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May 1980

Economic Measurement of Environmental Damages

Frank Krawiec

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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PREPARED UNDER TASK NO. 5326.10

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PREFACE

This research report was prepared as part of the SERI research activities on environmental benefits and costs of solar energy for the Division of Energy Technology of the U.S. Department of Energy. Organized into nine sections, it will review economic damages from air and water pollution in urban areas of the United States on human life, health, outdoor recreation, household soiling, materials, vegetation, production, and aesthetics. First, the methods for estimating environmental damages are examined. Then, damage functions relating physical and economic damages from water and air pollution on demographic, socioeconomic, and climatological variables are presented. Finally, the national gross damages of air and water pollution in the urbanized United States are discussed. The review ascertains whether present models that translate pollution level estimates provided by the Strategic Environmental Assessment System model into dollar damages can be improved.

Al Shaheen assisted in collecting voluminous literature on the subject. Also, the work could not have been completed without the contribution of Thomas E. Waddell and Wayne R. Ott of the Environmental Protection Agency and William Watson of Resources for the Future, Inc. Dennis Costello, Ronal Larson, Kathryn Lawrence, Dennis Schiffel, and Michael Yokell of SERI provided technical support.

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SUMMARY

OBJECTIVE

The objective of this research report is to review the literature on physical and economic damages from air and water pollution in urban areas of the United States on human life and health, outdoor recreation, household soiling, materials, vegetation, production, and aesthetics.

DISCUSSION

This study reviewed numerous research reports on the social value of pollution abatement. The methods for estimating environmental damage from air and water pollution were of primary concern. In reviewing literature, the author also focused on: (1) damage functions relating physical or economic damages from water and air pollution on demographic, socioeconomic, and climatological variables; (2) the limitations in estimating the physical damage functions; and (3) the national gross damages of air and water pollution in U.S. urban areas. The estimation resulting from reduction of water pollution damages to life and health, outdoor recreation, property value, and production were examined. The literature is reviewed on (1) major pollutants and their physical impacts on different groups at risk, and (2) methods for determining the economic impact of these damages. Functional relationships between water quality parameters and human behavior are emphasized in the review. A number of studies on air pollution damages to life and health, aesthetics, vegetation, and materials are included in the report. Specific diseases (bronchitis, emphysema, asthma, respiratory infections, heart disease, cancer of the respiratory and digestive tracts, and chronic nephritis) attributable to total suspended particulate matter, sulfur oxides, nitrogen oxides, oxidants, carbon menoxide, and hydrocarbons were discussed. The aggregate effect of all air and water pollutants is summarized in this study.

CONCLUSIONS AND RECOMMENDATIONS

National gross damages of air pollution of $20.2 billion and of water pollution of $11.1 billion for 1973 are substantial. These best estimates, updated for the economic and demographic conditions, could provide acceptable control totals for estimating and predicting benefits and costs of obtaining air and water pollution emissions. The economic techniques for evaluating benefits resulting from air and water pollution abatement are well developed. The major issues to be resolved are: (1) lack of available noneconomic data (dose-response function), (2) theoretical and empirical difficulties of placing a value on human life and health and on benefits such as aesthetics, and (3) lack of available demographic and economic data.

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SECTION 1.0

INTRODUCTION

1.1 BACKGROUND

Air and water pollution is a major environmental problem affecting life and health, outdoor recreation, household soiling, vegetation, material, and production. Numerous studies have assessed the physical and monetary damage to populations at risk from excessive concentrations of major air and water pollutants—sulfur dioxide, total suspended particulate matter, oxidants, and carbon monoxide in air; and nutrients, oil, pesticides, and toxic metals and others in water. The measurement of the damages is one of the most controversial issues in pollution abatement.

The increasing population—its densities, energy consumption, and economic development—significantly intensifies environmental degradation. Society has been forced to recognize that clean air and water are scarce resources. One way to minimize air and water pollution is to control either the emission source or the materials that generate the pollution. This requires, either explicitly (pollution control methods) or implicitly (foregone output), the use of scarce and alternative resources. The question is: To what pollution level should the emitter be required to control pollution output? The economic answer is: That point at which the incremental expense to emitters for control of pollution is equal to the incremental savings to society because of the reduction in pollution. If society desires to improve its well-being, it must apply to the use of air and water the same efficiency criteria that the private sector has traditionally applied to the allocation of other scarce goods.

The effects of air pollution are classified as follows:

- harm to human life and health;
- damage to vegetation;
- deterioration of materials;
- soiling of residential and commercial properties; and
- reduction of visibility and other atmospheric consequences.

The effects of water pollution are classified into four categories:

- harm to outdoor recreation;
- injury to human life and health;
- impairment to production; and
- damage to property.

1.2 PURPOSE AND SCOPE

The purpose of this research report is to review the literature on physical and economic damages from air and water pollution in urban areas of the United States on human life and health, outdoor recreation, household soiling, materials, vegetation, production, and

aesthetics. Of primary concern in determining the social value of pollution abatement are the methods for estimating environmental damages, which will be discussed first. Then, damage functions relating physical or economic damages from water and air pollution on demographic, socioeconomic, and climatological variables are presented. The limitations in estimating the physical damage function and its translation into economic terms are explicated. Finally, the national gross damages of air and water pollution in U.S. urban areas are discussed. The review ascertains whether present models, which translate pollution level estimates provided by the Strategic Environmental Assessment System (SEAS) model into dollar damages, can be improved.

SECTION 2.0

METHODS OF ASSESSING ENVIRONMENTAL DAMAGES

2.1 OVERVIEW

Researchers have isolated three approaches to placing monetary values on air and water pollution damages: (1) chain of effects, (2) market study, and (3) survey. These methods are discussed in the proceedings of a workshop summary on economic measurement of energy-related environmental damages (Yokell 1978).

2.2 CHAIN OF EFFECTS METHOD

The most widely used method, the chain of effects, assigns economic values to pollution, determined by physical or biological damage functions. The damage functions are derived as follows: (1) from experimental data by observing objects in conditions simulating their natural environment; (2) from estimates of the physical or biological damage function that relates damage to pollution levels; (3) from translation of the physical damage function into economic terms; and (4) from extrapolation of the function to the population, using appropriate coefficients, if an aggregate damage is desired (Waddell 1974).

Because of the lack of ambient data for air and water, the development of physical or biological damage functions is difficult. The following major problems can affect the accuracy and reliability of the benefits estimates derived using this method:

- Data on ambient air and water quality are very poor.
- Monitoring stations are limited in number.
- Data represent average values, and dose-response relationships may be different for acute and chronic effects.
- Controlled laboratory conditions usually have little resemblance to world conditions.

Because of inadequate damage functions, the damage factor approach is used to estimate the proportion of a damage category caused by air pollution. The estimates of air pollution damage are determined by applying the proportionality factor to the damage category.*

Often, proxy or surrogate measures are required to estimate air and water pollution damages. Damages to health, recreation, aesthetics, or mental health are aspects often neither privately owned nor exchanged through market transactions. Thus, they are not assigned adequate costs by the market system. "Given these limitations, the chain of effects method has been most widely used. And given the adaptability of the method of focusing on a single receptor and effect, the studies are quite amenable to the development of gross damage estimates" (Waddell 1974).

*Examples of this damage are given by Lave and Seskin (1977).

2.3 MARKET STUDIES

Although there is no explicit market price for the amenities of clean air, two market approaches—property value studies and wage rate studies—are widely used to ascertain the value people place on clean air.

In property value studies, air and water pollution damages are measured by market valuation of property in polluted relative to "clean" areas. The willingness to pay for clean air is inferred from prices in the housing market. The approach is based on the assumption that people will pay more for a house located in an area with good air quality than in an area with poor air quality.*

The second market study approach uses wage differentials among urban areas to infer the willingness to pay for clean air. It is based on the assumption that households will accept a lower wage to work in an urban area in which the air quality level is relatively clean than in an area where air is of poor quality. Examples of this wage rate approach are given by Nordhaus and Tobin (1972), Salman (1970), Waddell (1974), Smith (1976), and Rubenfeld (1977).

Many difficulties are associated with property value studies and wage rate studies.** First, the benefit estimates suggest aesthetic and tangible consumer values of locating in better environments. Some portion of the benefit estimates obtained by analyzing property values should be added to those associated with material damage, vegetation damage, or even health damage. The effects of air pollution from cleaning, maintenance, material life, and the general value of property, although significant, are difficult to separate. Second, to reflect accurately the effects of air pollution, housing markets must function in equilibrium, although since its value represents complex attributes and property does not often change ownership, the market rarely operates in equilibrium. Third, for the property value approach to be valid, buyers must know that pollution differs at various sites. Fourth, a high degree of intercorrelation among air pollutants makes it extremely difficult to separate the economic damages owing to the individual air pollutants. The presence of one pollutant often indicates the presence of others. Therefore, pollutants measured by these variables may not be causative agents but surrogates for others that produce damage. Fifth, it is extremely difficult to explain buyer preferences and behavior (e.g., transportation costs, quality of schools).

2.4 SURVEY METHODS

Opinion surveys of air pollution sufferers help one to understand how attitudes about pollution are shaped by changes in the environment. In his study on the economic damages of air pollution, Waddell (1974, p. 31) states:

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*This approach is discussed in detail by Ridker and Henning (1967, pp. 246-257), Crocker (1971), and Smith (1976).

**For an excellent explication of the problems of applying market data (property values) to estimate economic benefits from air quality improvement, see National Academy of Sciences (1974) and Smith (1976).

Opinion surveys have shown particular usefulness in understanding: (1) how attitudes about air pollution are formed and then affected by changes in air quality; and (2) what people do and do not perceive as air pollution effects. This method can also provide some insight into what people might be willing to pay for improvement in the air environment, or perhaps, what their demand might be for the reduced risk of experiencing certain adverse effects.

To be effective, a survey must assume that people know the effects of air pollution. The usefulness of the opinion survey can be summarized as follows: (1) it indicates the sufferer's understanding of the nature and extent of air pollution, and (2) this information can be used to improve sufferer knowledge enabling him to make more complete adjustments so that the air pollution damage function will change.

From surveys of legislative decisions or litigation awards one can derive information on air pollution damages. Three objectives of this approach are: (1) locate and report litigation that indicates the cost of air pollution; (2) determine the extent to which the residents of a given urban area have turned to the courts for redress; and (3) evaluate judicial data as estimators of damage functions.*

Other important surveys are the delphi method and the bidding game. The delphi approach, also called the subjective decision-making method, uses the the knowledge and professional experience of a diverse group of experts to quantify variables that are either intangible or uncertain (Pell 1973). Although this method can provide quick answers, its results are of little pragmatic value because it is subjective. A good example of this approach is given by the U.S. Department of Agriculture in estimating crop losses resulting from air pollution (USDA 1965).

The bidding game approach is also used to assess residents' and visitors' willingness to pay for a change in environment. People are asked (1) how much they are willing to pay to prevent a deterioration in the environment or (2) how much compensation they would accept to allow a deterioration in the environment (Schulze 1978). The results are subjective because:

- Thinking his bid will influence a decision, the bidder adjusts his bid to enforce his preference.
- The bids are affected by the manner in which the investigators ask questions.
- Participants tend to bid far more for environmental improvement than they could afford or would pay because they do not actually pay the amounts bid.
- As in any case of negative externalities, those affected by pollution often feel that they should not have to pay for the actions of others. Therefore, it is unlikely that the willingness to pay for environmental improvement will be equal to compensation required to maintain equal utility levels.

*For the discussion of this conceptual approach, see Waddell (1974).

SECTION 3.0

WATER POLLUTION DAMAGES

3.1 OVERVIEW

The economic damages from water pollution are substantial. This section discusses the estimation of benefits resulting from reduction of water pollution damages to life and health, outdoor recreation, property value, and production. The literature is reviewed on (1) major pollutants and their physical impacts on different groups and (2) methods for determining the economic impact of these damages. Functional relationships between water quality parameters and human behavior are emphasized in the review.

3.2 ASSESSMENT OF WATER POLLUTION DAMAGES

Tihansky (1973) gives the most useful review of estimated benefits of water pollution control.

> From an original collection of almost 200 studies, approximately 60 are selected as contributing the most. Less than 30% of them are theoretically valid. Even fewer seem cognizant of the applicability or the existence of welfare economics . . . if only recreational studies are considered, fewer than 10% follow from theory. . . . Although there is no theoretical basis for most benefit values, equally discouraging is the paucity of empirically derived damage functions. Only 20% of the surveyed literature derives dose-response relations from on-site data. With recreation studies, this proportion decreases to 10%.

The literature contains numerous estimates of the economic impact of polluted water. Some of these results are useful in calculating regional and national benefits of the reduction of water pollution damages. A brief review of empirical studies on the benefit estimations by the population at risk follows.

3.2.1 Damage to Outdoor Recreation

There are numerous studies of the adverse effects on outdoor recreation from the most important water pollutants—fecal coliform, biological oxygen demand (BOD), salinity, toxic substances, and temperature. Heintz, Hershaft, and Horak (1976), Jordening (1974), and Tihansky (1973) provide excellent reviews of the most important studies.

Analyses of the impact of water pollutants have concentrated on the most popular outdoor activities such as swimming, boating, and fishing. These activities are strongly affected by the quality of the water. In calculating damages to outdoor recreation, the following variables are of great importance: (1) changes in water quality, (2) recreationist reaction to changes in water quality, (3) value of recreation experience, and (4) number of recreation days.

Opinion surveys of water pollution sufferers have been particularly helpful in understanding how attitudes about pollution are governed by changes in water quality. This method has been applied by Ditton and Goodale (1972), Ericson (1975), the U.S. Fish and

Wildlife Service (1972), and the U.S. Bureau of Outdoor Recreation (1972) to estimate the willingness of sufferers to pay for an improvement in the quality of water. The two most important conclusions of these studies are:

- Not all current recreation (i.e., boating, fishing, and swimming) users shift to alternative waterways when water quality changes. Some would discontinue these water-based recreational sports entirely. A small proportion reported that they would stay in the same location but participate less (Ditton and Goodale 1972).
- Individuals are willing to pay an average of $5.75 per day of water-based recreation to avoid the worst polluted water, although the value varied by the income level of the individuals (Ericson 1975).

These two conclusions are generally supported by the results of the 1970 U.S. Fish and Wildlife Service (1972) survey of hunting and fishing and the National Recreational Survey conducted by the Bureau of Outdoor Recreation during September 1970.

