Section 3

3.0 *ENVIRONMENTAL IMPACTS OF POWER GENERATION*

3.1 *INTRODUCTION*

Most environmental impacts can be classified into those that primarily affect our air, water, or land. For example, emissions of nitrogen oxides (NO_x) from power plant stacks may affect smog levels; discharges of heated water into rivers and the Chesapeake Bay affect fish populations. Beyond environmental impacts, the construction of power plants and transmission lines can also affect valuable historical and archaeological resources.

Some activities at power plants can affect air, water, and land resources simultaneously. Acid rain, for example, arises partially from air pollutants that are released from power plant stacks, transformed in the atmosphere and then fall to the ground affecting lakes, rivers, and forests. Radiological releases from nuclear power plants enter the air, water, and river sediments. Each of these topics, as well as other environmental impacts of concern, are discussed in this chapter.

3.2 *AIR IMPACTS*

The combustion of fossil fuels to generate electricity at power plants in Maryland results in the release of air pollutants that can potentially degrade air quality, both locally and regionally. Since the 1970s, the U.S. Environmental Protection Agency (U.S. EPA) has taken action through provisions of the Clean Air Act (CAA) to monitor and control the effects of air pollutants from power plants and other sources. The first comprehensive CAA was passed in 1970. It has been amended twice, once in 1977 and again in 1990. The Act only regulates air quality over property to which the public has access (i.e., beyond plant fence lines). Air quality on privately owned property, such as power plants, is covered by regulations of the Occupational Safety and Health Administration, which is part of the Department of Labor.

The U.S. EPA has defined **National Ambient Air Quality Standards** (NAAQS), which are maximum ambient air concentrations of six pollutants known as **criteria pollutants**. NAAQS have been established to protect human health (primary standards) and welfare (secondary standards). The welfare standards are set to protect "quality of life" factors such as crops, soils, water, manmade materials, and visibility.

Currently in Maryland, measured ambient levels of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM), and carbon monoxide (CO) are within the standards set by the U.S. EPA (MDE 1994). Regions of the state in which the criteria pollutants are within standards are said to be "attaining the NAAQS," and are thus known as **attainment areas.** Figures 3-1, 3-2, and 3-3 (MDE 1994) show recent data on ambient concentrations of inhalable PM, SO_2, and NO_2, respectively, at various monitoring locations in Maryland.

While the entire state is attaining the NAAQS for PM, SO_2, and NO_2, many areas of Maryland are not meeting the NAAQS for ozone, making ozone one of three air quality issues of particular concern in Maryland. The ozone issue and the other two key issues — visibility and acid rain — are discussed in the following sections.

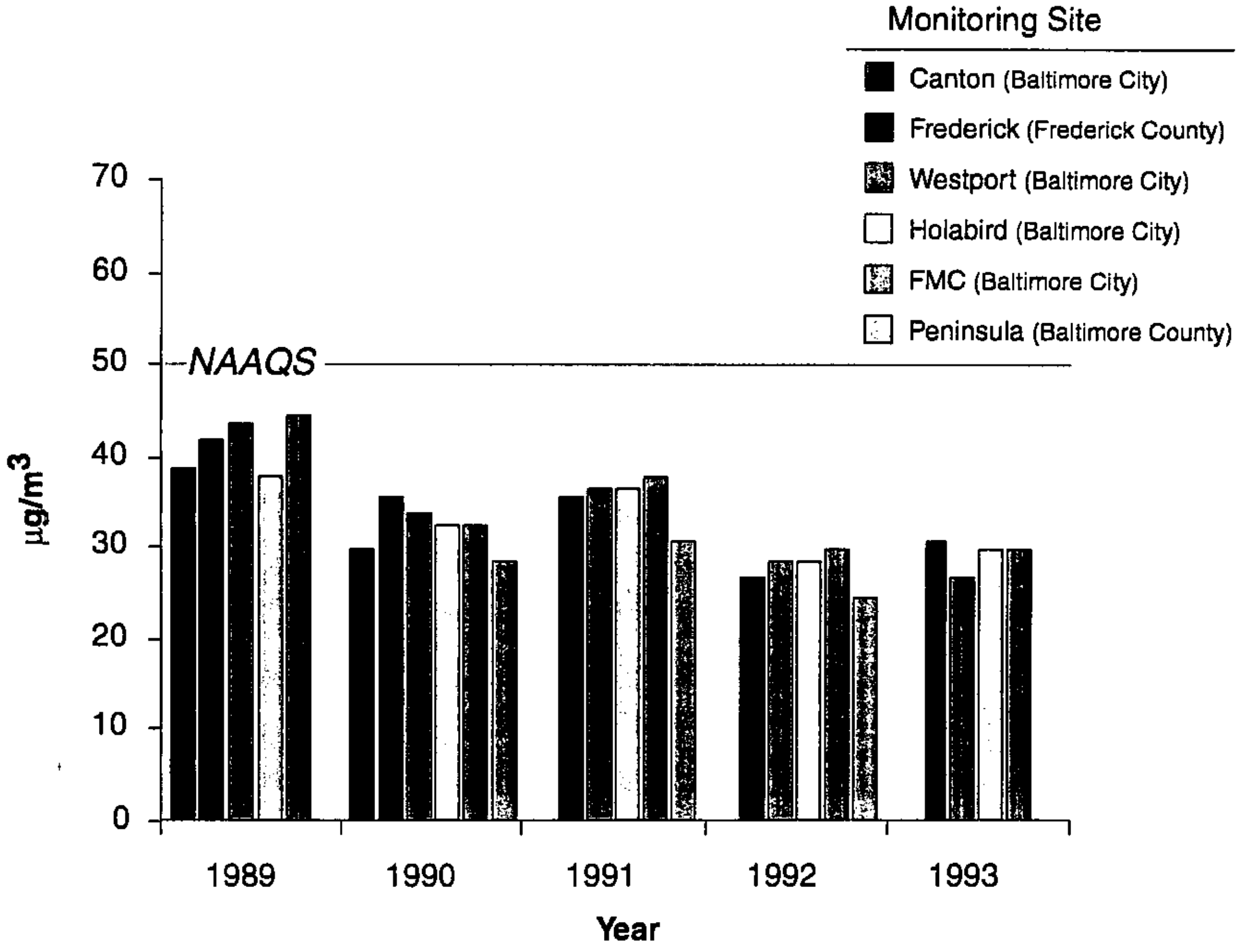
3.2.1 NO_x Emissions and Urban Ozone

Of the major pollutants for which the U.S. EPA has set NAAQS, the most pervasive problem continues to be ozone, an important component of urban smog. Ozone is formed when volatile organic compunds (VOCs) and NO_x react in the atmosphere under hot, stagnant weather conditions. One of the goals of the CAA is to bring areas that are not attaining the NAAQS (**nonattainment areas**) into attainment with the standard. In the past, ozone reduction strategies focused on controlling emissions of certain hydrocarbons, such as VOCs; however, recent studies indicate the need to control both VOC and NO_x emissions to attain the ozone NAAQS (USEPA 1991). Power plants are major sources of NO_x but only relatively minor sources of VOCs.

3.2.1.1 Ozone Levels in Maryland

Maryland's ozone air pollution is a significant concern. The ozone problems in the Baltimore and Washington, D.C. areas rank sixth and tenth worst in the nation, respectively (Wheeler 1994). Under the U.S. EPA's classification system for indicating the magnitude of ozone pollution, the Baltimore area is designated a "severe" ozone nonattainment area, and the Washington, D.C. area is designated a "serious" ozone nonattainment area (Figure 3-4). Violations of the ozone standard continue in Maryland. Figure 3-5 (MDE 1994) illustrates the number of days with maximum hourly ozone levels greater than the NAAQS, known as "violation days," for the Baltimore metropolitan region. Ozone measurements showed that the NAAQS was exceeded on 10 days in 1994 (Weiss 1995).

Figure 3-1
Annual Inhalable Particulate (PM_{10}) Ambient Concentrations in Maryland
(National Ambient Air Quality Standard = 50 μg/m³)



Locations of PM_{10} Monitoring Sites in Baltimore Area

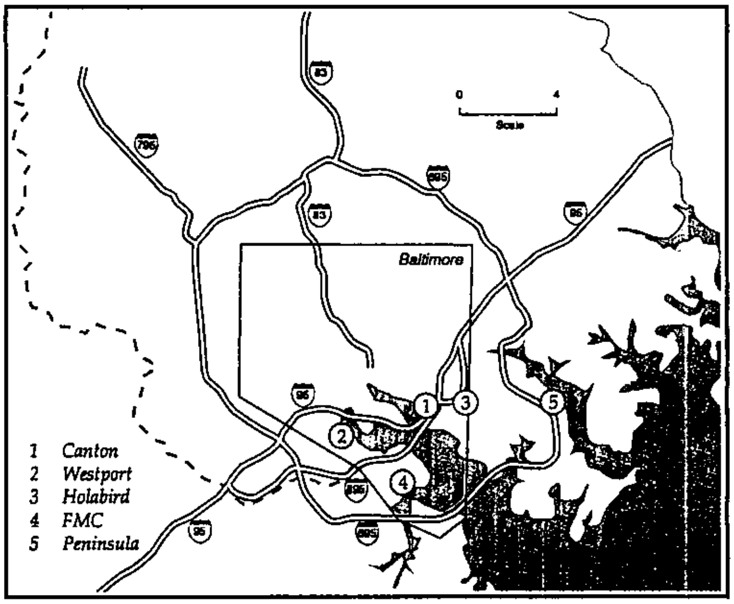
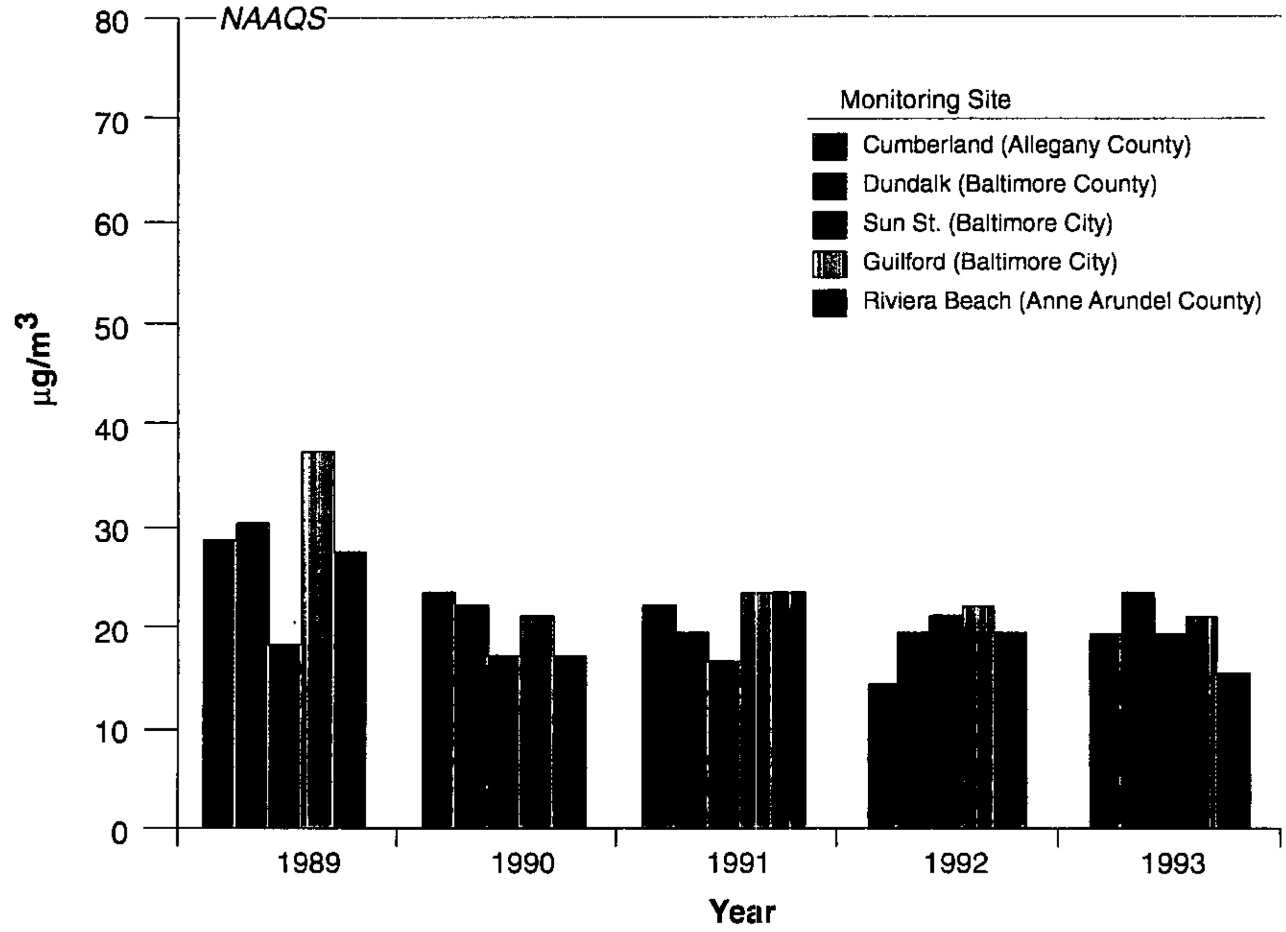


