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Direct/Delayed Response Project: Future Effects of Long-Term Sulfur Deposition on Surface Water Chemistry in the Northeast and Southern Blue Ridge Province

Volume III: Level III Analyses and Summary of Results

by

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A Contribution to the
National Acid Precipitation Assessment Program

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SECTION 10

LEVEL III ANALYSES - DYNAMIC WATERSHED MODELLING

10.1 INTRODUCTION

Previous sections have discussed (1) the principal theories and basic processes of acidification (Section 3); (2) the relationship among atmospheric deposition, watershed attributes, and surface water chemistry (Section 8); and (3) future changes that might occur in watershed sulfate adsorption and base cation exchange (Section 9) for up to the next 200 years. This section discusses the Level III Analyses - the application of dynamic watershed models in projecting future changes in surface water chemistry.

Three terms are used to describe simulations of future change:

- Predict - to estimate some current or future condition within specified confidence limits on the basis of analytical procedures and historical or current observations.

- Forecast - to estimate the probability of some future event or condition as a result of rational study and analysis of available data.

- Project - to estimate future possibilities based on rational study and current conditions or trends.

The distinction among these three terms and definitions is the intended use of the model output. Level III Analyses are defined, and intended to be used, as projections.

Predictions typically are made to compare different scenarios, controls, or management options. Predictions can be performed within specified confidence limits because of previous model evaluations, testing, applications, and comparisons with measured data for a variety of system types. Model predictions of various surface water attributes are legally required for many proposed management strategies that range, for example, from examining potential alterations of hydrologic regimes due to land use modifications to estimating mixing zones for effluent discharges to estimating phytoplankton response to nutrient reduction. Predictions generally are performed for short time periods (e.g., single events, parts of a season, or a few years) and focus on before-after comparisons such as water quality before and after wasteload reductions or plankton biomass before and after nutrient reductions.

Forecasts convey some estimate of the likelihood or probability that various conditions or events will occur in the future. Daily weather forecasting, with associated probabilities of showers, thunderstorms, etc., is a classic example of forecasting. This represents a short-term forecast. Weather forecasts also are made for annual or decadal time frames. Flood forecasts can be short term (daily or weekly), but also are made for long-term events such as the probability of 100-, 1000-, and 1,000,000-year events (NRC, 1988).

Projections, in contrast, are not accompanied by estimates of the probability that any of the conditions or events might occur in the future. Projections can be used as a basis for relative comparisons among various emission or deposition scenarios. While the probability that a scenario will occur cannot be estimated, projections do provide a relative basis for comparing costs and beneficial or deleterious effects associated with different control or management strategies. This information generally is relevant to policymakers and decisionmakers for evaluating different control strategies. The models in the Level III analyses are being used in projecting, not in forecasting, the effects of alternative acidic deposition scenarios on future changes in surface water acid-base chemistry.

In Level III Analyses integrated, process-oriented watershed models are used to project long-term changes (i.e., up to 100 years) in surface water chemistry as a function of current and alternative levels of sulfur deposition. The watershed models integrate our current understanding of how various processes and mechanisms interact and respond to acidic deposition. These mechanisms include soil-water interactions (including soil-water contact time), sulfur retention, base cation exchange and replacement of base cations through mineral weathering, and other watershed processes (e.g., vegetative uptake, in-lake processes, organic interactions). However, the present study does not establish the adequacy of the formulations that implement these processes, the mode of spatial aggregation of data, and the calibration approaches used for long-term acidification projections.

The three watershed models that have been applied are the Enhanced Trickle Down (ETD), Integrated Lake-Watershed Acidification Study (ILWAS), and Model of Acidification of Groundwater in Catchments (MAGIC). The DDRP is an applied project and has used existing techniques and models for these analyses. The use and application of these models to achieve the objectives of the DDRP was approved by peer reviewers in accordance with the Agency's standard competitive funding process and requirement for external review of environmental data collection programs (Section 4.4.3).

This section presents

- dynamic watershed models used in the Level III Analyses,
- operational assumptions of these analyses,
- watershed prioritization procedures,
- preparation of the modelling datasets (specifically identifying any differences required for Level III Analyses compared to Level I and II Analyses),
- general modelling approach,
- model calibration and confirmation,
- model sensitivity analyses,
- regional projection refinements,
- model projection and uncertainty procedures,

- regional population estimates and uncertainties,
- regional comparisons and uncertainties, and
- discussion and conclusions.

10.2 DYNAMIC WATERSHED MODELS

Processes that influence the acid-base chemistry of surface water, and that were considered by the NAS Panel (NAS, 1984), were described in Section 3. Although these processes can be individually identified, discussed, and represented empirically, they are not independent and do not occur in isolation from other processes. The observed lake or stream response to acidic deposition represents the integrated response of many watershed and lake/stream processes controlling surface water chemistry. To project the future response of a lake or stream to acidic deposition, therefore, requires dynamic watershed models that incorporate and integrate the important processes controlling the acid-base chemistry of surface water.

Both dynamic and steady-state models can be used to project changes in surface water chemistry as a function of changes in acidic deposition. A dynamic watershed model, however, simulates the time trends of various lake, stream, and watershed constituents, such as ANC, pH, sulfate, calcium, soil base saturation, and sulfate adsorption. A steady-state model can project conditions at only one time in the future, the time at which steady state is achieved (i.e., ultimate constituent concentration or value), and does not provide any indication of the changes that occurred between the initial conditions and steady-state condition or concentration. It is the computation of concentrations and processes as a function of time that distinguishes dynamic models from steady-state models.

Three dynamic watershed models were used to project surface water chemistry for the next 50 to 100 years both at current and alternative levels of acidic deposition in the Northeast (NE):

- Enhanced Trickle Down (ETD) (Nikolaidis et al., 1988; Nikolaidis et al., 1989)
- Integrated Lake-Watershed Acidification Study (ILWAS) (Chen et al., 1983; Gherini et al., 1985)
- Model of Acidification for Groundwater in Catchments (MAGIC) (Cosby et al., 1985a,b,c)

Two of these three watershed models also are being used to project changes in surface water chemistry in the Southern Blue Ridge Province (SBRP) - MAGIC and ILWAS.

Although each model incorporates the processes considered important in controlling the acid-base chemistry of surface water, process resolution and detail vary significantly among the models. Some of the processes included in the three models and their spatial/temporal resolution are compared in Table 10-1. The use of multiple models is important because:

- the level of detail by which each process or mechanism is represented varies between models, reflecting the relative importance of each process in the systems for which the model was first developed;

Table 10-1. Major Processes Incorporated in the Dynamic Model Codes (Parentheses Indicate Limited Treatment of Process, and Dashes Indicate Processes not Included in a Code) (Jenne et al., 1989)

	MAGIC/TOPMODEL	ETD/PEN	ILWAS
Atmospheric Processes			
- Dry deposition	X	X	X
- Wet deposition	X	X	X
Hydrological Processes			
- Snow sublimation	-	X	X
- Evapotranspiration	X	X	X
- Interception storage	(X)[a]	-	X
- Snowmelt	X	X	X
- Overland flow	X	X	X
- Soil freezing	-	X	X
- Macropore flow	X	-	-
- Unsaturated subsurface flow	X	X	X
- Saturated subsurface flow	X	X	X
- Stream flow	X	-	X
- Lake stratification	-	-	X
- Lake ice formation	-	-	X
Geochemical Processes			
- Carbonic acid chemistry	X	X	X
- Aluminum chemistry	X	-	X
- Organic acid chemistry	X	-	X
- Weathering	X	X	X
- Anion retention	X	X	X
- Cation exchange	X	X	X
Biogeochemical Processes			
- SO_4^{2-} reduction in lake	(X)[b]	X	X
- Nitrification in soil	(X)[b]	-	X
- Nutrient uptake	(X)[b]	-	X
- Canopy interactions	(X)[a]	-	X
- Litter decay	(X)[a]	-	X
- Root respiration	(X)[a]	-	X

a Cosby, B.J. (written review comments, 1988) considers that canopy interactions and root decay and respiration are implicitly included in the MAGIC code by use of a dry deposition factor and by designation of CO_2 partial pressure in soils and surface waters.

b Sulfate reduction, nitrification, and uptake of ions can be simulated with the MAGIC code by specifying uptake rates of SO_4^{2-} and NH_4^+ for various hydrologic compartments.

- identification of similar key watershed parameters and processes in each model and their relationship to measured watershed characteristics provides greater confidence in conclusions about which factors influence the acid-base chemistry of surface water; and

- long-term data sets for model validation/verification do not exist, so model accuracy and precision for long-term projections is unknown; however, similar projections of watershed responses among the models provides greater confidence in the conclusions.

10.2.1 Enhanced Trickle Down (ETD) Model

The ETD is a lumped parameter model based on the concept of ANC mass balance. Various chemical processes in the ETD model, such as mineral weathering, sulfate adsorption and desorption, and cation exchange, are incorporated as either consuming or producing ANC (Schnoor and Stumm, 1985). Rate expressions are used to describe mineral weathering, cation exchange, and sulfate reduction reactions. Equilibrium expressions are used to describe carbonic acid chemistry and sulfate adsorption and desorption. ETD explicitly incorporates mineral weathering rate reactions and sulfate reduction but does not explicitly incorporate chemical reactions involving aqueous aluminum, nitrate, or organic acid chemistry, although the ETD code does implicitly consider contributions to total acidity from these constituents. Mass balance calculations are considered for ANC (equivalent to the modified Gran ANC), sulfate, and chloride, with chloride considered to be a conservative constituent.

The Trickle Down model, a precursor to ETD, was formulated to perform assessments of the effects of acidic deposition on a number of seepage lakes in the Upper Midwest. The objective of the modelling effort was to provide a model with sufficient detail to calculate alkalinity concentrations in surface water, soils, and ground water, but sufficiently simple to apply using a microcomputer with one master variable (alkalinity) for acidic deposition assessments (Schnoor et al., 1984, 1986a). Enhanced Trickle Down was modified to include sulfate adsorption and desorption and improved hydrologic flowpaths (Nikolaidis, 1987). The hydrologic submodel simulates snowmelt, interflow, overland flow, groundwater flow, frost-driven processes, seepage, and evapotranspiration (Nikolaidis et al., 1989). ETD is spatially partitioned into three vertical components within the watershed: soil, unsaturated zone, and ground water. The watershed contributes to a lake compartment. The lake and terrestrial compartments are considered areally homogeneous. The temporal resolution of the ETD output generally is daily.

The meteorological and deposition input requirements for ETD are illustrated in Tables 10-2 and 10-3. The chemical constituents projected in soil solution and surface water are listed in Table 10-4. Because of the importance and pivotal role that ANC has in the projections of surface water acidification and chemical improvement, the components of the ANC calculations are shown for each of the three models in Table 10-5. The ANC calculation for ETD corresponds with the ANC calculation for the modified Gran titration method. These input requirements and output constituents are contrasted with those included in ILWAS and MAGIC.

The ETD model was originally applied to Lakes Clara and Vandercook in northcentral Wisconsin (Lin and Schnoor, 1986), as a joint effort by the U.S. EPA, U.S. Geological Survey, the Wisconsin Department of Natural Resources, and the University of Iowa. ETD reproduced the seasonal and annual changes in water chemistry for the short periods of record on these two lakes. ETD has since been

Table 10-2. Meteorological Data Required by the Dynamics Model Codes (from Jenne et al., 1989)

Meteorological Data	MAGIC/TOPMODEL	ETD/PEN	ILWAS
Interval for data measurement	Monthly[a] yearly	Daily	Daily
Precipitation	m	mm	cm
Relative humidity or dewpoint		%	%
Min. air temperature	°C		°C
Max. air temperature	°C		°C
Ave. air temperature		°C	
Mean daylight hours	%		%
Cloud cover (fraction)		(unitless)	(unitless)[b]
Atmospheric Pressure			mbars
Wind Speed		km day^{-1}	m sec^{-1}

[a] TOPMODEL runs with a daily time step.

[b] Average values per month required.

Table 10-3. Chemical Constituents in Wet and Dry Deposition Considered by the MAGIC, ETD, and ILWAS Codes (from Jenne et al., 1989)

	MAGIC		ETD		ILWAS	
Constituent	Wet	Dry[a]	Wet	Dry	Wet	Dry
$SO_x(g)$		(X)[b]				X
$NO_x(g)$		(X)[b]				X
H^+			X	X	X	X
Al (total)					X	X
Ca^{2+}	X	X			X	X
Mg^{2+}	X	X			X	X
K^+	X	X			X	X
Na^+	X	X			X	X
NH^{+4}	X	X			X	X
SO_4^{2-}	X	X	X	X	X	X
NO_3^-	X	X			X	X
Cl^-	X	X	X	X	X	X
F^-	X	X				
PO_4^{3-}					X	X
ANC			X	X		
TOC[c]			X		X	X
TIC[d]					X	X
H_4SiO_4					X	X
Units	μeq L^{-1}/interval		meq m^{-2}	meq m^{-2}	mg L^{-1}	mg m^{-3}
Interval	monthly or yearly ave.		-daily-		volume weighted monthly average	

[a] The MAGIC code requires that dry deposition be expressed by means of a dry deposition factor.

[b] Cosby, B.J. (written communication, 1988) considers that $SO_x(g)$ and $NO_x(g)$ are implicitly included by means of the dry deposition factor.

[c] Total organic carbon

[d] Total inorganic carbon

Table 10-4. Chemical Constituents Included in Soil Solutions and Surface Water for the MAGIC, ETD, and ILWAS Codes (from Jenne et al., 1989)

Chemical Constituent	MAGIC	ETD	ILWAS
ANC	X	X	X
Ca^{2+}	X		X
Mg^{2+}	X		X
K^{+}	X		X
Na^{+}	X		X
NH_4^{+}	X		X
H^{+}	X	X	X
Al^{3+}	X		X
$Al(OH)_n^{3-n}$ (n=1 to 4)	X		X
$Al(F)_n^{3-n}$ (n=1 to 6)	X		X
$Al(SO_4)_n^{3-n}$ (n=1 to 2)	X		X
Al-R[(a)]		X	
SO_4^{2-}	X	X	X
NO_3^{-}	X		X
Cl^{-}	X	X	X
F^{-}	X		X
$H_2PO_4^{-}$			X
H_4SiO_4(aq)			X
CO_2(g)	X	X	X
CO_2(aq)	X	X	X
H_2CO_3(aq)	X	X	X
HCO_3^{-}	X	X	X
CO_3^{2-}	X	X	X
HR'^{0}, R'^{-}[(b)]			X
$H_2R''_0$, HR''^{-}, R''^{2-}[(b)]	X		
$H_3R'''^{0}$, $H_2R'''^{-}$[(b)]			X
HR'''^{2-}, R'''^{3-}			

[a] Al-Refers to the various organic complexes of aluminum.
[b] R', R", and R''' refer to monoprotic, diprotic, and triprotic organic acids, respectively.

Table 10-5. Definitions of Acid Neutralizing Capacity (ANC) Used by the MAGIC, ETD, and ILWAS Codes (Brackets indicate concentration in molar or molal units, and R', R'', and R''' represent mono-, di-, and triprotic organic acids, respectively.) ANC Simulated by All Three Models is Equivalent to the Modified Gran ANC (from Jenne et al., 1989)

Code	Units	ANC Definition
MAGIC	$\mu eq\ L^{-1}$	$ANC = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] + [HR''^-]$
		$+ 2[R''^{2-}] + [Al(OH)_4^-] - [H^+] - 3[Al^{3+}]$
		$- 2[Al(OH)_2^+] - [AlOH^{2+}]$
ETD[a]	$meq\ m^{-3}$	$ANC = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] + [R'^-]$
ILWAS	$\mu eq\ L^{-1}$	$ANC = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] + [H_2R'''^-]$
		$+ 2[HR'''^{2-}] + 3[R'''^{3-}] + [R'^-]$
		$+ [AlOH^{2+}] + 2[Al(OH)_2^+] + 3[Al(OH)_3^0]$
		$+ 4[Al(OH)_4^-] + 3[AlR'''^0] + [AlR'^{2+}]$
		$+ 2[Al(R')_2^+] + 3[Al(R')_3^0] - [H^+]$

[a] The ETD code operates on the principle of ANC mass balance.

applied to several Adirondack lakes including Woods Lake, Panther Lake, and Clear Pond (see Appendix A), other lakes in the Upper Midwest, and several lakes in the Sierra Nevada mountains of California (Nikolaidis et al., 1988, 1989; Lee et al., in press).

10.2.2 Integrated Lake-Watershed Acidification Study (ILWAS) Model

The ILWAS model is a process-oriented model that uses both equilibrium and rate-limited expressions to describe mass balances for 18 chemical constituents (Table 10-4). The ILWAS algorithms represent the effects of biogeochemical processes on surface water chemistry (see Table 10-1). Mass balances for the major cations and anions and the effects of aqueous aluminum and organic acids on surface water chemistry are incorporated in the model. The ILWAS model was formulated to simulate the seasonal and long-term changes in water chemistry caused by acidic deposition. As a result, ILWAS has a strong assessment capability (Huckabee et al., 1989). The ILWAS model contains three modules:(1) a canopy module to simulate forest canopy interactions with both wet and dry deposition, (2) a hydrology and watershed soil module to route precipitation through the soil horizons and simulate soil-water physicochemical processes and biotic transformations, and (3) a lake module to simulate aquatic biochemical reactions (Chen et al., 1983; Gherini et al., 1985).

The vertical resolution in the ILWAS code includes the canopy, a snow component, stream segments, a lake component, and up to 10 soil layers for each subcatchment in the watershed (Chen et al., 1983). The ILWAS model can simulate up to 20 subcatchments and associated stream segments. For most DDRP watersheds, only one or two subcatchments were used. To calculate the distribution of water between flowpaths, the ILWAS model uses various forms of the continuity equation, Darcy's law for flow in unsaturated and saturated permeable media, and Manning's equation, Muskingum routing, and stage-flow relations for surface waters (Chen et al., 1982, 1983). The vertical layers within each subcatchment are assumed to be areally homogeneous. The lake is vertically one-dimensional with up to 80 vertical layers including snow and ice layers. For DDRP application, the layer thickness was set at 1 m so most lakes had between 3 and 7 layers. The temporal resolution of ILWAS output is generally daily, but more frequent output can be obtained (with added computational effort and increased input data).

The meteorological and deposition input requirements are shown in Tables 10-2 and 10-3. The output variables in the soil solution and water chemistry are listed in Table 10-4. The components of the ANC calculation are shown in Table 10-5. The ANC simulated by ILWAS is equivalent to the modified Gran ANC.

The ILWAS model was developed to further the understanding of how atmospheric and terrestrial acid-base processes interact to produce observed surface water chemistry. The model was developed as part of the Electric Power Research Institute's (EPRI) Integrated Lake-Watershed Study of three Adirondack lakes, Woods, Sagamore, and Panther (Chen et al., 1983; Gherini et al., 1985; Goldstein et al., 1984). The model reproduced the seasonal and annual changes in water chemistry in these three lakes for the 5 years of record (see Appendix A). The model has subsequently been applied to 25 watersheds in Wisconsin, Minnesota, North Carolina, Tennessee, Utah, and California (Chen et al., 1988; Davis et al., 1986; Gilbert et al., 1988; Greb et al., 1987; Munson et al., 1987). Regional assessments have been conducted as part of the EPRI- funded Regional Integrated Lake Watershed Acidification Study (RILWAS) and through other independent applications (Gherini et al., 1989).

10.2.3 Model of Acidification of Groundwater in Catchments (MAGIC)

MAGIC is a lumped-parameter model of intermediate complexity, originally developed to project the long-term effects (i.e., decades to centuries) of acidic deposition on surface water chemistry. One of the model's principal assumptions is that a minimum number of critical processes in a watershed influence the long-term response to acidic deposition. The model simulates soil solution chemistry and surface water chemistry to project the monthly or annual average concentrations of the water chemistry constituents listed in Table 10-4. Hydrologic flow of water through soil layers to the receiving system is simulated using a separate hydrologic model, TOPMODEL (Hornberger et al., 1985). TOPMODEL is a topography-based, variable contributing area, catchment model adapted from the version of Beven and Kirkby (1979). The model considers overland flow, macropore flow, drainage from the upper zone to the lower zone and to the stream, and baseflow from the lower zone. Flow routing through the watershed is provided from TOPMODEL to MAGIC, a model in which both equilibrium and rate-controlled expressions are used to represent geochemical processes. Mass balances for the major cations and anions and the effects of aqueous aluminum and organic acid species on ANC are incorporated in the model. The ANC simulated by MAGIC is equivalent to the modified Gran ANC. These processes are listed in Table 10-1.

MAGIC represents the watershed with two soil-layer compartments. These soil layers can be arranged vertically or horizontally to represent the vertical or horizontal movement, respectively, of water through the soil. A vertical configuration was used in the DDRP, and the soil compartments were assumed to be areally homogeneous. Annual output is the typical temporal resolution of the model, but monthly output also can be obtained.

The meteorological and depositional input requirements for MAGIC are shown in Tables 10-2 and 10-3. The output soil solution and water chemistry constituents are shown in Table 10-4. The components included in the ANC calculation are shown in Table 10-5.

MAGIC was originally formulated to be parsimonious in selecting processes for inclusion and was intended to be used as a heuristic tool for understanding the influences of the selected processes on surface water acidification. The spatial/temporal formulations in the model reflect the intended use for assessment and multiscenario evaluations. It was originally developed on two southeastern streams but has subsequently been applied to many watersheds in the Southeast, lakes in the Adirondacks, and watersheds in England, Scotland, Norway, Finland, and Sweden (Cosby et al., 1985a,b, 1986a,b,c, 1987; Lepisto et al., 1988; Musgrove et al., 1987; Neal et al., 1986; Whitehead et al., in press). MAGIC reproduced the annual changes in water chemistry for these systems for the short period of available record. It also has been used for a regional assessment of Norwegian lakes using the Norwegian lake resurvey data (Cosby et al., 1987; Hornberger et al., 1987a,b).

10.3 OPERATIONAL ASSUMPTIONS

There are several operational assumptions associated both with DDRP and the individual models (Table 10-6). These assumptions underlie the DDRP Level III Analyses *in toto*. Each of the models has specific assumptions in addition to those made for the DDRP. These specific assumptions, summarized by Jenne et al. (1989), are described in more detail by the authors and developers of the models (Chen et al., 1983; Cosby et al., 1985a,b,c; Gherini et al., 1985; Nikolaidis, 1987; Nikolaidis et al., 1988, 1989).

10.4 WATERSHED PRIORITIZATION

The general approach for selecting the DDRP watersheds was described in Section 5.2. This section presents the approach for prioritizing watersheds for Level III Analyses in the NE and SBRP.

10.4.1 Northeast

Developing a priority order for performing the watershed calibrations and forecasts permitted early comparisons among model outcomes, identified data problems of general concern to all three models as the problems developed, and permitted joint resolution of these problems by all modelling groups. The priority ordering ensured that problems encountered with regard to the watershed classes of highest interest or greatest concern could be addressed early in the projection period, so that if additional projections were precluded due to time or manpower constraints, projections for the highest priority systems would be completed by all three modelling groups.

A decision tree was developed for the watersheds in the NE (Figure 10-1). The decision tree was based on several criteria including previous calibration and projections, internal sources of sulfur, hydrologic type, sulfur retention, chloride status, and ANC [based on values from the Eastern Lake Survey Phase I (ELS-I), Linthurst et al., 1986a)]. These criteria were used to rank the watersheds in descending order of priority with the highest priority given to Class A watersheds and the lowest priority to Class I watersheds. The number of lakes in each priority class (A - I) is shown on the right-hand side of the priority class box.

Class A watersheds are those that previously had been investigated as part of an internal EPA evaluation for the Administrator. Two of the models previously had been calibrated on these watersheds, so minimal problems were anticipated in recalibration with aggregated soils data and site-specific deposition data. Watersheds with unequivocal internal sources of sulfate confound the effects of sulfur deposition on surface waters, so these systems were ranked lowest priority. Systems with no inlets or outlets, i.e., seepage lakes (see Section 5.3), also confound interpretation of sulfur deposition effects on surface water chemistry because of internal alkalinity generation; these systems also were ranked as a lower priority class for projections. Although drainage lakes with long residence times (i.e., > 1 yr) also can have significant internal sulfate reduction, the estimated median hydraulic residence time for northeastern lakes was 0.20 yr so internal alkalinity generation for the DDRP lakes was not considered to be a confounding factor. Watersheds that appear to be currently retaining sulfur were judged to be higher priority than watersheds that appear to be at or near sulfur steady state, because of the potential for acidification as sulfate (acting as a mobile anion) depletes soil base cations. Many northeastern watersheds are influenced by the application of road salt (calcium chloride, magnesium chloride, sodium

Table 10-6. Level III Operational Assumptions

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1. Index sample water chemistry from the NSWS provides an index of chronically acidic systems and systems with low ANC that are susceptible to acidic deposition.

2. Index soil data from the DDRP Soil Survey adequately characterize watershed attributes influencing surface water chemistry.

3. Projections of future acidification consider primarily chronic acidification. Episodic acidification is considered in the EPA Episodic Response Project.

4. Surface water acidification is a sulfur-driven process. Sulfur is assumed to be the primary acidifying agent in acidic deposition. Eastern deciduous forests generally are nitrogen-limited (Likens et al., 1977; Swank and Crossley, 1988) so there is low export of nitrate. In addition, annual nitrate deposition exceeds annual ammonium deposition in the eastern United States (Kulp, 1987) and nitrate has a slight alkalizing effect in the watershed (Lee and Schnoor, 1988).

5. The watershed processes controlling the effects of sulfur deposition on surface waters are sulfate adsorption and desorption and base cation depletion and resupply through mineral weathering and exchange.

6. The effects of organic acids on acid-base chemistry are constant through time and independent of sulfate.

7. These major processes are known well enough to be incorporated in the projection models used in the DDRP.

8. Current watershed attributes and conditions (e.g., climate, land use, basin characteristics) will remain relatively constant over the next 50 years.

9. Long-term projections using models are plausible and are the only feasible approach for evaluating the regional, long-term effects of sulfur deposition scenarios on surface water chemistry.

10. "Typical" year projections are not intended to represent future forecasts of water chemistry but rather to provide a common basis for comparisons among deposition scenarios to assess potential changes in surface water chemistry.

11. Acidification is reversible and the processes in the models are adequate to describe both chemical acidification and chemical improvement.

12. Physical and chemical processes are adequately considered in the Level III models.

13. Uncertainty calculations provide estimates of relative error for long-term comparisons among models and deposition scenarios but are not absolute error estimates.

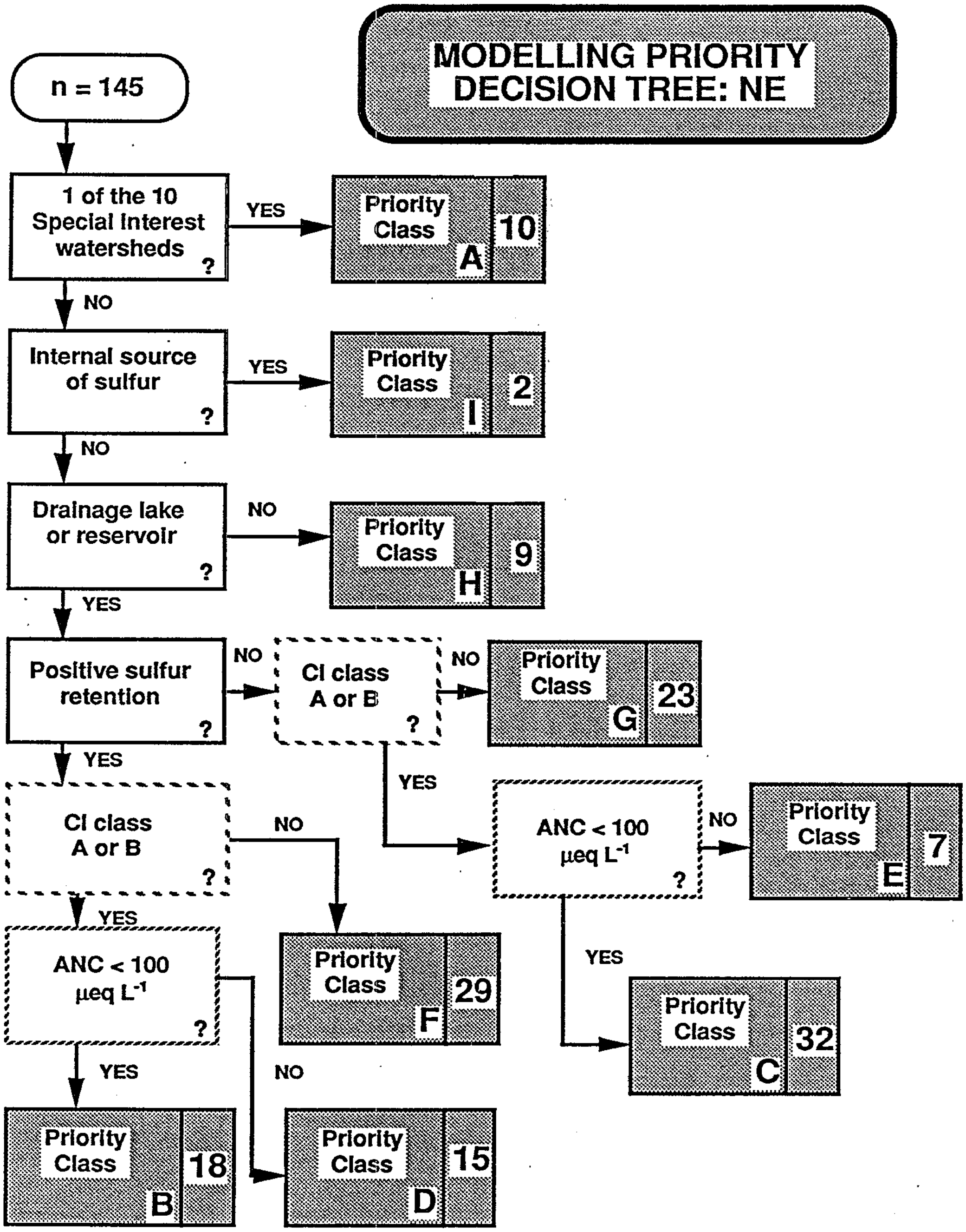


Figure 10-1. Modelling priority decision tree: Northeast.

chloride). The DDRP watersheds were screened to identify those systems for which the output chloride was greater than the input from atmospheric sources. Those watersheds with significant net chloride export were given a lower priority. Finally, those systems with initial ANC < 100 μeq L^{-1} were designated higher priority than watersheds with ANC $\geq$ 100 μeq L^{-1}.

All three modelling groups followed this priority order when making projections. The objective was to complete analyses on at least the first 60 watersheds, which included those with ANC <100 μeq L^{-1}, those that were the least disturbed with respect to road salt additions, those near sulfur steady state, and those currently retaining sulfur within the watershed (i.e., Classes A - C).

10.4.2 Southern Blue Ridge Province

A decision tree also was developed for the SBRP watersheds (Figure 10-2) using criteria similar to those for the NE with two exceptions: watersheds previously were screened for internal sources of sulfate, and none of the dynamic models was calibrated previously on SBRP watersheds. Therefore, the first criterion for prioritization was whether the watersheds are currently retaining sulfur, followed by whether chloride concentrations are less than 50 μeq L^{-1} (indicating little impact or disturbance by roadsalting practices). The chloride criterion was the same as that used for northeastern lakes. Those systems with ANC < 100 μeq L^{-1} [based on values from the National Stream Survey (NSS) Pilot Survey (Kaufmann et al., 1988)] also were given higher priority than those with ANC $\geq$ 100 μeq L^{-1}. The number of streams in each priority class is shown on the right-hand side of the priority class box (i.e., A - E). Of the 35 total watersheds for the SBRP, 25 were placed in the first two priority classes, which also resulted in a restricted target population. This priority order was followed by the ILWAS and MAGIC modelling groups in performing projections for watersheds in at least the first two priority classes. ETD was not applied to streams, so SBRP watersheds were not simulated using ETD.

10.4.3 Effects of Prioritization on Inclusion Probabilities

Watersheds were ranked in priority order to minimize comparability problems among models in the event that not every group could complete simulations on all 145 watersheds in the NE or 35 watersheds in the SBRP. This prioritization scheme does not affect the inclusion probability of any watershed. Inclusion probabilities are based on the statistical design and the manner by which the sample watersheds were selected from the population of watersheds in the region (see Section 5.2.6). Simulating only selected classes of watersheds, however, does affect the target population about which inferences can be drawn. For example, if no watersheds with initial ANC $\geq$ 100 μeq L^{-1} are included in the projection, no inferences or conclusions can be drawn about the future response of this class of systems to acidic deposition scenarios. Even though the original target population had ANC concentrations ranging from -87 to 400 μeq L^{-1} the new target population about which inferences can be reached refers only to that portion of the original population with ANC concentrations ranging from -53 to 100 μeq L^{-1}. The DDRP target population for the NE that corresponds to these Class A - C watersheds represents 1,851 watersheds compared with the full northeastern DDRP target population of 3,667 watersheds. The first two priority groups in the SBRP also represent a restricted target population of 1,051 watersheds compared with the full SBRP DDRP target population of 1,531 watersheds.

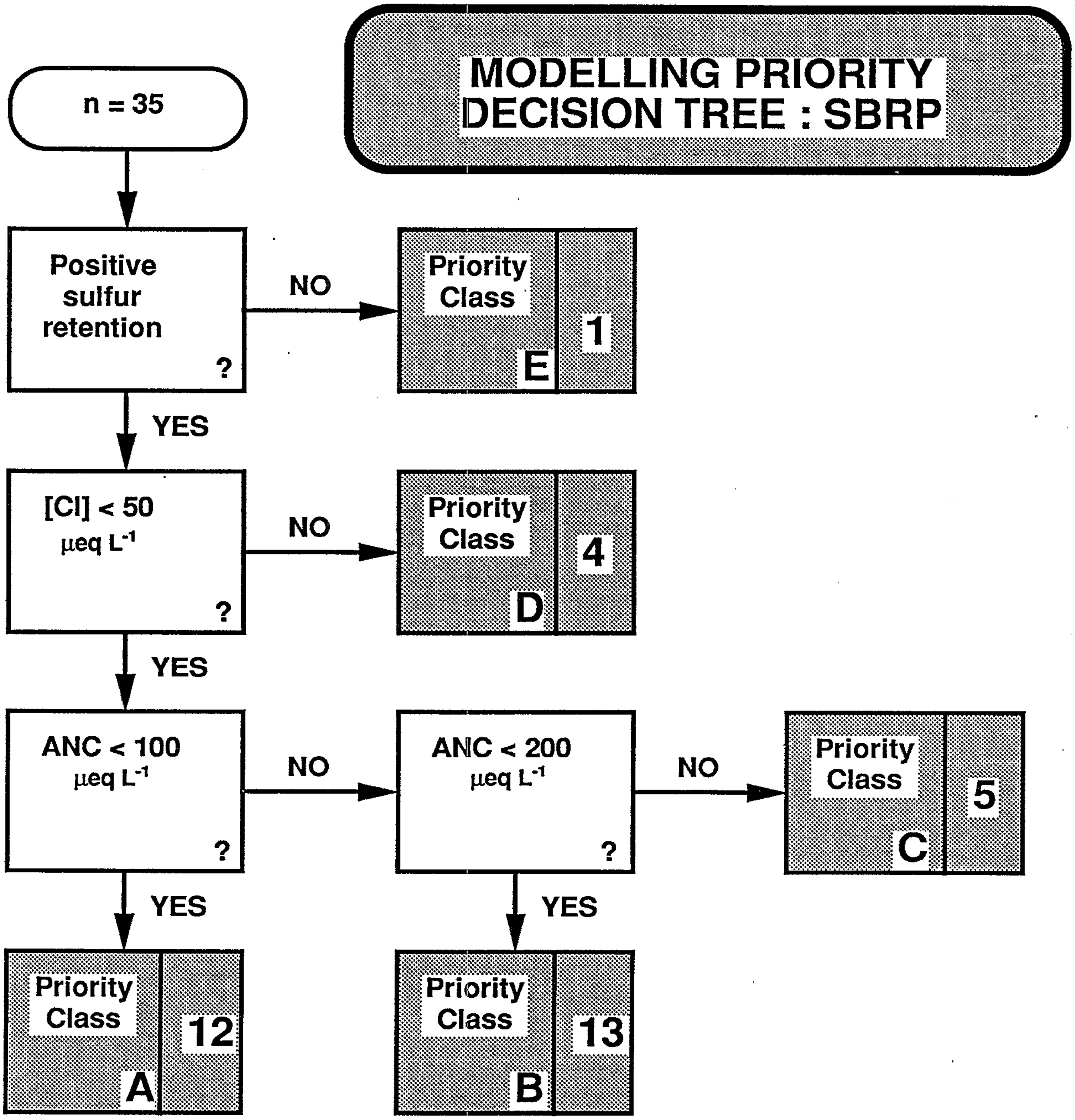


Figure 10-2. Modelling priority decision tree: Southern Blue Ridge Province.

10.5 MODELLING DATASETS

A major objective of the Level III Analyses was to ensure that all three modelling groups were given the same datasets, developed using identical procedures so that differences among model projectionsreflected differences in model process formulations and not differences in input data. Different process formulations among the models requires that different averaging or aggregation procedures be used to prepare model input and parameter data. The source data provided to each modelling group (e.g., meteorology, deposition, morphometry, soils, and water chemistry) on which these procedures operated, however, were identical for each model to minimize problems of comparability among model projections.

10.5.1 Meteorological/Deposition Data

The meteorological and deposition data for both the NE and SBRP were discussed in Section 5.6, with the exception of daily meteorological data, which were specific to the Level III Analyses. Meteorological data for daily temperature, dew point, pressure, wind speed, cloud cover, and solar radiation also were required as model simulation input for ETD and ILWAS. These data are not measured at as many locations as daily precipitation is. Typical meteorological year (TMY) data have been produced for 238 locations across the United States. These locations are usually in major cities. Ten different TMY sites were selected and matched to each DDRP site, based on geographic location and elevation. Temperature and dew point were adjusted to match 30-year normal temperatures for the period 1951-1980. TMY temperature data also were adjusted to closely match long-term monthly average temperatures at the TMY site. Hence, the monthly and daily temporal pattern for each TMY site was representative of the long-term norm. Because temperature is elevation dependent, the TMY data were adjusted to match the annual 30-year normal at a nearby site with an elevation comparable to the National Climatic Data Center (NCDC) site assigned to a DDRP lake. The adjustment was additive based on the difference between the annual average TMY temperature and the annual 30-year normal temperature. A similar adjustment was applied to dew point.