"The expenditure method of determining the value of recreation which equates benefits and expenditures, though of questionable validity, provides an alternative method of estimating outdoor recreation benefits" (Heintz, Hershaft, and Horak 1976). It has been applied by Owens (1970) and Burt and Brewer (1971). In his outdoor recreation study Owens (1970) found that: (1) recreationists travel farther to go on camping trips than to go swimming, (2) the speed of travel for recreation is closely associated with distance, and (3) highest average speeds are for the longer trips.

Heintz, Hershaft, and Horak (1976) estimated the 1973 damage to outdoor recreation and concluded that if water pollution was not controlled 41% fewer waterways would be available for recreation. Table 3-1 presents the 1973 estimates for outdoor recreation. The increased costs are based on a study by Ericson (1975) showing that a 20% change in water pollution can be expected to result in a 20 to 24% damage in travel to engage in water-based recreation. The damages were estimated for the 41% change in travel costs associated with the 41% change in waterways suitable for recreation. These are based on travel mileage for various types of recreation, average speeds, and vehicle costs statistics.

Ditton and Goodale (1972) showed that the cost increases caused by pollution would result in a 39% decrease in total days spent fishing, boating, and swimming. Using their data, an increase in the cost of recreation was estimated as a result of a decrease in use of the waterways.

The decreased value of recreational experiences owing to lower water quality is based on Ericson's (1975) willingness to pay $5.75 per recreation day to avoid polluted water; and the Ditton and Goodale (1972) estimate pointing out that 21% of existing users would experience higher value recreation if pollution were reduced by 1%.

3.2.2 Damage to Health

The health effects of water quality have been investigated for many years and have influenced the development of water treatment technologies. Microbiological inorganic chemicals, organic chemicals, radioactivity and physical water pollutants affect human health and life through public water supplies, food chains, transmission of communicable

Table 3-1. POTENTIAL ANNUAL ECONOMIC DAMAGES TO RECREATIONAL USERS FROM WATER POLLUTION FOR 1973[a]

($ million)

Recreation Activity	Recreation Days, 1973 (million days)	Increase in the Price of Existing Reaction Activity		Decrease in Recreation Activity Resulting from Higher Prices		Shift to a Lower Value Recreation Experience		Total	
		Range	Best	Range	Best	Range	Best	Range	Best
Fishing	776	781-2,240	1,510	178-512	345	236-2,360	906	1,200-5,110	2,760
Boating	434	360-1,020	686	51-143	96	238-2,380	913	649-3,540	1,700
Swimming (nonpool)	1,162	312-1,110	710	53-188	120	1,239-2,390	915	604-3,690	1,750
Waterfowl hunting	27	32-88	60	7-20	14	15-148	32	54-256	106
TOTAL	2,400	1,490-4,460	2,970	289-863	576	728-7,280	2,770	2,510-12,600	6,320

[a]Heintz, Hershaft, and Horak 1976, Table III-3, p. III-8.

diseases, and bodily contact. Major diseases from water pollution include infectious hepatitis, malaria, leptospirosis, congenital heart anomalies, mercury poisoning, cadmium poisoning, alteration of liver functions, and acute myocarditis and pericarditis.

Heintz, Hershaft, and Horak (1976) reported that approximately $644 million of damages could have been avoided in 1973 through reduction of bacterial and viral pollutants. This estimate is based on empirical studies by Liu (1970), Craun and McCabe (1971), Lackner (1976), and Sokoloski (1973) who reported crude cost estimates of the illnesses including the costs of treatment and of foregone compensation.

The Heintz, Hershaft, and Horak (1976) report of national damages to human life and health does not include the estimate of the damage from cancer. Page et al. (1976) reported that about 5% of cancer incidents could be attributed to carcinogens in drinking water obtained from a surface water source. Cooper and Rice (1976) estimated costs for all cancer cases, as measured by health care costs and foregone income, to be $20 billion per year. Hence, the damage from cancer due to water-borne carcinogens is approximately $1 billion.

3.2.3 Damage to Production

Water supply use affects input costs, final product prices, income redistribution, and international trade. Production impacts of water pollution include all raw material refinement, treatment and substitution, and process changes necessitated by deteriorating water quality. The effects of pollution on production also extend to all agricultural, municipal, and industrial structure changes; resulting capital losses; employment impacts; and relocation losses resulting from environmental degradation and mandatory pollution abatement standards.

The major pollutants most damaging to municipal water supplies, households, industry, agriculture, commercial fisheries, and materials are:

- physical constituents (color, odor, turbidity, temperature);
- microbiological organisms (coliform organisms, fecal coliforms);
- inorganic chemicals (alkalinity, ammonia, arsenic, barium, iron, lead, sulfate, fluoride, hardness, dissolved oxygen, pH, total dissolved oxygen, zinc, and many others);
- organic chemicals (pesticides: aldrin, chlordane, endrin, organic phosphates, carbamates, heptachlor; oil and grease; carbon chloroform extract; cyanide; herbicides).

Bergman and Lenormand (1966) estimated that national damages to municipal water supplies were between $1.18-10 million. They estimated industrial water-uses loss by using pollution-related treatment costs per thousand gallons and industrial water-use data for the year of the estimate. Unger et al. (1974) applied the consumer price index to Bergman and Lenormand's estimate of pollution-related treatment costs per thousand gallons and municipal water treatment data and estimated 1974 benefits.

A Barker and Kramer (1973) study found the cost of industrial treatment for man-made pollutants to be approximately four cents per thousand gallons.

The agricultural benefits from increased water quality were based on data relating water quality, cost of land, and sediment removal costs. Agricultural damages from the sediments and the increased salinity were reported by the Dow Chemical Company (1972), U.S. Department of the Interior (1974), and Kleinman et al. (1974).

Tihansky (1973) estimated the total annual damages to domestic water use by U.S. residents in 1970 to be in the range of $0.65-$3.45 billion, with the mean being $1.75 billion (i.e., $8.60 per person annually). These estimates were generated as follows: (1) physical damages and the associated water quality determinants were identified, then the physical effects were translated into economic losses; (2) damage functions were formulated to predict water quality changes on each household unit affected; (3) a computer program based on these functions was designed to estimate total damages per typical household and to aggregate them over selected regions; and (4) the program was applied to state-by-state data describing water supply sources and socioeconomic parameters. This is the primary source of the estimated damages to household appliances and personal items from chemicals and other constituents of the water (hardness and total dissolved solids, chlorides, sulfates, acidity).

The U.S. Environmental Protection Agency (1972) annual report provides information on the fish kill's location by state and source of pollution by sector.

Heintz, Hershaft, and Horak (1976) estimated the national damages from water pollution in production activities to be $1.6 billion in 1973. Table 3-2 presents these damages by category.

Table 3-2. ESTIMATED NATIONAL PRODUCTION DAMAGES ATTRIBUTED TO WATER POLLUTION FOR 1973[a]

($ billion)

Damage Category	Best Estimate	Range Low	Range High
Municipal	0.41	0.34	0.47
Industrial	0.30	0.22	0.37
Agricultural	0.07	0.05	0.08
Commercial Fisheries	0.10	0.02	0.14
Domestic	0.35	0.13	0.69
Materials Damage	0.42	0.32	0.53

[a]Heintz, Hershaft, and Horak 1976, Table III-4, p. III-18.

Heintz's findings of national damages to production from water pollution were calculated as follows.*

Treatment costs of five cents per thousand gallons of removing man-made pollution were assumed. As a result, the estimate for 1973 was $0.41 billion.

*Details of these estimations are provided by Heintz, Hershaft, and Horak (1976).

Total industrial damage was estimated to be $0.215 billion in 1973 and included $0.29 billion of damage costs of water pollution from volumes of water treated in 1973 and $1.6 million damage costs of water pollution from water used for cleaning pollutants from boilers and cooling towers. The pollution treatment costs of four cents per thousand gallons of self-supplied water were used.

The agricultural damages estimate primarily resulted from sediments. It was calculated in 1973 at $66 million on flood plains, irrigation ditches, and hydroturbines.

Estimates of total damages to marine and fresh water commercial fisheries were $102 million and consisted of $53 million of losses to commercial fisheries from decreased catch, increased costs, and decreased quality of fish, plus $49 million damages from water pollution that can be reduced through pollution control. In estimating damages to marine fisheries, the demand function was used to assess the impact of decreased catches on the price of fish to consumers.

Adjusted for inflation and population growth since 1970, the date of the original estimates, the 1973 estimate of harm to households from water pollution was $346 million.

The 1973 total estimate of damage to materials used in other production was $420 million. The primary category was navigations with an estimated $167 million annual loss in 1973. The costs result from increased maintenance and replacement for structures and vessels exposed to polluted water and from dredging sediments from inland navigation channels and harbors. The estimate of harm caused by sedimentation to water storage, vessels, and other waterborne equipment was $253 million in 1973.

3.2.4 Property Value Damages

Property value losses from water pollution not included in estimated material damages were calculated by Heintz, Hershaft, and Horak (1976) at approximately $84 million in 1973. These estimates were based on the Dornbusch and Barrager (1973) analysis of the variation in property value owing to location near waterways with improved water quality; property values within 4,000 ft of waterways increased from 3 to 5% as a result of pollution abatement. But the estimate of annualized damages, adjusted to reflect increases in property values, was substantially duplicative of estimates for other damages (i.e., outdoor recreation). This double-counting (i.e., the degree to which these measured benefits overlap the benefits obtained from other studies) is a very important issue. Most of the empirical studies reviewed in this chapter tried to obtain reasonable statistical bounds for property value benefits of improved water quality and to see to what extent these benefits can be attributed to improvements in specific pollutant levels. The reliability of these estimates is debatable. The literature review concluded by Heintz, Hershaft, and Horak (1976, p. III-24) pointed out that property value damage should be considered at this time as a confirmation of the damage of pollution but not as a source of additional damage estimates.

3.3 NATIONAL GROSS DAMAGES

Based on diverse studies reviewed, Heintz, Hershaft, and Horak (1976) estimated national damages of water pollution for 1973 to be about $10.1 billion. For each category, the best measure of damages was selected and updated for changes in prices, economic activity, population, and other variables. Heintz also presented each category's low and high limits, which reflect the substantial uncertainty of the best estimate. Table 3-3 shows the estimates of national damages from water pollution in 1973.

Table 3-3. ESTIMATED NATIONAL DAMAGES OF WATER POLLUTION FOR 1973[a]

($ billion)

Damage Category	Best Estimate	Range Low	Range High
Outdoor Recreation	6.3	2.5	12.6
Aesthetics and Ecology	1.5	0.6	2.8
Health	0.6	0.3	1.0
Production (including municipal, industrial, agricultural supplies; commercial fisheries and materials damage)	1.7	1.1	2.3
Total	10.1	4.5	18.7

[a]Heintz, Hershaft, and Horak 1976, Table III-1, p. III-1.

Heintz, Hershaft, and Horak (1976, p. III-2) believe, "Despite the difficulties met in developing national damage estimates for water pollution, the $10.1 billion estimate represents a useful indication that the damages are substantial."

If costs of $1 billion per year for health care and foregone income as a result of increased incidence attributed to carcinogens in drinking water obtained from surface water sources are added to the estimates provided in Heintz, Hershaft, and Horak (1976), the new estimated national water pollution damages come to $11.1 billion.

3.4 SUMMARY

Although there are numerous empirical studies on benefit cost analysis of water pollution, the results are limited. Stevens in Hershaft (1977) summarizes problems associated with empirical estimation of water pollution control benefits:

> The lack of adequate, generalizable behavioral relationships between water quality and consumer behavior, and hence, willingness to pay for quality improvements, is thus the predominant problem in assessing pollution control benefits. There is simply inadequate knowledge concerning why people "consume" leisure-type environmental activities, and especially how changes in water quality (objective and/or perceived) affect these consumption activities. Some creditable work has been done in estimating recreation benefits from pollution control in small areas, but extrapolation of these studies to national aggregates is not currently possible with any degree of precision. The monetization of aesthetic and option demand is, at present, even less well developed than for active recreation uses.

SECTION 4.0

AIR POLLUTION DAMAGE TO HUMAN LIFE AND HEALTH

4.1 OVERVIEW

During the past decade the public has become cognizant of the mortality and morbidity attributable to deteriorating air quality.* The best documented and defined health indicator, mortality, is the increase in deaths resulting from increased contamination in the air. Specific diseases associated with air pollution are bronchitis, emphysema, asthma, respiratory infections, heart disease, cancer of the respiratory and digestive tracts, and chronic nephritis.

In estimating the health effects of air pollution, the pollutants that result in mortality and morbidity must be specified. The pollutants include total suspended particulate matter (TSP), sulfur oxides (SO_x), nitrogen oxides (NO_x), oxidants (O_x), carbon monoxide (CO), hydrocarbons (HC), and radiation. The air pollution variable used as a surrogate for dose may be measured directly as concentration ($\mu g/m^3$) or estimated as emissions ($tons/mi^2$). Exposure to almost all pollutants in sufficient concentrations and for long enough periods can result in harmful physiological effects.** Unfortunately, there are no satisfactory methods of allocating the observed damages among a number of synergistically interacting stresses of air pollutants, nor can the damages be easily measured and reduced to economic terms (Waddell 1974).

Total suspended particulate matter affects human health by its chemical composition and size. For example, SO_2 acting as a surrogate for all damaging sulfur compounds in the atmosphere requires a carrier, such as particulate matter, to enter the body. Sulfur dioxide carried on particulate matter can impair lung tissue. Particles smaller than two or three microns can penetrate the respiratory system. When a multiplicative interaction term between SO_2 and total suspended particulate matter is used in a regression analysis of mortality and morbidity, the coefficient of this synergistic variable is predominantly positive and significant (Waddell 1974).

Photochemical smog is composed of oxidant pollutants like ozone (O_3) and peroxyacetylnitrate (PAN) derived from the interaction of NO_x and HC in the presence of sunlight. Hydrocarbons are associated with eye irritation. Aldehydes irritate the eyes and upper respiratory tract. The elevated levels of CO in the ambient air subtly affect the cardiovascular and central nervous systems.

Research has shown that SO_x, NO_x, and HC all break down to the particulate state. Thus, any individual particulate air quality measurement might also represent those pollutants that were originally emitted as gases. This complicates the estimation of health effects by pollutants. Also, these pollutants act synergistically to cause damage that might not result from the separate pollutants. It is difficult to weigh the effects of the

*For a detailed discussion on the effect of air pollution on health, see Riggan et al. (1976) and Schrimper (1975).

**These are discussed in great detail in U.S. Department of Health, Education, and Welfare (1969, 1970a,b,c), American Association for the Advancement of Science (1965, No. 85), National Tuberculosis and Respiratory Disease Association (1969).

pollutants that may be harmless alone but become harmful in the presence of other pollutants.

