November 1984

RESEARCH AND DEMONSTRATION OF IMPROVED METHODS FOR CARRYING OUT BENEFIT-COST ANALYSES OF INDIVIDUAL REGULATIONS

by

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VOLUME I

BENEFIT METHODOLOGIES APPLIED TO HAZARDOUS WASTE

Final Report
Submitted to U.S. Environmental Protection Agency
Cooperative Agreement 68-809-702-01-0

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EXECUTIVE SUMMARY

Environmental regulations are notoriously difficult to assess. Both the unregulated environmental assault and the protective regulation involve complicated scientific and economic relationships that make it difficult for the regulator to determine the overall effects of any intervention. Benefit-cost analysis is one useful tool developed by economists to assess the overall attractiveness of public programs. Although benefit-cost analysis cannot reduce the complexity of the scientific matters, the framework permits the analyst to put them in perspective.

The U.S. Environmental Protection Agency (EPA) now performs benefit-cost analysis on its major regulations, both for internal purposes and because of the requirements of Executive Order 12291. Although the EPA has developed sophisticated methodologies, there is a continuing need for research to improve the empirical and methodological foundations for these benefit-cost analyses, particularly for the regulations involving toxic pollutants. The public has only recently become aware of toxic pollutants and the potential health and ecological dangers they pose. As a result, the benefits of controlling toxics typically involve a great deal of uncertainty.

The purpose of this study is to develop improved methods for carrying out benefit-cost analyses of individual environmental regulations. Because the range of potential research topics is broad -- indeed, the EPA has an extensive and integrated research program of which this study is one part -- we have chosen to focus on the benefits of controlling toxic pollutants. Thus, we do not address the methodological issues associated with estimating the costs of regulations. The choice to focus on toxic pollutants was partly the result of the research support our project received within the EPA and partly the result of our belief that issues of controlling toxic pollutants had been studied less than the conventional air and water pollutants and that these pollutants would become increasingly important to the EPA in the years ahead.

Although this is a methodological study, we make extensive use of case studies of individual pollutants. Using actual examples is the most productive means of integrating theory and empirical issues. However, these case studies are not designed to be policy analyses. Our major objective is not to endorse specific policy choices or comment on regulatory alternatives. Indeed, since the data underlying the case studies have undoubtedly changed since we completed our empirical studies, we caution the reader about using the results reported in this study to make his or her own judgments.

The study is organized around four general topics. Like the overall study, these topics are a combination of conceptual and empirical issues. The first topic concerns the use of alternative methodologies to assess regulatory benefits. We use the case of controlling hazardous waste at landfill sites in Massachusetts to provide an empirical context for our comparison of methodologies.

The second topic is the use of benefit methodologies to assess ecological hazards. Most of the concern for toxic pollutants focuses on health hazards, particularly cancer. But many citizens and regulators worry about the long-term and pervasive changes that toxic pollutants might cause to ecosystems. Since the scientific issues are even more unsettled in this area than in the health effects area,the empirical component of this section is less developed than in the other sections.

The third topic is the use of benefit information to improve the cost-effectiveness of individual regulations. One key methodological issue in benefit-cost analysis is how to assess regulatory alternatives, which typically involve trade-offs between benefits, costs, or other distributional impacts. In the third section we discuss the more narrow topic of using information on benefits to design more cost-effective regulations. Although this section is closest to policy analysis, we stop short of recommending specific policies and focus on the methodological considerations in using benefit information.

The fourth and final topic concerns the strategies for dealing wtih uncertainties in the benefits of toxic regulations. As mentioned, these uncertainties pervade toxics control. In the other sections, we include sensitivity analyses to illustrate the implications of uncertainty. In this final section, we focus on the use of decision-analytic methodologies to guide EPA in deciding whether to collect additional information on control benefits.

The remainder of this Executive Summary provides brief summaries of the results and conclusions of the Study, organized around the four topics discussed above.

Benefit Methodologies Applied to Hazardous Waste Cleanup

The widespread presence of hazardous waste disposal sites is widely recognized as one of the most pressing environmental problems of this decade. Hundreds of such sites have been identified throughout the U.S., and billions of dollars have been budgeted for cleanup. Yet virtually no studies have investigated the benefits of cleanup, let alone determined which benefit assessment methodologies to employ.

This part of the report evaluates three methodological approaches for assessing the benefits of cleaning up hazardous waste sites. The first approach is based upon housing price differences. Specifically, we employ statistical techniques to determine households' implicit willingness to pay to locate further from hazardous waste sites. The empirical results are based upon housing transactions for single family detached residences in the metropolitan Boston area. The benefits of cleaning up a site depend upon the population density near the site, the prices of the homes near the site, and the characteristics of the site itself. To illustrate the application of the statistical results, we estimate the willingness to pay for the cleanup of three sites in the Boston area: in 1980 dollars, these benefits estimates range from $3.6 to $17.4 million.

The second approach is based upon scientific risk assessment. We estimate the expected increase in the risk of cancer to those affected by toxic discharges from a landfill site in Massachusetts. To facilitate comparisions across methodologies, this site is one of the three sites evaluated in the housing value approach. The risk assessment approach was based upon two scenarios concerning the length of time that chemicals contaminated the water supply of the town in which the landfill is located: (1) exposure for ten years, at which time the contamination is discovered and the wells are closed: and (2) exposure for 70 years, or the entire expected life of the chemical facility and its contamination of the town wells, on the assumption that the contamination is not discovered. Several estimates of toxic concentrations and of risk factors are used to predict risk. Our estimates indicate one expected ("statistical") fatality or less would have been prevented in the ten year case. For 70 years of operation and exposure, the predictions range from less than one to about 90 expected fatalities prevented; about half the predictions are greater than ten fatalities and half are less. If one assumes a range of $330,000 to $2.5 million per statistical death prevented, the median benefit estimate for preventing ten years of exposure is several hundred thousand dollars, and the median estimated value of preventing 70 years of exposure is several million dollars.

The third methodological approach is based upon the case in which contamination is discovered. When hazardous wastes contaminate water supplies, individuals and government bodies may act to avert the consequences. Such actions include buying bottled water, switching to another source of water, filtering contaminates out of the water, or even cleaning the contaminated aquifer. If they are undertaken, the costs of these actions -- the averting costs -- can be used as a measure of the benefits of improved hazardous waste disposal. This averting cost approach has not been used a great deal for air or water pollutants because there are few opportunities for averting actions; households simply must bear damages from environmental contamination. But averting costs are likely to be a more important component for hazardous waste because of the many opportunities to avoid the health risks of drinking contaminated water. Using the same site as in the housing value and risk assessment approaches, we estimated the dollar costs that would be saved if contamination had not occurred. We distinguish between total costs and costs that can be interpreted as the affected residents' willingness to pay to prevent the contamination. Our most likely estimate is that society will pay a total of approximately $1.7 million as a result of the contamination, $1.3 million of which reflects residents' willingness to pay. These empirical results are based on the actions that public agencies took to close contaminated wells, obtain alternative water supplies, and clean up the contamination. The benefit estimates do not include costs that individuals might have incurred in buying bottled water or otherwise averting the damages of the contamination.

Benefit Methodologies Applied to Ecological Hazards from Toxic Substances

Assessing the ecological benefits of controlling toxic pollutants raises a set of methodological issues. There are a variety of potential benefits that arise from preventing injury to plant and non-human species. The two parts of our study of ecological effects deal with the methodological and empirical issues involved in assessing these benefits. In the methodological study, we evaluate the alternative bases for economic evaluations of toxic effects on natural populations, discuss the applicability of specific methodologies, consider the peculiar effects of the dynamics of natural populations, and analyze the framework for obtaining empirical results. This part of the study lays out issues rather than coming to specific methodological conclusions.

The second part focuses on the use of qualitative modeling of ecosystems to assess the ecological benefits of controlling toxics, using pesticide regulation as a case study. This part of the study shows how the qualitative modeling methodology can be useful both in assessing the value of alternatives for additional scientific testing and in regulating ecological risks. Although the system and numbers used to demonstrate the methodology are hypothetical and considerably simplified, this part of the study does lead to some specific conclusions. For example, we conclude that prior qualitative analysis can provide considerable guidance as to the kinds of quantitative information about species interactions that would be helpful for regulatory decision making. Despite these conclusions, however, it is clear that more empirical research is required to assess the methodological advantages and disadvantages of the use of qualitative ecosystem modeling.

Use of Benefit Information to Improve Individual Regulations

Benefit-cost analysis is often viewed as a summary statement, assessing the overall benefits and costs of a set policy. In this part of the study, we evaluate the methodological issues in using benefit-cost analysis as a technique for identifying regulatory alternatives. Specifically, we discuss the use of information on the benefits of control to design regulatory alternatives. This part of the study consists of three related studies.

The first report uses the example of hazardous air pollutants to lay out the methodological and empirical issues surrounding the use of benefit information in environmental regulation. Information on three pollutants is used to provide a rich illustration of the advantages of evaluating benefits explicitly and the empirical consequences of using alternative regulatory approaches. This information also permits us to evaluate the major uncertainties surrounding benefit estimates and to assess how robust the conclusions are when plausible. alternative parameter values are used.

The second report extends the first to evaluate the usefulness of benefit information in a variety of environmental contexts. The key element is the tailoring of national regulations to the circumstances of individual situations, recognizing that case by case regulation is impossible. Thus, we develop the case for increasing the flexibility of regulations without giving up the advantages of centralized regulatory authority. We discuss a variety of methodological issues, including the practical issues of obtaining such detailed information, the distributional implications of such an approach, and the problems and opportunities of combining benefit and cost information in this context.

The third report focuses on a specific type of benefit information and its use in regulatory situations. In particular, we evaluate the use of information on the convexity of the damage function (i.e., the relationship between incremental damages and increasing levels of pollution) to establish regulatory priorities and set regulations. This part of the study first lays out the general issues surrounding the use of partial information on benefits before illustrating the use that can be made of information that the damage function is non-convex -- that is, that the damages from pollution rise with a decreasing rate as concentrations increase. This case is different than the standard view of the environmental damage function. This partial information on benefits can therefore be of considerable value to analysts and regulators, even if precise quantitative information is not available.

Strategies for Dealing with Uncertainty in Individual Regulations

Coping with uncertainty is a common theme of the entire study. This part of the study focuses on uncertainty and the value of reducing uncertainty concerning the benefits of controls. Three reports provide both an overview of the importance of uncertainty and a detailed case study.

The first study overviews the scientific uncertainties in benefit estimation of toxic substances. This part of the study is necessary to provide a systematic evaluation of the major uncertainties involved in the risk assessment process -- the key scientific process involved in benefit assessment -- and in the final estimates of health risks from toxics. The report proceeds by breaking down the assessment process into simple components, evaluating the uncertainties in each step, and combining the uncertainties.

The second report illustrates how uncertainties in risk assessment lead to increased expected costs of environmental regulation. This report also uses a case study of toxic air pollution to demonstrate that if the magnitude of the uncertainty is known, it may be possible to estimate the value of efforts to reduce uncertainty.

The third and final report in this part focuses on one means of acquiring information -- obtaining information under Section 8(a) of the Toxic Substances Control Act. We use a decision-analytic perspective to evaluate the value of this information, using a specific toxic substance as the basis for the empirical estimates. Although our general conclusion is not surprising -- we conclude that the decision-analytic perspective can be a very helpful complement to a standard benefit-cost framework -- the case study provides important insights into the methodological issues that are encountered in actually applying that perspective in individual regulations.

Future Work

Our study provides a number of insights into the methodological and empirical issues of benefit-cost analysis. Nevertheless, most of the studies raise as many issues as they answer, a trait common to most research projects. We discuss these areas for future work in the individual studies.

ACKNOWLEDGEMENTS

This study has benefited from the assistance of a large number of people over its history. The original impetus for the research project came from Dr. Alan Carlin of the U.S. Environmental Protection Agency (EPA), who has continued to provide guidance as part of his overall responsibility for economic research at EPA. Dr. George Provenzano of EPA served as Contract Officer and assisted in a great many tasks, including developing the research agenda, arranging with other parts of EPA to co-sponsor some of the research, and serving as liaison to officials outside EPA who became involved in the research. Others at EPA who assisted the study include Dr. Ann Fisher, who commented extensively and most helpfully on many of the individual studies, and Dr. Michael Shapiro and Mr. Sammy Ng, both of whom provided guidance and assistance in the study of Section 8(a) of the Toxic Substances Control Act.

The major debt is of course to the team of researchers who carried out the various components of the study. The Table of Contents identifies those who researched and wrote each section of the study, and there is no reason to repeat the list here. (In all, 18 persons participated directly in the research and writing of the report.) However, it is important to identify two individuals whose contributions extended beyond the research and writing of individual studies. Dr. Albert Nichols participated as a co-director of the study for the two years in which the bulk of the work was undertaken (1981-83), leaving the project in

August 1983 to become Director of the Economic Analysis Division in EPA's Office of Policy Analysis. In addition, Dr. Robert Repetto provided overall direction for the studies focusing on ecosystem effects.

The study also benefited from the guidance and assistance of others at Harvard University. The Energy and Environmental Policy Center at the John F. Kennedy School of Government provided overall administrative support for the study. The project is greatly indebted to both the Center's Director, Dr. William Hogan, and its Executive Director, Mr. Henry Lee, for their help in structuring the study and assisting in its management. In addition, both read drafts of many of the individual studies and made many important suggestions. Perhaps the greatest debt is due Ms. Marcia Duvall, who skillfully and gracefully edited and prepared the entire manuscript. Others in the Energy and Environmental Policy Center who helped include Ms. Kathleen Jervey, Ms. Joan Curhan, and Mr. James Marra.

The study was also fortunate to have the guidance of a number of Harvard University faculty. We are indebted in this regard to Professors Harvey Brooks, Robert Dorfman, Myron Fiering, Joseph Harrington, Donald Hornig, Thomas Schelling, Richard Wilson, and Richard Zeckhauser. Some of the individual studies were supported in part by two other research groups at Harvard University, the Interdisciplinary Programs in Health and the Department of Health Policy and Management Program, both at the Harvard School of Public Health. In addition, Professor V. Kerry Smith of Vanderbilt University provided important comments, particularly on the hazardous waste studies.

We in the study team are grateful to all of these individuals. Of course, we alone are responsible for the content of the final product. In particular, the final report has not undergone review by the U.S. Environmental Protection Agency, and thus the views and conclusions reached in this study do not necessarily represent those of the supporting agency.