Watershed specific "typical year" meteorological and deposition data were provided to the modelling groups for each watershed in the NE and SBRP. These typical year data were repeated year after year for 50 years in performing the watershed projection under current deposition levels. The altered deposition scenarios for the NE and SBRP followed a temporal sequence of current deposition levels for the first 10 years of the projection, altered sulfur deposition for the next 15 years to the desired percentage change relative to current deposition (30 percent decrease in the NE, 20 increase in the SBRP), and then constant sulfur deposition at this altered level for the final 25 years.

10.5.2 DDRP Runoff Estimation

Runoff is an important variable for the models used in Level III Analyses. The DDRP study sites are not gaged, so measured estimates of runoff were unavailable. A combination of techniques was used, therefore, to obtain estimates of annual and monthly runoff for the northeastern and SBRP watersheds.

10.5.2.1 Annual Runoff

Annual runoff was estimated for each of the 145 northeastern and 35 SBRP watersheds, as discussed in Section 5.7. Long-term average annual runoff estimates were based on 1951-1980 records.

The annual runoff was partitioned into average monthly fractions for use in calibrating the hydrologic submodels.

10.5.2.2 Monthly Runoff

10.5.2.2.1 Northeast -

Monthly runoff estimates were calculated for the NE based on USGS long-term monthly averages. USGS calculated a 30-year average monthly runoff proportion for a 12-month period (October - September) using 1951-1980 runoff data for stations that had complete records for the 30-year period and did not have diversions or regulations (D. Graczyk, personal communication). The final database contained runoff data for 134 USGS gaging stations.

The USGS sites were linked then to the 145 DDRP study sites and 3 intensive study sites. For the NE, a "nearest neighbor" linkage was used with physiographic considerations included when appropriate (R. Nusz, personal communication). Using the Geographic Information System (GIS), a map was prepared that depicted locations of USGS gaging stations and DDRP study sites. A USGS station was linked to each study site based on station proximity. In areas like the White Mountains of New Hampshire, physiographic considerations (e.g., elevation and topography) also were included in the linking process. Physiographic data were obtained from Krug et al. (in press). In the Adirondack Subregion (Subregion 1A in the ELS-I), USGS station density was extremely sparse relative to the number of ELS sites. In this area, a Thiessen polygon weighting system was used to link the few USGS stations to the ELS sites. In many cases, more than one DDRP site was linked to a single USGS station.

Monthly runoff for each study site was calculated by applying the 12 monthly proportions for each USGS station to the linked DDRP study sites. The average annual runoff value at each study site, interpolated from the map of Krug et al. (in press), was multiplied by each of the 12 monthly proportions to obtain 12 monthly runoff values (in inches) for each site.

10.5.2.2.2 Southern Blue Ridge Province -

Monthly runoff for the SBRP watersheds was estimated using a USGS database prepared similarly to the one for the NE. The resulting database contains 30-year average monthly proportions (October - September) for 41 USGS stations in the SBRP.

The USGS monthly proportion data were linked to the interpolated annual runoff at each site to calculate a long-term monthly runoff estimate for each of the 12 months for the water year. The USGS stations had limited spatial coverage of this region and did not overlap consistently with the DDRP study sites. The GIS was used to link the USGS sites and DDRP study sites based on topographic features and similar site characteristics. An average monthly proportion for each of the 12 months was calculated for the USGS sites within the major land resource area (MLRA) to obtain a single file of 12 monthly proportions. For the SBRP, all but one of the watersheds were located in a single MLRA.

Monthly runoff for each DDRP study site was calculated by applying the single file of 12 monthly proportions for each MLRA to the study sites located in the respective MLRAs. The average annual runoff value at each study site, interpolated from the map of Krug et al. (in press), was multiplied by each of the 12 monthly proportions to obtain 12 monthly runoff values (inches) for each site.

10.5.3 Morphometry

Basin, lake, and stream morphometry and characteristics were discussed in Section 5.4. These data, obtained from the DDRP Soil Surveys and the NSWS for the NE and SBRP, were provided to each modelling group for use in model calibration for each watershed in the NE and SBRP.

Lake volume and stage-discharge empirical relationships for the northeastern watersheds were formulated using data obtained from the ILWAS, RILWAS, ME, and VT lakes for which bathymetric information was available. These lakes were partitioned by surface area and relationships established between lake volume and lake area. Lake volume relationships were improved if the lakes were partitioned by surface area (i.e., surface area < 100 acres and surface area > 100 acres). These relationships are

$$\text{Volume (acre-ft)} = 4.486[\text{Lake Area (acres)}]^{1.382}$$
$$\text{for lake areas} < 100 \text{ acres}, r^2 = 0.87$$
$$\text{Volume (acre-ft)} = 5.670[\text{Lake Area (acres)}]^{1.227}$$
$$\text{for lake areas} > 100 \text{ acres}, r^2 = 0.96$$

Empirical relationships also were established between lake stage and discharge based on data available for ILWAS and RILWAS lakes. A relationship between discharge (Q), height of the lake spillway (h) and lake depth was established for different classes of lakes based on their watershed areas. These relationships, which were used in the ILWAS model, are

$$Q \text{ (cfs)} = 2.694h \text{ (ft)}^{3.538}$$
$$\text{for lakes with watershed areas} < 350 \text{ ha}, r^2 = 0.98$$
$$Q \text{ (cfs)} = 0.897h \text{ (ft)}^{5.279}$$
$$\text{for lakes with watershed areas } 350 - 600 \text{ ha}, r^2 = 0.98$$
$$Q \text{ (cfs)} = 3.160h \text{ (ft)}^{3.70}$$
$$\text{for lakes with watershed areas } 601 - 3000 \text{ ha}, r^2 = 0.96$$

Lake volume for the ETD and MAGIC simulations was assumed to be constant (i.e., inflow volume = outflow volume + evaporation volume + seepage volume) so a stage-discharge relationship was not required.

10.5.4 Soils

The soils data, discussed in Section 5.5, were aggregated (Sections 9.2.3.2 and 9.3.1.2) and provided to each modelling group on a model-specific basis. The soils data used by each modelling group were identical, but the aggregation procedures used by each group were model specific. The ILWAS modelling group used unaggregated data.

10.5.5 Surface Water Chemistry

As described in Section 5.3, surface water chemistry data were obtained from the NSWS and were described in detail by Kanciruk et al. (1986a) and Messer et al. (1986a). Both 1984 ELS-I and 1986 ELS-II data were provided for the northeastern watersheds, and NSS Pilot stream data were provided for the SBRP watersheds for all sampling periods in 1985.

10.5.6 Other Data

Watershed data such as bedrock geology, land use, vegetative cover, estimated depth to bedrock, and other data (discussed in Sections 5.4 and 5.5.6) were provided to each of the modelling groups for calibration of the individual watersheds. Because of different model formulations, the data were used differently during model calibration but the information provided to each modelling group was identical.

10.5.7 Chloride Imbalance

Preliminary mass balances for chloride indicated that chloride export exceeded deposition input for a significant number of northeastern watersheds. Road salt, watershed disturbances, and other factors might account for these additional chloride inputs. A decision tree approach (Figure 10-3) was used to identify watersheds with net chloride export and to correct this imbalance. First, a chloride concentration below which sites could be considered "unaffected" by any unusual sources was investigated. A concentration of 50 μeq L^{-1} was chosen following an examination of the data. This concentration was at the upper end of the range in concentrations found in "undisturbed" (see below) lakes. Some "disturbed" lakes had concentrations below 50 μeq L^{-1}, but just because a lake was classified as disturbed by our criteria does not mean that it actually was unusually or adversely affected. Rather, disturbed simply implies that the site has the potential for being affected because of the level of human activity associated with its watershed. "Unaffected" systems were designated as Class A (Figure 10-3), to which 80 sites were assigned.

Disturbance was based on a number of factors including location of roads in the watershed (e.g., proximity to lakes, streams, etc.), as well as the occurrence of mines, waste disposal sites, urban industrial sites, or residential areas. If a lake had chloride > 50 μeq L^{-1} but was undisturbed, then its distance from the coast was examined. A distance of 50 km from the coast was selected as a cutoff based on (1) plots of chloride vs. distance from the coast for undisturbed sites, (2) deposition data (A. Olsen, personal communication), and (3) sea salt effects relative to distance (R. Dennis, personal communication). Four undisturbed sites had chloride > 50 μeq L^{-1} but were within 50 km of the coast. These sites were classified as Class B lakes with sea salt influences only. The chloride inputs at these sites were treated as sea salt inputs distributed uniformly across the watersheds. The anion inputs were balanced by cations consistent with sea salt composition. The occurrence of undisturbed sites with chloride > 50 μeq L^{-1} at distances greater than 50 km from the coast was examined, and no such sites were found in the DDRP dataset, resulting in Class C.

Disturbed sites then were examined relative to distance from the coast. Disturbed sites exceeding distances of 50 km from the coast are probably influenced only by road salt practices. Sites close to

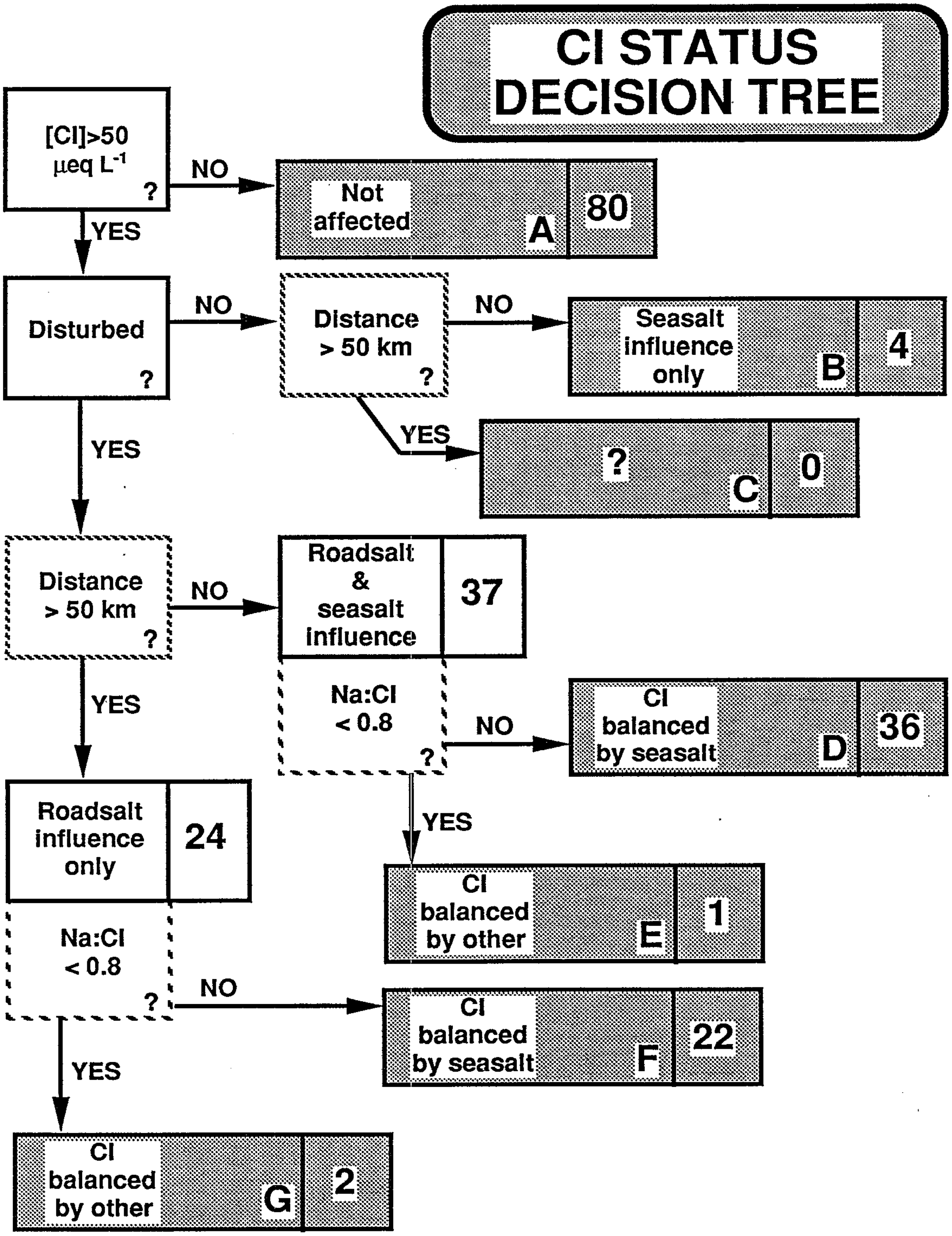


Figure 10-3. Decision tree used to identify watersheds with net chloride export and procedures for determining chloride imbalance.

the coast might show both road salt and sea salt effects. Thirty-seven sites fell into the latter category and 24 into the former. For those sites apparently affected by road salt only, point source inputs should be assumed. For the other sites, the inputs might be both "broadcast" and point source, but no method for discrimination between these possibilities was available. Therefore, these sites were treated as having point source inputs of salts directly to the lake rather than input sources spread evenly across the watershed.

The last factor to be examined was the composition of the salts. The molar ratio of sodium chloride in seawater is 0.864 (Harvey, 1969). Given the measurement uncertainty, a ratio less than 0.8 was used to screen lakes. Only three of the remaining sites fell into this category, with 0.72 the lowest ratio observed. These low ratios might be due to uncertainty and, because of the difficulty in developing a procedure for deciding which ions to use to balance the chloride, these sites also were balanced by base cations of sea salt composition "added" directly to the lake.

10.6 GENERAL APPROACH

The following general approach was used in performing the long-term projections of future change in surface water chemistry by each of the modelling groups:

- Model calibration
- Sensitivity analyses
- Regional projection refinement
- Future projections
- Uncertainty analyses
- Regional population estimates

This approach, illustrated in Figure 10-4, is fully consistent with the recommendations made by the Environmental Engineering Committee of the EPA Science Advisory Board (EPA-SAB) on the use of mathematical models by EPA for regulatory assessment and decision-making (EPA-SAB, 1988).

All three models were calibrated to three watersheds in the NE - Woods Lake, Panther Lake, and Clear Pond. In the SBRP, MAGIC was calibrated to White Oak Run, VA, and ILWAS was calibrated to Coweeta watershed 36. These watersheds are discussed in the next section. All three models performed sensitivity analyses to determine those parameters and inputs to which the models were most sensitive. Particular attention was given to these parameters and inputs during model calibration in preparation for the long-term projections. Sensitivity analyses are discussed in Section 10.9. Intensive site calibration and sensitivity analyses were conducted to document model behavior, to demonstrate that these models can predict short-term watershed responses, and to identify areas for improvement in calibration and projection procedures for the regional sets of watersheds. These refinements are discussed in Section 10.10.

The general approach for long-term projections followed by each of the modelling groups is illustrated schematically in Figure 10-5. The models were calibrated to each of the DDRP watersheds, or some subset, in the Northeast and SBRP. Long-term projections (i.e., for 50 years) were performed

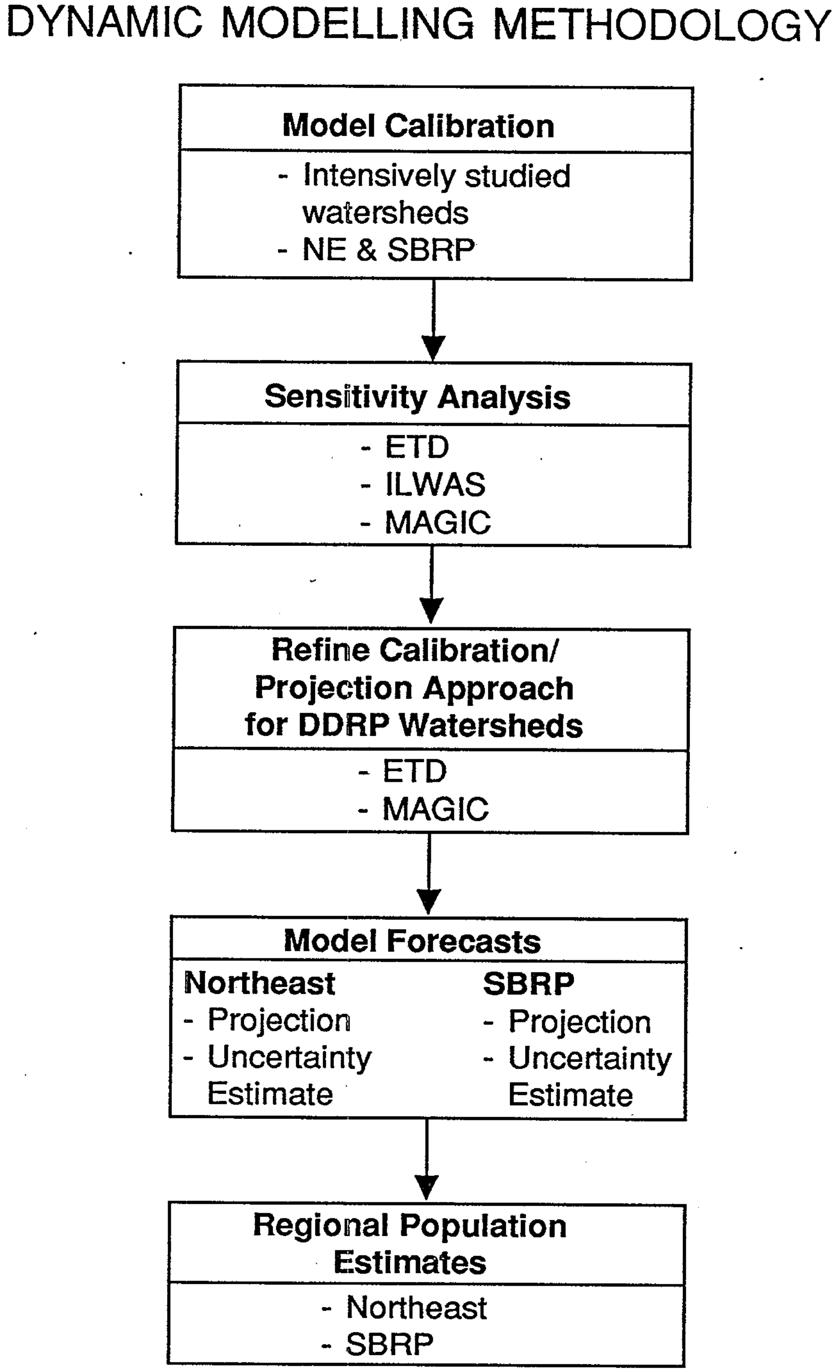


Figure 10-4. Approach used in performing long-term projections of future changes in surface water chemistry.

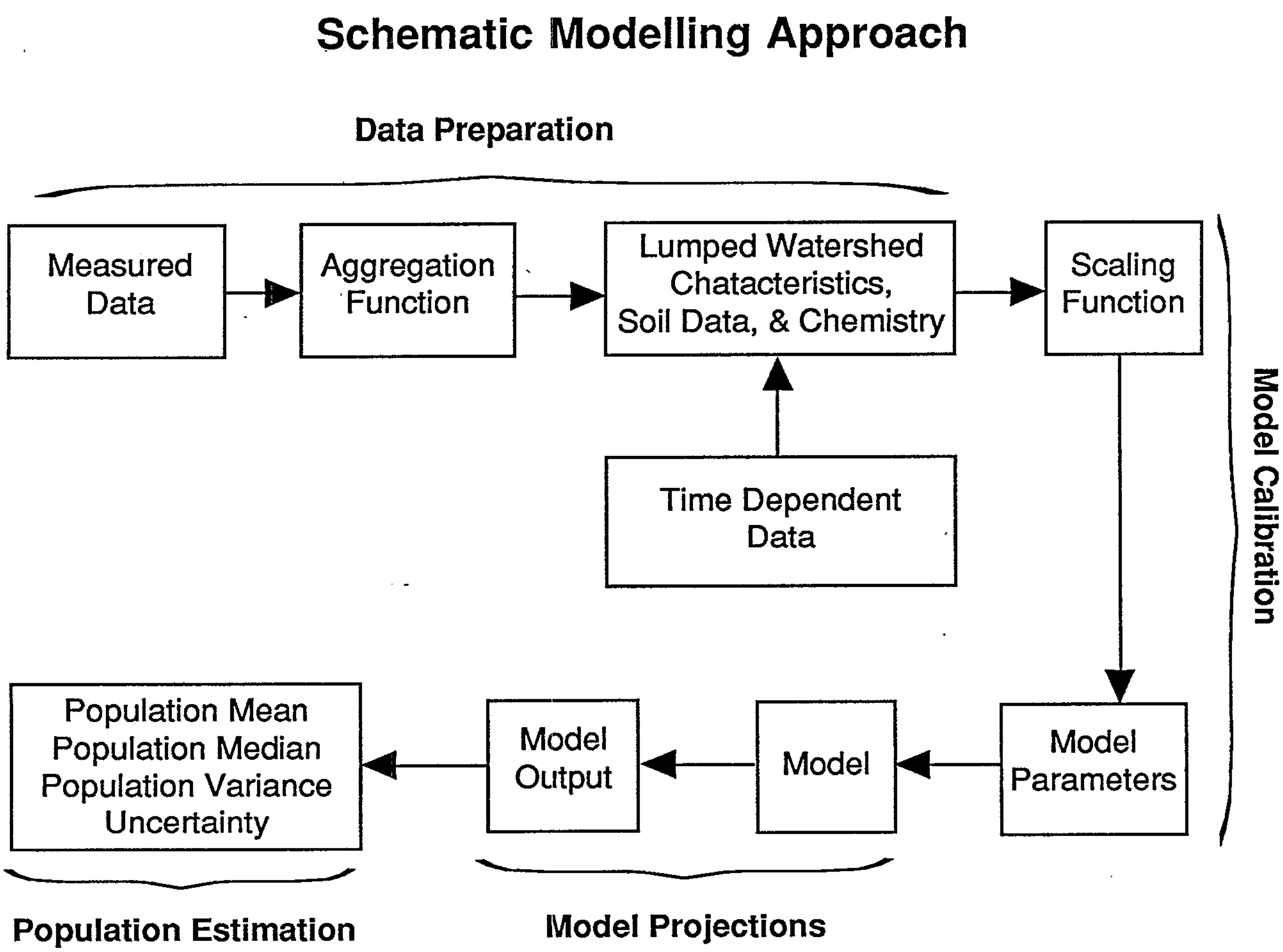


Figure 10-5. Schematic of modelling approach for making long-term projections.

on the individual watersheds and the results presented as population estimates for the NE or SBRP. The population estimates were generated as indicated in Section 6. Results from individual watersheds were of interest only with respect to their representation of the target population. Uncertainty analyses, described in Section 10.11, were incorporated in the confidence intervals about the regional population estimates. The following sections discuss each of these general topics in greater detail.

10.7 MODEL CALIBRATION

10.7.1 Special Interest Watersheds

Three intensively studied watersheds were selected for model calibration in both the NE and SBRP. Selecting multiple intensively studied watersheds for calibration was important for the following reasons:

- Watershed characteristics and parameter values vary from watershed to watershed, and thus a range of values can be simulated. For example, watersheds can be selected with varying combinations of sulfate adsorption, percent base saturation, depth of till and other watershed and lake attributes.

- The relationship among model parameters and measured parameters can be examined because extensive information on watershed processes, watershed characteristics, and system responses is available and an intensive time-series record exists.

- The short-term behavior of the models on a variety of systems can be evaluated.

- Comparable results among the models simulating a varying combination of watershed processes and responses provides greater confidence in using them for long-term projections.

The datasets for the six watersheds were each subdivided into a calibration dataset and confirmation dataset. The calibration dataset was provided to each modelling group for use in calibrating the model to the respective watershed. The confirmation dataset was retained by Oak Ridge National Laboratory until calibration was complete. The confirmation dataset consisted only of the model inputs and not the lake or stream water chemistry record. The modelling groups applied the calibrated models to the confirmation datasets and then compared the predicted output to the observed water chemistry record. For comparisons among models, calibration and confirmation root mean square errors (RMSE) were computed for the following output variables:

- Instantaneous flow ($m^3 s^{-1}$)
- Cumulative flow ($m\ yr^{-1}$)
- Chloride ($\mu eq\ L^{-1}$)
- Sulfate ($\mu eq\ L^{-1}$)
- Gran alkalinity ($\mu eq\ L^{-1}$)
- Calcium ($\mu eq\ L^{-1}$)
- Magnesium ($\mu eq\ L^{-1}$)

- Potassium (μeq L^{-1})
- Total aluminum (μg L^{-1})
- pH

10.7.1.1 Northeast

The three northeastern intensively studied watersheds are Woods Lake, NY, Panther Lake, NY, and Clear Pond, NY. Woods and Panther Lakes were EPRI ILWAS research sites (Chen et al., 1983; Goldstein et al., 1984; Gherini et al., 1985). Clear Pond was an EPRI RILWAS site. All basin and lake morphometry, soil chemistry, mineralogy, and hydrology data were obtained from EPRI (Valentini and Gherini, 1987; R. Goldstein, personal communication). Water chemistry data were collected approximately weekly during the study periods. All three watersheds also were sampled during the DDRP Soil Survey, and these data were provided to the modelling groups. The calibration and confirmation periods for these three sites were

Site	Calibration	Confirmation
Woods Lake	9/78 - 8/80	9/80 - 8/81
Panther Lake	8/78 - 8/80	9/80 - 8/81
Clear Pond	7/82 - 7/84	--

10.7.1.2 Southern Blue Ridge Province

The three intensively monitored stream watershed sites in the SBRP are Coweeta watershed 34, NC, Coweeta watershed 36, NC, and White Oak Run, VA. Watershed and stream morphometry, soil chemistry, water chemistry, and historical site information were obtained for the Coweeta sites from the USDA Forest Service's Coweeta Hydrological Laboratory (W. Swank and J. Waide, personal communication) and for White Oak Run from B. Cosby and G. Hornberger (personal communication). Water chemistry samples were collected approximately weekly during the study period. These sites also were sampled during the DDRP Soil Survey and these data provided to the modelling groups. The calibration and confirmation periods for these three sites were

Site	Calibration	Confirmation
WS 34	6/82 - 5/86	6/73 - 5/82
WS 36	6/73 - 5/79	6/79 - 5/86
WOR	1/80 - 12/82	1/83 - 12/84

The period of record at the Coweeta sites permitted partitioning the datasets for the purposes of both projecting and hindcasting. Because of time constraints, the Coweeta watersheds were not simulated. The ILWAS and MAGIC models will be calibrated on the Coweeta watersheds and the results presented as part of the DDRP Mid-Appalachian report in mid-1990. MAGIC was calibrated for White Oak Run using data collected for period January 1980 to December 1984. The MAGIC model was developed using data from White Oak Run and Deep Run, VA (Cosby et al., 1985a).

10.7.2 General Calibration Approach

The general approach for model calibration was, first, to calibrate the hydrologic submodel or companion model to the discharge records; next, calibrate the chemical submodel or model to a conservative constituent such as chloride; and finally to calibrate the watershed model to the suite of lake or chemical concentrations simulated by the model. Calibration was an interactive process. The hydrologic submodel can route flow through various soil horizons and still predict the observed stream hydrograph or lake discharge. Calibration to a conservative constituent provides confidence that mass balance is maintained in the models and also provides confidence in, and constraints for, the hydrologic calibration. If evapotranspiration, overland flow, subsurface flow, or other components of the hydrologic budget were not properly calibrated, a flow balance might be achieved, but it is unlikely that the model outputs would match the observed conservative constituent concentrations. Calibrating the model to additional nonconservative chemical constituents, such as anions (other than chloride) and cations, further constrains the hydrologic flowpaths through various soil horizons, because the physical and chemical attributes of the soils restrict the range of parameters for each compartment. If the observed stream or lake concentrations could not be predicted within these ranges, the hydrologic calibration was revised to provide additional flow through different soil horizons or along different flowpaths to achieve the observed water chemistry concentrations. Calibration of the models to predict the observed concentrations of multiple constituents provided relatively restrictive constraints on calibration parameters. Variables that could be calculated from measured soil or lake attributes were incorporated directly into the model without modification. These variables included constituents such as soil cation exchange capacity, exchangeable fractions of base cations, base saturation, porosity, and lake hydraulic residence time. The sampling and measurement errors in these variables were included in the uncertainty analyses. The mass-weighted mean or median values of the aggregated variables were used in the calibration process.

10.7.3 Calibration of the Enhanced Trickle Down Model

The ETD model represented the watershed horizontally as a homogeneous catchment with no subcatchments (Figure 10-6) and vertically with a snow compartment, soils, unsaturated zone, and saturated or groundwater compartment (Figure 10-7). Watershed data for ETD were lumped or aggregated to provide average or weighted average values for each of the soil layers. In the NE, the top soil compartment represented the mass-weighted average conditions of the O, A, and upper B horizons, the unsaturated zone was represented by mass-weighted averages of the lower B and upper C horizons, and the groundwater compartment was represented by mass-weighted averages for the lower C horizons.

The processes represented in the ETD model are shown in Table 10-1. ETD calibrations were achieved by decoupling the hydrologic, chloride, sulfate, and ANC-weathering submodels. The hydrologic calibrations were conducted first. Next the chloride submodel was calibrated. Chloride was assumed to be conservative and was used to evaluate the hydrologic calibration. Calibration was an iterative process because of the coupling between hydrology and chemistry. The sulfate submodel was calibrated next and the final calibration involved the ANC-weathering submodel. The calibration of each submodel was achieved by using a standardized optimization package, IDESIGN (Arora et al., 1985) coupled with ETD, and a trial-and-error procedure. The range of parameters for calibration was input to IDESIGN.

Woods Lake

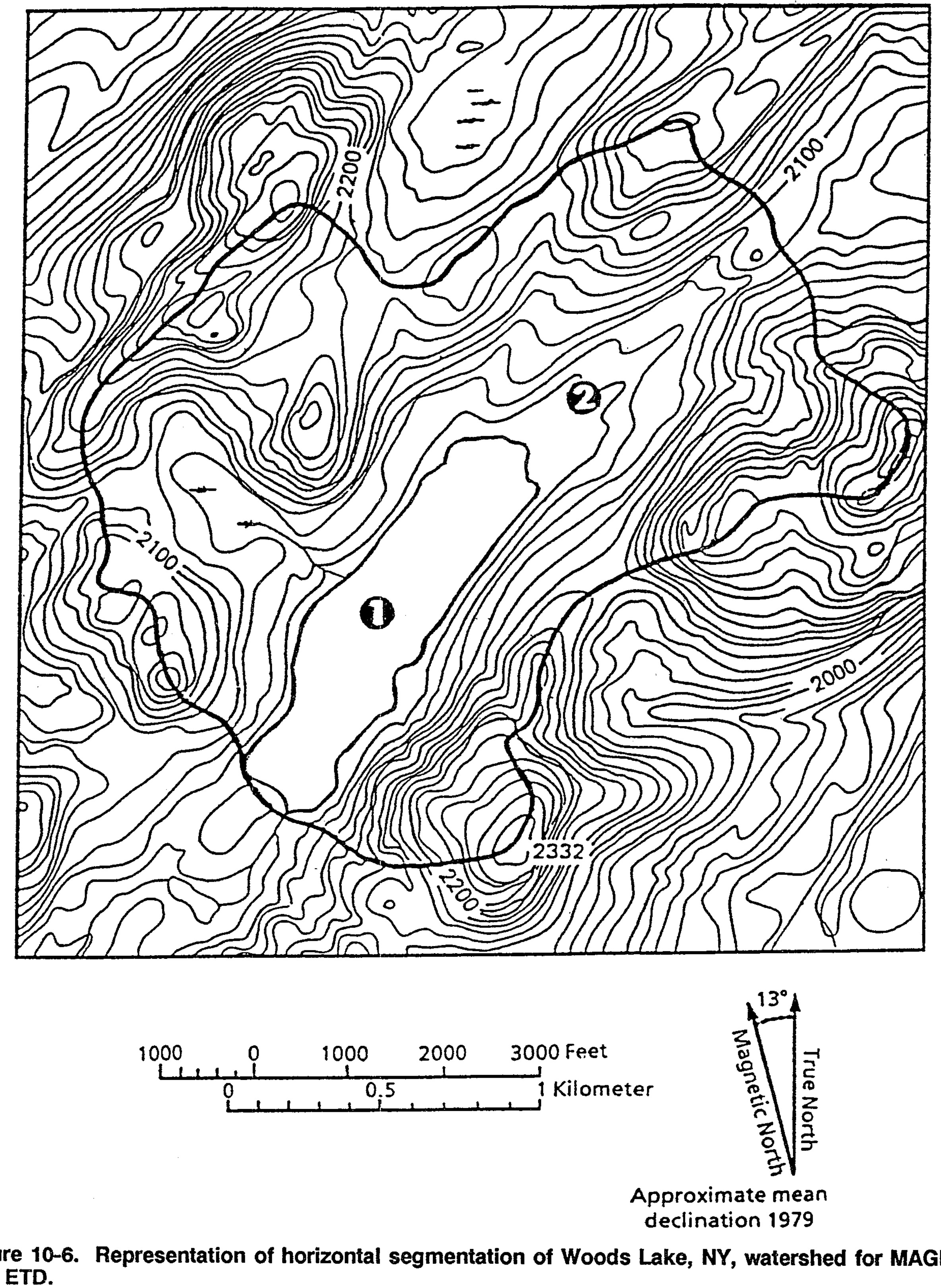


Figure 10-6. Representation of horizontal segmentation of Woods Lake, NY, watershed for MAGIC and ETD.

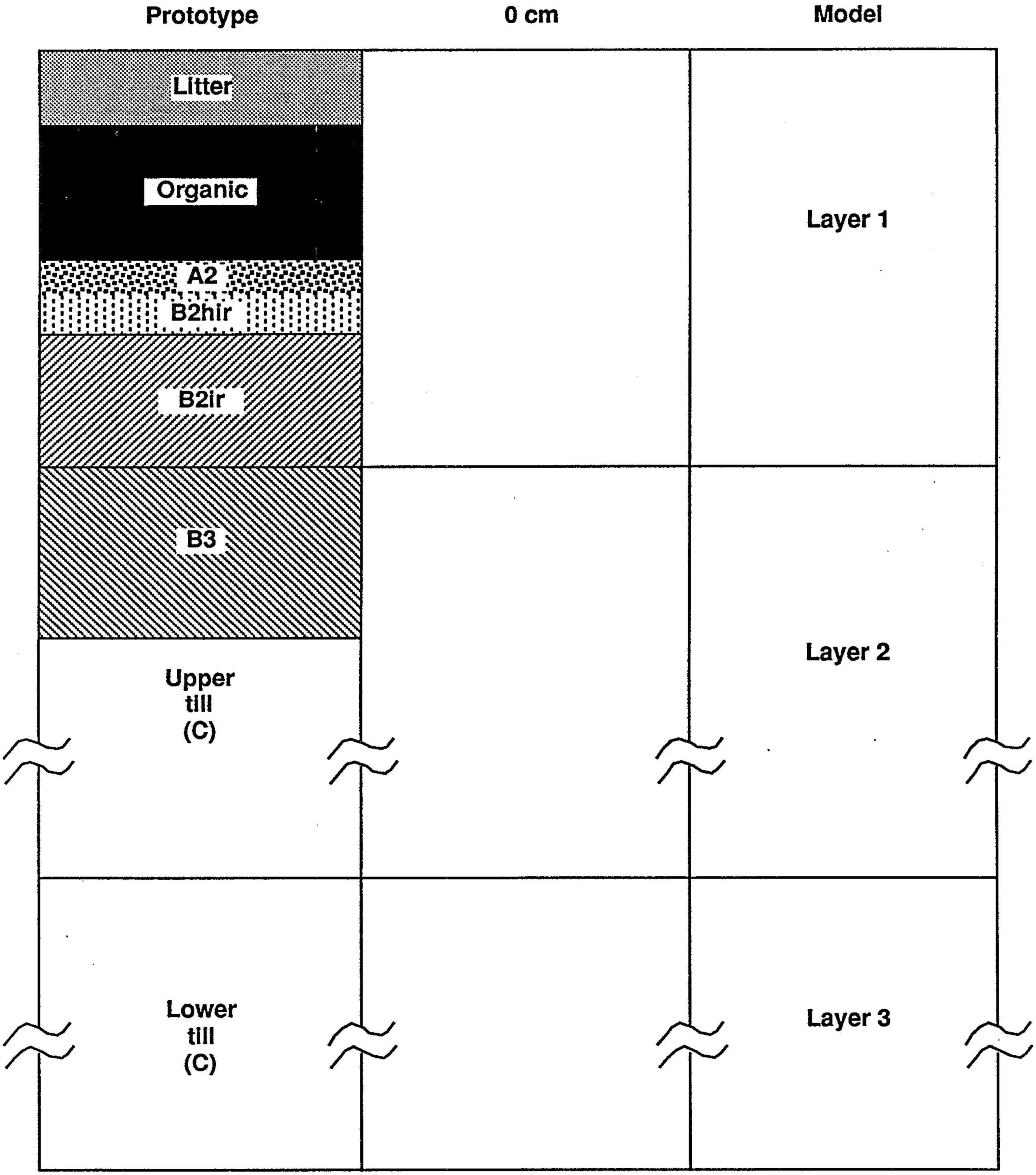


Figure 10-7. Representation of vertical layers of Woods Lake Basin for ETD.

A complete two-year simulation was performed at each iteration and a cost or penalty function evaluated. IDESIGN performs minimization of the cost function using the Fletcher-Reeves algorithm (gradient method). *A priori* bounds on physical quantities and parameters were included as constraints in the optimization process. In all gradient methods when the objective function is of the least-squares type, it is assumed that the residuals are homoscedastic, independent, and sufficiently small to assume normality. For the DDRP simulations, the residuals were not homoscedastic, which resulted in the IDESIGN optimizations being biased toward the extreme values of the residuals. The IDESIGN does, however, bring the parameters within reasonable range of their optimal values. Following the IDESIGN simulations, therefore, a trial-and-error method was employed to achieve optimal calibration. There were three main guidelines used for trial and error calibration:

(1) Obtain closure of cumulative flow or mass during the entire calibration period.
(2) Capture the seasonal variability of the state variables.
(3) Capture the peaks and valleys of the daily flows and concentrations.

This calibration process was followed for each of the submodels. The parameters for the previous submodel calibration were fixed during calibration of the succeeding submodel. In some instances, this was an iterative process. Calibration of the sulfate and ANC submodels might indicate that the flowpaths through the watershed would have to be changed to match observed water chemistry and maintain parameter values within a reasonable range for the soils on that watershed. The hydrology submodel, therefore, would be recalibrated and the process repeated. Calibration was an iterative process of constraining parameters to achieve an optimal calibration. Additional information on the ETD model calibration has been presented by Nikolaidis et al. (1987).

