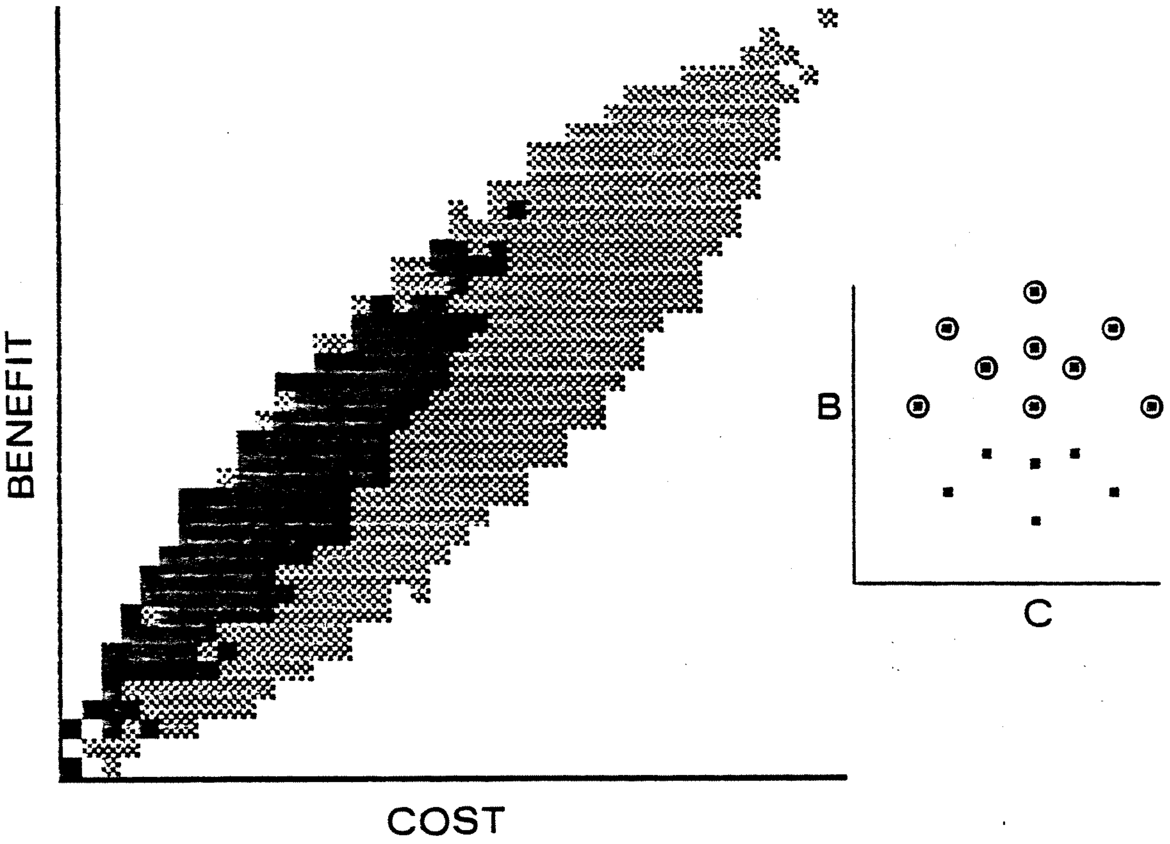


Figure 7. Representation of the subset of actions (dark shading) that remain after censoring the Canadian jurisdictional set of streams based on expected benefit only (circled points on the inset figure). [Note, the actual clusters are not identical to the corresponding ones within U.S. jurisdiction (Figure 4), but the salient patterns are the same.]

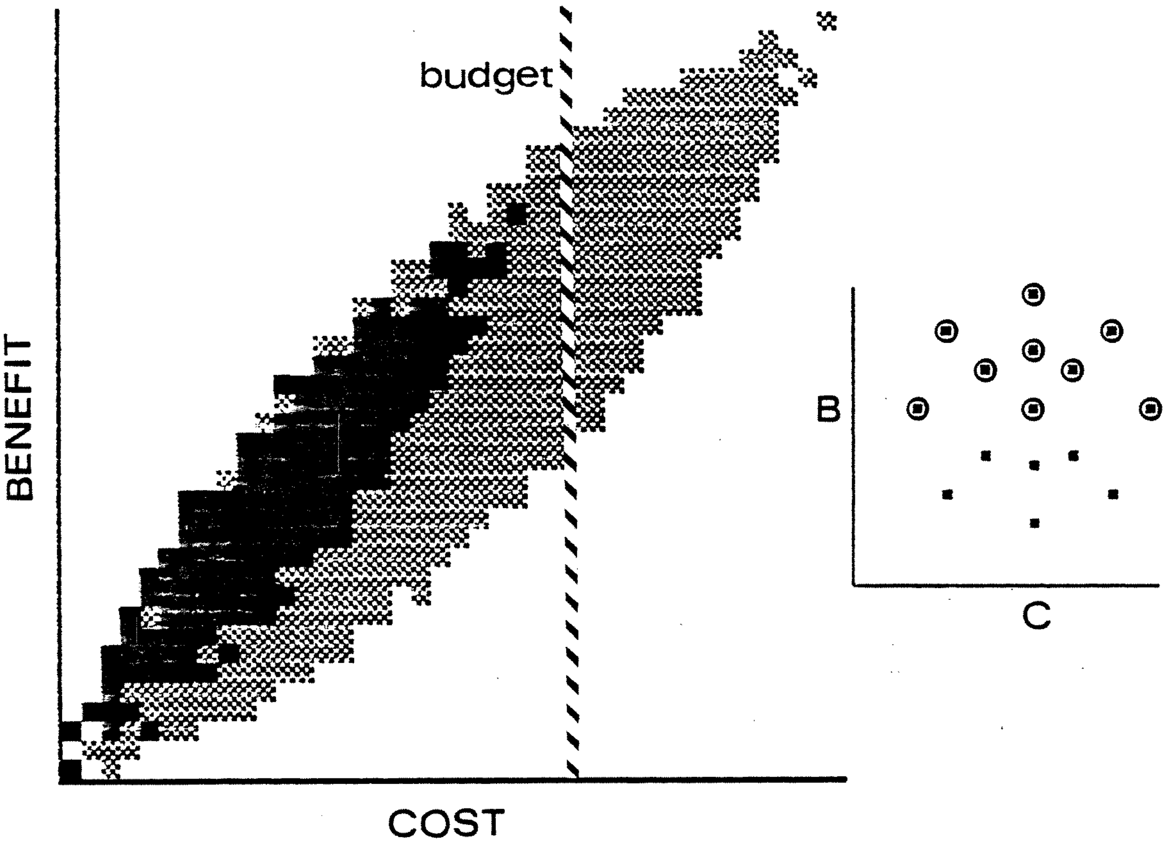


Figure 8. Representation of the budgeted amount for treatment relative to the total set of alternatives (light shading) and the censored set (dark shading) as it would look for the Canadian control unit.

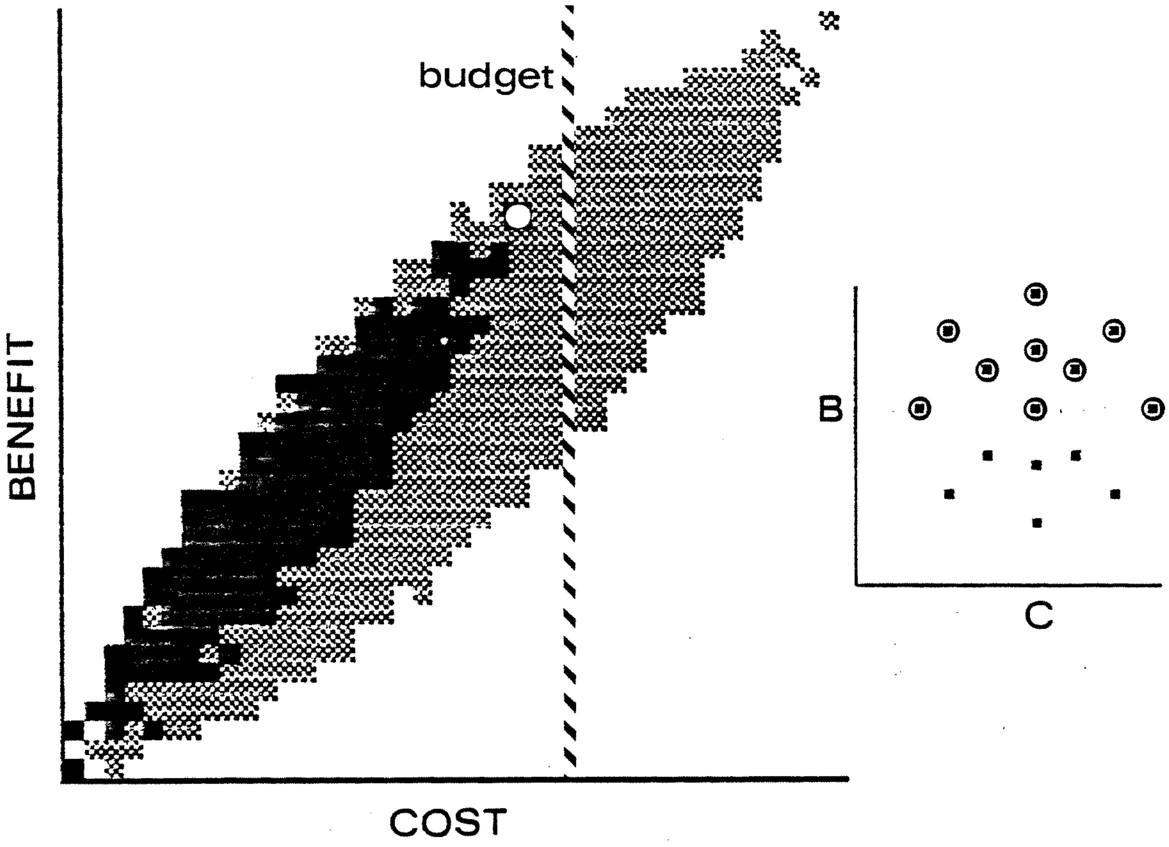


Figure 9. Representation of the action finally selected (white dot) under the approach employed by the Canadian control unit. That action is treatment of all streams within the censored subset and is characterized by the greatest benefit within budget for the censored subset of alternatives.

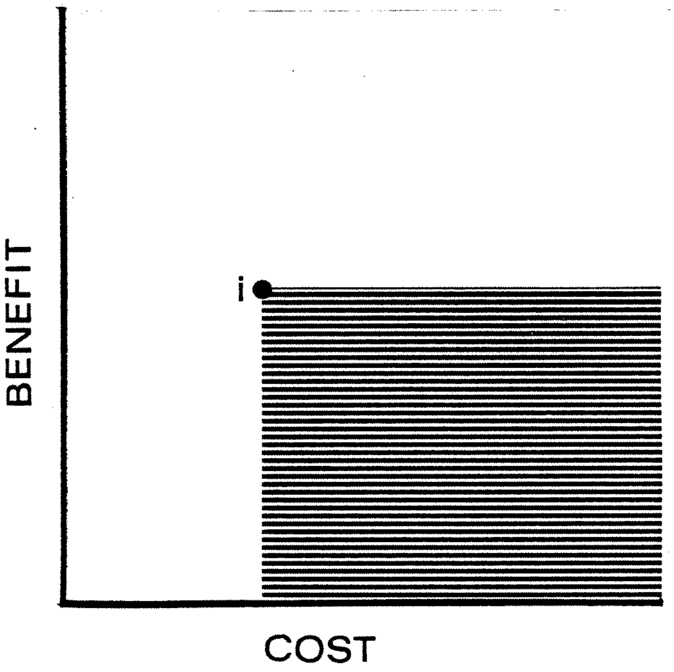


Figure 10. Representation of an action, i, and the region of actions that is dominated by it (shaded area).

alternatives is called the Pareto-optimal set or the efficient frontier (Figure 11). Selection of an action from the efficient frontier is a minimum requirement for achieving efficiency and is an appropriate baseline against which the decision strategies of the control unit and the GLFC can be compared.

The essence of the decision strategy for both control units is to select an action from an intelligently censored set of alternatives that maximizes expected benefits within budget. The censoring of streams considered for treatment is based on expected benefits; this tends to produce a subset of alternatives that includes actions close to the efficient frontier (Figures 4 and 7). Furthermore, selection from within that subset to maximize expected benefit produces those actions that are close to the efficient frontier for any level of cost. The approach employed by the control units is consistent with selecting actions close to, but not necessarily on the efficient frontier. Furthermore, the efficiency that actually is achieved depends on the accuracy of the predicted reduction in transformer production due to treatment and the effect that reduction has on the value of the fishery. No objective measures for either of these is presently available.

Whereas the approach employed by the control units may or may not produce actions on the efficient frontier an approach exists that guarantees selection of an optimal action under fairly general conditions. The approach is a solution to what is called the backpack problem (Wagner, H.M. 1975. Principles of Management Science. 2nd ed. Prentice Hall, Inc.) in reference to the problem of selecting a subset of items to carry in a backpack when the entire set of items you'd like to carry is too heavy.

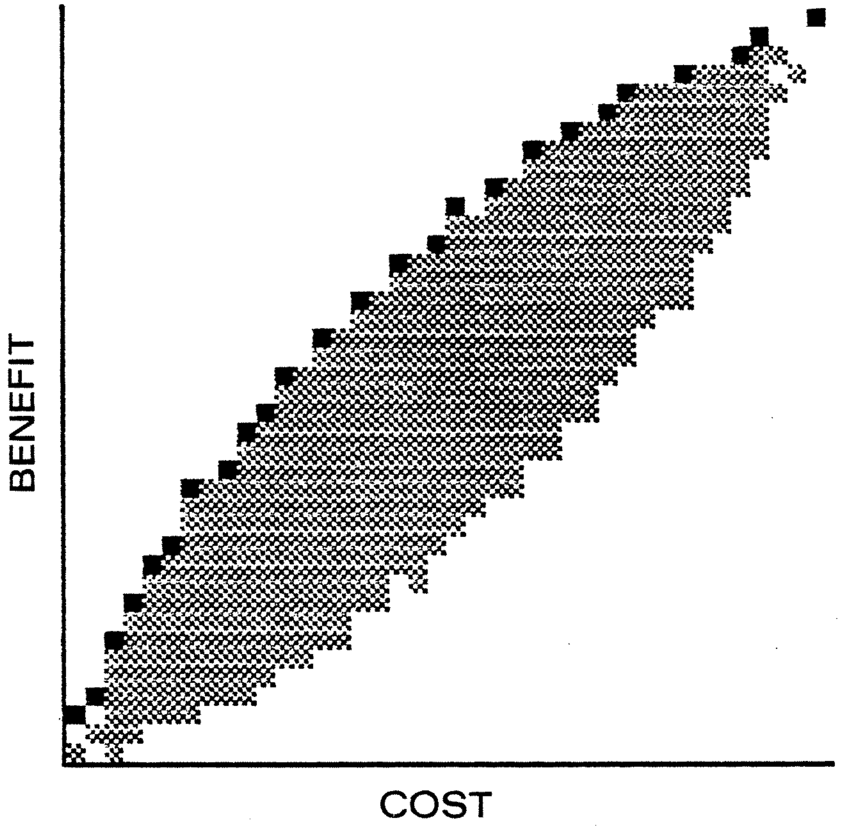


Figure 11. Representation of the efficient frontier (dark shading) relative to a set of alternative actions.

The general conditions are that the benefit from any subset of items is the sum of their individual benefits, and costs (weights) are similarly additive. The units of benefit do not have to be the same as those of cost. So, number of transformers killed as benefit and dollars as cost are appropriate units for this approach. If value of the fishery were considered as the benefit, the condition of additivity might not be met.

The approach is very straightforward. The benefit and cost for each item (stream treatment) of the entire set (streams with ammocoete populations within a lake watershed) are identified. The streams then are ranked according to their individual benefit/cost ratios. Streams are selected for treatment starting with the one with the highest benefit/cost ratio and continuing, by successively lower benefit/cost ratios, until the budget level is reached. The subset of streams so chosen will always be on the efficient frontier, regardless of the budget level.