In chemical reactions of pollutants, meteorological conditions can act independently of or with air pollution to place additional stress on the body. Cassell (1966) reported that many past air pollution disasters (Meuse Valley, Belgium, 1930; Donora, Pennsylvania, 1948; Sondom, 1952 and 1962; and others) were characterized by prolonged, anticyclonic high pressure with a secondary inversion. An inversion acts as a lid, retaining all air pollution emissions. Air pollutants build up, and a minor problem can become a severe episode if meteorological conditions persist.

Studies by Jaksch and Stoevner (1974), Lave and Seskin (1977), Winkelstein (1967), and others indicate that personal characteristics (smoking and drinking habits, occupation, marital status) and socioeconomic-demographic characteristics (household income, race, sex, age) significantly affect incidence of some diseases sensitive to pollution. Adverse health effects of air pollution result in economic losses of unknown magnitude that stem from (1) the medical costs incurred in treating the disease, (2) the value of the ill person's foregone production, (3) the value of mortality changes based on the present value of future income, and (4) the costs of suffering (Jaksch and Stoevner 1974; Waddell 1974).

4.2 REVIEW OF INDIVIDUAL STUDIES

4.2.1 Episodic Studies

A number of studies have estimated human mortality changes associated with extremely high levels of air pollution. Studies by Wilkins (1954) and Scott (1963) have supported the hypothesis that exposures to extremely high levels of air pollution may cause higher than normal mortality in large urban centers. Wilkins reported that the December 1952, London fog resulted in approximately 3,500 to 4,000 deaths over the norm. Specific diseases resulting from the pollution were chronic bronchitis, bronchial pneumonia, and heart disease. The major air pollutants that have been linked to this death episode were smog and SO_2. The 1962 Pittsburgh experience, the most recent air pollution episode examined, was analyzed by Riggan et al. (1976) who concluded that at least 14 deaths over the norm occurred.

The pragmatic value of episode studies is questionable, since quantification of air quality's influence on mortality was not possible owing to insufficient air quality data. Therefore, they can only indicate the illnesses likely to be exacerbated by air pollution. This limitation was perhaps best summarized by Gregor (1977):

> Although episodic studies have the advantage of being able to study human mortality, such studies are limited in usefulness since they deal only with specific episodes of abnormally high pollution. Therefore, episodic investigations are not applicable to the everyday ambient levels of pollution faced by individuals in urban areas, and any extrapolation of dose-response functions from these episodes must be considered tenuous.

4.2.2 Epidemiological Studies

Most epidemiological studies have indicated an inverse relationship between air quality and mortality. The main purpose of the studies is to isolate the effects of ambient levels of pollution on mortality at typical rather than abnormally high levels of exposure. Two major procedures used in these studies are calculating mortality rates for populations exposed to different air quality levels and translating the physical damage into monetary terms.*

The damage factor method includes three steps: (1) estimating the value of total health losses; (2) determining a proportionality factor for the share of this value attributable to air pollution; and (3) multiplying total health losses by this factor in order to obtain the value of health losses from air pollution.

Ridker and Henning (1967) estimated the total national cost of morbidity and mortality for many respiratory diseases, including cancer of the respiratory system, chronic and acute bronchitis, pneumonia, emphysema, asthma, and the common cold. For 1958, the cost estimates for each disease included the costs of premature death and burial, treatment, and absenteeism. From studies of respiratory mortality rates and lung cancer mortality rates in urban and rural areas, Ridker estimated that 18-20% of the approximately $2 billion in national health costs for respiratory diseases are due to air pollution. He corrected his proportionality factors for age, sex, race, smoking habits, and the proportion of the U.S. population that is urban. Applying these coefficients, he estimated the damage to health from air pollution in 1958 to be about $0.4 billion.

The Environmental Protection Agency's Community Health and Environmental Surveillance System (CHESS) program evaluated the cost of adverse health caused by exposure to the air pollution composite SO_2 total suspended particulates and sulfates. Costs included (1) direct medical expenditures for doctor visits, medicine, etc., (2) work-loss days, (3) homemaker disability days and (4) school days lost (U.S. EPA 1974). The objective of this study was to estimate the benefits of reducing SO_2 and total suspended particulate concentrations to primary air quality standard levels and, in the case of sulfates, to an assumed annual average standard of 6-8 $\mu g/m^3$. The adverse long-term health effects were a prevalence of chronic bronchitis in adults, acute lower respiratory infections in children, incidences of acute respiratory illnesses in families, and decreases in the ventilatory functions of children. Aggravation of cardiopulmonary symptoms and asthma were short-term adverse health results.

The second approach to epidemiological studies investigates the relationship between air pollution and mortality rates using multivariate regression analysis, controlling for factors such as age, racial composition, population density, income, and others that influence an individual's probability of death. But many other variables correlated with air pollution that affect mortality are not adequately controlled by partial correlation coefficients. Since personal attributes, socioeconomic characteristics, demography, and climate all influence mortality, problems occur in isolating the influence of air quality on mortality through conventional least squares and linear or log-linear regression methods. The major difficulties encountered in estimating such a physical damage function include: (1) errors in variables, nonnormality, heteroscedasticity, multicolinearity

*The framework of these methods is discussed by Waddell (1974) and Gregor (1977).

among air pollutants, and other explanatory variables; and (2) lack of knowledge of the function's shape that depicts the relationship between air pollution and health.*

Table 4-1 summarizes the relationship between air pollutants and health effects obtained from selected epidemiological studies (Hershaft, Morton, and Shea 1976).

Health effects examined were mortality and morbidity characterized by respiratory and cardiovascular dysfunctions, neoplasms, and impaired fetal development and mental function. Hospital admissions and residence days, doctor visits, personal histories, and work and school absenteeisms are listed as the indicators of morbidity.

But most of the studies—time-series analyses with sample observations restricted to a specific area or a small number of areas—provide little knowledge for designing a general air pollution control policy, which would require information on an "average" damage function expressed in both physical and economic terms and applicable to all metropolitan areas.

Lave and Seskin (1977) investigated the relationship between sulfate and particulate pollution and mortality rates for specific diseases in more than 100 standard metropolitan statistical areas (SMSA), applying multivariate regression analysis and controlling for age, racial composition, income, population density, and geographic size of SMSA. They found that the association between air pollution and mortality is significant and of substantial magnitude. First, an increase of $\mu g/m^3$ in the minimum biweekly sulfate (raising the mean from 4.72 to 5.72 $\mu g/m^3$) was associated with an increase of 6.3 per 100,000 in the total death rate. Second, an increase of 10 $\mu g/m^3$ in the mean biweekly particulate levels (raising the mean from 118.1 to 128.1 $\mu g/m^3$) was associated with an increase of 4.5 per 100,000 in the total death rate.

Lave and Seskin (1977) also studied the relation between mortality rates and SO_2, NO, NO_2, CO, and HC in Chicago, Denver, Philadelphia, St. Louis, and Washington, D.C. Based on regressions including current and lagged values of daily SO_2 levels, three weather factors, day of the week, and daily mortality in Chicago, they concluded that a 50% decrease in the daily SO_2 level results in a 5.5% decrease in daily deaths.

From the estimated quantitative relationship between respiratory mortality rates, the level of air pollution and two climatic variables, Koshal et al. (1974) reported that about a 50% reduction in air pollution would imply a social saving of about $1.9 to $2.2 billion per year in respiratory disease.

Applying multivariate regression analysis, Jaksch and Stoevener (1974) attempted to isolate the effect of air pollution on services used by enrollees in the Kaiser prepaid health plan. The authors hypothesized that by aggravating certain diseases, air pollution increases the use of outpatient medical services. By considering measures of suspended particulate air pollution and meteorological conditions and socioeconomic-demographic variables, Jaksch and Stoevener conclude that air pollution increases the consumption of outpatient medical services for certain respiratory diseases.

*See, for example, Freeman (1972), Liu and Yu (1976) for a detailed discussion of major difficulties of estimating physical change function.

Table 4-1. SELECTED STUDIES OF HEALTH EFFECTS OF MAJOR AIR POLLUTANTS[a]

Pollutants	Target Population	Covariates	Results	Source
Particulates, sulfates	U.S. SMSAs	Population: density, age, race, income	A 10% reduction in minimum biweekly sulfate and mean biweekly particulates associated with mortality.	Lave and Seskin 1973
Sulfur dioxide	Chicago, Denver, Philadelphia, St. Louis, Washington, D.C.	Weather, day of the week	A decrease of 0.092 ppm in the mean concentration of sulfur dioxide associated with a decrease of 63 deaths per day (Chicago).	Lave and Seskin 1977
Sulfur dioxide	U.S. SMSAs	Temperature, precipitation, humidity, age, race, sex, socioeconomic factors	Sulfur dioxide found significant in explaining mortality rates.	McDonald and Schwing 1973
Sulfates	U.S. SMSAs; white males over 65	Various climatic, demographic, and socio-economic factors	Found significant association between sulfates and mortality from arteriosclerotic heart disease and cancer of respiratory and gastro-intestinal tract.	Sprey and Takacs 1973
Particulates, sulfur dioxide	New York City	Weather	Found significant association between sulfur dioxide and particulate levels and mortality from respiratory and heart disease.	Hodgson 1970
Smoke shade, sulfur dioxide	New York City	Weather	Found association of daily mortality with sulfur dioxide stronger than with any weather varible.	Glassar and Greenburg 1971
Smoke shade	New York City	Weather, day of the week	Between 18.12-36.76 deaths/day above the norm associated with air pollution; 80% ascribed to smoke shade, 20% to sulfur dioxide	Schimmel and Greenburg 1971

Table 4-1. SELECTED STUDIES OF HEALTH EFFECTS OF MAJOR AIR POLLUTANTS[a] (continued)

Pollutants	Target Population	Covariates	Results	Source
Sulfur dioxide	New York metropolitan region	Temperature, epidemics, disasters, holidays, day of the week, time trends	Found association between sulfur dioxide levels and residual mortality.	Buechley et al. 1973
Particulates	Buffalo, NY	Age, sex, race, income	Mortality from chronic respiratory disease found twice as high at high particulate levels than at low levels	Winkelstein et al. 1967
Particulates	Buffalo, NY	Age, sex, race	Mortality from gastric and prostatic cancer found twice as high at high particulate levels than at low levels	Winkelstein and Cantor 1969a, 1969b
Particulates	Buffalo, NY	Age, sex, race, income	Found association between particulate levels and mortality from arteriosclerotic heart disease, cerebrovascular disease, and cirrhosis of the liver.	Winkelstein and Gay 1971
Particulates, soiling, dust, sulfur dioxide and sulfation	Nashville, TN	Age, sex, race, income	Found association between soiling, and sulfur dioxide and total and cardiovascular disease morbidity; association between sulfation, dustfall, and particulates and cardiovascular disease in females.	Heidberg et al. 1954
Particulates, soiling, dust, sulfur dioxide and sulfation	Nashville, TN	Age, sex, race, income	Found association between particulates and cardiovascular mortality in females; association between soiling and sulfation and mortality from respiratory disease but not lung cancer.	Zeidberg et al. 1967a, 1967b
Particulates, soiling, dust, sulfur dioxide and sulfation	Nashville, TN	Age, sex, race, income	Found association between pollutant levels and total cancer mortality and cancer of esophagus, stomach and bladder, but not lung cancer.	Hagstrom et al. 1967

Table 4-1. SELECTED STUDIES OF HEALTH EFFECTS OF MAJOR AIR POLLUTANTS[a] (continued)

Pollutants	Target Population	Covariates	Results	Source
Particulates, sulfur dioxide	Los Angeles	Weather	Found significant association between pollutant levels and disease-specific hospital admissions and lengths of stay.	Sterling, et al. 1966, 1967, 1969
Soiling	Allegheny County (Pittsburgh)	Weather, day of the week	Doubling of soiling index associated with 22% increase in admissions for respiratory emergency.	Silverman 1973
Particulates, sulfation	Berlin, NH & Chilliweek, SC	Smoking	Found association between particulate and sulfation levels and incidence of chronic respiratory disease.	Ferris and Anderson 1962, 1964; Anderson et al. 1965; Ferris et al. 1973
Nitrogen oxide	Chattanooga school children	Smoking, socio-economic	Rates of acute respiratory illness found higher in areas with high NO_2 levels.	Shy et al. 1970a, 1970b, 1973
Nitrogen oxide	Chattanooga school children	Years of exposure	Found association between exposure to NO_2 and incidence of bronchitis.	Pearlman et al. 1971
Nitrogen oxide	Parents of Chattanooga school children	Smoking, ages, sex, race	No association found between NO_2 and chronic bronchitis.	Chapman et al. 1973
Nitrogen oxide	U.S. SMSAs; white males and females over 65	Weather, socioeconomic	Mortality from hypertensive heart disease increased by about 0.2%; lung cancer increased by 50% for males, and 130% for females upon increasing NO_2 levels from 0.03-0.08 ppm.	Sprey and Takacs 1973
Photochemical oxidants	School children in Los Angeles		Found no significant association between oxidant levels and school absenteeism due to respiratory illness.	Wayne and Wehrle 1969
Photochemical oxidants	Student nurses in Los Angeles	Nitrogen dioxide, carbon monoxide, temperature	Developed thresholds for several health symptoms.	Hammer et al. 1974

Table 4-1. SELECTED STUDIES OF HEALTH EFFECTS OF MAJOR AIR POLLUTANTS[a] (concluded)

Pollutants	Target Population	Covariates	Results	Source
Carbon monoxide	Los Angeles County	Oxidants, temperature	Found significant association between daily mortality and carbon monoxide, but not oxidants.	Hexter and Goldsmith 1971
Carbon monoxide			Found association between carbon monoxide and angina and intermittent claudication	Aronow et al. 1972, 1973, 1974
Nonspecific air pollution	Students at 7 California universities	Climatic and socioeconomic variables, holidays, chronic conditions	Found association between air pollution and excess incidence of respiratory illness.	Durham 1974
Benzopyrene	U.S. and 19 other countries		An increase of 1 mg/1000 m^3 in concentration of benzopyrene was associated with 5% increase in mortality from lung cancer.	Carnow and Meier 1973
Oxidants, nitrogen dioxide, carbon monoxide	California		Developed a series of dose-effect functions on the basis of expert opinions.	Leung et al. 1975

[a]Hershaft, Morton, and Shea 1976.