10.7.4 Calibration of the Integrated Lake-Watershed Acidification Model

In the ILWAS model the watershed was partitioned into a series of subcatchments to represent the horizontal variation in the watershed (Figure 10-8) and a series of vertical layers to represent various soil horizons (Figure 10-9). Basin data are used quantitatively to characterize the system to be simulated and delineate the appropriate number of subcatchments.

The ILWAS model requires specification of over 200 parameters, coefficients, and initial conditions for model calibration to represent the processes listed in Table 10-1. These values can be classified into three groups: constants, measured values, and calibration parameters. Constant values include thermodynamic constants or other factors that do not vary from watershed to watershed. Measured values included watershed area, base saturation, lake volume, and other attributes that were either directly measured or calculated from measured data at a specific site but were not varied during model calibration. The third set of values was calibration parameters such as mineral weathering rates, hydraulic conductivity, nitrification rates, and other parameters that are not well known and were modified during calibration to match the observed watershed and lake constituent concentrations. The general rules for calibration were: calibrate the system's hydrologic behavior before calibrating the chemical behavior; calibrate in the same order as water flows through the basin; and calibrate on an annual basis first, then seasonally, and finally to the instantaneous (daily) behavior.

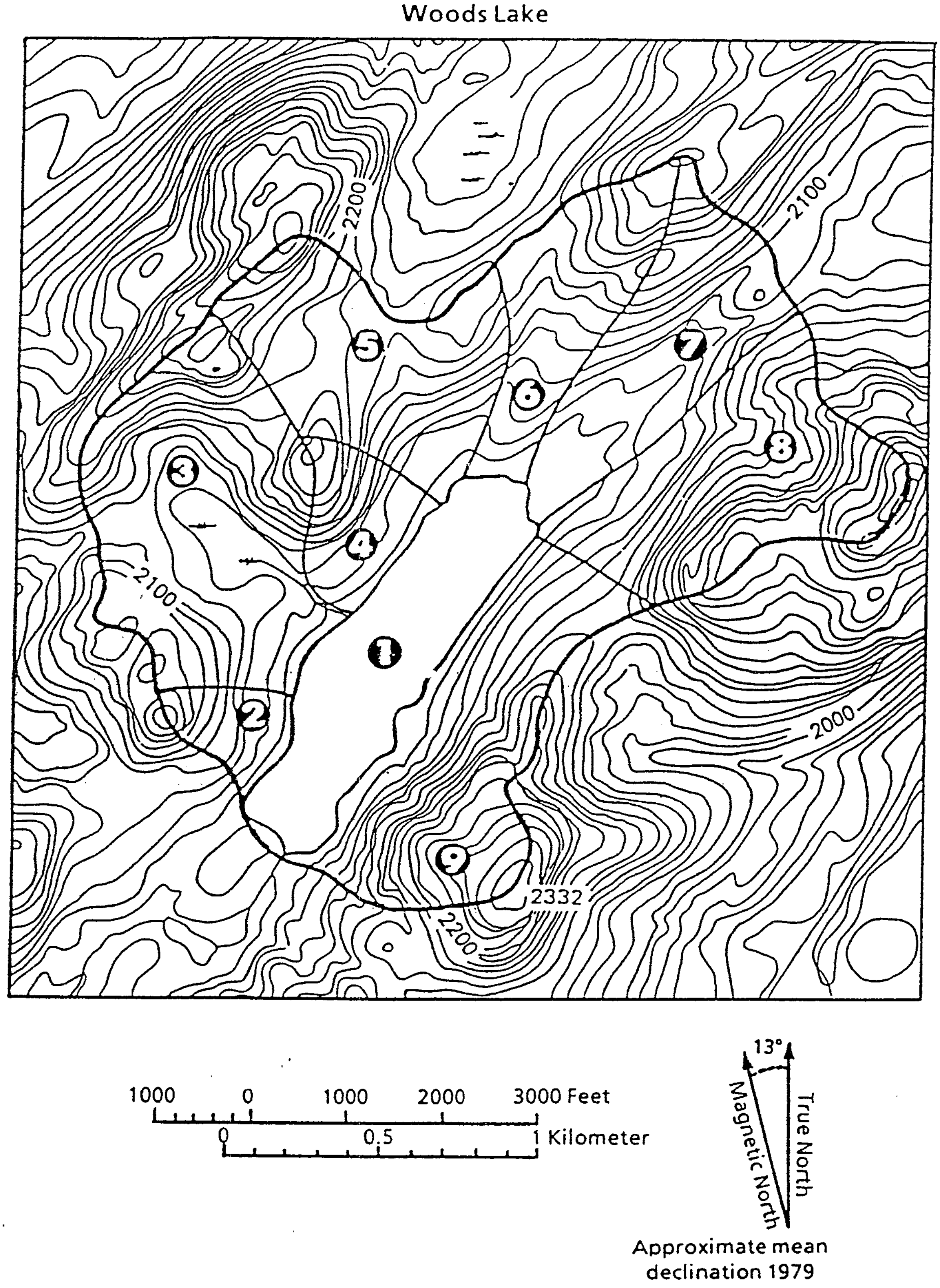


Figure 10-8. Representation of horizontal segmentation of Woods Lake Basin for ILWAS.

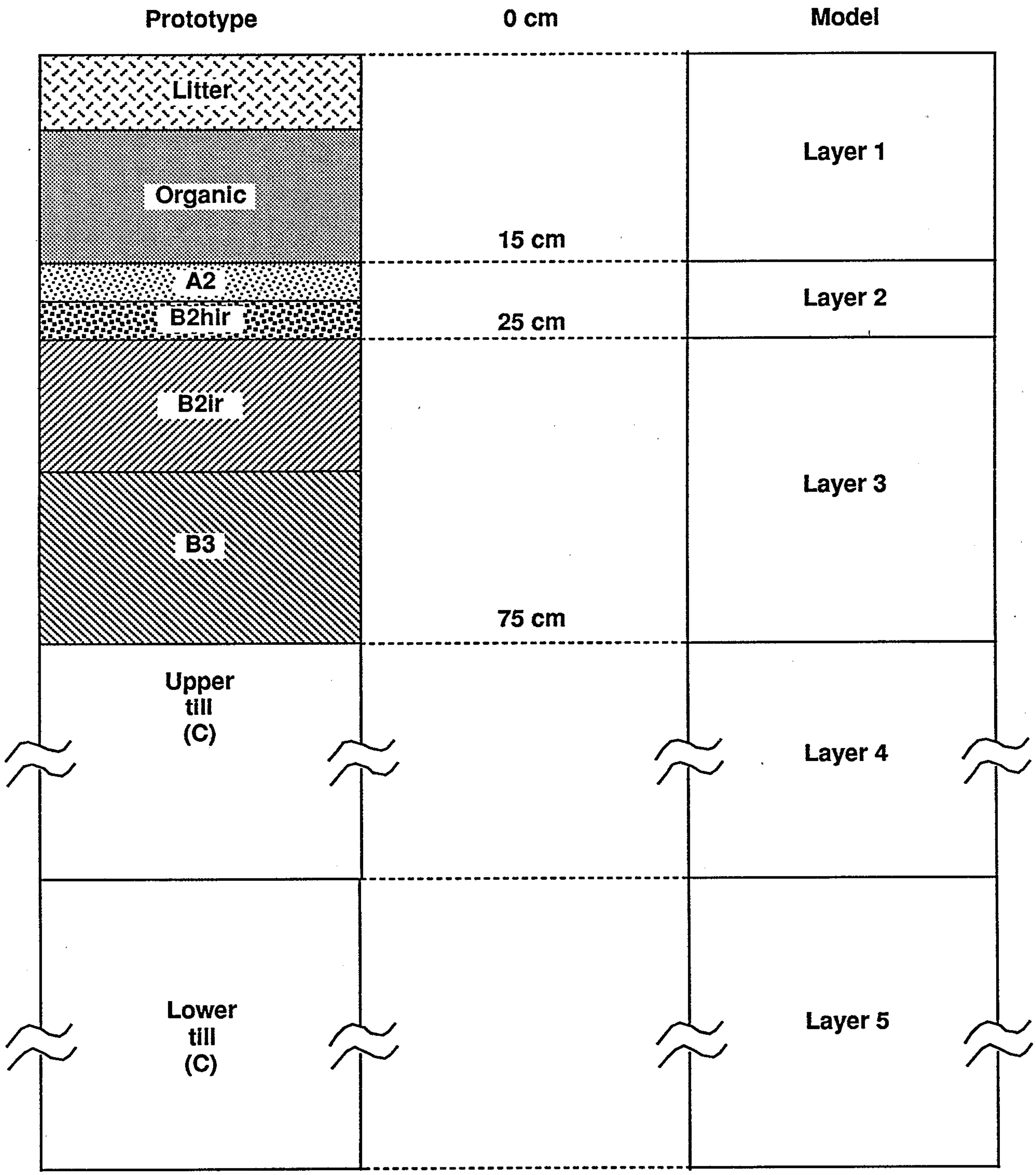


Figure 10-9. Representation of vertical layers of Woods Lake Basin for ILWAS.

The hydrologic calibration typically involves first matching the annual cumulative lake/stream discharge by adjusting the basin evapotranspiration coefficient. Seasonal flow variations are matched byvarying the seasonal evapotranspiration coefficient. Flow through the watershed, both laterally and vertically, is adjusted by varying the hydraulic conductivity to match the instantaneous discharge. Chemical calibration involves varying canopy, snowpack, and soil parameters to match the observed surface and groundwater chemical concentrations.

Although there was a significant number of parameters, and, therefore, significant degrees of freedom in selecting parameter values, only certain combinations of parameter values resulted in predicted constituent concentrations that matched observed concentrations. The interactions among parameters and parameter combinations placed limitations on the number of feasible parameter combinations. For example, increasing the in-lake nitrification rate coefficient will lead to decreased ammonium, increased nitrate, decreased ANC, and decreased pH values. These feedbacks provide a robust set of constraints for calibration.

The calibration exercise involved identifying the set of parameters that minimized the differences between the set of predicted versus observed constituent concentrations. Additional information on the ILWAS model calibration has been presented by Munson et al. (1987).

10.7.5 Calibration of the Model of Acidification of Groundwater in Catchments

MAGIC represents the horizontal dimension of the watershed as a homogeneous unit with no subcatchments (Figure 10-6) and the vertical dimension as two soil layers (Figure 10-10). Watershed data for MAGIC were lumped or aggregated to provide average or weighted average values for each of the soil layers. The top soil compartment represented the mass-weighted average conditions of the A and B Master horizons in both the NE and SBRP. The lower soil compartment represented the mass-weighted average conditions in the C Master horizon in both regions.

Projecting long-term effects of acidic deposition on surface water chemistry using MAGIC involves coupling MAGIC with TOPMODEL (Cosby et al., 1985a,b,c). Both models were calibrated using an optimization procedure that selected parameters so that the difference between the observed and predicted measurements was minimized. The calibration exercise was a three-step process. The first step was to specify the model inputs such as precipitation, deposition (both wet and dry), an estimate of historical inputs for the long-term chemical model, and fixed parameters or parameters whose values correspond directly to (or can be computed directly from) field measurements, e.g., topographic variables such as slope, aspect, area. This approach, in effect, assigns all of the uncertainty associated with sampling, aggregation, and intrinsic variability to the "adjustable" parameters. The adjustable parameters are those that are calibrated or scaled to match observed field measurements.

The second step was the selection of optimal values for the adjustable parameters. These adjustable parameters were selected using optimization. The method of Rosenbrock (1960) was used. Optimal values were determined by minimizing a loss function defined by the sum of squared errors between simulated and observed values of system state variables. Different loss functions were used for the hydrologic and chemical models. The hydrologic model used daily stream flow volumes while the chemical model used weekly lake outflow chemistry or observed soil chemistry.

Table 10-7. Comparison of Calibration/Confirmation RMSE for Woods Lake Among ETD, ILWAS, and MAGIC Models, with the Standard Error of the Observations

Constituent[a]	Calibration			Observed	Confirmation		
	ETD	ILWAS	MAGIC	SE	ETD	ILWAS	MAGIC
Inst. Discharge	0.05	0.09	0.05	-	0.07		0.07
Chloride	5.5	3.3	1.9	3.1	1.9		3.8
Sulfate	17.5	17.3	11.4	16.4	10.5		16.9
Alkalinity	27.9	31.4	17.9	18.6	14.7		16.4
Calcium		6.6	16.6	55.8			6.9
Magnesium		1.8	6.7	56.9			2.9
Sodium		4.4	6.5	5.82			3.2
Potassium		1.9	3.2	1.4			1.7
Tot. Aluminum		7.9	3.5	16.5			6.2
Hydrogen		8.1	1.3	---			6.9

[a] All units in $\mu eq\ L^{-1}$ except instantaneous discharge ($m^3\ s^{-1}$) and total aluminum ($\mu g\ L^{-1}$).
[b] ILWAS was calibrated prior to the DDRP using all the data so the dataset could not be split for confirmation.

Table 10-8. Comparison of Calibration/Confirmation RMSE for Panther Lake Among ETD, ILWAS, and MAGIC Models, with the Standard Error of the Observations

Constituent[a]	Calibration			Observed	Confirmation		
	ETD	ILWAS	MAGIC	SE	ETD	ILWAS	MAGIC
Inst. Discharge	0.03	0.01	0.03	-	0.04		0.05
Chloride	5.1	4.5	5.6	4.3	2.4		2.1
Sulfate	11.3	17.6	16.0	14.0	11.7		15.0
Alkalinity	82.6	47.1	87.4	71.0	70.0		57.7
Calcium		36.7	40.4	150.3			40.0
Magnesium		8.8	9.4	154.8			8.4
Sodium		8.1	9.9	8.7			9.9
Potassium		2.0	1.7	1.7			2.8
Tot. Aluminum		3.2	4.6	11.1			2.1
Hydrogen		1.9	3.7	---			1.4

[a] All units in μeq L^{-1} except instantaneous discharge (m^3 s^{-1}) and total aluminum (μq L^{-1}).
[b] ILWAS was calibrated prior to the DDRP using all the data so the dataset could not be split for confirmation.

Table 10-9. Comparison of Calibration RMSE for Clear Pond Among ETD, ILWAS, and MAGIC Models, with the Standard Error of the Observations

	Calibration			Observed
Constituent[a]	ETD	ILWAS	MAGIC	SE
Inst. Discharge	0.16	0.03	0.15	-
Chloride	2.4	1.4	4.7	1.6
Sulfate	8.9	10.6	9.5	9.7
Alkalinity	18.6	17.9	18.6	18.8
Calcium	23.6	21.1	21.2	
Magnesium	5.0	4.7	4.7	
Sodium	6.3	5.0		
Potassium	1.0	0.7		
Tot. Aluminum	1.1	1.2		
Hydrogen	1.0	0.2		

[a] All units in μeq L^{-1} except instantaneous discharge (m^3 s^{-1}) and total aluminum (μg L^{-1})

snowmelt (Chen et al., 1983; Gherini et al., 1985). The volume averaging by the models conserves mass but will result in lower predicted constituent concentrations if this snowmelt moves as a thin lens under the ice (Gherini et al., 1985). In the models, the higher/lower concentrations in this lens will be mixed with the rest of the volume in the lake or that layer to compute the constituent concentrations.

Although these models were (1) developed for different systems in different regions of the United States, (2) calibrated independently using model-specific procedures, and (3) run using different computational time steps (daily versus monthly), the RMSEs for all constituents are similar. Woods Lake, a chronically acidic lake (ANC = -10 μeq L^{-1}), Clear Pond, with an average annual ANC of approximately 100 μeq L^{-1}, and Panther Lake, with an average annual ANC of approximately 150 μeq L^{-1}, span the range of DDRP systems of interest in the NE, and the results indicate all three models can predict acid-base water chemistry with precision similar to that observed in the measured data for short-term periods of record. These results do not, however, necessarily ensure calibration for long-term projections. Long-term calibrations can be achieved *only* with long-term data (Simons and Lam, 1980).

Comparisons of the time series of predicted versus observed values for each of the model applications to Woods Lake, Panther Lake, and Clear Pond are described and shown graphically in Appendix A.1. The calibration and confirmation exercise indicated the three models produced comparable results for three watersheds with a range of watershed characteristics, from deep to shallow till depth, and lake chemistry, from ANC concentrations of -40 to over 200 μeq L^{-1}. Although, there is variability for individual daily values, the models reproduce the flow-weighted average annual constituent values. Average annual estimates, and the change in these estimates, represent the focus of the DDRP.

This calibration/confirmation exercise and calculation of RMSEs is consistent with the recommendations of the Environmental Engineering Committee of the Science Advisory Board for model confirmation with field data (EPA-SAB, 1988). The next step recommended for using environmental models was to conduct sensitivity analyses (EPA-SAB, 1988).

10.8 MODEL SENSITIVITY ANALYSES

Sensitivity analysis is a formalized procedure to identify the impact of changes in various model components on model output. Sensitivity analysis is an integral part of simulation experiments and model applications. Models represent aggregations and simplifications of watershed and soil processes, including physical, chemical, and biological processes. Parsimony is introduced to represent these multiple processes by a single (or few) aggregated process(es) and a transfer coefficient or parameter. Sensitivity analysis is an approach used to determine if model output or system response is sensitive or responsive to small changes in these transfer coefficients. Those parameters for which the model output was sensitive received greater attention during model calibration for long-term projections.

Sensitivity analyses were performed on the three intensively studied watersheds in the NE. Examining the sensitivity of model output over a short simulation period (e.g., 3-5 years) provides useful information about model behavior; however, these short-term analyses might not reveal the full dependence of the simulated system response on these parameter values. Certain parameters, for example, might have little effect on short-term model behavior but might be critical for long-term projections. This caveat must be considered in evaluating the model sensitivity analyses and the long-term projections.

10.8.1 General Approach

Sensitivity analyses were performed using the Woods and Panther Lakes and Clear Pond datasets following the model calibration and confirmation exercises for the MAGIC model and those for ETD on Woods and Panther Lakes. The ETD sensitivity analyses were conducted as part of a Ph.D. Thesis (Nikolaidis, 1987). The Clear Pond dataset was not available in time to be included in this Thesis. Sensitivity analyses were performed for ILWAS prior to the initiation of the DDRP. These qualitative analyses for ILWAS are included in Appendix A.1. The classical approach of Tomovic (1963) was used in performing sensitivity analyses on each of the models. Each coefficient or parameter was individually varied by ±10 percent with all other coefficients retaining their original, calibrated values. The relative change in model output RMSE for different variables or model components was noted to determine their sensitivity to this parameter change. If the increase in the RMSE was large, the model was considered sensitive to this parameter. RMSEs permitted a quantitative estimate of the increase in variance associated with each parameter.

The optimization procedures used with ETD and MAGIC also indicated relative parameter sensitivity. The response surface around an optimum parameter value was evaluated to determine if the surface was relatively flat or steep. A relatively flat response surface indicated several parameter values could be selected without influencing the optimum system response. A steep surface, however, indicated that small changes in the parameter value would affect the optimum system response or that the system response would be sensitive to that parameter.

All three modelling groups selected coefficients or parameters for processes expected to control or strongly influence both hydrologic and water chemistry output variables, including hydrologic routing parameters, sulfate adsorption, ion exchange, and weathering rate parameters. Selection of these parameters was based on previous analyses and published results by each modelling group (Cosby et al., 1985a,b,c; Gherini et al., 1985; Nikolaidis et al., 1988; Lee et al., in press; Georgakakos et al., in press). The specific parameters evaluated are listed in Table 10-10. This evaluation provided an estimate of the variability introduced by the parameter in the system response, and, therefore, an indication of the range over which the parameter could vary without significantly altering the model output.

10.8.2 Sensitivity Results

The parameters selected for sensitivity analyses are ranked in priority order from most sensitive to least sensitive in Table 10-10. The effects of a ± 10 percent change in these parameters on the RMSE for predicted lake ANC concentrations also are listed with these parameters.

Parameters related to weathering and hydrologic transport processes, in general, were sensitive in each of the three models. Parameters related to sulfate adsorption and bulk soil processes such as cation exchange capacity were not particularly sensitive in any of the models. Sulfate adsorption would not be expected to be an important process in the NE if lakes are near sulfate steady state. The models

Table 10-10. Percent Change in RMSE for MAGIC and ETD for a Ten Percent Change in Parameter Values. Parameters are Ranked in Descending Order of Sensitivity from Left to Right

Factor	MAGIC Weathering		Capacity		SO_4^{2-} Adsorp.		Hydrol.		Ion Exchange	
Parameter[a]	Weath.+	Weath.-	Depth+	Depth-	EMax+	EMax-	PMAC+	PMAC-	Selec+	Selec-
Woods Lake										
Alkalinity	-2.1	2.1	-1.0	2.1	-1.0	2.1	1.1	-1.0	0.0	1.1
Hydrogen ion	0.5	-0.6	0.0	-0.6	0.0	-0.6	-0.6	0.0	0.0	0.0
Panther Lake										
Alkalinity	0.0	2.6	0.0	0.2	0.0	0.2	0.0	-0.1	0.0	0.1
Hydrogen ion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Clear Pond										
Alkalinity	4.3	4.9	0.1	0.2	-0.2	0.1	-0.1	-0.1	0.0	0.0
Hydrogen ion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Factor	ETD Weathering		Ion Exchange		Snowmelt Rate		Lat./Vert.		Hydraul.Cond.	
Parameter[a]	KH5+	KH5 -	RE+	RE-	KAPPA+	KAPPA-	KLAT3+	KLAT3-	KPERC3 +	KPERC-
Woods Lake										
Alkalinity	-7.0	9.4	-3.1	3.7	4.7	-3.8	3.1	2.2	-2.5	8.9
Panther Lake										
Alkalinity	4.6	3.9	6.2	-2.6	-3.8	3.1	-1.0	-0.9	3.5	-2.2

[a] MAGIC Parameters

- Weath = Weathering rate for base cations (meq m^{-2} yr^{-1})
- Depth = Estimated average depth to bedrock of the watersheds (m)
- EMax = Maximum sulfate adsorption capacity (meq kg^{-1})
- PMAC = Unsaturated zone channeling parameter
- Selec = Specific base cation (e.g., Ca) to aluminum selectivity coefficient

[b] ETD Parameters

- KH5 = Hydrolysis rate constraint for water body (eq m^{-2} d)
- RE = Ion exchange reaction rate coefficient (m^3/eq^{-1} d^{-1})
- KAPPA = Snow melt rate (in d^{-1} °C^{-1})
- KLAT3 = Lateral flow recession constraint for the soil compartment (l d^{-1})
- KPERC3 = Vertical hydraulic conductivity for soil (md^{-1})

all appeared to be robust to small changes in bulk soil properties, which also can be measured directly in the field.

The specific parameters that were sensitive for each model differ because of different process formulations among the models. For example, a 10 percent change in weathering rates for MAGIC resulted in a 2 to 5 percent change in the RMSE for predicted average annual ANC concentration. A 10 percent change in weathering parameters in ETD resulted in a 4 to 9 percent change in the RMSE for predicted average annual ANC. A 10 percent change in ILWAS weathering parameters resulted in a minimal change in the RMSE for predicted average annual ANC because the change was compensated for by ion exchange in these short-term simulations (see Appendix A).

Weathering rate parameters (which are calibration parameters) were not, and generally are not, measured in the field. These weathering rate parameters, however, are not completely unconstrained. Weathering rates are constrained, in part, by cation-anion balances and ratios in surface waters and by ranges observed in the literature for watersheds with similar geology, mineralogy, and soil and water chemistry.

Hydrologic parameters also are constrained during calibration. Maintaining mass balance for conservative constituents constrains evapotranspiration and runoff processes. Calibration of the sulfate adsorption and ion exchange submodels constrains lateral and vertical hydraulic conductivity parameters and, therefore, flowpaths through the watershed.

While there are similarities in several sensitive parameters among models, process formulations are different among the three models. This is evident by the different parameters to which the predicted output is sensitive among models. There is not a 1:1 mapping between parameters and processes for any of the models. Mass balance, electroneutrality, and other requirements, however, constrain the parameter values for all models including sensitive parameters. Similarities in calibration/confirmation RMSEs indicate parameter values for all the processes can be constrained by watershed and lake attributes to achieve calibration within the range of observed values.

10.9 REGIONAL PROJECTIONS REFINEMENT

The intensively studied watershed calibration/confirmation and sensitivity analysis exercises were conducted to evaluate model behavior and the calibration procedures. These exercises resulted in improvements and refinements in the calibration procedures used in the long-term DDRP projections. These refinements are discussed below.

10.9.1 Enhanced Trickle Down

Calibration of the northeastern DDRP watersheds using ETD followed a similar procedure as that used for the three intensively studied watersheds. The optimization program, IDESIGN, was used initially to optimize parameters followed by trial-and-error procedures. For the DDRP watersheds, the hydrologic optimization focused on the evaporation rate for the lake and the lateral and vertical hydraulic conductivities for the soil compartments. Sensitivity analyses indicated the model output was sensitive to these three hydrologic parameters. The watershed/soil physical and chemical attributes and lake water chemistry were used to estimate values for the other hydrologic parameters for each DDRP watershed, chemistry were used to estimate values for the other hydrologic parameters for each DDRP watershed, which were fixed during calibration. All of the chemistry parameters were optimized and calibrated for each watershed. ETD used the aggregated soil data discussed in Section 8.8.3 to determine the watershed hydrologic and biogeochemical parameter values (e.g., cation exchange capacity, sulfate adsorption, base saturation) used in calibration.

Initial conditions for each watershed simulation were set at the recalculated ELS-I ANC values and the 1984 ELS - I value for other appropriate chemistry variables. Subsequent comparisons of calibrated versus observed values in 1984 for ETD, therefore, will be identical.

10.9.2 Integrated Lake-Watershed Acidification Study

The ILWAS calibration procedure for the DDRP watersheds was similar to the calibration procedure used for the intensively studied watersheds. The primary difference was a reduced number of subcatchments for each of the DDRP watersheds. In general, only one or two subcatchments were used to represent the DDRP watersheds. Individual soil pedon data, instead of aggregated soils data, were used to calibrate the soil parameters, similar to the procedure used in calibrating these parameters on the intensively studied watersheds.

10.9.3 Model of Acidification of Groundwater in Catchments

The MAGIC calibration sequence was similar to that used for the intensively studied watersheds but the procedure was refined and automated, where possible, for the DDRP watersheds. First, TOPMODEL was calibrated using daily rainfall and monthly runoff to derive flow routing parameters for the two-layer structure of MAGIC. Next, MAGIC was calibrated using annual time steps to simulate average volume-weighted lake chemical concentrations for comparison with the 1984 index lake chemistry values. No calibration was attempted for chloride because it was assumed to be a conservative ion (except for those northeastern watersheds in Priority Classes F - I where the chloride balance was completed by sea salt correction). Sulfate was not calibrated in the NE. The aggregated sulfate adsorption parameters computed during aggregation of the soils data were used directly in MAGIC for the northeastern watersheds. Sulfate adsorption parameters, however, were calibrated in the SBRP. The aggregated half-saturation constant for sulfate adsorption was scaled by a constant factor for all catchments in the SBRP. In the NE, the Baker et al. (1986b) model and coefficients for in-lake sulfate reduction were used. This model computes sulfate reduction, in part, based on theoretical hydraulic residence times in the lake. No sulfate reduction was used in SBRP stream projections.

Finally, base cation concentrations were calibrated using an optimization procedure based on the Rosenbrock (1960) algorithm. The base cation calibration involved fitting the results of long-term model simulations to currently observed water and soil base cation data (i.e., target variables). The target variables were both soil exchangeable fractions (for both soil compartments) and lake index concentrations of calcium, magnesium, sodium, and potassium. The target variables comprised a vector of measured values, all of which must be reproduced by the model for a successful calibration. The use of multiple, simultaneous targets in an optimization procedure provided robust constraints on model calibration (Cosby et al., 1986a).

Those physicochemical soil and surface water attributes measured in the field in the DDRP Soil Surveys were considered "fixed" parameters in the model, and the measurements were used directly in the models during the calibration procedure. The maximum sulfate adsorption capacity and sulfate half-saturation coefficient, determined for individual horizons and aggregated to the watershed, were used directly in the model and were not calibrated. Base cation weathering rates and base cation exchange selectivity coefficients for the soils were not directly measured and were used as "adjustable" or optimized parameters in the calibration process. The calibrations were performed on simulations run from 1844 to 1984 for the NE and 1845 to 1985 in the SBRP. The historical deposition sequence over this period was estimated by scaling the present-day deposition provided in the DDRP database to a reconstruction of sulfur emissions for the NE or Southeast (OTA, 1984). This scaling procedure has been described by Cosby et al. (1985b). After each simulation, the 1984 and 1985 simulated versus observed values were compared; the adjustable parameters were modified as necessary to improve the relationship between simulated and observed values; the simulation was re-run and the procedure repeated until no further improvements in these relationships were achieved.

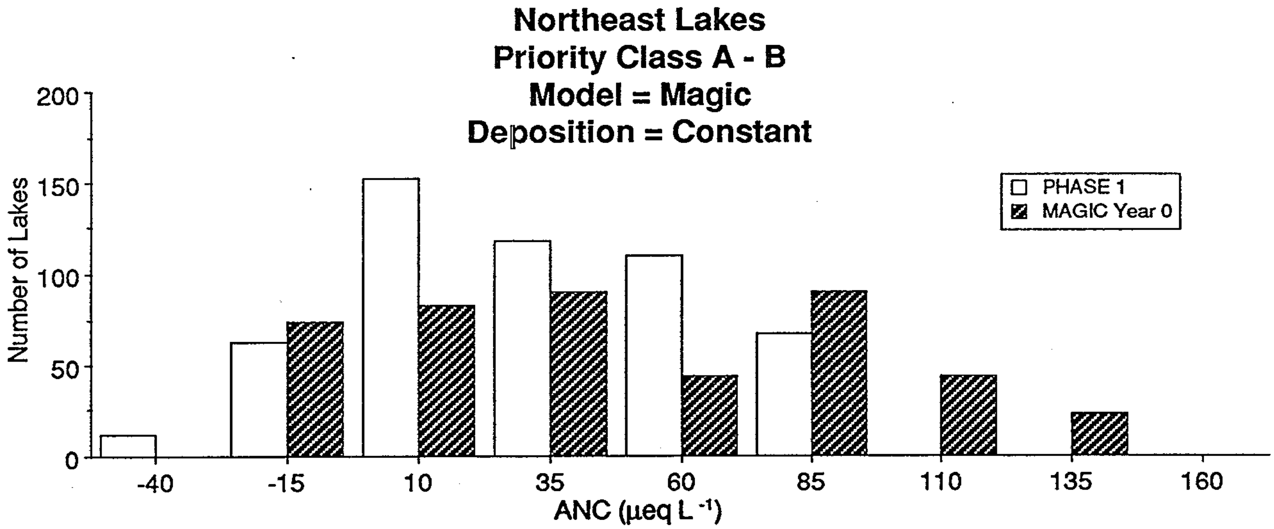
10.9.4 DDRP Watershed Calibrations

The three models can be compared for the target population of lakes with ANC < 100 μeq L^{-1}, which corresponds to 495 northeastern lakes. The comparisons for ANC and sulfate for the three models are shown as population histograms in Figures 10-11 and 10-12, respectively. Estimated aluminum concentrations were added to estimated MAGIC alkalinity concentrations so the MAGIC ANC projections are consistent with the ILWAS ANC estimates. The ILWAS and MAGIC models are calibrated on base cations and acid anions so ANC is a computed, not a calibrated value (e.g., ANC = sum base cations - sum acid anions). The ETD histograms are not discussed here because ETD assumed the 1984 ELS-I lake index chemistry value was the calibrated value for initiating the long-term forecasts. Comparison of the histograms for the calibrated 1984 ETD value versus the ELS-I value, therefore, are nearly identical. The discrepancies between the ELS-I distributions and the ETD values represent lakes that were not simulated by ETD in Classes A - E.

10.9.4.1 Integrated Lake-Watershed Acidification Study

ILWAS was not calibrated on the very acidic lakes (i.e., ANC < -30 μeq L^{-1}) but generally matched the ANC of moderately acidic lakes (ANC ~ -15 μeq L^{-1}) (Figure 10-11). In general, the calibrated ANC for the low ANC lakes (0 < ANC < 75 μeq L^{-1}) was greater than the observed as evidenced by the larger number of calibrated lakes with higher ANC than observed in the DDRP Priority Class A-B target population (Figure 10-11).

Calibrated sulfate concentrations generally were underestimated for lakes with observed sulfate concentrations less than 75 μeq L^{-1} and overestimated for lakes with observed sulfate concentrations between 75 and 125 μeq L^{-1} (Figure 10-12). Calibrated sulfate values were overestimated for lakes with sulfate concentrations greater than 125 μeq L^{-1}.



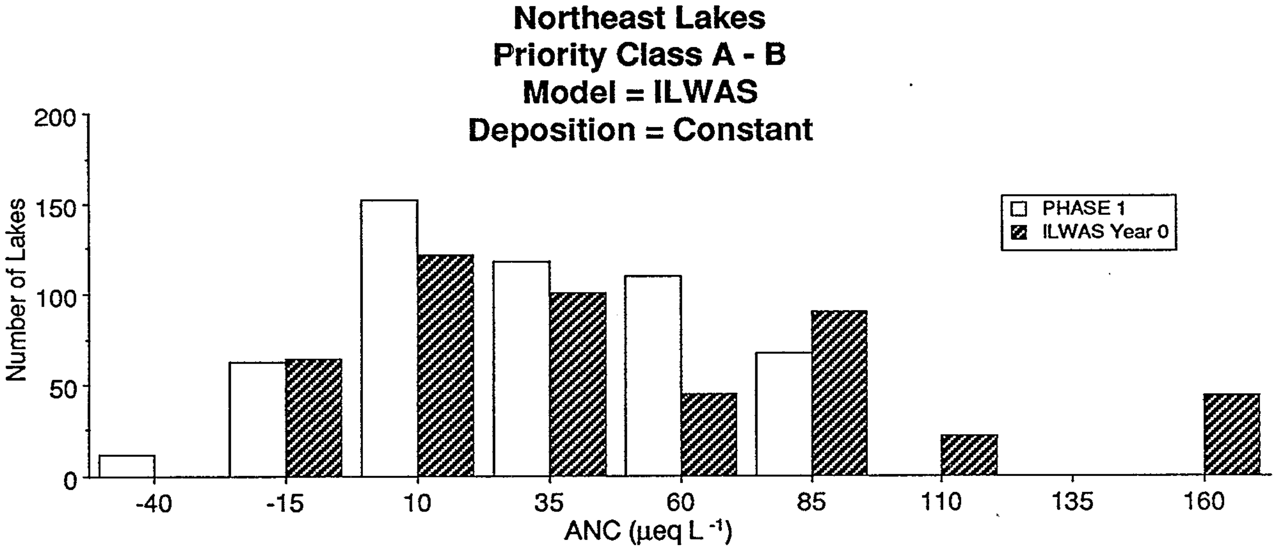
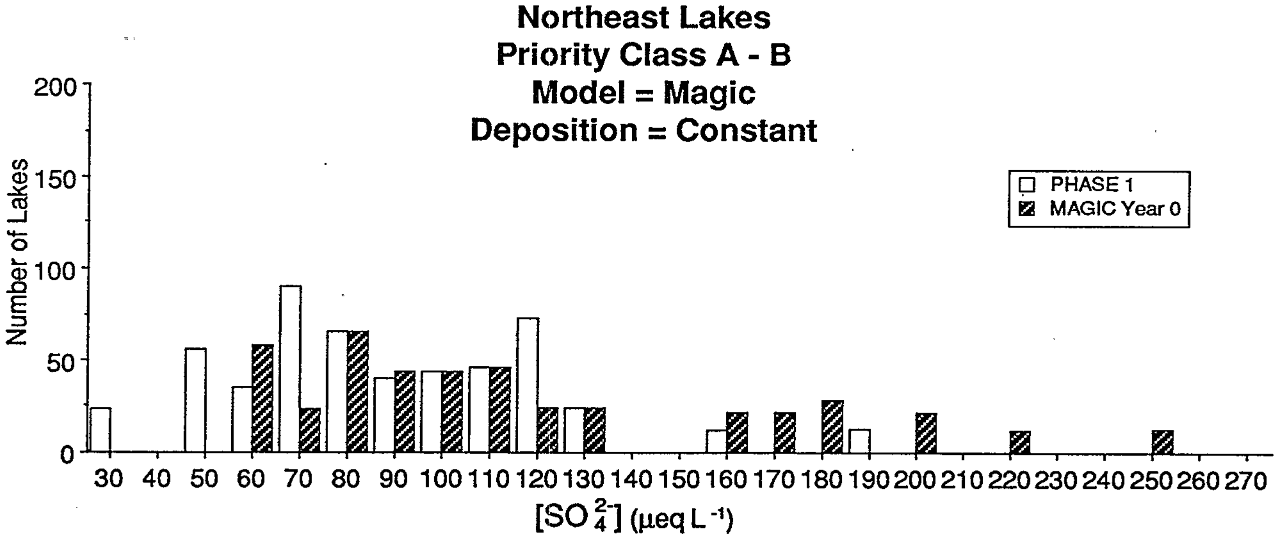


Figure 10-11. Comparison of population histograms for simulated versus observed (Eastern Lake Survey Phase I 1984 values) ANC for ILWAS and MAGIC. ETD used the ELS-I values as initial model conditions, so the simulated values are nearly identical to the observed values.