The backpack approach in contrast to the general approach employed by the control units can be seen graphically. The present approach basically is the ranking of streams by benefits only with selection of streams proceeding from the stream with the highest benefit to that with the next highest benefit and so on until the budget level or arbitrary minimum benefit level is reached. This process can be depicted as lowering a horizontal line from above the cluster of points for streams (Figure 12). The cost of each point that is passed is summed and the line is lowered until the sum of costs is just within the budget or until the minimum benefit level is reached. Those streams represented by points above the line are included for treatment.

The process of the backpack approach can be depicted as lowering a line hinged at the origin through the cluster of points for streams (Figure 13). Again, the cost of each point that is passed is summed and the line

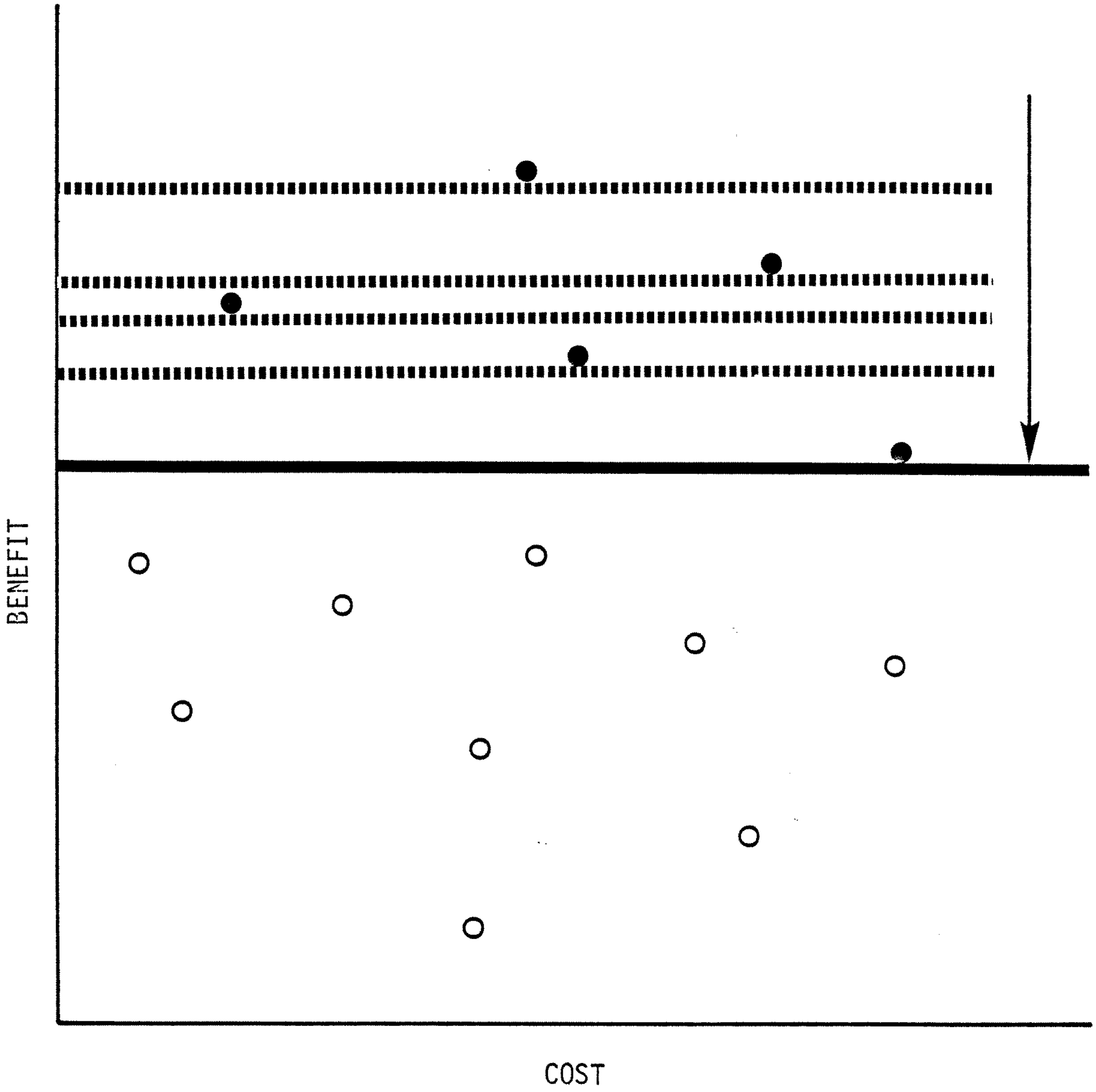


Figure 12. Representation of selection of streams in order of decreasing benefit until the sum of costs is just within budget. Streams represented by black dots (i.e. dots that are passed by the horizontal line as it is lowered) are selected; the sum of those costs is just within budget.

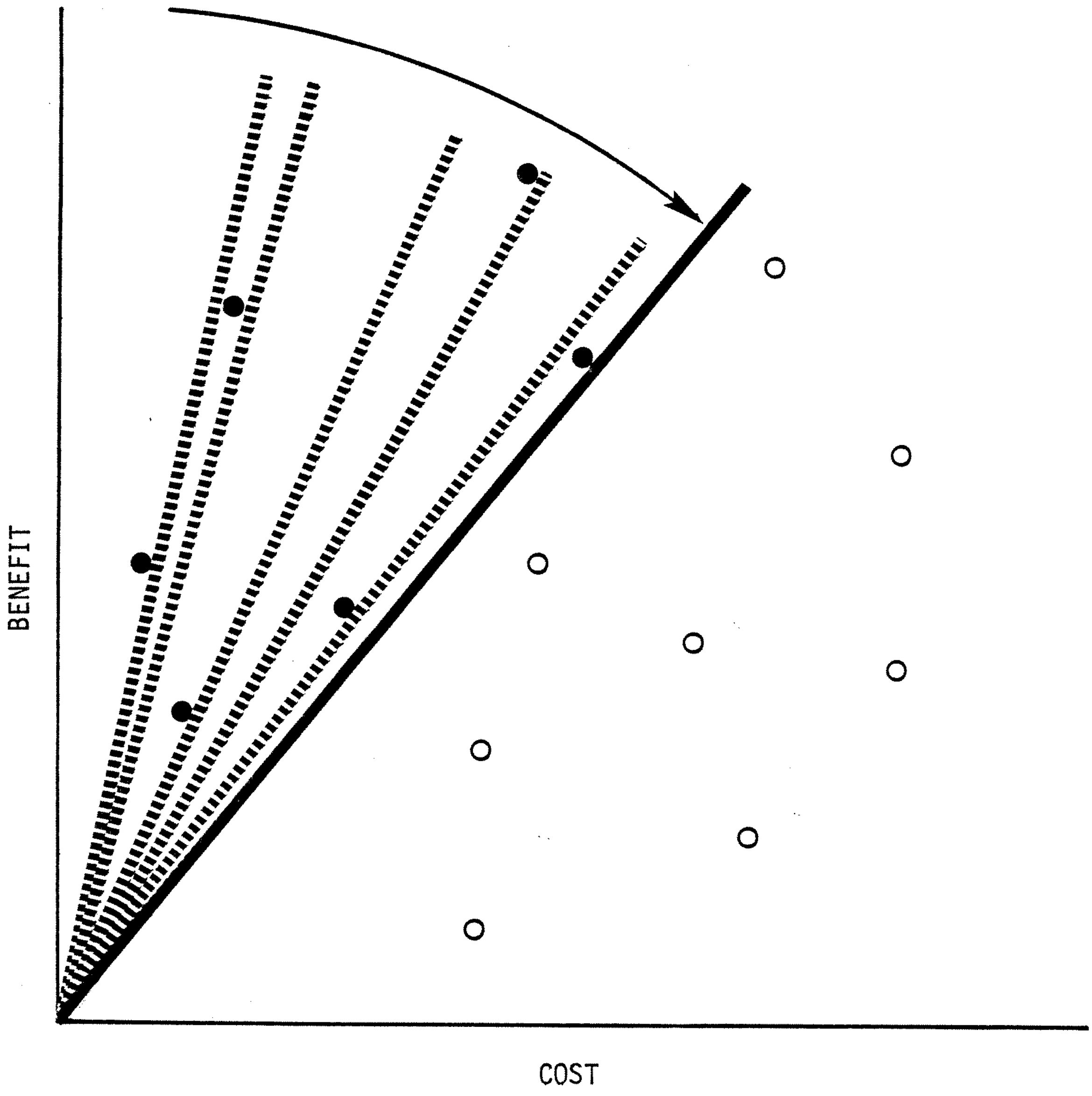


Figure 13. Representation of selection of streams in order of decreasing benefit/cost ratio. Streams represented by black dots (i.e. dots that are passed by the line, hinged at the origin, as it is lowered) are selected; the sum of those costs is just within budget.

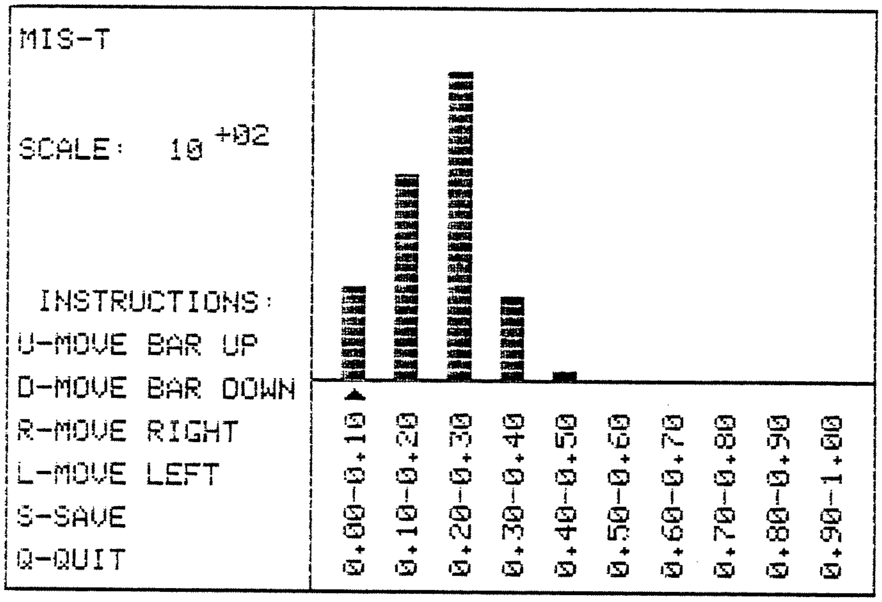
is lowered until the sum is just within budget. Those streams represented by points above the line are included for treatment.

The increase in efficiency from employing the backpack approach rather than selection by benefit only can be substantial. That increase can be viewed as an increase in effectiveness at some cost level or a cost savings at some level of effectiveness. The actual increase in efficiency is sensitive to the location of the cluster of points relative to the two axes. Consequently without such plots for streams within a lake, we cannot suggest the magnitude of change to be expected.

Generating the plots requires that the numbers of transformers killed and the cost for treatment be identified for each stream. Presently no quantitative estimate for number of transformers present or number killed is made by either control unit. However, control unit staff members appear to hold fairly well defined (albeit subjective) judgements about numbers of transformers in streams and numbers killed during treatment. This type of information could be formalized and used as a surrogate for statistical estimates in making a preliminary assessment of the potential increase in efficiency that might result from using the backpack approach. Indications of a large increase in efficiency might be cause to initiate a program for estimating transformer numbers. Such a decision should depend on the additional cost for the estimation program balanced against the potential savings from increasing efficiency.

Bob Braem, Director of the USFWS Sea Lamprey Control Station, invited Doug Heimbuch to Marquette in March 1982 to demonstrate a method for formalizing subjective judgements of the U.S. control unit staff about transformer numbers. The demonstration was conducted as a trial of the method for formalizing subjective judgements and, at the time, was not intended for use in connection with the backpack approach for stream selection. The trial method was in the spirit of assessing prior probability distributions for Bayesian analysis and was implemented as an interactive computer program on an Apple II computer system.

The trial was conducted on two days with two different groups of staff members. Two streams, the Two Hearted River and the Misery River, were the subjects of the trial assessment on each day. The assessment for the number of transformers that would be killed during treatment began with the staff members specifying a reasonable range (of number killed) within which most streams could be characterized. The staff then had to specify their best guess of the number of transformers killed for a given stream. The computer then divided the specified range into ten equal categories and displayed a bar graph with one bar per category. The bar corresponding to the category in which their best guess fell was displayed with a maximum height and all other bars were displayed with a minimum height. The computer then prompted the staff to adjust the height of all bars relative to that of their best guess. They were instructed that the height of each bar was to represent their relative strength of belief that the actual number killed would be within the cateory corresponding to the bar. After some discussion, a graph was completed that represented their _a priori_ beliefs about the number of transformers that would be killed in a treatment of that stream (Figure 14). The computer stored the heights of the bars and normalized the distribution so the heights summed to one. An _a priori_ distribution for cost of treatment was constructed in the same manner (Figure 15). A single predicted cost could not be made due to the temporal changes in stream conditions that affect costs but are uncontrollable. The assessment for numbers killed and cost was conducted for the two streams by each group (Figures 16 and 17) with little difficulty.



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MIS-T

SCALE:  10 +02

 INSTRUCTIONS:
U-MOVE BAR UP
D-MOVE BAR DOWN
R-MOVE RIGHT
L-MOVE LEFT
S-SAVE
Q-QUIT
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Figure 14. Copy of the computer printout of a histogram representing subjective beliefs about the number of transformers killed in treatment of the Misery River. The instructions refer to the means for entering information at the keyboard. The height of each bar represents relative strength of belief that the number killed will be in the corresponding category.

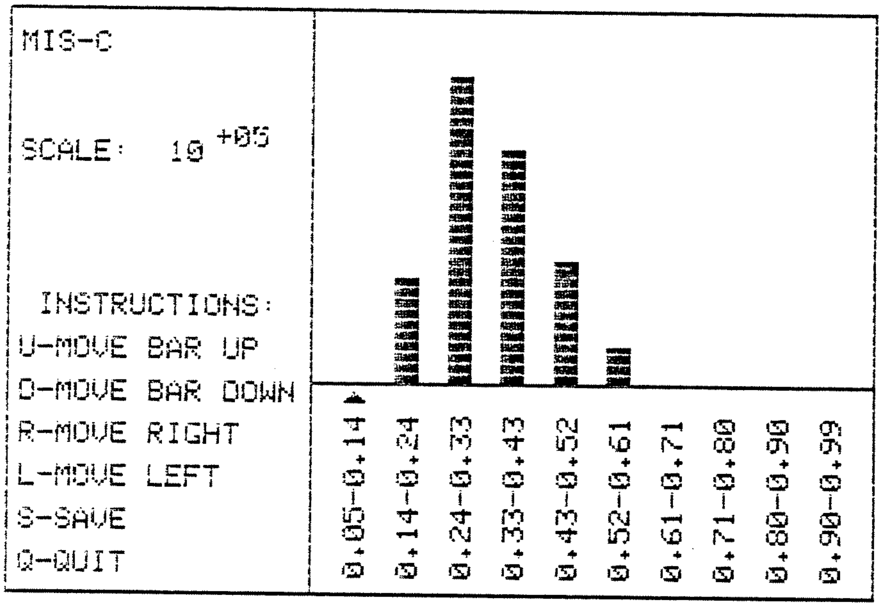


Figure 15. Copy of the computer printout of a histogram representing subjective beliefs about the cost (in dollars) for treatment of the Misery River. The instructions refer to the means for entering information at the keyboard. The height of each bar represents relative strength of belief that the cost of treatment will be in the corresponding category.

