DIVISION OF THE HUMANITIES AND SOCIAL SCIENCES

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91125

A COST-BENEFIT APPROACH TO DRINKING WATER AND CANCER

Talbot Page
California Institute of Technology

Robert Harris
Clement Associates, Inc.
Washington, DC

Paper presented at Conference on Water Chlorination: Environmental Impact and Health Effects, Asilomar Conference Center at Pacific Grove, CA, Oct. 18-23, 1981. Forthcoming in <u>Water Chlorination: Environmental Impact and Health Effects</u>, vol. 4, edited by R. L. Jolley and R. B. Cumming. Ann Arbor, MI, Ann Arbor Science.

SOCIAL SCIENCE WORKING PAPER 462

January 1983

A COST-BENEFIT APPROACH TO DRINKING WATER AND CANCER

Talbot Page and Robert Harris

ABSTRACT

The problem of controlling carcinogens in drinking water is one of decision-making under uncertainty. Although much information has been gained in the last eight years, pervasive uncertainties remain. The paper identifies some of the trends in the accumulation of the evidence, and attempts to evaluate the currently existing uncertainty.

A COST-BENEFIT APPROACH

TO DRINKING WATER AND CANCER

Talbot Page
California Institute of Technology

Robert Harris
Clement Associates, Inc.
Washington, DC

INTRODUCTION

This paper reports a cost-benefit analysis of the control of carcinogens in drinking water. (For a previous discussion, see References [1] and [2].) We focus on the use of cost-benefit analysis in dealing with uncertainty. We suspect that, to many scientists at this conference, a cost-benefit approach to drinking water and cancer may seem infeasible, unethical, or both. In fact, we agree that there are important ethical and practical problems in the application of cost-benefit analysis to the health and safety area. Having considered these problems elsewhere [3], we nonetheless believe that a cost-benefit approach offers a useful perspective to the problem of chemicals in drinking water.

Our approach differs from that commonly taken by epidemiologists or toxicologists; we attempt to highlight this difference as it relates to the analysis of uncertainty. The difference arises primarily from viewing the problem of chemicals in drinking water as a decision problem, where choices have to be made about the amount of precautionary control, rather than as a science problem, where knowledge is sought for its own sake. We consider uncertainty under three headings: location of the decision problem, risk assessment, and evaluation of uncertainty.

LOCATION OF THE PROBLEM

To many critics of cost-benefit analysis, a central problem is the difficulty in placing a value on life; to an epidemiologist or toxicologist, a central problem is establishing a causal link between chemicals in drinking water and increased cancer rates. To a practitioner of cost-benefit analysis, neither strikes at the heart of the problem. In studying this problem, one finds enormous uncertainties associated with many of the critical decision factors. These uncertainties can be interpreted in alternative ways. Although opportunities exist for reducing the uncertainties, these opportunities are costly and often involve substantial time delays. Potential irreversible costs, such as latent cancers, may result from the time delays. To a practitioner of cost-benefit analysis, the heart of the problem is the value of information--the costs and benefits of acquiring new information and interpreting existing information.

The cost-benefit approach is to look for gaps in information. Where the cost of reducing a gap is small compared with the expected gain in improved decision making, research attention and analytical skill should be focused. Application of this principle locates the heart of the problem, not on the proof of causality or on the

valuation of life but on the risk assessment. To place the value-of-life issue in a framework of uncertainty, we can say that uncertainty exists about what ethical basis should be used in deciding when to initiate a life-saving program or when to cut it off.