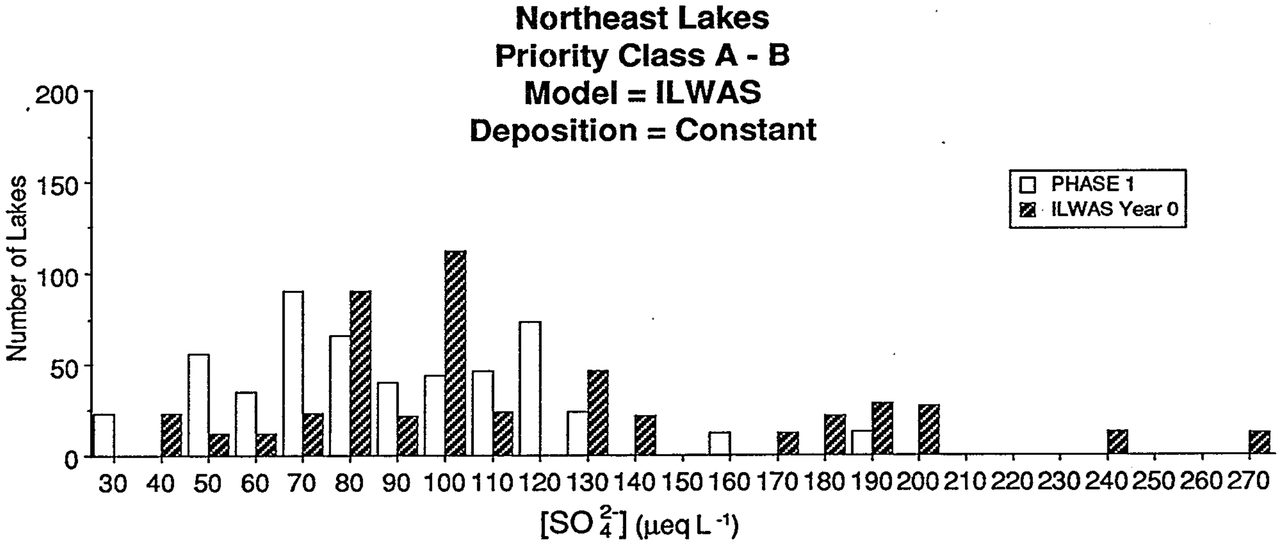


Figure 10-12. Comparison of population histograms for simulated versus observed (Eastern Lake Survey - Phase I 1984 values) sulfate concentrations for ILWAS and MAGIC, Priority Classes A and B. ETD used the ELS-I values as initial conditions, so the simulated values are nearly identical to the observed values.

10.9.4.2 MAGIC

10.9.4.2.1 Priority Classes A and B -

MAGIC was not calibrated for the very acidic lakes (i.e., ANC < -30 μeq L^{-1}) but generally matched the observed ANC for the moderately acidic lakes (ANC ~-15 μeq L^{-1}) (Figure 10-11). Calibrated ANC concentrations, in general, were consistently higher than observed ELS-I ANC concentrations as indicated by the underestimated number of lakes with lower ANC and overestimates of the number of lakes with higher ANC (Figure 10-11).

The low sulfate lakes (e.g., SO_4^{2-} < 50 μeq L^{-1}) were not represented in the MAGIC calibration (Figure 10-12). The calibrated and observed sulfate concentrations were comparable for lakes with sulfate concentrations between 75 and 115 μeq L^{-1} (Figure 10-12). The calibrated sulfate concentrations typically exceeded observed sulfate concentrations for lakes with observed sulfate concentrations greater 150 μeq L^{-1}.

10.9.4.2.2 Priority Classes A - E -

The calibrated ANC concentrations generally were higher than observed ANC concentrations for the low ANC lakes (i.e., < 100 μeq L^{-1}) but were lower than observed for moderate ANC lakes (i.e., 120-175 μeq L^{-1}) (Figure 10-13). The calibrated ANC concentrations for higher ANC lakes (i.e., > 175 μeq L^{-1}) were similar to or greater than observed ANC concentrations.

The calibrated sulfate concentrations were higher than observed for the low sulfate lakes (e.g., < 75 μeq L^{-1}) and generally lower than observed sulfate concentrations for the moderate sulfate systems (i.e., 75 < SO_4^{-2} < 135 μeq L^{-1}). The calibrated sulfate concentrations generally exceeded observed sulfate concentrations for the high sulfate lakes (Figure 10-13).

10.9.4.2.3 Priority Classes A - I -

The calibrated ANC concentrations generally were higher than observed for the low ANC lakes (i.e., <100 μeq L^{-1}) but similar for the higher ANC lakes (Figure 10-14). Calibrated sulfate concentrations exhibited a varied pattern compared with the observed pattern that, in general, was slightly lower for low sulfate lakes and slightly higher for high sulfate lakes (Figure 10-14).

10.9.4.3 Southern Blue Ridge Province

10.9.4.3.1 Priority Classes A and B -

Calibrated versus observed ANC and sulfate concentrations are shown for the ILWAS and MAGIC models in Figure 10-15. The MAGIC calibrations overestimated the number of low ANC and high ANC streams and underestimated the number of moderate (i.e., 75 to 125 μeq L^{-1}) ANC streams (Figure 10-15). ILWAS-calibrated ANC was similar to observed ANC for the low ANC streams (e.g., <75 μeq L^{-1})

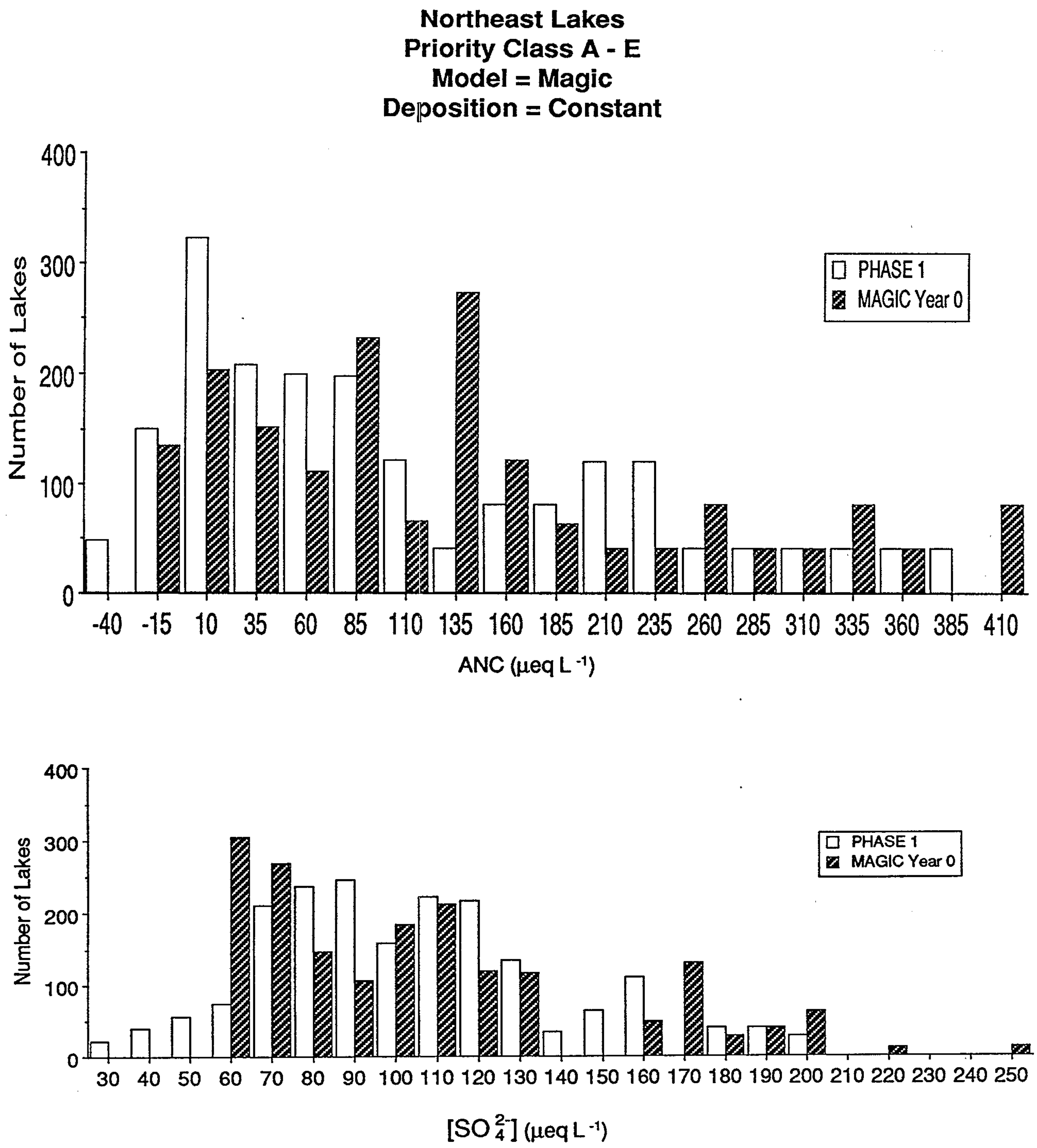


Figure 10-13. Comparison of population histograms for simulated versus observed (Eastern Lake Survey Phase I 1984 values) ANC and sulfate concentrations for MAGIC, Priority Classes A - E.

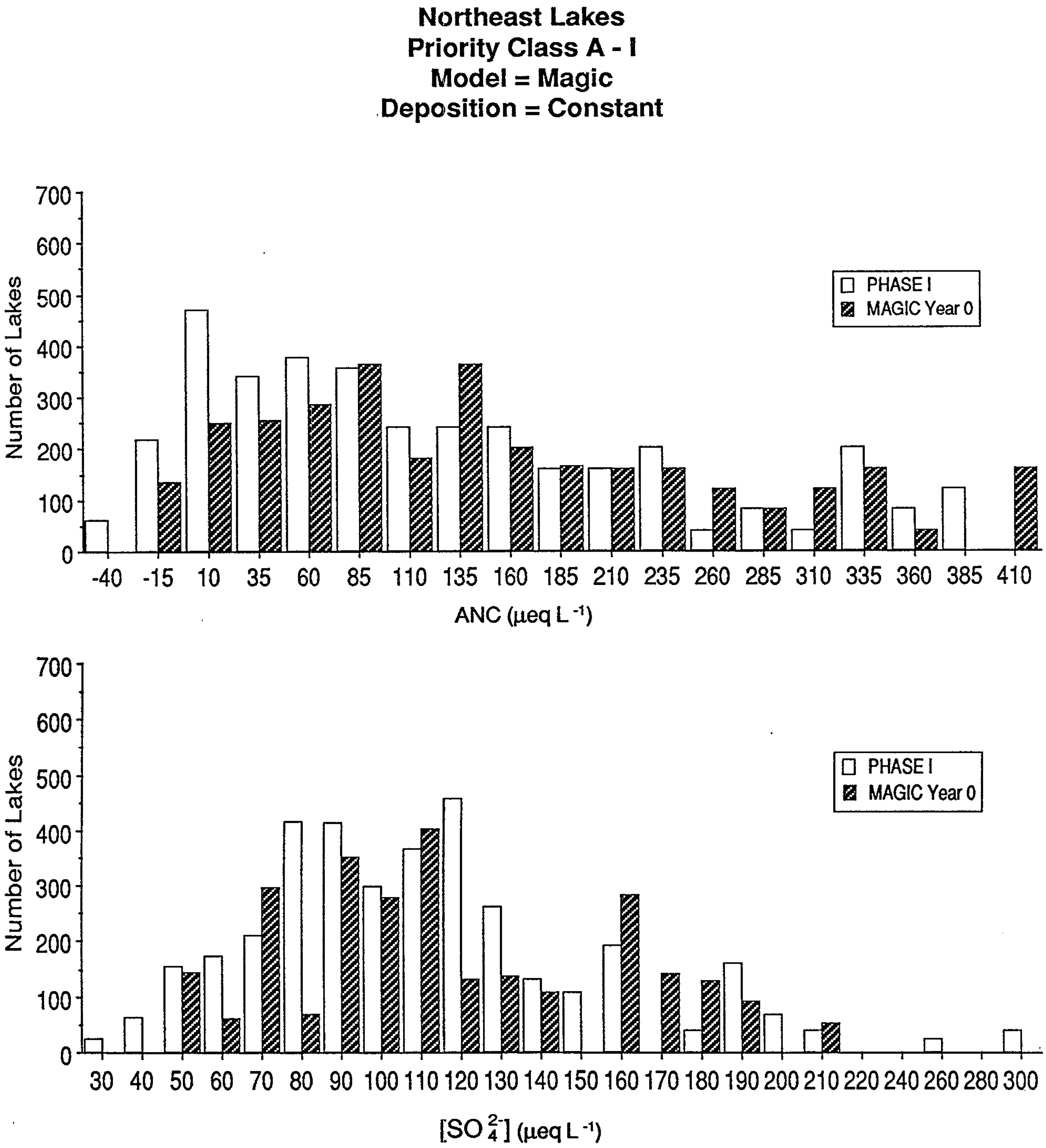
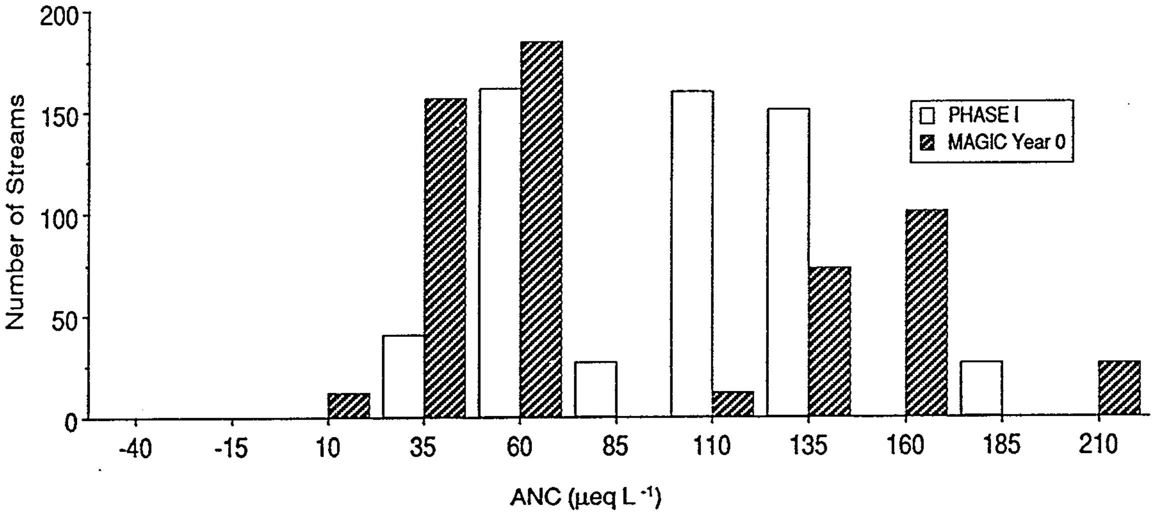


Figure 10-14. Comparison of population histograms for simulated versus observed (Eastern Lake Survey Phase I 1984 values) ANC and sulfate concentrations for MAGIC, Priority Classes A - I.

SBRP Stream Reaches
Priority Class A -B
Model = Magic
Deposition = Constant



SBRP Stream Reaches
Priority Class A -B
Model = ILWAS
Deposition = Constant

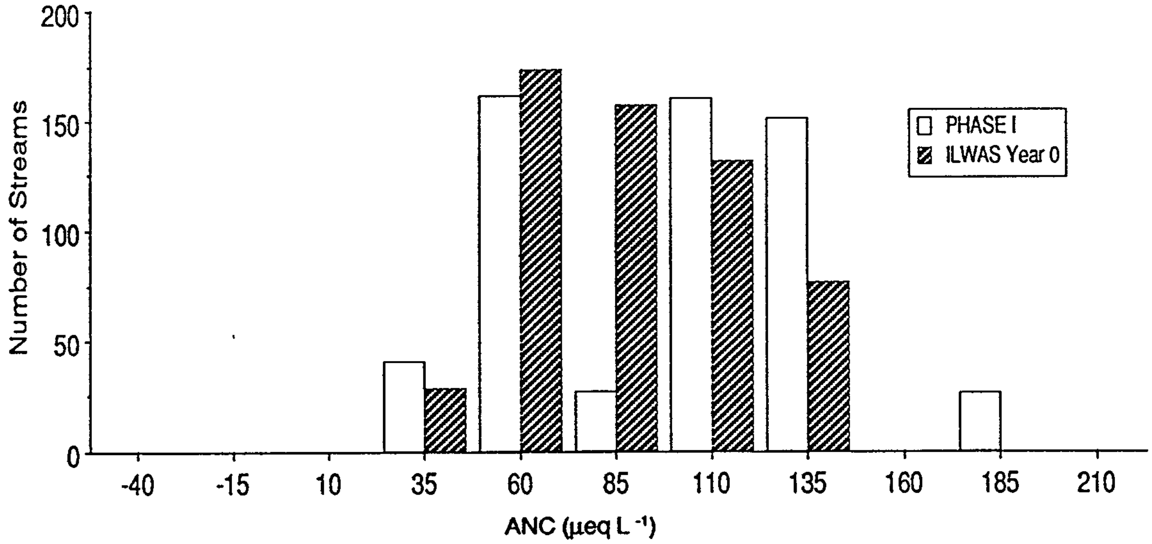


Figure 10-15. Comparison of population histograms for simulated versus observed (NSS Pilot Survey values) ANC, Priority Classes A and B using ILWAS and MAGIC.

but overestimated the number of moderate ANC systems and underestimated the number of high ANC streams (Figure 10-15).

MAGIC underestimated the number of low sulfate streams and overestimated the number of higher sulfate streams (Figure 10-16). ILWAS also underestimated the number of low sulfate streams and overestimated the number of higher sulfate streams (Figure 10-16).

10.9.4.3.2 Priority Classes A - E -

Calibrated versus observed ANC and sulfate concentrations for the MAGIC model in Priority Classes A - E are shown in Figure 10-17. MAGIC overestimated the number of low ANC streams but, in general, the distribution of calibrated ANC was similar to the observed ANC distribution. The calibrated sulfate distribution for MAGIC underestimated the number of low sulfate streams (e.g., $< 40\ \mu eq\ L^{-1}$) and slightly overestimated the number of higher sulfate streams (Figure 10-17).

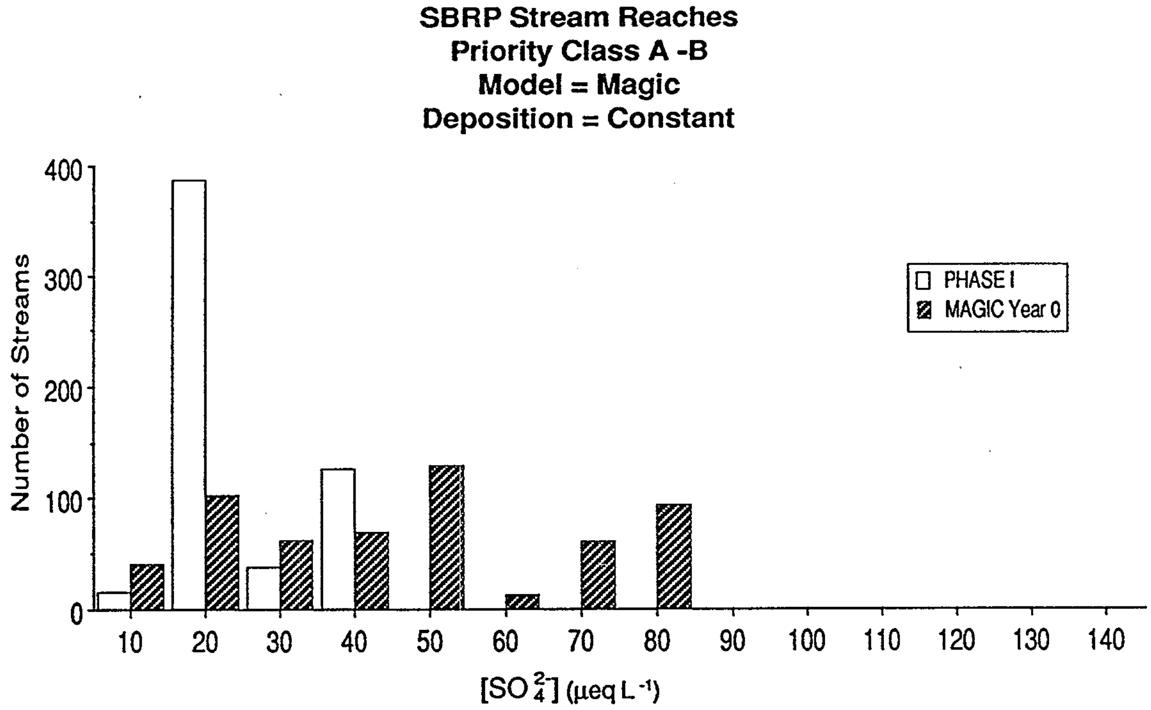
10.10 MODEL PROJECTIONS

10.10.1 General Approach

The general approach for performing long-term projections of the effects of sulfate deposition on surface water chemistry over the next 50 years in the NE and SBRP is illustrated schematically in Figure 10-4. The two simulated deposition scenarios were illustrated previously in Figure 5-25. In the first scenario in the NE, the current deposition rate at each individual site was maintained over the 50-year interval. The models then projected changes in lake water chemistry over that 50 years. In the second deposition scenario, current deposition rates at each site were held constant for the first 10 years, decreased by a total of 30 percent over the next 15 years, and then held constant at this reduced deposition rate for the next 25 years. This phasing corresponded with one possible scenario of how deposition rates might change if emissions controls were implemented in the NE in year 1 of the simulation (OPPE, personal communication). Deposition rates have been declining in the NE over the past 15 years and would decline further if emissions controls were promulgated. Current deposition rates at each individual watershed in the SBRP also were simulated, but the alternative deposition scenario was an increase in deposition. For the alternative scenario, deposition rates were held constant for the first 10 years, increased by a total of 20 percent over the next 15 years, and then held constant at this increased rate for the next 25 years (Figure 5-25). Deposition rates are expected to increase in the Southeast (OPPE, personal communication).

Each model was calibrated on individual watersheds using the data sources indicated in Section 10.5. The projected change in surface water chemistry in the individual lake or stream was simulated for the next 50 years using the typical year meteorology and deposition data, discussed in Section 10.5. Output for each model represents flow-weighted annual average constituent concentration. The projected ANC is defined similarly and is consistent among all three models.

Not all watersheds in the NE and SBRP were simulated by all three modelling groups. For the MAGIC model, there were some watersheds for which the optimization and calibration criteria were not satisfied. Long-term projections for these watersheds, therefore, were not performed (Table 10-11). In



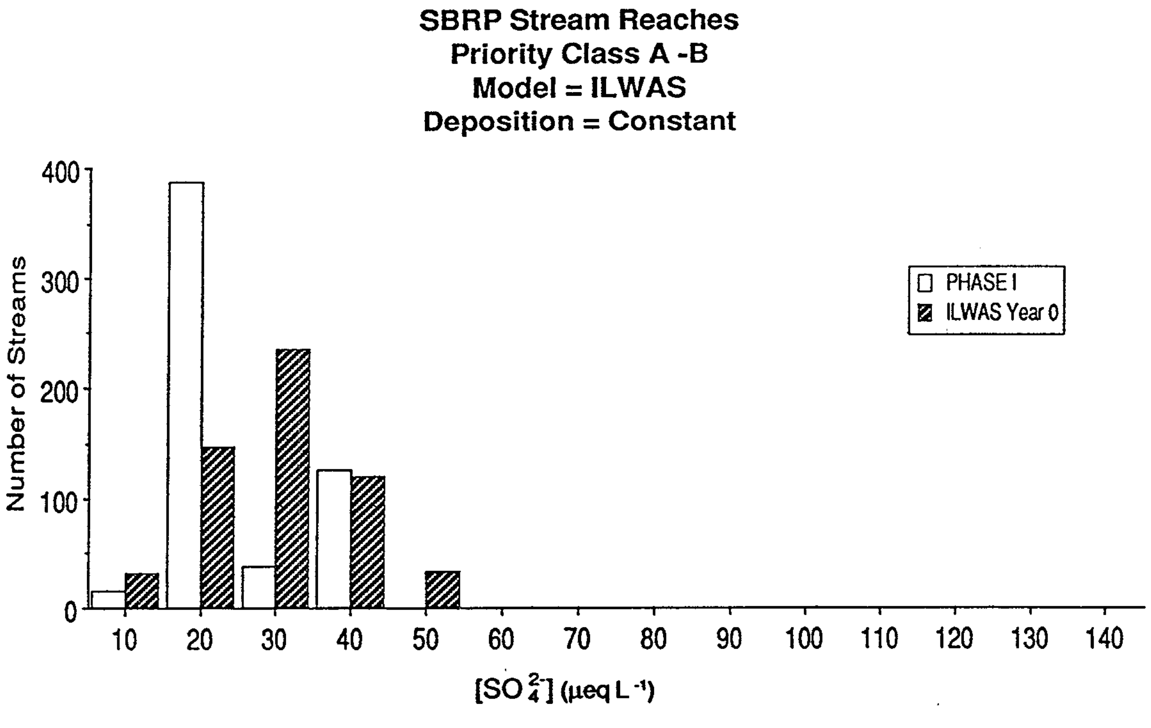
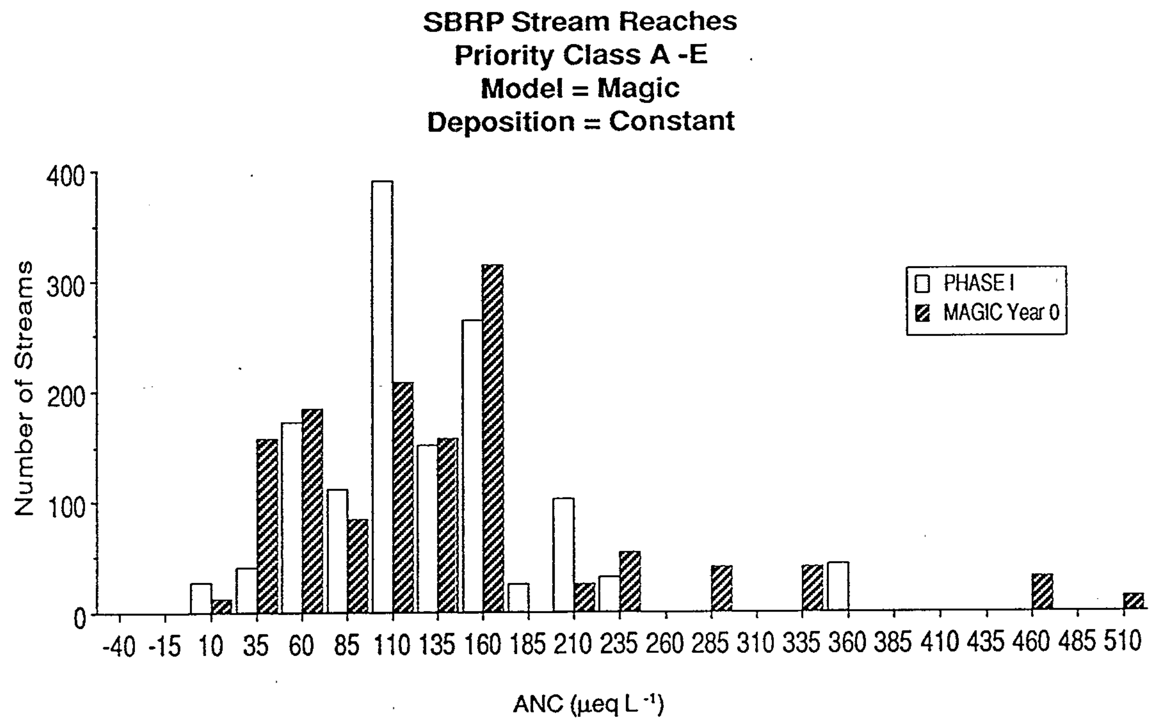


Figure 10-16. Comparison of population histograms for simulated versus observed (NSS Pilot Survey values) sulfate concentrations, Priority Classes A and B using ILWAS and MAGIC.



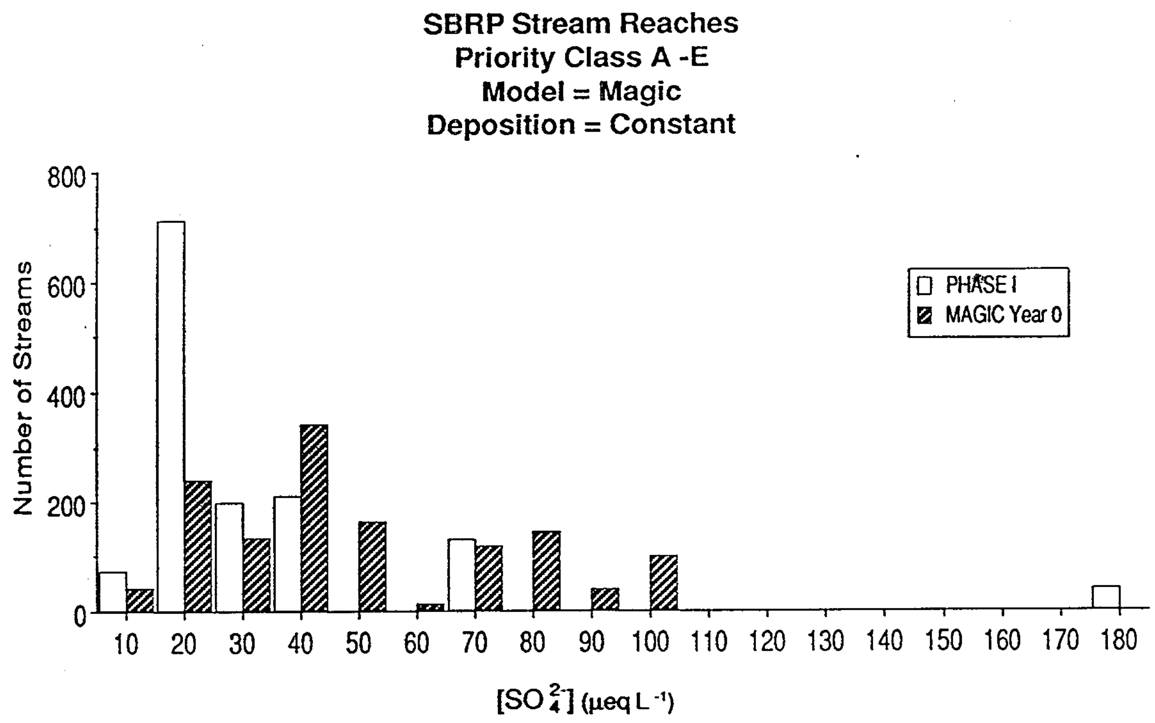


Figure 10-17. Comparison of population histograms for simulated versus observed (NSS Pilot Survey values) ANC and sulfate concentrations, Priority Classes A - E using MAGIC.

Table 10-11. Watersheds, by Priority Class, For Which Calibration Criteria Were Not Achieved

Region	Priority Class	Watershed ID Model ETD	ILWAS	MAGIC
Northeast	A	0	0	1D2-027
	B	0	0	1C1-068
				1B3-056
				1E1-106
	C	0	NA	1D3-002
				1A2-004
	D	1E2-069	NA	0
	E	0	NA	1A2-058
	F	NA	NA	1B1-043
				1D3-003
				1D2-094
	G	NA	NA	1D1-067
				1D3-029
				1C2-054
				1D2-049
				1D1-031
	H	NA	NA	1C3-055
				1A3-028
				1D2-036
				1D1-068
SBRP	A	NA		2A07811
		NA		2A07816
	B	NA	2A07821	0
			2A08803	
	C	NA	NA	2A07702
				2A07803
				2A08801
	D	NA	NA	0
	E	NA	NA	0

the NE, optimizations criteria generally could not be achieved either because of chloride imbalances or because cation inputs exceeded outputs. Time and funding constraints restricted the number of ETD simulations to northeastern watersheds in Priority Classes A - E (Figure 10-1). Similar constraints occurred with the ILWAS model; only watersheds in Priority Classes A and B were simulated in both the NE and SBRP. Optimization and calibration criteria for some northeastern watersheds also were not satisfied for the ETD and ILWAS models. These watersheds are listed in Table 10-11. The individual watersheds simulated by each model in each region are presented in Appendix A.2 and are listed by NSWS lake or stream identification number, name (if available), state, latitude and longitude, and initial NSWS ANC. Comparisons among models are made only for similar target populations, and the target population is clearly identified for each comparison.

The results discussed below have been obtained by weighting the individual watershed estimates by the appropriate inclusion probability. Weighting by the appropriate inclusion probability is critical for any analyses performed on these data. The individual watershed estimates are of interest only as they relate to the distribution of the population attributes.

10.10.2 Forecast Uncertainty

An integral part of all the analyses performed in the DDRP is the estimate of error associated with the analyses or projections. Each modeling group conducted error analyses on its respective model, which were incorporated in the confidence intervals about the population estimates.

10.10.2.1 Watershed Selection

The computational time required to conduct uncertainty analyses on all simulated DDRP watersheds would have been prohibitive. Therefore, six northeastern watersheds were selected from Priority Classes A - D. The watersheds were sorted by the following criteria:

- previously simulated for the EPA Internal Staff Paper
- no internal sulfur sources
- drainage lakes versus seepage lakes (drainage lakes preferred)
- percent sulfur retention (positive sulfur retention preferred)
- watershed disturbance as indicated by chloride balance (undisturbed watersheds preferred)
- ANC class (watershed/lake systems with ANC < 100 μeq L^{-1} preferred).

This sorting emphasized (1) those systems considered likely to show a response, (2) those for which early modelling output might be available, and (3) those that provided a representative cross-section of potential watershed responses. The six watersheds randomly selected for uncertainty analyses were

(1) one watershed (1A3-048) from Class A - previously simulated
(2) two watersheds (1A2-045, 1E1-111) from Class B - low ANC, positive sulfur retention
(3) two watersheds (1A1-003, 1C2-035) from Class C - low ANC, negative sulfur retention
(4) one watershed (1D3-025) from Class D - high ANC, positive sulfur retention

Characteristics of these six watersheds follow:

Watershed ID	Priority Class	ANC	% S Ret.	Soil Type	WA	LA	WA:LA
1A3-048	A	14.6	-99.0	Spodosols	228	54	4.7
1A2-045	B	13.2	4.0	Spodosols	168	26	6.4
1E1-111	B	11.0	12.2	Mixed	80	24	3.4
1A1-003	C	-9.9	-36.7	Mixed	96	13	7.5
1C2-035	C	73.6	-15.6	Spodosols	215	11	19.0
1D3-025	D	149.3	14.6	---	57	8	7.4

These watersheds include a lake with negative ANC, systems with low ANC and relatively high ANC (i.e., 74 and 150 μeq L^{-1}), watersheds in four of the five subregions, a distribution of watersheds across the deposition gradient, and watersheds selected from clusters representing the majority of watersheds with ANC <100 μeq L^{-1}. Uncertainty analyses conducted on these watersheds were assumed to be representative of the other watersheds within these priority classes.

In the SBRP, five watersheds were randomly selected for uncertainty analyses. The watersheds were sorted in priority order, as illustrated in Figure 10-2. Two watersheds were selected from Priority Class A: watersheds with ANC < 100 μeq L^{-1} and chloride < 50 μeq L^{-1} , and with positive sulfur retention. Two watersheds were selected from Priority Class B: watersheds with ANC >100 μeq L^{-1} but <200 μeq L^{-1} , chloride < 50 μeq L^{-1}, and with positive sulfur retention. One watershed was selected from Priority Class D: this watershed had ANC < 200 μeq L^{-1} but chloride > 50 μeq L^{-1} , indicating possible watershed disturbance. This watershed also had positive sulfur retention. Characteristics of these five watersheds follow:

Watershed ID	Priority Class	ANC	% S Ret.	Soil Type	WA
2A07828	A	37.0	81.1	Acid crys., high org.	19.1
2A08802	A	71.0	83.6	Acid crys., low org.	5.7
2A08810	B	114.4	77.9	Acid crys., low org.	4.9
2A08811	B	95.3	49.0	Acid crys.,/meta sedmt., low org.	3.3
2A07830	D	163.0	58.2	Acid crys., low org.	14.0

Uncertainty analyses conducted on these watersheds were assumed to be representative of other watersheds or similar watersheds within these classes.

10.10.2.2 Uncertainty Estimation Approaches

Three different approaches were used with the individual models to estimate the error associated with the projections. The three approaches were first order second moment analyses (ETD), first order error analyses (ILWAS), and "fuzzy" optimization and multiple simulations (MAGIC). These approaches reflect differences in model formulations, which required different uncertainty estimation approaches. Uncertainty estimates were computed for both input and parameter error. However, parameter error and input error were computed separately for each of the models.

Variance estimates were derived from the aggregated soils data and from the deposition monitoring sites. Variance algorithms were used with the soils aggregation procedures to obtain variance estimates for the physical and chemical variables aggregated to the watershed level. These variance estimates were used to scale the parametric variance associated with these different variables. For example, hydraulic conductivities were a function of soil porosity, sulfate half-saturation coefficients were a function of soil sulfate adsorption, and ion exchange selectivity coefficients were a function of soil cation exchange capacity and percent base saturation. Estimating the effect of parametric uncertainty on model output involved propagating this range of watershed parameter values through the model and observing the range in model output constituent concentrations or values.

Wet deposition uncertainty estimates were computed by calculating the variance for individual chemical species over the period of record at each Acid Deposition System (ADS) station used in the NE or SBRP, and adding the variance associated with (1) kriging of precipitation to the individual NE or SBRP sites and (2) extrapolating from the nearest ADS site to the simulated watershed. This latter variance component was obtained using resampling or jackknifing procedures following random deletion on an ADS site. The wet deposition relative standard deviations are listed, by species, in Table 10-12. Dry deposition estimates for these species were assumed to be ± 50 percent of the estimated annual dry deposition values at each individual site. Deposition uncertainty estimates were evaluated by varying the deposition (both wet and dry) consistently up or consistently down for all chemical species. Meteorological variability was not specifically investigated. The operational assumption is that typical year projections provide a common basis for comparisons among deposition scenarios to assess potential changes in surface water chemistry. Deposition uncertainty is an important part of these comparisons. Meteorological variance is implicitly incorporated in the deposition uncertainty but there is no intent to investigate interannual or interdecadal variance in meteorology.

10.10.2.2.1 Enhanced Trickle Down -

Input, initial condition, and parameter errors were evaluated for the ETD model using first order second moment analyses. First order second moment analyses involve replacing the nonlinear model with a first order Taylor series approximation for error covariance propagation. First order second moment analyses includes not only the simultaneous effects of all state variables, inputs, and parameters on each state variable, but also the propagation of uncertainties in inputs, parameters, and state variables (Lee et al., in press). Initial condition and parametric error were evaluated for the six northeastern watersheds listed above. Input (i.e., deposition) uncertainty was evaluated only for Kalers Pond (1E2-063) (Georgakakos et al., in press).

10.10.2.2.2 Integrated Lake-Watershed Acidification Study -

First order error analysis was used to estimate uncertainty in the ILWAS model. First order error analysis is similar to sensitivity analysis. Parameters or input variables were subjected to small perturbations and the change in selected output variables relative to the perturbation provided an estimate of the first derivatives. The first derivative estimates were used as weights to propagate the parametric or input variance to an output variance. This procedure is similar to the first order second moment analysis but the covariance matrix is not estimated with the first order error analysis.