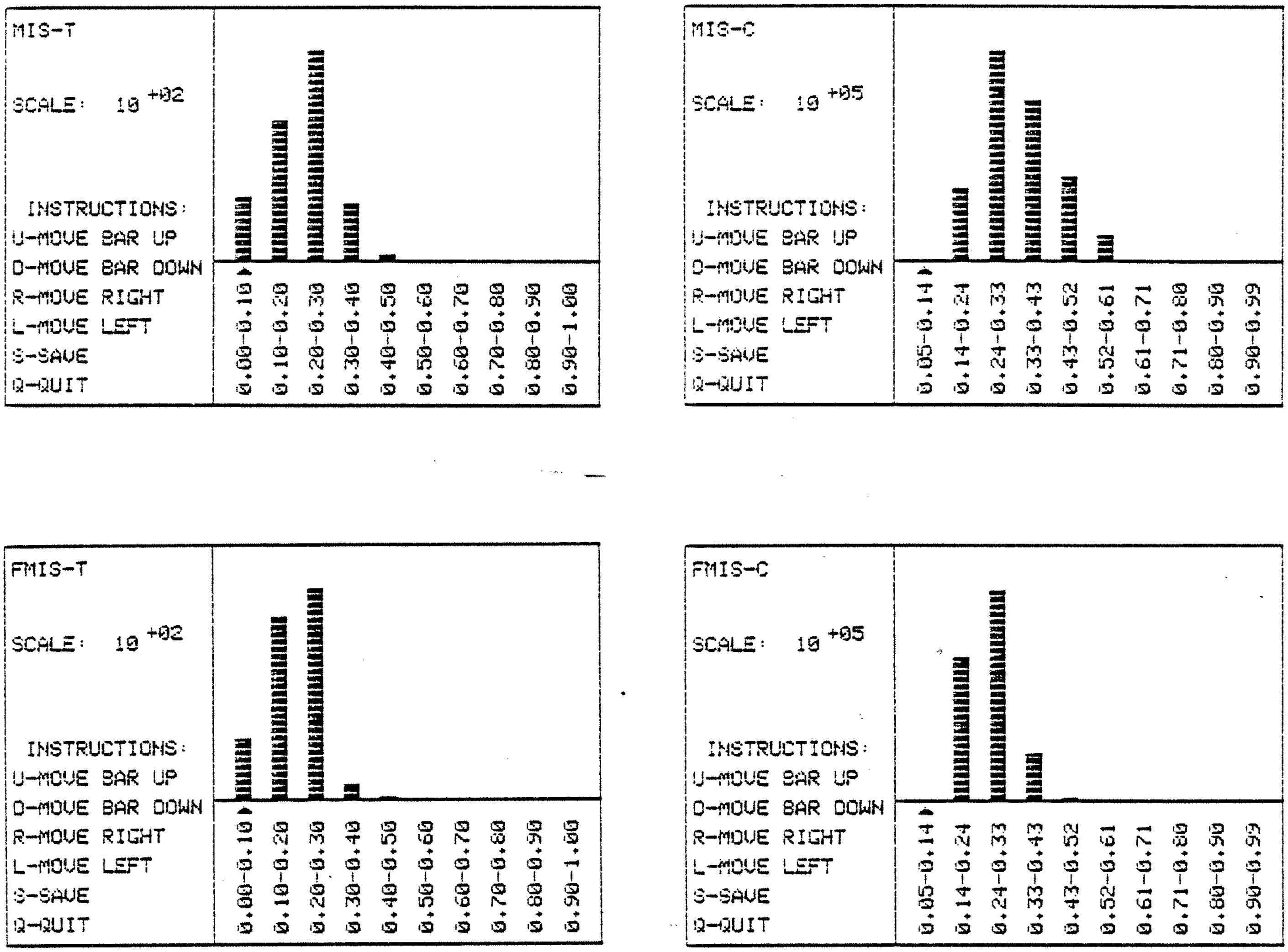


Figure 16. Copies of the completed histograms for numbers of transformers killed (right two printouts) during and cost for treatment (left two printouts) of the Misery River. The top two were generated by one group of USFWS staff at Marquette and the bottom two were generated by the second group (see text).

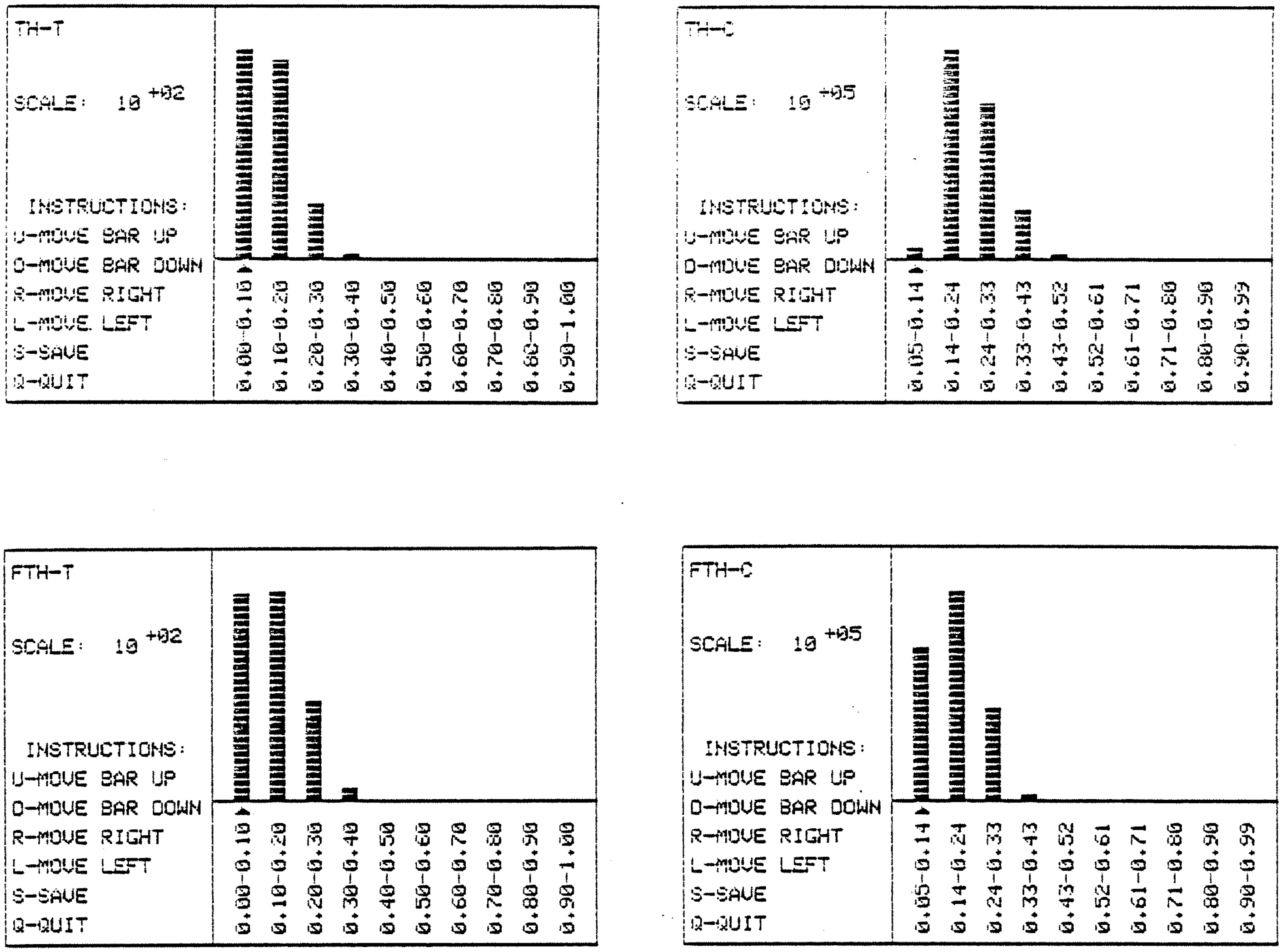


Figure 17. Copies of the completed histograms for numbers of transformers killed (left two printouts) during and cost for treatment (right two printouts) of the Two Hearted River. The top two were generated by one group of USFWS staff at Marquette and the bottom two were generated independently by the second group (see text).

The *a priori* distributions that result from the method are formal statements of subjective judgements. Each pair (benefit, numbers killed, and cost for one stream) can be reduced to a form useful in a preliminary evaluation of the backpack approach by computing the expected benefit/cost ratio, E(B/C), for each stream. The *a priori* E(B/C) for each stream could be used as a surrogate for the actual benefit/cost ratio in ranking streams for selection by the backpack method. The expected efficiency for the set of streams so selected then could be compared to the expected efficiency for the set selected by the present method.

PROGRAM EFFICIENCY

Efficiency within the separate jurisdictions of the control units has been our focus thus far. Overall program efficiency is affected by the strategy used for defining the jurisdictions as well as the strategies for choice of actions within jurisdictions. The effect of dividing the set of all streams into two mutually exclusive subsets based on international boundaries and independent of expected benefits and costs must be considered (Figure 18). Unlike the intelligent censoring employed by the control units, defining two subsets of streams without regard for expected benefits does not produce subsets of actions that tend to be close to the efficient frontier of the set of all alternatives (Figure 19). This in itself is not critical because the program-wide action is a combination of one action selected independently by the Canadian control unit and one selected independently by the U.S control unit. Assuming that each control unit is successful in selecting an action from the efficient frontier of its jurisdictional subset, the program-wide action will always consist of a

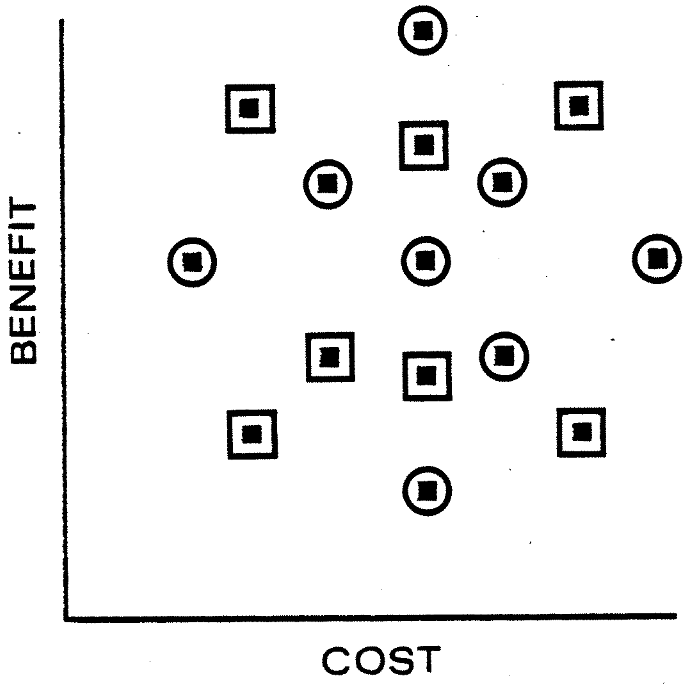


Figure 18. Representation of non-informative division of a set of streams into two mutually exclusive subsets (circles or squares) as might occur in defining the two national jurisdictions.

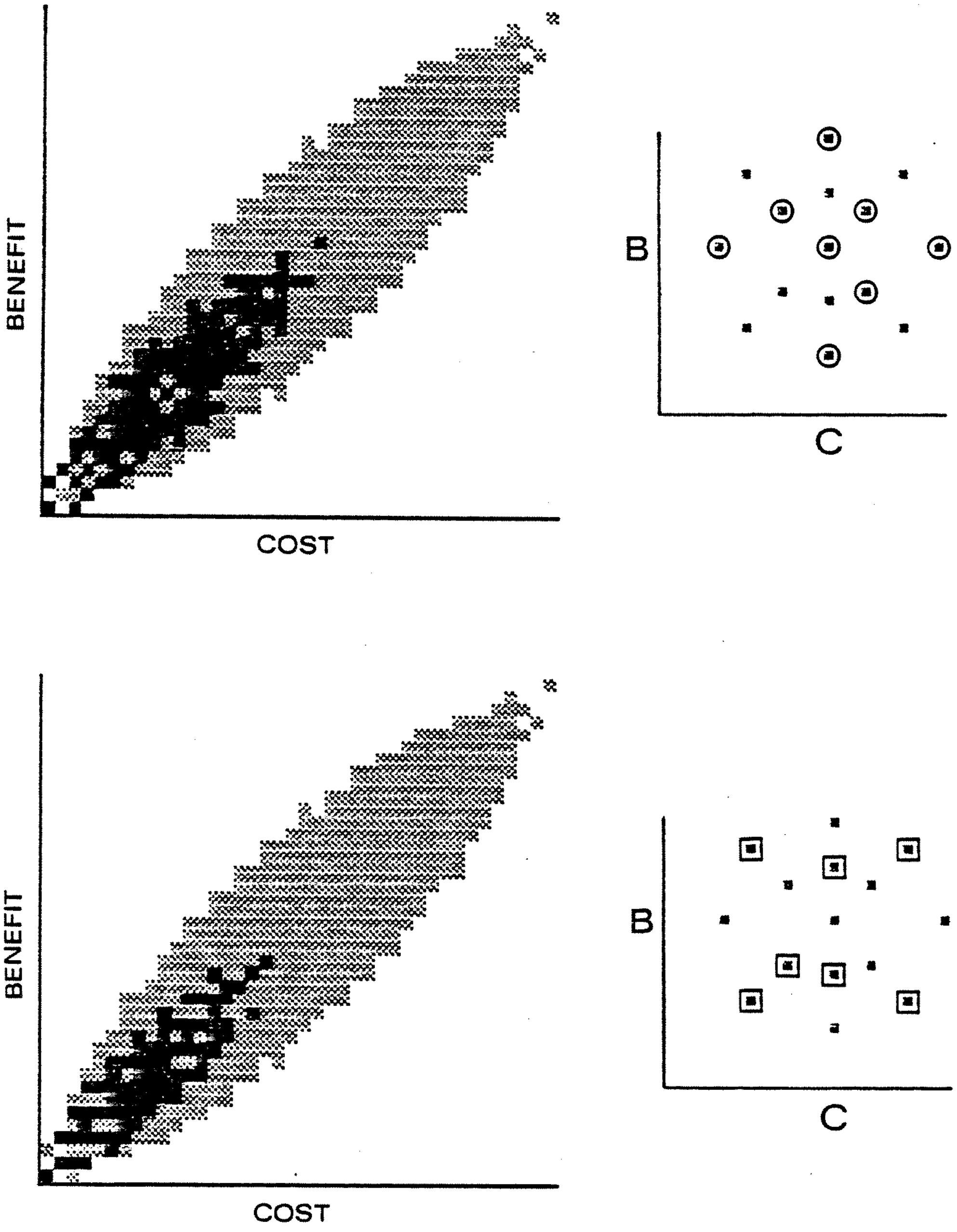
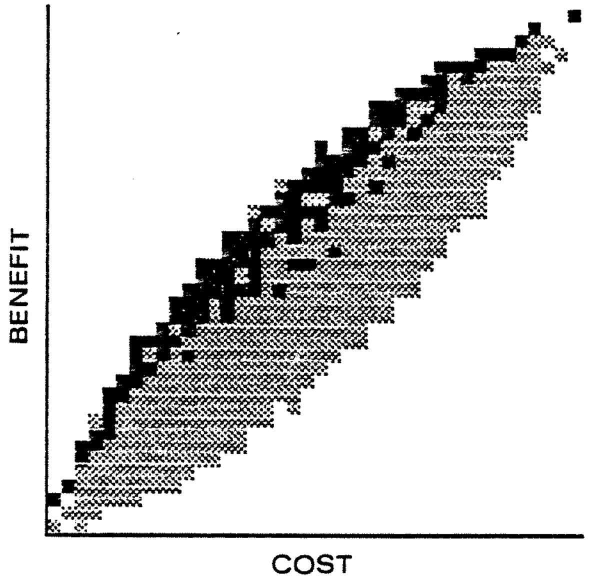


Figure 19. Representation of the two subsets of actions that result from a non-informative division of streams into two mutually exclusive subsets (as is the case with two national jurisdictions).

group of streams that comprise an action on the efficient frontier of the U.S. jurisdictional subset plus a group of streams that comprise an action on the efficient frontier of the Canadian jurisdictional subset. The set of combinations defined in this way is not restricted to the efficient frontier of the overall set of alternatives (Figure 20). Even if each control unit selects an efficient action from its jurisdictional subset, the resulting action may be far from efficient in the program-wide context.



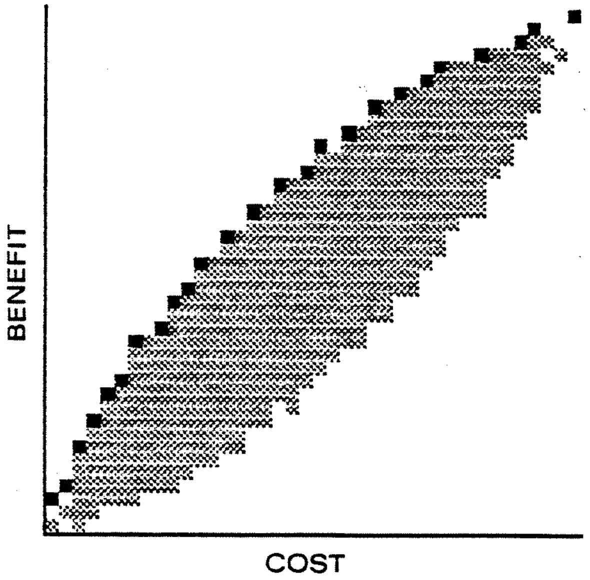


Figure 20. Top: representation of the subset of actions (dark shading) defined by one action from the efficient frontier of each jurisdictional subset relative to the program-wide set of alternatives. Bottom: the dark shading represents the efficient frontier for the program-wide set of alternatives.