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PART 1

USING THE HEDONIC HOUSING VALUE METHOD TO ESTIMATE THE BENEFITS OF HAZARDOUS WASTE CLEANUP

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I. INTRODUCTION

Since the classic paper by Ridker and Henning (1967), the hedonic housing price approach has been an important tool used by economists to estimate the benefits of public projects. The great strength of the approach is its use of actual decisions by house purchasers to infer the value placed on public goods such as cleaner air or better schools. Since houses differ in their access to better schools or cleaner air, the market prices established for individual houses should reflect the amount of the "good" (or bad) associated with each house as well as the dollar valuation that local residents place on the amount. These dollar valuations can in turn be used to estimate the value that households would place on changes in the amount of public goods, i.e., better schools or improved air quality.

The hedonic housing price methodology is currently at a crossroads. The enthusiasm for its use following Ridker and Henning and an influential paper by Rosen (1974) has given way recently to skepticism about the ability to obtain estimates of willingness to pay from housing transactions. Rosen proposed a two-step process in which the first step is to estimate a nonlinear hedonic price function using housing price and housing nonlinear hedonic price function using housing price and housing attribute data. This function constitutes the price surface facing home purchasers. In the second step, the derivatives from the hedonic function are used along with household characteristics of the home purchasers to estimate a willingness to pay function based upon the first order conditions from the homeowner's maximization problem. Using this willingness to pay function -- which is equivalent to having a utility function for housing attributes -- economists estimated the benefits of non-marginal changes in public goods such as school quality, air quality, or noise levels.[1] However, recently Brown and Rosen (1982) pointed out unresolved difficulties in identifying the parameters of the willingness to pay function. They showed that without some identifying restrictions the second step might simply recreate the hedonic price function. They suggested either using a priori judgments about the relative nonlinearity of the two functions or pooling data from several cities whose combined price surfaces could trace out the willingness to pay function. Although several studies have attempted to overcome these difficulties, none is completely satisfactory.[2]

A second major difficulty with the Rosen procedure relates to general equilibrium effects. If the changes in the public good (such as air quality) are large, for some units, then in general some homeowners will be tempted to move. In this case, the compensating variations computed from the preferences estimated in the second stage of the Rosen procedure will understate the dollar benefits of the public good improvement.

Furthermore, if the changes in the public good are widespread, many homeowners will move, and these movements will alter the hedonic price structure itself. As a result of these and other difficulties with the hedonic approach (see Brown 1982), economists are turning to other techniques -- such as the survey approach -- to estimate the benefits of public goods.[3]

These difficulties with the hedonic housing price have, however, obscured the possibility of using the technique in situations where the two major difficulties do not arise. In particular, the technique can be used without these two difficulties for local -- rather than area-wide -- public goods changes. Although a local change may be nonmarginal and thus change local housing prices enough to induce moves in the neighborhood, if the project is small with respect to the entire metropolitan area these changes will not alter the area-wide hedonic housing price function. As a result, the general equilibrium (i.e., moving) effect of the change can be captured simply by comparing housing prices before and after the project using prices generated by the "first step" hedonic housing price equation. There is no need for a second step and thus no issue of identifying the willingness to pay function from the housing price function.

A major purpose of this paper is to illustrate the applicability of the hedonic technique to a public good that fits the category of providing a nonmarginal but localized benefit -- the cleanup of a single hazardous waste site. We use data from the Boston urban area to estimate a hedonic housing price function that includes measures of the risks posed by the eleven hazardous waste sites in the area. Although air quality policies -- which have been the traditional target of hedonic analyses -- tend to affect air quality throughout the urban area, and thus this technique would not apply, the cleanup of a single hazardous waste site would affect only a fraction of the housing units in the area. We can thus use the hedonic housing price equation directly to estimate the benefits of cleanup by predicting the resulting change in housing prices.

We use hazardous waste as an illustration of the approach not simply because it fits the category of a localized public good. Neighbors of sites containing hazardous wastes are concerned about the health and other risks posed by improper disposal, and the government has responded by developing programs to clean up existing sites (the Superfund program) and to regulate the disposal of future wastes. However, the costs of these programs are enormous; the U.S. Congress has recently passed legislation authorizing $6.4 billion for the Superfund cleanup program. Despite these large expenditures, there are currently few estimates of the dollar benefits of controls (Desvousges and Smith, 1983) Information on the dollar benefits of cleanup will help regulators to focus control efforts where they produce the greatest benefits. Thus, the second major objective of this paper is to provide reliable estimates of the benefits of cleaning up hazardous waste sites using the hedonic housing price approach.

The paper is organized as follows. In the next section, the model of individual behavior that underlies the subsequent empirical work is presented, Section III describes the data set and econometric strategy we use. The primary empirical results, presented in Section IV, are estimates of the cleanup of several hazardous waste sites in the Boston metropolitan area. We present estimates for more than one site to illustrate the variation in benefits depending upon the characteristics of the site and the number and characteristics of neighboring housing units. We also provide information on the sensitivity of the benefit estimates to alternative specifications of the hedonic housing price equation. Section IV summarizes the conclusions of the study and comments on the relationship of these benefit estimates to those obtainable from other benefit estimation techniques.

II. CONCEPTUAL BACKGROUND

The basic rationale for the property value approach is that purchasers take into account the level of public goods associated with houses in making their choice. As a result, the market valuation of these public goods will be embedded in the hedonic price function facing home buyers. The purpose of this section is to develop a formal model of consumer behavior that describes how the characteristics of hazardous waste sites enter the hedonic price function. The next section builds on this general background to identify a specific empirical strategy for estimating a hedonic housing price equation and calculating the benefits of cleaning up a hazardous waste site using the data we developed for the Boston housing market.

The losses nearby residents might experience from a hazardous waste site can be separated into two categories -- aesthetic problems and health problems. Industrial sites might cause unsightly visual impacts, noise, traffic or odor. However, these effects are largely independent of whether wastes are hazardous or not. The health risks due to hazardous waste include the risks of drinking contaminated groundwater, breathing contaminated air, coming in contact with contaminated soil, and having an explosion or fire at the site. Because these health risks are critical and because uncertainty is so important, it is useful to formulate the model in terms of consumer choice under uncertainty.

We assume that each household seeks to maximize expected utility. The commodities available to the household are z, a vector of non-waste housing attributes, and w, a vector of housing attributes associated with local waste disposal sites, and x, a composite of all other goods and services with unit price. The aesthetic characteristics of waste sites are represented as A(w). The household's utility, including its valuation of commodities, will depend upon the state of health of the household members. To simplify the presentation, we consider two states of health, well and unwell. Thus, the state-dependent household utility can be represented as,

$$U = \begin{matrix} U_0(x,z,A(w)) & \text{if well} \\ U_1(x,z,A(w)) & \text{if unwell} \end{matrix} \qquad (1)$$

We assume that the subjective probability of becoming ill as a result of exposure to toxic pollutants from a hazardous waste facility is q, which is a function of w, the waste attributes. The hedonic housing price function, p(z,w) translates the vectors of nonwaste and waste housing attributes at each location into a rental price that influences the decisions of both suppliers and demanders of housing attributes. If we denote the household's income as y,then the total expenditures are the value of nonhousing purchases, x, and p(z,w), or $y = x + p(z,w)$. The house purchaser's decision is the following:

Maximize

$$EU(x,z,w) = q(w)U_1(x,z,A(w)) + (1-q(w))U_0(x,z,A(w)) \quad (2a)$$

subject to the constraint,

$$y = x + p(z,w) \quad (2b)$$

Implicit in this formulation are the following important assumptions: [4]

(1) All consumers accurately perceive the characteristics represented by the vectors z and w at each location.

(2) There is sufficient variation in z and w so that the function p(z,w) is continuous, with continuous first partial derivatives.

(3) The market is in equilibrium.

(4) Spatial variations in housing characteristics (including hazardous waste aesthetic and health-related effects) are capitalized into differentials in housing prices.

Given these assumptions, we can generate the form of the hedonic housing price function that is consistent with households' first order conditions for utility maximization. If we let U_{0x} denote the partial derivative of U_0 with respect to x, and similarly for the other variables, the resulting relationships for the nonwaste and waste variables are the following:

$$h_z = \left[\frac{U_{0z}}{U_{0x}}\right]\left[\frac{1 + q((U_{1z} - U_{0z})/U_{0z})}{1 + q((U_{1x} - U_{0x})/U_{0x})}\right] \quad (3a)$$

$$h_w = \left[\frac{U_{0w}}{U_{0x}}\right]\left[\frac{1 + q((U_{1w} - U_{0w}) + q_w((U_1 - U_0)/U_{0w})}{1 + q\ ((U_{1x} - U_{0x})/U_{0x})}\right] \tag{3b}$$

This expected utility framework generates a different formulation of the hedonic housing price function than the conventional treatment (see, e.g., Rosen 1976 or Quigley 1982) because of the terms depending upon the subjective probability, q(w). However, the formulation above can be viewed as a more general model in which the standard utility maximization result is a special case. If the subjective probability of being exposed to hazardous waste and consequently falling ill is zero, then the conditions in equations (3a) and (3b) reduce to the simple condition that, at the optimum, the amount paid for an additional unit of the goods z or w is just the marginal rate of substitution between these goods and the composite commodity x.

Although the formulations with the probability q and its derivative complicate the model, the formulation can be simplified if we assume plausibly that the state of health enters additively in the utility function. Consider first equation (3a), the relationship for the nonwaste variables. The amount of the nonwaste attributes "purchased" (e.g., number of bedrooms) will in general depend upon the relative change in marginal utilities of the attribute and the composite good between the well and unwell states. But if the state of health enters additively, the marginal utilities will be the same in both the well and unwell states, and thus equation (3a) will reduce to a simple relationship in which the "prices" of nonwaste housing attributes are proportional to their marginal utilities. But even in this case, equation (3b) would differ: the marginal rate of substitution between the waste vector, w, and x would increase by an amount equal to one plus the marginal probability of illness due to an additional unit of w, times the decrease in utility from becoming ill, divided by the marginal utility of x. Thus, the value placed on the w vector in the hedonic house price function will depend upon perceptions of the linkages of w with illness and the disutility of becoming ill.[5]

It would be possible in principle to derive a specific hedonic housing price function from an assumed form for the probabilities, the first order conditions, the preferences and incomes of households, and an assumption of a fixed supply of housing units.[6] However, this approach has proved to be intractable to empirical implementation under realistic specifications of preferences and population characteristics, and we do not pursue it in this paper. Instead, in the following section we use the formulation in equations (3a) and (3b) to develop a plausible (as opposed to an exact) specification for an hedonic price function that includes both the aesthetic and health risk aspects of hazardous waste sites.

As mentioned in the introduction, we focus on localized cleanup efforts in this paper. As a result, we can use the hedonic housing price function to estimate willingness to pay in general equilibrium, i.e., when households are assumed to move in response to the cleanup. The theoretical rationale for this calculation is based upon the "small open city" model developed by Polinsky, Rubinfeld, and Shavell in a series of papers.[7] If the city is "open" -- i.e. there is perfect migration between it and other areas -- there will be a common level of utility throughout the system. If the city is "small," this level of utility may be treated as exogenous. To obtain the constant utility, the rent of each house must reflect the valuation each household places on local amenities, including the perceived risks from hazardous waste sites.[8] Thus, the equilibrium hedonic housing price function can be used to compute the new housing price following a change in public goods or amenities, and this price change is an accurate measure of the benefits of the change in public goods. As Freeman concludes, "The benefits of the change actually accrue to land owners; and the increase in land rents is a compensating variation measure of these benefits (Freeman, 1979, p. 16). Polinsky and Shave11 (1976) point out that these conclusions may be applied to a "small" neighborhood in a single "large" urban area, which is the case we consider. "If there is perfect mobility throughout the urban area, then amenity changes in the neighborhood can be analyzed as in the small-open city model" (Polinsky and Shavell, 1976, p. 129). As a result, the coefficients on hazardous waste variables in a hedonic housing price equation can be used to predict the benefits of cleaning up a single waste site.

III. DATA AND EMPIRICAL STRATEGY

Data

This study uses data for 2,182 individual housing transactions in the Boston urban area (excluding the city of Boston) from November 1977 to March 1981.[9] Most of the transactions occurred in 1979 and 1980. Following the example of most studies of this kind, we focus on the market for single family homes. The dependent variable in the hedonic housing price equation is an actual selling price (in 1980 dollars) rather than rent or census tract average. The independent variables include 14 structural attribute variables, four employment accessibility variables, and four neighborhood variables. The data set is described in detail in Appendix A.