In recent years the public has realized that hundreds of thousands of persons may develop cancer from exposure to ionizing radiation at levels lower than had been considered harmful.*

A study of the federal nuclear-research facility in Hanford (In These Times 1978) and a power plant near Richland, Washington showed that the average radiation dose for employees who die from cancer was higher than for those who died from other causes. Working with the Boston Globe, Dr. Thomas Najarian discovered that the Portsmouth, New Hampshire naval shipyard workers who were exposed to radiation had a cancer death rate more than twice the national average and nearly 80% higher than the rate for shipyard workers who were not exposed to radiation. Also, exposed workers died of leukemia more than four times as often as the general population. (In These Times 1978.)

Dr. Irwin Bross, director of biostatistics at Roswell Park Memorial Cancer Institute in Buffalo, New York, studied the side effects of ordinary diagnostic x-rays. His work indicates that (1) infants whose parents had been exposed to x-rays had a high rate of genetic damage, and (2) the x-rays nearly doubled the rate of leukemia in men who were exposed to them (Waddell 1974).

The studies suggest that low-level radiation significantly affects the occupational health of all nuclear workers, as well as the health of those who occasionally have diagnostic x-rays. These findings have prompted Congress to hold hearings and the President to order a full review of the federal government's involvement in occupational radiation hazards. The Senate Subcommittee on Nuclear Regulations has added $5 million to the Nuclear Regulatory Committee's 1979 budget to begin the first nationwide epidemiological study of cancer. At the most, the investigations could lead to tougher standards for radiation exposure. At the least, the studies could force industry and government to spend millions on improved monitoring of radiation exposure and radiation workers' health.

4.3 NATIONAL ESTIMATE OF HEALTH DAMAGE

Two major sources can be used for estimating gross damages from mortality and morbidity—the work of Lave and Seskin on mortality and EPA's CHESS program on morbidity. Applying the EPA study to an analysis of the CHESS findings on health effects of SO_2, TSP, and suspended sulfates, Waddell (1974) estimated the human morbidity costs for 1970 to range from roughly $0.9 to $3.2 billion.

Next, using the Lave and Seskin numerical value of the regressor showing that a 26% reduction in air pollution in major urban areas would lower the mortality rate by 2.33% and cost figures developed by Rice (1966), Waddell calculated the value for this percentage reduction inmortality and morbidity in 1963 to be $2.24 billion. Extrapolating this value to 1970, the estimate became $3.73 billion, which includes morbidity and mortality costs associated with respiratory diseases considered by EPA and others.

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*The defunct National Council of Radiation Protection defines low-level radiation as the 5-rem/gr standard that covers private and government employees who routinely work with radiation or radioactive material (nuclear weapons testing, operation of radar and nuclear-power plants, and manufacture of heart pacemakers, x-ray machines, nuclear fuel, etc.).

To make the two estimates additive, Waddell subtracted the component identified as morbidity and the direct expenditure for respiratory disease from the $3.73 billion, resulting in a health estimate of $3.51 billion. Since only 73.5% of the total population in 1970 lived in urban areas, the estimate of health costs is reduced to $2.58 billion. By considering the variance about the mean, a range of $0.7-4.4 billion was assumed for 1970. If this figure is added to the range of $0.9-$3.2 billion estimated by extrapolating the CHESS data, the range of gross estimates of health costs associated with air pollution for 1970 becomes $1.6-7.6 billion, with a best estimate of $4.6 billion.

From updated results of the work of Lave and Seskin (1973), Waddell (1974), Rice (1966), and U.S. EPA (1974), Heintz et al. (1976) estimated health damages attributed to air pollution in 1973 to be $5.7 billion. The 1970 estimates reflect increases in cost and level of direct health expenditures, increases in total mortality and morbidity resulting from population growth, increases in mean earnings, and better data on the value of housewives' services. No adjustments have been made for changes in demographic patterns or for the age and sex distribution of illnesses.

In summarizing the gross estimate of health costs associated with air pollution, Heintz et al. (1976, p. II-11) reflected:

> These estimates are based only on costs of medical care expenses and foregone earnings or productivity. Such estimates clearly understate the total social value of improved health. They do not include the value of leisure time lost through illness, of time lost by people who do not receive monetary compensation for their labor (e.g., volunteers, housewives, retirees, children), or of avoiding the discomfort, pain, and anxiety associated with illness.

SECTION 5.0

AESTHETIC DAMAGES OF AIR POLLUTION

5.1 OVERVIEW

Attempts have been made to assess the damages that high concentrations of air pollutants impose on the aesthetics of urban living, but aesthetic damages are particularly difficult to quantify: they take the form of reduced visibility; irritation of eyes, nose, or throat; and bad odors. They may also result in changes in property values.

Aesthetic effects are measured monetarily by assessing people's willingness to pay for improvements in air quality, accomplished through opinion surveys of air pollution sufferers or through market studies that use property values to measure air pollution losses. Various pollutants (ozone, aldehydes, ammonia, hydrogen sulfide, suspended particulates, sulfide, oxidant, sulfur dioxide, nitrogen oxides, and oxidants) are considered in the assessment of the aesthetic air pollution damages.

5.2 REVIEW OF INDIVIDUAL STUDIES

The aesthetic effects that high concentrations of air pollutants (components of photochemical smog, suspended particulates, and many other minor pollutants) impose on urbanites have been recognized for several years. Some of the earliest studies on the assessment of public concern about air pollution were done by de Groot et al. (1966) in Buffalo, New York, Medalia and Finkner (1965) in Clarkston, Washington, and Williams and Edminsten (1965) in Nashville, Tennessee. They found a direct relationship between people's perceptions and attitudes concerning environmental pollution and air quality in the area.

Recently Mason (1972) and Vars and Sorenson (1972) surveyed the opinions of tourists on reduced visibility resulting from heavy smoke problems in the Willamette Valley (Salem and Eugene), Oregon, caused by the annual burning of grass stubble. The results suggested that: (1) perceived changes in air quality in a community are defined or redefined by the local mass media, which is sufficient to form attitudes toward the topic, and (2) attitudes do not alter as a result of known changes in air quality.

Randall et al. (1974) used bidding games to assess willingness to pay for abatement of particulate emissions among several population subgroups near Farmington, New Mexico. The residents and tourists had to determine the maximum amounts that households would be willing to pay for improvements in the ambient air quality after they had viewed three sets of photographs, each showing the asthetics of different levels of pollution. The study estimated that local households would be willing to pay $50 annually for a 73% reduction in particulate emissions. This estimate, however, is questionable because of user fees, suspected response bias, and the uncommonness of the local situation.

There are two principal means of estimating the value of aesthetic effects: the bidding game approach and the analysis of property value. The use of property value tests the hypothesis that air pollution represents an economic cost to the affected community and that such cost is reflected in property values.

Table 5-1 shows a summary of the property value studies of primary interest in developing national estimates of the aesthetic damages of air pollution. By applying multiple regression and correlation analyses, all studies found a statistically significant, inverse relationship between air pollution and property values.

Empirical studies that measure the willingness to pay for cleaner air from housing value differentials estimate an equation in which housing values are regressed against pollution levels as well as other housing attributes, such as location, neighborhood, occupant, and physical property characteristics. The estimated damage functions differ from city to city because: (1) the pollutant measures in the different studies are not homogeneous, and (2) cities vary in their meteorology and emission density. Ridker and Henning (1967) as well as Zerbe (1969) used only one of the pollutant regressors in their equations, while Anderson and Crocker (1970), Crocker (1971), and Peckham (1970) applied both. Anderson and Crocker argue that the identification of the separate influences of the two highly correlated pollution variables can best be achieved when both appear as regressors in the same equation. If this argument is true, the marginal damages reported by Ridker and Henning and Zerbe probably reflect the influence of both sulfation and particulate variations.

In the empirical estimation of the willingness to pay for air quality improvements, Harrison and Rubenfeld (1978) used the concentration of NO_x as a measure of air quality since the air pollution variables (NO_x and suspended particulates) in their data base were so highly correlated that specification of their independent impacts on housing values in the Boston SMSA was extremely difficult. Assessing the quantitative importance of the NO_x coefficient, they found that the change in NO_x concentration depends upon the level of NO_x and the levels of the other explanatory variables. When they substituted suspended particulates for NO_x in estimating the same housing value equation, the coefficient of suspended particulates was negative and statistically very significant. In addition, the coefficients of the nonpollution variables were virtually the same with either suspended particulates of NO_x in the equation, supporting the view that the various pollution variables reflect an aversion to pollution generally rather than to individual pollutants.

Freeman (1974) and Small (1975) argued that the benefit estimation procedure used by most empirical studies (Ridker and Henning (1967) and others) is correct for valuing marginal improvements in air quality. In using these regression results to estimate the total benefits arising from a nonmarginal improvement in air quality, they assume the value placed on a marginal improvement in air pollution concentration is independent of the level of air pollution and independent of household income and tastes. This is equivalent to assuming a linear damage function for air pollution that is identical for all households.

5.3 NATIONAL DAMAGE ESTIMATES

The value placed on marginal improvement in air pollution is of great importance in estimating national pollution damages. Most of the empirical studies indicate that the magnitude of the marginal capitalized sulfation damage for residential structures for a marginal decrease of 0.1 mg SO_2/100 cm^2 per day lies roughly between \$100 and \$600. This relatively high uniformity of results for six major metropolitan areas warrants some confidence in the usefulness of national pollution damages. The total capitalized pollution damage depends on the following:

Table 5-1. SUMMARY OF PROPERTY VALUE STUDIES[a]

Study	City	Pollution Measure	Pollution Coefficient	R^2	Marginal Capitalized Damage
Ridker-Henning (1967)	St. Louis	Sulfation[b]			100[e]
Zerbe (1969)	Toronto	Sulfation[b]	-0.12	0.94	97[e]
	Hamilton	Sulfation[b]	-0.08	0.92	
Anderson-Crocker (1970)	St. Louis	Sulfation	-0.10	0.76	
		Suspended particulate	-0.12[c]		
	Kansas City	Sulfation	-0.08	0.82	300-700[f]
		Suspended particulate	-0.09[c]		
	Washington, D.C.	Sulfation	-0.07	0.70	
		Suspended particulate	-0.06[d]		
Crocker (1971)	Chicago	Sulfur dioxide	0.06[d]	0.77	470[g]
		Suspended particulate	-0.40		
Peckham (1970)	Philadelphia	Sulfation	-0.10	0.76	600-750[f]
		Suspended particulate	-0.12		
Spore (1972)	Pittsburgh	Sulfation	0.03[c]	0.81	150-200[h]
		Dustfall	-0.12		
NAS (1974) & NAE (1974)	Boston and Los Angeles	Oxides of nitrogen Suspended particulate			
Nelson (1975)	Washington, D.C.	Oxidants			
Harrison-Rubinfeld (1978)	Boston	Oxides of nitrogen	-0.006	0.81	1,613[i]

[a]Waddell 1974; Nelson 1975; Harrison and Rubinfeld 1978, Vol. 5: pp. 81-102.

[b]Single pollution variable probably measures effect of both sulfation and suspended particulates.

[c]Not significantly different from zero at the 0.01 level.

[d]Not significantly different from zero at the 0.05 level.

[e]Mean change in Marginal Property Value (MPV) per change of 0.1 mg SO_3/100 cm^2-day.

[f]Mean change in MPV per change of 0.1 mg SO_3/100 cm^2-day plus 10 g/m^3 per day change in suspended particulates.

[g]Mean change in MPV per change of 0.0001 ppm/72 hr SO_2 plus 10 g/m^3 per day change in suspended particulates.

[h]Mean change in MPV per change of 0.005 ppm/day of SO_2 plus a 5 tons/mi^2 per month change in dustfall.

[i]Mean change in median value of owner-occupied homes (MV) per change in 1 pphm change in NO_x and the other variables.

- choice of marginal capitalized sulfation damage coefficient,
- desired background sulfation rate,
- annual arithmetic mean sulfation rate for the metropolitan area,
- number of housing units over which the aggregation occurs, and
- discount rate.

Given these data and the assumption that sulfation changes are always evenly distributed among housing tracts, Waddell (1974) estimated the national pollution damages. First, he crudely estimated sulfation damage (as captured in property value differentials) by the following equation:

DAMAGE = (Marginal capitalized sulfation damage)
x (number of marginal changes needed to reduce arithmetic annual mean sulfation rate for the metropolitan area to desired background)
x (number of housing units).

The damage given by this relation represents total capitalized pollution damage. Second, total annual damage (or the decrease in real property income from pollution) was obtained by multiplying the total capitalized damage by a discount rate reflecting the average return on capital in the economy.

As a result of this estimation procedure, and with an assumed range of marginal capitalized damage coefficients of \$200 to \$500 for each reduction in 0.1 mg SO_2/100 cm^2 per day, the national annual estimate for 1970 of air pollution damages measured via the property value differential methods was between \$3.4 and \$8.4 billion. Since the best approximation would be a middle estimate for a marginal property value of \$350, the total damage to aesthetic properties and soiling was calculated as \$5.9 billion.

Based on the property values synthesized by Waddell in 1974, Heintz, Hershaft, and Horak (1976) estimated the aesthetic damages from air pollution for 1973 to be \$9.7 billion. The study by the National Academy of Sciences (1974) and the National Academy of Engineering (1974) supports, in general, Waddell's estimate by a range of \$1.5-5.0 billion for automotive pollutants.

In adjusting 1970 estimates, Heintz followed these steps:

- the \$5.9 billion was updated to reflect the increase in urban housing—growth and inflation of the economy was \$8.9 billion; and
- \$0.8 billion for oxidants was added to the \$8.9 billion for SO_2 and particulates giving a total of \$9.7 billion as the best estimate of the aesthetic damages of air pollution for 1973, as reflected in property values.

A recent study by Nelson (1975) of the relationship between property values and oxidant levels resulting from automotive air pollution in Washington, D.C., estimated \$0.8 billion for oxidant damages. He concluded that the reduction in damages reflected in nationwide property values from 45% reduction in oxidant concentration would be \$0.8 billion.

A common criticism of the property value studies is that they underestimate total aesthetic damages. Total damage estimates reflect only those damages capitalized in the residential property market and measured through site and improvement differential values. In using property value to estimate total damage costs, one should prepare separate studies for residential, commercial, industrial, and agricultural land.

SECTION 6.0

AIR POLLUTION DAMAGE TO VEGETATION

6.1 OVERVIEW

The adverse effects of air pollutants on vegetation have long been recognized. Studies are voluminous but inconsistent on the effects of the four major pollutants—sulfur dioxide, oxidants, acid rain, and fluoride compounds. Analyses of these air pollutants on vegetation have tried to determine susceptibilities of individual plant varieties rather than a broadly applicable relationship between dose and effect. Scientists have shown little interest in coordinating research efforts or in setting uniform standards that allow aggregation or comparison of different studies (Hershaft, Morton, and Shea 1976).