Figure 3-2

Annual Sulfur Dioxide (SO_2) Ambient Concentrations in Maryland

(National Ambient Air Quality Standard = 80 $\mu g/m^3$)



Locations of SO_2 Monitoring Sites in Baltimore Area

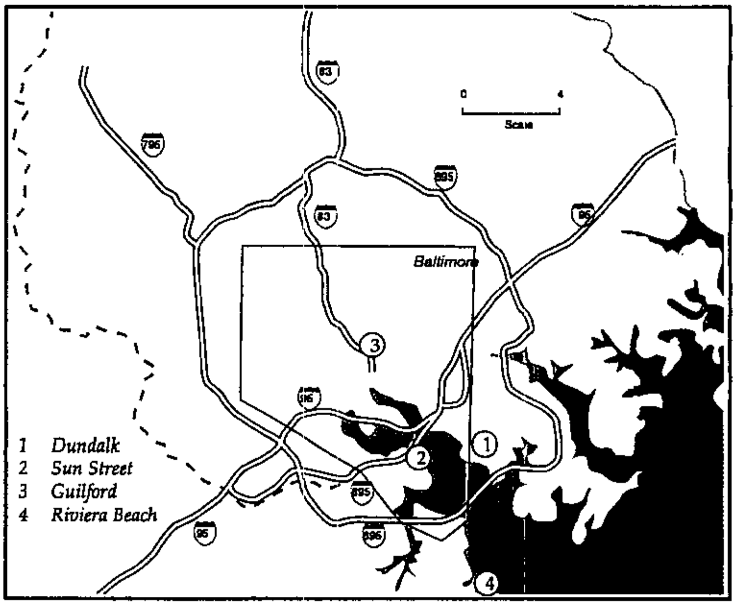
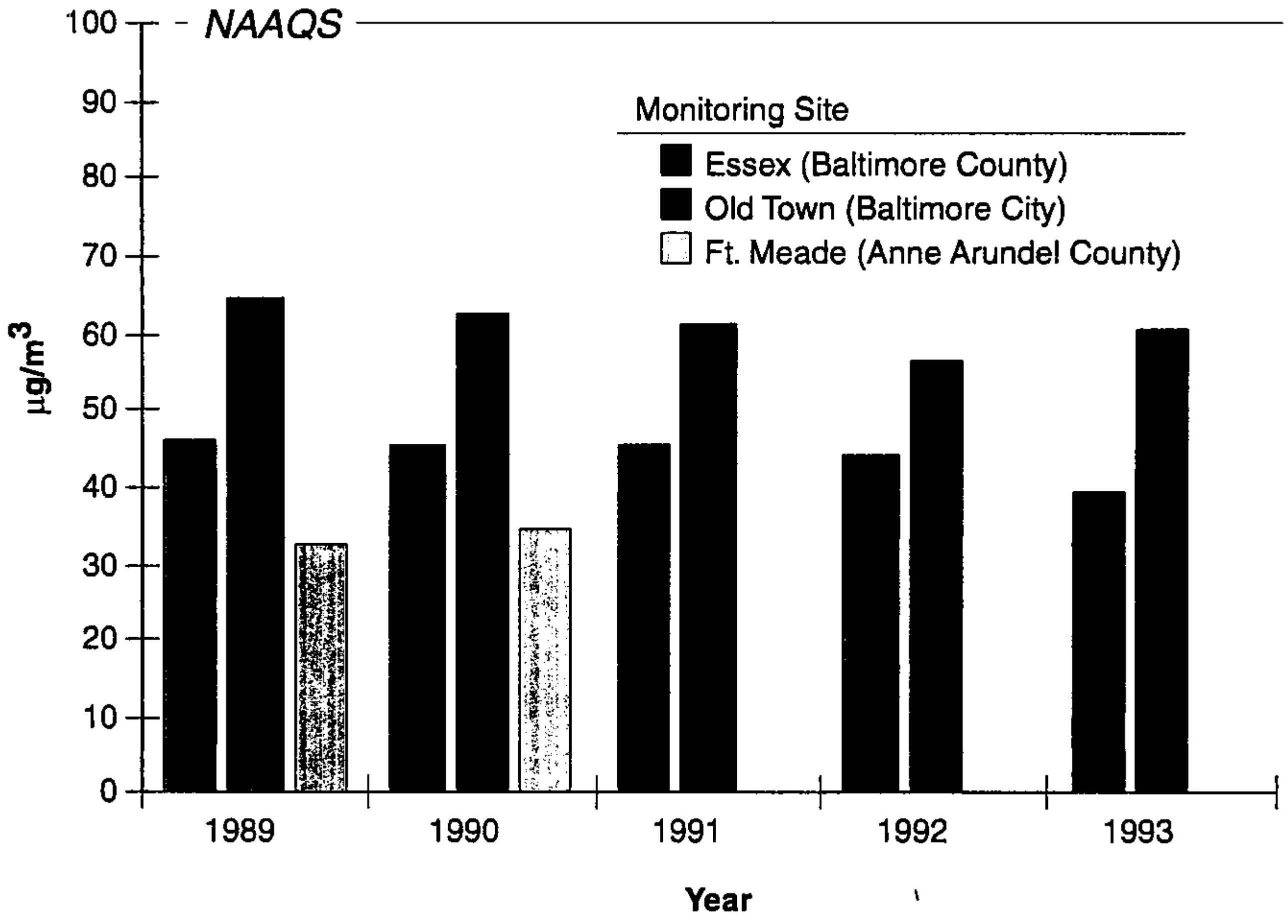


Figure 3-3
Annual Nitrogen Dioxide (NO_2) Ambient Concentrations in Maryland
(National Ambient Air Quality Standard = 100 $\mu g/m^3$)