Table 10-12. Deposition Variations Used in Input Uncertainty Analyses

Chemical Species	Deposition Wet % RSD	Deposition Dry % RSD
Sulfate	17.8	50
Nitrate	17.2	50
Chloride	46.9	50
Ammonium	38.1	50
Sodium	57.6	50
Potassium	70.9	50
Calcium	35.5	50
Magnesium	29.6	50
Hydrogen	Used to complete charge balance	

10.10.2.2.3 Model of Acidification of Groundwater in Catchments -

Uncertainty estimates for the MAGIC model were obtained using a fuzzy optimization procedure. The fuzzy optimization procedure consisted of multiple calibrations of each catchment using perturbations of the values of the fixed parameters to reflect the sampling and measurement error in these parameters. These error estimates were obtained from the aggregated soils data. Each of the multiple calibrations began with (1) a random selection of perturbed values of fixed parameters, and (2) a random selection of the starting values of the adjustable parameters. The adjustable parameters then were optimized using the Rosenbrock algorithm to achieve a minimum error fit to the target variables. Using the fuzzy optimization on multiple calibrations (i.e., an average of 7 calibrations for each DDRP catchment with a minimum of 3 and a maximum of 10 calibrations/catchment), uncertainty bands of maximum and minimum values were computed for each output variable for each year. These uncertainty bands encompass the range of variable values that were simulated given the specified uncertainty in fixed parameter values and measured target variables. The difference between maximum and minimum simulated values defines an uncertainty width about the simulated value arising from parametricuncertainty for each output variable for each DDRP catchment. The values of the uncertainty widths for each variable in the calibration year were regressed against the simulated value of the variable in the calibration year across all the DDRP catchments to derive a percentage uncertainty value for each value, representative of the region.

10.10.2.3 Relationship Among Approaches

Each of the approaches used for uncertainty analyses is appropriate for the model being used for DDRP Level III projections. MAGIC runs on a microcomputer, for example, and was coded for the fuzzy optimization analyses because computational time was not a consideration for MAGIC simulations. This approach was developed for the DDRP to incorporate both input and parameter uncertainty. The ETD model is intermediate in complexity and requires greater computational effort. The first order second moment analysis provides an estimate of simulation uncertainty and permits partitioning this uncertainty into input and parameter components (Lee et al., in press). The ILWAS model has the greatest number and most complex set of formulations. The ILWAS model, therefore, is not compatible with optimization or first order second moment analyses but is compatible with first order error analyses, which provide an estimate of simulation uncertainty.

The relationship between the uncertainty estimates using the two different procedures for MAGIC and ETD is shown for ANC and sulfate in Figure 10-18. For both models, the magnitude of the standard deviation was a function of the ANC or sulfate concentration as indicated by the slope of regression line. A multiplicative error term, therefore, was used in the uncertainty analyses. The slope of the line for both models was nearly identical with the differences occurring in the offset. This offset resulted in greater uncertainty estimates for MAGIC than ETD. The MAGIC simulations, however, incorporated both input and parameter error while the ETD simulations (with the exception of Kaler's Pond) included only parameter error. Kaler's Pond included both input and parameter error and is comparable to the MAGIC standard deviation estimates. The offset between the two models represents the input error. Because of the similarity between MAGIC and ETD for Kaler's Pond, the MAGIC standard deviations were used to compute confidence intervals for both ETD and MAGIC.

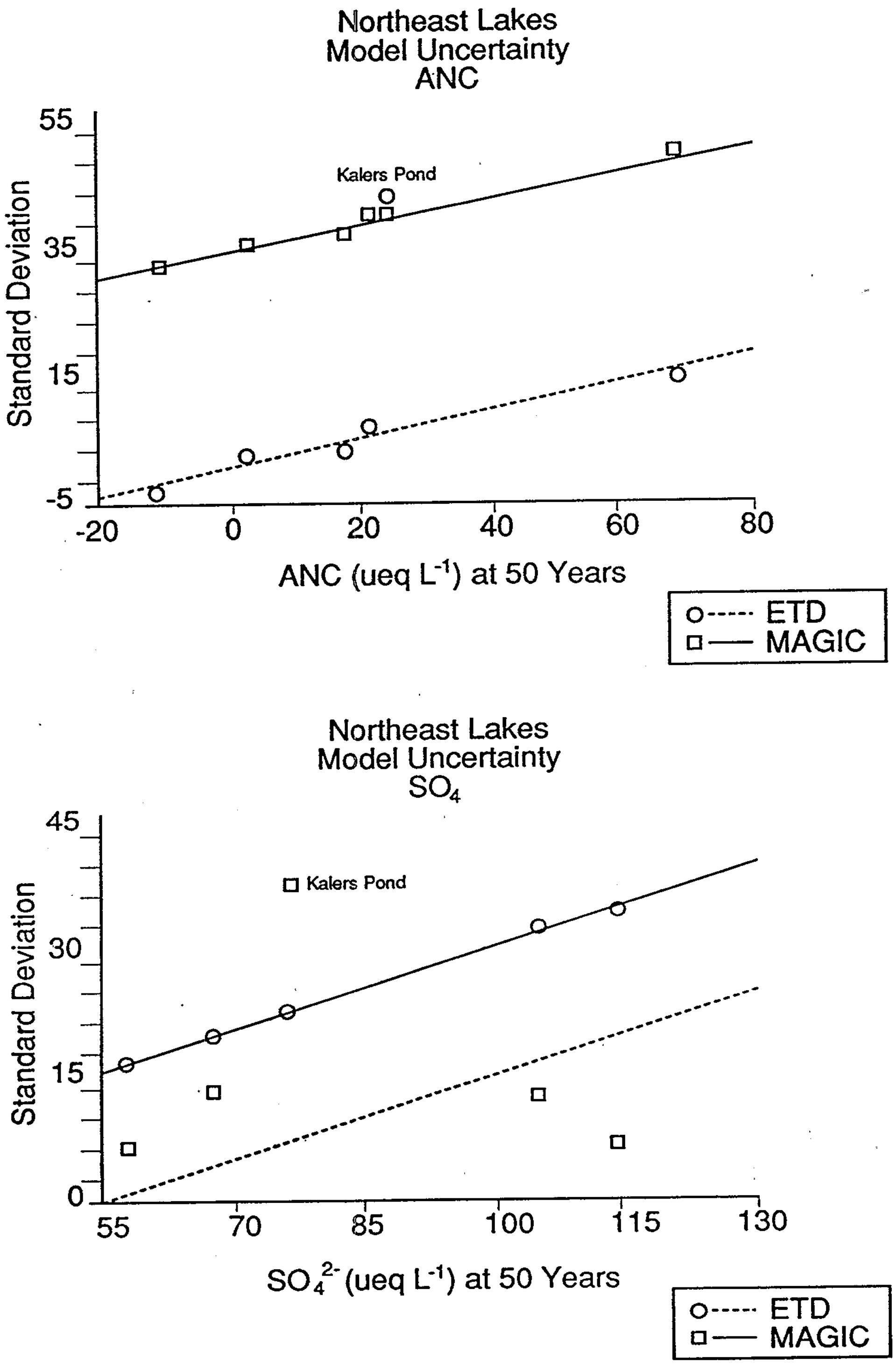


Figure 10-18. Comparison of projection standard errors as a function of ANC (top figure) and sulfate (bottom figure) concentrations for the NE uncertainty analysis watersheds using ETD and MAGIC.

The estimates of parametric uncertainty using the ILWAS model also are consistent with the regional estimates of both MAGIC and ETD (i.e., Kaler's Pond). Input uncertainty estimates were computed by all three models using the individual uncertainty estimation procedures discussed above. The input uncertainty estimates computed for all three models were on the same order as the parametric uncertainty. Parametric variance estimates, therefore, were doubled to obtain estimates of projection uncertainty for the ILWAS model. The procedures described in Section 6 were used to integrate this projection error with sampling error and compute confidence intervals for the population estimates presented in the next section.

10.10.2.4 Confidence Intervals

Upper and lower bounds for a 90 percent confidence interval were computed for ANC, pH, and sulfate projections from all three models and for calcium and magnesium for MAGIC and ILWAS (Appendix A.3). The confidence intervals were computed using the variance estimator discussed in Section 6. This variance estimator includes estimates of sampling and measurement error, parameter and input error, and regional estimation error. Time constraints prevented the inclusion of confidence intervals for the ILWAS SBRP projections. These figures will be incorporated in the Mid-Appalachian Report in mid-1990.

10.11 POPULATION ESTIMATION AND REGIONAL FORECASTS

Population estimation procedures were discussed in Section 6. The uncertainty estimation procedures were discussed in the previous section, Section 10.10. Comparisons among model projections are presented only for comparable target populations. The number of watersheds simulated with each model differed; therefore, it is critical that comparisons be made only among or between models that simulated the same watersheds, i.e., those that represent the same target population. The population estimates discussed below represent three different target populations. The target population discussed in each of the following sections is clearly defined. These definitions are essential for the proper interpretation of the results. The models, target populations, and population attributes for both the NE and SBRP are shown in Table 10-13.

10.11.1 Northeast Regional Projections

10.11.1.1 Target Population Projections Using MAGIC

An estimated 3227 lakes in the target population in the NE were simulated using MAGIC, compared to the DDRP total target population of 3667. The smaller target population reflects an exclusion of lakes for which MAGIC was unable to satisfy the calibration criteria. The simulated target population represents Priority Classes A - I, which includes both disturbed and undisturbed watersheds based on chloride concentrations (See Section 10.5.7), watersheds that had both positive and negative sulfur retention, and watersheds that had initial ELS-I ANC concentrations ranging from -53 to 392 μeq L^{-1}. The MAGIC simulations for this target population extend to 100-year projections. Projections using other models were restricted to 50 years, because time and computational requirements prohibited longer simulations. The 100-year time frame provides additional insight into the cumulative effects of sulfur deposition on changes in surface water chemistry.

Table 10-13. **Target Populations for Modelling Comparisons and Population Attributes**

Region	Priority Class	Models	Target Population	Population Attributes
Northeast	A and B	ETD,ILWAS MAGIC	502	ANC<100 μeq L^{-1} (Int. Staff Paper)
	A - E	ETD,MAGIC	1813	ANC<400, Undisturbed Watersheds
	A - I	MAGIC	3227	ANC<400,Representative of entire NE population
Total DDRP Target Population (NE)			3667	
SBRP	A and B	ILWAS, MAGIC	567	ANC<200,Undisturbed Watersheds
	A - E	MAGIC	1323	Representative of entire SBRP population
Total DDRP Target Population (SBRP)			1531	

10.11.1.1.1 Deposition scenarios -

Projected changes in ANC and sulfate concentrations that might occur over a 100-year period, assuming current and decreased deposition, are shown in Figure 10-19. The confidence limits about the individual simulations are included in Appendix A.3. Confidence intervals are not included on the figure in order to increase the contrast among model projections or between deposition scenarios.

The projected changes in median ANC concentrations over 100 years assuming either current and decreased deposition were small (Figure 10-19). The median ANC concentration projected after 50 years for constant deposition at current levels was 124 $\mu eq\ L^{-1}$ and for a 30 percent deposition decrease was 135 $\mu eq\ L^{-1}$, representing a difference of 11 $\mu eq\ L^{-1}$ (Table 10-14). The change projected in median sulfate concentration after 50 years for current deposition was 99 $\mu eq\ L^{-1}$ and for decreased deposition was 71 $\mu eq\ L^{-1}$, representing a -28 $\mu eq\ L^{-1}$ difference. The changes projected in median ANC over a 100-year period between current and decreased deposition were 121 versus 134 $\mu eq\ L^{-1}$, respectively, or a difference of 13 $\mu eq\ L^{-1}$. The projected changes in median sulfate concentration after 100 years for current deposition and a 30 percent decrease in deposition were 99 versus 70 $\mu eq\ L^{-1}$, respectively, or a difference of -29 $\mu eq\ L^{-1}$. A small decline in ANC concentrations, (less than 1 $\mu eq\ L^{-1}$) was indicated between year 50 and year 100 for both current and decreased deposition. Projected calcium and magnesium concentrations also showed a small but continual decline over the 100-year period under both current deposition and a 30 percent deposition decrease (Table 10-14). Sulfate concentrations declined during the initial 50-year period, asymptotically approaching steady state, and were projected to remain essentially constant from year 50 to year 100 under current deposition and to decrease slightly over this same period for decreased deposition. The confidence limits about the projected CDFs represented a projection error of about $\pm$ 36 $\mu eq\ L^{-1}$ in ANC and $\pm$ 32 $\mu eq\ L^{-1}$ in sulfate concentrations. Both the changes projected for 50 and 100 years, assuming different deposition scenarios, were within the uncertainty bounds of the projections.

The projections of the sulfate concentrations indicated that the watersheds would be near sulfate steady-state after 50 years under current deposition with the median projected watershed sulfur retention of about 5 percent in both year 50 and year 100 (Table 10-14). The interquartile range varied from about 1 to 11 percent in both year 50 and 100, indicating the majority of the watersheds were projected to be near sulfate steady state. The median projected sulfur retention under decreased deposition for these watersheds was nearly zero. From year 50 to year 100, the projected median sulfur retention changed from 0 to a slightly positive sulfur retention (~5 percent) in the watersheds. The interquartile ranges for the 50- and 100-year periods were -7 to +8 percent and -1 to +9 percent, respectively.

Projected changes in pH that might occur over a 100-year period, assuming current and decreased deposition are shown in Figure 10-20 and listed in Table 10-14. The projected changes in pH over a 100 year period under constant and decreased deposition were small (Figure 10-20). The projected differences between the median pH under constant and decrease deposition after 100 years were less than 0.05 pH units (Table 10-14). The projected differences in pH for the lower quartile after 100 years under the two deposition regimes were less than 0.1 pH units, varying from 6.67 under current deposition to 6.75 under decreased deposition (Table 10-14).

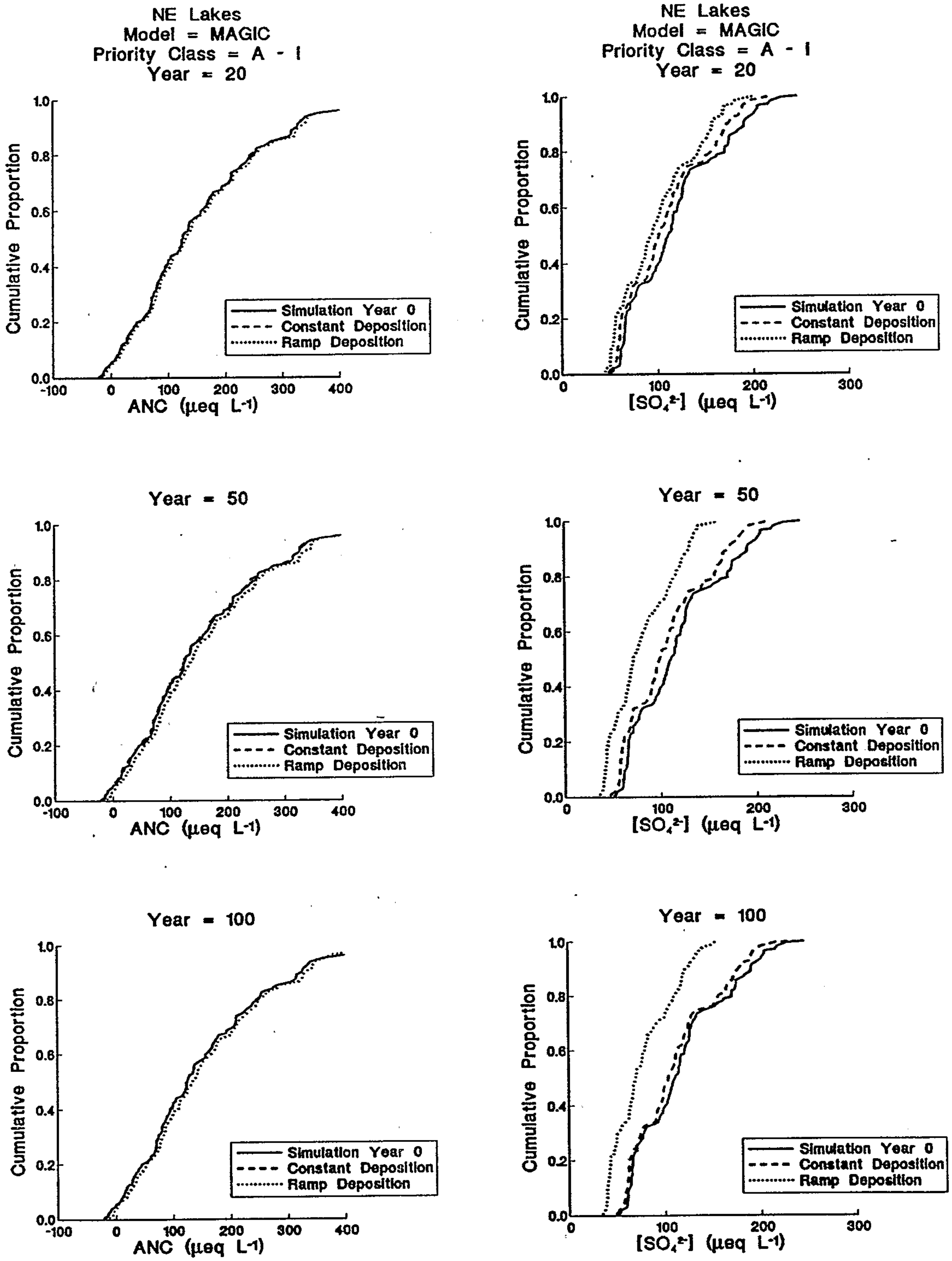


Figure 10-19. Projections of ANC and sulfate concentrations for NE lakes, Priority Classes A - I, using MAGIC for 20, 50, and 100 years, under current deposition and a 30 percent decrease in deposition.

Table 10-14. Descriptive Statistics of Projected ANC, Sulfate, pH, Calcium Plus Magnesium, and Percent Sulfur Retention for NE Lakes in Priority Classes A - I Using MAGIC for Both Current and Decreased Deposition

Year	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			Current Deposition				
MAGIC All, ANC							
Yr 0	151	114	-21	70	126	223	416
Yr 20	151	114	-21	70	126	224	417
Yr 50	149	114	-22	67	124	224	414
Yr 100	146	113	-22	62	121	216	409
MAGIC All, SO_4^{2-}							
Yr 0	117	48	50	71	111	152	246
Yr 20	108	44	47	70	101	147	221
Yr 50	106	43	46	68	99	142	215
Yr 100	106	43	45	66	99	140	214
MAGIC All, pH							
Yr 0	6.01	0.60	4.47	6.73	6.97	7.22	7.49
Yr 20	6.02	0.60	4.49	6.73	6.98	7.22	7.49
Yr 50	5.99	0.62	4.48	6.71	6.98	7.22	7.49
Yr 100	5.90	0.66	4.47	6.67	6.96	7.21	7.48
MAGIC All, Ca + Mg							
Yr 0	229	122	41	128	197	296	560
Yr 20	221	121	40	124	190	288	544
Yr 50	217	120	38	121	186	284	540
Yr 100	213	120	37	118	182	280	531
MAGIC All, % S Retention							
Yr 0	-4	10	-25	-11	-3	4	19
Yr 20	4	9	-20	-1	3	10	25
Yr 50	6	8	-18	1	5	11	26
Yr 100	6	8	-19	2	5	11	27

continued

Table 10-14. (Continued)

Year	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			30% Decrease in Deposition				
MAGIC All, ANC							
Yr 0	151	114	-21	70	126	223	416
Yr 20	156	115	-20	74	131	227	425
Yr 50	160	115	-18	76	135	231	431
Yr 100	158	114	-19	74	134	231	428
MAGIC All, SO_4^{2-}							
Yr 0	117	48	50	71	111	152	246
Yr 20	99	40	44	63	93	132	202
Yr 50	80	33	35	52	71	107	157
Yr 100	77	32	34	48	70	103	153
MAGIC All, pH							
Yr 0	6.01	0.60	4.47	6.73	6.97	7.22	7.49
Yr 20	6.13	0.56	4.52	6.74	6.99	7.23	7.50
Yr 50	6.28	0.52	4.58	6.77	7.01	7.24	7.50
Yr 100	6.26	0.53	4.58	6.75	7.01	7.24	7.50
MAGIC All, Ca + Mg							
Yr 0	229	122	41	128	197	296	560
Yr 20	217	120	39	120	184	286	539
Yr 50	203	118	35	113	173	267	529
Yr 100	198	117	32	110	170	268	511
MAGIC All, % S Retention							
Yr 0	-4	10	-25	-11	-3	4	19
Yr 20	-10	11	-44	-16	-10	-1	17
Yr 50	-1	13	-44	-7	1	8	24
Yr 100	3	11	-36	-1	4	9	26

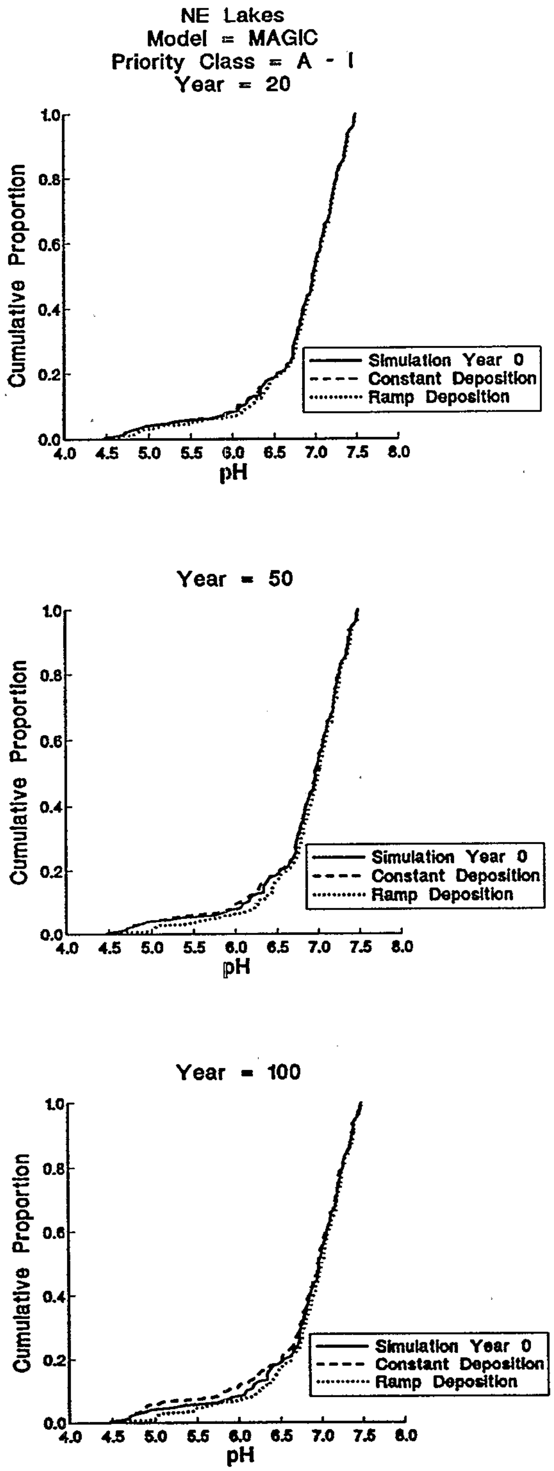


Figure 10-20. pH projections for NE lakes, Priority Classes A - I, using MAGIC for 20, 50, and 100 years, under current deposition and a 30 percent decrease in deposition.

Projections of the number of lakes currently not acidic that might become acidic in the next 50 years for current deposition were 87 (3 percent) lakes and 50 (2 percent) for a 30 percent deposition decrease based on an estimated target population of 3227 lakes. Projections of the number of lakes currently not acidic that might become acidic in the next 100 years under current deposition and a 30 percent deposition decrease were 100 (3 percent) and 50 (2 percent), respectively. The number of currently acidic lakes (i.e., 162 lakes in the target population with ANC <0 μeq L^{-1}) that might chemically improve (increase in ANC) under current deposition levels and a 30 percent deposition reduction after 50 years were projected as 64 (39 percent) and 125 (77 percent), respectively. The number of currently acidic lakes that might chemically improve after 100 years at current and decreased deposition levels was projected as 52 (32 percent) and 113 (70 percent), respectively. The percentages for chemical improvement are based on the number of currently acidic lakes estimated in the target population (i.e., 162 lakes).

10.11.1.1.2 Rate of change of ANC, sulfate, and pH over 100 years -

The projected changes in ANC, sulfate concentrations, and pH over the next 100 years are displayed as box and whisker plots (Figures 10-21 through 10-23). Box and whisker plots illustrate how both the target population constituent median and interquartile range vary through time.

The median ANC concentrations projected for current deposition changed from an initial calibrated concentration of 126 μeq L^{-1} to 124 μeq L^{-1} after 50 years and to 121 μeq L^{-1} after 100 years (Table 10-14). For a 30 percent deposition decrease, the median ANC was projected to change from 126 μeq L^{-1} at year 0 to 135 μeq L^{-1} at year 50, remaining essentially unchanged over the next 50 years. The median calcium plus magnesium concentration decreased linearly over the entire 100-year simulation period for current deposition with a projected decrease from 197 to 182 μeq L^{-1} (about 0.15 μeq L^{-1} yr^{1}). Median calcium plus magnesium concentrations also declined from 197 to 170 μeq L^{-1} over the 100-year period for decreased deposition and from 197 μeq L^{-1} in year 0 to 173 μeq L^{-1} in year 50 (approximately 0.5 μeq L^{-1} yr^{-1}). The projected rate of change for the next 50 years decreased (less than 0.1 μeq L^{-1} yr^{-1}) but retained a negative slope.

The projected change in median sulfate concentration for current deposition was an asymptotic decrease toward sulfate steady state (or to a small positive retention due to in-lake retention) with concentrations near steady state after the first 10 years. For the scenario of decreased deposition, the projected change in the median sulfate concentration was -40 μeq L^{-1} and was essentially complete by year 50. The mean projected change in the median sulfate concentration over the subsequent 50 years was slightly less than -2 μeq L^{-1}.

The median pH values changed from 6.97 to 6.96 under current deposition and from 6.97 to 7.01 under decreased deposition, a change of less than 0.05 units (Table 10-14). The variance in pH remained relatively constant through time (Figure 10-23).

Neither the change in ANC nor change in sulfate concentration was a function of the initial ELS-I ANC, for either current deposition or for a 30 percent decrease in deposition (Table 10-15). Shifts in the population distribution of median ANC and sulfate concentrations over the 40-year period from year

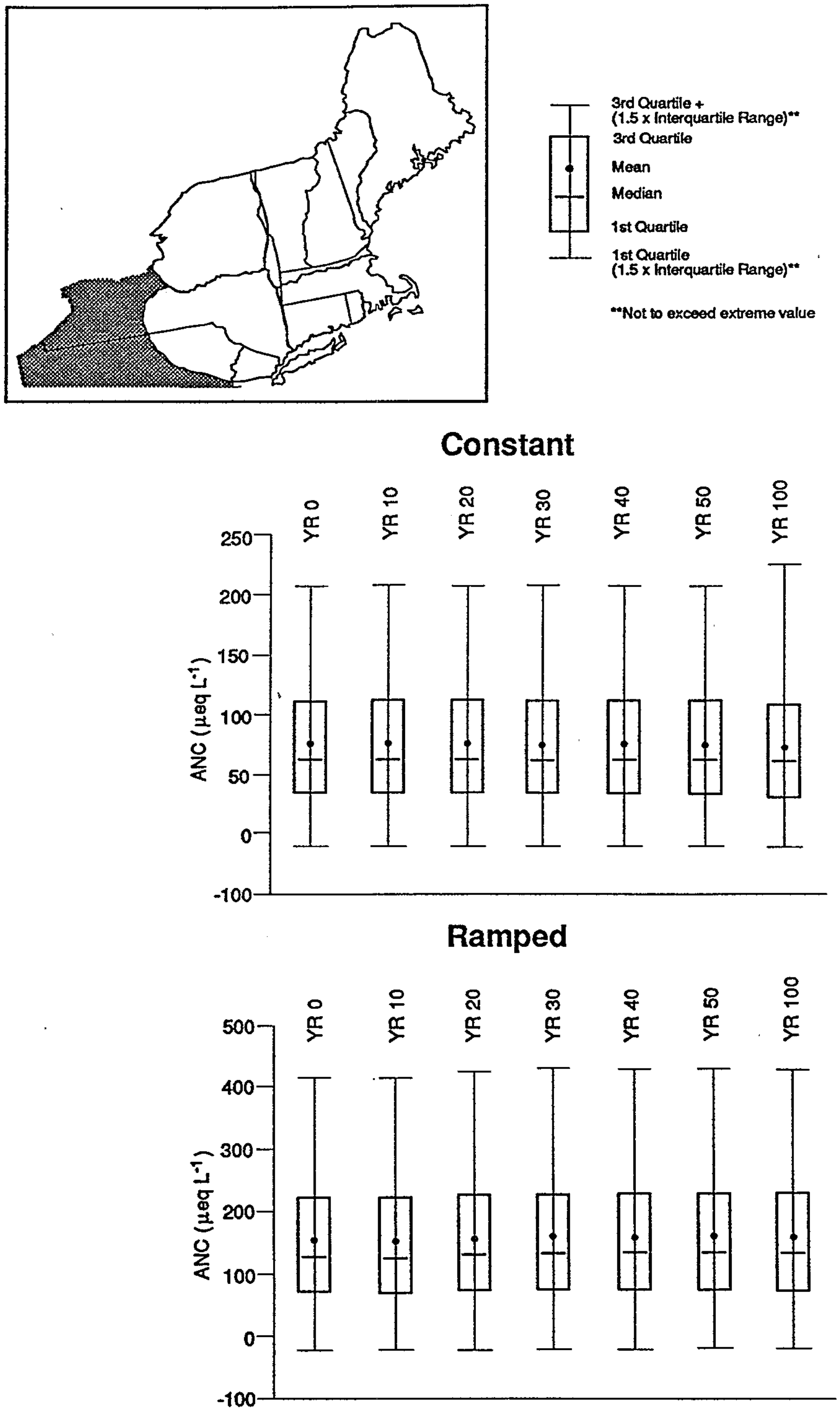


Figure 10-21. Box and whisker plots of ANC distributions at 10-year intervals for NE Priority Classes A - I using MAGIC.

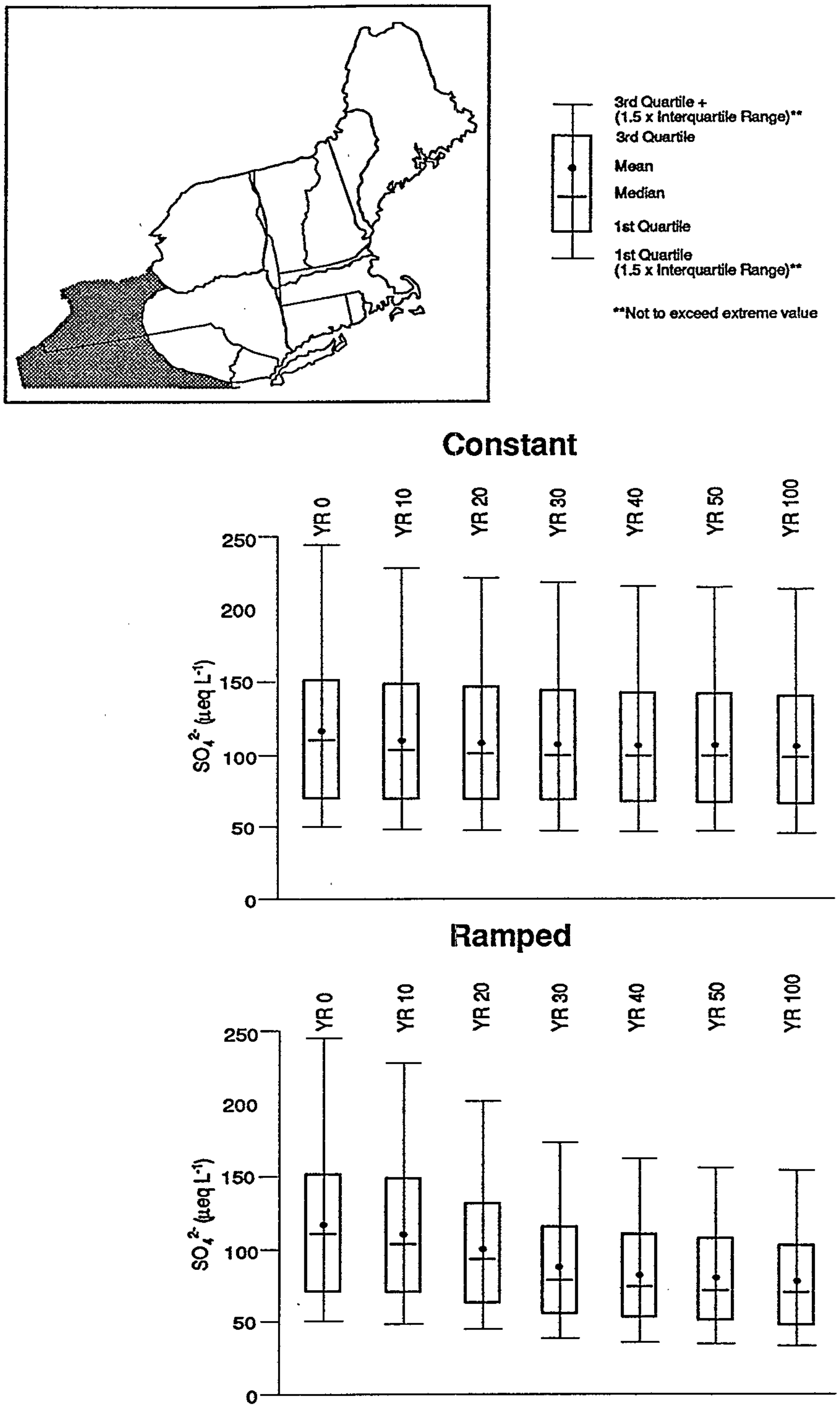


Figure 10-22. Box and whisker plots of sulfate distributions at 10-year intervals for NE Priority Classes A - I using MAGIC.

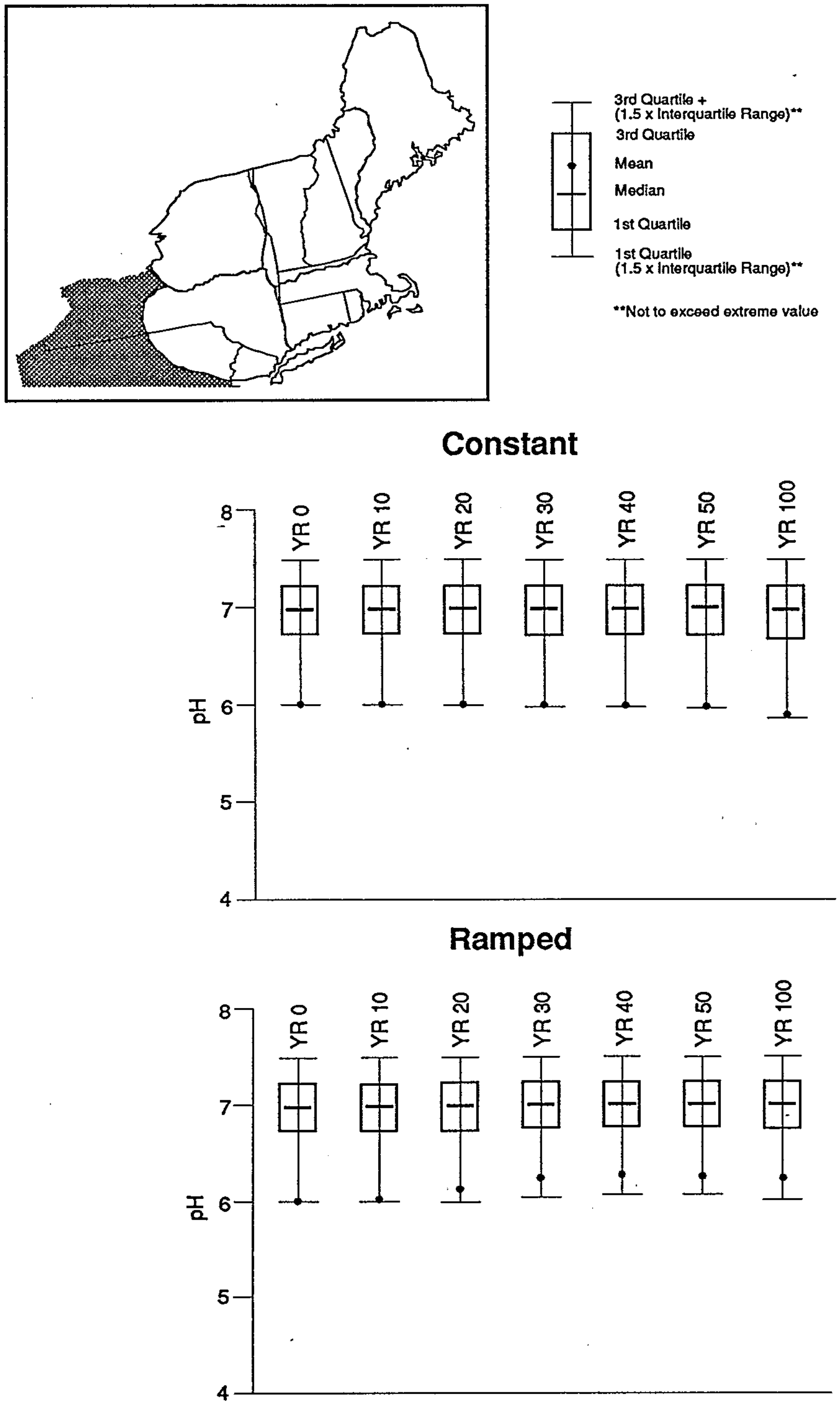


Figure 10-23. Box and whisker plots of pH distributions at 10-year intervals for NE Priority Classes A - I using MAGIC.

10 to year 50 indicate a relatively uniform change among ANC and sulfate intervals (Figures 10-24 and 10-25). The 40-year interval was selected as the period for comparison because the ramp change in deposition did not occur until year 10; the first 10 years of all projections represent, therefore, current deposition levels. The change in ANC was smaller for acidic lakes for decreased deposition but similar among the other three ANC groups (Table 10-15).