Crucial to our study was the development of a detailed data base on hazardous waste disposal sites in the Boston urban area. The Boston area was chosen as the locus for the study largely because of the availability of detailed information on waste sites, both hazardous and nonhazardous. In 1981, the Massachusetts Department of Environmental Quality Engineering (DEQE) published a detailed listing of 367 waste sites in the state. Using information contained in this document, supplemented by detailed investigations of the DEQE files, we identified 11 sites that contained hazardous material. Figure 1 shows the location of the sites and Table lists their areas and

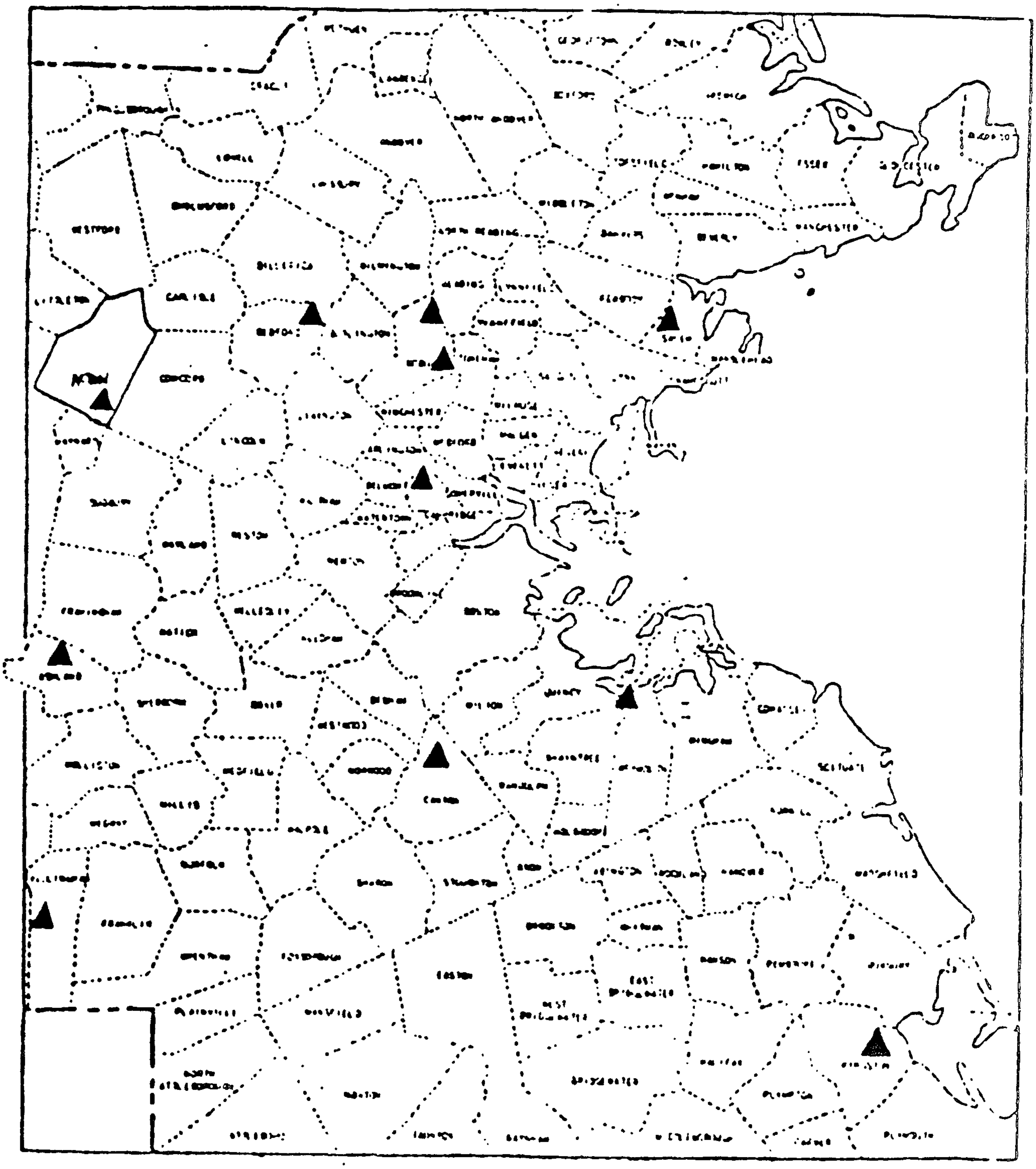

Figure 1. Map of hazardous waste sites in the Boston urban area

Table 1. Hazardous Waste Sites in the Boston SMSA Identified Before 1982

Site Name	Town	Approximate Land Area (acres)	Date of Discovery
W.R. Grace Company	Acton	400	Dec. 1978
Nyanza, Inc.	Ashland	30	1967
BSAF Industries	Bedford	5	May 1978
Benzenoid Organics	Bellingham	4	Oct. 1980
W.R. Grace Company	Cambridge	10	Mar. 1979
Indian Line Farm	Canton	25	Dec. 1980
Marty's GMC	Kingston	1	Apr. 1980
Salem Acres, Inc.	Salem	180	Sept. 1980
Agrico	Weymouth	10	May 1980
Industriplex 128	Woburn	300	June 1979
Wells G and H	Woburn	200 (plume) .005 (wells)	Sept. 1979

the dates on which the presence of hazardous material were verified by Massachusetts officials. Most of the hazardous sites are on-site lagoons used to store process wastes. For example, the Acton site is owned by a chemical company that maintained three lagoons to handle the wastes from their operations. The site is identified as hazardous because the lagoons contain a variety of halogenated and aromatic organic compounds that are listed as toxic under the Resource Conservation and Recovery Act (RCRA). The other ten sites contained hazardous material judged to be equivalent in toxicity to the Acton wastes by the rating scheme used for the Superfund.

To distinguish the disamenity effects of living near a waste site from the health risk effects of the confirmed nearby presence of hazardous material, we identified 41 non-hazardous industrial sites that stored wastes on-site and 49 commercial and municipal landfills in the Boston metropolitan area. The industrial sites are similar to the hazardous sites except in the composition of the wastes and thus represent a good approximation to a site after cleanup; after cleanup, the industrial character would remain but no hazardous material would be present.

These data allowed us to develop variables to proxy the subjective probability of exposure to hazardous material for each house in our sample. As mentioned above, exposure might come about through drinking contaminated water, breathing contaminated air, coming in contact with contaminated soil, or experiencing the results of an explosion or fire at the site. The variables we constructed are suggested by a very simple physical model of exposure: given uniform dispersion through a homogeneous three dimensional medium, the concentration of contaminants at any point will decline with the inverse of the square of the distance from the source to that point. Thus, if the mass of the kth of k chemicals at the jth of 11 sites is M_{kj} and if d_j is the distance from site j, subjective probabilities of illness might be proxied by,

$$\sum_{j=1}^{11} M_{kj} d_j^{-2}, \quad k=1,\ldots,K$$

Since neither public authorities nor the house purchasing public knows the masses of each chemical at the 11 sites, this formulation cannot be used directly. Instead, we assume that site area is a reasonable proxy for the volume of chemicals at the site. Since the 11 sites contain roughly equally dangerous chemicals, we can thus model subjective probabilities as depending upon the inverse square of the distance to each site, and upon the inverse square of distance weighted by the area of the site:[10]

$$\text{RISK1} = \sum_{j=1}^{11} d_j^{-2} \tag{5a}$$

$$\text{RISK2} = \sum_{j=1}^{11} \text{Area}_j d_j^{-2} \tag{5b}$$

To control for the aesthetic effects of waste sites -- which would not be eliminated if the site were cleaned up -- we calculated the number of sites (hazardous, industrial, and landfills) within various distance annuli from the house. The coefficients on these SITES variables should be negative, reflecting the negative aesthetic effects of industrial sites. In addition, we used equivalent variables for the hazardous waste sites to calculate semiparametric estimates of the influence of distance on housing prices (see below).

Estimation Strategy

The estimation strategy in this paper is directed toward producing estimates of the expected value and variance of the benefits of cleaning up a single hazardous waste site. We first estimate a hedonic housing price equation using a specification based upon previous studies and additional a priori considerations. The average willingness to pay to clean up a site is estimated by reclassifying the site as "industrial" and calculating the price of each housing unit in the sample. As discussed in Section II, the difference between the predicted price of the house before and after the cleanup provides an estimate of the benefit to the household.

To obtain estimates of the total benefits of cleaning up a site, it is necessary to aggregate the benefits across housing units. Since some towns are oversampled in our data base, we calculate a weighted average. The weights for each town, z_i, are based upon the ratio of the number of single family detached houses in the town, as reported in the 1980 Census of Housing, to the number of observations in the town. Defining $\hat{P}_i$ and $\hat{P}_i^*$ as the predicted prices of house i before and after the cleanup, our estimate of the average benefits of cleaning up the site (B) is:

$$B = n^{-1} \sum_{i=1}^{n} z_i \left(\hat{P}_i^* - \hat{P}_i\right) \qquad (6)$$

Under standard assumptions, this estimator will be asymptotically normal. We calculated the total benefits of the site using B and an estimate of the total number of households in the Boston suburban area.

We approximate the variance of B using standard asymptotic techniques. Let x_i present the vector of independent (possibly transformed) variables for the ith observation, and let x_i^* denote this vector after the simulated cleanup. In the hedonic housing price equations reported below, we use the natural logarithm of house price as the dependent variable and estimate price surfaces linear in X. Thus, the variance of the asymptotic distribution of the estimator of B is:

$$V = \left[n^{-1} \sum_{i=1}^{n} z_i \left(e^{X_i^* \beta} X_i^* - e^{X_i \beta} X_i \right) \right]' \qquad (7)$$

$$\operatorname{Var}(\hat{\beta}) \left[n^{-1} \sum_{i=1}^{n} z_i \left(e^{X_i^* \beta} X_i^* - e^{X_i \beta} X_i \right) \right]$$

where β is the vector of true regression coefficients, $\hat{\beta}$ is its estimator, $\operatorname{Var}(\hat{\beta})$ is the covariance matrix of $\hat{\beta}$, and where ' denotes vector transposition. The variance V can be estimated by replacing $\operatorname{Var}(\hat{\beta})$ by its estimator and replacing $\exp(X_i^* \beta)$ and $\exp(X_i \beta)$ by the predicted prices, $\hat{P}_i^*$ and $\hat{P}_i$, respectively.

IV. RESULTS

In this section, we present estimates of the benefits of cleaning up specific hazardous waste sites. In particular, we consider the benefits of cleaning up three sites that differ in their size and the density and income profile of their neighbors. We also present results showing the relationship between willingness to pay and distance from the site obtained from a nonparametric estimation procedure.

Following previous research, we estimated equations with log price as the dependent variable.[11] The basic equation used to estimate benefits included three features based upon a priori considerations. First, despite the large number of housing attributes in our data set, many neighborhood characteristics are omitted. To account for the characteristics common to each town, we included town dummies in the equation. Second, because the observations covered a five year period during which interest rates and other common influences on housing prices varied widely, we included dummies for the quarter in which the sale occurred. These two corrections constitute a fixed effects model controlling for town and time effects. Finally, it is often assumed that environmental amenities are a luxury good; if so, the price of houses having such amenities will be bid up by those best able to afford them. In equilibrium, then, the nearby presence of a hazardous waste site might interact nonlinearly with the house price itself. To account for such a relationship, we included interaction terms in which the two hazardous waste variables (RISK1 and RISK2) were multiplied by a predicted price obtained from an initial regression. We anticipated that the interaction term would be negative to reflect an increasing marginal value of waste cleanup as predicted house price rises.[12]

The basic equation results are given as model (1) in Appendix B. In general, the coefficients conform to our a priori expectations about the influence of each variable on housing price. The structural variables all have the expected sign and are statistically significant. The neighborhood variables also performed well. The accessibility variables have the expected signs (with the exception of EMP2), although the individual terms are not statistically significant.

With regard to the waste variables, the SITES variables are all positive rather than negative as expected, although none is statistically significant. The most plausible explanation for the positive signs is that proximity to waste sites proxies local accessibility advantages that are not accounted for by our area-wide accessibility measures. Although industrial and municipal waste sites no doubt create disamenities as we hypothesize, they also represent important industrial and commercial centers within a town or region. Apparently the advantages of proximity overwhelm the aesthetic disadvantages.

The results for the RISK terms suggest, however, that the housing market does reflect the negative effects of proximity to hazardous waste sites. The interaction terms are negative, suggesting that as expected the adverse effects of living near a hazardous waste site form a relatively larger component of the price of expensive homes. However, the complicated specification of the hazardous waste variables makes it difficult to interpret the coefficients directly. Instead, Figure 2 summarizes the results implied by the basic equation. The graphs shows the willingness to pay for the cleanup of a hypothetical 30 acre site as a function of the distance from the site and the ex ante housing price. Willingness to pay increases both for houses closer to the site and for more expensive houses. For example, for a $100,000 house, the willingness to pay for cleanup of a site 1.5 miles away is $1,600; if the site is only one-half mile away the estimated willingness to pay jumps to $13,500. The variation is also great across house prices: For a 30 acre site one mile away, the estimated willingness to pay ranges from $1,060 for a $60,000 house to $5,020 for a $120,000 house.

Table 2 presents the estimates of the benefit of cleaning up individual sites based upon the basic equation. These estimates appear to be plausible estimates of the cleanup benefits, The total benefit ranges from $3.6 million for the Ashland site to $17.4 million for the Acton site. The benefits per household range from $9 for Ashland to $44 for the Acton site.

The standard errors indicate substantial uncertainty about the precise estimate of benefits, particularly for the Woburn site. A major factor contributing to this imprecise

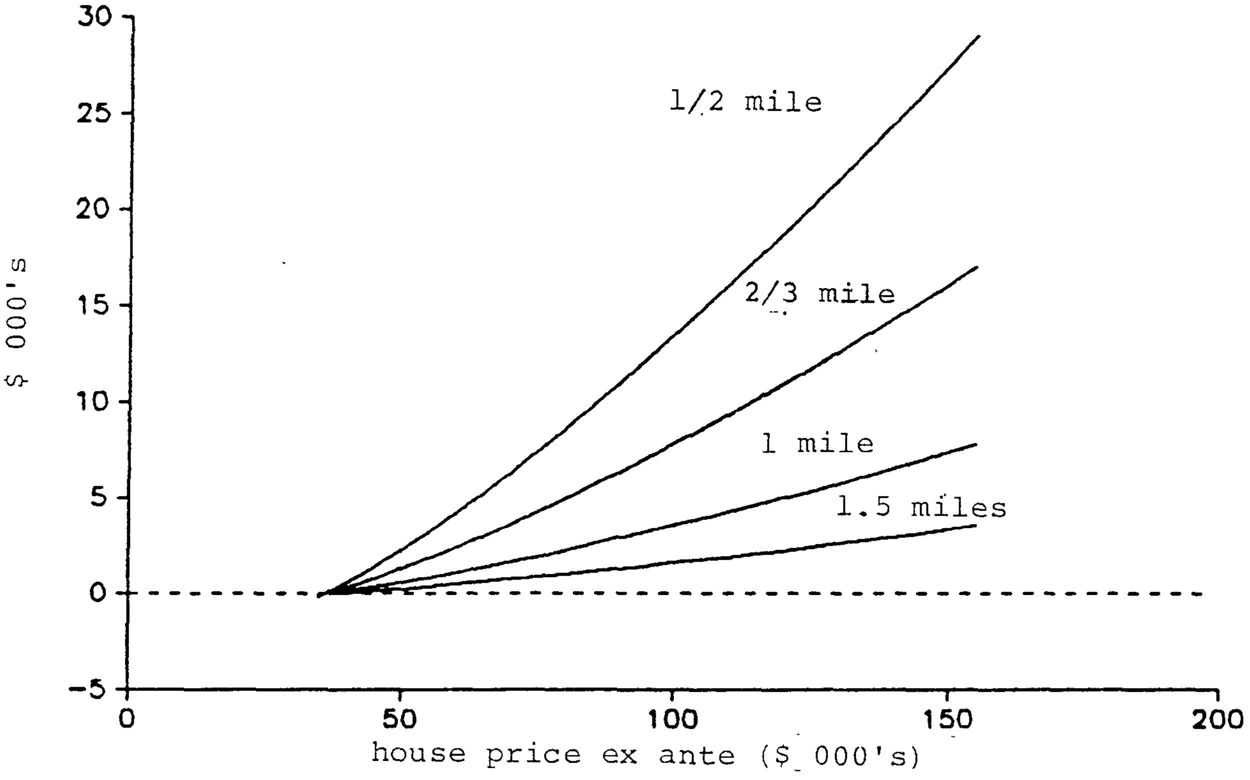

Figure 2. Willingness to pay for cleanup of a 30 acre hazardous waste site ($1980)

Table 2. Benefit Estimates for the Basic Equation[a]

Site	Clean Up Benefit ($$10^6$)	Benefits per Owner Household[b] (standard error)
Acton	$17.4	$44.0 (24.6)
Ashland	3.6	9.2 (14.7)
Woburn	7.0	18.0 (15.1)

Notes:

[a] The basic equation is reported in Appendix B. Results are in 1980 dollars.