Locations of NO_2 Monitoring Sites in Baltimore Area

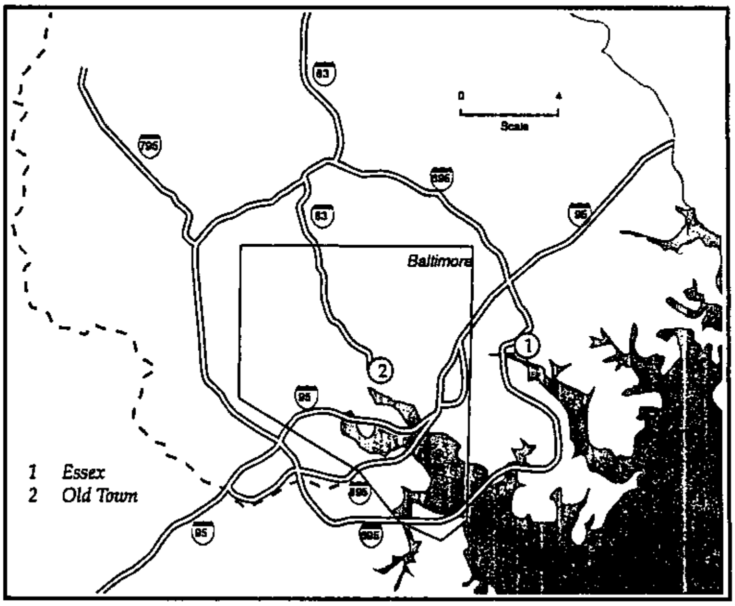


Figure 3-4
Ozone Nonattainment Areas in Maryland

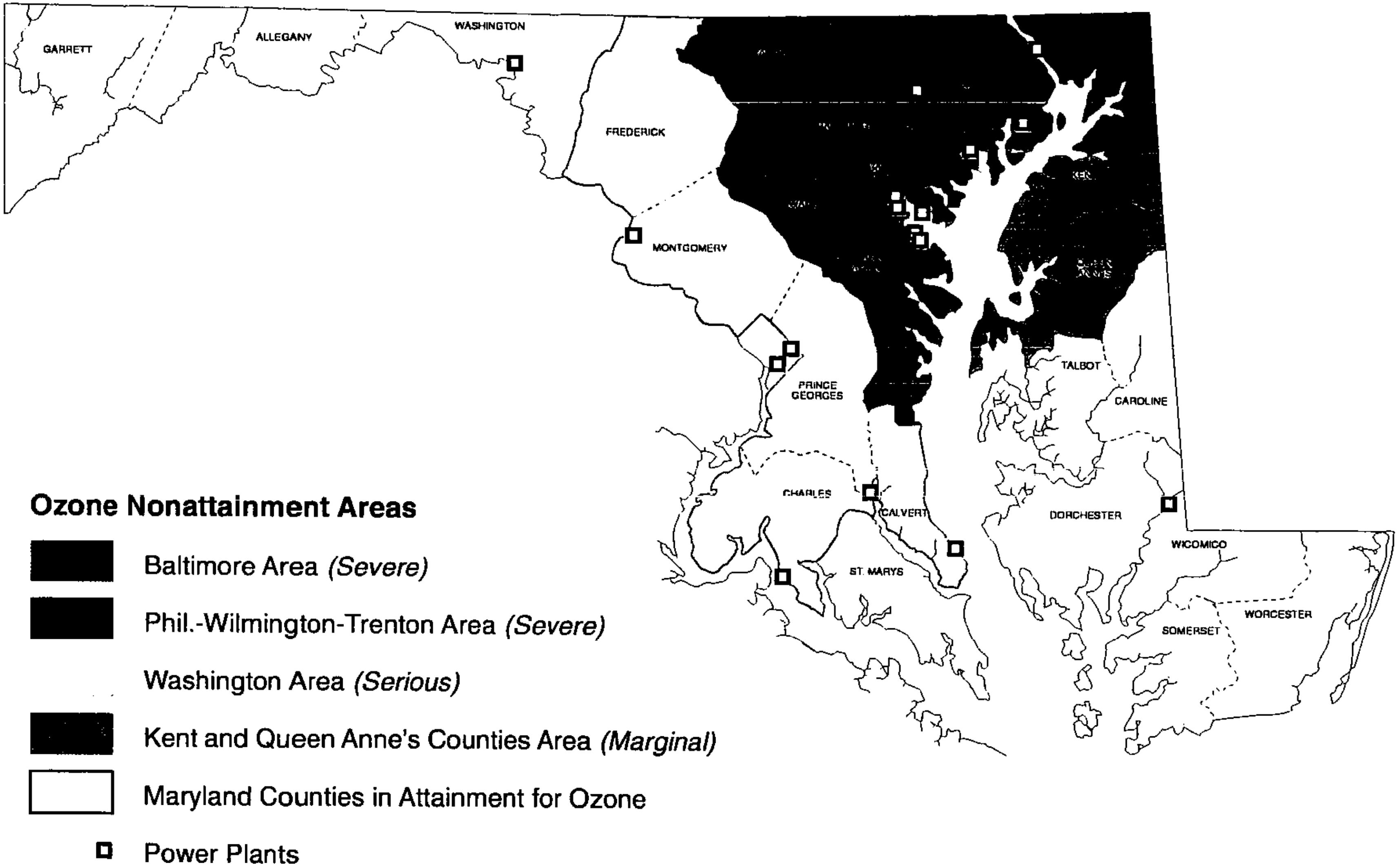
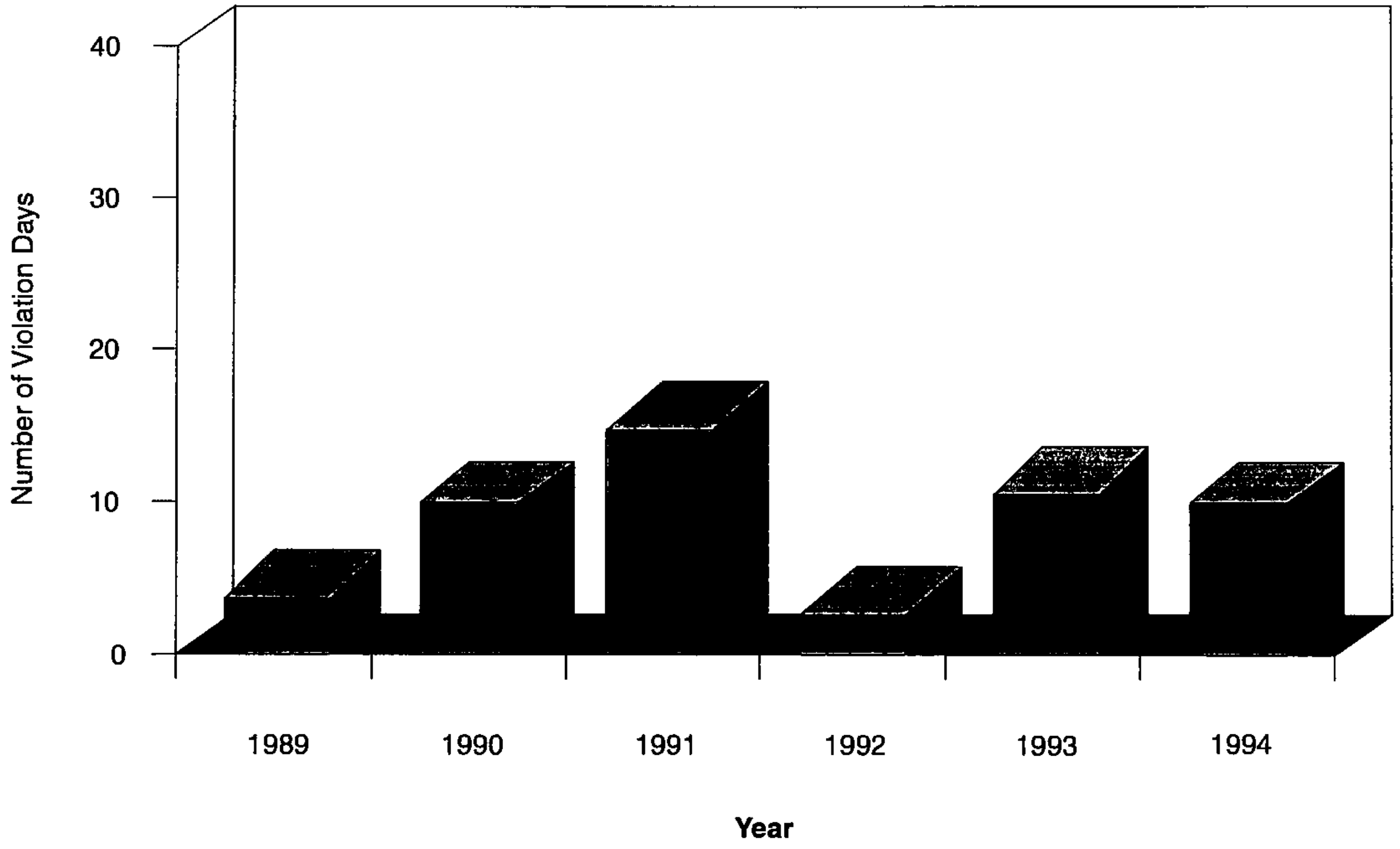


Figure 3-5
Ozone Violation Days in the Baltimore Metropolitan Region



AIR QUALITY INDEX

The U.S. EPA has defined National Ambient Air Quality Standards (NAAQS), or upper limit air concentration levels of various pollutants, that it judges to be necessary to protect public health. The Maryland Department of the Environment (MDE), in coordination with the University of Maryland, has devised a system for forecasting air quality, with respect to the ozone NAAQS, called the Air Quality Forecast Scale. The forecast scale is based on the MDE Air Quality Index (AQI). The AQI ranges from 0 to 500, with 100 corresponding to the NAAQS for ozone. The purpose of the forecast is to provide advanced warning of periods of unhealthy levels of ozone.

In making the air quality forecast, pollutant concentrations are assessed at 9 a.m., 1 p.m., and 4 p.m. daily. The one-day forecast, issued to the public in the afternoon for the following day, is reported according to the following color-coded scale:

- Code Green (good air quality) - AQI between 0 and 50;
- Code Yellow (moderate) - AQI between 51 and 88;
- Code Orange (approaching unhealthful) - AQI between 89 and 99; and
- Code Red (unhealthful) - AQI of 100 or greater.

It is not uncommon to have a few summer days in a row with a "Code Red" forecast; however, unhealthful levels of ozone will typically occur in only the afternoon hours of each of these days. When the air quality is forecast to be "Code Red," MDE advises that 1) individuals with heart or respiratory ailments, emphysema, asthma, or chronic bronchitis reduce outdoor activities; 2) children and elderly individuals reduce outdoor activities; and 3) healthy individuals limit strenuous outdoor exercise.

Maryland began issuing daily air quality forecasts in 1994 for the Baltimore metropolitan area. The forecast area now includes the Washington metropolitan area as well. The forecast can be obtained from the MDE Air Quality Hotline (410-631-3247).

3.2.1.2 *Power Plant Emissions Contributions*

Total **anthropogenic** emissions (those resulting from human activities) of NO_x and VOCs from point or stack sources (e.g., power plants), area sources (numerous small sources, such as bakeries, dry cleaners, etc.), non-road mobile sources (e.g., farm tractors), and on-road mobile sources (e.g., cars) in Maryland are given in Table 3-1. These data are from Maryland's 1990 Base Year Ozone Precursor Emissions Inventory. **Biogenic** (i.e., natural) sources in Maryland are estimated to emit approximately 900 tons per day of VOCs, which is roughly the same level of VOC emissions as from anthropogenic sources (Franks 1994).

Table 3-1 ***NO_x and VOC Emissions by Source Category for Anthropogenic Sources in Maryland, 1990***

	Emissions (Tons per Day)	
Source Category	**NO_x**	**VOCs**
Point	559	62
Area	107	319
Non-road Mobile	138	109
On-road Mobile	354	302
TOTAL	**1,158**	**792**

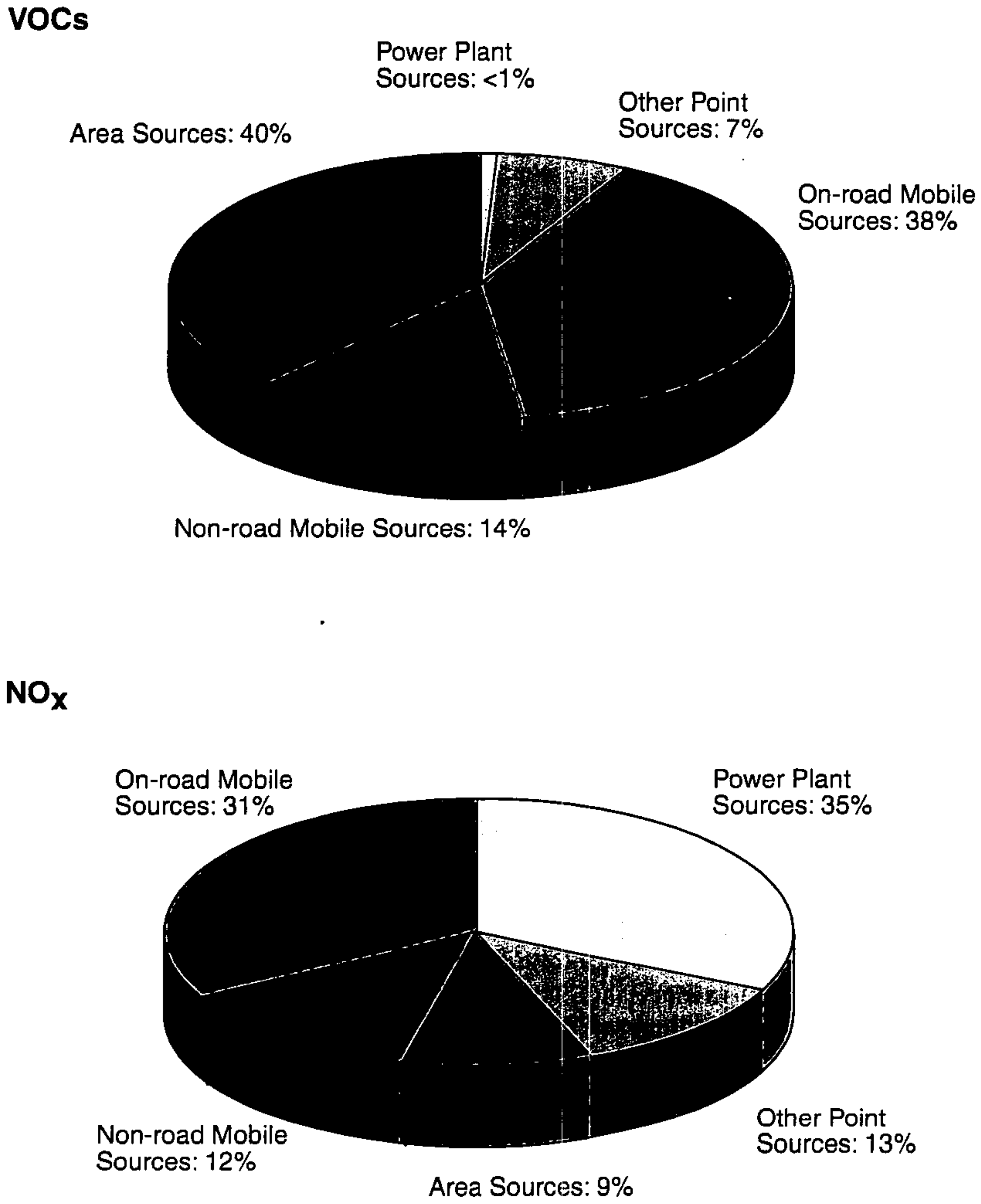
Source: Franks 1994

As shown in Figure 3-6, mobile sources and area sources are the prime emitters of VOCs. Power plants are responsible for less than 1% of the total VOC emissions (Franks 1994). On the other hand, power plants are significant emitters of NO_x. NO_x emissions from power plants are formed by high-temperature chemical reactions during the combustion of fuels. These NO_x emissions consist primarily of NO_2 and nitric oxide (NO); the NO converts to NO_2 in the atmosphere. Power plant emissions are, by far the largest point source contributor, and account for 35% of the total NO_x emissions in Maryland. Mobile sources account for the next largest percentage of the total NO_x emissions (Figure 3-6) (Franks 1994).

3.2.1.3 *Regulatory Approaches to Reducing NO_x Emissions*

The CAA Amendments of 1990 address the ozone problem by requiring reductions in emissions of **ozone precursors** (NO_x and VOCs). The CAA requires all states, including Maryland, to submit plans to the U.S. EPA for meeting the ozone NAAQS. Most importantly for power plants, these state plans must include for the first time both VOC and NO_x emissions

Figure 3-6
Sources of VOCs and NO$_x$ in Maryland, 1990



control and reduction as part of the solution to the ozone problem. The state plans must outline specific controls or emission limits, representing **Reasonably Available Control Technology** (RACT), to reduce NO_x and VOC emissions from existing facilities. Proposed new sources whose NO_x and VOC emissions will exceed certain levels are subject to even stricter control requirements, known as **Lowest Achievable Emission Rate** (LAER) technology. Additionally, a proposed new source must include provisions to offset its new NO_x and VOC emissions with reductions from other sources in the area. The offset ratio must be greater than 1 to 1, meaning that there must always be a larger quantity of emissions reduced than the amount of new emissions added. Depending on the severity of the ozone nonattainment area, different offset ratios are imposed. For example, in the Baltimore area, an offset ratio of 1.3 to 1 is required.