However, upper and lower limits are fairly well agreed upon, and these limits imply a relatively small range in the value of a life compared with other uncertainties associated with drinking water and cancer. Defining the lower limit is the notion of productivity. Even the most callous persons tend to agree that it is worthwhile to pay as much to keep a worker alive as his contribution to the economy's productivity. "Human capital" theories set this minimal value at somewhere around $200,000 per average worker (most human capital theorists are willing to use this figure to include the retired or otherwise nonworking). Defining the upper limit is the notion of feasibility. Even the most compassionate do not advocate spending the nation's entire resources on health and safety. Estimates of economic feasibility vary, but they are seldom more than $2 million per life saved when stated explicitly. For limited programs and specially identified individuals (e.g., those on kidney machines), the amount is sometimes more; but for large programs, much more is generally considered economically infeasible, although desirable. (Economists generally prefer the willingness-to-pay approach, on ethical grounds, to either of these extremes. This approach leads to a value of life on the order of $200,000 to $500,000.)

The important thing to note is that little more than a single order of magnitude exists between the upper and lower limits arising from productivity and feasibility bases in valuing life. Moreover, the area of strongest consensus is probably well within this range. By strenuous ethical debate, one might possibly narrow the consensus and strengthen conviction, but clearly the ranges of uncertainty in other aspects of the problem are much larger. Pike [4] discusses reasons why cancer risk estimates from extrapolation models may be two or more orders of magnitude in error. Kraybill [5] and Crump and Guess [6] discuss sources for similar magnitudes of error in epidemiologic studies. Not only are the ranges of uncertainty larger, but also the opportunities for narrowing the ranges are greater. Thus, by the value-of-information principle, risk assessment is a more pivotal part of the drinking water problem, for decision purposes, than further clarifying issues concerning the value of life. In other words, an epidemiologic study that convincingly shows that chemicals in drinking water raises the cancer rate by 10% contributes more to decision making than a convincing argument that shows that the ethical base of a willingness-to-pay approach is better than the human capital approach.

The value-of-information principle also suggests that proving causality is less important than other aspects of risk assessment. To see this, we again put the matter into a framework of uncertainty ranges. The mere fact that known carcinogens exist in drinking water strongly suggests that there is a causal link between drinking water and cancer. However, this fact does not "prove" causality

under the criteria described by Hill [7] and discussed for the case of drinking water by Crump and Guess [6]. To establish causality under Hill's criteria would require expensive and time-consuming investigation (where one of the principal costs of delay is the expected cost of preventable cancers if drinking water is carcinogenic).

Given the evidence that existed, say by 1977, we believe that a reasonable person would be justified in assigning a 90% probability that chemicals in drinking water contribute to cancer. The cost-benefit practitioner must ask: how much is it worth to amass more evidence so that this 90% will increase to 100%, or close to it. (Or if the evidence is negative, to something less than 90%. To make use of negative evidence, the tests would have to be designed differently than they now are. They would have to be designed to estimate "minimum detectable effects" at various probability levels.) In terms of affecting the expected value of improved decisions, the additional information is worth something.

Our calculations [2] of expected cancers and the costs of control indicate that, if there were a 90% certainty of causality and a 90% chance that the drinking water effect were in the ranges estimated (along with a 10% chance of no effect at all), then there would be a net benefit associated with installing granular activated carbon (GAC) filters for large cities with high levels of organics. With 100% certainty of a drinking water effect in the ranges estimated, our calculations indicate net benefits in

GAC filtration for additional cities. But this difference, arising from a narrowing of uncertainty as to whether there is a drinking water effect at all, is not nearly so striking as the difference to be obtained from narrowing uncertainty associated with estimates of likely numbers of excess cancers associated with particular levels of exposure, or narrowing the range of uncertainty about exposure itself. These latter ranges of uncertainty span orders of magnitude.

The comparison reveals a fundamental difference in approach between science and policy. Science is concerned with truth, and resolving the last bit of uncertainty as to a causal link may be very important. Public policy is concerned with decision making and cost--here, the expected cost of preventable cancers and the cost of prevention. In cost-benifit terms, resolving the last bit of uncertainty about causality is less important than narrowing the range of uncertainty associated with estimates of excess mortality. Policy making accepts a standard different from science rather than a lower standard. A scientist may wish to reduce, as efficiently as possible, uncertainty in some narrowly focused area; a cost-benefit practitioner wishes to resolve, as efficiently as possible, uncertainty over the entire decision process. A scientist can suspend judgment while awaiting resolution of uncertainty; a decision maker cannot avoid making decisions under existing uncertainty. A decision to postpone action, awaiting better information, is just as much a decision as one to undertake action.