[b] Average benefits for suburban Boston owner households.

measurement of the benefits is that although the data set contains 2,182 observations, many of these observations are of sales which occurred far from any hazardous waste site. For example, only 515 observations have a hazardous waste site within four miles of the house.

The benefit estimates vary because of differences in the sizes of the sites and in the surrounding land use. The benefits of cleaning up the Acton site are large because the site is large (400 acres) and located near relatively densely populated areas and expensive homes. In contrast, the Ashland site is small (30 acres) and located in a predominately rural area. Benefits for the Woburn site clean up are intermediate because although the site is large (300 acres) and near relatively densely populated suburbs, these suburbs have generally low house prices.

The construction of the primary hazardous waste variables (RISK1 and RISK2) in the basic equation implies a specific functional form for the relationship between the distance of the site and the willingness to pay to remove its toxic material. Although the form was chosen on sensible a priori grounds and generates plausible benefit estimates, it is useful to explore a less restrictive formulation. To this end, we developed an alternative econometric approach in which we estimated a series of equations adding variables based on the number of hazardous waste sites falling in half-mile rings. These WASTES variables are analogous to the SITES variables for the total number of industrial, landfill and hazardous sites. To obtain a nonparametric estimate of the effect of distance on the willingness to pay, we varied the distances at which the half-mile rings began. Four regressions were run, with the second ring respectively beginning at 0.125, 0.250, 0.375, and 0.5 miles. The coefficients on the WASTES variables provide a semiparametric estimate of the benefits of cleaning up a site at a given distance; for example, the benefit of cleaning up a site 1.5 miles away is given by the coefficient on the wastes variable representing the ring from 1.25 to 1.75 miles.

The results of the semiparametric estimation procedure are shown in Figure 3. These results confirm the implication of the basic equation that the value of cleaning up a hazardous waste site is substantial for houses near the site. For example, using the semiparametric technique the estimated value of clean up for a site 0.25 miles from a house is equal to 7.2% of the houses value. This value declines sharply with distance and becomes negative for distances greater than one mile. The pattern of negative estimates for houses located between one and two miles from a site suggests the site variables are picking up the effect of omitted beneficial aspects of proximity to the sites. As suggested above for the total SITES variables, waste sites might be accessible to job concentrations or shopping areas. As a result, the benefits estimated using the semiparametric technique may underestimate the true value that households place on removing toxic material.[13]

To test for the importance of the specification of the housing price equation, we calculated estimates of cleanup benefits for several alternative formulations. Table 3 presents

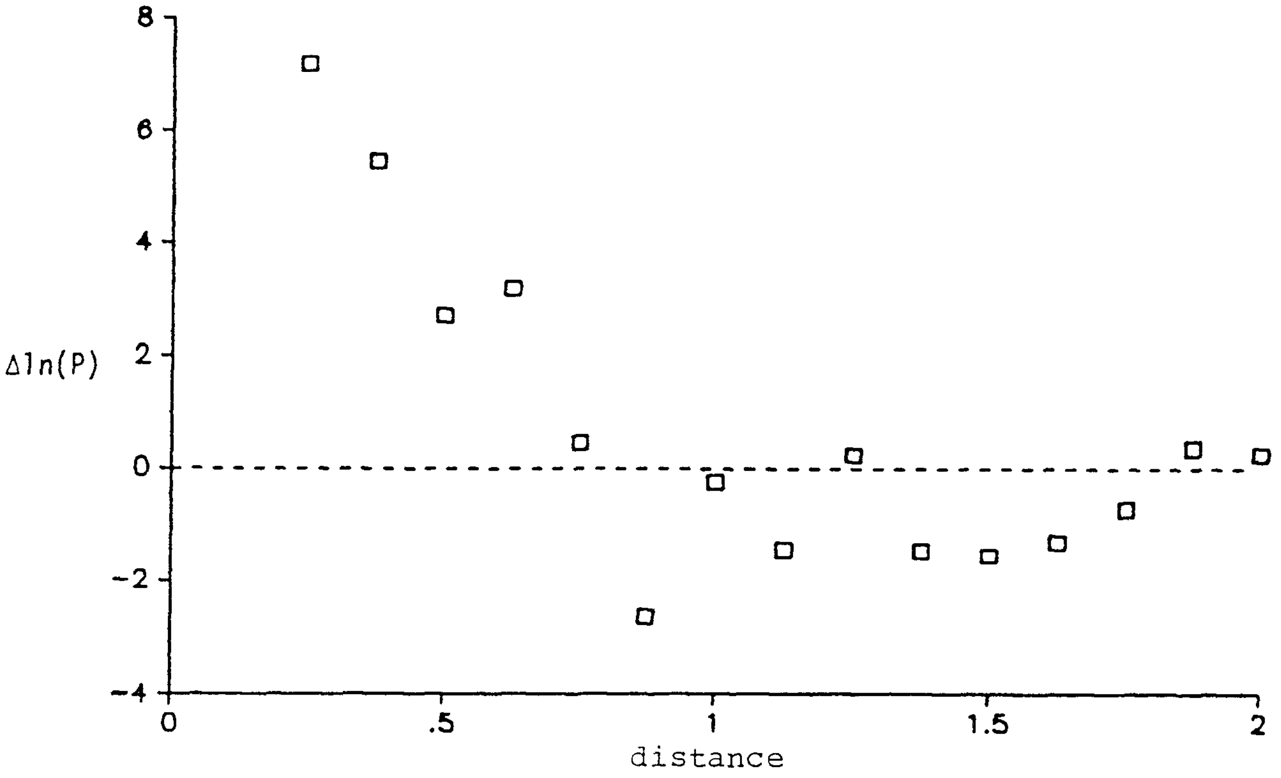

Figure 3. Semiparametric estimate of average willingness to pay

Table 3. Sensitivity of Benefit Estimates to Alternative Specifications[a]

Model	Acton		Ashland		Woburn		Test Results	
	Per House (standard error)	Total (10^6)	Per House	Total (10^6)	Per House	Total (10^6)	vs. Model	F Test[b]
(1) Basic equation	\$44.0 (24.6)	\$17.4	\$9.2 (14.7)	3.6	\$18.0 (15.1)	\$7.0m		
(2) Delete interaction terms	35.6 (35.2)	13.8	1.9 (6.0)	0.73	22.2 (19.7)	8.6	(1)	0.297 (2)
(3) Delete town effects	0.82 (173)	0.32	-42.5 (123)	-16.4	24.1 (153)	9.3	(1)	9.19* (79)
(4) Delete time effects	47.9 (34.6)	18.5	3.3 (16.4)	1.3	21.8 (22.6)	8.4	(1)	6.43* (12)
(5) Delete two accessibility variables	44.3 (33.7)	17.1	9.2 (16.6)	3.6	17.8 (22.0)	6.9	(1)	0.062 (2)

Table 3 (continued)

Model	Acton		Ashland		Woburn		Test Results	
	Per House (standard error)	Total (10^6)	Per House	Total (10^6)	Per House	Total (10^6)	vs. Model	F Test[b]
(6) Delete town effects; add neighborhood variables	14.1 (30.7)	5.5	-53.0 (14.3)	-20.5	-1.87 (23.2)	7.1	(1)	7.09* (77)
(7) Delete town effects and interaction; add neighborhood variables	20.9 (27.9)	8.1	-7.7 (6.0)	-3.0	10.6 (18.5)	7.3	(2)	7.29* (77)

Notes:

[a] Benefits are in 1980 dollars.

[b] Numerator degrees of freedom in parentheses.

*Rejection at the .1% level.

the results. The first alternative eliminates the interaction terms, thereby presuming that a nearby site has the same percentage effect on house price regardless of house price. The coefficients on the two hazardous waste variables have the expected negative sign. As expected, the omission of the interaction terms decreases the benefits for the cleanup of Acton and Ashland (located near high priced houses) and increases the estimate for Woburn (low income area). Except for Ashland, the sizes of the changes are quite modest.

Deleting the town effects causes a much greater change in the housing value equation. The interaction terms switch signs, implying that the marginal percentage value of cleaning up a waste site declines with estimated price. These changes in the equation lead to dramatically different benefit estimates. Estimated benefits for the Acton site fall to zero and the benefit of cleaning up the Ashland site is negative. The figure for the Woburn site increases. These results are consistent with general information on the characteristics of the towns around the sites that would cause the biased results. With an F statistic of 9.2, the hypothesis that the town effects are all zero is readily rejected at the 0.01 level. Indeed, the results for this experiment provide clear evidence of the potential for omitted variable bias when an inadequately specified equation is used to estimate the benefits of cleaning up hazardous waste sites. Including town effects in the hedonic housing price equation is crucial to a proper specification of the relationship between housing prices and exposure risk from hazardous wastes.

The changes are much less dramatic when the time effects are excluded from the equation, although the Ashland results do appear to be sensitive to the change. As with the town effects, the hypothesis that the quarter effects all equal zero can be rejected at the 0.01 level (the F statistic is 6.4). Deleting two of the accessibility variables (Model 15) produces quite small changes, although they are in the expected direction. The semiparametric results suggested that the clean up estimates may be biased downward because distance from the sites may be correlated with omitted accessibility variables. Deleting two of the four variables shows such a downward bias, although the changes are modest and not statistically significant.

The final two changes provide additional evidence of the importance of incorporating town effects in the equation. The estimates in the final two rows result from deleting the town dummies and adding two local variables widely recognized as important influence on housing price, the town property tax rate and school quality. In the second of the two rows the interaction terms are also deleted. Both sets of results are implausible, particularly for the Ashland site. The F statistics for the tests of the validity of these two restrictions are highly significant (7.3 and 7.1, respectively), indicating that we can confidently reject the hypothesis that the town effects are all zero even when two important town variables are in the equation.

V. CONCLUSIONS

The hedonic housing value approach provides a conceptually sound approach for estimating the benefits of localized public goods. Even where the local changes are non-marginal -- as is the case in cleaning up a hazardous waste site -- the results of a hedonic housing price equation can be used to estimate the willingness to pay. Indeed, in the case of localized changes, the benefit estimates are also estimates of the change in housing prices when general equilibrium (i.e., moving) effects are taken into account. This positive case for the use of the hedonic approach has tended to be overlooked in the recent theoretical literature, which emphasizes the difficulties in obtaining willingness to pay estimates for area-wide, non-marginal changes.

Using this approach, we estimated the benefits of cleaning up individual hazardous waste sites using data for the Boston housing market. The results generated plausible estimates of the willingness to pay for cleaning up a site, ranging from $3.6 to $17.4 million, depending upon the site. These estimated benefits are greater when the site is larger, when there are more close neighbors, and when local housing prices are higher. Our semiparametric results showed that the benefits of cleanup are very substantial for houses within one half mile of a site.

The results proved to be relatively insensitive to changes in the specification of the hazardous waste variables, to changes in the non-waste variables, and to the quarter dummies we used to control for the time of sale. But the results were extremely sensitive to the presence of town dummies. When the town variables were excluded, the results were implausible, even when two important town-specific variables (tax rate and school quality) were substituted. We concluded that, at least for a highly localized public good such as proximity to hazardous waste sites, incorporating town effects is crucial. Indeed, these results cast some doubt on the results of the many hedonic housing price studies that do not include town effects.

Finally, it is useful to consider potential biases or omissions in using the results of this study to estimate the benefits of cleaning up hazardous waste sites. Two factors suggest our estimates are underestimates of the true willingness to pay to clean up a site. First, there is evidence that our estimates might be biased downward because some advantages of living near waste sites -- such as accessibility to local centers of employment or commerce -- were omitted from the hedonic equation. Second, some adverse effects of waste sites could not be estimated with our data. In particular, we could not estimate the value of contaminated well water; Boston towns are served by town wells and any adverse effects of town well water contamination (including the cost of mitigating actions) cannot be disentangled from other town characteristics using our data set. Estimating well water effects would require other data or other techniques.[11] Nevertheless, the benefits estimates presented in this paper provide important measures of the value that households place on cleaning up hazardous waste sites.

APPENDIX A

DATA USED IN THE HOUSING VALUE EQUATION

Most of the empirical results are based upon a common specification of the housing value equation:

$$
\begin{aligned}
&\text{Log (PRICE)} = a_{1jt} + a_2 \text{ SITES} + a_3 \text{ RISK1} + a_4 \text{ RISK2} + a_5 \text{ RISK1} * \\
&(\text{Log}\hat{\ } \text{PRICE}) + a_6 \text{ RISK2} * (\text{Log}\hat{\ }\text{PRICE}) + a_7 \text{ Log (SPACE)} + \\
&a_8 \text{ Log (LOT)} + a_9 \text{ Log (BATH)} + a_{10} \text{ STORIES} + a_{11} \text{ HEATING} + \\
&a_{12} \text{ BASEMENT} + a_{13} \text{ FIREPLACE} + a_{14} \text{ PARKING} + a_{15} \text{ QUALITY} + \\
&a_{16} \text{ CONDITION} + a_{17} \text{ YEAR BUILT} + a_{18} (\text{YEAR BUILT})^2 + \\
&a_{19} \text{ Log (ACCESS)} + a_{20} \text{ Log (RAD)} + a_{21} \text{ Log (EMP1)} + \\
&a_{22} \text{ Log (EMP2)} + a_{23} \text{ Log (LSTAT)} + a_{24} \text{ Log (NOX)} + a_{25} \text{ (CHAS)} \\
&+ \text{ Error}
\end{aligned}
$$

where a_{1jt} varies over sites j and the quarter of the transaction t.