II. Selection of Lampricide Concentration

INTRODUCTION

Both control units make a distinction between the minimum lethal and maximum allowable lampricide concentration. The former is related to sea lamprey ammocoete mortality and the latter to mortality of non-target animals. We will deal with lamprey mortality in this section, i.e. only with the minimum lethal concentration, and address non-target mortality in a later section.

The decision rules for selecting the minimum lethal concentration of lampricide for treatment are far more concrete and better defined than the rules for selecting streams for treatment. As such they can be subjected to a more quantitative analysis. That analysis, however, depends on specifying a mortality model representing the relationship between lampricide concentration and time to death of exposed ammocoetes. We will use the mortality model that underlies the decision rule of the Canadian control unit. It seems biologically reasonable and Canadian bioassay data are claimed to be generally consistent with the model.

MORTALITY MODEL

The basic premise of the model is that the effect of lampricide on individual ammocoetes in a population varies by degrees. The time of death from the onset of exposure is not the same for each individual - some die sooner, some later. The collection of time to death for every individual in the population comprises a frequency distribution of time to death (Figure 21). The shape of the frequency distribution for a given population in a given stream depends on the concentration of lampricide to which the ammocoetes are exposed. Although each frequency distribution is

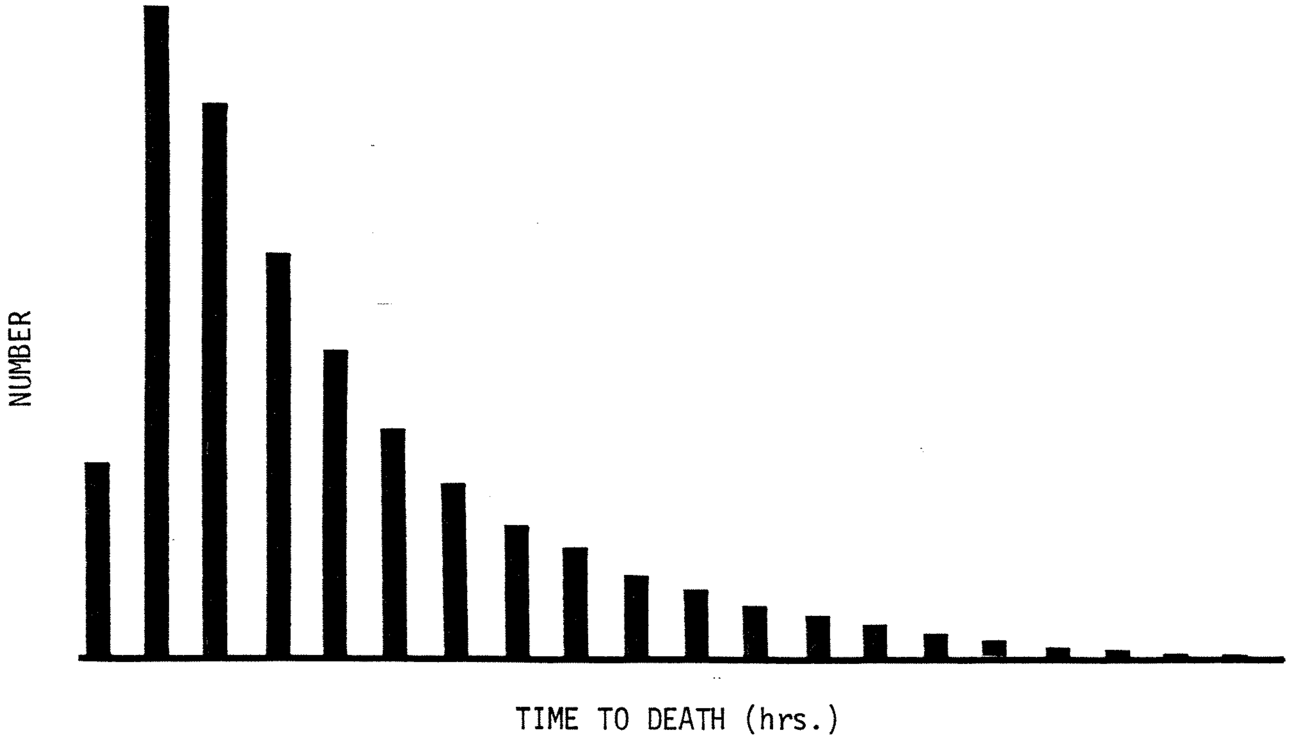


Figure 21. Hypothetical frequency histogram for time to death of ammocoetes in a population exposed to lampricide. The sum of the heights of all bars is equal to the population size.

actually discrete it can be approximated by a continuous frequency curve. The area under such a curve equals the populaton size (Figure 22). Specifically, the shape of each frequency curve is assumed to be approximately log-normal and conditional on lampricide concentration.

$$f(x|u) \doteq N \cdot \frac{1}{x} \frac{(b/\sigma)}{\sqrt{2\pi}} \cdot \exp\left\{-\frac{1}{2}\left[\left(\frac{\alpha+c\beta-a}{\sigma}\right) + \left(\frac{d\beta}{\sigma}\right) \ln u - \left(\frac{b}{\sigma}\right) \ln x\right]^2\right\}$$

$$x>0,\ u>0,\ \beta<0$$

where

x = time to death in hours,

u = lampricide concentration in ppm,

$f(x|u)$ = frequency of time to death given concentration,

N = population size, and

a, b, c, d, α, β and σ are shape parameters.

(Note: this is an over parameterized description of the curve but will facilitate subsequent transformations.)

Also, $E(x|u) = w\rho$

$\mathrm{var}(x|u) = w^2\ (w^2-1)\rho^2$

where,

$$w = \exp\left[\frac{\sigma^2}{2b^2}\right] \quad \text{and}$$

$$\rho = \exp\left[\frac{\alpha + c\beta \ - a + d\beta \ln u}{-b}\right]$$

(Kendall, M. and Stuart, A. 1977.
The Advanced Theory of Statistics.
Vol. 1. MacMillan Publ. Co.)

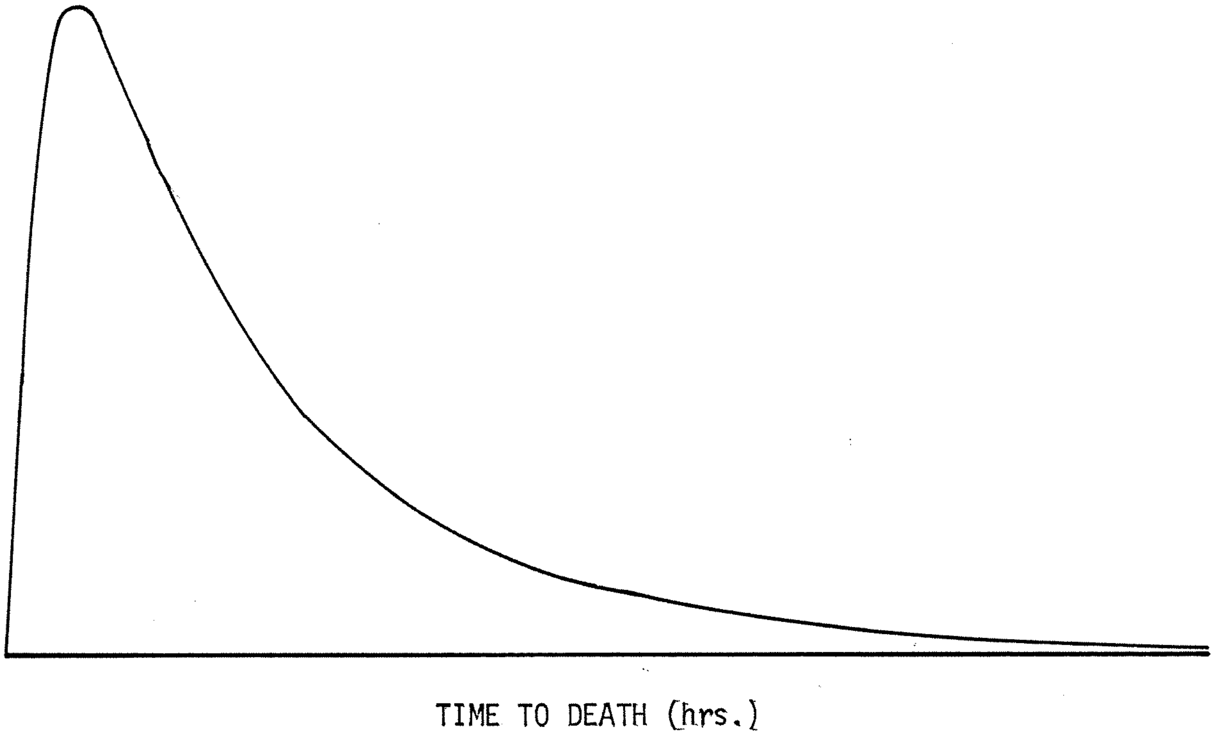


Figure 22. Frequency curve for time to death of ammocoetes in a population exposed to lampricide. This curve approximates the frequency histogram of Figure 21. The area under the curve is equal to the population size.

So, both the mean and variance of time to death are reduced as the concentration of lampricide is increased.

This family of curves can be transformed into the more familiar form of normal distributions (Figure 23) by changing from arithmetic to $\log_e$ (ln) units for both time of death and concentration.

Let $Y = a + b \ln x$ and
$V = c + d \ln u$.

Then,

$$f(Y|V) \doteq N \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp\left\{-\frac{1}{2}\left[\frac{(\alpha + \beta V) - y}{\sigma}\right]^{2}\right\}$$

$$-\infty \leq Y \leq \infty$$
$$\infty \leq V \leq \infty$$
$$\beta \leq 0$$

where α, β and σ are again shape parameters.

$$E(Y|V) = \alpha + \beta V$$
$$\operatorname{var}(Y|V) = \sigma^{2} \text{ for all } V.$$

So, the mean of time to death is reduced as the concentration is increased but the variance does not change. This inconsistency with the trends for variance in arithmetic units is an illusion due to the non-linear log transformation. For example, the interval of 4 to 6 in $\log_e$ units corresponds to the interval of 54.6 to 403.4 in arithmetic units and the interval of 0 to 2 in $\log_e$ units corresponds to the interval of 1 to 7.4 in arithmetic units. The width of both intervals is 2 in $\log_e$ units but in arithmetic units the width changes with changes in the location of the interval.

The conditional mean in $\log_e$ units, $E(Y|V)$, is a simple linear regression of Y on V. The mean of a normal distribution is also the

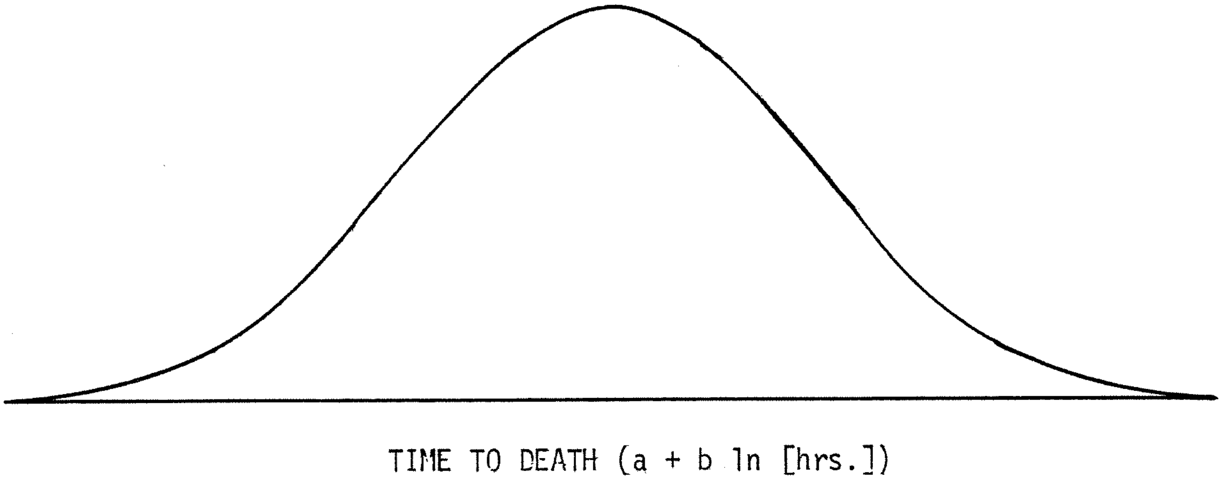


Figure 23. Frequency curve for time to death, in $\log_e$ units, of ammocoetes in a population exposed to lampricide. This curve results from transforming the units of the curve in Figure 22 to a + b ln [HOURS]. (Note, a and b are arbitrary scaling constants.)

median, therefore, the regression line, $\alpha + \beta V$, represents the time (in $\log_e$ units) to 50% mortality. The parameter, α, represents the time to 50% mortality at some very low, but effective concentration. The parameter, β, represents the rate at which the time to 50% mortality decreases with increases in concentration. The parameters, α, β and σ, depend on the chemical properties of the water, the type of lampricide and the ammocoete population under consideration. Situations of high toxicity, e.g. low alkalinity or TFM plus Bayer, are likely to have relatively small values for α and σ and relatively large absolute values for β. Conversely situations of low toxicity are likely to have relatively large values for α and σ and relatively small absolute values for β (Figure 24).

With this model, a mortality curve can be constructed relating mortality, M, to lampricide concentration given the parameters, α and β , the common standard deviation, σ, and the duration of exposure, T (in the same units as Y). The number dead by time T is the sum of the numbers that die at each time prior to T. This is the area under the frequency curve to the left of T (Figure 25).

$$M = \int_{-\infty}^{T} \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{ -\frac{1}{2}\left[\frac{\alpha + \beta V - Y}{\sigma}\right]^2 \right\} dY$$

where M = proportion dead by time T, and as

before Y = α + b ln x,

X = time to death in hours,

V = c + d ln u, and

U = lampricide concentration in ppm.