10.11.1.2 Target Population Projections Using MAGIC and ETD

An estimated target population of 1920 lakes was simulated using both ETD and MAGIC. These lakes represent Priority Classes A - E (Figure 10-1), which have ANC concentrations ranging from -53 to 392 μeq L^{-1}. These priority classes contains watersheds that have both positive and negative sulfur retention but, based on chloride concentrations (Section 10.5.7), are relatively undisturbed.

10.11.1.2.1 Deposition scenarios -

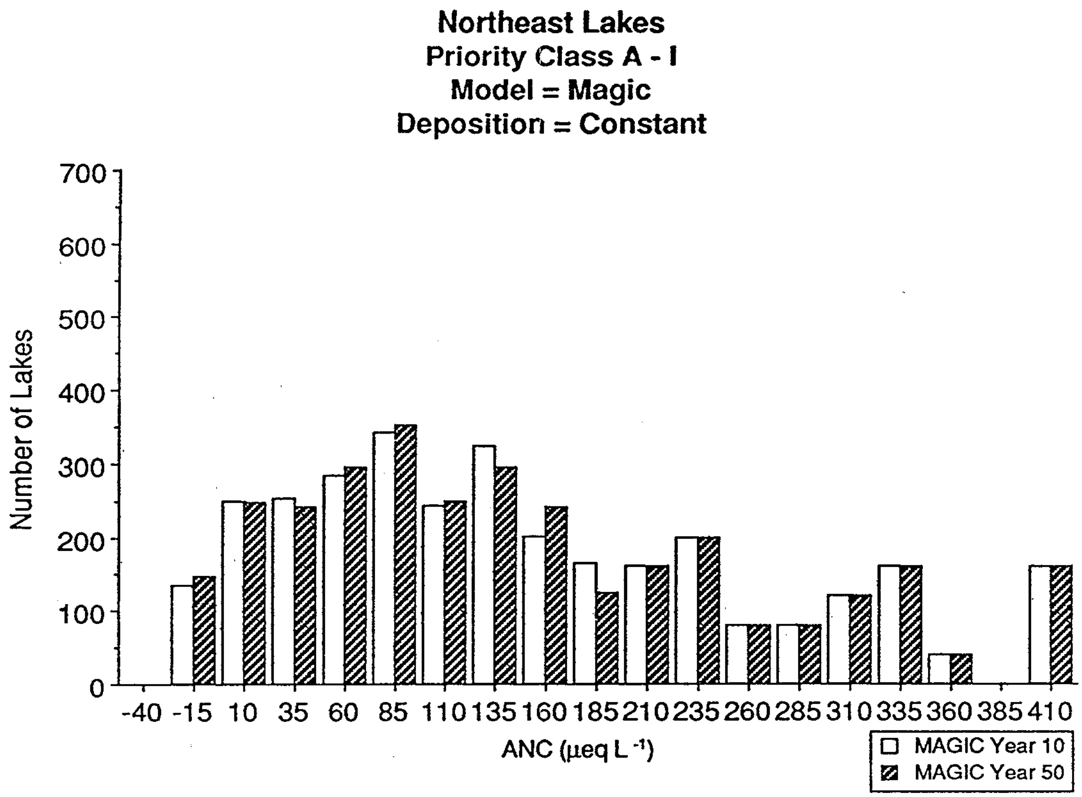
ETD and MAGIC projected similar changes in ANC, sulfate, and pH over the 50-year period for both current deposition and a 30 percent deposition decrease (Figures 10-26 through 10-28). Confidence intervals for each of the projections are included in Appendix A.3. For current deposition levels, the median ANC concentrations projected after 50 years using ETD and MAGIC were 74 and 110 μeq L^{-1}, respectively (Table 10-16). Under a 30 percent deposition decrease, the median ANC concentrations projected using ETD and MAGIC after 50 years were 85 and 119 μeq L^{-1}, respectively. The differences between the model projections result primarily from the initially calibrated ANC concentrations. The median calibrated ANC concentration for MAGIC was 116 μeq L^{-1}, while the median (ELS-I) ANC concentration assumed as the initial model condition for ETD was 77 μeq L^{-1}. The difference between the ETD initial and 50-year projected ANCs was 4 μeq L^{-1} , similar to the 6 μeq L^{-1} difference observed for MAGIC (Table 10-16). Similar differences between the initial and 50-year projections occurred for sulfate and pH. These relatively minor discrepancies reflect differences in the calibration procedures for both models (See Section 10.9) and are within the uncertainty bounds on the projections.

Results of within-model comparisons of the effects of alternative deposition scenarios on surface water chemistry are shown in Figures 10-29 through 10-31. Changes in median ANC projected for both deposition scenarios after 50 years using either model were small and were consistent with the MAGIC projections discussed in the previous section. For example, differences in the median ANC projected after 50 years using ETD versus MAGIC, between current deposition and a 30 percent deposition decrease were 74 μeq L^{-1} versus 85 μeq L^{-1} (+11 μeq L^{-1}) and 110 μeq L^{-1} versus 119 μeq L^{-1} (+9 μeq L^{-1}), respectively. The differences in the median sulfate concentrations projected after 50 years using ETD and MAGIC between current deposition and a 30 percent deposition decrease were 100 versus 70 μeq L^{-1} (-30 μeq L^{-1}) and 91 versus 64 μeq L^{-1} (-27 μeq L^{-1}), respectively.

The differences in the median pH at the end of 50 years under current and decreased deposition for MAGIC were 6.92 versus 6.95 (+0.30) and for ETD were 6.80 versus 6.86 (+0.06), respectively. The sulfate concentrations projected using both models indicated the watersheds were near sulfate steady state after 50 years. The median sulfur retention for the watersheds projected using both models ranged

Table 10-15. Change in Median ANC and Sulfate Concentrations Over a 40-Year Period as a Function of the Initial ELS-Phase I or NSS Pilot Survey ANC Groups

	ANC ($\mu eq\ L^{-1}$)				Sulfate ($\mu eq\ L^{-1}$)			
	< 0	0 - 25	25 - 100	100 - 400	< 0	0 - 25	25 - 100	100 - 400
NE								
Priority Class AB								
ETD, cons.	-0.4	5	3	-	2	-1	-9	-
ETD, ramp	7	12	14	-	-44	-34	-24	-
ILWAS, cons.	-3	-3	-6	-	5	-	-	-
ILWAS, ramp	8	10	5	-	-52	-21	-20	-
MAGIC, cons.	-0.6	0.4	-3	-	-5	-5	-6	-
MAGIC, ramp	5	13	6	-	-48	-37	-27	-
Priority Class A-E								
ETD, cons.	-0.5	1	2	-4	-5	-1	4	-10
ETD, ramp	4	9	14	11	-37	-31	-25	-28
MAGIC, cons.	-2	-3	-0.5	0.5	-0.5	-5	-0.6	-4
MAGIC, ramp	5	6	7	7	-30	-21	-27	-20
Priority Class A-I								
MAGIC, cons.	-2	-2	-1	-3	-0.5	-2	-3	-7
MAGIC, ramp	5	10	10	15	-30	-33	-30	-34
SBRP								
Priority Class AB								
ILWAS, cons.	-	-	-15	-6	-	-	37	25
ILWAS, ramp	-	-	-16	-7	-	-	53	33
MAGIC, cons.	-	-	-14	-14	-	-	27	31
MAGIC, ramp	-	-	-21	-24	-	-	44	47
Priority Class A-E								
MAGIC, cons.	-	-	-14	-24	-	-	27	31
MAGIC, ramp	-	-	-21	-34	-	-	44	47



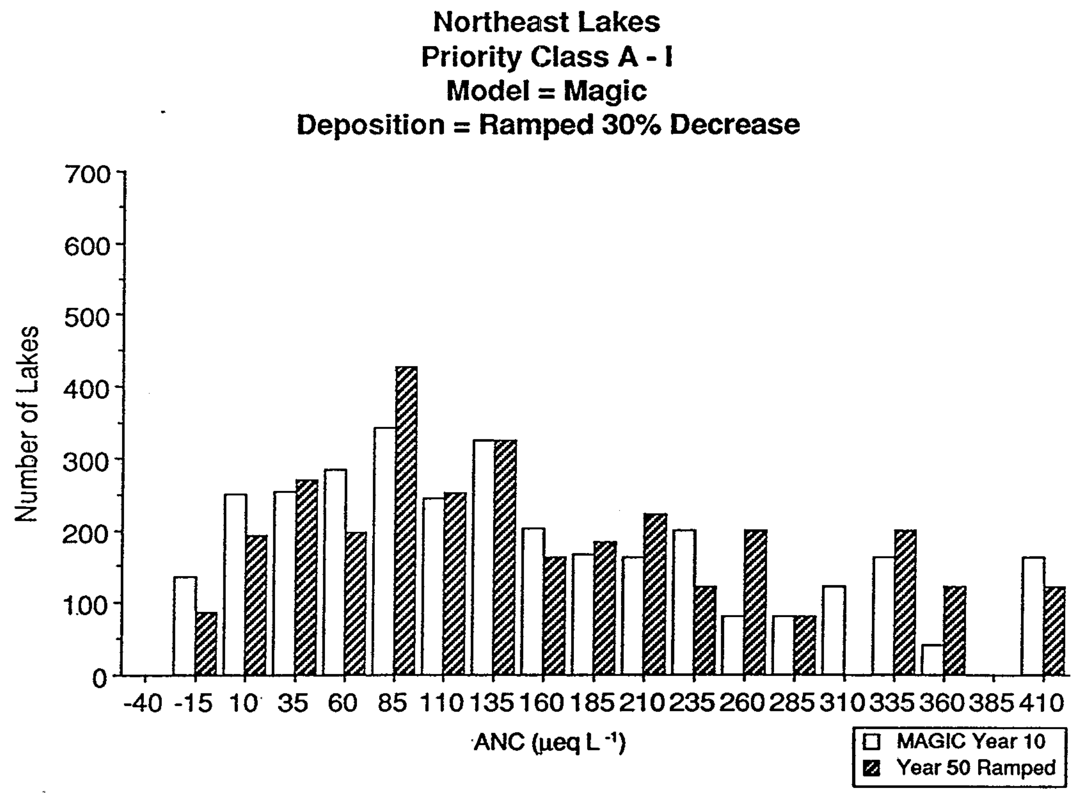
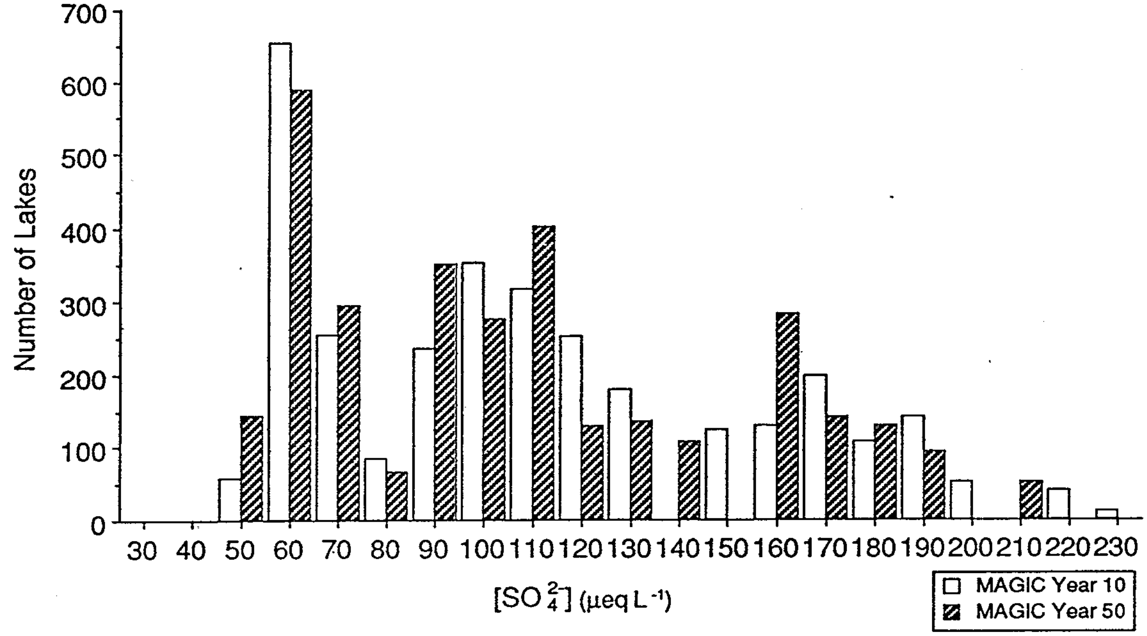


Figure 10-24. Comparison of population histograms for ANC under current levels of deposition and a 30 percent decrease in deposition for NE lakes, Priority Classes A - I, using MAGIC.

Northeast Lakes
Priority Class A - I
Model = Magic
Deposition = Constant



Northeast Lakes
Priority Class A - I
Model = Magic
Deposition = Ramped 30% Decrease

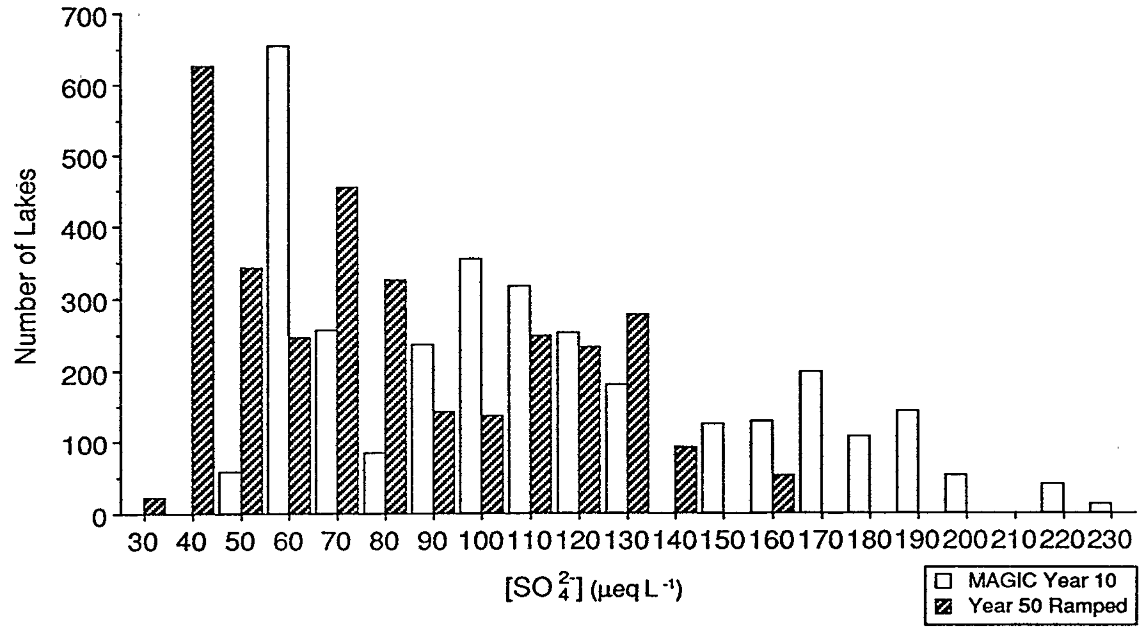


Figure 10-25. Comparison of population histograms for sulfate concentrations at current levels of deposition and a 30 percent decrease for NE lakes, Priority Classes A - I, using MAGIC.

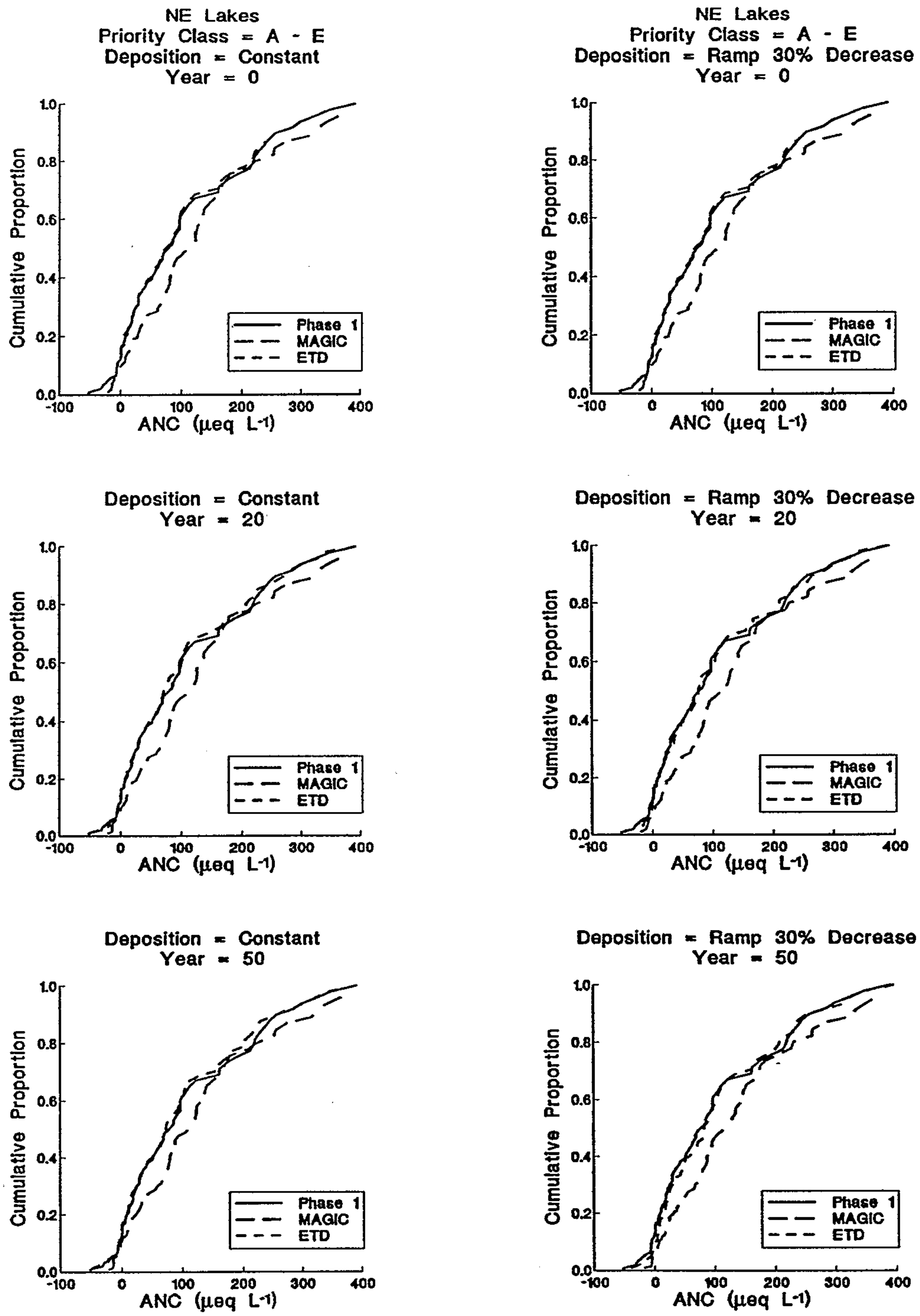


Figure 10-26. Comparison of MAGIC and ETD projections of ANC for NE lakes, Priority Classes A - E, under current and decreased deposition.

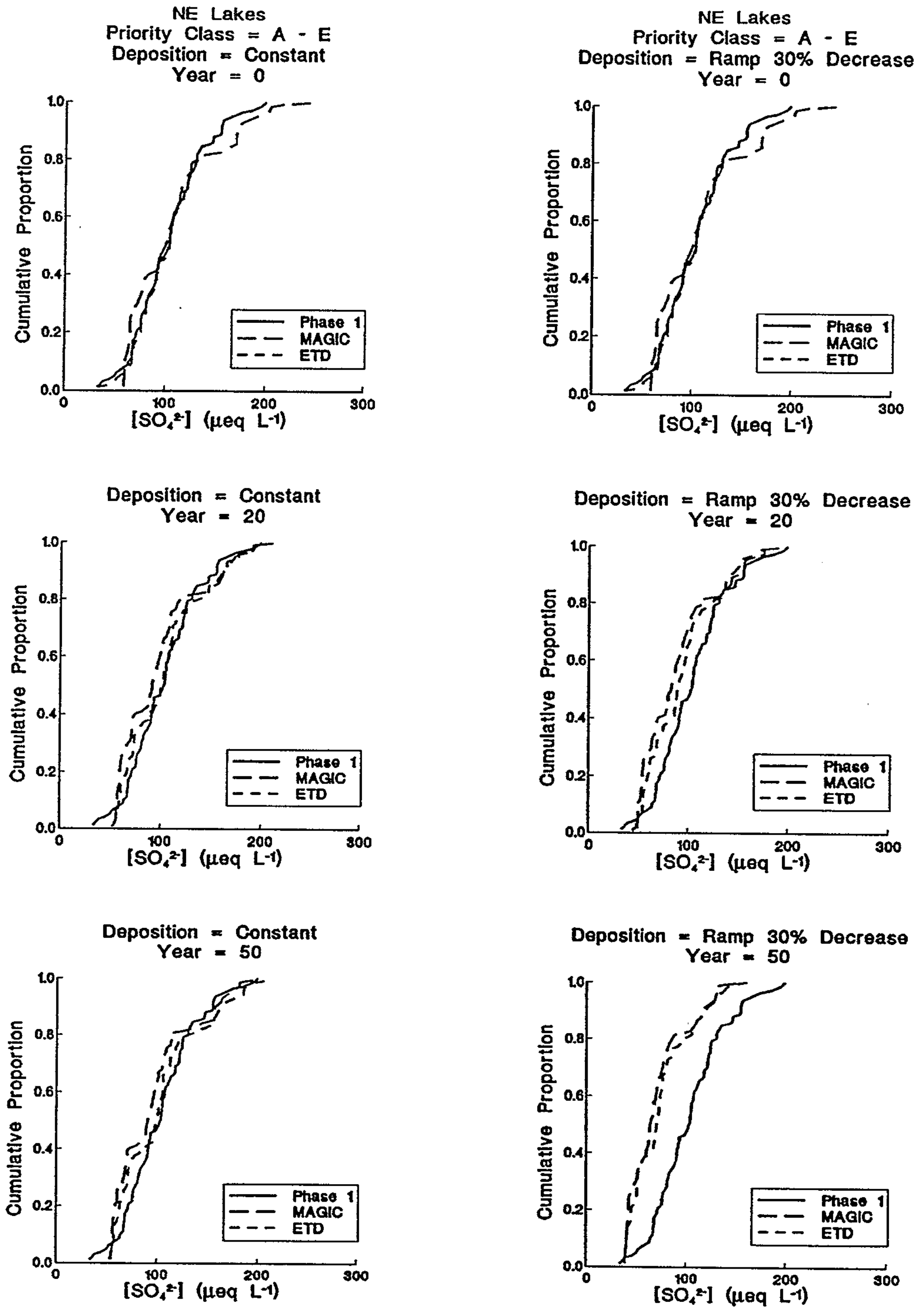


Figure 10-27. Comparison of MAGIC and ETD projections of sulfate concentrations for NE lakes, Priority Classes A - E, under current and decreased deposition.

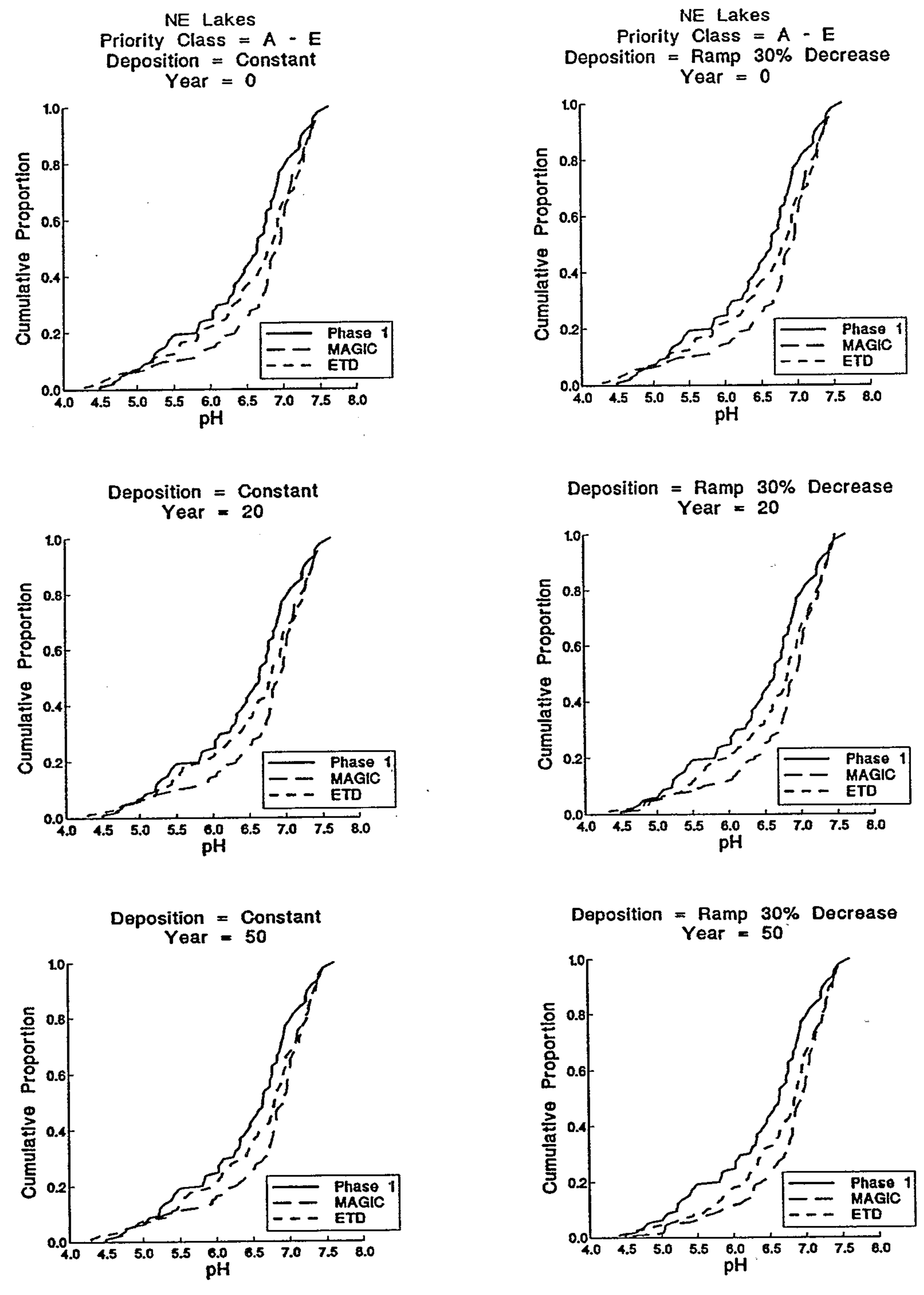


Figure 10-28. Comparison of MAGIC and ETD projections of pH for NE lakes, Priority Classes A - E, under current and decreased deposition.

from 3 to 6 percent for current deposition and from 2 to 4 percent for decreased deposition (Table 10-16). Although there was a range in this distribution of sulfur retention, the upper and lower quartile values for current deposition ranged from -3 to 9 percent for ETD and 4 to 13 percent for MAGIC; under decreased deposition, percent sulfur retention ranged from -4 to 7 for ETD and -1 to 10 for MAGIC after 50 years, indicating most of the watersheds were near sulfur steady state (Table 10-16).

Projection of the number of lakes not currently acidic that might become acidic in the next 50 years for current deposition using ETD and MAGIC were 49 (3 percent) and 87 (5 percent), respectively. The number of lakes currently not acidic that might become acidic for a 30 percent deposition decrease using ETD and MAGIC were 37 (2 percent) and 50 (3 percent), respectively. The number of currently acidic lakes that might chemically improve under current deposition after 50 years was projected by ETD and MAGIC to be 52 (23 percent) and 64 (39 percent), respectively. Under a 30 percent deposition reduction, the projections of chemical improvement were estimated to be 103 lakes (46 percent) for ETD and 125 lakes (77 percent) for MAGIC.

10.11.1.2.2. Rate of change of ANC, sulfate, and pH over 50 years -

The changes in ANC and sulfate concentrations and in pH projected over the next 50 years using both the ETD and MAGIC models are shown in Figures 10-32 through 10-37. The change in median ANC projected using ETD and MAGIC under current deposition over the next 50 years was a total decrease of -3.1 and -5.3 μeq L^{-1}, respectively (Table 10-16). The change in median sulfate concentrations using ETD and MAGIC was -3.9 and -8.9 μeq L^{-1}, respectively, for current deposition. The change in median pH using ETD and MAGIC under current deposition was -0.02 units for each model. With a 30 percent deposition reduction, the ANC increase projected using ETD and MAGIC was from 77 to 85 (+8) and 116 to 119 (+4) μeq L^{-1}, respectively, similar to the change projected for the larger target population in the previous section. The decrease projected in sulfate concentrations with a 30 percent deposition decrease using ETD and MAGIC was from 104 to 70 (-34) and 164 (-36) μeq L^{-1}, respectively, over 50 years. These values are roughly equivalent to the measurement or projection error determined for sulfate. The pH increase projected under decreased deposition using either model was less than +0.05 units over 50 years. The variance in ETD projections, although larger than MAGIC projections, also remained relatively constant through time (Figures 10-34 and Figure 10-37).

The changes in ANC or sulfate concentration were not functions of the initial ELS-I concentrations using either MAGIC or ETD for either deposition scenario (Table 10-15). Histograms of projected change in the population distribution of median ANC and sulfate from year 10 to year 50 indicate a relatively uniform change among ANC and sulfate intervals using both ETD and MAGIC (Figures 10-38 through 10-41). A slightly greater change in ANC was projected for non-acidic lakes with decreased deposition.

10.11.1.3 Restricted Target Population Projections Using All Three Models

There were an estimated 495 lakes in the target population simulated using all three Level III models. This target population represents Priority Classes A and B (Figure 10-1). Lakes in this target

Table 10-16. Descriptive Statistics of Projected ANC, Sulfate, and Percent Sulfur Retention for NE Lakes in Priority Classes A - E Using MAGIC and ETD for Both Current and Decreased Deposition

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
Current Deposition							
MAGIC vs. ETD, ANC							
Model Year 0							
ETD	107	110	-53	20	77	191	392
MAGIC	134	116	-21	45	116	179	410
Model Year 20							
ETD	106	109	-52	16	71	192	383
MAGIC	134	116	-21	44	114	179	408
Model Year 50							
ETD	105	107	-52	15	74	177	384
MAGIC	133	116	-22	42	111	178	407
MAGIC vs. ETD, SO_4^{-2}							
Model Year 0							
ETD	106	34	34	79	104	125	199
MAGIC	107	43	60	67	100	125	246
Model Year 20							
ETD	104	38	53	73	101	121	222
MAGIC	98	39	55	63	92	111	221
Model Year 50							
ETD	103	40	54	68	100	118	216
MAGIC	97	38	53	61	91	109	215
MAGIC vs. ETD, pH							
Model Year 0							
ETD	5.61	0.81	4.27	6.24	6.82	7.22	7.53
MAGIC	5.78	0.72	4.47	6.53	6.94	7.12	7.48
Model Year 20							
ETD	5.64	0.80	4.29	6.17	6.79	7.22	7.52
MAGIC	5.80	0.71	4.49	6.53	6.93	7.12	7.48
Model Year 50							
ETD	5.62	0.79	4.29	6.13	6.80	7.18	7.52
MAGIC	5.77	0.73	4.48	6.51	6.92	7.12	7.48
MAGIC vs. ETD, % S Retention							
Model Year 0							
ETD	-5	32	-97	-19	-7	18	69
MAGIC	-1	8	-16	-8	-1	4	19
Model Year 20							
ETD	2	9	-24	-4	2	7	30
MAGIC	6	7	-5	2	5	11	24

continued

Table 10-16. (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
30% Decrease in Deposition							
Model Year 50							
ETD	4	8	-17	-1	3	9	27
MAGIC	18	6	-1	4	6	13	24
MAGIC vs. ETD, ANC							
Model Year 0							
ETD	107	110	-53	20	77	191	392
MAGIC	134	116	-21	45	116	179	410
Model Year 20							
ETD	109	108	-47	18	77	204	389
MAGIC	139	116	-20	49	118	193	415
Model Year 50							
ETD	112	107	-40	22	85	198	399
MAGIC	143	116	-18	51	119	204	417
MAGIC vs. ETD, SO_4^{2-}							
Model Year 0							
ETD	106	34	34	79	104	125	199
MAGIC	107	43	60	67	100	125	246
Model Year 20							
ETD	94	34	44	63	90	108	186
MAGIC	89	36	49	55	83	103	202
Model Year 50							
ETD	74	29	39	51	70	86	162
MAGIC	71	29	38	44	64	81	157
MAGIC vs. ETD, pH							
Model Year 0							
ETD	5.61	0.81	4.27	6.24	6.82	7.22	7.53
MAGIC	5.78	0.72	4.47	6.53	6.94	7.12	7.48
Model Year 20							
ETD	5.72	0.76	4.33	6.20	6.82	7.24	7.52
MAGIC	5.91	0.67	4.52	6.57	6.95	7.16	7.48
Model Year 50							
ETD	5.82	0.71	4.40	6.30	6.86	7.23	7.53
MAGIC	6.08	0.61	4.58	6.59	6.95	7.18	7.49
MAGIC vs ETD, % S Retention							
Model Year 0							
ETD	-5	32	-97	-19	-7	18	69
MAGIC	-1	8	-16	-8	-1	4	19
Model Year 20							
ETD	-10	12	-50	-17	-9	-3	27
MAGIC	-6	9	-22	-13	-6	-0	16
Model Year 50							
ETD	1	11	-50	-4	2	7	24
MAGIC	4	9	-18	-1	4	10	24

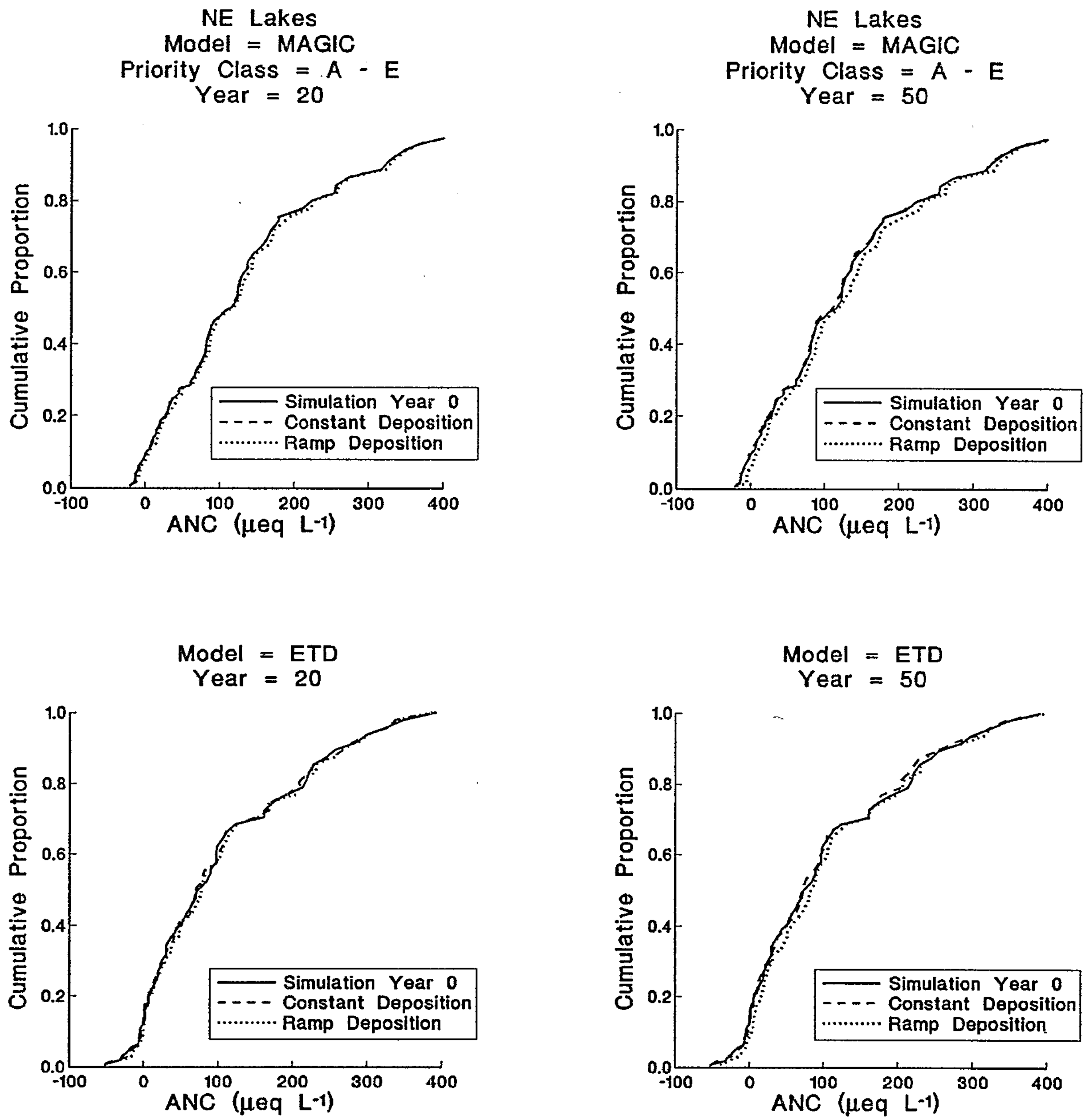


Figure 10-29. Comparisons of projected change in ANC under current and decreased deposition for NE Priority Classes A - E, using ETD and MAGIC.