The states must demonstrate to the U.S. EPA that the ozone NAAQS will be attained by the deadlines mandated in the CAA Amendments. A critical element for measuring progress in complying with the CAA and, ultimately, attainment of the ozone standard, is an accurate inventory of NO_x and VOC emissions. All states with ozone nonattainment areas are required by the CAA to submit, every three years, an inventory of NO_x and VOC emissions during the peak ozone season (i.e., the summer months). The initial ("base year") inventory is for the calendar year 1990. Periodic reductions in ozone precursor emissions, necessary to meet CAA-mandated percent reduction targets, will be determined from these emissions data. The actual demonstrations of attainment are made through the use of computer modeling that predicts smog levels based on projected future emissions, photochemistry, and meteorology. The U.S. EPA has developed such a computer model for the entire northeast region of the United States, including Maryland. Current studies for this region suggest that additional NO_x and VOC emissions reductions from existing sources are needed throughout the region to attain the ozone standard.

Concurrently, studies using a more detailed model are being conducted by states, including Maryland. The goal of the state studies is to identify scenarios in which NO_x and VOC reductions will help achieve the ozone standard. The Maryland Department of the Environment (MDE) is currently conducting the modeling analysis of the Baltimore-Washington, D.C. area with assistance from the University of Maryland. These results will be critical for designing appropriate control plans for the various source categories, including power plants, and for determining areas where NO_x emissions control would help in attaining the ozone NAAQS. PPRP is following the progress of these studies closely.

OFFSET REQUIREMENTS

Although offset requirements have been part of the air quality permitting process since 1977, there have been few offset transactions outside of California. With the passage of the 1990 Clean Air Act (CAA) Amendments, however, emissions offset transactions likely will occur more frequently. This is due to the establishment of many more ozone nonattainment areas, the creation of the Northeast Ozone Transport Region (OTR), and the institution of lower offset trigger levels and higher offset ratio requirements.

An additional change with the 1990 Amendments is the allowance of interstate trading within the OTR. Although the details pertaining to interstate offset transactions are not fully developed, a fundamental criterion is that offsets for a particular new source must be obtained from an area that has an equal or higher (i.e., a more severe) nonattainment classification.

Another significant change resulting from the 1990 Amendments is that both volatile organic compound (VOC) and NO_X emissions are regulated as ozone precursor emissions. In the past, only VOC emissions were regulated as ozone precursors. Thus, now new and modified major NO_X sources must also obtain emission offsets.

3.2.1.4 *Power Plant NO_x Control Options*

NO_x is generated during the combustion of fossil fuels in two ways: 1) **thermal NO_x** formation and 2) **fuel NO_x** formation. Thermal NO_x results from the high-temperature reaction of nitrogen and oxygen in the air used for combustion. As the combustion temperature increases, the amount of thermal NO_x that is formed increases. Fuel NO_x results from the oxidation of nitrogen bound in the fuel during combustion. Increasing amounts of fuel-bound nitrogen will result in higher NO_x emissions.

In 1994, power plants in Maryland emitted approximately 115,000 tons of NO_x into the atmosphere. Nearly 80% of these emissions come from utility boilers, as opposed to combustion turbines and other generating units. Most of the utility boilers in Maryland burn coal as their primary fuel. On the other hand, combustion turbines burn relatively clean fuels, such as natural gas and distillate oil, and operate for shorter periods than boilers. Consequently, the greatest stationary source NO_x reductions will be realized by controlling utility boilers.

There are generally three ways that NO_x emissions from boilers can be reduced:

- Fuel conversions, which reduce NO_x emissions by burning fuels with lower nitrogen contents (for instance, changing from coal to oil or natural gas, co-firing natural gas with oil, or switching to a lower nitrogen content coal or oil);
- Combustion modifications, which reduce the amount of NO_x that is formed during the combustion process, including such techniques as **low-NO_x burners** or **overfire air**; and
- Post-combustion control equipment, which reduces NO_x after it has formed by injecting a reagent (e.g., ammonia) into the exhaust gas to convert NO_x into atmospheric nitrogen and water, including such control devices as **selective catalytic reduction** (SCR) and **selective non-catalytic reduction** (SNCR).

Table 3-2 presents an overview of NO_x control technologies appropriate for utility boilers in Maryland. For each technology, the table presents reduction percentages and early estimates of installed-capital cost ranges, along with general comments about each technology.

OZONE: GOOD GUY OR BAD GUY?

The topic of ozone is frequently in the press, usually with reference to either the "ozone layer" or the "urban ozone problem." These are two completely different issues. In the first case, we are worried about the destruction of ozone; in the second case, we are worried about its formation. What is ozone? And why are we so concerned about it? It is the difference in location and origin that leads to confusion regarding ozone. The same chemical with the same properties is regarded as a "good guy" or a "bad guy" depending on where it is found in the atmosphere and how it is formed.

Ozone is a colorless gas composed entirely of oxygen. It is most recognizable by its odor — the electrical smell noticeable immediately after the passage of a strong thunderstorm is ozone. Ozone occurs naturally in the stratosphere (about 18 to 30 miles above the ground) and in trace amounts at the Earth's surface. The naturally occurring ozone found in the stratosphere is essential for life on earth because it absorbs most of the dangerous ultraviolet radiation coming into the atmosphere. A major reduction in this stratospheric ozone layer could produce a substantial increase in the number of human skin cancers and major changes in the Earth's flora and fauna (NRC 1991).

Ozone also results from human activities but, unlike most air pollutants, there are very few human activities that generate ozone directly. Instead, ozone is formed indirectly from other air pollutants. When these "ozone precursors" (such as nitrogen oxides from power plants and cars, and hydrocarbons from cars and petroleum-based chemicals) are heated by sunlight under stagnant weather conditions, large quantities of ozone can be formed near the ground.

The ozone found near the ground that results from human activities is considered an air pollutant because, among other effects, it reduces lung function in humans and causes damage to forests, crops, rubber, and fabrics (Wark and Warner 1976). It is the presence of this ground-level ozone of human origin that gives rise to the urban ozone problem.

Table 3-2 Overview of NO$_x$ Control Technologies for Utility Boilers

NO$_x$ Control Technology	Percent NO$_x$ Reduction	Installed Capital Cost (million dollars)(a, b)	Comments
Low-NOx Burner	30-50	2.7 to 9(c)	• Magnitude of reductions site-specific • Minor heat rate penalty • Higher CO emissions • Reductions dependent on air and fuel delivery systems
Overfire Air	10-30	1.5 to 3(d)	• Minor heat rate penalty • Required boiler modifications • Feasibility dependent on specific boiler design
Low-NOx Burner with Overfire Air	40-65	Wall-fired: 4.8 to 9(c) Tangential: 8.4 to 12(c)	• Magnitude of reductions site-specific • Minor heat rate penalty • Higher CO emissions • Reductions dependent on air and fuel delivery systems • Minor heat rate penalty • Required boiler modifications • Feasibility dependent on specific boiler design
Burners-Out-Of-Service	10-40	Low	• Applicable to wall-fired boilers • Possible derating • Minor heat rate penalty
Reburning	40-60	6 to 12(d)	• Feasibility dependent on specific boiler design • Higher CO emissions
Selective Noncatalytic Reduction	30-70	1.5 to 4.5(d)	• Feasibility dependent on specific temperature window • Uses ammonia or urea/water as reactant
Selective Catalytic Reduction	70-90	20.4 to 80.4(c)	• Feasibility dependent on specific temperature window • Uses ammonia as reactant • Some catalysts considered hazardous waste • Significant heat rate penalty

(a) Based on a "generic" 300-MW power plant.

(b) Capital costs do not include boiler-pressure part modifications, ancillary equipment, or continuous emission monitors.

(c) Acurex Environmental (1991)

(d) Eskinazi (1992)

In April 1993, Maryland adopted RACT regulations mandating NO$_x$ reductions from existing fuel-burning equipment. For boilers, utilities have the option of meeting prescribed emissions limits, which are based on the type of fuel burned and the particular boiler design, or of submitting a RACT proposal with an alternative emission limit for review. The proposal must include baseline NO$_x$ emissions data, a description of the proposed NO$_x$ controls and limitations, and a demonstration that the proposed alternative emissions limit meets RACT requirements. RACT proposals that have been submitted by the Maryland utilities suggest that

REGIONAL NO_X STRATEGY

On September 27, 1994, air quality officials from Northeastern and mid-Atlantic states voted to develop regulations reducing NO_x emissions by at least 55% from 1990 levels by May 1, 1999. The action is part of an effort to move the Ozone Transport Region (OTR) into attainment of the Federal ozone standard. Nearly all of the reductions will come from utility boilers. The Memorandum of Understanding (MOU) splits the OTR into three regions: the inner, outer, and northern zones. The inner zone extends from Washington, D.C., to southeastern New Hampshire. Major stationary NO_x sources in this zone must either meet a 65% reduction, or comply with a NO_x emission rate of 0.2 lb/MMBtu. The MOU also requires the Ozone Transport Commission to develop a region-wide trading program, an element that many industry representatives feel is vital to achieve the required NO_x reductions (CAR 1994a). Furthermore, under the MOU, the states must re-evaluate the need for controls prior to implementing the reduction requirements, to assess their effectiveness towards achieving the ultimate MOU goals.

combustion modifications, as opposed to any type of post-combustion controls, will meet RACT requirements. The NO_x controls were required to be implemented by May 1995.

For proposed new fuel-burning equipment subject to LAER, routine combustion controls (e.g., standard low-NO_x burners) alone probably will not be sufficient to satisfy the regulatory requirements. For example, Delmarva Power is planning to use SCR in conjunction with low-NO_x burners to meet LAER requirements for NO_x emissions for its proposed Dorchester plant, a 300-MW coal-fired unit. This control scheme will reduce NO_x emissions by more than 70% from uncontrolled levels. Although SCR has been used on coal-fired units in Europe and Japan for a number of years, there are currently only about five coal-fired boilers in the United States that use (or propose to use) SCR.

3.2.1.5 *Tradeoffs of Control Options*

Selecting one control strategy over another often involves an environmental tradeoff. In some instances, one pollutant can increase as a result of reducing another. For example, using a common technology called water injection to control NO_x emissions from combustion turbines results in an increase of both CO and unburned hydrocarbon emissions. Similarly, the use of SCR technology results in ammonia emissions. Some control technologies transfer contaminants from one environmental medium to another (such as from the air to a solid waste). For example, periodic replacement of the catalyst used in SCR results in generation of a hazardous waste. In the case of low-NO_x burners in boilers, unburned fuel (in the form of carbon) present in the ash is not uncommon; however, high-carbon carryover can reduce the commercial use of the ash. Post-combustion technologies, such as SCR, using ammonia injection for NO_x control have also been found to contaminate ash, possibly hampering its reuse. Tradeoffs also occur in generating efficiency. For example, water injection can increase the power output of a combustion turbine, while the use of an SCR system can reduce the efficiency. Aspects of the environmental tradeoffs are considered by the regulators and affected utilities to select the best economic and technically feasible control strategy.

3.2.2 *Power Plants and Acid Rain*

Power plant emissions contribute to another regional air quality problem — the formation of acid rain. Acid rain is produced by the oxidation of precursor compounds, SO_2 and NO_x, in the atmosphere to form sulfuric and nitric acids.

The majority of SO_2 emissions, and a significant but smaller percentage of NO_x emissions, arise from the burning of fossil fuels in power plants and other combustion sources. In Maryland, power plant emissions account for 35% of the total NO_x emissions, by far the largest point source contributor (see Figure 3-6) (Franks 1994). Maryland power plants are responsible for roughly 85% of the total SO_2 emissions (PPER 1991).