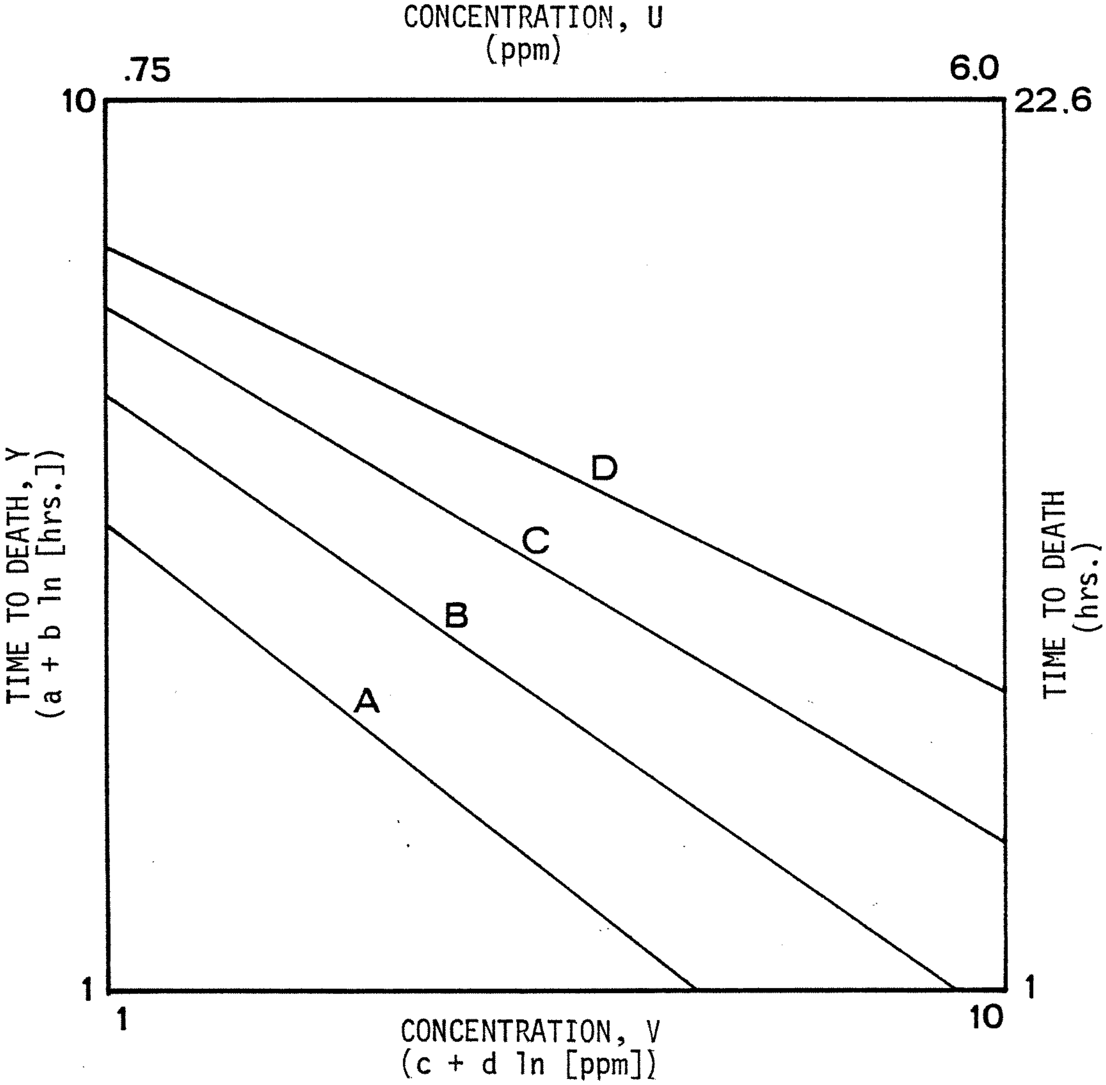


Figure 24. Depiction of 4 regressions, E(Y V), representing situations of decreasing toxicity - A is most toxic, D is least toxic. The regressions are linear in the transformed units of Y and V (as drawn) but are curvilinear in units of X and U. Case B represents a 1980 Black River bioassay with TFM and case A represents a 1980 Black River bioassay with TFM + 1.6% Bayer (anon. Black River Report. NYO-19. Aug. 18-20, 1980. Sea Lamprey Control Centre, Sault Ste. Marie, Ontario). Cases C and D are hypothetical.

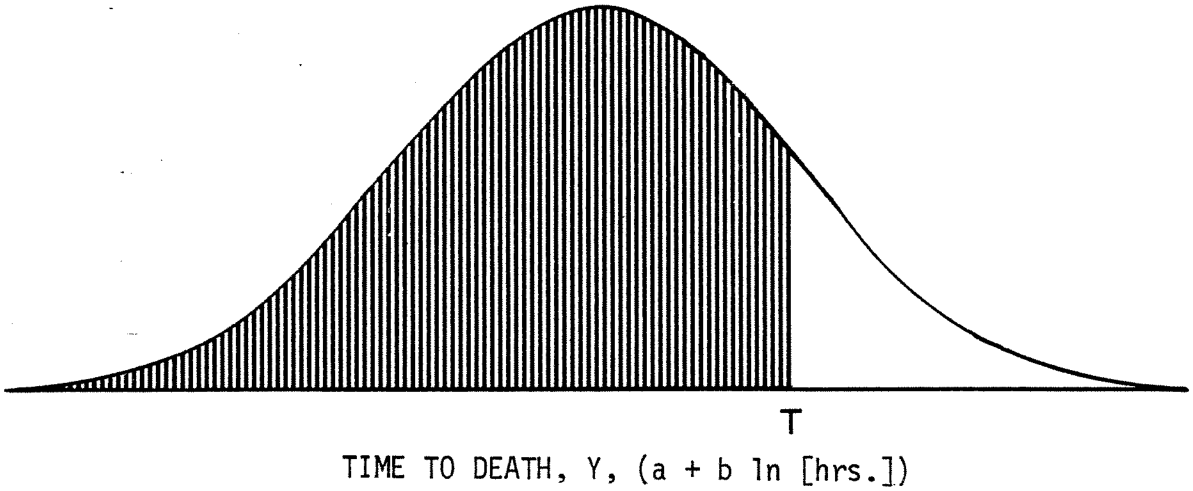


Figure 25. Representation of the number of ammocoetes dead by time T as the area under the frequency curve and to the left of T. The proporiton dead, M, is the ratio of the shaded area to the entire area under the curve.

Mortality response curves for the four cases depicted in Figure 24 with a 12 hour exposure, i.e. $T = a + b \ln(12)$, are displayed in Figure 26. Each mortality response curve is a delineation of the mortality that will result from exposing the entire population to possible lampricide concentrations. Both control units acknowledge that not all ammocoetes in a stream are exposed at the targetted concentration for the targetted duration. Furthermore, this variability appears different from stream to stream and no objective measure of it is available. For this reason we will distinguish between the actual, but unknown, mortality resulting from treatment and the targetted mortality, M, derived from the mortality model.

CANADIAN CONTROL UNIT

The method employed by the Canadian unit for selecting a concentration closely follows the mortality model. (For a detailed description of the bioassay method see Smith, B.R., J.J.Tibbles and B.G.H. Johnson. 1974. Control of the Sea Lamprey (Petromyzon marinus) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26, and Johnson, B.G.H. "Procedure for Graphical Presentation of Time to Death from Bio-Assay Results.") Bioassays are conducted with 10 lampricide concentrations, $V = 1,2,3,\ldots,9,10$, and 10 observation times, $Y = 1,2,3,\ldots,9,10$. Both observation times and concentration are in $\log_e$ units as defined in the previous section. Sixteen ammocoetes are subjected to each lampricide concentration. They constitute a random sample of size 16 drawn from the population in the stream under consideration. Time to death (in $\log_e$ units) for each individual in the sample is assumed to be distributed as a normal random variable with mean, $\alpha + \beta V$, and variance, σ^2. At each observation time the number of dead animals in each concentration is recorded. At the conclusion of the bioassay the times to 50%, 78% and 94% cumulative mortality are interpolated for each of the 10 concentrations with at least 50%, 78% and 94% mortality respectively (Figure 27).

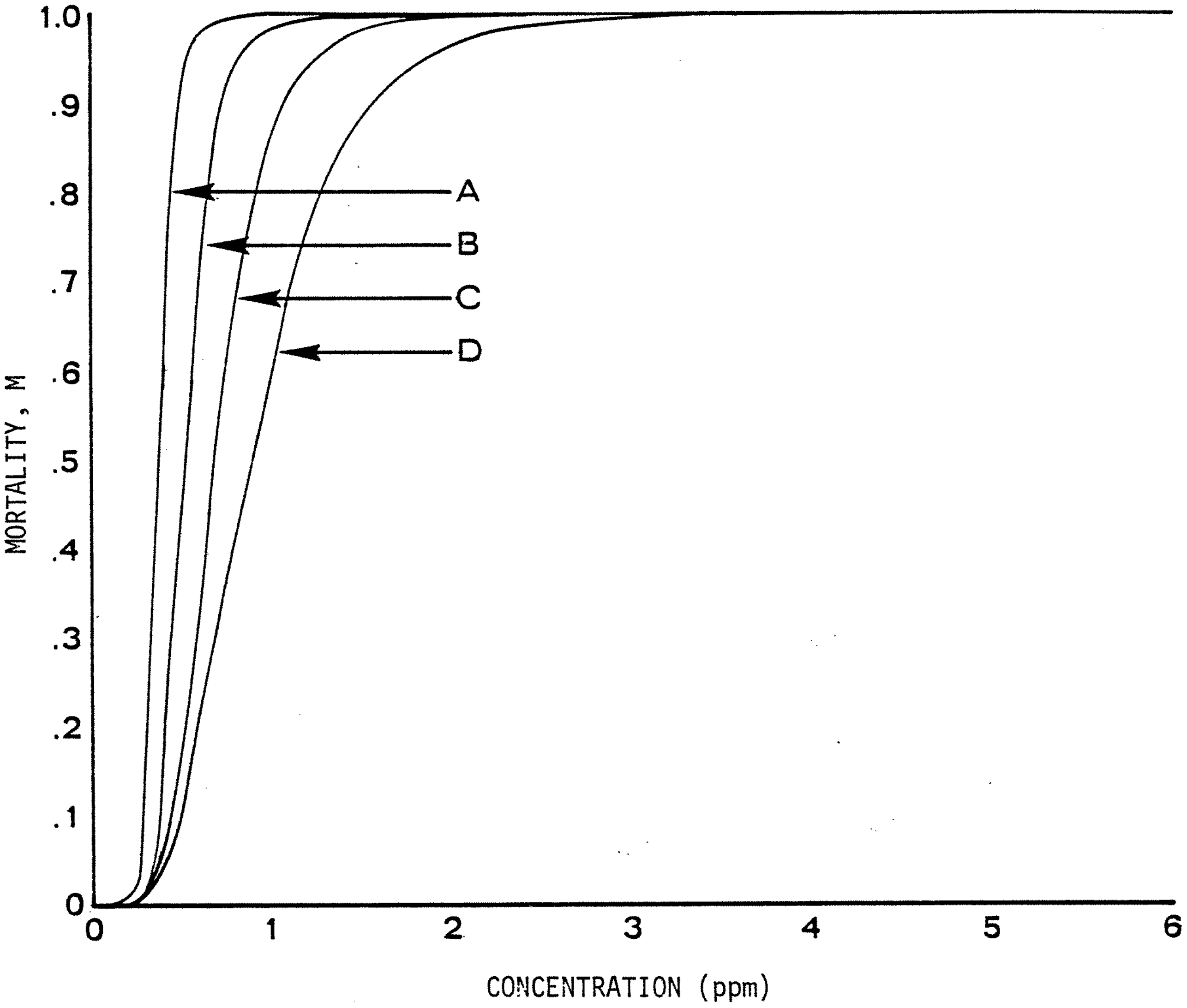


Figure 26. Mortality response curves for the 4 cases from Figure 24. Each curve represents the increase in targetted mortality (proportion killed) as a function of increasing lampricide concentration. Cases A to D represent situations of decreasing toxicity.

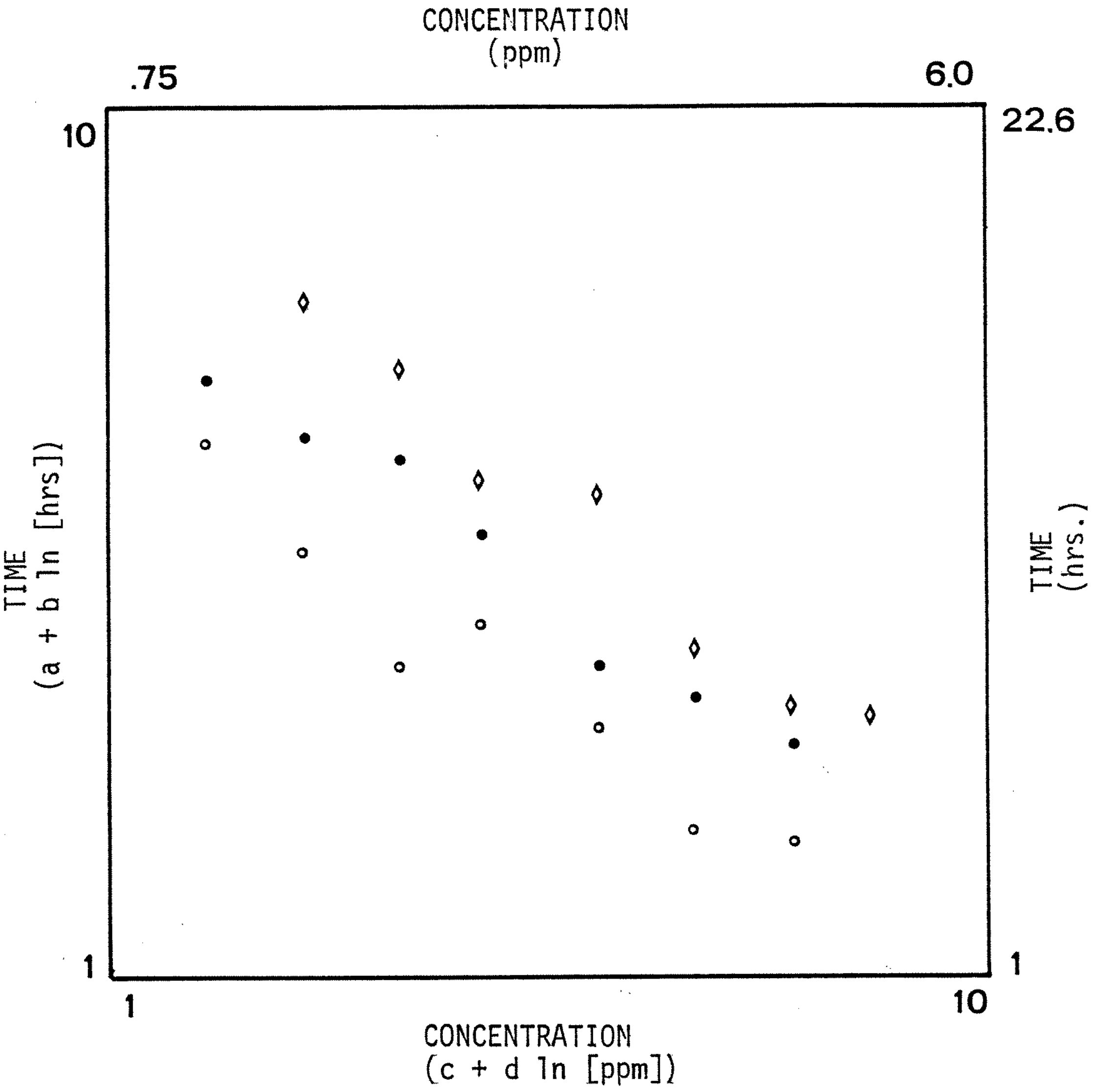


Figure 27. Display of bioassay data for use in selecting lampricide concentration acording to the Canadian control unit decision rule. Open dots represent observed times to 50% mortality, solid dots represent observed times to 78% mortality and diamonds represent observed times to 94% mortality. (After Smith, B.R., J. J. Tibblers and B.G.H. Johnson. 1974. Control of the Sea Lamprey (*Petromyzon marinus*) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26.)

Under the mortality model, the time to 50% mortality in the population exposed to a concentration of V is the mean, $\alpha + \beta V$. The time to 78% mortality is $\alpha + \beta V + .77\sigma$, i.e. .77 standard deviation units to the right of the mean. Similarly, the time to 94% mortality is $\alpha + \beta V + 1.545\sigma$ (Figure 28).

The population parameters, α and β, are estimated implicitly by visually fitting the regression line, $Y = \alpha + \beta V$, through the observed 50% mortality points (Figure 29). The population standard deviation, σ, is estimated implicitly by averaging the observed within concentration differences between the time to 94% mortality, $\alpha + \beta V + 1.545\sigma$, and the time to 50% mortality, $\alpha + \beta V$. The distance implicitly estimated is actually a multiple of the standard deviation, 1.545σ. The mortality model can be specified completely with the estimates for α, β and σ.

The Canadian unit targets for a mortality of no less than 99.9%. Under the model the time to 99.9% mortality is $\alpha + \beta V + 3.09\sigma$, i.e. the conditional mean, $\alpha + \beta V$, plus 2 times 1.545σ. To be on the safe side the regression line, $\hat{\alpha} + \hat{\beta} V$, first is shifted upward such that all observed 50% mortality points are below it; then it is shifted an additional $3.09\hat{\sigma}$ units upward (Figure 30). The resulting line represents the predicted time to 99.9+% mortality as a function of lampricide concentration. The minimum lethal concentration for an exposure of duration T is the concentration corresponding to time T on that line. For example, a typical duration is 12 hours which by the Canadian control unit's $\log_e$ transformation is 8.17. The minimum lethal concentration is found by locating the concentration, V, corresponding to the time, Y = 8.17 (Figure 31). The concentration, V, in $\log_e$ units then is transformed back to units of ppm.