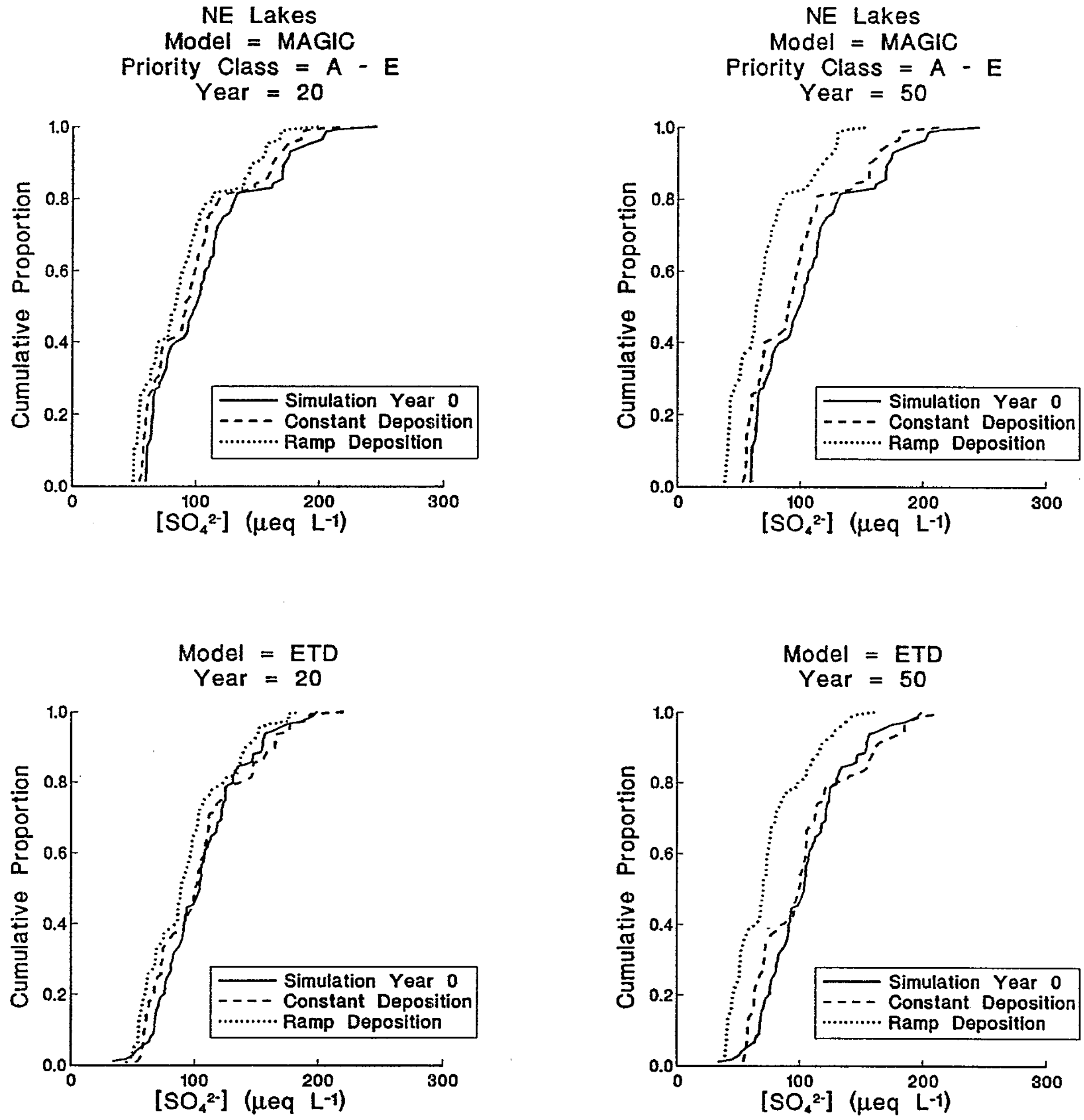


Figure 10-30. Comparisons of projected change in sulfate concentrations under current and decreased deposition for NE Priority Classes A - E, using ETD and MAGIC.

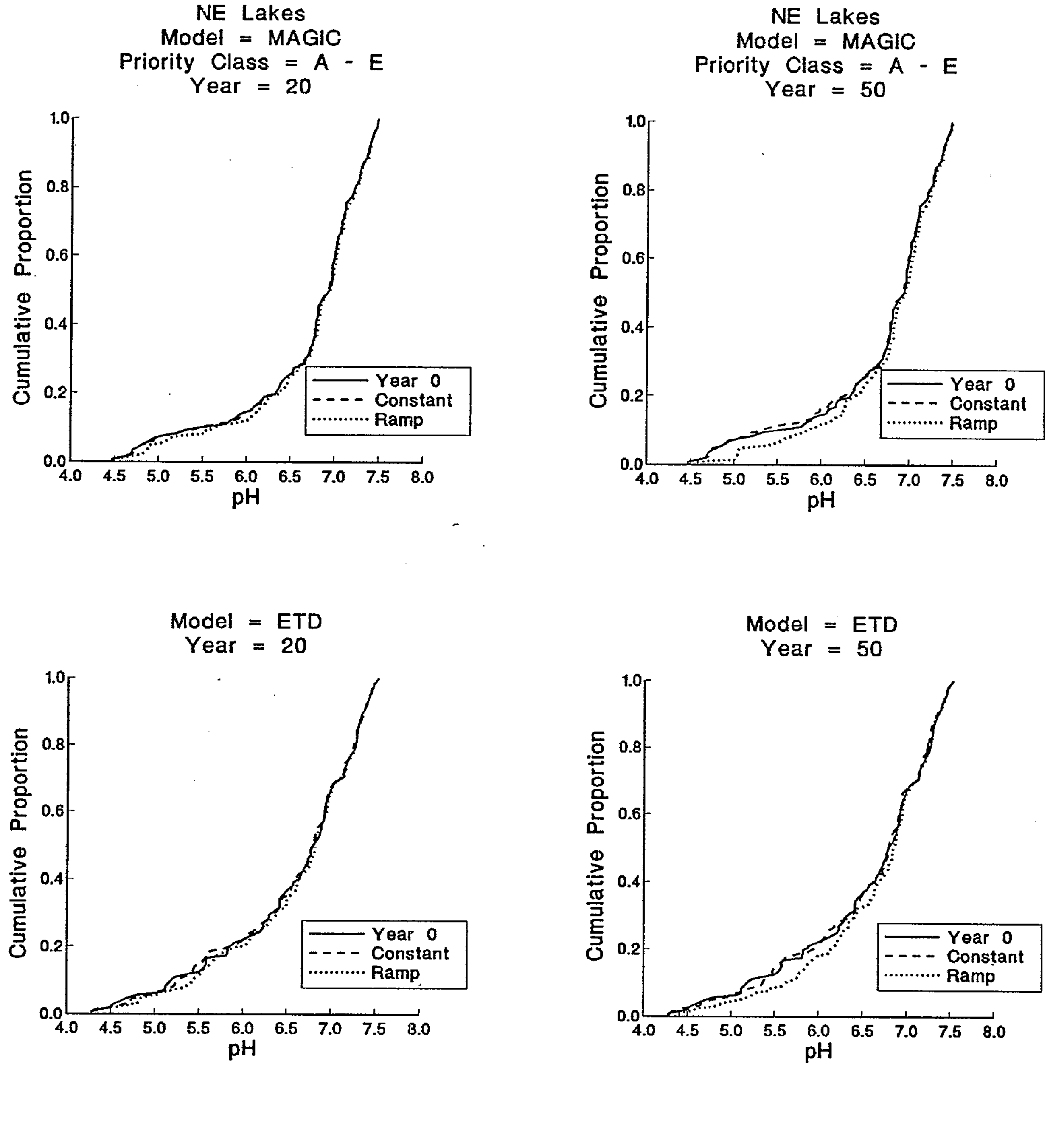


Figure 10-31. Comparisons of projected change in pH under current and decreased deposition for NE Priority Classes A - E, using ETD and MAGIC.

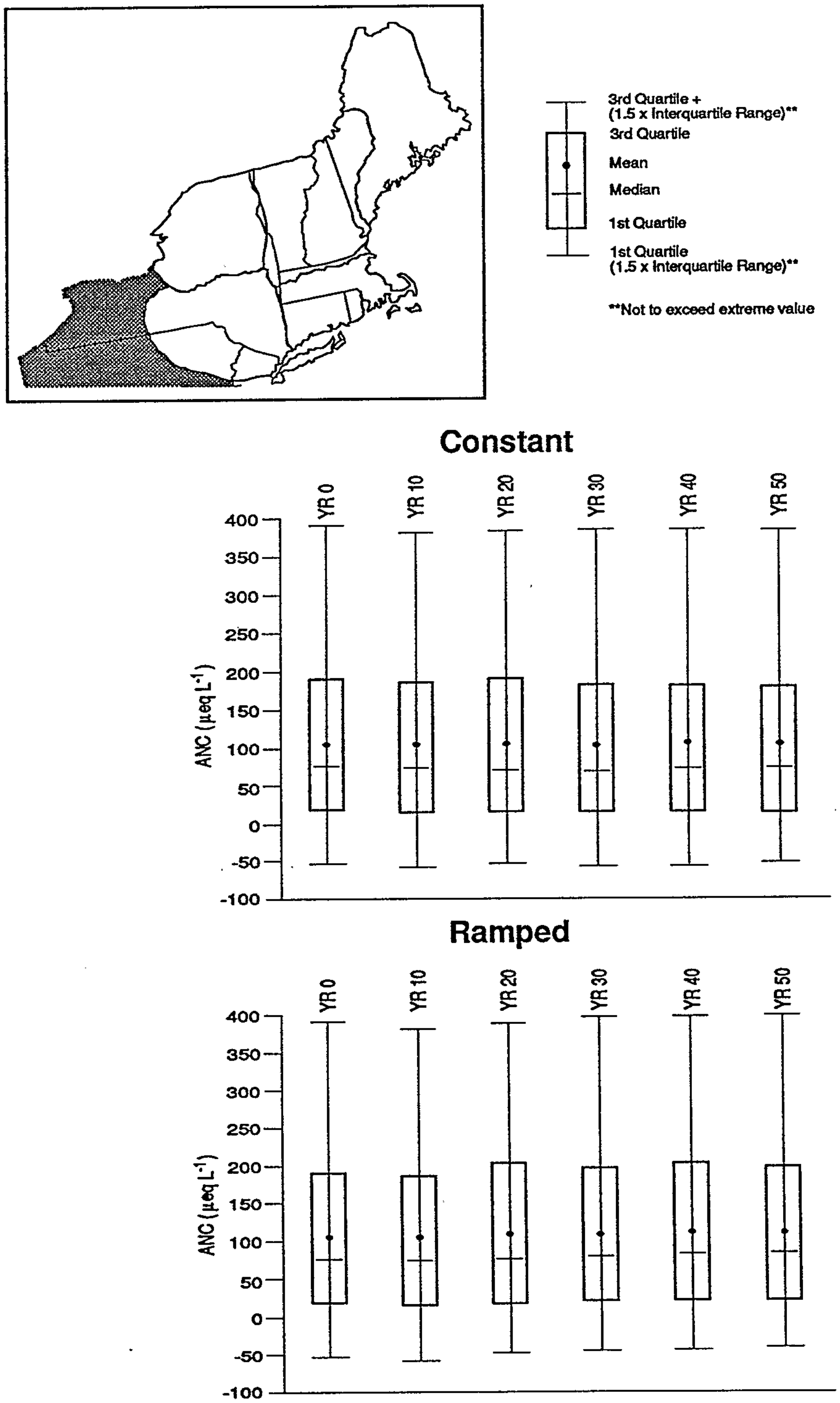


Figure 10-32. Box and whisker plots of ANC distributions projected using ETD in 10-year intervals for NE lakes, Priority Classes A - E.

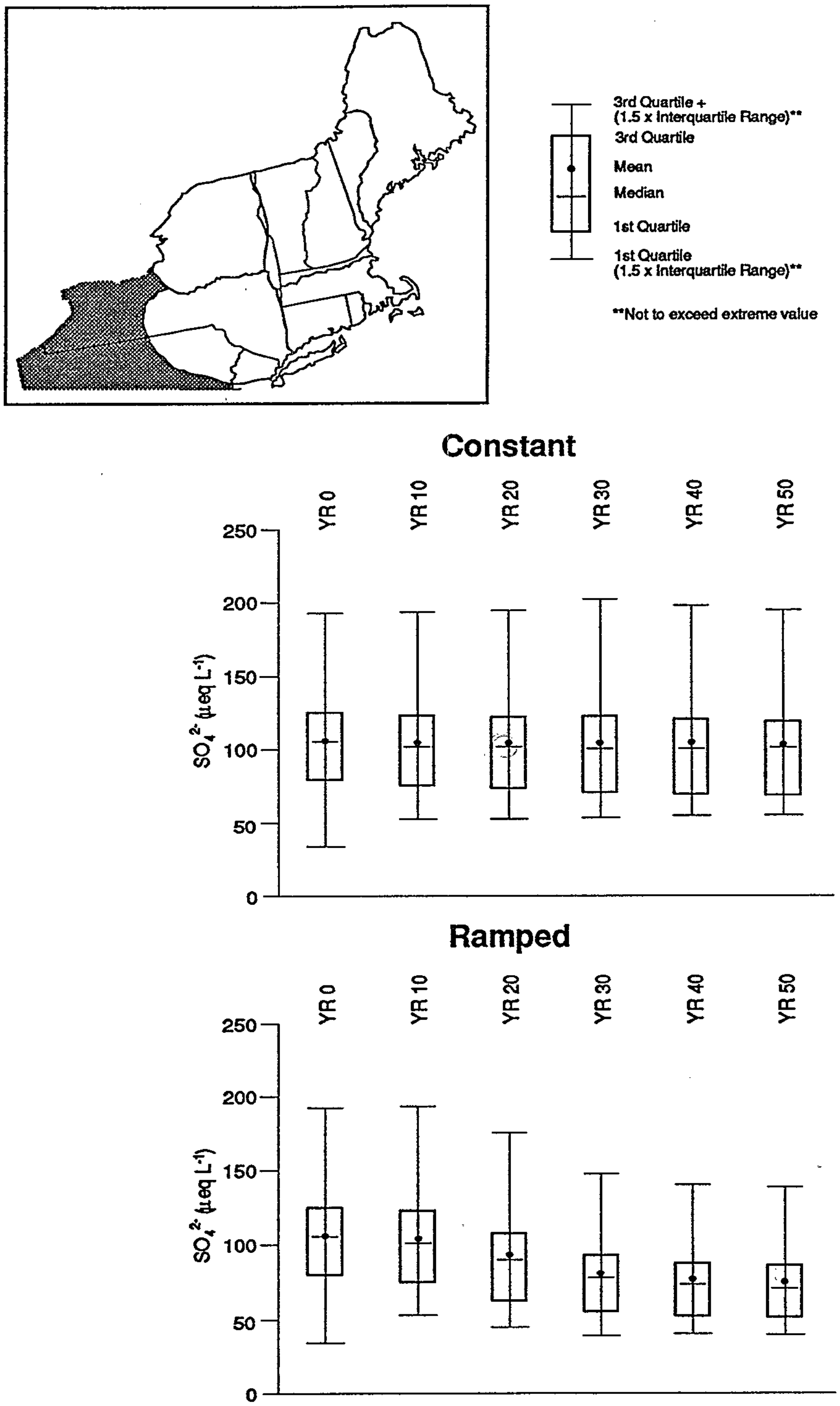


Figure 10-33. **Box and whisker plots of sulfate distributions projected using ETD in 10-year intervals for NE lakes, Priority Classes A - E.**

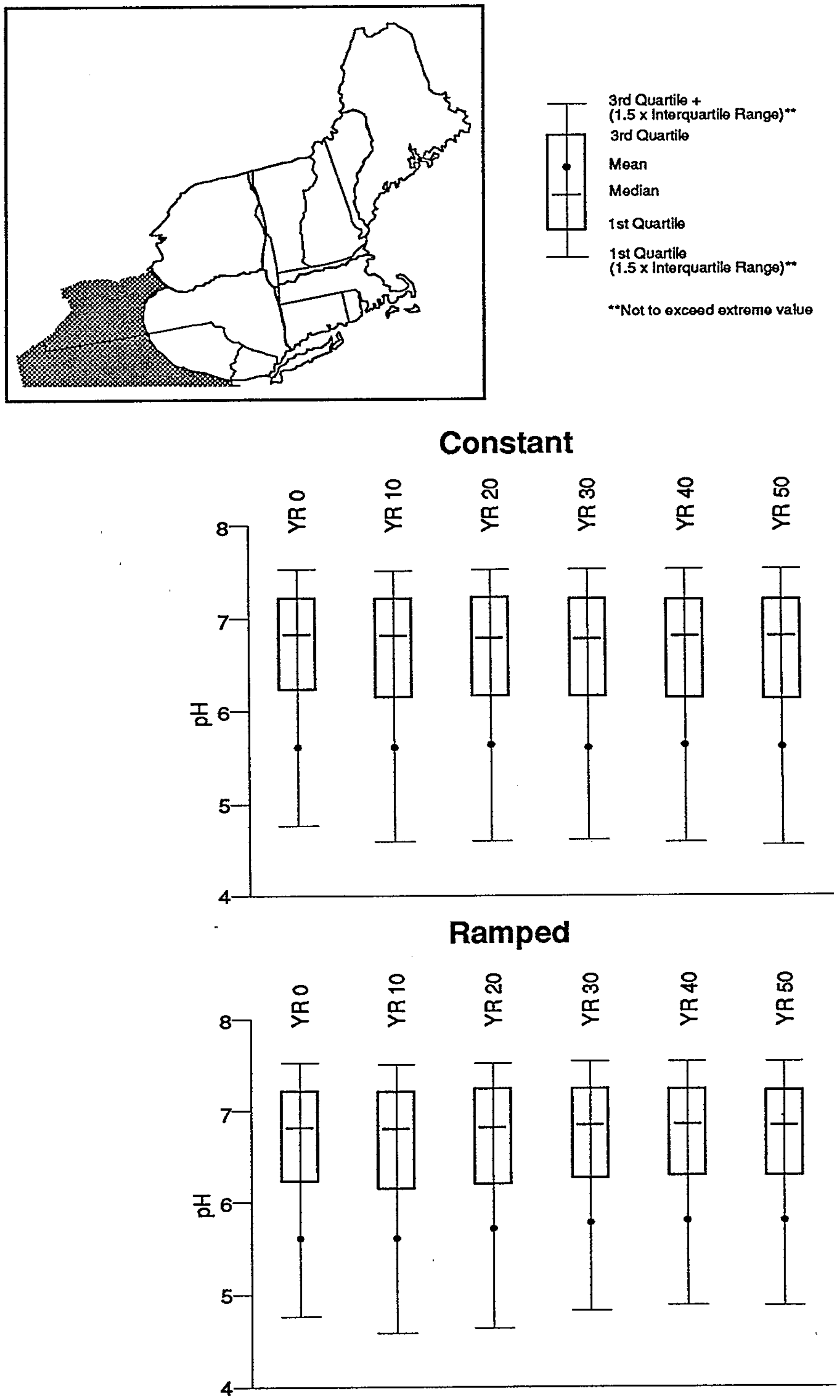


Figure 10-34. Box and whisker plots of pH projected using ETD in 10-year intervals for NE lakes, Priority Classes A - E.

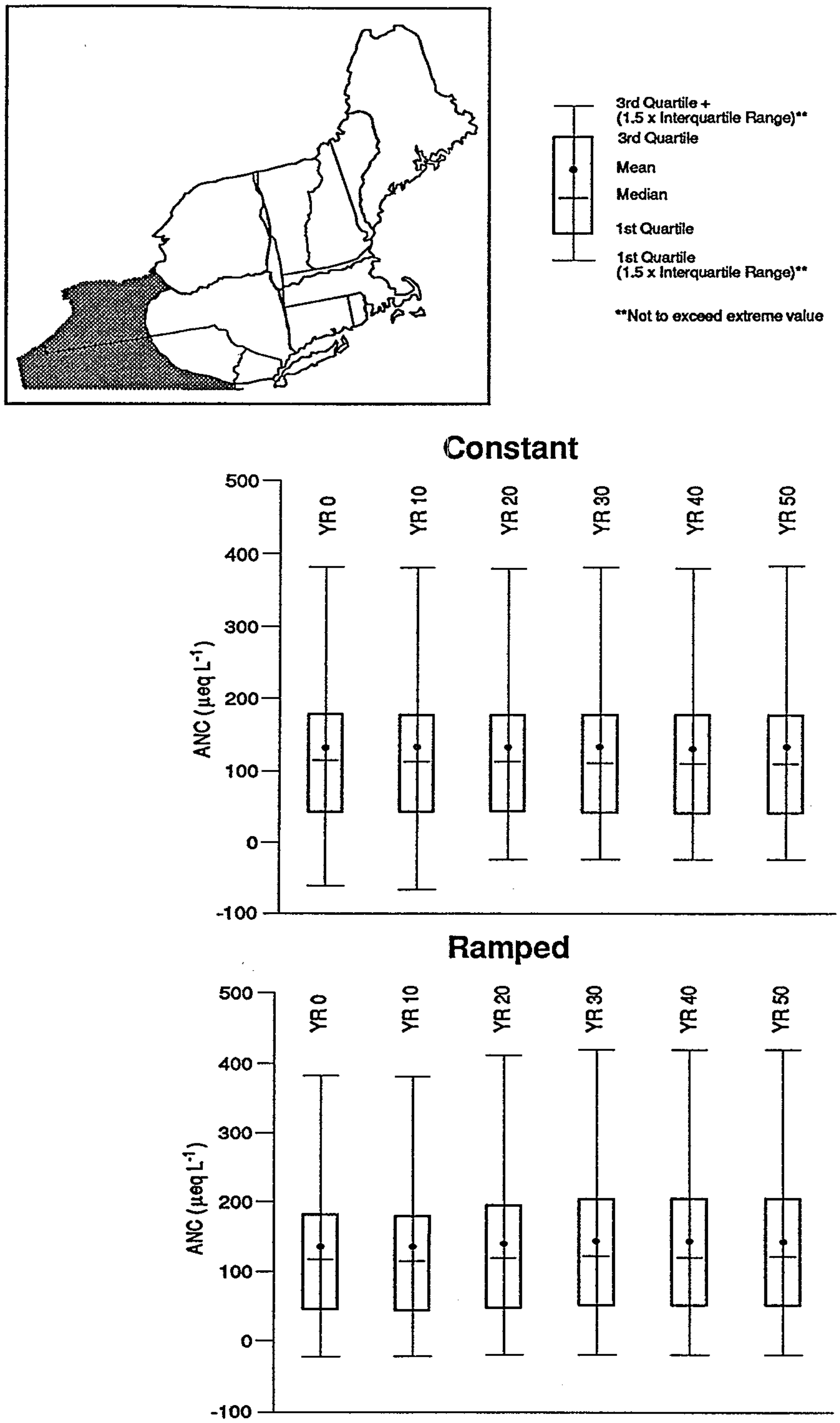


Figure 10-35. Box and whisker plots of ANC distributions in 10-year intervals using MAGIC for NE lakes, Priority Classes A - E.

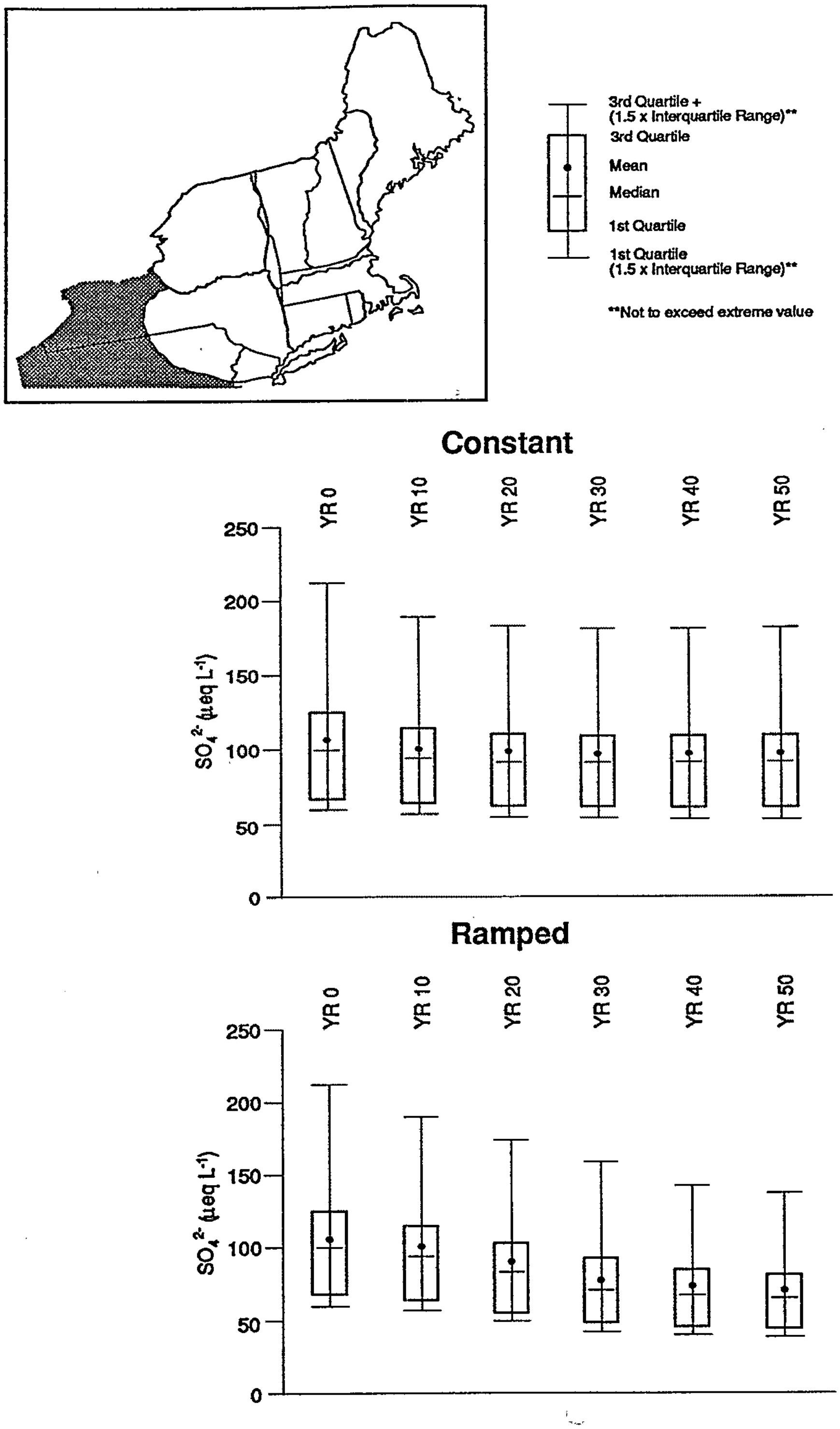


Figure 10-36. Box and whisker plots of sulfate distributions in 10-year intervals using MAGIC for NE lakes, Priority Classes A - E.

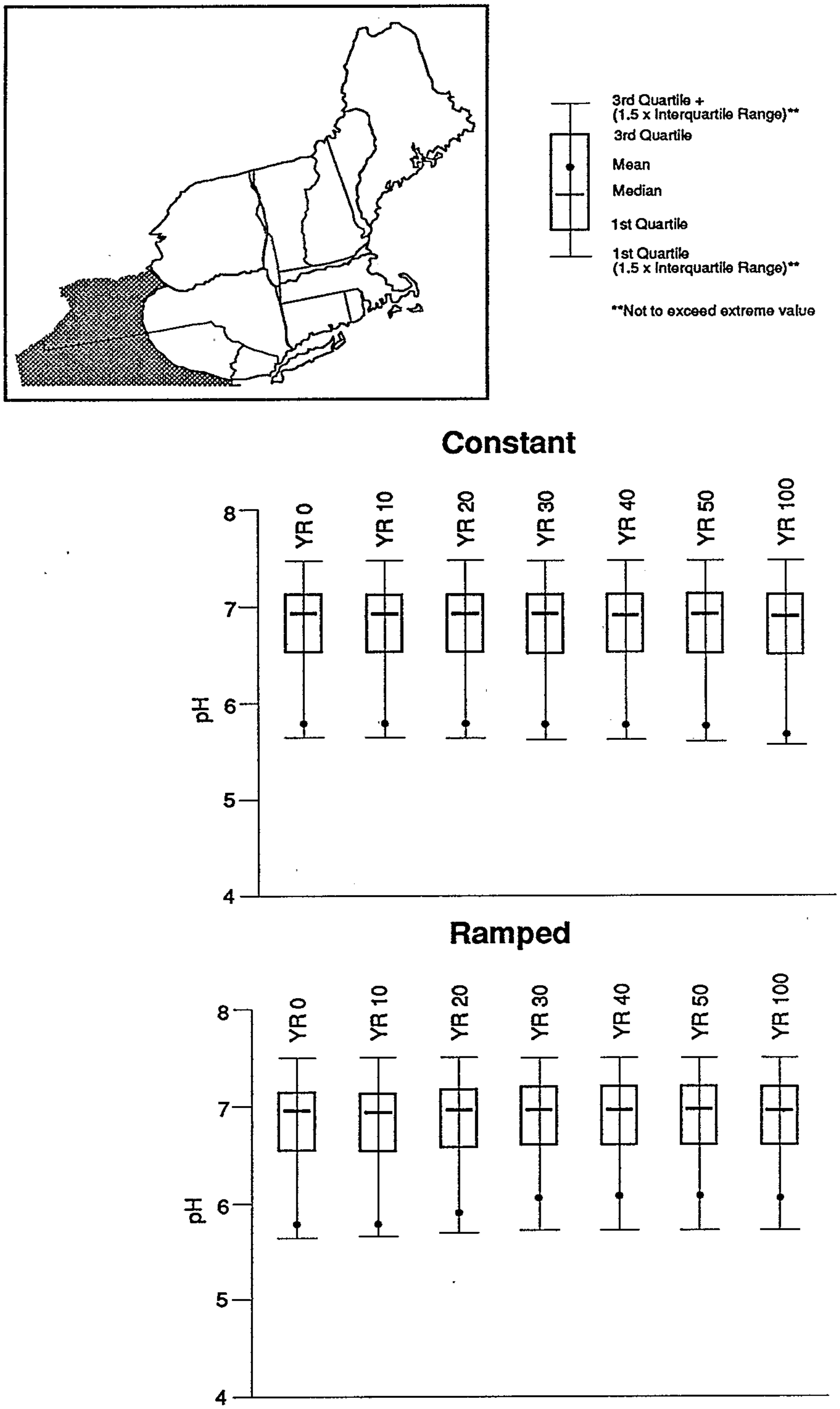
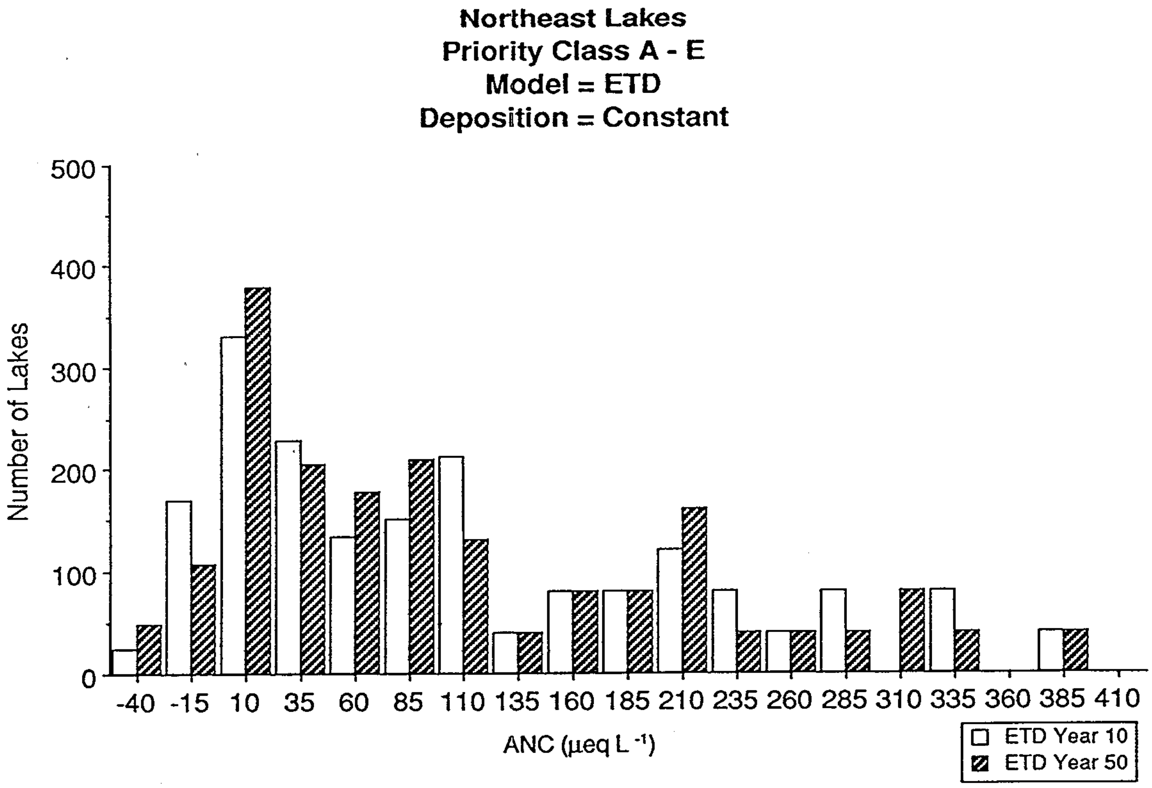


Figure 10-37. Box and whisker plots of pH in 10-year intervals using MAGIC for NE lakes, Priority Classes A - E.



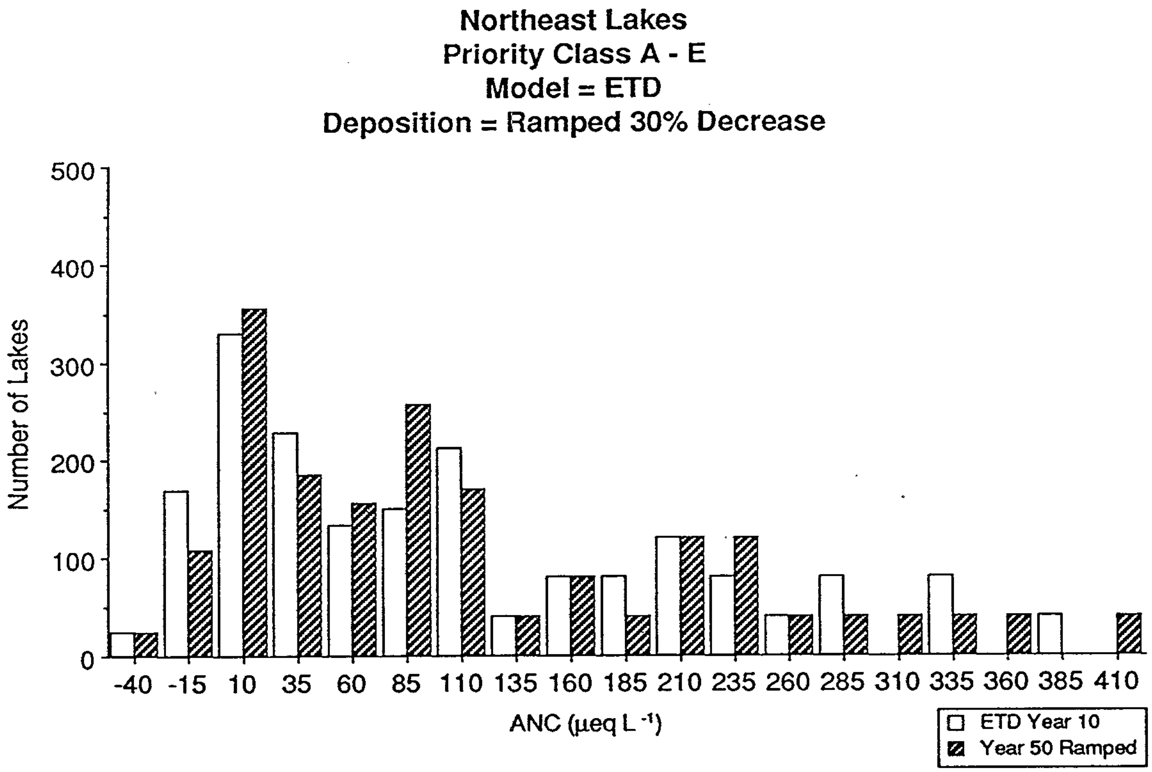
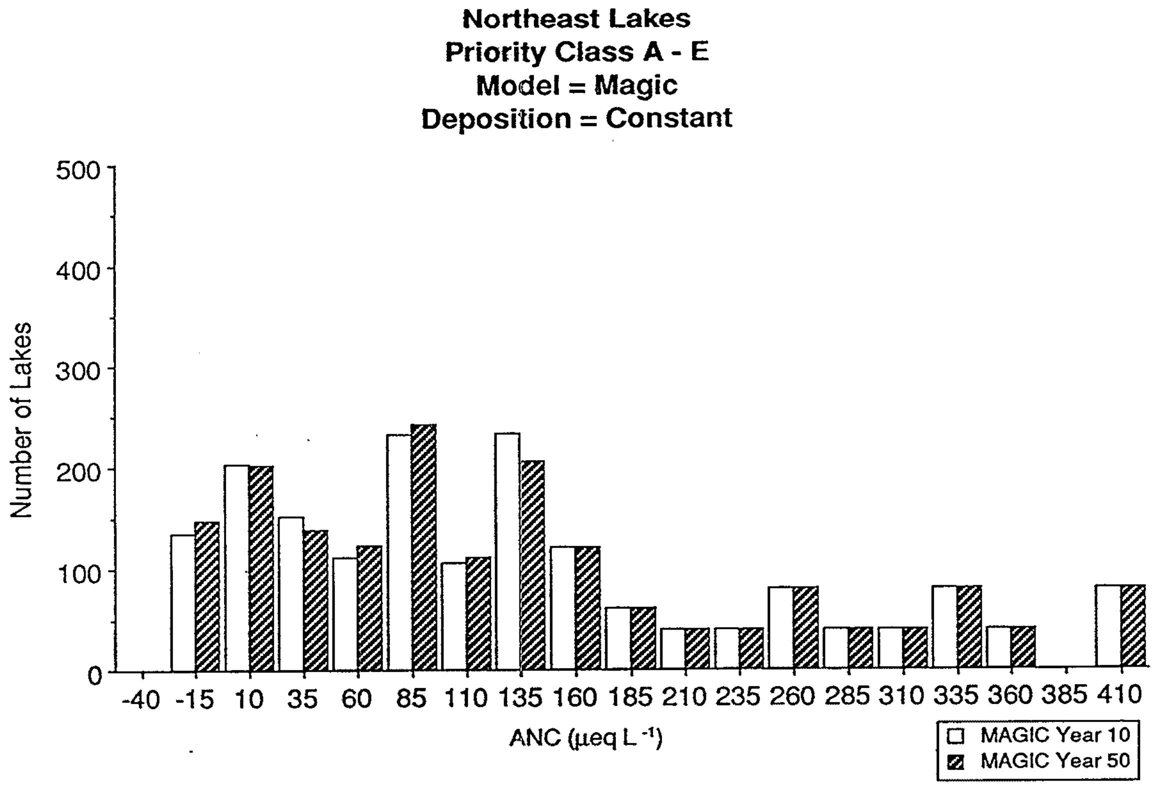


Figure 10-38. ETD ANC distributions at year 10 and year 50 for NE lakes, Priority Classes A - E, under current and decreased deposition.