From 1960 until 1970, nationwide SO_2 emissions increased by approximately 40%. Emissions of NO_x steadily increased by nearly 50% between 1960 and 1980 (South 1991). Emissions of both precursors have generally declined nationwide during the past decade; however, SO_2 and NO_x emissions appear to have increased in Maryland since 1980. Estimates of annual emissions of SO_2 and NO_x, VOCs, and particulate matter from stationary sources in Maryland are provided in Appendix E. The data, covering the period from 1980 to 1994, include the combined emissions of all power plants in the state, as well as emissions from other stationary sources. Plant-specific data for 1993 are also listed in Appendix E.

3.2.2.1 *Regulatory Approaches to Reducing Acid Rain*

Title IV of the CAA Amendments of 1990, the acid rain program, sets forth an innovative program to control acid rain precursor emissions. The program is directed primarily toward coal- and oil-burning utility plants, because of the magnitude of their SO_2 and NO_x emissions.

The acid rain program mandates significant SO_2 and NO_x reductions. Power plants must meet a national emissions cap of 8.9 million tons of SO_2 per year from all electric utilities across the United States, a reduction of 10 million tons per year compared to 1980. These reductions will be achieved in two phases. In Phase I, which begins in 1995, the 110 largest utility plants located in 21 eastern and midwestern states, including six units at three power plants in Maryland, must meet an intermediate SO_2 emissions limitation. In Phase II, beginning in the year 2000, the annual emission limits imposed on the Phase I plants will be tightened, and the number of plants subject to the limits will be greatly expanded.

The acid rain program also sets a reduction goal of approximately two million tons per year of NO_x emissions below 1980 levels. Utility coal-fired boilers will be required to meet new emissions standards based on the installation of low-NO_x burner technologies. Because Maryland is in the Northeast Ozone Transport Region, utility boilers here will have to comply with RACT emission limits for NO_x that may be more restrictive than those under Title IV.

SO_2 ALLOWANCE TRADING

On 27 March 1995, the third annual SO_2 allowance auction was conducted by the Chicago Board of Trade. More than 176,000 allowances were sold; prices ranged from $1 to $350 each, with a typical price in the $100 to $150 range. Allowance Holdings Corporation, Duke Power Company, and Virginia Power were top bidders in terms of number of allowances purchased. The sales from the 1995 auction were roughly $22.8 million, down nearly $4 million from the 1994 auction. Substantial trades and direct sales also occur throughout the year independent of the annual SO_2 allowance auctions. Like the annual auctions, the U.S. EPA administers these sales through the Chicago Board of Trade. EPA is expecting prices and trading activity to increase as Phase II approaches (1997-1998 time frame) (US EPA 1995).

The centerpiece of the acid rain program for SO_2 control is a pollution trading system based on the use of marketable emission **allowances**. An allowance is effectively a permit to emit one ton of SO_2. Existing electric utility units are granted annual allowances based on their historic fuel use and the emission limitations specified in the acid rain program. Table 3-3 lists the number of allowances that will be allocated to the Phase I units in Maryland. Beginning in 1995, each utility must ensure that SO_2 emitted from its Phase I units does not exceed the total number of allowances held by those units.

Table 3-3 *Affected Phase I Units in Maryland, Their SO_2 Allowances, and Historical SO_2 Emissions (tons)*

Plant	Unit No.	Phase I Allowances	1990 SO_2 Emissions (tons)	1993 SO_2 Emissions (tons)
Chalk Point	1	21,910	25,823	26,636
	2	24,330	23,680	19,836
C.P. Crane	1	10,330	11,323	18,876
	2	9,230	12,619	21,901
Morgantown	1	35,260	41,907	35,772
	2	38,480	52,610	41,276

Under Phase II, which begins in the year 2000, virtually all units will have to hold allowances to cover their emissions, and utilities must demonstrate compliance on a system-wide basis. New generating units (units starting commercial operation after 15 November 1990) must obtain allowances before beginning operation. Table 3-4 gives the allowances allocated to Maryland units for Phase II. The U.S. EPA is reserving a small percentage of each unit's allowances for the years 2000 to 2009 to be offered at auction or for direct sale. Any Maryland power plants not shown on this table — such as the recently constructed combustion turbine at Perryman, and the Panda-Brandywine combined cycle plant under construction — have not been allocated allowances. To operate these new plants, the utility (or NUG, in the case of Panda) must obtain allowances for their SO_2 emissions from other units in the system, or must purchase allowances from other utility systems. The new Perryman turbine and Panda facility will burn primarily natural gas, and therefore will produce very little SO_2.

Table 3-4 ***Maryland Phase II Allowance Allocations***

Plant	Unit No.	Total Annual Phase II Allowances for Years 2000-2009	Total Annual Phase II Allowances for Years 2010 and Thereafter
Brandon Shores	1	18,354	18,475
Brandon Shores	2	7,729	7,780
C.P. Crane	1	4,312	4,341
C.P. Crane	2	4,008	4,034
Chalk Point	1	9,124	9,185
Chalk Point	2	10,132	10,199
Chalk Point	3	12,458	5,210
Chalk Point	4	2,578	2,595
Chalk Point	GT 3	702	706
Chalk Point	GT 4	702	706
Chalk Point	GT 5	887	892
Chalk Point	GT 6	887	892
Dickerson	1	5,799	5,837
Dickerson	2	5,454	5,489
Dickerson	3	5,797	5,834
Dickerson	H CT-1	1,079	1,087
Dickerson	H CT-2	1,079	1,087
Gould Street	3	814	820
H.A. Wagner	1	1,280	1,288
H.A. Wagner	2	1,287	1,297
H.A. Wagner	3	8,311	8,365
H.A. Wagner	4	1,507	1,517
Morgantown	1	16,788	16,900
Morgantown	2	16,051	16,157
R.P. Smith	3	335	337
R.P. Smith	4	2,295	2,264
Riverside	1	188	189
Riverside	2	170	171
Riverside	3	351	353
Riverside	4	451	454
Riverside	5	292	294
Vienna	8	3,629	1,813
Westport	3	185	186
Westport	4	257	258

Source: 40 CFR 73.10

The market-based allowance approach is designed to allow utilities to meet their emission control requirements in the most cost-effective manner possible. As part of its compliance strategy, a utility may install SO_2 emission controls, switch to fuels that contain less sulfur (either lower-sulfur coals or oil or natural gas), or purchase allowances from another utility. Utilities may purchase allowances from distant utilities, even ones that are out of state. For example, an early SO_2 allowance trade involved Wisconsin Power selling 10,000 allowances to the Tennessee Valley Authority. The rationale behind such long-distance trading is that acid rain is a regional problem, caused by emissions over a large area, not by sources concentrated in a particular location. Consequently, the specific location in which the emission reductions actually occur is unimportant, assuming the total regional reductions are achieved.

In addition to individual private sector trades, Title IV mandates that the U.S. EPA establish a special allowance reserve containing allowances to be offered for auction or direct sale. The auction and sales programs are intended to stimulate the market in allowance trading and help establish an early market price for allowances. In the fall of 1992, the U.S. EPA delegated the administration of the auctions and sales to the Chicago Board of Trade, which has held annual auctions since.

3.2.2.2 *Power Plant SO_2 Control Options*

Emissions of SO_2 from combustion sources result from the oxidation of sulfur and sulfates contained in the fuel. Unlike NO_x emissions, SO_2 emissions are not affected by conventional boiler modifications. For conventional boilers, the alternatives for limiting the amount of sulfur in the exhaust gas are to: 1) limit the sulfur contained in the fuel, or 2) remove the SO_2 after it has been formed during combustion.

A common way to limit the sulfur contained in the fuel is to simply switch to a fuel that contains less sulfur. Most often this involves changing from a higher to a lower sulfur content coal. Coals with lower sulfur content may also have other characteristics that differ from the coal currently used. Power plant boilers are designed to burn coal with a specific range of characteristics, so utilities must evaluate potential lower-sulfur coals carefully before switching fuels. In general, fuel switching options involve relatively low capital investment and can be implemented in a short time frame. A potential risk with fuel switching, however, is the uncertainty in the future cost and availability of low-sulfur fuels.

For the second alternative, the SO_2 emissions can be reduced by a **flue gas desulfurization** system, otherwise known as a scrubber. Scrubbers are commercially proven pollution control systems that can remove SO_2 very efficiently. However, potential drawbacks of scrubbers include the high capital and operating costs, some loss of generating efficiency of the power plant, and the production of relatively large amounts of by-product, which may present a costly disposal problem.

Some advanced combustion technologies, such as fluidized bed combustion (FBC), achieve SO_2 removal in the combustion zone as it is being created. FBC technology results in high generating efficiency, but retrofitting requires significant capital expenditure. FBC boilers also create a large amount of solid by-product.

Generally, power plants that have the largest SO_2 reduction requirements may consider the more capital-intensive strategies, such as installing scrubbers. On the other hand, utility units with more modest SO_2 reduction requirements may find that fuel switching is more cost-effective. A third option for a source is simply the purchase of emission allowances from other sources, without any SO_2 emission reduction. Naturally, the costs for control equipment, fuel, and allowances must all be factored into a utility's compliance strategy.

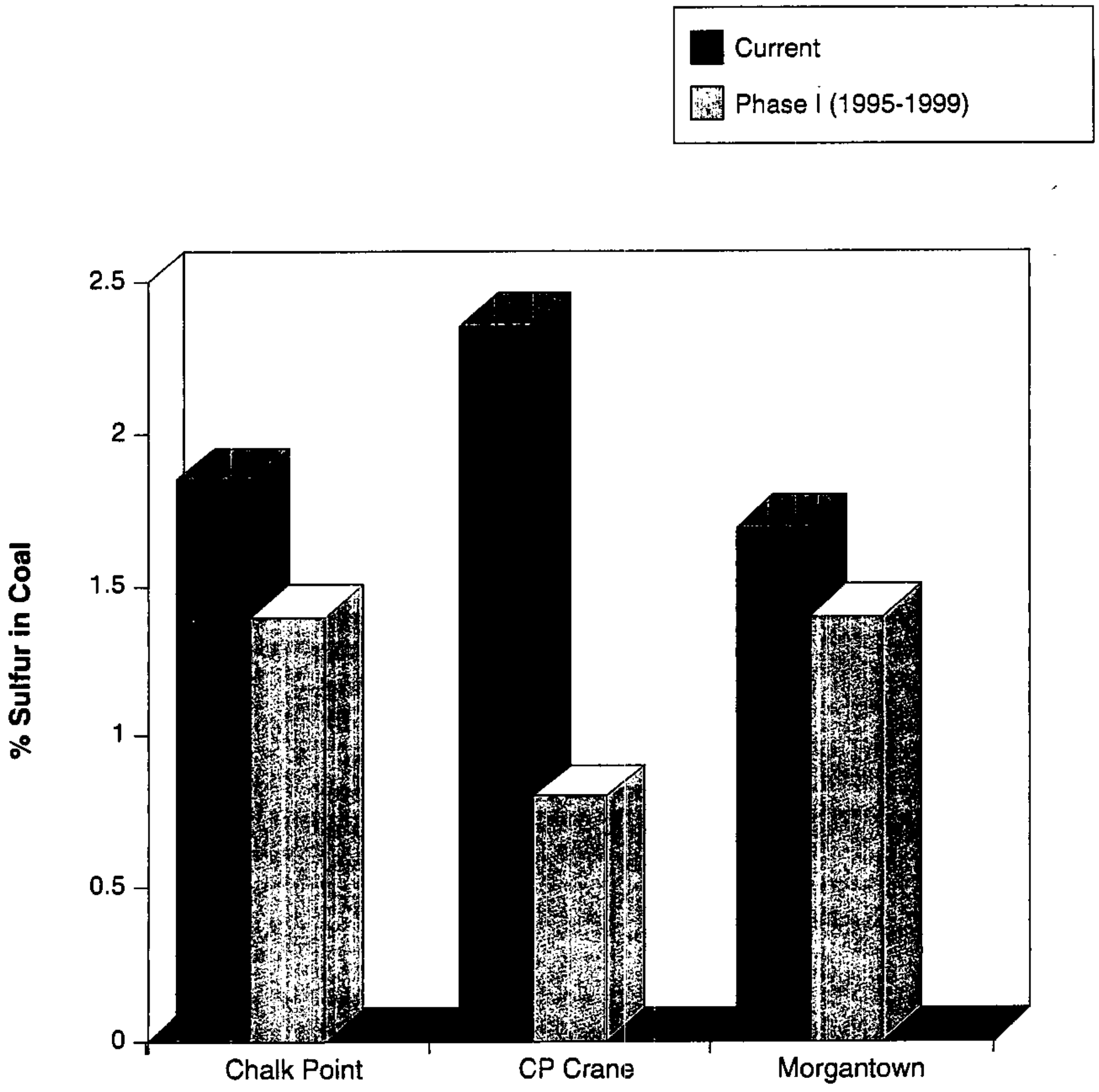
3.2.2.3 *SO_2 Control Plans for the Maryland Utilities*

Two electric utilities have generating units in Maryland that are subject to acid rain controls in Phase I: PEPCO's Chalk Point Units 1 and 2 and Morgantown Units 1 and 2; and BGE's C.P. Crane Units 1 and 2. Under Phase II (beginning in 2000), virtually all generating units in Maryland will be affected. Maryland utilities have outlined Phase I acid rain control strategies, but due to uncertainties in fuel prices and allowance prices, compliance strategies for Phase II are not yet finalized. Utilities must file their Phase II compliance plans with the state by early 1996.