The study uses data for 2,182 housing transactions in 80 towns in the Boston urban area (excluding the city of Boston) over the period from November 1977 to March 1981. Most of the transactions occurred in 1979 and 1980. The housing price and characteristic data were obtained from the Society of Real Estate

Appraisers. Prices were put into 1980 dollars using the definition of each variable, its expected sign, and the data source are indicated in Table A-1.

The most difficult and time-consuming data collection task was to determine the location (latitude and longitude) of each house in our data base. For approximately two-thirds of the transactions, we used computer readable maps developed by the U.S. Bureau of the Census, referred to as the GBF/DIME file. Only the urban areas of the Boston Standard Metropolitan Statistical Area (SMSA) are included in the file. Each record of the file contains a street name, census tract, ranges of street numbers (both odd and even sides), and the latitudes and longitudes of two consecutive intersections along the street. We wrote a computer program that identified the census tract, street and address range on the GBF/DIME that corresponded to the address of the house on our SREA dataset. Then, assuming a linear spacing of address numbers between the two consecutive intersections for which the latitudes and longitudes were given, we estimated the latitude and longitude of the house. For houses outside the urban area, we hand coded the latitudes and longitudes using indexed maps, street guides, and the detailed census tract maps for the Boston SMSA published by the Bureau of the Census.

The data waste sites were based on information compiled by the Massachusetts Department of Environmental Quality Engineering (DEQE). In 1981, DEQE published information on sites storing industrial wastes. In order to develop sufficiently detailed information to categorize the wastes as hazardous or non-

Table A-1. Variables Used in the Housing Price Equation

Variable	Definition	Source
Dependent		
PRICE	Housing price (1980 dollars)	SREA
Waste		
SITES (multiple)	Total number of sites (hazardous, industrial, landfill) within one-half mile annuli around the house starting at distances of 0, 0.5, 1.0, ... 2.5 miles. Should reflect the aesthetic disamenities of waste disposal	Author calculations and Massachusetts Department of Environmental Quality Engingineering(1981)
WASTES (multiple)	Number of hazardous sites within one-half mile annuli around the house. Should reflect the risks from hazardous waste sites. Used in the semiparametric estimation described in the text.	Authors' calculations
RISK1	Inverse square of the distance from the house to each of the 11 hazardous waste sites. Proxy for the subjective probability of illness from hazardous waste exposures. Should be negatively related to house price.	Authors' calculations
RISK2	Inverse square of the distance from the house to each of the 11 hazardous waste sites weighted by the area of the site. Should be negatively related to house price.	Authors' calculations
Structural		
SPACE	Living area (square feet). Represents spaciousness and, in a certain sense, quantity of housing. It should be positively associated to price.	SREA
LOT	Lot size (square feet). Should be positively related to price.	SREA

Table A-1. (continued)

Variable	Definition	Source
BATH	Number of bathrooms. Should be positively related to housing price.	SREA
STORIES	Number of stories of the house. May be positive or negative.	SREA
HEATING (multiple)	Dummy variables indicating whether the house has forced air, hot water, steam, or other heat source (intercept).	SREA
BASEMENT	Fraction of the basement area that is finished. Should be positively related.	SREA
FIREPLACE	Number of fireplaces. Should be positively related to house price.	SREA
PARKING	Covered parking (1=yes, 0=no)	SREA
QUALITY	Estimated construction quality on a scale from 1 (poor) to 5 (excellent). Should be positive.	SREA
CONDITION	Estimated current condition on a scale from 1 (poor) to 5 (excellent). Should be positive.	SREA
YEAR BUILT	Year the house was constructed. At early years, the house price might be increased reflecting preferences for older styles. However, in later years, households might prefer the reduced maintenance of newer units. One expects, therefore, a non-linear relationship between year built and price.	SREA

Table A-1. (continued)

Variable	Definition	Source
Accessibility		
ACCESS	Average distance from the house to the centers of the towns in the Boston area, weighted by the fraction of 1980 employment in each town. Traditional theories of urban land rent gradients imply that housing values should be higher near employment centers; thus the expected sign is negative.	Authors' calculations
RAD	Index of accessibility to radial highways. Should be positive.	Harrison and Rubenfeld (1978)
EMP1	Employment in towns within three miles of the house. Designed to capture the localized accessibility advantages that otherwise would cancel out the disadvantages of proximity to waste sites. Should be positive.	Authors' calculations based on 1980 U.S. Census
EMP2	Ratio of employment within three miles (EMP1) to population of towns within three miles	Authors' calculations based on 1980 U.S. Census
Neighborhood		
LSTAT	Proportion of population within the census tract that are lower status. Calculated as the averages of the proportion of workers with blue collar jobs and the proportion of adults with at most a high school education. Should be negative.	1980 U.S. Census
NOX	Nitrogen oxide concentrations in pphm (annual average concentration in parts per hundred million.	Harrison and Rubenfeld (1978)

Table A-1. (continued)

Variable	Definition	Source
Neighborhood		
CHAS	Charles River dummy; = 1 if census tract bounds the Charles River; 0 = if otherwise captures the amenities of a riverside location and thus the coefficient should be positive.	1980 U.S. Census
TAX	Full value property tax rate ($/$10,000). Measures the cost of public services in each community. Nominal tax rates were corrected by local assessment ratios to yield the full value tax rate for each town. Intra-town differences in the assessment ratio were difficult to obtain and thus not used. The coefficient of this variable is theoretically ambiguous, depending on the efficiency of the production of public goods.	Vogt, Ivers, and Associates
PTRATIO	Pupil-teacher ratio by town school district. Measures public sector benefits in each town. The relation of the pupil-teacher ratio to school quality is not entirely clear, although a low ratio should imply each student receives more individual attention. We expect the sign on PTRATIO to be negative.	Massachusetts Department of Education
TOWN (multiple)	Dummy variable for the town. Should control for the positive or negative unobserved characteristics of each town.	SREA
QUARTER (multiple)	Dummy variable for the quarter of sale (from third quarter 1977 to first quarter 1981). Should control for the changes in financing and credit conditions over our sample period.	SREA

Table A-1. (continued)

Variable	Definition	Source

Notes:

SREA: Society of Real Estate Appraisers.

hazardous, we supplemented the published reports with examination of the files and detailed interviews with officials familiar with all the potential hazardous sites. The DEQE report classified sites into five categories: (1) confirmed hazardous waste site, site secured; (2) confirmed hazardous waste site, site under investigation; (3) site under evaluation; (4) no hazardous waste present; and (5) municipal waste and wastewater treatment plant. The majority of sites fell into categories 3, 4, and 5. Of the 20 sites in the Boston urban area in categories 1 and 2, we concluded that 9 were non-hazardous after our detailed investigation. For each of the 11 hazardous waste sites, we collected information on the date the site was "discovered" to have hazardous material, the nature of the wastes, and the area of the site. In order to develop a ranking of the severity of the hazard from each site, we consulted the criteria used in the ranking of Superfund sites for cleanup. All 11 sites contained material judged to pose equal hazards under that ranking scheme.

We also collected information on industrial disposal sites and landfills. The 41 industrial sites consisted of the nine from categories 1 and 2, and thirty-two from categories 3 and 4. Using information from a DEQE report, Inventory of Active and Inactive Solid Waste Landfills, we identified 49 active commercial or town landfills in the Boston urban area.

To calculate the distance variables that are crucial for our study, we determined the location of each of the 101 waste disposal sites from U.S. Geological Survey maps upon which the DEQE had marked each site's location. The distance calculation is based on simple plane geometry:

$$D = ((SLO-HLO)*51.252)^{2} + (((SLA-HLA)*68.988)^{2})^{(1/2)}$$

where

D = distance in miles from house to site
SLO = site longitude
HLO = house longitude
51.252 = miles in a degree longitude
SLA = site latitude
HLA = home latitude
68.988 = miles in a degree latitude

APPENDIX B

ESTIMATED HOUSING VALUE EQUATIONS[a]

Variable	(1) Basic Equation	(2) Delete Interaction Terms	(3) Delete Town Effects	(4) Delete Time Effects	(5) Delete Accessibility Variables	(6) Delete Town Effects and add Neighborhood Variables	(7) Delete Town Effects and Interaction, add Neighborhood Variables
SITES (<0.5)	0.0003	0.0013	0.0117	0.0019	0.0001	0.0052	0.0027
	(0.0172)	(0.0172)	(0.0185)	(0.0175)	(0.0172)	(0.0179)	(0.0179)
SITES (0.5-1.0)	0.0169	0.0164	0.0100	0.0136	0.0168	0.0070	0.0100
	(0.0098)	(0.0099)	(0.0094)	(0.0100)	(0.0098)	(0.0091)	(0.0091)
SITES (1.0-1.5)	0.0056	0.0054	0.0044	0.0054	0.0056	0.0005	0.0020
	(0.0068)	(0.0068)	(0.0067)	(0.0069)	(0.0068)	(0.0065)	(0.0065)
SITES (1.5-2.0)	0.0031	0.0034	-0.0033	0.0026	0.0031	-0.0078	-0.0082
	(0.0058)	(0.0058)	(0.0056)	(0.0059)	(0.0058)	(0.0054)	(0.0054)
SITES (2.0-2.5)	0.0037	0.0040	0.0045	0.0053	0.0037	0.0040	0.0032
	(0.0050)	(0.0050)	(0.0049)	(0.0051)	(0.0050)	(0.0048)	(0.0048)
SITES (2.5-3.0)	-0.0038	-0.0033	-0.0035	-0.0029	-0.0036	-0.0047	-0.0060
	(0.0051)	(0.0050)	(0.0049)	(0.0051)	(0.0050)	(0.0047)	(0.0047)
RISK1	0.3159	-0.0002	-1.7625	0.0031	0.3205	-2.3043	0.0163
	(0.6908)	(0.0105)	(0.6729)	(0.6991)	(0.6894)	(0.6530)	(0.0108)

APPENDIX B (continued)

Variable	(1) Basic Equation	(2) Delete Interaction Terms	(3) Delete Town Effects	(4) Delete Time Effects	(5) Delete Accessibility Variables	(6) Delete Town Effects and add Neighborhood Variables	(7) Delete Town Effects and Interaction, add Neighborhood Variables
RISK2	0.0020	-0.0001	-0.0044	0.0019	0.0020	0.0045	-0.0001
	(0.0055)	(0.0001)	(0.0057)	(0.0055)	(0.0055)	(0.0056)	(0.0001)
RISK1x (Lôg PRICE)[b]	-0.0302	--	0.1688	-0.0005	-0.0306	0.2202	--
	(0.0657)		(0.0638)	(0.0664)	(0.0655)	(0.0619)	
RISK2x (Lôg PRICE)	-0.00019	--	0.0004	-0.0002	-0.0002	-0.0004	--
	(0.0005)		(0.0005)	(0.0005)	(0.0005)	(0.0005)	
SPACE	0.3621	0.3600	0.3341	0.3611	0.3622	0.3504	0.3539
	(0.0169)	(0.0166)	(0.0181)	(0.0171)	(0.0169)	(0.0176)	(0.0175)
LOT	0.0552	0.0550	0.0751	0.0556	0.0551	0.0599	0.0608
	(0.0074)	(0.0074)	(0.0076)	(0.0075)	(0.0074)	(0.0075)	(0.0075)
BATH	0.1299	0.1295	0.1221	0.1203	0.1298	0.1519	0.1560
	(0.0245)	(0.0245)	(0.0267)	(0.0248)	(0.0245)	(0.0259)	(0.0260)
STORIES	-0.0101	-0.0098	-0.0067	-0.0073	-0.0102	-0.0111	-0.0110
	(0.0088)	(0.0087)	(0.0096)	(0.0089)	(0.0087)	(0.0093)	(0.0093)
HEATING - air	0.0356	0.0352	0.0465	0.0369	0.0354	0.0409	0.0431
	(0.0134)	(0.0133)	(0.0146)	(0.0134)	(0.0134)	(0.0141)	(0.0141)

APPENDIX B (continued)

Variable	(1) Basic Equation	(2) Delete Interaction Terms	(3) Delete Town Effects	(4) Delete Time Effects	(5) Delete Accessi-bility Variables	(6) Delete Town Effects and add Neighborhood Variables	(7) Delete Town Effects and Interaction, add Neighborhood Variables
HEATING - water	0.0690 (0.0138)	0.0684 (0.0138)	0.0755 (0.0152)	0.0729 (0.0138)	0.0690 (0.0138)	0.0750 (0.0147)	0.0767 (0.0147)
HEATING - steam	0.0265 (0.0179)	0.0264 (0.0178)	0.0503 (0.0196)	0.0273 (0.0180)	0.0263 (0.0179)	0.0459 (0.0190)	0.0455 (0.0190)
BASEMENT ÷ 1000	0.5418 (0.1810)	0.5089 (0.1806)	0.4237 (0.2000)	0.5303 (0.1835)	0.5138 (0.1809)	0.0004 (0.0002)	0.0005 (0.0002)
FIREPLACE	0.0762 (0.0062)	0.0759 (0.0062)	0.0878 (0.0068)	0.0764 (0.0063)	0.0763 (0.0062)	0.0821 (0.0066)	0.0833 (0.0067)
PARKING	0.0670 (0.0088)	0.0667 (0.0088)	0.0705 (0.0097)	0.0667 (0.0089)	0.0671 (0.0088)	0.0701 (0.0094)	0.0706 (0.0094)
QUALITY	0.0280 (0.0057)	0.0279 (0.0057)	0.0479 (0.0060)	0.3602 (0.0057)	0.0280 (0.0057)	0.0357 (0.0059)	0.0363 (0.0059)
CONDITION	0.0414 (0.0043)	0.0413 (0.0043)	0.0357 (0.0048)	0.0386 (0.0044)	0.0415 (0.0043)	0.0394 (0.0046)	0.0396 (0.0046)
YEAR BUILT	-0.0018 (0.00069)	-0.0018 (0.00069)	-0.0031 (0.00075)	-0.0017 (0.00070)	-0.0018 (0.00069)	-0.0033 (0.0007)	-0.0034 (0.0007)
YEAR	0.0540	0.0539	0.0658	0.0537	0.0542	0.0001	0.0001

APPENDIX B (continued)