RISK ASSESSMENT

From a cost-benefit perspective, the key question is not, "Can it be proved beyond a reasonable doubt that chemicals in drinking water raise cancer rates?" Instead, the fundamental question is "How much evidence is enough to justify a precautionary action?" From a cost-benefit perspective, we do not need to know whether there is a strong scientific consensus that at least a 99.9% probability exists of at least a 0.0001% increase in cancer over background as a result of drinking water. Learning whether there is a scientific consensus that at least a 60% probability exists of at least a 5% increase associated with chemicals in drinking water would be more useful. From a cost-benefit perspective, we need to concern ourselves with the latter, more middle range of uncertainty. Some evidence of hazard--highly incomplete--and a range of precautionary actions exists. Some precautionary actions, such as changing the point of chlorination, are so inexpensive that little evidence of hazard is needed to mandate them. Some, such as GAC, are more expensive and require greater weight of evidence to mandate them. What evidence is enough? How is it to be interpreted? How do we proceed in such cases of uncertainty? A more detailed discussion of these questions can be found in our cost-benefit analysis [1,2], with additional considerations presented here.

One useful procedure in situations where considerable uncertainty exists about the truth of a theory is to use the theory to make predictions. If the prediction is confirmed by later experiment

Looking at the weight of evidence as it has accumulated over the past 9 years, we would say that the dichotomy between surface waters and groundwaters as a predictor of carcinogenic risk appears less solid now than then. However, identification of gastrointestinal and urinary tract cancers, estimation of the order of magnitude of the effect, and identification of the problem of statistical power all seem more solidly based. The trend in the accumulation of evidence has been to support the theory of a link between cancer and organic chemicals in drinking water, particularly those produced by the addition of chlorine to water [6].

A second useful procedure, when considerable uncertainty exists about a theory (and still considerable uncertainty remains), is to look for independent estimates of the same parameter, where the independent estimates use different data bases and different computations. If there is nothing to the theory, the two estimates are not likely, by chance, to be close. For the problem of drinking water, we are fortunate to have two independent ways of estimating risk. One is epidemiologic. It uses human data on cancer, data on direct human exposure to various qualities of drinking water, data on occupational exposures, and data on socioeconomic factors. The other is rodent bioassay. Here, the data are on doses of specific chemicals to rodents and their responses, along with measurements of concentrations of these specific chemicals in drinking water. The modeling assumptions have to do with the additivity of effects of specific chemicals in combination, with extrapolation, and with interspecies comparison. Elsewhere [1,2], we discuss the range of error that can be associated with each of the two estimation procedures, concluding that each method could easily have a range of uncertainty of a couple of orders of magnitude.

In the comparison, the risk estimate produced by the two methods are roughly an order of magnitude apart, with the bioassay extrapolations lower. The estimates overlap in their ranges of resolution, and we view this comparison as strongly suggestive evidence in support of the link between cancer and drinking water. (For further discussion of this comparison, see Crump and Guess [6].)

A third useful procedure for a risk assessment, where a great deal of uncertainty exists, is to provide a range of risk estimates and a discussion of why the limits were chosen where they were and of the likelihood that the actual risk might fall outside the range in either direction. In the Brookings paper [1], we derive a range of risk estimates, as shown in Table 1. The low estimate is based on the experimental animal (mouse) most sensitive to chloroform, and the high estimate is based on the epidemiologic studies in New York and Louisiana.