The effects of air pollution on vegetation can be classified into two categories: (1) visible effects, which are identifiable pigmentations of foliage as a result of major physiological disturbances to plant cells; and (2) subtle effects, which are not visible and are identified only by physiological changes in the plant. Liu and Yu (1976) noted that disturbance of biochemical processes at the molecular level is the cause of both effects. Within the category of visible effects, acute and chronic injury can be identified.

Two variables, pollutant concentration and exposure duration, help one to understand pollutant effects on vegetation. Soil type, plant age, temperature, light intensity, and humidity also affect plant injury (Heck 1968; U.S. EPA 1973). These variables and dose-response relationships allow a physical damage function to be constructed. Since a mathematical model that contained all of the variables might be too complex, one might assess only the most important variables. Heck and Brandt (1974) indicated that two models are needed: one for acute response and one for chronic response. Injury resulting from repeated acute exposure could also be studied.* Acute injury is a severe injury as a result of a short-term but high concentration of the pollutant. Chronic injury is a light to severe injury developing from exposure to long-term, low-pollutant concentration.

In general, symptoms of the effects of air pollutants on vegetation are reductions in quantity of output and degradation of the quality of the product. The extent of leaf injury is the indication of the adverse effects of air pollutants on vegetation. Several indices have been developed relating this indicator to yield loss. Leaf injury is a particularly important indicator in certain plants, such as lettuce and tobacco, since leaf appearance affects salability. However, in other cases, the indicator is not adequate. For example, substantial losses of fruit, grain, and timber have been found even in the absence of significant leaf injury.

Translation of the physical damage function into an economic damage function requires knowledge of time and growing season, market price of the plant, the possibility of growing a different crop, and cost of the site for plant growth.

Waddell (1974) presented two approaches to assess the economic loss of plants owing to air pollution. The first surveys the damage losses statewide by using county agricultural

*For a detailed discussion on the studies of injury owing to repeated acute exposure, see Heck and Tingey in Englund and Beery (1971, p. 249).

agents and commissioners. These local damage estimates are extrapolated to the national level to arrive at a crude estimate of gross damages. Waddell's second approach is to construct predictive models by relating data on crop losses to crop values, pollution emission, and meteorological parameters. Such models are refined as greater knowledge is gained about dose-response relationships and as the local situation is better defined.

6.2 SURVEY OF INDIVIDUAL STUDIES

6.2.1 Sulfur Dioxide

Stoeckhardt (1971) reported sulfur dioxide (SO_2) injury to plants as early as 1871. Since then, experiments and surveys have broadened the knowledge of SO_2 injury to plants. More than 700 articles have been published about the effects of SO_2 on vegetation. Studies by Roberts (1976), Bleasdale (1973), Davis (1972), Dochinger et al. (1972), and Mansfield and Butt (1972) indicated that in some instances, prolonged exposure to low concentration levels of sulfur dioxide causes reduced growth and yield before visible symptoms of injury occur. Sometimes chronic exposure has no detrimental effect on plant growth.

Roberts (1976) reported symptoms of the exposure of two-year-old grafted clones of air-pollution-susceptible (the chlorotic dwarf syndrome) and air-pollution-tolerant white pine to high- or low-SO_2 concentrations. Foliar injury and reduced leaf growth were observed on susceptible clones growing in the high SO_2 environment. Tolerant clones at the same site showed much more sulfur than corresponding plants grown in the low-ambient SO_2 environment. The most significant increases in sulfur content were detected in leaf tissue and suggest that foliage of white pine absorbs SO_2 from the atmosphere.

Davis (1972) examined the relationship between leaf injury and yield loss during a three-year period in 485 plots of soybeans. Sulfur dioxide fumigations were conducted at two growth stages during the first two years and at seven growth stages during the last year. No direct link was established between SO_2 concentration and yield.

Dochinger et al. (1972) assessed SO_2 fumigation on a special variety of hybrid poplar. Fumigation was carried out at 5 ppm for 0, 3, 6, 9, and 12 hours in controlled environment chambers. A strong correlation was found between percentage leaf injury and hours of fumigation for both lower and upper shoots and for clonal variations within the species.

More diversified studies of the effects of SO_2 focused on ornamentals, mosses, and lichens. Since ornamentals have aesthetic value, deterioration in plant appearance reduces their salability. Mansfield and Butt (1972) found that lichens and mosses suffer extensive damage or death at SO_2 concentrations as low as 0.01 ppm. Severe injury is due to concentration of toxic substances in the plant tissue over long periods of time, and uptake of airborne SO_2 as part of nutrient requirements. With the aid of controlled environmental chambers, Temple (1972) studied exposure of four species of ornamental trees to SO_2. Damages to foliage as high as 95% were found at concentrations of 4 ppm for 6 hours.

Tingey et al. (1971) and Dunning, Tingey, and Reinert (1970) working with atmospheres of NO_2 and SO_2 found that atmospheres of NO_2 below 200 pphm (parts per hundred million) or of SO_2 below 50 pphm did not cause leaf injury.

Hill et al. (1974) fumigated 80 native desert species in Utah and New Mexico with sulfur dioxide and a combination of SO_2 and NO_2 in portable environmental chambers. Most of the species were resistant to two-hour exposures at ambient concentrations to 2 ppm but showed a marked injury increase at either 6 or 10 ppm. No synergistic effects of SO_2 and NO_2 were found at these levels.

Dochinger et al. (1970) found that 10 pphm of either O_3 or SO_2 produced little acute damage on eastern white pine but that a mixture of 10 pphm of each gas caused needle mottling and abscission. Jaeger and Banfield (1970) repeated this work, using levels of SO_2 and O_3 at 5 pphm. Exposures to the individual gases for 10 days or more resulted in minor or no damage, but the combination of gases produced acute damage on some trees and chronic injury on all trees.

A well-known response of pinus strobus to atmospheric pollutants is called the chlorotic dwarf syndrome, perhaps caused by photochemical oxidants and SO_2 (Tingey et al. 1971; U.S. Army Environmental Hygiene Agency 1969). Less susceptible white pine typically responded to ambient pollution with increased needle abscission, tipburn, and mottle or banding resulting in an overall chlorotic appearance.

Philips, Skelly, and Burkhart (1977) investigated growth inhibition of asymptomatic white pines subjected to three peaks in pollution levels during a 35-year period. Four levels of symptoms developing in eastern white pine exposed to SO_2 and NO_x categorized the sample trees for computer analysis of their growth rates. Analysis of regression correlations revealed no significant growth rate differences between symptom classes during pollution peaks: growth of asymptomatic trees was reduced as much as that of injured trees during peak pollution.

6.2.2 Oxidants

6.2.2.1 Ozone

Effects of photochemical oxidants, including ozone (O_3), on vegetation have attracted much attention, especially in the wake of the recent discovery of high oxidant levels in rural areas.

Injury to agricultural crops by O_3 was initially reported on grapes in 1958 and on cigar wrapper tobacco in 1959 (Heggestad and Middleton 1959). Similar symptoms were observed on Maryland tobacco as early as 1952 (Burk and Heggestad 1956; Menser, Hodges, and McKee 1973). The disease was called weather fleck and appeared following several days of smog. The most abundant photochemical oxidant component, ozone, was found to be the major cause of flecking symptoms on tobacco (Heggestad and Middleton 1959).

The initial symptoms of weather fleck on tobacco are visible on the lower leaves of the plant as small, dark, water-soaked spots which, within 24-48 hours, appear on the upper surfaces of leaves as small, irregularly shaped lesions, light gray to tan (Heggestad 1968; Heggestad and Middleton 1959). Sulfur dioxide worsens the injury caused by ozone (Menser and Heggestad 1966; Menser, Hodges, and McKee 1973). High light intensity during exposure, high relative humidity, high soil moisture, and nitrogen deficiency increase injury on tobacco by air pollutants (Heck 1968; Leone and Brennan 1969; Menser and Street 1962).

The prevalence of weather fleck on tobacco throughout Maryland prompted Huang, Mulchi, and Aycoe (1976) to study the relationship between air pollution (oxidant, ozone) damage and certain agronomic, chemical, and physical characteristics of Maryland tobacco. In 1972, 36 Maryland tobacco entries, including 8 parent cultivars and 28 hybrids, were grown at three locations with differing soil types. The plants were scored for air pollution injury (weather fleck) at maturity. This study concluded that: (1) plants grown on deep sandy soils and showing drought stress symptoms exhibit less injury from air pollution than plants grown on sandy loam or silt loam soils; (2) reductions in yield, average price, and value of the cured tobacco are associated with increases in weather fleck intensity at two of the three locations; (3) taller plants and wider internode lengths are related to increased fleck intensity at two of the three locations; (4) days to flower, filling capacity, and burn duration are associated with increased fleck intensity in a positive manner and total alkaloid contents in a negative manner at single locations only; and (5) correlation values for either total nitrogen content or leaves per plant with weather fleck intensity are not significant at all locations.

Turner et al. (1972) assessed ozone damage to tobacco by measuring height, dry weight, leaf area, amount of fleck injury, as well as total leaf stomatal conductance (an indirect measure of photosynthesis and respiration). Four cultivars of varying sensitivity were grown under field conditions during both years of the study and in greenhouses during the second year. The air quality data specify both diurnal variations and daily peak oxidant readings throughout the growing season. The uninjured leaf area for the most tolerant (6524) and the most sensitive (Bel W-3) cultivars was 10% and 71%, respectively, in filtered air. The susceptibility and resistance of various sweet corn hybrids and inbreds to leaf injury by O_3 have been recognized for several years (Cameron 1975; Cameron et al. 1970; Cameron and Taylor 1973). Episodes involving both high O_3 levels and high temperatures can cause rapid killing of sensitive areas on otherwise healthy leaves. Evidenced by premature mottling, yellowing, and senescence of older leaves, chronic injury also regularly occurred on some cultivars.

The effects of acute and chronic injury upon corn plant and ear quality are not easily determined in field plantings because of the absence of uninjured control plants (Thompson, Kats, and Cameron 1976). Heagle, Body, and Pounds (1972) exposed two small-sized sweet corn cultivars to 0, 5, and 10 pphm of O_3 in field chambers throughout the season. At 10 pphm, leaf injury was sharply increased in "Golden Midget," and several ear and seed characters were significantly affected. Thompson, Kats, and Cameron (1976) evaluated two sweet corn hybrids, "Bonanza" and "Monarch Advance," for their relative susceptibility to ambient photochemical air pollutants (principally O_3) in outdoor chambers at Riverside, Calif. The plants were exposed daily to ambient or activated carbon filtered air from seedling emergence to fresh market harvest. Premature yellowing and senescence of lower leaves and marked paleness of upper leaves were evident in "Monarch Advance." Leaves of "Bonanza" were not visibly affected except for a slight yellowing of lower leaves. Significant yield reduction was reported. In the case of "Monarch Advance," a susceptible variety, fresh weight per husked ear was reduced 28% by exposure to smog over the growing season. For "Bonanza" corn, a more resistant variety, ear weight was only slightly affected, but the number of second ears was reduced 75% as compared with plants grown in filtered air.

Brewer and Ferry (1974) studied effects of oxidant exposure on cotton yield at four locations in the San Joaquin Valley during a two-year period. Cotton grown in filtered air was found to produce 10 to 30% more yield than control plants grown in chambers containing unfiltered air or those grown on the outside.

Williams, Brady, and Wilson (1977) outlined the extent and intensity of oxidant-induced disease observed on forest tree species in 1974 between Kings River and the East Fork of the Kawenh River in California (the Hume Lake District of the Sequoia National Forest and the Sequoia-Kings Canyon National Park). The advective oxidant concentrations were maximal at the inversion layer juncture with the mountain slopes. Thus, slight to moderately severe symptoms of O_3 caused chlorotic mottle disease on ponderosa pine at Pinehurst (elevation 1363 m), more severe symptoms at intermediate elevations (Giant Forest at 1864 m; Park Ridge at 2300 m; and Whitaker Forest at 1640 m), plus a general decrease in disease severity at and above 3100 m (Buck Rock Fire Lookout Station). Ponderosa pine and other tree species growing on the rims of canyons and steep slopes in contact with the inversion boundaries exhibited the most O_3 injury. Williams, Brady, and Wilson concluded that injury to forest stands of southern Sierra Nevada suggests that the growth losses and mortality rates observed in the San Bernardino Mountains of southern California could develop in the survey area (McBride, Simion, and Miller 1975; Taylor and Miller 1973).

Davis and Wood (1972) surveyed effects of oxidants on coniferous trees. The study focused on leaf injury to new growth in two- to six-year old seedlings, and showed that the injury may affect the photosynthesis process and thus eventual growth of the trees. Six species of pine, two of larch, and eastern hemlock were found to be susceptible to eight-hour exposures to 0.25 ppm ozone levels every two weeks. Nine other coniferous species including four spruce, two fir, Douglas fir, aborvitae, and red pine were resistant to damage at these levels. Photosynthesis in three species of yellow pine was examined by Barnes (1972) who concluded that photosynthesis is sometimes enhanced at O_3 levels to 5 pphm, but extended exposures to 15 pphm reduces CO_2 exchange in most cases.

Feder (1970) and Feder et al. (1972) reported that carnation, geranium, and poinsettia cultivars grown to maturity in 0.10 to 0.12 ppm ozone concentrations had reduced or delayed bract or flower development and depressed growth. Leaf area was reduced 10% in geraniums and bract area decreased 39% in poinsettias grown in air containing 0.12 ppm ozone. Carnations showed significant delay in flower bud initiation in 0.10 ppm ozone but further bud development was not affected.

6.2.2.2 Nitrogen Oxide and Nitrogen Dioxide

Two oxides of nitrogen, nitrogen oxide (NO) and nitrogen dioxide (NO_2), are gases whose importance as phytotoxicants is being tested. These oxides are byproducts of combustion engines and of many industrial processes and are extremely difficult to control at the source (Rossano 1969; Wood 1971). Numerous atmospheric reactions of the several oxides, rapid fluctuations in their levels, lack of measurement techniques, and synergistic effects with SO_2 and oxidants (O_x) have caused researchers to introduce NO_2 as a proxy for all NO_x damage to vegetation. In addition, to circumvent the lack of measurement techniques, researchers relied on controlled laboratory exposures or on concentration predictions based on emission levels (Hershaft, Morton, and Shea 1976).