Variable	(1) Basic Equation	(2) Delete Interaction Terms	(3) Delete Town Effects	(4) Delete Time Effects	(5) Delete Accessibility Variables	(6) Delete Town Effects and add Neighborhood Variables	(7) Delete Town Effects and Interaction, add Neighborhood Variables
BUILT^2 ÷1000	(0.0085)	(0.0085)	(0.0092)	(0.0086)	(0.0084)	(0.0000)	(0.000)
ACCESS	0.0946 (0.0633)	0.0939 (0.0632)	-0.3071 (0.0231)	0.1186 (0.0640)	0.0975 (0.0619)	-0.2557 (0.0234)	-0.2687 (0.0231)
RAD	0.2011 (0.1957)	0.2016 (0.1957)	0.0471 (0.0136)	0.1576 (0.1985)	0.2003 (0.1956)	0.0486 (0.0136)	0.0452 (0.0136)
EMP1	-0.0069 (0.0205)	-0.0073 (0.0205)	-0.0272 (0.0119)	-0.0039 (0.0208)	--	0.0170 (0.0125)	0.0157 (0.0125)
EMP2	0.0074 (0.0211)	0.0075 (0.0211)	0.0606 (0.0147)	0.0056 (0.0214)	--	0.0114 (0.0150)	0.0159 (0.0149)
LSTAT	-2.2224 (0.2254)	-2.2117 (0.2248)	-3.4737 (0.1968)	-2.2200 (0.2280)	-2.2243 (0.2244)	-2.9681 (0.1960)	-3.075 (0.1942)
NOX	-9.1095 (2.7833)	-8.8490 (2.7267)	-14.9588 (1.5633)	-8.9687 (2.8149)	-9.1566 (2.7788)	-8.0363 (1.6399)	-8.6889 (1.6259)
CHAS	-0.0249 (0.0341)	-0.0246 (0.0341)	--	-0.0191 (0.0345)	-0.0247 (0.0341)	0.0930 (0.0258)	0.0923 (0.0258)

APPENDIX B (continued)

Variable	(1) Basic Equation	(2) Delete Interaction Terms	(3) Delete Town Effects	(4) Delete Time Effects	(5) Delete Accessibility Variables	(6) Delete Town Effects and add Neighborhood Variables	(7) Delete Town Effects and Interaction, add Neighborhood Variables
TAX	--	--	--	--	--	-0.3012 (0.0294)	-0.2961 (0.0291)
PTRATIO	--	--	--	--	--	-0.1265 (0.0442)	-0.1270 (0.0443)
TOWN	yes	yes	no	Yes	Yes	no	no
QUARTER	yes	yes	Yes	no	yes	Yes	yes
R^2 (adj)	.80	.80	.74	.79	.80	.76	.75

Notes:

[a] Standard errors are in parenthesis.

[b] The RISK interaction terms are based on multiplying RISK1 and RISK2 by the predicted log price price obtained using model (2). .

NOTES

1. See, for example, Brookshire et al (1982), Harrison and Rubinfeld (1978), Nelson (1982), Quigley (1982), Sonstelie and Portney (1980) and Witte et al. (1979).

2. The Brown and Rosen identification problem takes different forms, depending on whether the data set is based on observations from a single or multiple housing markets. On the one hand, if data from a single housing market is used, then identification must be obtained from arbitrary assumptions about the nonlinearity of the hedonic pricing function. On the other hand, obtaining identification by pooling data from several housing markets has its own difficulties: the assumption that the homeowners in all housing markets have the same preference parameters becomes less credible, and the number of independent housing markets must become large to ensure the statistical validity of the procedure. In both cases, as Bartik (1983) points out, the two stage approaches are subject to a basic problem of all demand analysis: in the absence of panel data, variations in preference parameters across individuals cannot be treated satisfactorily and generally will result in estimator bias. For more complete reviews of these issues and the attempts to resolve this identification problem, see Brown (1982) and Diamond and Tolley (1983).

3. Attempts to survey households on their willingness to pay for public goods have become more frequent in recent years. The studies are often referred to as "contingent valuation" studies to emphasize the hypothetical nature of the valuation. See Brookshire et al (1982) for a careful example of the technique and Desvousges and Smith (1983) for a recent survey.

4. See Harrison and Rubinfeld (1978).

5. This formulation is closely related to that used in studies of the willingness to pay for reductions in risk in the workplace. Studies such as Viscusi (1979, 1983) have related objective and subjective levels of risk in different jobs to wage differentials and have interpreted these differentials as risk premia. Although this approach has much in common with our examination of the hedonic housing price equation, there are several important differences. First, the wage studies do not distinguish between health risk reduction and aesthetic benefits of a policy. In contrast, cleaning up a hazardous waste site could have an aesthetic as well as health benefit. Second, even if the studies use survey data on subjective probabilities, usually little attention is paid to the components or formation of

subjective probabilities associated with certain risks. (Viscusi and O'Connor (1983) are an exception: they use experimental data in an attempt to model worker response to different warning labels for hazardous substances.) This paper takes a more agnostic view of the formation of subjective probabilities, however, and the hedonic pricing equation is allowed to depend on several attributes related to hazardous wastes which could reasonably influence subjective probabilities.

6. For example, Scotchmer (1984) presents several examples of general equilibrium hedonic pricing functions derived under the assumption that lot size is divisible.

7. See Polinsky and Shave11 (1975), Polinsky and Shave11 (1976), and Polinsky and Rubinfeld (1977). Freeman (1979) provides a concise summary of the theoretical models. The hypothesis that local public goods are capitalized in housing prices is an old one: for a recent discussion and review, see Yinger (1982).

8. Polinsky and Shavell (1976) derive this result using an indirect utility function approach. In the indirect utility function, a household's utility is expressed as a function of prices at a particular location, income net of transportation costs from that location, and amenities at that location. Each household has a common level of utility, V*, which is independent of location:

$$V^* = V(p(k), y - T(k), a(k))$$

where p is the price per unit of housing, y is income, T is transportation cost, and a is the index of amenities. Adjustment in land rents is the mechanism by which utility is equalized over space. Given an individual's income, transportation costs, and the level of amenities, there is only one level of rent that will result in utility V*.

9. The sales price and housing attribute date were obtained from the Society of Real Estate Appraisers.

10. These formulations may not measure the subjective probability of exposure from drinking contaminated water, which would be related to the presence of a site near town wells and not to distance from the site. Two of the sites actually did contaminate drinking water supplies, causing the towns to undertake expensive mitigation measures. In theory, these expenditures -- and any residual health risks -- would be reflected in housing prices. Unfortunately, it is not possible to distinguish the town effect due to contaminated water supplies from other omitted variables associated with the town. Thus we could not measure the

value that households place on risks from contaminated drinking water or test the hypothesis that mitigation costs are reflected in housing prices.

11. Initial investigation suggested that this functional form was appropriate for our data.

12. Our strategy is designed to estimate a nonlinear price surface in which we allow the possibility of general equilibrium effects of environmental amenities being luxury goods. Adding a term in which hazardous waste variables interact with a characteristic highly correlated with house quality is one means of allowing for these general equilibrium effects. We use the house price predicted from a preliminary regression as our measure of quality.

    An alternative way to view this aspect of our estimation strategy is as a two-step estimator applied to the nonlinear model

$$Y = (1 + X_2a) Xb + U$$

where X2 is contained in X, a and b are parameter vectors, and U is an independent error. In the two-step implementation, b is first estimated by setting a = 0 and applying OLS; then the regressor $X_2(Xb)$ (i.e. RISK1 x (log PRICE) and RISK2 x (log PRICE)) is constructed and a and b are re-estimated by OLS. The two-step estimator is consistent if all third moments of X are zero or if a = 0. In general, however, the two-step estimator will be inconsistent within the framework of the nonlinear model. Inconsistency did not appear to be a significant problem in our model since the coefficients of the non-hazardous waste variables did not change appreciably between the two stages (i.e. between equations (1) and (2) of Appendix B).

13. The estimates obtained from the semiparametric approach are likely to be biased for two other reasons as well. The first arises from the nonlinearity of the willingness to pay as a function of distance to the site: in the plausible case that this function is convex, then by Jensen's inequality, the semiparametric estimator will be biased upwards. However, assuming a uniform locational distribution of houses, there will be in theory (and are in our data set) a greater density of observations near the outside of any given annulus. As long as the willingness topay function is decreasing with distance, this will impart a negative bias to the semiparametric estimator.

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PART 2

USING THE RISK ASSESSMENT METHOD TO ESTIMATE THE BENEFITS OF HAZARDOUS WASTE CLEANUP

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I. INTRODUCTION

The model that we have used to assess risk is made up of essentially three components: (1) a source term, (2) a transport model, and (3) an exposure term. First, we identify the chemical contaminants thought to impose risk, by type, amount, and their source. Then, a transport model, such as a groundwater flow model, is proposed to predict the movement and behavior of the contaminants and to predict the exposure concentrations of the pollutants. Third, on the basis of our estimated concentration levels, we predict the risk (as expected fatalities) associated with exposure. In this case study, drinking of contaminated well water is the exposure route of principal concern. The risk estimates that we apply to the situation are drawn from toxicological studies primarily on animals that have been performed by experts in the field of health risk assessment.

In this study, estimates are made of the risk associated with the disposal of chemicals in three lagoons on a site in Acton, MA, that is owned by the W.R. Grace Company, a manufacturer of chemicals. The goal of the work was to be part of a comparison of methodologies. The information used was that available in the summer of 1982 and has not been updated. The report seeks to assess the risk of the ten years of well use from that information and to extrapolate to a risk of seventy years of well use, a strictly hypothetical case, as the wells were taken out of use in 1979. Figure 1 shows the area investigated: the figure is from a 1980 report by Goldberg, Zoino, and Associated, cited hereafter as Goldberg et al. (1980). We concluded that the general flow of groundwater is from the primary and emergency lagoons operated by the company toward the Assabet wells No. 1 and No. 2. Little or none of the material in the vicinity of the secondary lagoon is thought to reach the town wells. The situation is complicated by the pumping of industrial wells that are owned by the company and by other potential sources of contamination in the study area. These aspects are discussed in Sections III and IV.

Risk is expressed as the number of expected fatalities from exposure to contaminants found in the Acton wells and believed to come from the company site. Some disagreement exists about which chemicals in the town wells are the responsibility of the company (see Appendix C).

The fundamental, approximate, equation we use is:

$$F = N\bar{c}R \tag{1}$$

F is the number of deaths expected in a lifetime of 70 years. N is the number of people assumed to be using the water supply, estimated at 20,000. The two Assabet wells supply about 40% of the town's water. The water pumped from these wells flows into a

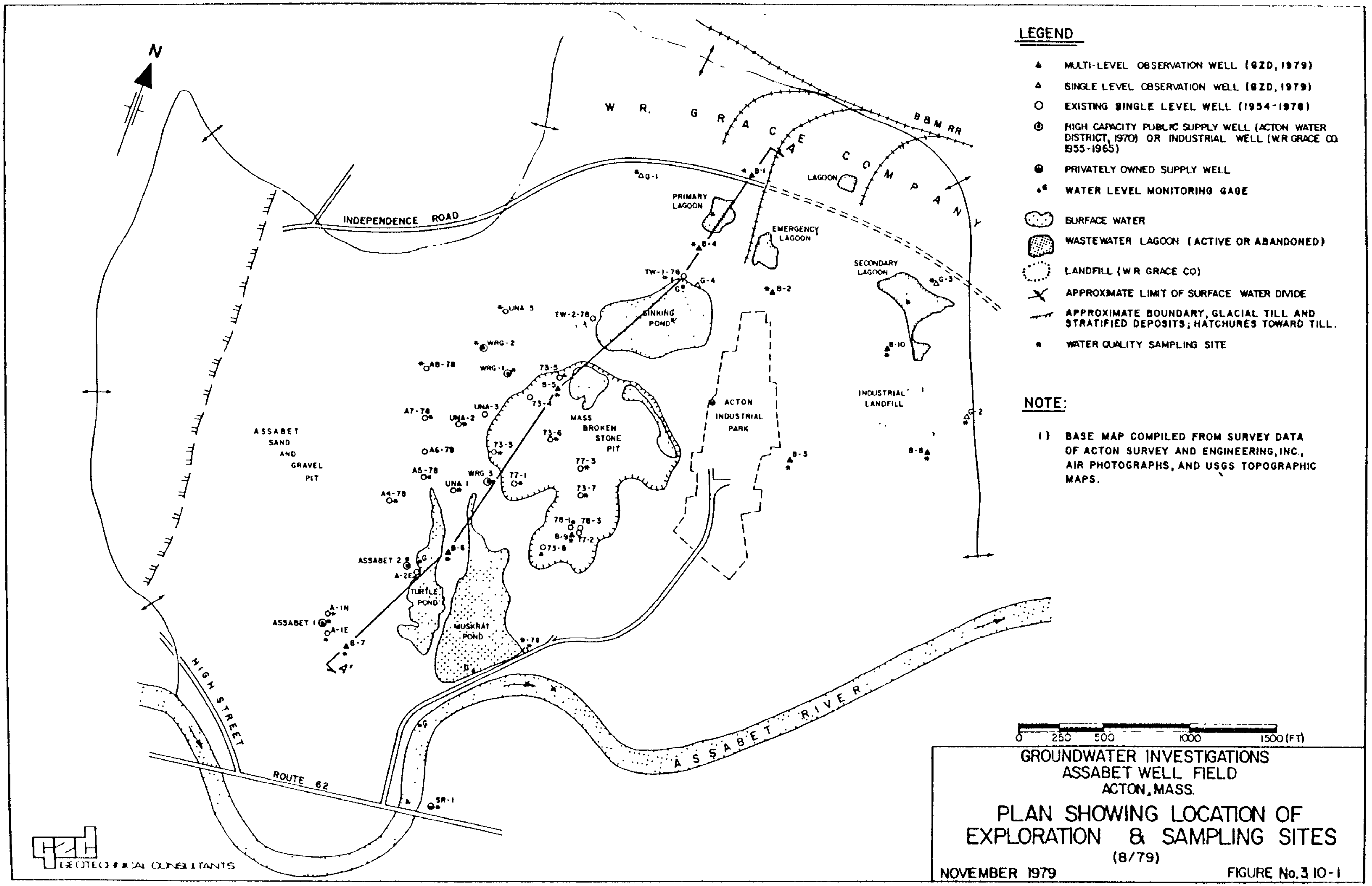


Figure 1. Study area (Goldberg et al., 1980)

central distribution system before it is sent out to town residents; here we assume complete mixing takes place. $\bar{c}$ is the mean concentration of the water being consumed by town residents over the lifetime of any individual drinking it, based on either a 10-year period between 1970 and 1979 or a 70-year period which represents a lifetime. R is the risk estimate, the probability of death in a lifetime of drinking the water per ppb (ug per liter) of each compound in the water. These risk estimates are taken from several authoritative sources; yet, for the same chemicals, the upper and lower estimates differ by factors from 20 to 700. The uncertainty in these risk estimates makes it unnecessary to obtain very accurate estimates of mean concentration, $\bar{c}$, a difficult task in any case.