Table 1

Risk Estimate	Annual Excess Cancer Deaths per Million Population[a]
Low	20
Medium	150
High	300

[a]This excess is based on water comparable to Mississippi River water.

or evidence that was unavailable at the time of the prediction, this is taken as evidence in support of the theory itself. Causality is not established this way, but confidence in the theory is increased. In our 1974 study [8], we made several predictions. Looking back to see how well later evidence supports or denies these predictions, we make four observations:

1. We identified the drinking water effect principally with gastrointestinal and urinary tract cancers. At the time of our study, we could find no existing studies associating these or other sites with carcinogens in drinking water; the identification of gastrointestinal and urinary tract cancers came entirely from the regression analysis itself. This association has been well supported by later studies [6], which strongly suggest that chlorination of drinking water increases the risk of rectal cancer and, to a lesser extent, colon and bladder cancer.

2. We interpreted our regression coefficients to provide a rough estimate of the magnitude of a possible drinking water effect. The 1974 calculation of effect was a 10 to 15% excess in total cancer mortality over background rates. At the time, we considered this finding more tentative than finding 1, above, because of the statistical problems; nonetheless, this estimate is rather consistent with estimates from different data bases in later studies.

3. An obvious implication of finding 2 was that problems of statistical power (problems of false negatives) would exist. This conclusion arises from the estimated low risk factor (10 to 15%),

in contrast to risk factors of 3 or more, typically encountered in epidemiological studies. With a relatively small drinking water effect, patterns of results are likely to have an overlay of random "noise." Problems of low statistical power have occurred in following studies, and these problems have made confirming or refuting the link between cancer and drinking water difficult. Although these problems were forecast in the original 1974 study, they have received little attention. For example, few studies calculate probabilities of false negatives and minimum detectable effects. For some discussion of the problem of false negatives, see Crump and Guess [6] and Harris et al. [9]

4. We postulated that the dichotomy between surface and groundwater would be a good surrogate for differences in organics in drinking water in Louisiana. This was based on work by Laseter [10], indicating that organics were 1,000-fold greater in concentration in the Mississippi River than in groundwater, and the fact that what then was considered a large number of organics of suspected toxicity had been identified for the Mississippi River. Since 1974, research has shown that groundwater is sometimes far more contaminated than surface water, and methods of directly measuring trihalomethanes and other organics have become available. Contamination of groundwater was probably less of a problem in the years of exposure relevant to the study (exposure from about 1930 to 1960, leading to cancers from 1950 to 1969), and for Louisiana the dichotomy still appears to be a good indicator of the degree of chlorination.

EVALUATION OF UNCERTAINTY PROFILES

A naive view of cost-benefit analysis would provide for a single, point estimate of the excess risk of cancer from drinking water. This estimate could then be compared with an estimate of the cost of control and matched with (either implicitly or explicitly) a value of life, and a net benefit could be calculated by simple algebra. To do so treats the risk estimate as though no uncertainty were attached to it, thus ignoring the value-of-information principle that is the heart of a cost-benefit approach.

It makes a difference where the major uncertainties lie in a decision problem and what the structure of risk looks like. People have preferences about the characteristics of risk they accept or reject, and one tenet of the cost-benefit approach is that governments should reflect these preferences.

For example, most people are risk-averse toward certain types of risks. The classic illustration of risk aversion is the St. Petersburg paradox. The paradox is illustrated by a simple lottery. A fair coin will be flipped until the first head. The coin will, sooner or later, come up heads. Write n as the number of flips before the first head. You will be paid 2^{n+1} dollars. The question is how much are you willing to pay for the opportunity to play the lottery. (Before reading on, decide what your own willingness to pay is for this risk.) Note that the expected value of the lottery is infinite $|(1/2)(2) + (1/4)(4) + (1/8)(8) + . . .|$.

Many studies of willingness to pay for this lottery have

been conducted: most people are willing to pay from $5 to $30. The important and obvious point is that this amount differs strikingly from the amount a risk-neutral, expected-value-maximizing gambler would be willing to pay (which is his whole income, or any finite amount). The St. Petersburg paradox is only a paradox if you believe that people are not risk-averse. A naive cost-benefit analysis, which takes a "best" estimate of risk and uses it as a single, point estimate (as though no uncertainty were attached to it) in totaling up costs and benefits, is completely ignoring risk aversion.