The type of plant damage resulting from NO_2 exposure depends upon NO_2 dosage (Stone and Skelly 1974). Acute damage on coniferous plants appears as reddish-brown tip necrosis, or tipburn, of the needles and occasional scattered necrotic areas along the needles. The tipburn progresses toward the base of the needles if acute exposure levels are maintained. Usually a sharply defined band separates the necrotic tip from the green tissue. Early abscission of deciduous leaves and of conifer needles is typical of both

acute and chronic NO and NO_2 exposure. Chronic injury from the NO_x occurs as chlorosis, reduced metabolic function, and overall reduced growth rate on both broadleaf and coniferous plants (Heck 1968).

Stone and Skelly (1974) studied the relationship between NO_2 emission levels and amount of growth in 43 white pine trees near Radford, Virginia. The production volumes in the nearby Radford Army Ammunition Plant, a major local source of nitrogen oxides, was used as a proxy to estimate NO_2 emission levels. Growth rates were determined by measuring the width of the annual growth ring. An inverse relationship, significant at the 99.5% level of confidence, was found between the fluctuating production levels of the arsenal and the annual increment growth of the trees.

6.2.2.3 Peroxyacetylnitrate

The effects of peroxyacetylnitrate (PAN) on vegetation has been studied in some detail. Peroxyacetylnitrates, produced in sunlight from unsaturated hydrocarbons (HC) and NO_x, create a glazing, silvering, or water-soaked condition on the lower surface of several leaf vegetables, such as lettuce, chard, and spinach (Taylor 1968). Taylor (1969) reported that exposure to 15 ppb of PAN for four hours produced acute injury on petunia and tomato plants. The entire ambient photochemical oxidant complex reduces photosynthesis in isolated lemon branches and in whole trees. Also, studies on both lemon and orange trees showed reduced yield and increased leaf drop (Thompson, Taylor, and Ivie 1969). The predisposition to injury from ambient levels of PAN for navel orange trees in the Los Angeles Basin was investigated by Thompson, Kats, and Cameron (1976) in two parallel studies. In one study, grafted young orange trees were tested to determine the effects on growth, leaf drop, and other vegetative responses. The second study utilized branches of equal size from a mature tree. Young navel orange trees and branches of a mature tree were enclosed and exposed for two years to activated carbon-filtered air, carbon-filtered air plus ambient levels of PAN, or ambient air. The growth of the young trees was reduced by the addition of synthetic PAN at levels in ambient air. Leaf drop increased. With enclosed branches, significantly less growth occurred with PAN. Trends toward reduced yield of mature fruit were seen. Short-term apparent photosynthesis was not affected by fumigating a young tree with 20 to 80 ppb of PAN.

6.2.3 Acid Rain

Acid rain is also a serious environmental problem. Over the past two decades, an increased amount of strong inorganic acids appeared in the precipitation over much of northern Europe and the northeastern United States, causing the pH of the rainfall to drop to levels of 4.0 and less (Royal Ministry of Foreign Affairs 1972; Likens and Bormann 1974). This trend is linked to mounting levels of gaseous pollutants such as sulfur and nitrogen oxides, which can be converted chemically in the atmosphere to strong acids (H_2SO_4 and HNO_3).

Although the effects of acidified rain on trees and ecosystems have not been intensively studied, recent investigations suggest that increases in precipitation acidity may cause: (1) a decrease in the pH and base saturation of forest soils; (2) an increase in foliage losses of the forest canopy (Eaton, Likens, and Bormann 1973); and (3) abnormal needle development in some species of pines (Gordon 1968). These may, in turn, cause a reduction in forest productivity by limiting the availability of nutrients or by reducing the tree's ability to assimilate them successfully.

To test the possible effects of precipitation pH on the development of plants, Wood and Bormann (1974) exposed the yellow birch seedlings to artificial acid mists ranging in pH from 4.7 to 2.3 for up to 15 weeks. Foliar tissue damage was observed at pH 3.0 and below. Significant growth decreases were observed at pH 2.3.

Kratky et al. (1974) reported that certain tomato plants grown under rain shelters averaged 5-kg per plant of salable fruit, whereas plants grown in natural rainfall yielded no salable fruit because of blossom drop, poor fruit set, or reduction in fruit quality. A pH drop from 5.0 to 4.5 in the rainwater caused a reduction in pollen tube germination from 5.3 to 2.2%.

6.2.4 Fluoride

The last major pollutant causing substantial damage to vegetation is fluoride. Fluorides are emitted during production of aluminum, steel, ceramics, and phosphate fertilizers and present a localized pollution problem. Fluoride injury occurs through direct interaction with plant enzymes or tissues or through induced changes in cellular nutrient and hormone balance (McCune and Weinstein 1971).

Atmospheric fluorides influence plant growth, as well as many enzymes and metabolic processes. The effect of fluorides on water balance has received less study. Navara and Kozinka (1967) found stomatal closure and reduced transpiration in several fluoride-fumigated plant species. Hydrogen fluoride fumigation on water economy was studied by Poovaiah and Wiebe (1973). Moisture, temperature, and sunlight influenced fluoride uptake. Soybean exposed to 15 ml/l fluoride levels for four days exhibited 60-70% reductions in transpiration rate, whereas exposures of six hours per day produced smaller reductions. Drought before exposure reduced fluoride injury owing to decreased stomatal uptake, while post-fumigation drought increased injury. High temperature or sunlight accelerated foliar injury by as much as 40%. Effects of interrupted fumigation during the day were somewhat less severe compared to those of continuous fumigation; nighttime fumigation caused only minor effects. Fluoride uptake was also much less from nighttime than from daytime fumigation.

6.3 NATIONAL DAMAGE ESTIMATE

The importance of air pollution damage to vegetation depends on an area's economy. The magnitude of air pollution varies within states and the nation as a whole, but losses assume significance when their magnitudes are determined at the local level (Lacasse and Weidensoul 1970).

Estimates of economic loss to agricultural crops and ornamentals from air pollution for 1964 are assessed by Stanford Research Institute (SRI) to be as high as $132 million. The breakdown of this estimate is given in Table 6-1.

Table 6-1. PLANT LOSSES RESULTING FROM AIR POLLUTION[a]

($ million)

Pollutant	Oxidants	SO_2	Fluorides	Total
Crops	78	3.3	4.3	85.6
Ornamentals	43	3.0	0.2	46.2
TOTAL	121	6.3	4.5	131.8

[a]Waddell 1974.

The total dollar loss to agricultural crops in the United States for 1964 was calculated to be $85.5 million and the loss to ornamentals $46 million. These loss estimates result from the most extensive survey of plant losses caused by air pollution in the United States, undertaken by Benedict, Miller, and Smith (1973) of Stanford Research Institute (SRI). To ensure national coverage in the survey by county, the counties selected were those in which the major air pollutants (oxidants, sulfur dioxide, and fluorides) were likely to reach plant-damaging concentrations. The selection was based on fuel consumption and large single-source emitters.

Based on emissions area and pollution episode days, the severity of the pollution in each county was estimated. In estimating a county's crop, the monetary worth of grass, hay, and pastures was calculated. Annual estimates of the value of forests and the maintenance cost of ornamental plantings were apportioned by area and population. The determination of the percentage loss to crops and ornamentals was based on the sensitivity of plant species to the pollutants. Then tables were prepared showing the loss that might be expected to crops and ornamentals in the counties. Applying these losses to the value of the crops, forests, and ornamentals grown in the polluted counties, the dollar loss value for each county was recorded. Finally, state, regional, and national estimates were obtained.

Although the loss estimate of $132 million generated in the SRI study for 1964 is the most defensible, it still reflects a lower bound of the plant-associated losses resulting from air pollution (Waddell 1974) because the reported losses do not reflect costs from grower relocation, crop substitution, reduction in productivity, and land erosion.

The SRI estimates are consistent with the individual estimates for California (Middleton and Paulus 1956; Millican 1971), Pennsylvania (Lacasse and Weidensoul 1970), New Jersey (Feliciano 1972; Dell 1973) and New England (Naegele, Feder, and Brandt 1972). States estimates of losses of ornamentals generated by the SRI model are higher than those developed through statewide surveys.

Assuming that the percentage value of crops lost in 1970 was the same as in 1964 and that the value of ornamental plantings increased by the same proportions as cash crops, Waddell (1974) estimated the cost of air pollution damage to vegetation to be $150 million. He rounded off this estimate to $0.2 billion (from a range of 50% or $0.1 to 0.3 billion). Refinement of the basic estimates that form the building blocks of the national estimates has been minimal.

National air pollution damages to vegetation in 1973 were estimated to be $2.9 billion.* The estimate reflects the application of new data on rural oxidant levels and results of yield loss experiments. Table 6-2 presents the detailed breakdown of this estimate.

TABLE 6-2. ESTIMATED AIR POLLUTION DAMAGE TO VEGETATION FOR 1973[a]

Pollutant	Vegetation Type	Damage ($ billion)
Oxidants	Crops	2.80
	Ornamentals	0.09
Sulfur Dioxide & acid rain	Forest	0.01
Fluorides		0.01
Total		2.90

[a]Heintz, Hershaft, and Horak 1976.

The oxidant damage to crops was estimated by multiplying yield loss coefficients corresponding to rural oxidant levels by 1973 crop values in those regions where high oxidant concentrations were suspected. The other values were obtained by updating Benedict's (1973) 1964 estimate.

In reviewing the studies of air pollution damages to crops, Hershaft (1977) noted that they focus upon the physical response; i.e., the influence of air pollution on the magnitude of outputs and inputs. The calculated economic damages assume that changes in outputs and inputs do not influence the unit price of the output or the costs of the inputs. The determination of these price effects requires a detailed econometric model of the particular agricultural market—such models should be applied to air pollution studies (Hershaft 1977).

Certain types of damages are not included in the above estimates because of the difficulty of assigning a monetary value including: reduced insolation due to absorption by atmospheric particulates, acid rain and other pollutants that harm plant foliage, and the cost of developing pollution-resistant plant varieties (Heintz, Hershaft, and Horak 1976).

*The detailed description used to estimate air pollutant damages to vegetation in 1973 is given by Heintz, Hershaft, and Horak (1976).

SECTION 7.0

AIR POLLUTION DAMAGE TO MATERIALS

7.1 OVERVIEW

The magnitude of the effects of air pollutants on materials under environmental conditions cannot be easily assessed. Its assessment, however, is less complicated than those of health or vegetation effects because both exposure and the target population can be controlled. Nevertheless, there are only a few useful damage studies, largely confined to corrosion of metals by sulfur oxides and soiling of exposed surfaces by particulates. Other air-borne pollutants that have been studied include nitrogen oxides and oxidants.

Environmental (e.g., organic gases) and climatic (i.e., humidity, temperature, sunlight, and air turbulence) variables have to be considered (Liu and Yu 1976) in studying material damage for air pollution. Humidity is particularly important in the corrosion of metals; the critical humidity level that produces a sharp rise in corrosion rates varies 60-90% depending on the specific pollutant and target metal. Wind speed enhances the contact of pollutants, including the contact between abrasive particulates and the material surface. Elevated temperature increases the rate of chemical attack. Sunlight contributes to the formation of photochemical oxidants. Inorganic gases tarnish and corrode metals; attack stone, marble, slate, and mortar; and deteriorate natural and synthetic fibers.

Particulate pollutants soil the surfaces on which they are deposited. They may also catalyze the corrosive reactions between metals and acid gases. Additional damages to surfaces and textiles include wearing imposed by extra cleaning of particulate soiling. Degradation of painted surfaces may take the form of chalking, cracking, erosion, flaking, or changes in the color or tensile strength of paints. Sulfur oxides act synergistically with oxidants and moisture to form sulfuric acid, which causes corrosion of metals, damage to electrical contacts, deterioration of paper, textiles, leather, finishes, and coatings, and erosion of building stone strength by conversion of calcium carbonate to the soluble sulfate. Ozone shortens the life of rubber products, dyes, and paints. Nitrogen oxides also cause fading of dyes and paints.

A pollutant's effects under the same environment may vary widely from one material to another; therefore, the target population of materials must be accurately specified. To determine the effects of long-term exposures of air pollutants to various materials, test panels have been exposed for long periods of time. The results of these field studies are questionable because of the poor ambient level measurements and the failure to account for all environmental variables. Laboratory studies have attempted to determine short-term effects by subjecting test panels to elevated pollutant concentrations. These studies confirm that humidity exerts a major influence on the severity of most effects, with temperature and air flow playing significant but lesser roles (Hershaft, Morton, and Shea 1976).

7.2 REVIEW OF INDIVIDUAL STUDIES

Among the common air pollutants, sulfur oxides (SO_x) have generated the most concern. Despite its importance, only a few studies on the effect of SO_x have been reported. Haynie and Upham (1971) reported that the three types of steel exposed to SO_2, NO_x, and O_x at eight urban sites showed an increased corrosion with higher SO_2 level, but

decreased corrosion with higher oxidant concentrations. They also exposed test samples of zinc in eight urban areas and found that the amount of SO_2 in the air is the major factor in determining the rate of zinc corrosion. They concluded that little zinc corrosion would occur in an environment in which SO_2 was not present (Gillette and Upham 1973).

Spence, Haynie, and Upham (1975b) demonstrated a dose-response relationship for galvanized steel and SO_2, NO_2, and O_3 in controlled environmental chambers. Of the three pollutants, SO_2 was shown to help determine the corrosion rate of galvanized steel. In a similar chamber study for weathering steel, they found that corrosion accounts for 99% of the variability for the clean air and pollutant experimental data (i.e., relative humidity, temperature, and SO_2) (Spence, Haynie, and Upham 1975a).

Spence and Haynie (1974) exposed specimens of zinc to polluted and clean air in controlled environmental chambers. Uniform corrosion of zinc occurred in the polluted exposures, whereas pitting corrosion of zinc was observed in the clean air exposures.

Fink, Buttner, and Boyd (1971) investigated the corrosion of galvanized steel structures in clean and polluted atmospheres. They attempted to develop a more realistic assessment of the added cost of corrosion damage to metals in the United States from both technical and economic viewpoints. National shipment value data were used to compute average pollution costs. The economic marginal cost of corrosion caused by air pollution over the typical cost in clean air service was determined by: (1) the extra amount of protection and maintenance required in polluted atmospheres to prevent serious corrosion attack, and (2) the cost resulting from the shortened life of the structures caused by corrosion from polluted air. The total corrosion cost for nine major categories of materials most damaged by air pollution (outdoor metal work, chain link fencing, pole line hardware, galvanized wire and rope, steel storage tanks, bridges, streetlight fixtures, power transformers, and transmission towers) was about $1.45 billion or approximately $7.10 per person per year.