II. BACKGROUND

As consultants to the town, the firm of Goldberg, Zoino & Associates (GZA) performed hydrogeological modeling and investigated past and present land use practices within the study area to locate the possible sources of contamination of the Assabet wells No. 1 and no. 2. GZA reported that in 1945 the company of Dewey and Almy acquired the site to manufacture hexane-based synthetic rubber products. Dewey and Almy initiated the use of the primary and secondary lagoons and the landfill area for waste disposal. They also drew upon the Sinking Pond for industrial cooling water. the W.R. Grace Company acquired Dewey and Almy in 1954, when we assume the type of operations being studied commenced.

Grace has been using the primary lagoon as a settling basin for contact process wastewater from its chemical plant. the supernatant from the settling process in the primary lagoon was typically pumped into the secondary lagoon, where a flow of about 75,000 gallons per day of partially treated process wastewater entered the ground (Goldberg et al., 1980). The sludge from the primary lagoon was landfilled on the site. The emergency lagoon received wastewater overflows from the primary lagoon; it was also used when the primary lagoon was being dredged. None of the lagoons were lined to prevent leaching, although sludge deposits would form on the lagoon bottoms, consequently affecting seepage rates from the lagoons.

The consultants for the company, Camp Dresser & McKee, Inc. (CDM), provided information on the lagoons in their latest report (CDM, 1982). The primary lagoon covers an area of approximately 24,000 square feet. The volume of standing water in the lagoon as of fall 1980 was about one million gallons. No wastewater has been discharged to this lagoon since 1980, and in May 1982 a negligible amount of standing water remained in the lagoon. CDM estimated the volume of sludge at about 5000 cubic yards.

The secondary lagoon, an area of about 100,000 square feet, had not been used since February 1980. According to CDM, the total standing water had not changed substantially since 1980; it is estimated at 300,000 gallons. Approximately 5000 cubic yards of sludge were thought to be in the secondary lagoon.

The emergency lagoon had not received wastewater since 1978. It covered an area of 24,000 square feet. CDM estimated that the volume of standing water in the emergency lagoon was about 500 gallons. The sludge volume was estimated to be 1800 cubic yards.

III. SOURCE ESTIMATION

Three major sources are studied: the (1) primary, (2) emergency, and (3) secondary lagoons on the company site. We sought to estimate the fraction of material emitted to the lagoons that would eventually end up in the town wells. The bases of our modeling are groundwater maps prepared by GZA (Goldberg et al., 1980).

The consultants for the town, GZA, conducted a five-day water quality sampling program between 2 August and 10 August 1979, during which 75 locations in the aquifer were sampled. Samples were collected from multilevel wells, single-level observation wells, surface water bodies, and wastewater lagoons. The consultants prepared maps of the area1 distributions of contamination for eight chemicals: 1,1 dichloroethylene, chloroform, 1,1,1 trichloroethane, trichloroethylene, methylene chloride, toluene, ethylbenzene, and benzene (Goldberg et al., 1980). In addition, they mapped the distribution of the sum of all the chlorinated hydrocarbons present, both horizontally and vertically. These maps form the basis of our estimates of the emission rates, other estimates being unavailable. The mapped distributions of organic compounds detected in multilevel installations were based on the highest observed concentration level, using data from one sampler per well. According to GZA, samples collected at single-level wells at various depths may not represent "worst-case" water quality conditions, nor typical conditions.

Lacking reliable information on the amounts of the chemicals in question emitted by the company's operations, we used concentration profiles of the aquifer developed by GZA to estimate emission rates. The methodology used to estimate the amount of each contaminant present in the aquifer is described in Appendix B. We calculated upper and lower estimates for five chlorinated hydrocarbons and three aromatic hydrocarbons, the compounds of interest in this risk assessment. Table 1 contains these source emission estimates (in kilograms, kg) and the relative percentage (by weight) of the compounds within the two classes of hydrocarbons. We estimate that between 1200 and 12,000 kg of chlorinated hydrocarbons are present in the plumes emanating from the emergency and primary lagoons, and between 400 and 4000 kg for the aromatics.

Although the upper estimates are inherently high, they are not necessarily upper bounds; these values come from measurements that show what is in the groundwater but not what is adsorbed onto the surface of ground materials and could be released if concentrations in the water diminish. If the movement of contaminants through the aquifer is very slow, and adsorption is negligible, these estimates could represent nearly the entire emissions inventory for the 1955 to 1979 period.

The estimations of the mean concentrations over 70 years of particular compounds in the well water were obtained by multiplying the 25-year mass totals by 70/25 (in columns 3 and 4 of Table 1) and then dividing them by 70 years' worth of flow into the wells: 2000 cubic meters/day x 365 days/year x 70 years = 50 million cubic

Table 1. Source Emission Estimations

Chemical	Weight percentage	Weight(kg)		Estimated 70-year mean concentration (ppb) of Assabet well water	
		Upper estimate	Lower estimate	Upper estimate	Lower estimate
Chlorinated hydrocarbons					
1,1 dichloroethylene	51%	6000	600	340	34
methylene chloride	30%	4000	400	220	22
chloroform	17%	2000	200	110	11
trichloroethylene	1%	100	10	6	0.6
1,1,1 trichloroethane	1%	100	10	6	0.6
Aromatic hydrocarbons					
benzene	25%	1000	100	56	5.6
ethylbenzene	42%	2000	200	112	11.2
toluene	33%	1000	100	56	5.6

meters. (See Table 1.) The lower estimates in Table 1 are generally within a factor of ten of the values that were measured in the wells in 1979. If steady-state ("fast transport") conditions obtain, one would expect the mean concentrations to match those measured in the wells. Our upper estimates may be higher than the values in the wells because: (a) steady-state has not been reached, (b) our approximations tend to overestimate the masses, or (c) chemical transformation of some of the species may have occurred. We will use the upper and lower estimates for our "slow transport" estimation procedure.

IV. TRANSPORT

Groundwater in the region flows generally south toward the Assabet River, with the natural flow perturbed by recycling of some of the water by Grace and by withdrawal of water by the Assabet wells. Appendix A discusses some of the geological and hydrological characteristics of the Sinking Pond Aquifer, where the Assabet wells are located. Locally, the water flows normal to the contours of equal well height, flowing parallel to the head gradient. Figure 2 shows the estimated contours developed by GZA for the situation in which the Assabet wells and the three company wells (WRG-1, WRG-2, and WRG-3) are flowing at their typical rates (see the figure key), with the water from the company wells being recharged to Sinking Pond and the secondary lagoon. From the flow contours, we have estimated a flow boundary line that separates the flow that goes to the Assabet wells from that which goes to the Assabet River (the eastern portion of the region).

Figure 3 shows the head contours for the situation that existed before 1970, when only the company's wells were operating. Although some of the flow would go to the company's wells, this recirculation only delayed the eventual emptying of contaminated water into the Assabet River.

As we have mentioned, Figure 2 shows the head contours and our estimated flow division for the situation in which the company and town wells are operating. We estimate that essentially all of the

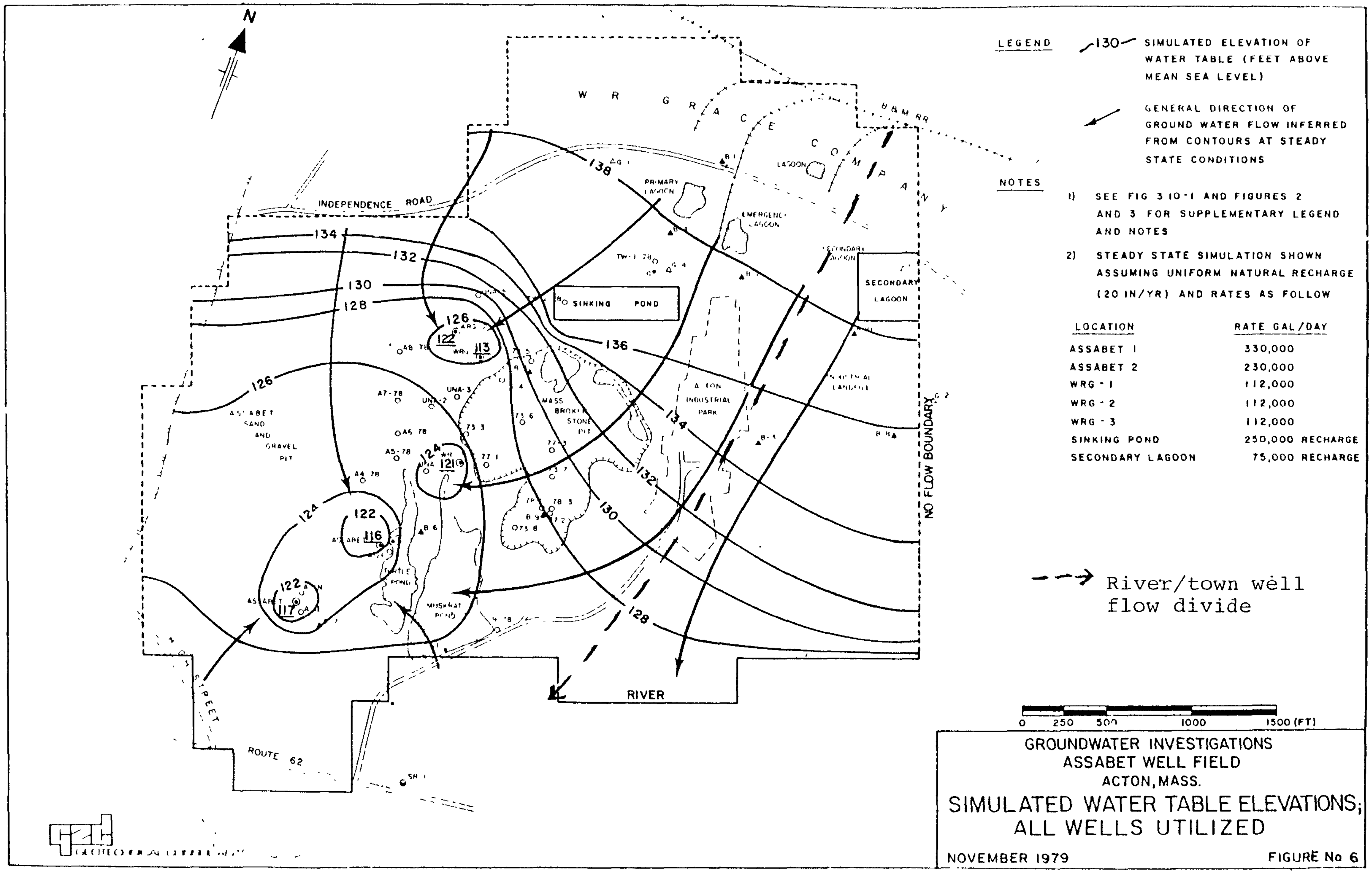


Figure 2. Estimated flow boundary line (Figure, taken from Goldberg et al, 1980, has been modified by author).

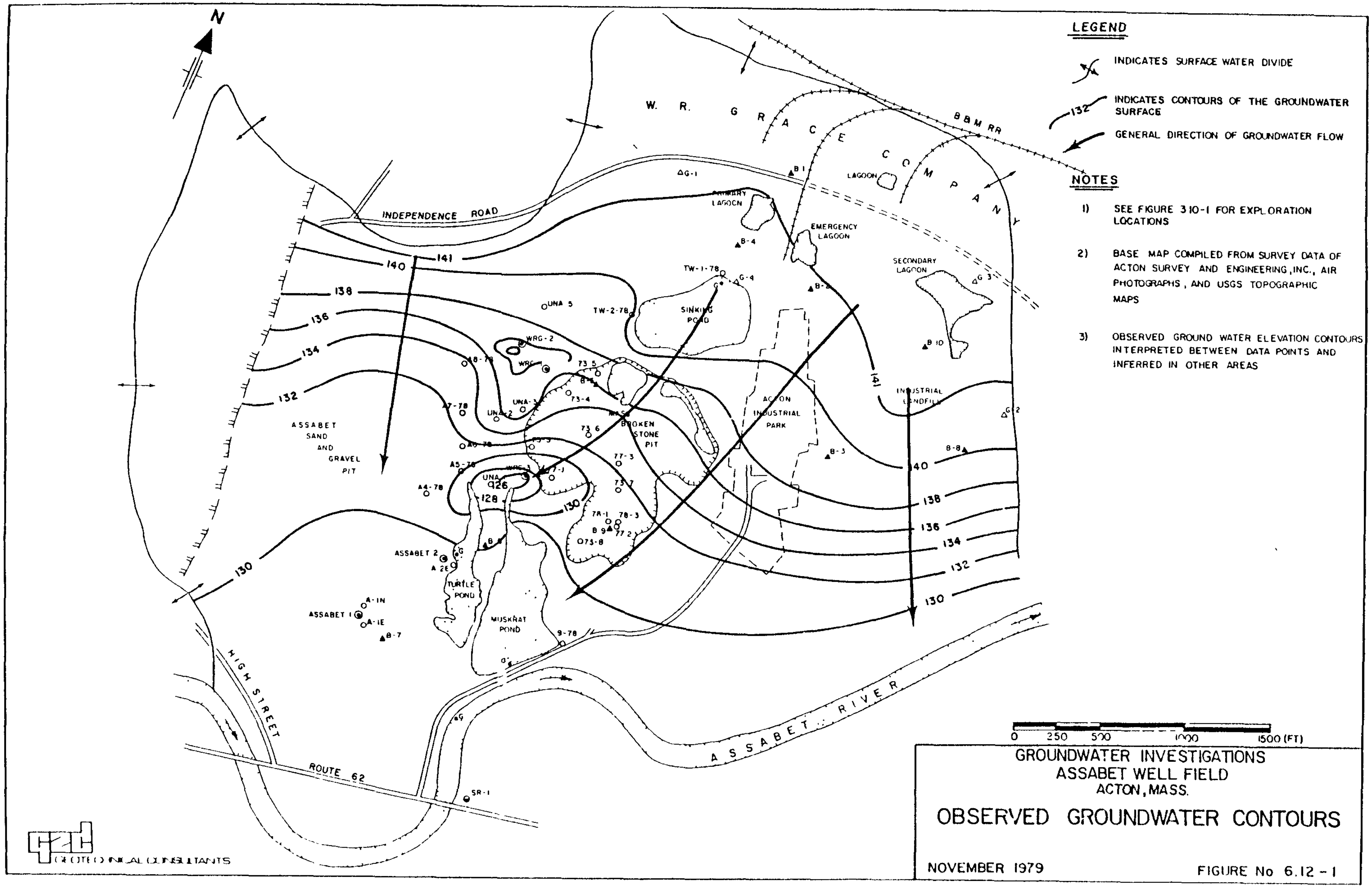
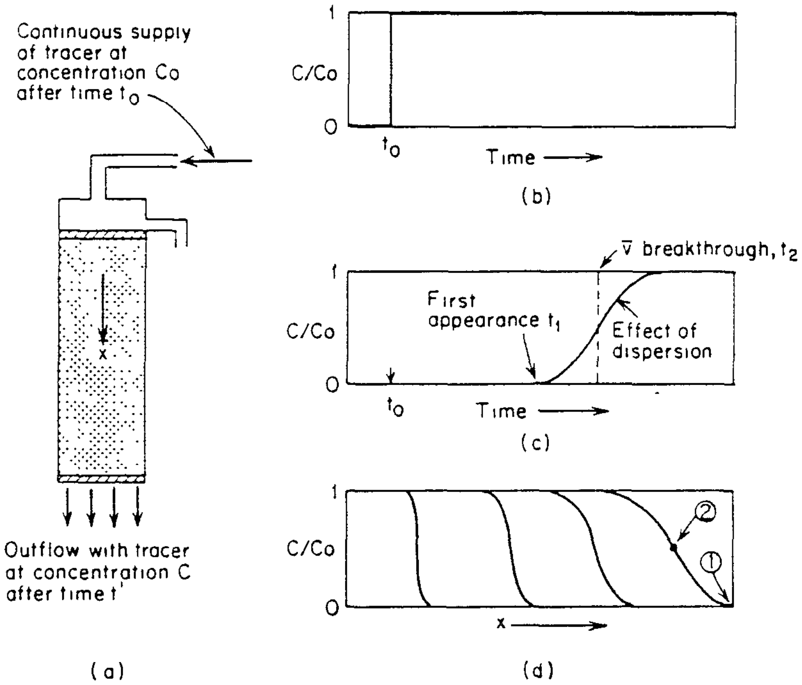