In some situations assuming that people are not risk-averse appears reasonable, but these situations do not apply in the case of cancer and drinking water for two reasons:

1. People may be risk-averse when they are dealing with many small risks so that losses and gains can be averaged out to approach expected values. In the case of drinking water, we are dealing with a unique risk, uncertainty as to the state of a fact--the actual hazard associated with cancer and drinking water, augmented by other hazards such as teratogenicity, with which even greater uncertainty is associated. The stakes associated with this unique risk are quite large.

2. If the potential loss is small and the potential gain is large, people may actually be risk-preferring. For example, gamblers regularly pay more than the expected value of a gamble for the privilege of taking the risk. However, the situation is the reverse for the problem of drinking water and cancer.

Here, if society decides to accept risk, the potential gain is the \$5 or so each individual saves per year by not contributing to the cost of GAC or other precautionary measures and the potential loss is cancer or other genotoxic disease. In such cases assuming that no risk aversion exists would be a mistake.

There is evidence that our concern for risk aversion should be strengthened when there is less certainty about the probability estimates themselves. In the case of drinking water, the evidence is sufficient so that many scientists would attribute at least a 60% probability to there being a 5% or greater drinking water effect (5% or more of the total cancer mortality rate attributable to contaminated drinking water). But this 60% is itself uncertain. Scientists will disagree about it, and new information is likely to lead to its revision. The less solid our information, the more fluid our judgment about the probability.

Ellsberg [11] illustrated this source of risk aversion by the following example. You know that one urn holds 50 red and 50 black balls, 100 balls altogether. If you draw a red ball, you get \$100. A second urn also has 100 balls, which may be red or black. But you have no information as to the proportion of red. Again, if you draw a red, you get \$100. Which gamble would you prefer? If you are a risk-neutral, expected-value-maximizer, you might assign a "white prior" corresponding to no information, to the second urn, and hence, a probability of red equal to 0.5. In this case, you would be indifferent between the two gambles, each having the same expected value, \$50. However, a real difference exists

between the two gambles. Additional information from sampling the urns will affect your judgment of the probability in the second case but not the first, where this information is perfect already (by definition). For example, if you were allowed to draw a sample of five balls from each urn, your judgment of the probability of red could be altered for the second urn but not for the first. The probability of red is ambiguous in the second case, but not in the first. Also, most people (about 70%) prefer the first gamble to the second, and only about 20% consider the gambles the same.

Clearly, a great deal of ambiguity is associated with judgments about the probability of drinking water effects of various magnitudes (e.g., the assignment of a 60% probability of a 5% or greater excess cancer attributable to contaminated drinking water). The more ambiguity, the more reason for this second form of risk aversion. The implication of risk aversion of either form is to undertake a greater degree of precautionary action than would be indicated by calculations from expected values and point estimates alone.

CONCLUSION

In the past few years concern has increased over protecting the public against "over-regulation," and as a means of protection, it is increasingly suggested that formal cost-benefit analysis be required on proposed regulations before promulgation. Others, particularly those concerned with protecting the public health, view cost-benefit analysis as a means of attacking regulations in general, by increasing delays and the cost of administration. Lest cost-benefit analysis become no more than a polemicist's weapon, note that a cost-benefit approach can be applied to cost-benefit analysis itself, as we have emphasized in this paper. Cost-benefit analysis is subject to diminishing returns; it should not be open-ended and endless. Some information is not worth obtaining; it costs too much in terms of its expected benefits. A cost-benefit approach strongly suggests that proving definitely that risk exists before taking precautionary action is not worthwhile.