Both PEPCO's and BGE's plans for Phase I include substantial SO_2 emission reductions at the Conemaugh plant located in Pennsylvania, a plant in which both utilities (in addition to others) share ownership. The owners of the Conemaugh units have elected to install high-efficiency SO_2 scrubbers on two generating units; this measure will reduce emissions beyond the level required in Phase I, thereby generating excess allowances that can be applied elsewhere or sold. PEPCO's Phase I plan entails using its share of these excess allowances and switching to lower-sulfur coal at Chalk Point and Morgantown (see Figure 3-7). PEPCO has also begun co-firing with natural gas at its Chalk Point boilers. BGE will benefit from the installation of the Conemaugh scrubbers also. Excess allowances generated there will help to offset the reduction requirements for the C.P. Crane units. Additionally, BGE plans to use lower-sulfur coal at C.P. Crane (see Figure 3-7). During 1994, EPA approved the Maryland utilities' Phase I compliance plans.

To meet Phase II requirements, PEPCO tentatively is evaluating switching to even lower-sulfur coal and/or co-firing with natural gas at both its Chalk Point and Dickerson plants. For the Morgantown boilers, PEPCO is considering burning lower-sulfur coal and oil, if economical. PEPCO is also evaluating the open allowance market to buy allowances when economical. For Phase II, BGE is considering continuing burning low-sulfur coal at Crane, switching to lower-sulfur coal at H.A. Wagner Units 2 and 3, and purchasing allowances when economical. BGE also may benefit from the possible installation of a scrubber at the Keystone power plant in Pennsylvania, a plant in which BGE has part ownership.

Figure 3-7
Average Coal Sulfur Content for Phase I Affected Maryland Power Plants



Generally, Maryland utilities have emphasized flexibility in their acid rain compliance plans. To date, no utility has proposed a scrubber for any existing generating units at Maryland power plants to achieve SO_2 reductions. The cost of lower-sulfur coal, which will likely increase due to increased demand, and the market price of allowances will have a large impact on the future compliance actions taken by Maryland utilities. PPRP has had continuing contact with the utilities on the status of their compliance plans, and participated in hearings before the PSC on PEPCO's Phase I proposal. The goal of PPRP's involvement is to ensure that all facets of compliance alternatives are considered.

3.2.2.4 *Biological Effects of Acid Deposition*

The formation of acid rain, or **acid deposition**, has been evaluated in a number of projects nationally over many years. Years of research have enabled scientists to characterize the types and amount of emissions of acid deposition precursors. However, researchers have found it more difficult to discern how acid deposition actually affects terrestrial and aquatic resources. As a result, Congress created the National Acid Precipitation Assessment Program (NAPAP) in 1980 to conduct scientific and economic analyses of the causes and effects of acid deposition.

In addition to federal research efforts, PPRP has conducted a substantial amount of research on the generation and effects of acid deposition in Maryland (PPRP 1987, 1988; CBRM 1989, 1990, 1991, 1992, 1994, 1995). This research program is ongoing, and the state has sponsored a variety of acid deposition studies in recent years (Janicki and Anderson 1994). Projects have been designed to evaluate the effects of acid deposition on resources unique to Maryland or to address topics important to understanding acid deposition in Maryland that are not being studied elsewhere. Recent research has focused on three areas:

- acidification processes and biological effects,
- mitigation, and
- "critical loads."

Acidification Processes and Biological Effects

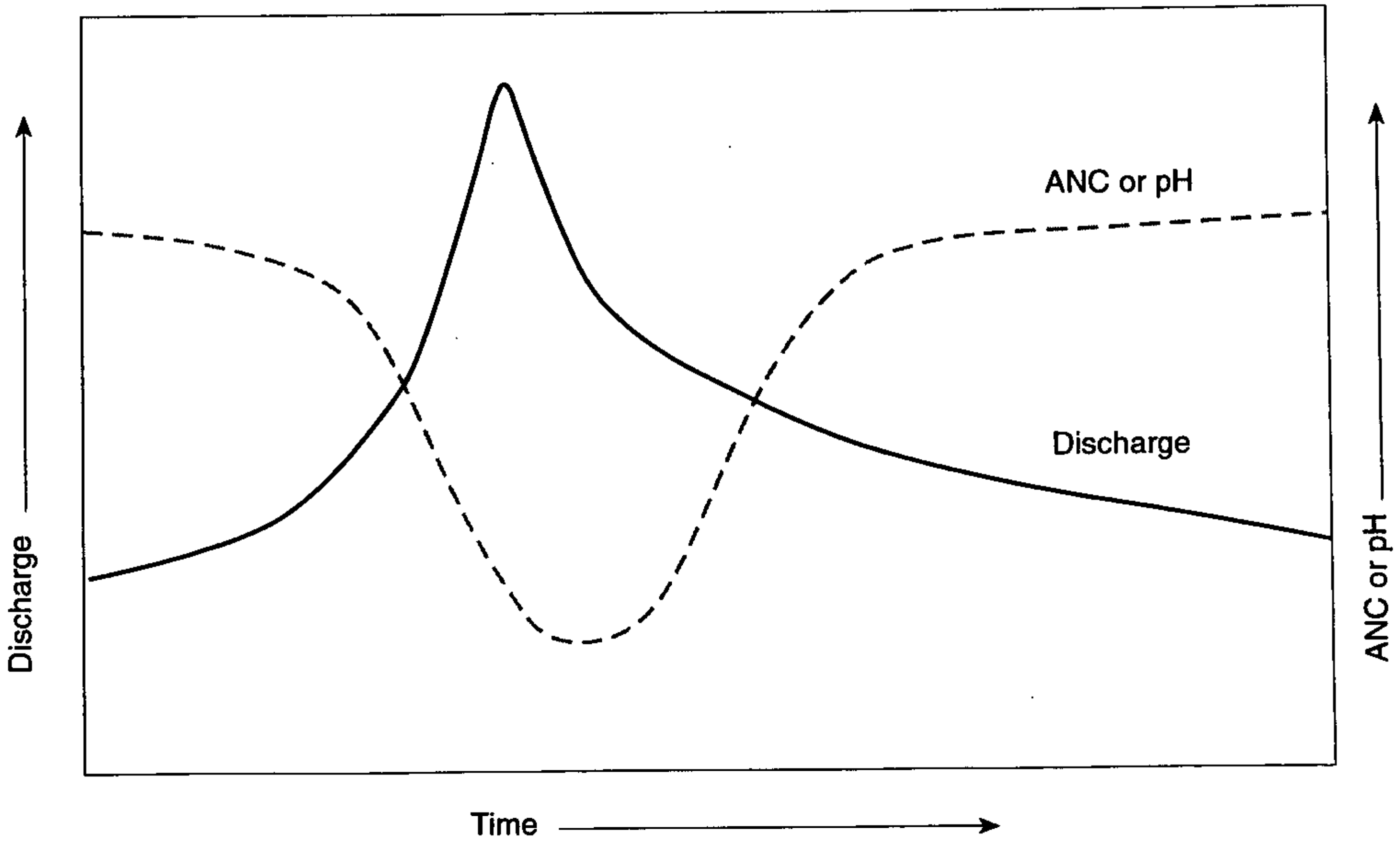
Studies have shown that the deposition of acidified materials can affect terrestrial and aquatic resources. The magnitude and type of impact of the acid deposition, however, depends on a variety of complex factors, including the amount of materials deposited, the relative ability of the water body or soils to buffer the effects of the acidity, the sensitivity of organisms to pH changes, and the types and amount of vegetation. PPRP has examined a number of these processes in recent years because studies have shown that some aquatic resources in Maryland are particularly sensitive to acid deposition.

In 1990, a survey was conducted to assess the biological effects of acid deposition on 79 stream reaches in western Maryland, an area of the state with a high proportion of sensitive streams and fish. The researchers correlated the presence and abundance of fish in these streams with chemical and physical characteristics of the water bodies (Morgan *et al.* 1991). Those data were then used to estimate the number and proportion of stream reaches on the Appalachian Plateau that have fish communities affected by adverse water quality. More recently, the statewide, multi-year Maryland Biological Stream Survey (MBSS) was initiated in the 1990s to assess the status and trends of biological resources (Janicki *et al.* 1993). The MBSS collects information on aquatic biota (fish and macroinvertebrates), physical habitat, and water quality to assess the fishability and biological integrity of Maryland streams. The MBSS will yield a comprehensive assessment of the extent to which acidic deposition may be affecting critical biological resources within streams of the state.

Several other ongoing studies are developing methods for detecting effects of acid deposition in the presence of other factors contributing to degradation of Maryland's stream resources. One such study used satellite imagery to characterize the degree of vegetation cover and types of land use in the catchment upstream of sites sampled during a stream survey (Kazyak *et al.* 1992). Other studies have evaluated and developed the **index of biotic integrity** (IBI) approach to characterizing stream health (Jacobson *et al.* 1992; Hall *et al.* 1993, 1994). Development of an IBI for fish communities in Maryland began during 1992 in 24 Coastal Plain streams. The goal of the 1992 study was to evaluate the ecological status of fish communities in 12 acid-sensitive and 12 acid-insensitive streams. In addition, water quality, physical habitat, land use, and watershed area in each stream were measured and compared. The IBI approach shows promise as a tool for assessing impacts of acid deposition, and interest is growing in using the approach for assessing other types of impacts.

Other studies have been conducted to investigate the impact of **episodic acidification**, a short-term peak in acidity caused by an acid rain event or runoff of acidic materials from the ground into a stream or lake. Figure 3-8 illustrates the typical relationship between streamflow (or discharge) and pH under episodic acidification. DNR sponsored two studies on the effects of episodic acidification of Maryland streams — the Catoctin Mountain Stream Studies in conjunction with the U.S. Geological Survey, and the Big Run Episodes Study (Morgan *et al.* 1994) — because earlier studies indicated that short-term pulses of extremely high acidity during high stream discharges can have significant adverse impacts on aquatic biota (Rice and Bricker 1992).

Figure 3-8
Variation in Streamflow and Acid Neutralizing Capacity (ANC) or pH for an Idealized Acid Episode



(Source: Wigington *et al.* 1993).