Figure 3. Head contours with only Grace wells in operation (Goldberg et al, 1980).

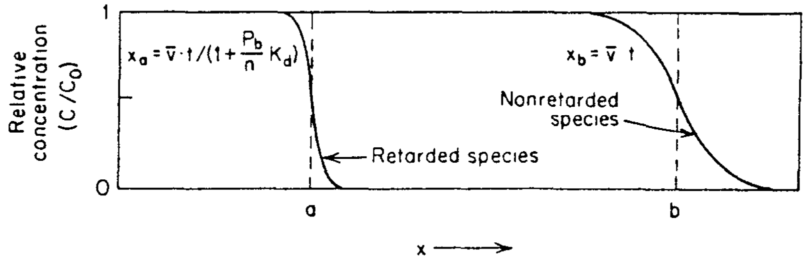
material from the primary and emergency lagoons eventually flows into the wells, unless it is irreversibly adsorbed or changed chemically during passage. We estimate that all or nearly all of the water flowing beneath the landfill eventually discharges to the Assabet River rather than to the town wells. Some of the water flowing under the secondary lagoon is likely to reach the town wells. Hydrogeological models often describe boundary regions with less accuracy than other areas, which means that the flow division in the vicinity of the secondary lagoon is particularly uncertain. GZA concluded that some of the material in the secondary lagoon might reach the Assabet wells. The conclusions of CDM (CDM, 1980) differed from those of GZA; CDM concluded that water flowing from the primary and emergency lagoons eventually empties into the town wells but that the secondary lagoon waters do not. In our risk estimation, we assume that secondary lagoon waters do not empty into the town wells, but rather empty into the Assabet River, where the material becomes sufficiently diluted so that it does not contribute significantly to the risk. (See Section V for more discussion of downstream effects.)

Figure 4, taken from Freeze and Cherry's <u>Groundwater</u> shows the general behavior of contamination in a system for which dispersion along the direction of flow is much greater than that perpendicular to flow, an approximation often appropriate for groundwater modeling. A source of concentration c_0 is started at time equal to zero and injects the contamination into a previously uncontaminated region. c_0 is the ratio of the mass rate of emissions to the volume flow rate of water containing the emissions. At any position downstream, the concentration, initially at zero, will



Longitudinal dispersion of a tracer passing through a column of porous medium. (a) Column with steady flow and continuous supply of tracer after time t_0; (b) step-function-type tracer input relation; (c) relative tracer concentration in outflow from column (dashed line indicates plug flow condition and solid and illustrates effect of mechanical dispersion and molecular diffusion); (d) concentration profile in the column at various times.

Figure 4. Contaminant Behavior (Freeze and Cherry, 1979)



Advance of adsorbed and nonadsorbed solutes through a column of porous materials. Partitioning of adsorbed species is described by K_d. Relative velocity = $1/[1 + (\rho_b/n)K_d]$. Solute inputs are at concentration C_0 at $t > 0$.

Figure 5. Retardation of Contaminant Movement (Freeze and Cherry, 1979)

increase to c_0, assuming no destruction of the chemical. There is a delay time that is characterized by the water's mean velocity divided into distance from the source. At any time, the relationship between concentration and distance is shown, with concentrations of c_0 until the vicinity of the break through zone, at a distance that is approximately the velocity multiplied by the time since the source was turned on. If the source were to cease, then these curves would have a trailing edge quite similar to the leading edge, giving a pulse shape broader at its base than at its top, but having the same total mass as the original input.

If no interaction occurs between the contaminant and the medium through which the groundwater is flowing, the characteristic velocity is simply the mean flow velocity, which is approximately equal to:

$$\overline{v} = (k/n)\,(dh/dx) \tag{2}$$

where k is conductivity (in length per time), (dh/dx) is the change of head per unit distance (length per length), and n is porosity. Hydraulic conductivities in the vicinity of Assabet wells No. 1, No. 2, and WRG-1 are, respectively: 150 ft/day, 110 ft/day, and 85 ft/day (Goldberg et al., 1980). The typical head gradient is 0.004 (Goldberg et al., 1980). Porosity averages around 0.25 to 0.40 for gravel and 0.25 to 0.50 for sand (Freeze and Cherry, 1979); we believe n is approximately 0.35. The above values produce estimates of 1 to 2 ft per day for mean flow velocities. The emergency lagoon is about 2800 ft from the Assabet well No. 2, meaning a travel time of about 4 to 8 years. The secondary lagoon is about 4300 ft from the Assabet well No. 1, resulting in a transport time estimate of 7 to 12 years.

The mean transport time estimates suggest that contaminants from the primary and emergency lagoon would have reached the Assabet wells in nearly full strength within the ten years the wells were operating.

Also important, however, is the effect of interactions between the chemicals and the material through which the groundwater flows. Figure 5 (Freeze and Cherry, 1979) shows the retardation of the velocity of contaminant movement that can result from such interactions; this behavior is analogous to that of a chromatograph, which uses interactive effects to separate chemical compounds. The contaminant velocity is generally between two values, $\bar{v}/(1+4K_d)$ and $\bar{v}/(1+10K_d)$, where K_d (the "distribution coefficient") ranges from 0 to 1000 milliliters per gram (mL per g); values of Kd much larger than 1 mL per g make the chemical almost immobile.

A decrease in concentration with distance from the source can be due not only to dispersion and retardation, but also to chemical transformation. For reactions having rates proportional to the concentration of the contaminant, one expects a decrease during travel of approximately exp(-kt), where t is time and k is the reaction rate:

$$dc/dt = -kc \qquad (3)$$

The exact treatment of this complex behavior is beyond the scope of this report. We assume that no chemical destruction of the contaminants takes place.

Figure 6 shows schematically the behavior of the contaminants at the town wells, under two different transport models: slow and fast. Concentrations in 1979 are assumed known (although actually a range of concentration values were obtained). Under our fast transport model that assumes 1979 concentrations represent equilibrium concentrations, we estimated the mean concentration of each compound to be half of the maximum concentration measured in 1979. Since the lowest concentration values were typically too small to be detected, virtually zero, this choice of half the maximum corresponds to use of the mid-range as the statistic to characterize the mean concentration (unknown). If the distribution of concentrations had a standard deviation much smaller than the mean, the mid-range would tend to underestimate the mean, if based on a few measurements (<10). If the distribution has a standard deviation that is large compared with the mean and if many measurements (>10) were made, then the mid-range would be expected to over-estimate the mean. Two underlying assumptions of the fast transport model are: (1) the 1979 concentrations existed from the time the well was first used (probably an overestimate), and (2) the 1979 concentrations represented maximum concentration levels at the wells over their period of use.

Table 2 shows concentration values measured in the town wells and at several other locations by GZA (Gardner and Ayres, 1980). If a transport time estimate of 5 years is correct, then the concentrations in the wells in 1979 are about what one would expect to continue for the life of the company plants. In this case, a "fast transport" estimate of risk is made by assuming that these

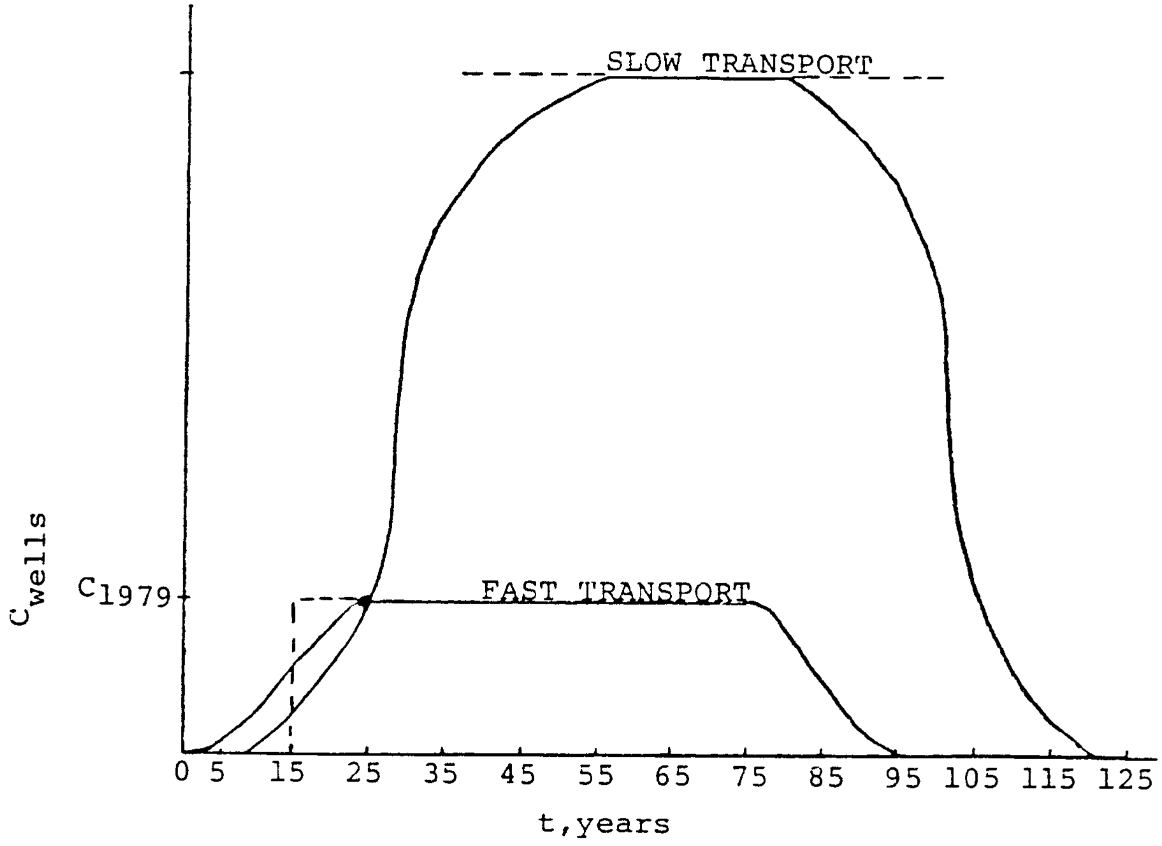


Figure 6. Schematic of Concentration Levels Versus Time Since the Lagoons Were First Used for Two Transport Assumptions

Table 2. Maximum Concentrations of Organic Chemicals Found at Selected Locations

Compound of Intrest	Concentration in ppb Detected at:								
	Town Wells		Industrial Wells			Waste Water Lagoons		Sinking Pond	River
	1	2	1	2	3	Primary	Secondary		
1,1-dichloroethylene	1-10	56	1-10	-	62	4900	1300	1-10	-
Benzene	-	1-10	-	-	1-10	-	-	-	-
Methylene Chloride	1-10	1-10	-	-	180	800	720	-	36
Toluene	-	1-10	≥1	-	-	-	-	-	-
Trichloroethylene	1-10	-	-	-	-	4500	1900	≥1	23
1,1,1-trichloroethane	1-10	-	-	≥1	-	-	-	-	-
Chloroform	-	≥1	-	≥1	58	220	76	-	-
Ethylbenzene	1-10	1-10	-	-	-	15000	14000	-	-
Chlorobenzene	-	1-10	-	-	-	-	-	-	-

concentrations continue for 70 years. If the company's operations diminished or ceased within 70 years, less material than we expected would reach the Acton population; the opposite would be true if operations expanded.

As Figure 6 also shows, if the transport is relatively slow, the concentrations in 1979 could be much less than those reached later. As we have noted, the mass from an input pulse of a chemical that is not irreversibly adsorbed nor destroyed should eventually pass through the flow system. Our slow transport model assumes that a 1979 concentration is part of an increasing concentration pattern. As mentioned in section III, our "slow transport" estimates of concentrations in well water are derived by taking the total mass we expect to be emitted (of each species) over 70 years and dividing it by the total well flow for the 70 years.