The location of the predicted 99.9+% mortality line depends on the

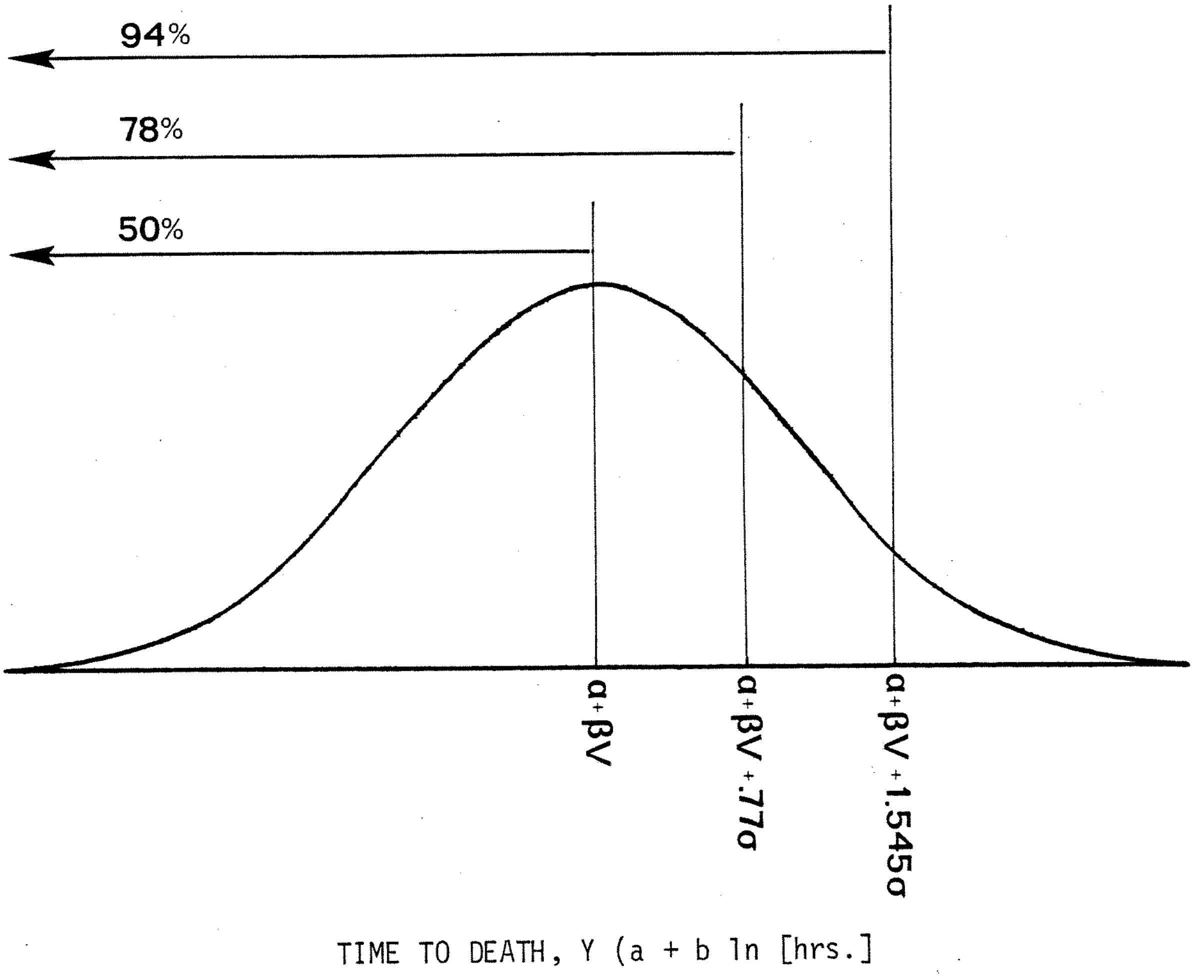


Figure 28. Time to 50%, 78% and 94% cumulative mortality (area under the curve) as equally spaced points on a normal frequency curve. Fifty percent of the area is to the right of the mean, $\alpha + \beta V$, (where V is lampricide concentration in $\log_e$ units). Seventy-eight percent is to the right of the mean plus .77 standard deviations, σ, and 94% of the area is to the right of the mean plus 1.545 σ.

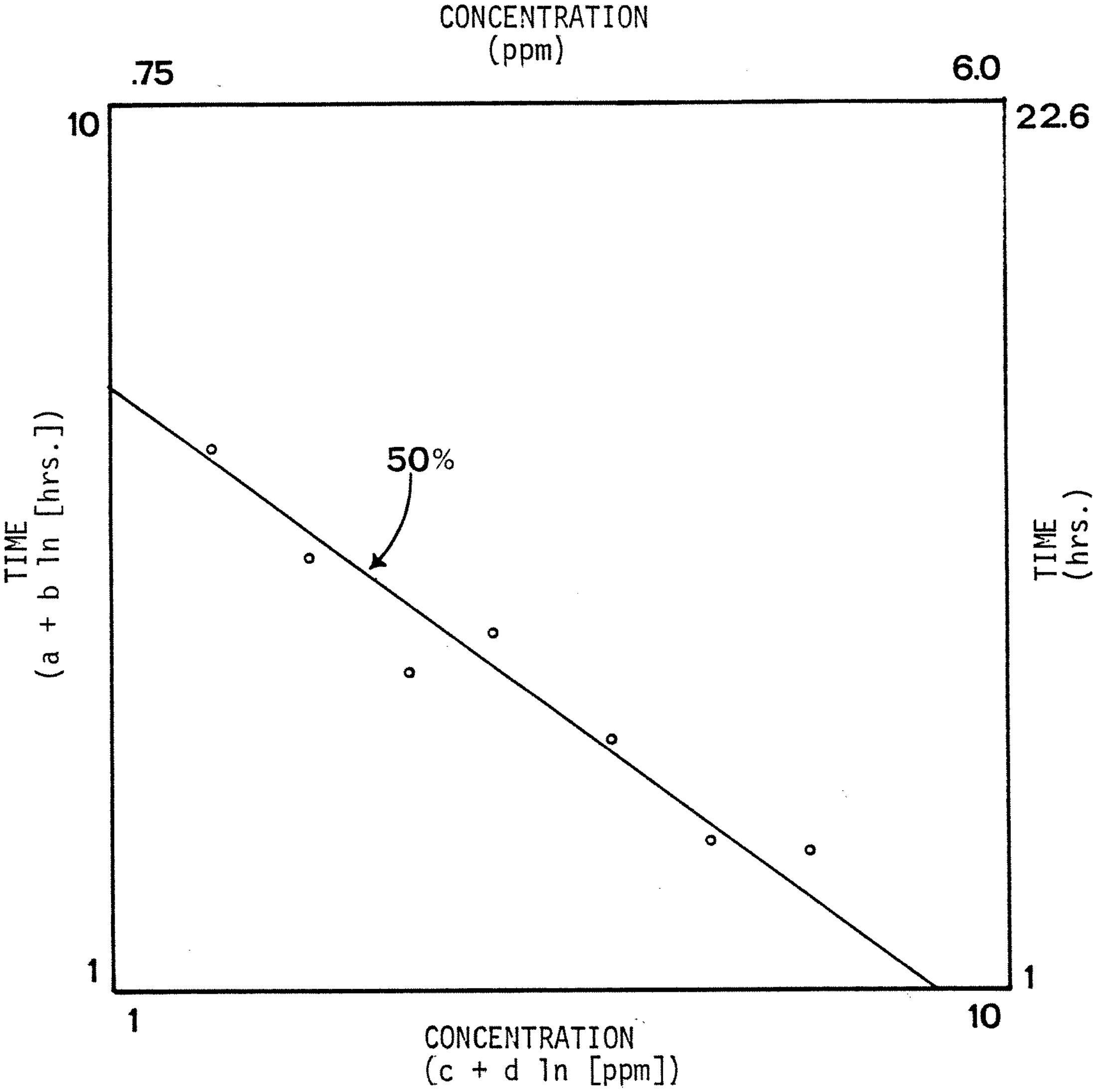


Figure 29. Representation of a straight line visually fitted to the points of the observed times to 50% mortality. (After Smith, B.R., J.J. Tibbles and B.G.H. Johnson. 1974. Control of the Sea Lamprey (*Petromyzon marinus*) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26.)

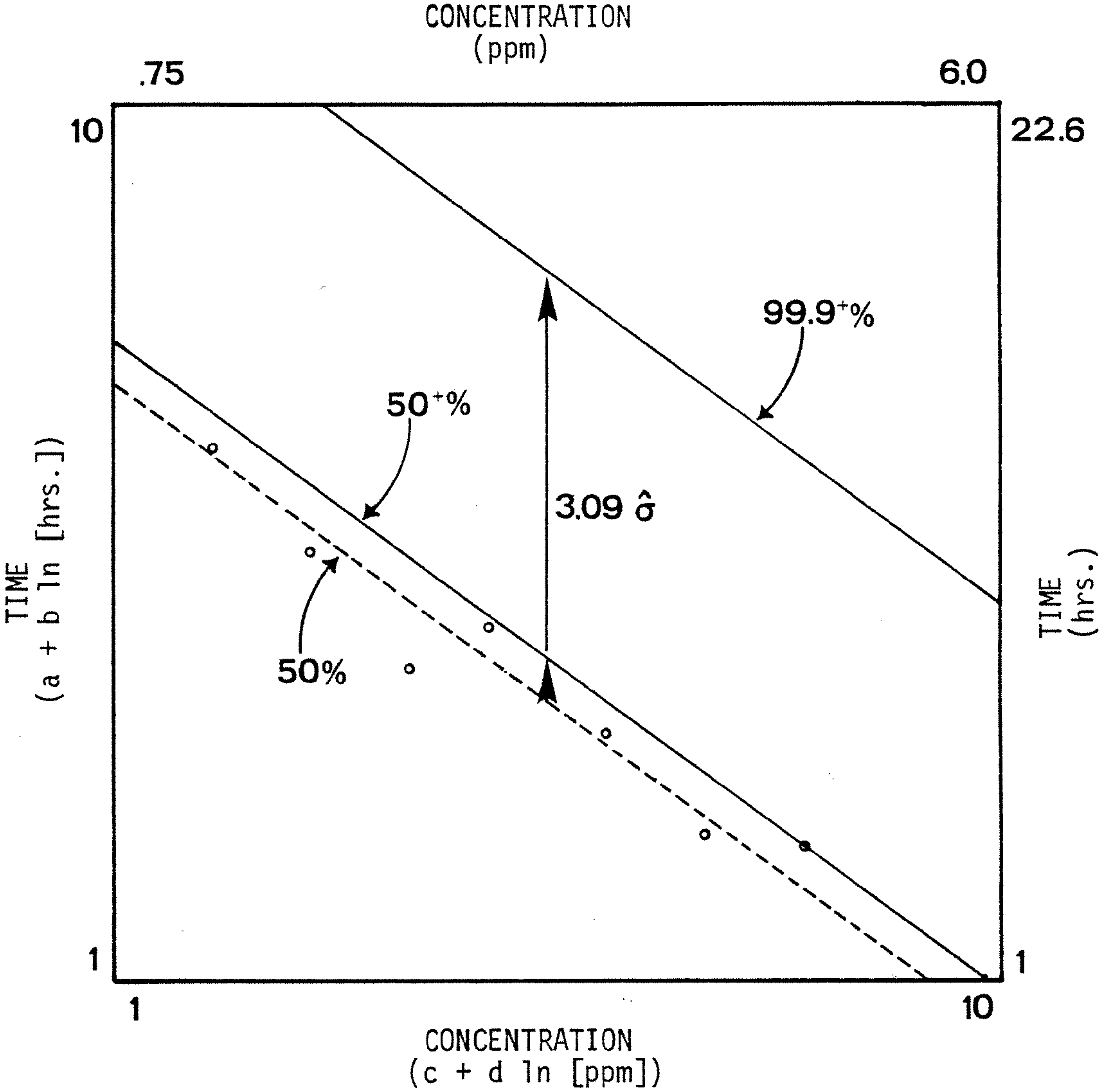


Figure 30. Depiction of twice shifting the visually fitted 50% mortality line to represent the predicted 99.9+% mortality line. The 50% mortality line first is shifted to just above all observed 50% mortality points, then it is shifted upward an additional 3.09 $\hat{\sigma}$. (After Smith, B.R., J.J. Tibbles and B.G.H. Johnson. 1974. Control of the Sea Lamprey (Petromyzon marinus) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26.)

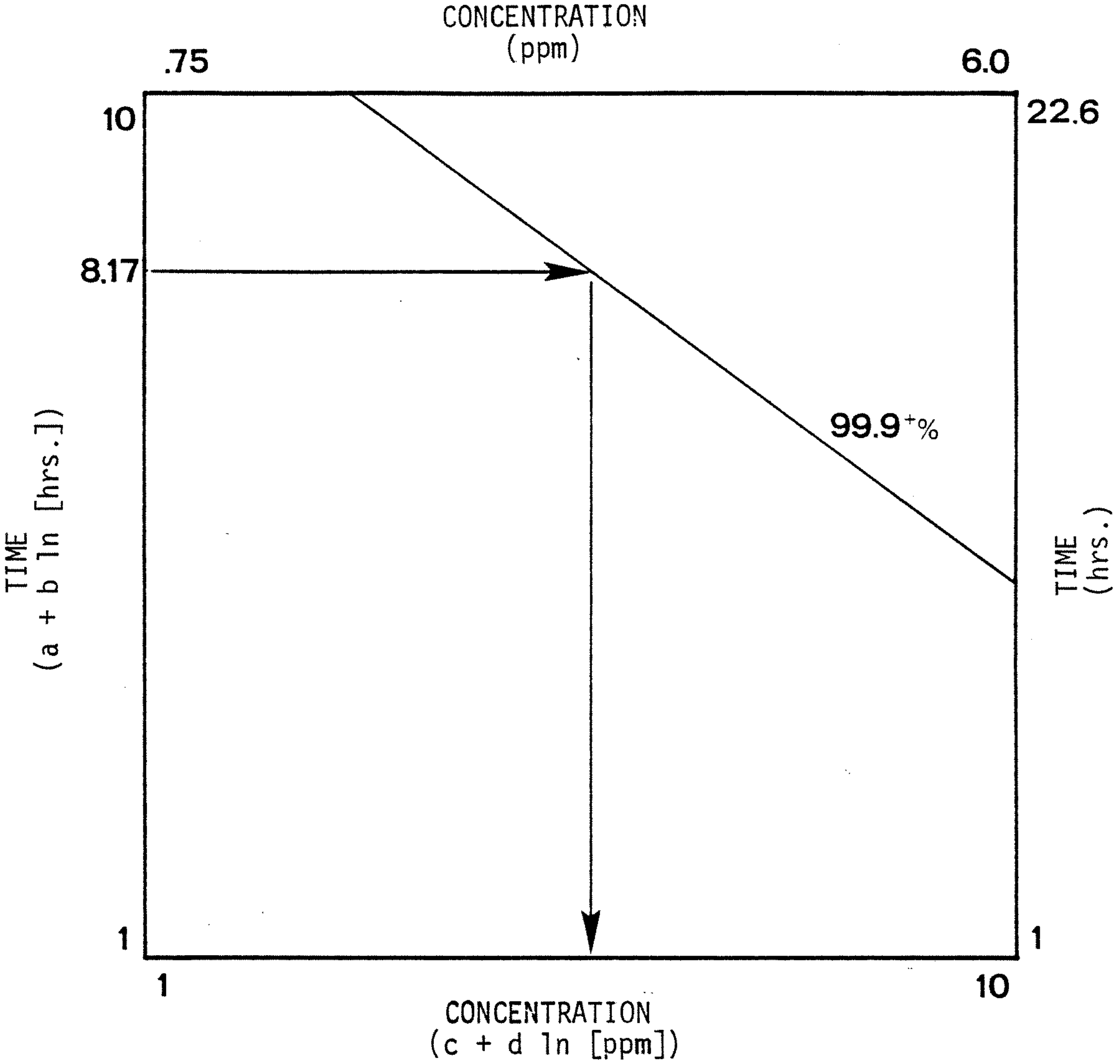


Figure 31. Locating the concentration of lampricide (in $\log_e$ units) required for 99.9+% mortality in 12 hours based on the predicted 99.9+% mortality line. Twelve hours is 8.17 in the transformed $\log_e$ units. (After Smith, B.R., J.J. Tibbles and B.G.H. Johnson. 1974. Control of the Sea Lamprey (*Petromyzon marinus*) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26.)

estimates of α, β and σ which depend on the particular (random) sample of ammocoetes selected from the population for the bioassay. The predicted 99.9+% mortality line therefore is subject to random variability as is the calculated minimum lethal concentration.