The goal of much of Maryland's acid rain research is to generate information needed for effective management, including mitigation, of the acid deposition problem in Maryland. One study recently conducted in the Coastal Plain examined the relative contribution of agricultural and atmospheric sources of acidity (Janicki and Wilson 1994). DNR is also currently sponsoring the development of mathematical models for identifying streams in western Maryland at risk of episodic acidification (Eshleman 1994). In this study, data from the Maryland Synoptic Stream Chemistry Survey, Western Maryland Stream Survey, and Upper Big Run Episodes Study, as well as information on bedrock geology for the study area, are being used in conjunction with existing episodic acidification models from the U.S. EPA Episodic Response Program and others. The objective of the project is to determine if the combinations of models and data can identify the streams most at risk. These streams would then form the pool of candidate streams for acid deposition mitigation in that region of the state.

Mitigation

Once it is determined that streams, fish, or other wildlife habitats are sensitive to acid deposition and that impacts have occurred, questions are raised about how the impacts can be mitigated. Maryland has conducted a number of research projects to investigate the effectiveness of various liming applications to mitigate acidification of Maryland surface water bodies. Pilot projects have been undertaken to demonstrate the feasibility of different approaches such as stream, lake, and watershed liming.

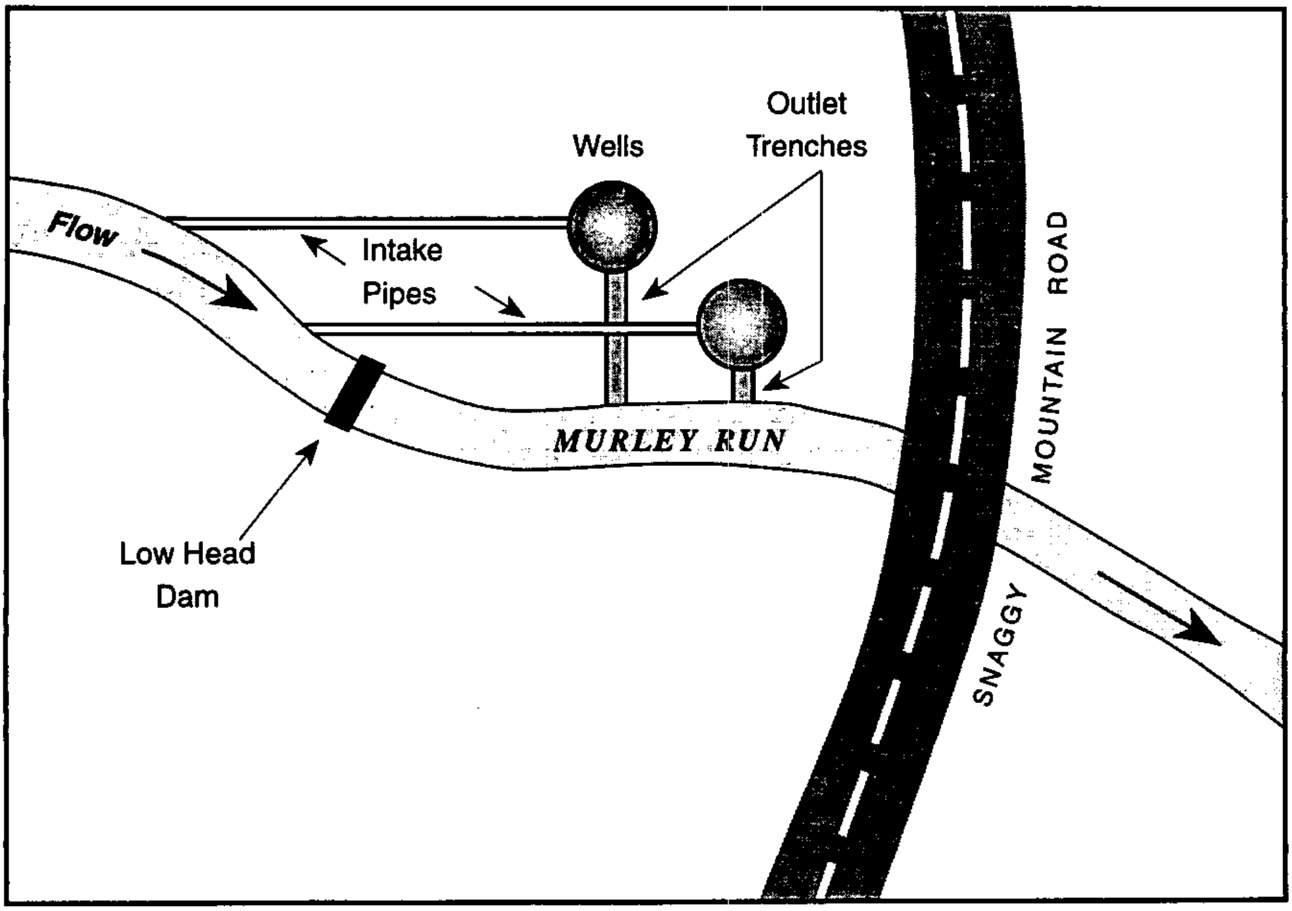
Initial studies investigated the use of automated stream liming devices to neutralize acidic episodes in several Maryland Coastal Plain streams. Some of this research was prompted by the observation that early life stages of some migratory fish species (such as blueback herring) that spawn in Coastal Plain streams are particularly sensitive to acidified streams (Klauda 1989). In stream liming projects, limestone materials, which are basic (as opposed to acidic materials), are added to streams in an attempt to neutralize acidity. Maryland has been testing stream liming methods in two Coastal Plain streams since the mid-1980s. In these projects, researchers operated **dosers** in study streams, which automatically release liming materials at preset intervals into the streams. Greening *et al.* (1987, 1989) and Janicki and Greening (1988) reported that, although the dosers were able to mitigate acidic pulses during storm events, the devices experienced mechanical breakdowns and power failures during long-term use.

Another project addressed fish kills in Herrington Lake in Garrett County as a result of early spring episodic acidification (Pavol 1992, 1993). Direct application of over 30 tons of limestone into Herrington Creek at the upstream inlet to Herrington Lake increased lake pH until heavy rainfall and snowmelt from an unusually large snowpack resulted in significant drops in pH. No fish kills were reported during the next fish stocking period and, given the worst case conditions of a heavy snowfall and the very low retention time of Herrington Lake, the liming project was regarded as a success.

In addition to direct stream liming, PPRP has been evaluating a different type of mitigation technique for acidified streams known as **watershed liming**. With this technique, limestone materials are placed over the land area of a watershed and natural precipitation processes wash the limestone into the stream over time, instead of a doser applying the materials directly to the stream. The research is designed to determine whether watershed liming is an appropriate and feasible strategy to mitigate acidification of western Maryland streams. After extensive review of potential study watersheds, PPRP selected Alexander Run in Garrett County as the subject for a long-term watershed liming project. Since the initial liming of the watershed in October 1991, PPRP has been monitoring stream chemistry, stream discharge, soils, vegetation, and aquatic life to evaluate the effects of the liming (Price *et al.* 1993). The lack of a long-term change in the water chemistry of Alexander Run suggests that the ground water that provides base flow to the stream is not coming in contact with the limed soils. Hydrologic event monitoring will help determine whether watershed liming can be an effective mitigation method in this system. Nonetheless, this method of liming shows promise in the remote, mountainous regions of western Maryland where electrical energy and the maintenance of mechanical equipment are serious impediments to the use of stream dosers.

DNR recently launched the Maryland Acid Stream Mitigation Demonstration Project, in which innovative acid mitigation techniques will be studied at two recreational streams in Garrett County and a trout hatchery in Frederick County (Olem and Jacobson 1994). Implementation of these mitigation projects will demonstrate the feasibility and effectiveness of two innovative mitigation designs: diversion wells and constructed wetlands. Diversion wells have been successful in Sweden, but have only been implemented at a few sites in the United States. They involve diverting the acidic water from the stream into a cylindrical concrete well with limestone on the bottom; neutralized water is then returned to the stream (Figure 3-9). Constructed wetlands have never been attempted as a mitigation for acid deposition, but they could provide an economical means of raising stream pH, while at the same time contributing wildlife habitat and other benefits to the landscape. If successful, these methods can be added to the repertoire of potential mitigation alternatives for acid streams in Maryland.

Figure 3-9
Use of Limestone Diversion Well for Acid Mitigation in Western Maryland



Critical Loads

Maryland has also sponsored studies to determine the **critical loads** of streams. The critical load for a particular location is defined as the level of acidic deposition below which adverse impacts to sensitive biological resources would not be expected. Maryland's research in this area, which began in the late 1980s, is being conducted to determine the critical loads of sulfur and nitrogen that can be accommodated by sensitive Maryland streams without causing further acidification. The work will also be used to evaluate the ability of various precursor emission control strategies at power plants to achieve these critical load targets.

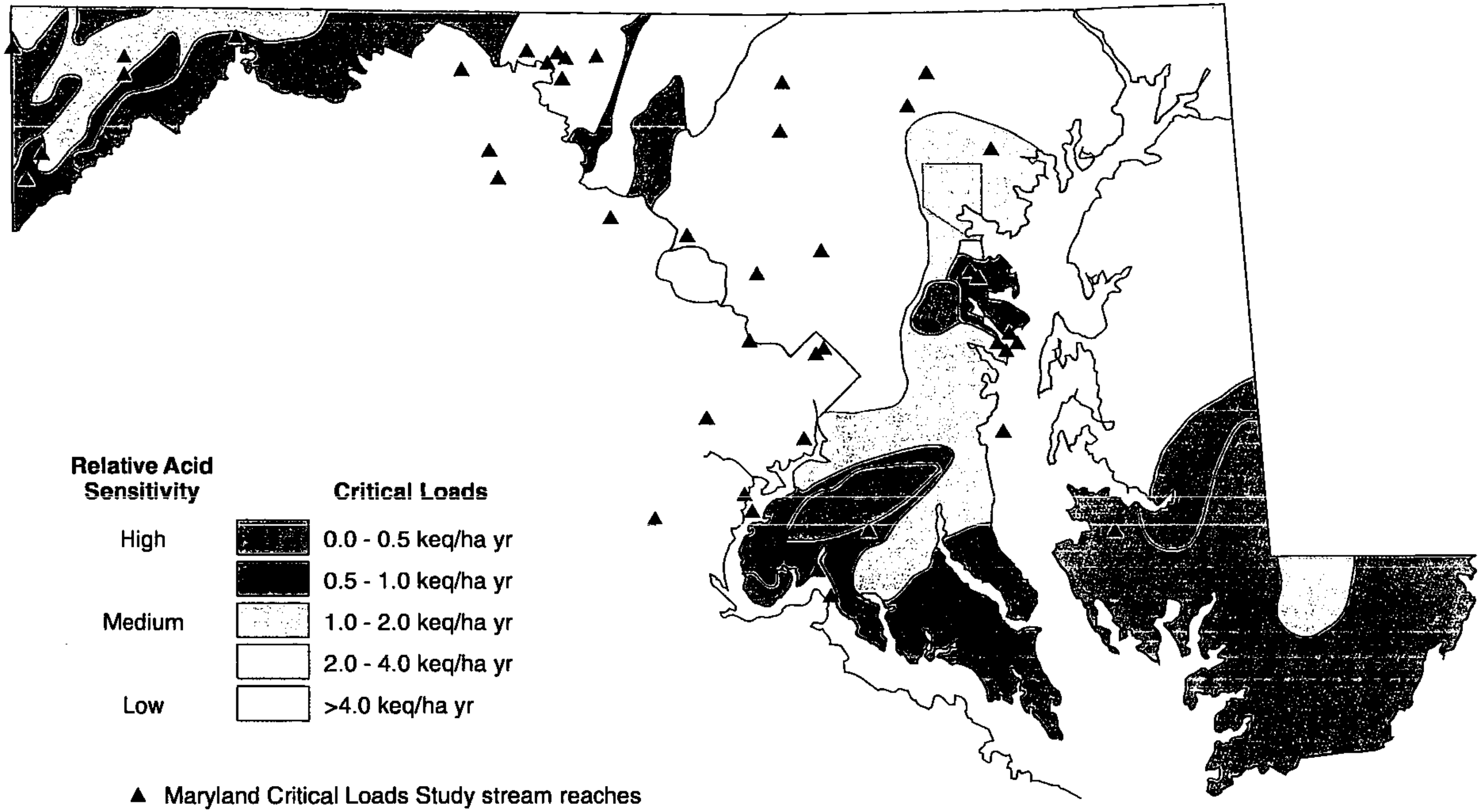
The critical load concept is an approach that quantifies the amount of acidification an ecosystem can withstand before selected indicators show signs of ecological damage. The purpose of this determination is to set goals for future acid deposition that will protect sensitive Maryland ecosystems. The objectives of the **Maryland Critical Loads Study** (MCLS) were the following (Janicki *et al.* 1995):

- estimate critical loads of sulfate and nitrate for Maryland streams,
- estimate the number and percentage of streams with various critical loads on a statewide and regional basis,
- estimate future changes in acidic deposition in Maryland in response to a number of emission reduction scenarios,
- predict stream chemistry responses to a number of future acid deposition scenarios, and
- assess the ability of various air pollutant emissions reduction strategies to achieve critical loads in Maryland.