Over-regulation is a regulatory false positive; under-regulation a regulatory false negative. A balanced cost-benefit approach does not single out over-regulation to the neglect of the possibility of under-regulation. It attempts to estimate the potential costs of each kind of mistake and the probabilities of each. It then attempts to minimize the expected cost of regulatory mistakes of either type. Applying this approach to the problem of drinking water demonstrates that much more attention has been directed to analysis or statistical significance (probability of false positive) than to analysis of statistical power (probability of false negative). If, as appears likely, the cost of a false negative (preventable but unprevented cancers) is higher than the cost of a false positive (unnecessary precautionary treatment), then uncertainty associated with the probability of a false negative is more pivotal than uncertainty associated with the probability of a false positive. This, in turn, means that more attention

should be focused on questions of statistical power and the minimum detectable effects.

A balanced cost-benefit analysis takes into account uncertainties leading to probabilities of both false positives and false negatives, and it carries its analysis of uncertainty throughout the whole analysis. This means not relying on single, point estimates and treating them as though they were certain. In attempting to weigh the uncertainties, observing how later evidence confirms or refutes earlier predictions and comparing independent sources of evidence for consistency checks are useful. Characterizing the profile of uncertainty for the case of drinking water suggests that some degree of risk aversion is appropriate. This means one should take precautionary actions greater than would be implied by straight, expected net benefit maximization alone. We estimated net benefits [2], without risk aversion, finding that GAC treatment is warranted for some cities. This conclusion is strengthened once the profile of uncertainty is taken into consideration.

REFERENCES

[1] Page, T., R. Harris, and J. Bruser. "Removal of Carcinogens from Drinking Water: A Cost-Benefit Analysis," in Scientific Basis for Health and Safety Regulation, R. Crandail and L. Lave, Eds. (Washington, DC: Brookings Institution, 1981).

[2] Page, T., R. Harris, and J. Bruser. "Removal of Carcinogens from Drinking Water: A Cost-Benefit Analysis," Social Science Working Paper No. 230 (Pasadena, CA: California Institute of Technology, 1979).

[3] Page, T., and E. Mishan. "The Methodology of Cost-Benefit Analysis--With Particular Reference to the Ozone Problem," in The Economics of Managing Chloroflourocarbons, J.H. Cumberland, J.R. Hibbs, and I. Hoch, Eds. (Washington, DC: Resources for the Future, 1982).

[4] Pike, M. "Epidemiological Methods for Determining Human Cancer Risks from Exposure to Chlorination By-products," in Water Chlorination: Environmental Impact and Health Effects, Vol. 3, R.L. Jolley, W.A. Brungs, and R.B. Cumming, Eds. (Ann Arbor, MI: Ann Arbor Science Publishers, Inc., 1980).

[5] Kraybill, H. "Animal Models and Systems for Risk Evaluation of Low-Level Carcinogenic Contaminants in Water," in Water Chlorination: Environmental Impact and Health Effects, Vol. 3, R.L. Jolley, W.A. Brungs, and R.B. Cumming, Eds. (Ann Arbor, MI: Ann Arbor Science Publishers, Inc., 1980).

[6] Crump, K., and H. Guess. "Drinking Water and Cancer: Review of Recent Findings and Assessment of Risks," prepared for Council on Environmental Quality (Washington, DC, 1980).

[7] Hill, A.B. "The Environment and Disease: Association or Causation?" Proc. R. Soc. Med. 58:295-300(1965).

[8] Page, T., and R. Harris. "Statistical Analysis of Cancer Mortality in Louisiana," in The Implications of Cancer-Causing Substances in Mississippi River Water (Washington, DC: The Environmental Defense Fund, 1974), Appendix A.

[9] Harris, R., T. Page, and N. Rieches. "Carcinogenic Hazards of Organic Chemicals in Drinking Water," in Origins of Human Cancer (Cold Spring Harbor, NY: Cold Spring Harbor Laboratory, 1977).

[10] Laseter, J.L. Personal communication, 1974.

[11] Ellsberg, D. "Risk, Ambiguity, and the Savage Axioms," Q. J. Econ. 75(1961).