To observe the behavior of this random variability we conducted a computer simulation of the decision process leading to the calculation of the minimum lethal concentration for a 12 hour exposure for each of the 4 cases in Figure 24. In particular we wantd to identify the expected value and the standard error of the calculated minimum lethal concentration.

The expected values for minimum lethal concentrations for cases A, B, C and D were 1.22 ppm, 1.57 ppm, 2.75 ppm and 4.65 ppm respectively. The standard errors for cases A, B, C and D were .16, .15, .32 and .72 respectively. The average minimum lethal concentration increases and the spread of calculated values increases as toxicity decreases, which would be expected.

The targetted mortality for each mean value can be read from the corresponding mortality response curve (Figure 32). The targetted mortalities (significant to 4 places) for cases A, B, C and D are 1.0000, 0.9999, 0.9999, and 0.9999 respectively. In each case the targetted mortality corresponding to the expected minimum lethal concentration is consistent with the stated objective of no less than 99.9% mortality.

UNITED STATES CONTROL UNIT

Typically the bioassay of the U.S. control unit consists of 9 lampricide concentrations (e.g. U = .5, 1, 1.5, ..., 5.5, 6) and 8 observation times (X = 1, 2, 3, ..., 7, 8). (For a detailed description of the bioassay method see Howell, J.H. and W.M. Marquette. 1962. Use of Mobile Bioassay Equipment in the Chemical Control of Sea Lamprey. USFWS

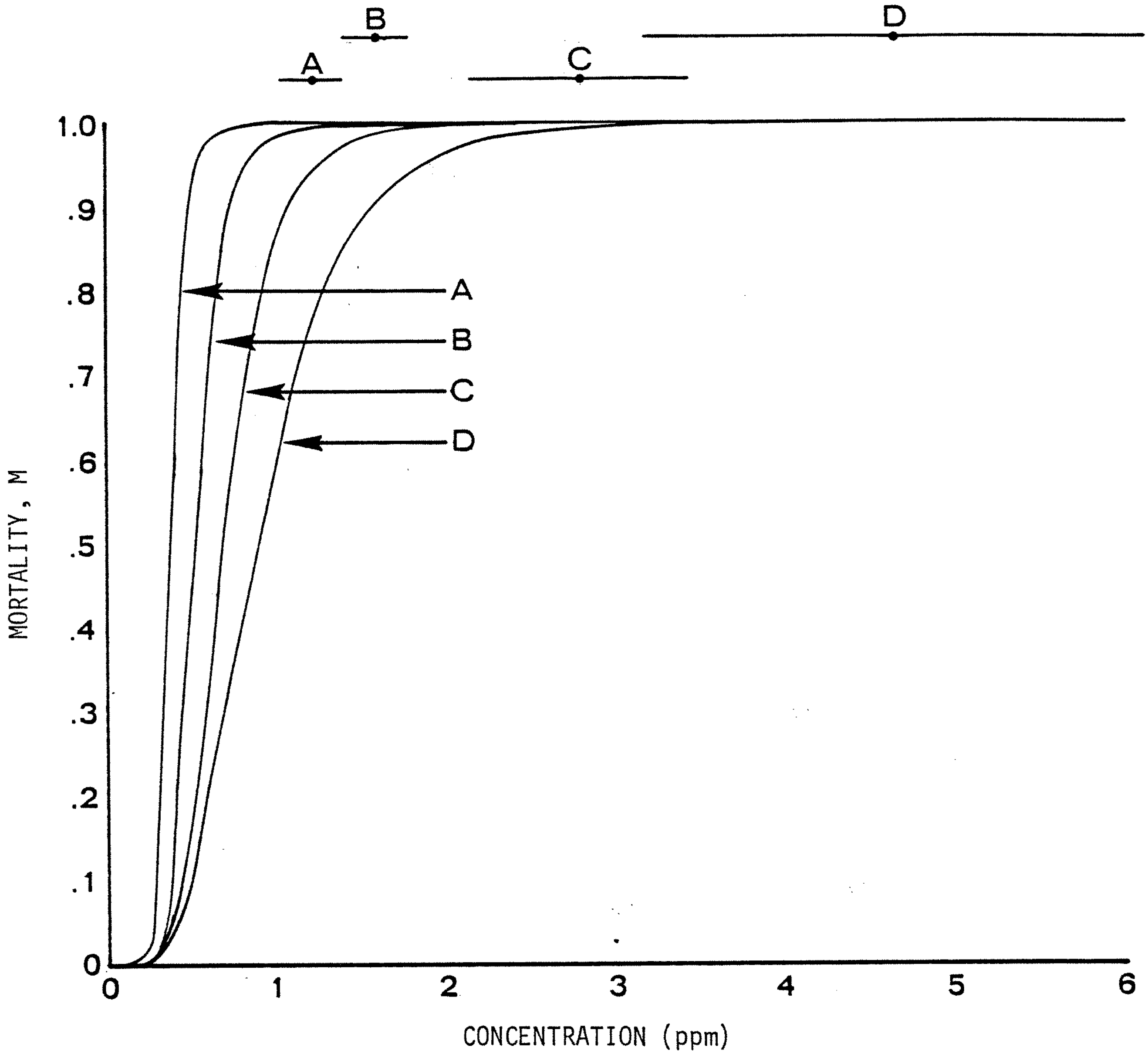


Figure 32. Mean selected concentrations (± 2 s.e.) under the decision process of the Canadian control unit for the 4 cases of Figure 24. The dots represent the mean concentrations for cases A, B, C and D shown relative to the corresponding mortality response curves.

Spec. Sci. Rep. Fish. 418:9 p.) Both observation times and concentrations are in arithmetic units: U in ppm and X in hours. Ten ammocoetes are subjected to each lampricide concentration. Petromyzon marinus ammocoetes are the preferred subjects but Lampreta sp. ammocoetes may be used as substitutes if enough P. marinus ammocoetes are not available. Selected lampricide concentrations based on Lampreta sp. bioassays are thought to be higher than those based on P. marinus because Lampreta sp. ammocoetes are believed to be somewhat less sensitive to lampricide than P. marinus ammocoetes. At each observation time the number of dead ammocoetes in each concentration is recorded.

The decision rule is to select the minimum concentration in which all 10 subjects died within 8 hours. That concentration is the minimum lethal concentration for a 12 hour exposure. Again, the calculated minimum lethal concentration is subject to random variability because the ammocoetes used in the bioassays are a random sample from some population. To examine the behavior of this random variability we conducted a computer simulation of this decision process for each of the 4 cases in Figure 24. We made the simplifying assumption that all test animals were P. marinus randomly selected from the population under consideration. The calculated minimum lethal concentrations therefore should be viewed as low values.

The expected values for minimum lethal concentration for cases A, B, C and D were 1.02 ppm, 1.48 ppm, 2.11 ppm and 3.15 ppm respectively. The standard errors for cases A, B, C and D were .10, .27, .38 and .56 respectively. Like the method of the Canadian unit, the mean values and standard errors increase with decreasing toxicity. The targetted mortality for each mean value can be read from the appropriate mortality response curve (Figure 33). The targetted mortalities (significant to 4 places) for cases A, B, C and D are 1.000, 0.9998, 0.9989 and 0.9974 respectively.

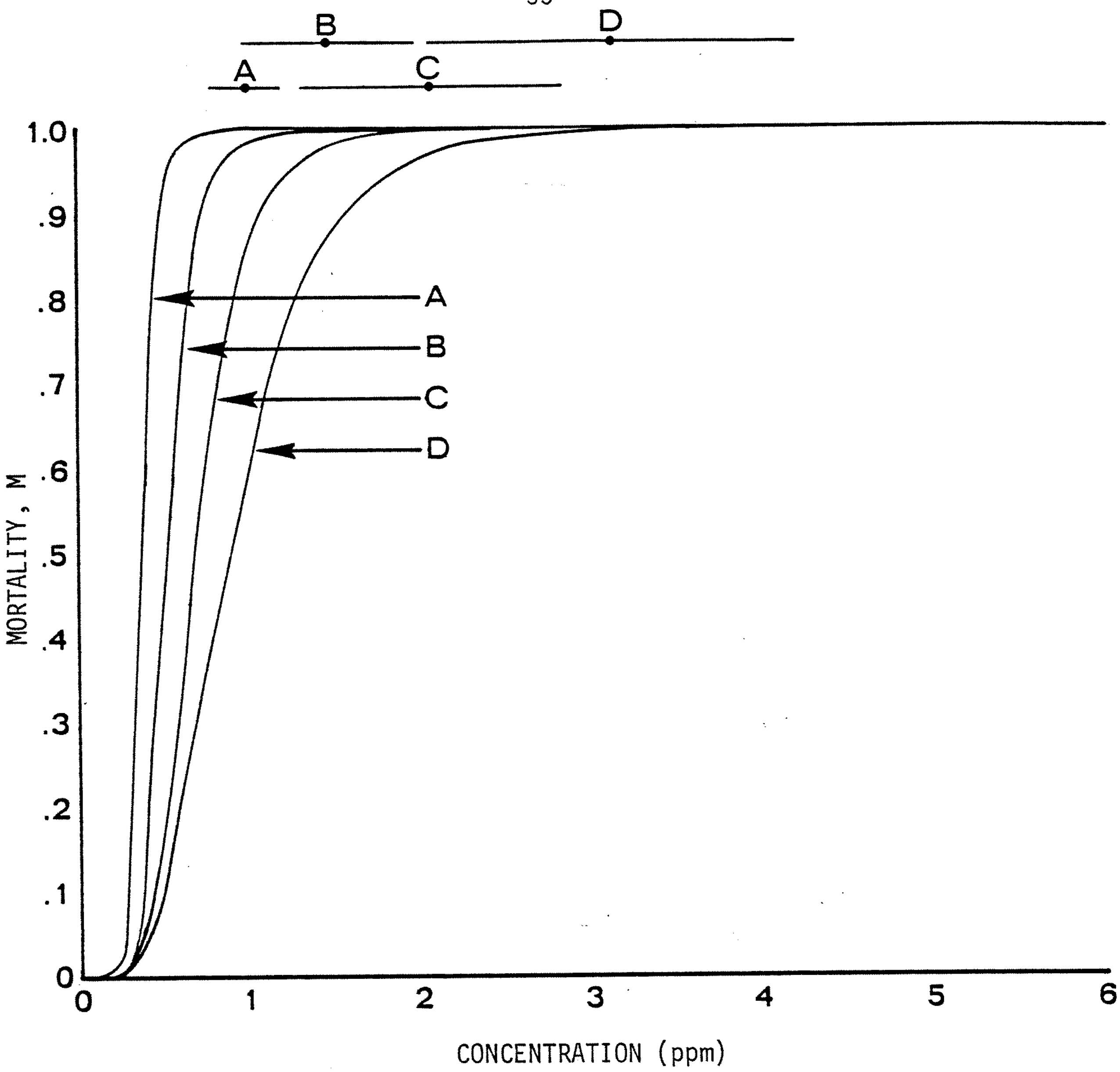


Figure 33. Mean selected concentrations (± 2 s.e.) under the decision process of the U.S. control unit for the 4 cases of Figure 24. The dots represent the mean concentrations for cases A, B, C and D shown relative to the corresponding mortality response curve.

REDUCTION OF TARGETTED MORTALITY

The selected concentrations for both control units lie near the asymptotes of the respective mortality response curves. Although the numerical value of the mean selected concentration differs from one mortality response curve to another, i.e. for situations with different toxicities (Figures 32 and 33), the location of a selected concentration relative to the corresponding curve is similar for all curves. This similarity can be seen by plotting targetted mortality (proportion killed) against percent of the present concentration, or more correctly of the expected concentration, selected under the present decision rules. These mortality response curves, normalized to present chemical use levels, are quite similar regardless of toxicity (Figures 34 and 35). The normalized mortality response curves for both control units are quite flat to the immediate left of the present concentration level. This indicates that a moderate reduction in chemical use per stream would result in only a small reduction in effectiveness.

Identifying an optimal mix of reduced concentration and reduced effectiveness requires a context for evaluation. For this we will assume the backpack approach for selecting streams for treatment. Recall that under the backpack approach the streams are ranked by individual benefit/cost ratios where the benefit is number of transformers killed and the cost is total expenditure for treatment. Also, the greatest overall efficiency is achieved if the individual benefit/cost ratios are maximized for each stream. Therefore, we will define the optimal mix of reduced concentration and reduced effectiveness as that which maximizes the benefit/cost ratio per stream.

Two important factors must be considered in relating numbers of

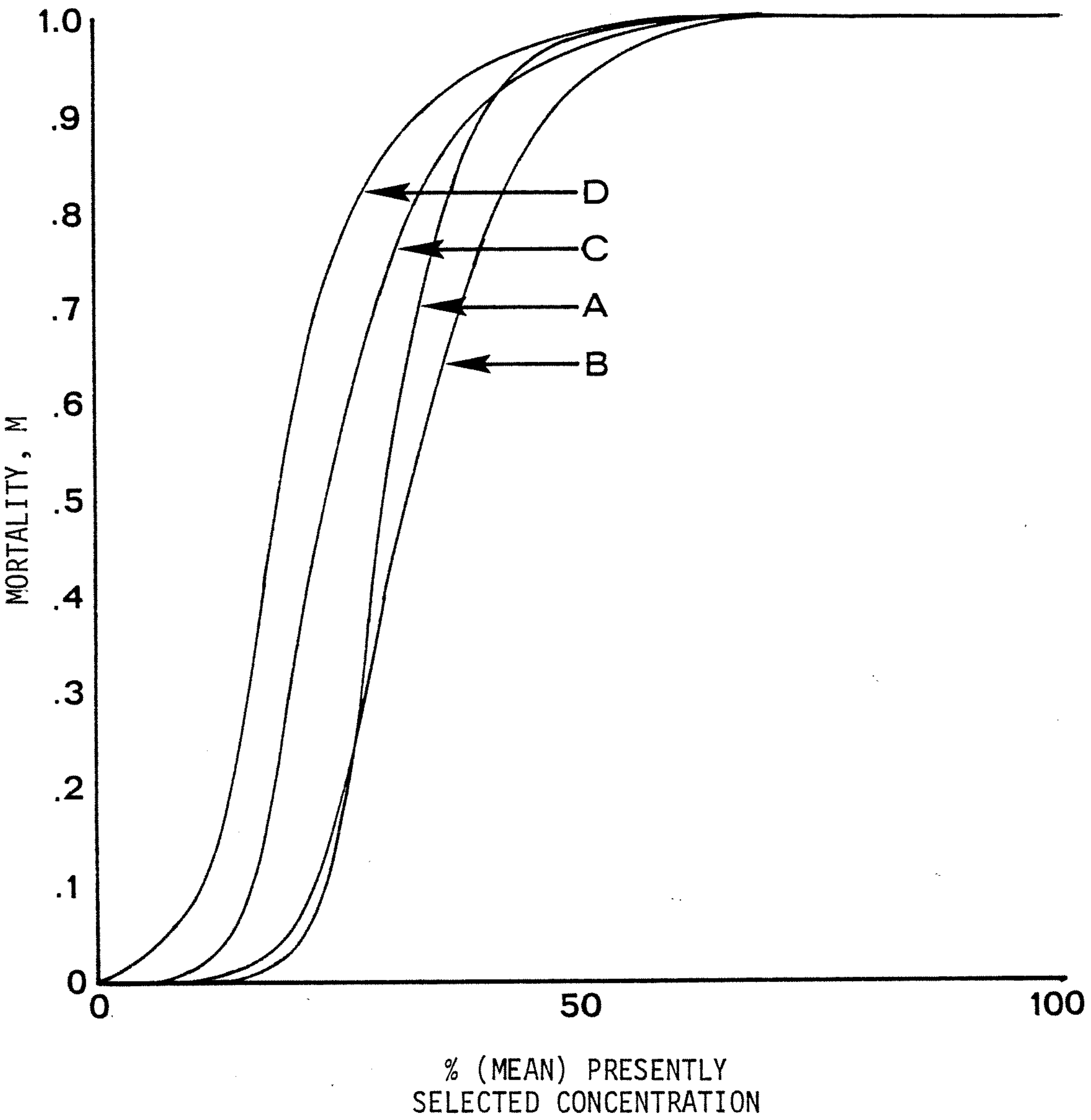


Figure 34. Mortality response curves for cases A, B, C and D (from Figure 24) normalized to the mean selected concentrations under the decision process of the Canadian control unit. The normalized curves, especially between 50% and 100% of present concentration levels, are very similar regardless of toxicity.