In this study, streams were established as the resource of concern and the critical pH conditions (threshold of adverse effects) for four fish species were used to define a critical load. Models were used to simulate the chemical and physical behavior of soils and to predict responses in stream chemistry to changes in the level of acid deposition. The deposition level that caused adverse effects, according to model predictions, was defined as the critical load for a given stream segment.

The resulting critical load map for Maryland is presented as Figure 3-10. It illustrates that the Appalachian Plateau, the Coastal Plain, and portions of the Blue Ridge provinces of Maryland all are highly acid sensitive, as indicated by the low critical load values for acid precursors (less than 0.5 kiloequivalents per hectare per year (keq/ha/yr) or approximately 24 kg SO_4/ha/yr). Low critical loads mean that these streams will acidify more quickly under a given acidic deposition rate than will streams in other

Figure 3-10
Critical Loads for Streams in Maryland



parts of the state. The Valley and Ridge, the Piedmont, and the remaining portion of the Blue Ridge provinces may accommodate deposition rates approximately an order of magnitude higher (greater than 2.0 keq/ha/yr or approximately 96 kg SO_4/ha/yr). The results further confirm that stream sensitivity to acid deposition is closely correlated with bedrock and soil type (Sverdrup *et al.* 1992).

The MCLS project team concluded that some streams in Maryland are still acidifying under the present deposition load, as determined by mapping steady-state stream chemistry (Janicki *et al.* 1995). By comparing current deposition rates to critical loads calculated for particular watersheds, sensitive locations in Maryland can be identified (approximately half of the 73 study watersheds in the MCLS had current deposition levels in excess of their critical loads). The critical load values can be used as a reference point for judging the benefits of lower sulfate and nitrate deposition rates. Evaluations under the MCLS indicate that, following the 10 million ton reduction in emissions mandated by the 1990 CAA Amendments, the critical loads at all but a few study streams located in the Coastal Plain and Appalachian Plateau should be met. However, at those Coastal Plain and Appalachian Plateau sites that have very low critical loads, deposition would continue to exceed critical loads even if all Maryland power plant emissions were eliminated.

3.2.3 Power Plants and Regional Haze

3.2.3.1 Visibility

Reduced visibility, particularly in the summertime, often results from pollutants building up in stagnant air, leading to a widespread, uniform haze. These air pollution events or episodes may be the most noticeable effects of anthropogenic pollution. Recent studies have shown that 80% of people are aware of poor visual air quality (Trijonis 1990).

Although most people understand what is meant by poor visibility, there is no one definition of visibility that is universally accepted. The definition of visibility has its origins in military applications, such as the greatest distance at which an enemy vessel can be seen. The World Meteorological Organization definition of visibility reflects this idea, defining visibility as "...the greatest distance at which a black object...can be seen and recognized." However, much of the concern today regarding visibility deals with the aesthetic value of a scenic vista. If the atmosphere is sufficiently hazy that an object is barely perceptible, then in the eyes of most people the object has essentially no scenic value. The ambiguity over the definition of visibility is indicated by the fact that even though most people are aware of poor visual quality, only one-third of the people in one study were able to properly rank the best to worst visibility pictures (Trijonis 1990; Niemeyer 1990).

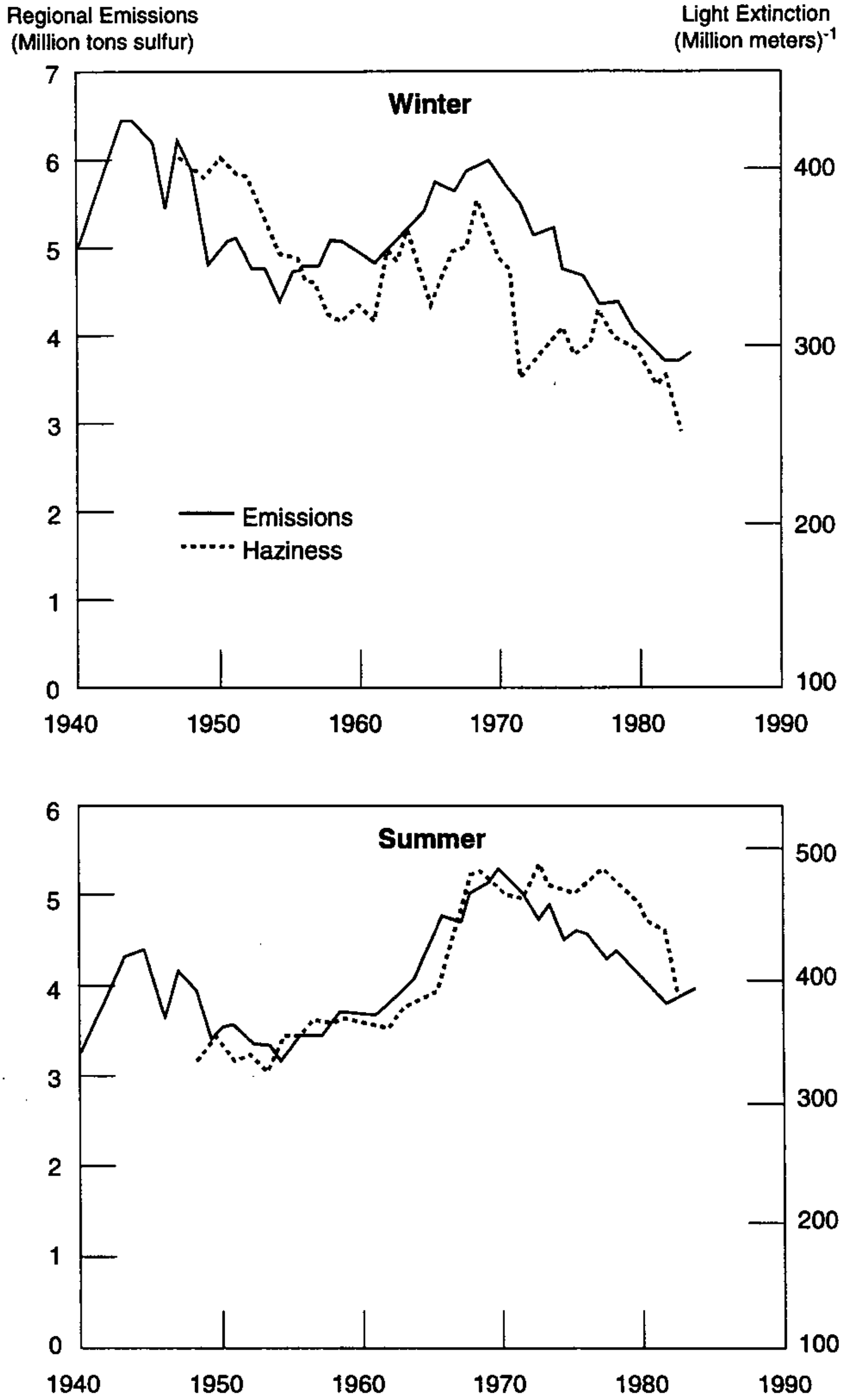
Visibility impairment can be caused by a variety of processes, both natural and of human origin. For example, fog is a naturally occurring form of visibility impairment, while air pollution is a form of visibility degradation resulting from human activities. While anthropogenic sources emit a variety of air pollutants, power plants emit two pollutants in particular that can have a deleterious effect on visibility: SO_2 and NO. SO_2, as it travels through the atmosphere, converts to sulfate particles. These particulates scatter light efficiently, and thereby reduce visibility. The National Park Service (NPS) has stated that sulfates are the most important contributor to visibility degradation in the parks of the eastern United States. NO, as it travels through the atmosphere, converts to NO_2, a precursor to nitric acid. At high concentrations, the presence of NO_2 can be detected by the brownish color of the sky, as visible light is absorbed by NO_2 (Stern *et al.* 1984). NO may also react in the atmosphere to form nitrate aerosols, which can contribute to urban haze. However, in the eastern U.S., sulfate far outweighs nitrate as a contributor to regional visibility degradation.

Over the past 50 years or so, the northeastern United States has experienced a decline in haziness during the winter months while the amount of summer haziness has generally increased. The haziness increased the most in the 1950s and 1960s, then leveled off and even decreased after the early 1970s. Total sulfur emissions have followed a similar pattern, with sulfur emissions peaking about 1970 and then decreasing in the following years. The correlation between these two parameters is depicted in Figure 3-11 (Trijonis 1990).

Millions of people visit national parks and wilderness areas throughout the United States each year. Although people visit these places for a variety of reasons, an often-cited reason is for the scenic vistas. As a result, the NPS and the U.S. Forest Service are particularly concerned with regional haze and visibility degradation. In general, visibility at national parks is poorest during the summer when visitation is highest.

There are other reasons besides haze at national parks to be concerned about poor visibility. For instance, a reduction in visibility usually corresponds to a reduction in solar energy, leading to an increased demand for artificial lighting and heating (Stern *et al.* 1984). Poor visibility also promotes delays and accidents in all modes of transportation, and inhibits photosynthesis in plants (Stern *et al.* 1984).

Figure 3-11
Comparison of Historical Trends for Sulfur Emissions and Haziness (light extinction) for the Northeast U.S.



Source: Trijonis 1990

3.2.3.2 *Recent Impact Assessments*

The U.S. Congress, through the 1977 CAA Amendments, established as a national goal "...the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from manmade air pollution." In 1979, the U.S. EPA, in cooperation with the U.S. Department of the Interior, promulgated a list of **Class I areas** (national parks with an area greater than 6,000 acres, or national wilderness areas with an area greater than 5,000 acres) across the country where visibility is considered an important value (USEPA 1979). Congress also established that a new major source undergoing review for a Prevention of Significant Deterioration (PSD) permit must assess its effects on visibility at "surrounding" Class I areas that could potentially suffer adverse air quality effects from the source. Congress gave the Federal Land Manager (FLM) at each national park and wilderness area the responsibility to protect the air quality related values (AQRVs), including visibility, of such lands. In recent years, FLMs at Class I areas have been requiring PSD permit applicants to conduct more extensive, detailed analyses of the effects of proposed emissions on AQRVs. The four Class I areas closest to Maryland are indicated in Figure 3-12.

Recently, two proposed coal-burning power plants — one in western Maryland and the other on Maryland's Eastern Shore — had to assess their impacts at nearby Class I areas as part of the PSD permitting process.

- Applied Energy Systems, Inc. (AES) addressed the effects on visibility at Shenandoah National Park in Virginia, and the Dolly Sods and Otter Creek Wildernesses in West Virginia, due to emissions from the proposed Warrior Run cogeneration facility in Cumberland. Using state-of-the-art plume optics models and NPS-approved methodologies, AES established that its proposed project would not adversely affect visibility at the three Class I areas (Murtlow 1994b). Moreover, AES went a step further and showed insignificant visibility impacts at six recreational areas in Maryland within 15 kilometers of the Warrior Run site (Murtlow 1993).
- Delmarva Power assessed potential visibility impairment due to emissions from the proposed Dorchester power plant near Vienna at the nearest Class I area, the Brigantine National Wildlife Refuge in New Jersey, using standard U.S. EPA conservative modeling techniques. Delmarva Power's analysis indicated that the proposed plant would have no adverse effects on visibility at Brigantine (KBN 1993).