Sulfur dioxide was found to be the most important corrosive pollutant. For example, the accelerated corrosion of zinc by SO_2 accounted for more than 90% of the national economic burden imposed by air pollution corrosion. They projected the annual damage costs of metals owing to SO_2 under a variety of SO_2 concentration levels. Damages are estimated to increase from the present $1.45 billion to $2.1 billion by 1980 if there is a 55% increase in pollution. A 10% increase in the SO_2 level would result in an increase in annual loss by $0.3-1.73 billion in 1980.

Waddell (1974) believes that the Fink, Buttner, and Boyd study makes a systematic and reasonable estimate of the costs of corrosion to materials and the costs of related losses. However, he identified the following weaknesses: (1) no attempt is made to relate material damage to the severity or type of air pollution and (2) the role of relative humidity in the corrosion and deterioration of materials is not considered.

Gillette and Upham (1973) applied the same approach to a much more comprehensive assessment of the economic damages from SO_x and relative humidity by SMSA. While the Fink et al. study supposes that about 80% of materials are located in polluted areas, Gillette assumes that materials are distributed according to human population. Data on population distributions, SO_2, and an average annual relative humidity for about 150 SMSAs for the years 1968-1972 were used to estimate materials' populations-at-risk.

Applying the best available damage function data for corrosion and paint deterioration, Gillette estimated for 1970 that SO_x damage to metals and paints was approximately $0.4 billion. He also concluded from dose-response data that SO_x effects on textiles, building materials, leather, paper, and dye fading are economically negligible because materials are exposed to indoor air where pollutant levels are much lower than outdoor air, current SO_2 levels are generally lower than several years ago (presumably because of the substitution of cleaner fuels), and the service life of many of the materials is short.

Salmon (1970) undertook the most comprehensive study on pollution damage to materials. The study presented a systematic analysis of all of the physical and chemical interactions among 53 economically important materials, pollutants, and environmental parameters. The rate of economic loss was calculated as the product of the economic value of material exposed to air pollution and an interaction value. The value of interaction was calculated by estimating the difference between the rate of material deterioration in a polluted and a clean environment, expressed as dollars lost per year. An estimated $100 billion in added cleaning costs would be necessary to keep these materials in polluted areas as clean as they would be in a nonpolluted environment. Deterioration of these materials causes yearly damage losses of approximately $4 billion. Paint and zinc are most affected by soiling and deterioration, accounting for more than half of the total losses in each category.

In decreasing order of economic importance, the pollutants and the materials they damage are as follows: (1) SO_2 (metals, cotton, finishes, coatings, building stone, paints, paper, and leather); (2) O_3 (rubber, dyes, and paints); (3) NO_x (dyes and paints); (4) CO_2 (building stone); and (5) particulates (stone, clay, and glass) (Salmon 1970).

Sulfur dioxide and particulate matter play an important role in the chemical deterioration of exterior paints. Spence and Haynie (1972) examined the chemical damage of air pollutants for four classes of exterior paints (household, automotive refinishing, coil coating, and maintenance). The total cost was estimated at $0.7 billion annually. Household paints sustain damage representing 75% of the total.

Recent work by Spence, Haynie, and Upham (1975c) showed that SO_2 concentration and relative humidity accounted for 61% of the variability in oil base house paint, which experienced the highest erosion rates. Vinyl and acrylic coil coatings showed very low erosion rates.

The major effects of particulate exposure on materials are soiling and deterioration of painted and other exposed surfaces. Painted surfaces degrade by chalking, cracking, eroding, flaking, or changing the color or tensile strength of paint films. A major problem from atmospheric pollution is the increased rate of soiling. Beloin and Haynie (1975) examined the soiling of various building materials and associated soiling to concentration levels of atmospheric particulates. Painted cedar siding, concrete block, brick, limestone, asphalt shingles, and window glass were exposed at five sites in Birmingham, Ala. to particulate levels ranging from an annual geometric mean of 60 mg/m^3 at the clean site to 250 mg/m^3 at the most polluted site over a two-year period. Soiling was expressed in terms of reflectance measurements for opaque surfaces and as haze measurements for glass. The degree of soiling of painted cedar siding was proportional to the square root of the particulate exposure, whereas the degree of soiling for shingle siding was directly proportional to the exposure. Soiling of limestone, concrete, brick, and glass surfaces showed no clear correlation with particulate exposure.

The maintenance frequency of painted surfaces exposed to particulates has been investigated in Philadelphia by Booz-Allen and Hamilton Inc. (1970) and in five other locations by Michelson and Tourin (1967). The results indicated that the intervals between repainting decreased as the particulate concentrations increased. Although there appears to be a positive relationship between frequency of repainting and particulate concentrations, the doubtful data generated in the Michelson and Turin study makes its use questionable (Waddell 1974). Many of the analytical and statistical problems in the Michelson studies were minimized in the Booz-Allen and Hamilton study.

Damages to materials from oxidants and oxides are expressed in premature fading of fabric dyes. Spence, Haynie, and Upham (1975c) reported the fading of three drapery fabrics after exposure to air pollutants and other environmental influences. Nitrogen dioxide (NO_2) was a major factor in determining the fading rate for one of the fabrics. The other two fabrics did not fade significantly in the presence of the air pollutants.

Beloin (1973) examined twenty dye fabrics exposed to two levels each of NO_2, O_3, and SO_2. Appreciable dye fading was caused by O_3 and SO_2, whereas NO_2 has little or no effect. In another study, Salvin (1970) estimated costs of dye fading in textiles attributed to NO_x and O_3 to be approximately \$0.2 billion.

Correlating the effects of air pollution on rubber products Stickney, Mueller, and Spence (1971) estimated the yearly pollution cost; total cost at the consumer level was about \$500 million. They concluded that ozone causes almost all damage to rubber. Very little is known about effects of other pollutants on elastomers.

7.3 NATIONAL ESTIMATES OF DAMAGES TO MATERIALS

Based on the studies reviewed in the previous section, Waddell (1974) developed a national gross damage estimate of \$2.2 billion in 1970 for pollution-caused material damage. Because these studies are inexact, this estimate is only indicative of the general magnitude of damage in 1970. This estimate is the sum of the following studies: \$0.5 billion (rounded off) from the Stickney, Mueller, and Spence (1971) elastomer; \$0.4 billion from the Gillette and Upham (1973) SO_x; \$0.2 billion from the dye-fading (Salvin 1970); \$0.7 billion from the Spence and Haynie (1972) paint; and \$0.4 billion from the Salmon study.*

Heintz, Hershaft, and Horak (1976) estimated damages to materials from air pollution in 1973 to be \$1.9 billion (Table 7-1). This estimate is based on studies summarized by Waddell (1974).

The national gross damage estimates of the two studies by Waddell (1974) and Heintz, Hershaft, and Horak (1976) disagree, although both are based on the same studies. Heintz adjusted the Spence and Haynie (1972) estimate of damage losses to eliminate overlap between residential painting and property value damages and has not adjusted the Salvin (1970) estimated costs of dye fading in textiles. Changes in stocks of exposed materials were not adjusted.

*Adjusted to eliminate overlap with other materials damage estimates.

Table 7-1. ESTIMATES OF DAMAGE TO MATERIALS[a]

Material	Source	1973 Damages ($ billion)
General Materials[b]	Salmon (1970)	0.5
	Gillette (1973)	0.5
Elastomers	Mueller and Stickney (1970)	0.6
Dyes	Salvin (1970)	0.2
Paints	Spence and Haynie (1972)	0.2[c]
		1.9[d]

[a]Heintz et al. 1976.

[b]Adjusted to eliminate overlap with other materials damage estimates.

[c]Adjusted to eliminate overlap between residential painting and property value damages.

[d]Values do not add up because of rounding.

SECTION 8.0

NATIONAL GROSS DAMAGES OF AIR POLLUTION

8.1 OVERVIEW

Previous sections examined methods of economic valuation of environmental damages of air pollution. Difficulties that beset these studies center around distinguishing the effects of different pollutants, nonuniform definitions of damage, and the difficulty of attaching monetary values to damage. Among the methods for estimating the cost of air pollution, only two give marginally defensible damage estimates—the market (property value) and technical coefficients methods.

Damages from total suspended particulates (TSP), sulfur oxides (SO_x), hydrocarbon(HC), carbon monoxide (CO), and nitrogen oxides (NO_x) were examined. This section investigates the aggregate effect of all these air pollutants and summarizes estimates of national gross damages of air pollution for health, aesthetics, vegetation, and materials.

8.2 GROSS ESTIMATES

National gross air pollution damage estimates are based on studies by Barrett and Waddell (1973) and Waddell (1974), which use results from studies discussed in previous sections.

Gianessi et al. (1977) estimated the national air pollution damages (in 1970 dollars) of the total 1968 emissions of five principal air pollutants: TSP, SO_x, HC, NO_x, and CO (Table 8-1). Their estimate is based on the Barrett and Waddell (1973) estimate of total U.S. damage from air pollution of $16.1 billion, which does not include the effects on health and property of the mobile-source pollutants (i.e., CO, HC, and NO_x) and the Babcock and Nagda (1973) estimate of $20.2 billion. To account more fully for the probable health and property damages of mobile-source pollutants, Babcock and Nagda used estimates of the relative severities of air pollutants. As a result, their estimate is substantially higher than that derived by Barrett and Waddell. Table 8-1 presents the Babcock and Nagda estimates of pollutant damages.

The Babcock-Nagda estimate is complicated by two problems. First, the relative severities rely on EPA air quality standards, which depend on EPA estimates of the pollutant's effects on health. Hence, a close correlation between health effects and materials damage is implicit in their nonhealth damage estimates for HC and NO_x. Second, threshold health effects helped to establish severity rates. Whether these threshold concentrations can be translated into dollars is questionable.

Heintz et al. (1976) prepared a more recent national estimate of air pollution damage for 1973 for the four major classes of benefits, in terms of best estimates and corresponding ranges. The estimates, based on studies summarized by Waddell (1974), were updated to determine the national gross damages for 1973.

TABLE 8-1. NATIONAL AIR POLLUTION DAMAGE ESTIMATES FOR 1968[a]

(1970 dollars)

Pollutant[b]	Tons x 10^6	\$ x 10^6
PM	141.3	5,878
SO_x	33.2	8,295
NO_x	20.6	3,062
HC	32.0	2,667
CO	100.1	250
TOTAL	327.2	20,152

[a]Gianessi et al. 1977, p. 206.
[b]PM = particulate matter;
SO_x = sulfur oxides;
NO_x = nitrogen oxides;
HC = hydrocarbons; and
CO = carbon monoxide.

The best estimate of $20.2 billion understates the total air pollution damages because it does not reflect important potential damages such as the threat to preservation of the environment (including unique ecosystems and species) and the value of lost leisure time or the psychic costs of illness and death. In the Heintz, Hershaft, and Horak (1976) estimate (see Table 8-2), the effects on health and property of CO, HC, and NO_x, the mobile-source pollutants, are not included. Thus, it significantly understates the total damage of air pollution.

Table 8-2. ESTIMATED NATIONAL DAMAGES OF AIR POLLUTION FOR 1973[a]
($ billion)

Damage Category	Best Estimate	Range	
		Low	High
Health	5.7	2.0	9.4
Aesthetic	9.7	5.7	13.7
Vegetation	2.9	1.0	9.6
Materials	1.9	0.8	2.7
TOTAL	20.2	9.5	35.4

[a]Heintz, Hershaft, and Horak 1976.

8.3 SUMMARY

Economic techniques for evaluating benefits resulting from air pollution abatement are well developed. Economics provides the concept of benefits and basis of their measurement (Hershaft 1977). Benefit estimation, however, must be built upon a noneconomic base. To estimate health benefits owing to an improvement in air quality, one needs to know the relationship between pollutant concentrations and health. Lack of basic information about the relationship between pollutant levels and physical properties of a material severely limits estimation of economic benefits.

In estimating benefits at the national level, one proceeds by estimating benefits for each region's air or water basin and then summing them over the nation. The severity of air pollution damage is often regionally dependent (with regions defined as air sheds, river basins, or political subdivisions). Regional data constitute the building blocks of national estimates. Freeman in Hershaft (1977, p. II-4) noted that: "If nothing meaningful can be said about the benefits of a specific pollution control plan in a particular region, then no meaningful aggregation to the national level is possible."

Successful benefit estimation at either the local or national level is limited because:

- noneconomic data (dose-response functions) are often unavailable;
- issues remain unresolved concerning the economic value of life and health and aesthetics; and
- demographic and economic data are seldom available at modest cost.

This lack of knowledge about key parameters and relationships seriously undermines usefulness of the benefit-cost analysis.

SECTION 9.0

SUMMARY AND CONCLUSIONS

The densities, energy consumption, and economic development of the increasing population exacerbate environmental degradation. Air and water pollution is a major environmental problem affecting life and health, outdoor recreation, household soiling, vegetation, material, and production. The literature review indicated that numerous studies have assessed the physical and monetary damage to populations at risk from excessive concentrations of major air and water pollutants—sulfur dioxide, total suspended particulate matter, oxidants, and carbon monoxide in air and nutrients, oil, pesticides, and toxic metals and others in water. The measurement of the damages was one of the most controversial issues in pollution abatement.

9.1 POLLUTION DAMAGE QUANTIFICATION

Numerous studies pointed out that the methods most often employed in past empirical studies to determine the societal value of pollution abatement are: (1) chain of effects, (2) market approaches (property value and wage differential studies), and (3) surveys. Because of their conceptual and empirical perspectives, the market studies are most insightful about air and water pollution damages. In applying property values to estimate the economic losses resulting from air and water pollution, the analyst uses market information (observable market prices) to evaluate the pollution sufferer's adjustments and to make individual properties commensurable to aggregate them. The second market study approach uses the wage differentials among urban areas to infer the willingness to pay for clean air. The primary concerns in applying the market methods are: (1) the assumed explicit market for the amenities of clean air and water and (2) the extent to which the water and property value benefits overlap the benefits obtained from health and benefits from related studies.

The chain of effects and survey methods help one to understand how environmental changes mold attitudes about pollution. The chain-of-effects method, based on the application of physical or biological damage functions, illuminates receptor-response to air and water pollution. Opinion surveys, surveys of legislative decisions or litigation awards, and delphi and bidding games analyze a person's perception of the effects of air and water pollution. These methods are less successful than the market study approaches in environmental damage measurement because of theoretical problems, subjective opinion, and the complexities of dose-response information.

The reviewed empirical studies indicate a lack of an ideal methodology to convert non-market benefits and costs into market-measure dollars. Even if pain, suffering, excess death, and reduced life expectancy could be measured, dollar values for them would still be unknown.