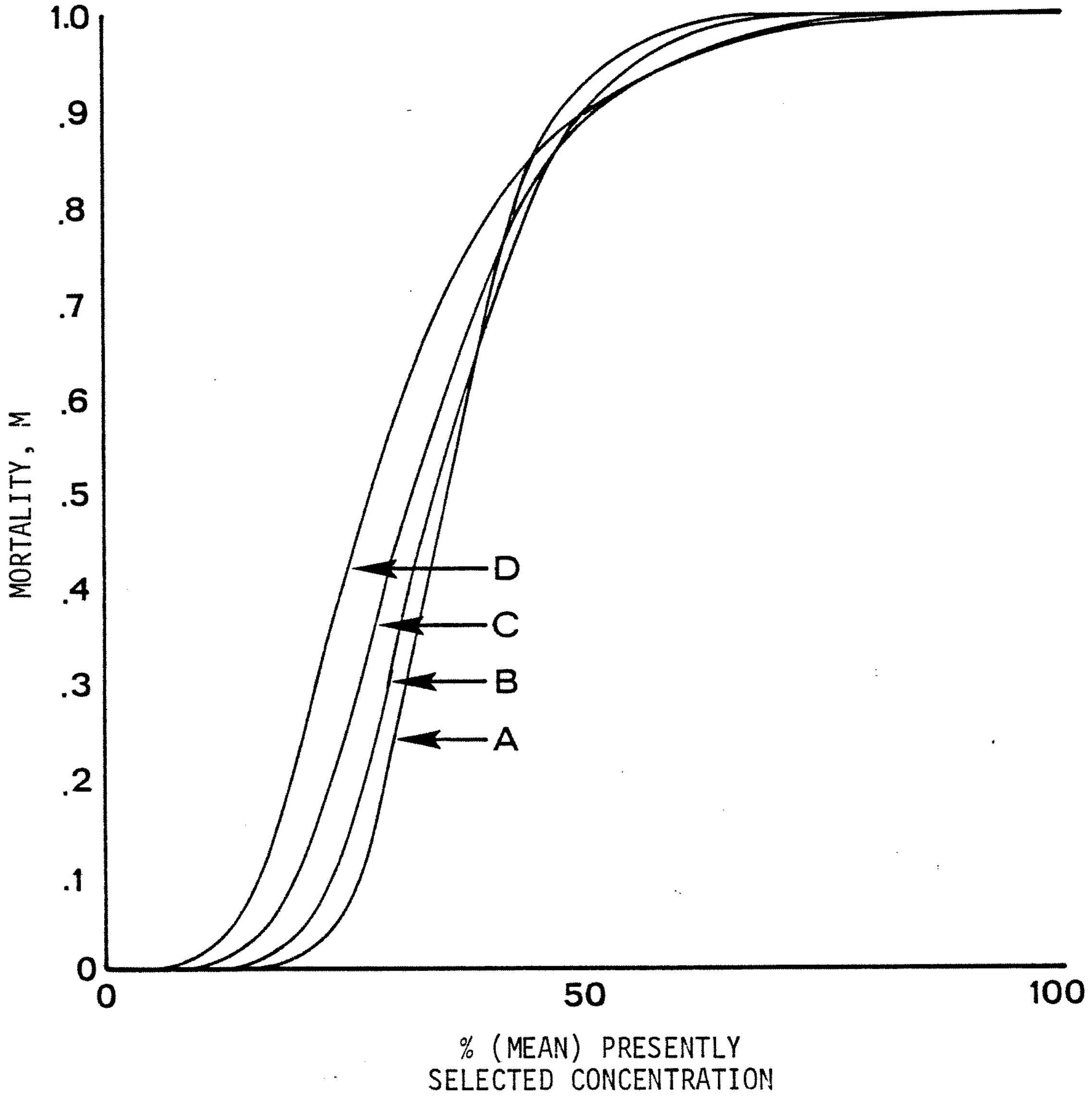


Figure 35. Mortality response curves for cases A, B, C and D (from Figure 24) normalized to the mean selected concentrations under the decision process of the U.S. control unit. The normalized curves, especially beween 50% and 100% of present concentration levels, are very similar regardless of toxicity.

transformers killed (the measure of benefit) to the targetted mortality, M, (the variable of the normalized mortality response curves). They are the number of transformers present, N, and the proportion of those present that will be exposed to lampricide during treatment, P. Benefit now can be expressed in terms of M if we assume that the sub-population of transformers actually exposed to lampricide receive the targetted dose and respond according to the mortality response curves and further assume that all those not exposed survive. Under these conditions,

$$\text{Benefit} = N \cdot P \cdot M$$

Similarly, the cost for treatment can be expressed in terms of the proportion of the expected concentration under present selection. Let,

K = proportion of present concentration,

D = total cost for treatment with present concentration,

and note that approximately 25% of the total treatment cost is chemical cost (Report of the Audit of the GLFC is Program of Sea Lamprey Control and Research. 1980), then

$$\text{Cost} = D\ (.75 + .25K).$$

Therefore the benefit/cost ratio can be rewritten,

$$B/C = \frac{N \cdot P}{D} \cdot \left(\frac{M}{.75 + .25\ K}\right)$$

where $\frac{N \cdot P}{D}$ is independent of concentration for a given stream. Consequently the benefit/cost ratio is maximized when the ratio,

$$\frac{M}{.75 + .25K}$$

is maximized. The two curves of Figure 36 are representations of

$$\frac{M}{.75 + .25K}$$

as a function of K, one curve corresponding to each control units decision rule. Each curve is based on median values of M from cases A, B, C and D read from Figures 34 and 35.

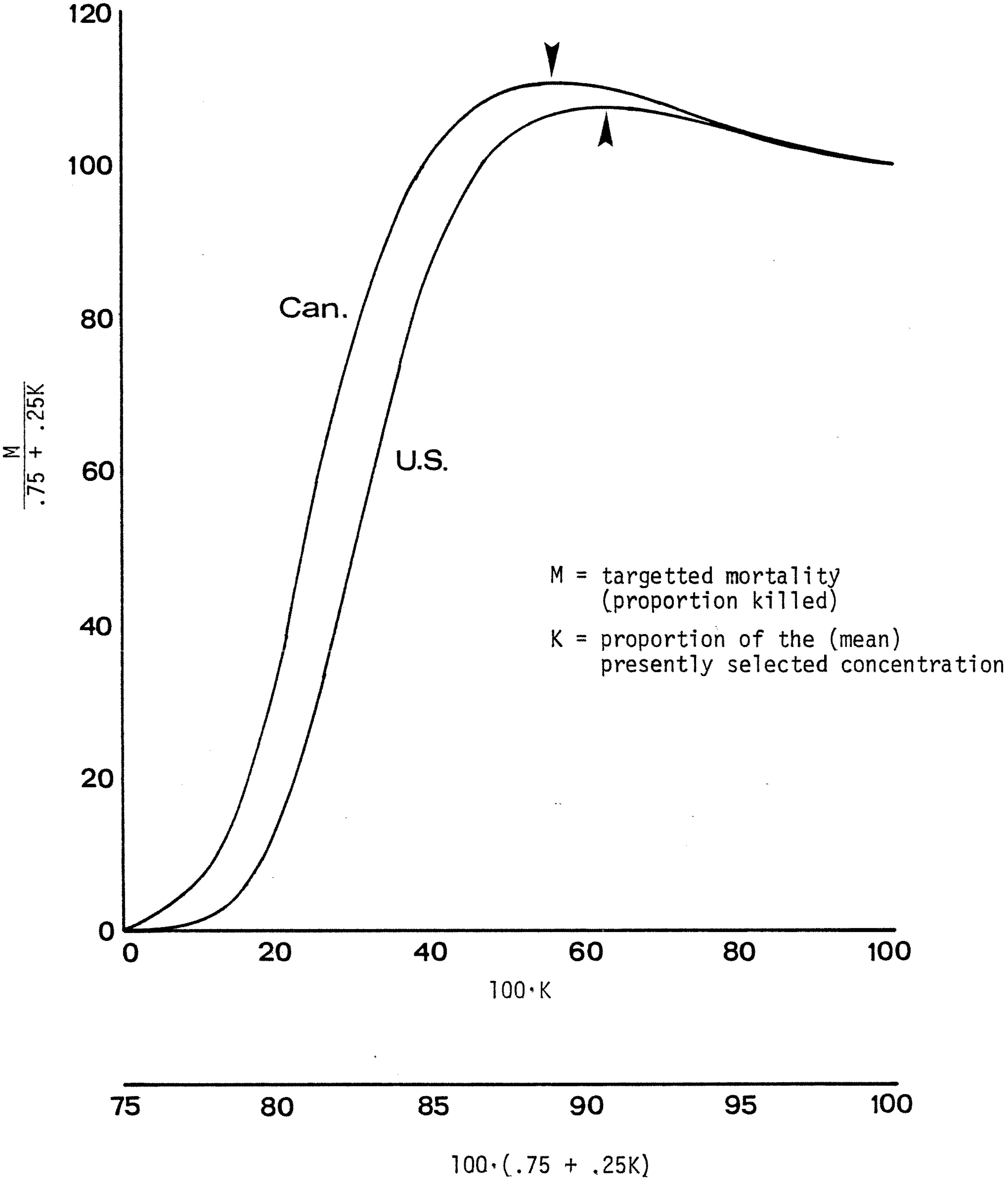


Figure 36. Representation of a standardized benefit/cost ratio, 100·M/(.75+.25K), as a function of percent present chemical use (100·K) or percent total treatment cost (100·(.75+.25K)) per stream. For both Canadian and U.S. control units an increase in the per stream B/C (as M/(.75+.25K)) can be realized by decreasing lampricide concentration for treatments. Arrows locate points of maximum B/C.

The maximum benefit/cost ratio per stream for the U.S. control unit would be achieved with a reduction to approximately 63% of the presently selected concentrations. It would be achieved for the Canadian control unit with a reduction to approximately 56% of the presently selected concentrations. These reductions in concentration would result in a drop of effectiveness from the present 99.9+% to approximately 98% targetted mortality.

MAXIMUM ALLOWABLE CONCENTRATION

Both control units attempt to protect against excessive non-target mortality by identifying a maximum allowable concentration based on bioassays with non-target species. Usually the non-target subjects are hatchery stock, mostly rainbow trout, brook trout and white suckers. The Canadian unit defines 25% non-target mortality as the maximum allowable level. The concentration predicted to produce 25% mortality is identified in a manner similar to their method for identifying the minimum lethal concentration (Smith, B.R., J.J. Tibbles and B.G.H. Johnson. 1974. Control of the Sea Lamprey (Petromyzon marinus) in Lake Superior, 1953-70. GLFC Tech. Rept. No. 26.). A curve is visually fitted to points corresponding to 25% cumulative mortality on a plot of $\log_e$ time vs $\log_e$ concentration. The maximum allowable concentration for any duration of exposure then can be read from that line. The U.S. control unit defines maximum allowable as the maximum concentration that kills no non-target subjects within 8 hours. As with their decision rule for selecting a minimum lethal concentration some expected population mortality is implicit in this rule.

The maximum allowable levels are admittedly arbitrary in terms of the level of intended protection for non-target animals. In addition to that arbitrariness, this approach to protecting non-target animals has two underlying weaknesses. For the bioassays to be relevant to in-stream mortality, the response of hatchery stock subjects to lampricide must be related to, if not representative of, mortality in the non-target community of the stream. Characterization of such a relationship is not a standard consideration in establishing a maximum allowable concentration.

A more fundamental difficulty is the units of mortality from the bioassay - proportion killed (implicit or explicit). Basing a trade-off between two attributes of value (ammocoetes killed, a positive value, and non-target animals killed, a negative value) solely on proportions of each can be wholly inappropriate. For example, if 99.9% ammocoete mortality is always worth 25% trout mortality then a treatment resulting in 999 dead ammocoetes with 2000 dead trout would be viewed the same as one resulting in 1998 dead ammocoetes and only 250 dead trout. The former represents a stream with 1000 ammocoetes and 8000 trout and the latter represents a stream with 2000 ammocoetes and 1000 trout.

To some extent these weaknesses are academic. Both units report that their maximum allowable concentration rarely is as low as their minimum lethal level and therefore no conflict arises. Rather, the maximum allowable level serves as a ceiling to increases in concentration over the minimum lethal level to compensate for vagaries in stream flow.

III. Conclusions and Recommendations

SUMMARY COMMENTS

Both control units acknowledge that eradication of sea lamprey is unattainable under existing conditions and that eradication is not what they are attempting. Yet the decision rules we have examined appear to reflect the objectives of an eradication program rather than a control program. The overriding concern in both selection of streams and selection of concentrations of lampricide is the number of transformers killed rather than a balance of numbers killed against cost. Streams are prioritized for treatment based on the expected number of transformers killed (albeit implicity) and selected concentrations of lampricide correspond to target mortalities approaching 100%.

If eradication were the goal, this approach would be appropriate as every sea lamprey killed would bring us closer to our goal. However, if the goal is to depress sea lamprey stocks to acceptably low levels, knowing eradication is impossible, then additional factors must be considered for rational management. The immediate question 'What is an acceptably low level?' gives rise to consideration of the benefits derived from selected reductions in sea lamprey numbers and the cost required to produce those reductions. Decision rules appropriate to a control program should address benefits and costs, i.e. efficiency, not just benefits, i.e. effectiveness, as is appropriate to a well funded eradication program.

Related to balancing reductions in effectiveness against cost savings is balancing reductions in effectiveness against acquisition of information. An aspect of the decision process common to both control units is a heavy reliance on subjective judgement and a paucity of objective measures. Both units state their intentions for maximizing effectiveness but neither can demonstrate it rigorously. The information required to rigorously demonstrate effectiveness is expensive. Objective estimates of ammocoete numbers in streams before and after treatments are a minimum requirement for demonstrating effectiveness. However, under present conditions, that information likely would be paid for with a reduction in effectiveness, i.e. time spent in assessment isn't spent killing ammocoetes. The control units have opted for effectiveness almost to the exclusion of being able to objectively demonstrate that effectiveness. To the extent the control units are the avowed experts whose judgements and beliefs are fully accepted, the trade-off made is an appropriate one.

Demonstrating efficiency (in the conventional sense of maximizing net return) requires even more information than does demonstrating effectiveness. The relationship between numbers of transformers killed and the value of the fishery should be identified for a rigorous and meaningful assessment of efficiency. Delineating that relationship seems to fall well outside the purview of the control units and will be a major task for whomever undertakes it. The perceived need for this information coupled with an understanding of how difficult it would be to acquire might be cause enough to base decisions on effectiveness rather than efficiency.

RECOMMENDATIONS

1. The relationship between numbers of sea lamprey killed and the value of the fishery is fundamental to efficient program management and accountability. The methodology of adaptive environmental assessment (AEA) workshops is well suited to addressing this kind of complex relationship.

We recommend the GLFC sponsor one or more AEA workshop(s) (as a follow-up to the AEA workshop held in Sault Ste. Marie) to explore the relationship between numbers of sea lamprey killed in a lake and the resulting value of the fishery.

2. Another fundamental information need is for objective measures of the number of ammocoetes in streams. We recommend the GLFC identify a method for statistically estimating ammocoete numbers and estimate the cost for implementing the procedure.

3. Substantial increases in efficiency, in principle, can be realized by selecting streams for treatment by the backpack method. We recommend a trial implementation of the backpack approach using formalized subjective judgements (Bayesian priors) as surrogates for objective estimates of the numbers of transformers killed. The expected increase in efficiency that results taken with the estimated cost for obtaining estimates of numbers of ammocoetes might form the basis for evaluating an estimation program.

4. We have demonstrated that independently selecting streams for treatment from two jurisdictional subsets may produce suboptimal results. In the absence of objective evidence that indicates otherwise, we recommend selecting streams on a lake by lake basis without regard to national boundaries.

5. We have demonstrated that under the described mortality model a reduction in lampricide concentrations in stream treatments can result in greater efficiency (number of transformers killed/total treatment cost). We recommend reducing lampricide concentrations for treatment to approximately 60% of present levels. This reduction is equivalent to targetting for approximately 98% ammocoete mortality.