The greatest deficiencies in economic measurement of environmental damages are caused by the lack of acceptable damage functions based on empirical research. Damage functions relate one's willingness to pay to avoid air or water pollution. The development of such functions requires the use of complex models of the diffusion and assimilation of specific pollutants with their respective media. For example, transformation of sulfur dioxide concentrations requires the use of a long distance transport model that has the capability of reflecting:

- source conditions such as stack height and plume exit temperature;
- meteorological conditions such as wind direction and speed, mixing height, humidity and rainfall;
- pollutant characteristics such as chemical transformation rates for converting sulfur dioxide into sulfates and wet and dry deposition rates for sulfur dioxide and sulfates; and
- atmospheric conditions such as presence of catalytic oxidants and particulates that speed or inhibit conversion of sulfur dioxide into sulfates.

Although the documented results regarding the economic effects of air or water pollution on health, materials, vegetation, soiling, aesthetics, and residential property values are becoming available, the physical and economic damage functions are still in the embryonic stage. There are no satisfactory methods for allocating damages among synergistically interacting stresses, nor can the damages themselves be easily measured and reduced to economic terms.

9.2 WATER POLLUTION DAMAGES

The most damaging pollutants to municipal water supply, households, industry, agriculture, commercial fisheries, and materials are:

- physical constituents (odor, color, turbidity, temperature);
- microbiological organisms (coliform organisms and fecal coliforms);
- inorganic chemicals (alkalinity, ammonia, arsenic, barium, iron, lead, sulfate, fluoride, dissolved oxygen, pH, total dissolved oxygen, zinc, and many others);
- organic chemicals (pesticides, aldrin, endrin, chlordane, organic phosphates, carbonates, heptachlor, oil and grease, carbon chloroform extract, cyanide, herbicides).

The literature contains numerous estimates of the economic damages from water pollution. There are two major techniques to estimate water pollution damages: (1) opinion surveys, and (2) expenditure method. Most of the reviewed studies of water pollutants (fecal coliforms, BOD, salinity, toxic substances, and temperature) concentrate on swimming, boating, and fishing. In estimating damages to outdoor recreation the following variables were considered: (1) the change in water quality, (2) reactions to changes in water quality, (3) the value of recreation experiences, and (4) the number of recreation days.

Some of the empirical studies applied the expenditure method to determine the value of recreation that equates benefits and expenditures. Empirical evidence indicates three effects from a decrease in water quality: (1) increased costs, particularly travel costs because of shifts to less polluted waterways located farther from major population centers; (2) decreased participation in water-based recreation; and (3) decreased value of recreational experiences because of poorer water quality.

Only Heintz, Hershaft, and Horak (1976), using the expenditure method, estimated the 1973 national damage of water pollution on recreation—$6.3 billion.

The estimated national production damages of water pollution in 1973 are $1.6 billion (Heintz, et al. 1976), the sum of estimates presented in the empirical studies surveyed in this research report. Production impacts include raw material refinement, treatment and distribution, and process changes necessitated by deteriorating water quality, agricultural, municipal, and industrial structure changes; capital losses; employment impacts; and losses from relocating to meet mandatory pollution abatement standards.

Most of the empirical studies concentrate on the property value damages from water pollution not included in the estimates of material damages. The resulting estimates of the property value damages from water pollution duplicate estimates for other areas such as outdoor recreation. The property value damages from water pollution not included in the estimates of material damages in 1973 were approximately $84 million (Heintz et al. 1976).

Only a few fragmented studies investigated illness (infectious hepatitis, malaria, leptospirosis, congenital heart anomalies, mercury poisoning, cadmium poisoning, alteration of liver functions, and acute myocarditis and pericarditis) resulting from microbiological inorganic chemicals, organic chemicals, radioactivity, and physical water pollutants. The economic consequences of national damages from water pollution are minimal—medical service demands, productive work lost, and human life lost.

Approximately $677 million of damages could have been avoided in 1973 through reduction of bacterial and viral pollutants (Heintz, et al. 1976). This estimate does not include damage from cancer, which is approximately $1 billion (Page et al. 1976).

The estimated national gross damage of water pollution for 1973 is a substantial $11.1 billion. This value includes (1) the $10.1 billion estimated by Heintz et al. (1976) and (2) $1 billion per year for health care and foregone income as a result of increased carcinogens in drinking water obtained from surface water estimated by Page et al. (1976).

Most empirical studies on benefit cost analysis of water pollution are of limited value because there is: (1) a lack of behavioral relationships between water quality and consumer behavior, (2) inadequate knowledge concerning why people consume leisure-type environmental activities, (3) substantial difficulty in extrapolating recreation benefits in small areas to national aggregates, and (4) lack of a procedure that monetizes the aesthetic and option demand (Stevens in Hershaft 1977).

9.3 AIR POLLUTION DAMAGES

Categories affected by air pollution damages are: (1) damage to life and health, (2) damage to aesthetics, (3) damage to vegetation, and (4) damage to materials.

9.3.1 Damage to Life and Health

A number of studies have attempted to place monetary values on air pollution damages to life and health. Mortality and morbidity attributable to total suspended particulate matter (TSP), SO_x, NO_x, O_x, CO, HC, and radiation are the best documented and defined health indicators. Specific diseases associated with air pollution are bronchitis, emphysema, asthma, respiratory infections, heart disease, cancer of the respiratory and digestive tracts, and chronic nephritis.

In estimating the health effects of air pollution one must consider: (1) pollutants, (2) meteorological conditions, (3) personal characteristics (smoking and drinking habits, occupation, marital status), and (4) socioeconomic-demographic particulars (household income, race, sex, age) that result in mortality and morbidity. In chemical reactions of pollutants, meteorological conditions act independently of or in conjunction with air pollution to harm one. Personal and socioeconomic-demographic characteristics influence the incidence of diseases affected by pollution.

Epidemiological studies indicate an inverse relationship between air quality and mortality. These studies use two major approaches to calculate mortality rates for populations exposed to different air quality levels and to translate the physical damage into monetary terms. The first approach, the damage factor method, involves three steps: (1) estimating the value of total health losses, (2) determining a proportionality factor for the share of this value attributable to air pollution, and (3) multiplying total health losses by this factor to obtain the value of health losses from air pollution.

The second approach investigates the relationship between air pollution and mortality rates using multivariate regression analysis, controlling for socioeconomic variables. The major difficulties in estimating a physical damage function include: (1) errors in variables, nonnormality, heteroscedasticity, multicolinearity among air pollution, and other explanatory variables; and (2) lack of knowledge of the shape of the function that depicts the relationship between air pollution and health.

The health damages attributed to air pollution in 1973 have been estimated to be $5.7 billion (Heintz, et al. 1976). This estimate is based on the updated results of the work of Lave and Seskin (1977), Waddell (1974), Rice (1966), and EPA (1974). In considering the practical value of the $5.7 billion of damages to human health and life from air pollution, one should note that they reflect only costs of medical care expenses and foregone earnings or productivity. They do not include the value of leisure time lost through illness and of time lost by people who do not receive monetary compensation for their labor.

9.3.2 Damage to Aesthetics

Aesthetic effects of high concentrations of air pollutants (principally, components of photochemical smog, suspended particulates, and the host of other minor pollutants) imposed on urban dwellers take the form of reduced visibility, irritation of eyes, nose, or throat, and bad odors—all result in changes in property values.

The aesthetic damages are monetarily measured by assessing people's willingness to pay for both marginal and nonmarginal improvements in air quality through opinion surveys of air pollution sufferers or through market studies that employ property values to measure air pollution losses.

The aesthetic harm from air pollution for 1973 was estimated to be $9.7 billion (Heintz, et al. 1976) from property value studies synthesized by Waddell (1974). The total damage estimates based on the property value studies reflect only those damages capitalized in the residential property market and measured through site and improvement differential values. To estimate total damage costs using property values, one must conduct separate studies for residential, commercial, and agricultural land.

9.3.3 Damage to Vegetation

Studies about the adverse effects of air pollutants (SO_x, O_x, acid rain, and fluoride compounds) on vegetation are voluminous but inconsistent. Most of the studies determine susceptibilities of individual plants rather than a broadly applicable relationship between dose and effect.

The two categories of the effects of air pollution on vegetation are: (1) visible effects (acute and chronic injury), and (2) subtle effects. Two variables, pollutant concentration and exposure duration, help one to understand pollutant harm to vegetation. Soil type, plant age, temperature light intensity, and humidity also contribute to plant injury. From these variables and dose-response relationships, physical damage functions have been constructed.

Two general approaches have been used to assess the economic loss of plants resulting from air pollution. The first surveys the damage losses statewide by using local county agricultural agents and commissioners. These local estimates of damage are extrapolated to the national level to arrive at a crude estimate of gross damages. The second method constructs predictive models by relating data on crop losses to crop values, pollution emission, and meteorological parameters.

The total economic loss from air pollution damage to vegetation including agricultural crops and ornamentals for 1973 is as high as $2.9 billion (Heintz et al. 1976). This estimate includes both visible and subtle effects on vegetation.

9.3.4 Damage to Materials

Only a few useful studies present the effects of air pollutants on materials. Most of these studies are largely confined to metal corrosion by sulfur oxides and soiling of exposed surfaces by particulates. Other pollutants that have been studied are nitrogen oxides and oxidants. Environmental (e.g., organic gases) and climatic (i.e., humidity, temperature, sunlight, and air turbulence) variables have also been considered in these studies.

To develop reasonable estimates of air pollution damages to materials, one needs the following information: (1) the geographical and temporal distribution of air quality levels and receptors' exposure to pollution, (2) physical damage functions for important receptors, and (3) regional data on other socioeconomic, demographic, and environmental factors.

Based on a number of studies summarized by Waddell (1974), Heintz et al. (1976) estimated the materials damages attributed to air pollution in 1973 were approximately $1.9 billion.

9.3.5 National Gross Damages

The estimates of national gross damages of air pollution on health, aesthetics, vegetation, and materials are based on the studies by Barrett and Waddell (1973) and Waddell (1974).

The value of national gross damages (in 1970 dollars) of the total 1968 emissions of the five principal air pollutants—TSP, SO_x, NO_x, HC, and CO—was estimated to be $20.2 billion (Gianessi et al. 1977). This figure is based on the Barrett and Waddell (1973) estimate of the U.S. damage from air pollution of $16.1 billion (that does not include the effects on health and property of CO, HC, and NO_x) and the Babcock and Nagda (1973) estimate of $20.2 billion. To account more fully for the probable health and property damages of mobile-source pollutants, Babcock and Nagda used estimates of the relative "severities" of air pollutants. As a result, their estimate is substantially higher than that derived by Barrett and Waddell.

The Babcock-Nagda estimate is complicated by two problems. First, the relative severities rely on EPA air quality standards which depend on EPA estimates of the pollutants' health effects. Hence, a close correlation between health effects and materials damage is implicit in their nonhealth damage estimates for HC and NO_x. Second, threshold health effects helped to establish severity rates. Whether these threshold concentrations can be translated into dollars is questionable.

Heintz, Hershaft, and Horak (1976) prepared a more recent national press estimate of damages from air pollution for 1973 for the four major classes of benefits in terms of best estimates and corresponding ranges. This best estimate is $20.2 billion but does not include the effects of health and property of CO, HC, and NO_x, the mobile-source pollutants.

The best estimate of $20.2 billion understates the total air pollution damages because it does not reflect important potential damages such as the threat to preservation of the environment (including unique ecosystems and species) and the value of lost leisure time or the psychic costs of illness and death.

Economic losses from air pollution on domestic animals and wildlife and the natural environment are not estimated because of data limitations. Another problem with gross damage estimates is that the value of life implicit in them is based on lost productivity rather than willingness to pay for reductions in the probability of death. Willingness to pay for increased life expectancy in the range of $340,000 to $1 million, rather than $30,000 per life, as the recent studies suggest, would substantially elevate the air pollution damages to health (Yokell 1978).

But information on air pollution damages still helps policy makers to understand the seriousness of air pollution and to realize the benefits of abating air pollutant emissions.

9.4 CONCLUSIONS

National gross damages of air pollution of $20.2 billion and of water pollution of $11.1 billion for 1973 are substantial. These best estimates, updated for the economic and demographic conditions, could provide acceptable control totals for estimating and predicting benefits and costs of abating air and water pollutant emissions.

Although the economic theory and analytical techniques for evaluating most classes of benefits are relatively well developed, these major issues remain: (1) lack of availability of noneconomic data (dose-response function), (2) theoretical and empirical difficulties of placing a value on human life and health and on benefits such as aesthetics, and (3) lack of availability of demographic and economic data. Freeman in Hershaft (1977) recommends that:

- More effort should be devoted to large-sample, carefully controlled epidemiological studies to examine long-term chronic and short-term acute effects of air pollutants. An attempt should be made to move beyond the interurban comparisons similar to those of Lave and Seskin (1977).
- Studies on the value of human life should be extended in two directions: the individual willingness-to-pay model, in which one element of choice is a small change in the probability of death, should be developed further; and government and other collective decisions involving safety, health, medical research, etc., should be analyzed carefully to determine the implied or explicit values placed on human life or changes in the probability of death.
- A series of surveys of recreation participation should be commissioned by the U.S. EPA to determine values for recreation days and their variance with changes in water quality and other attributes of recreation sites.
- A series of studies should be designed to investigate property value using improved measures of property value, consistent theoretical models, and consistent techniques for all cities.
- To develop a comprehensive estimate of national benefits of pollution control, a group of experts with backgrounds in environmental economics, the economics of project evaluation, econometrics, environmental health, limnology and marine biology, agricultural sciences, and engineering should be convened, perhaps under the auspices of the National Academy of Sciences.

SECTION 10.0

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16. Abstract (Limit: 200 words)

The densities, energy consumption, and economic development of the increasing population exacerbate environmental degradation. Air and water pollution is a major environmental problem affecting life and health, outdoor recreation, household soiling, vegetation, materials, and production. The literature review indicated that numerous studies have assessed the physical and monetary damage to populations at risk from excessive concentrations of major air and water pollutants-sulfur dioxide, total suspended particulate matter, oxidants, and carbon monoxide in air; and nutrients, oil, pesticides, and toxic metals and others in water. The measurement of the damages was one of the most controversial issues in pollution abatement. The methods that have been used to estimate the societal value of pollution abatement are: (1) chain of effects, (2) market approaches, and (3) surveys. National gross damages of air pollution of $20.2 billion and of water pollution of $11.1 billion for 1973 are substantial. These best estimates, updated for the economic and demographic conditions, could provide acceptable control totals for estimating and predicting benefits and costs of abating air and water pollution emissions. The major issues to be resolved are: (1) lack of available noneconomic data, (2) theoretical and empirical difficulties of placing a value on human life and health and on benefits such as aesthetics, and (3) lack of available demographic and economic data.

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