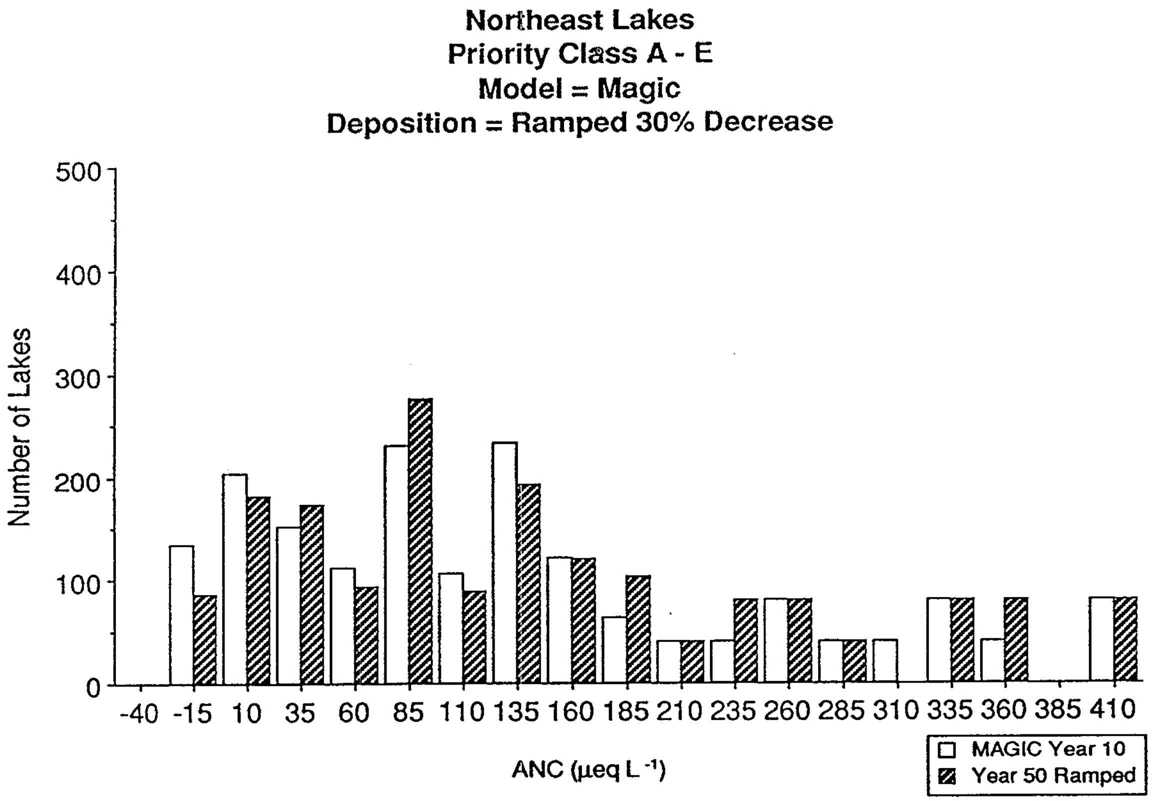


Figure 10-39. MAGIC ANC distribution at year 10 and year 50 for NE lakes, Priority Classes A - E, under current and decreased deposition.

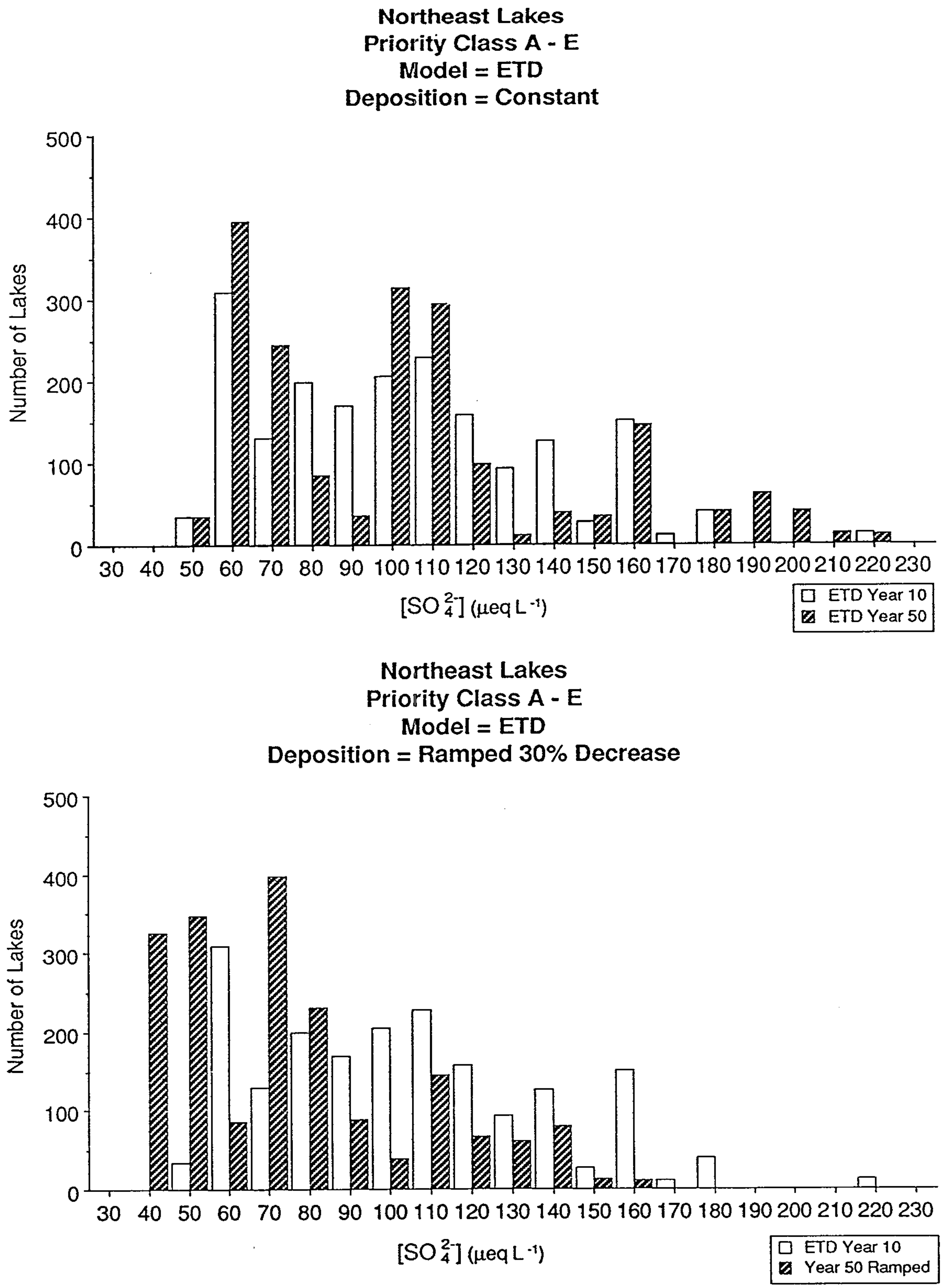
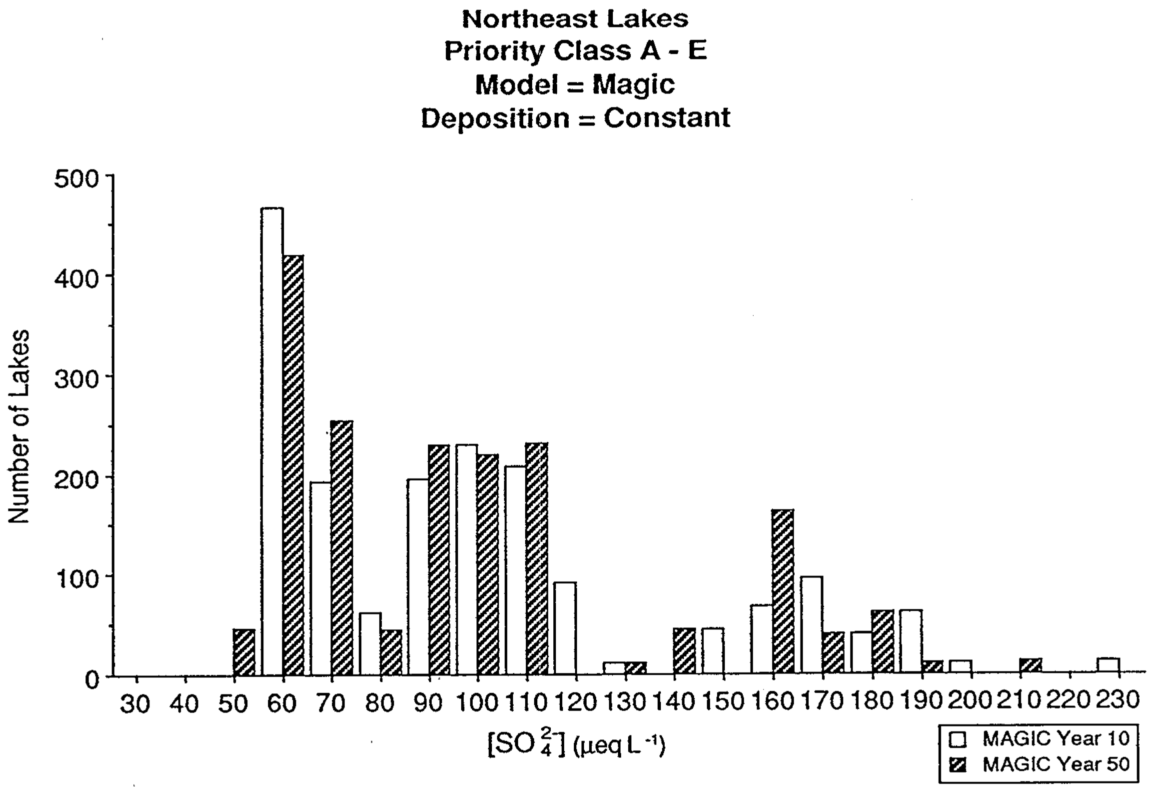


Figure 10-40. ETD sulfate distributions at year 10 and year 50 for NE lakes, Priority Classes A - E, under current and decreased deposition.



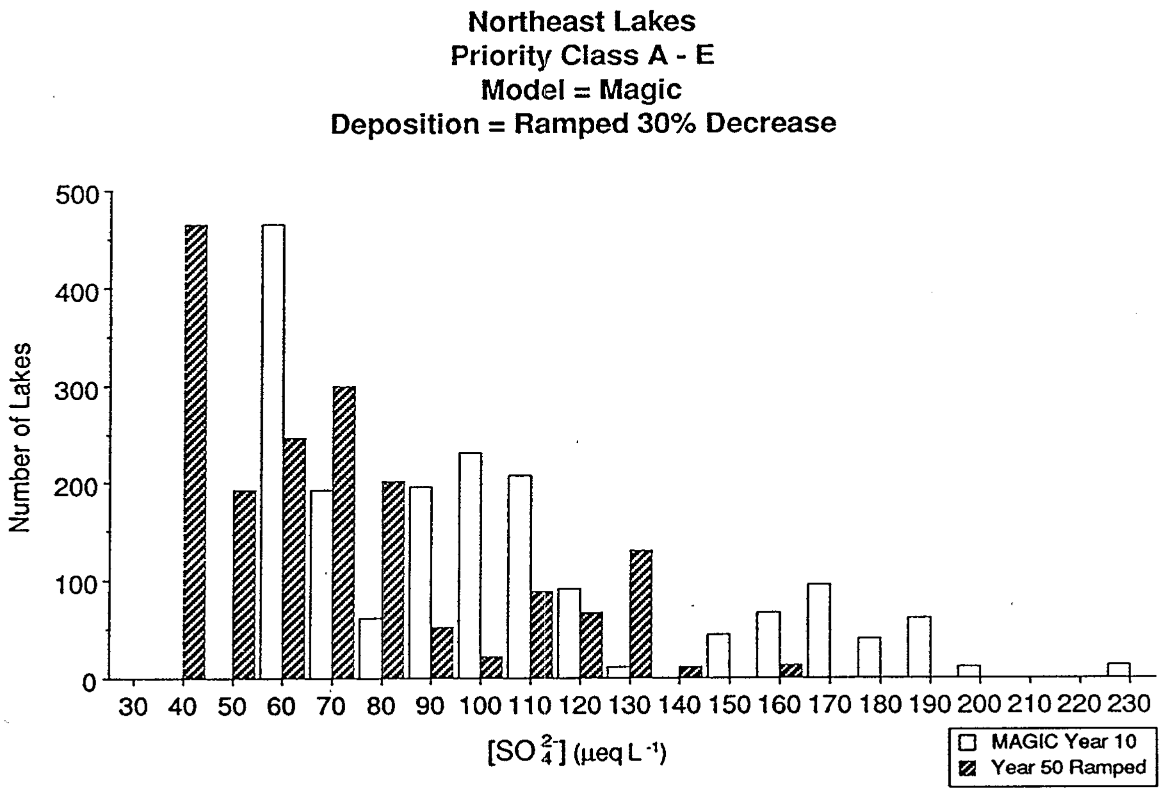


Figure 10-41. MAGIC sulfate distributions at year 10 and year 50 for NE lakes, Priority Classes A - E, under current and decreased deposition.

population had initial ELS-I ANC < 100 μeq L^{-1}, ranging from -43 to 86 μeq L^{-1}. The watersheds were undisturbed, based on chloride concentrations (See Section 10.5.7), and in general had positive sulfur retention.

10.11.1.3.1 Deposition scenarios -

All three models simulated comparable changes in ANC, sulfate, and pH over the 50-year period assuming current deposition or a 30 percent deposition decrease (Figures 10-42 through 10-44). Confidence intervals computed for each of the projections are included in Appendix A.3. Projections for all three models were comparable at the lower ANC concentrations (i.e., ANC < 25 μeq L^{-1}) but deviated at higher ANC concentrations. Projections from MAGIC deviated the most at the higher ANC concentrations but were still within the uncertainty bounds about the projections (Appendix A.3). Projected ANC values were similar, however, among all three models for lakes with ANC in the lower quartile of the population (Table 10-17). Lower quartile values of ANC projected using ETD, ILWAS, and MAGIC with current deposition after 50 years were 2.6, 5.9, and 11.9 μeq L^{-1}, respectively. Lower quartile values for sulfate projected using the ETD, ILWAS, and MAGIC models after 50 years of current deposition were 70.4, 80.6, and 69.4 μeq L^{-1}, respectively. Assuming a 30 percent deposition decrease, lower quartile values of ANC projected using ETD, ILWAS, and MAGIC after 50 years were 10.5, 19.6, and 25.1 μeq L^{-1}, respectively. Sulfate concentrations projected under similar conditions using ETD, ILWAS, and MAGIC were 51.7, 66.5, and 53.2 μeq L^{-1}, respectively. These values were all within the uncertainty bounds for the projections (Appendix A.3).

The projected pH values were similar at the higher pHs but deviated at low pH with the greatest difference between ILWAS and the other two models. The projected median pH after 50 years with ETD, ILWAS, and MAGIC under current and decreased deposition was 6.4, 6.1, 6.4 and 6.4, 6.5, 6.5, respectively. The projected lower quartile pH values after 50 years with ETD, ILWAS, and MAGIC under current and decreased deposition were 5.6, 4.9, 5.9 and 6.0, 5.6, 6.2, respectively. At the lower pHs, the projected ILWAS pH was from 0.5 to 1.0 pH unit less than projected by the other two models.

Changes in surface water chemistry under different deposition scenarios were compared within models (Figures 10-45 through 10-47). Differences in median ANC concentrations between current deposition and a 30 percent deposition decrease projected using ETD, ILWAS, and MAGIC after 50 years were 30.9 versus 31.5 (+0.6), 30.3 versus 48.9 (+18.6), and 64.9 versus 70.6 (+5.7) μeq L^{-1}, respectively. Differences in median sulfate concentrations between current deposition and a 30 percent deposition decrease projected using ETD, ILWAS, and MAGIC after 50 years were 106.5 versus 76.2 (-30.3), 103.6 versus 82.5 (-21.1), and 95.2 versus 67.6 (-27.6) μeq L^{-1}, respectively. Differences in median pH between current and decreased deposition projected using ETD, ILWAS, and MAGIC after 50 years were 6.43 versus 6.44 (+0.01), 6.09 versus 6.53 (+0.04), and 6.40 versus 6.54 (+0.14), respectively.

All three models indicated northeastern watersheds were near sulfate steady state or near zero percent net sulfur retention after 50 years for scenarios of either current or decreased deposition (Table 10-17).

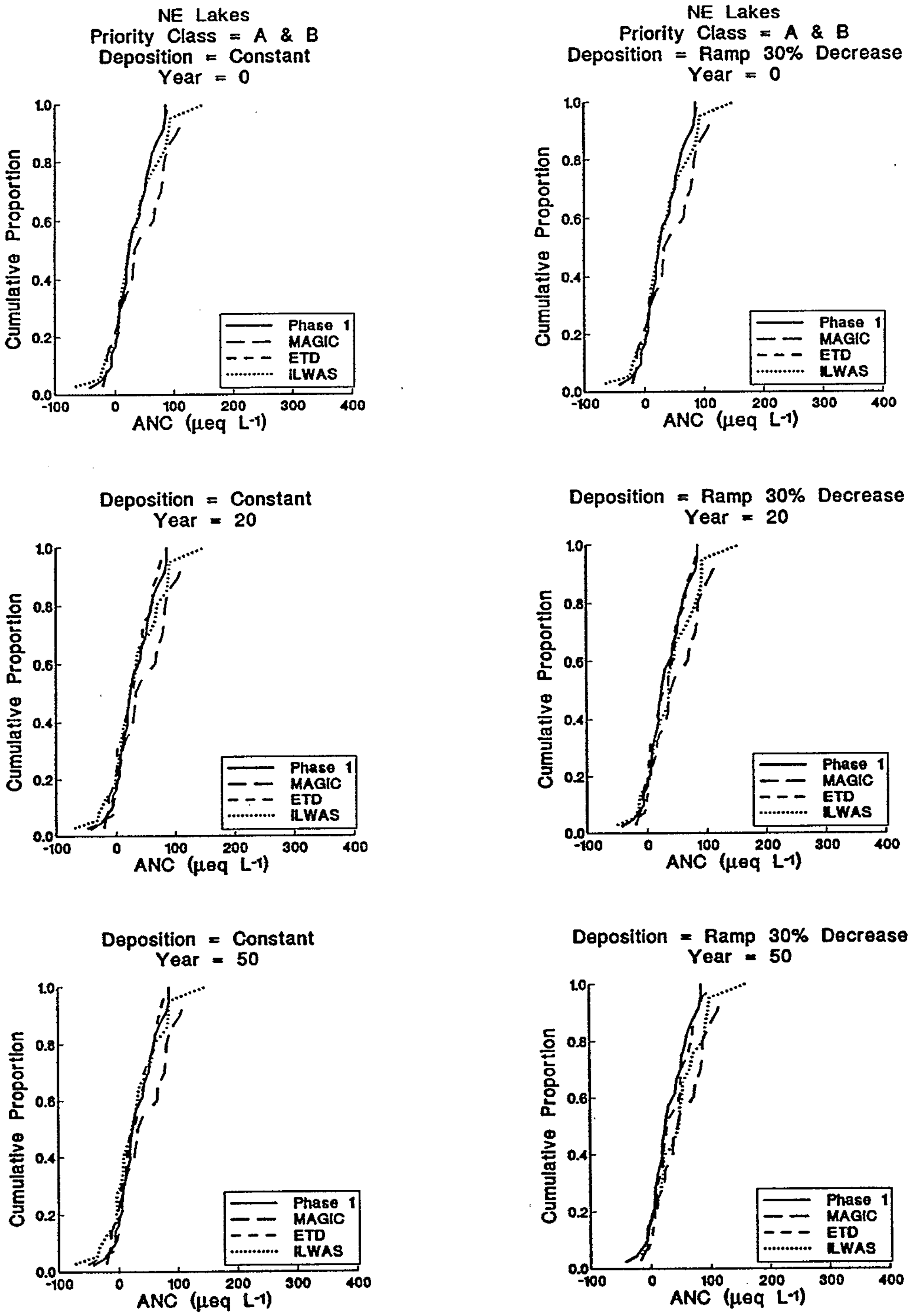


Figure 10-42. Comparison of ANC projections using ETD, ILWAS, and MAGIC for NE lakes, Priority Classes A and B, under current and decreased deposition.

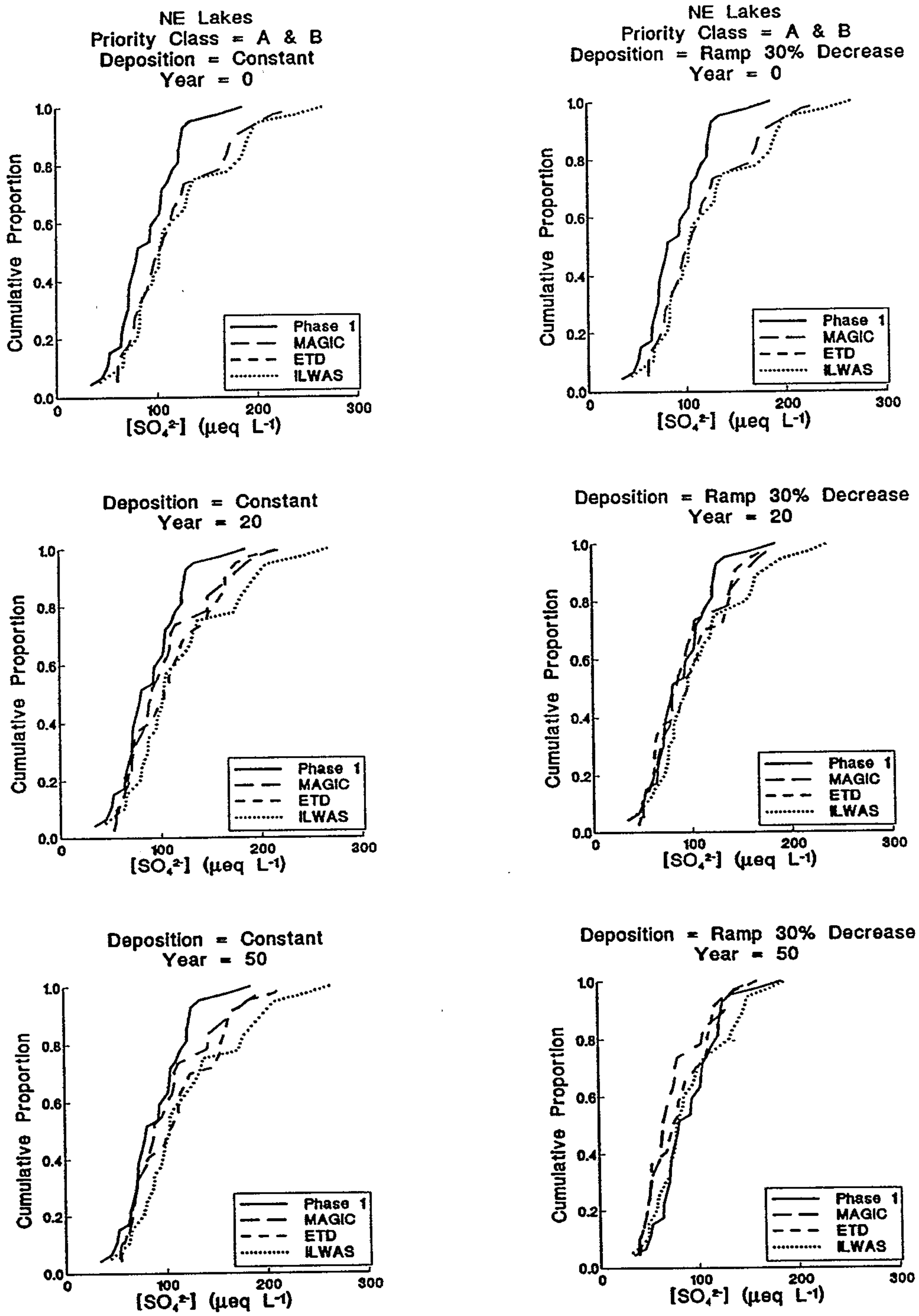


Figure 10-43. Comparison of sulfate projections using ETD, ILWAS, and MAGIC for NE lakes, Priority Classes A and B, under current and decreased deposition.

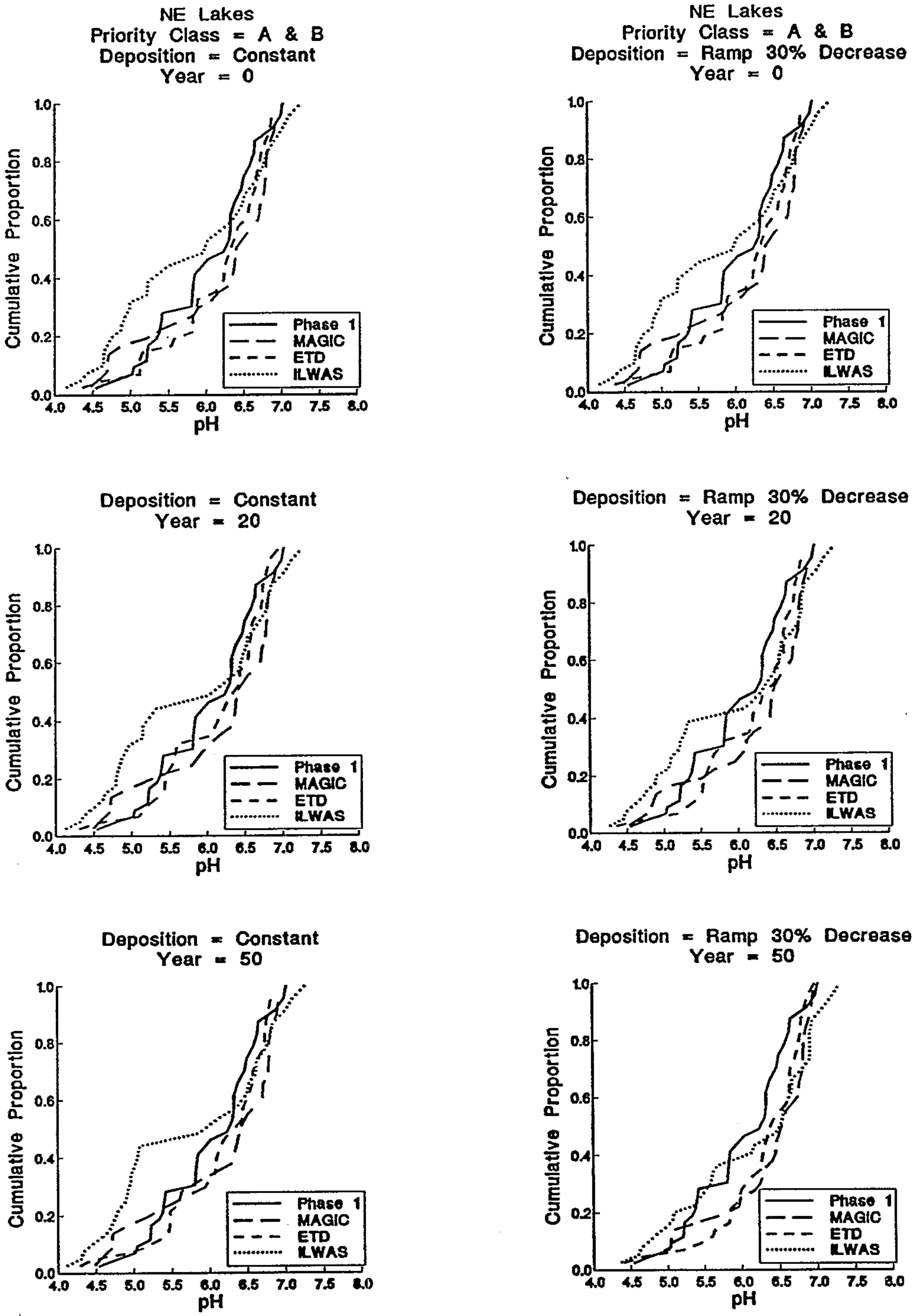


Figure 10-44. Comparison of pH projections using ETD, ILWAS, and MAGIC for NE lakes, Priority Classes A and B, under current and decreased deposition.

Table 10-17. Descriptive Statistics for Projected ANC, Sulfate, Percent Sulfur Retention, and Calcium Plus Magnesium for NE Lakes in Priority Classes A and B Using ETD, ILWAS, and MAGIC for Both Current and Decreased Deposition

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			Current Deposition				
All Models, ANC							
Model Year 0							
ETD	32	33	-43	6	26	59	90
ILWAS	44	52	-67	8	36	86	159
MAGIC	57	52	-21	15	66	84	175
Model Year 20							
ETD	30	33	-49	1	30	61	105
ILWAS	43	53	-70	8	33	86	161
MAGIC	57	51	-21	14	67	84	173
Model Year 50							
ETD	30	34	-52	3	31	63	106
ILWAS	39	53	-74	6	30	82	161
MAGIC	56	51	-22	12	65	82	171
All Models, SO_4^{2-}							
Model Year 0							
ETD	90	32	34	67	81	113	185
ILWAS	118	52	42	83	102	136	266
MAGIC	114	46	50	78	106	126	246
Model Year 20							
ETD	110	44	53	70	103	147	222
ILWAS	118	53	44	81	103	137	267
MAGIC	105	42	47	71	96	126	221
Model Year 50							
ETD	110	45	54	70	107	154	216
ILWAS	118	53	44	81	104	138	264
MAGIC	103	41	46	69	95	127	215
All Models, pH							
Model Year 0							
ETD	5.55	0.64	4.36	5.83	6.36	6.71	6.89
ILWAS	5.07	0.95	4.15	4.93	6.02	6.75	7.26
MAGIC	5.39	0.79	4.47	5.83	6.40	6.79	6.97
Model Year 20							
ETD	5.50	0.66	4.31	5.55	6.42	6.72	6.96
ILWAS	5.04	0.98	4.13	4.86	6.24	6.78	7.27
MAGIC	5.41	0.78	4.49	5.95	6.40	6.79	6.97
Model Year 50							
ETD	5.48	0.66	4.29	5.63	6.43	6.73	6.96
ILWAS	5.01	0.99	4.11	4.91	6.09	6.74	7.27
MAGIC	5.40	0.79	4.48	5.94	6.40	6.79	6.97

continued

Table 10-17. (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
<u>All Models, % S Retention</u>							
Model Year 0							
ETD	20	21	-17	6	27	33	69
ILWAS	1	20	-33	-15	0	12	63
MAGIC	1	9	-14	-9	3	7	19
Model Year 20							
ETD	6	11	-14	2	4	12	30
ILWAS	1	19	-30	-14	3	12	64
MAGIC	9	7	-5	3	10	14	21
Model Year 50							
ETD	7	9	-7	0	7	12	27
ILWAS	1	19	-30	-14	3	11	63
MAGIC	11	6	-1	6	11	17	21
<u>ILWAS vs. MAGIC, Ca + Mg</u>							
Model Year 0							
ILWAS	122	40	45	102	119	141	204
MAGIC	131	51	41	99	122	145	281
Model Year 20							
ILWAS	122	42	43	103	116	143	220
MAGIC	124	52	40	90	114	139	280
Model Year 50							
ILWAS	119	42	41	102	111	143	211
MAGIC	121	53	38	86	111	135	280
Delta Ca+Mg							
ILWAS	-3	5	-11	-7	-3	0	8
MAGIC	-6	3	-12	-9	-5	-4	-2
30% Decrease in Deposition							
<u>All Models, ANC</u>							
Model Year 0							
ETD	32	33	-43	6	26	59	90
ILWAS	44	52	-67	8	36	86	159
MAGIC	57	52	-21	15	66	84	175
Model Year 20							
ETD	33	33	-44	4	36	63	108
ILWAS	50	52	-51	12	36	91	161
MAGIC	61	51	-20	17	69	87	178
Model Year 50							
ETD	38	34	-40	11	32	68	111
ILWAS	56	50	-40	20	49	93	163
MAGIC	64	50	-18	25	71	88	179

continued

Table 10-17. (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
<u>All Models, SO_4^{2-}</u>							
Model Year 0							
ETD	90	32	34	67	81	113	185
ILWAS	118	52	42	83	102	136	266
MAGIC	114	46	50	78	106	126	246
Model Year 20							
ETD	99	39	44	62	95	135	186
ILWAS	107	47	37	76	96	124	238
MAGIC	97	38	45	66	87	121	202
Model Year 50							
ETD	80	32	39	52	76	110	162
ILWAS	91	38	31	67	83	113	190
MAGIC	77	31	38	53	68	104	157
<u>All models, pH</u>							
Model Year 0							
ETD	5.55	0.64	4.36	5.83	6.36	6.71	6.89
ILWAS	5.07	0.95	4.15	4.93	6.02	6.75	7.26
MAGIC	5.39	0.79	4.47	5.83	6.40	6.79	6.97
Model Year 20							
ETD	5.59	0.63	4.35	5.68	6.49	6.73	6.97
ILWAS	5.18	0.93	4.25	5.11	6.41	6.84	7.30
MAGIC	5.52	0.73	4.52	6.11	6.48	6.81	6.98
Model Year 50							
ETD	5.67	0.58	4.40	6.00	6.44	6.76	6.98
ILWAS	5.37	0.86	4.36	5.57	6.53	6.91	7.32
MAGIC	5.67	0.66	4.58	6.17	6.54	6.82	6.99
<u>All Models, % S Retention</u>							
Model Year 0							
ETD	20	21	-17	6	27	33	69
ILWAS	1	20	-33	-15	0	12	63
MAGIC	1	9	-14	-9	3	7	19
Model Year 20							
ETD	-5	14	-37	-14	-6	5	27
ILWAS	-12	22	-51	-26	-10	1	60
MAGIC	-5	9	-24	-12	-4	1	14
Model Year 50							
ETD	3	13	-38	-3	4	9	24
ILWAS	-9	21	-40	-25	-14	2	60
MAGIC	5	9	-11	-1	6	11	20

continued

Table 10-17. (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
ILWAS vs. MAGIC, Ca + Mg							
Model Year 0							
ILWAS	122	40	45	102	119	141	204
MAGIC	131	51	41	99	122	145	281
Model Year 20							
ILWAS	120	42	41	100	115	140	213
MAGIC	121	52	39	85	112	138	279
Model Year 50							
ILWAS	112	41	35	89	106	127	201
MAGIC	108	53	35	74	98	125	274
Delta Ca+Mg							
ILWAS	-11	7	-32	-13	-11	-4	0
MAGIC	-18	9	-54	-23	-15	-13	-5

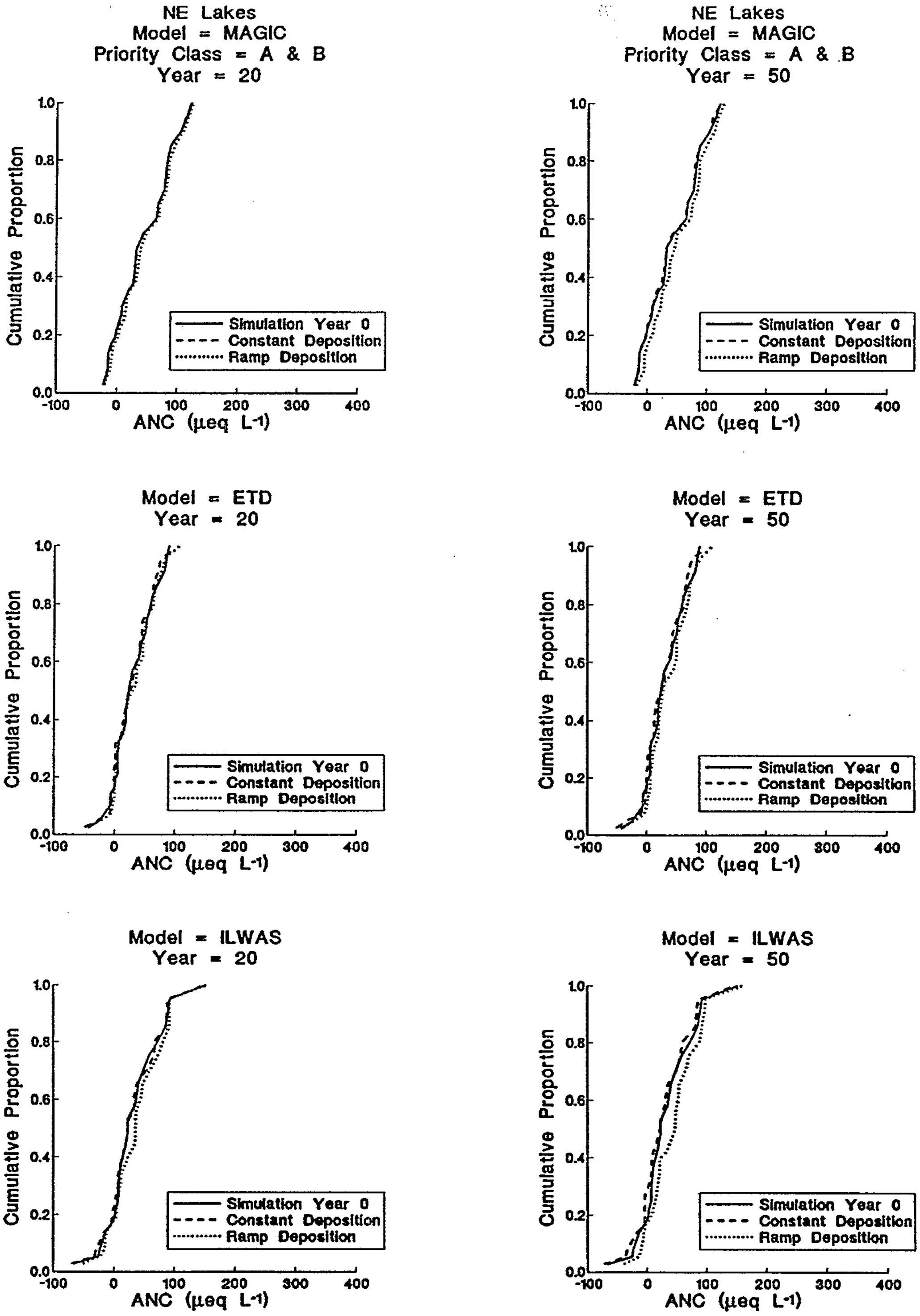


Figure 10-45. Comparison of ANC projections under current and decreased deposition for NE lakes, Priority Classes A and B, at year 20 and year 50 using ETD, ILWAS, and MAGIC.

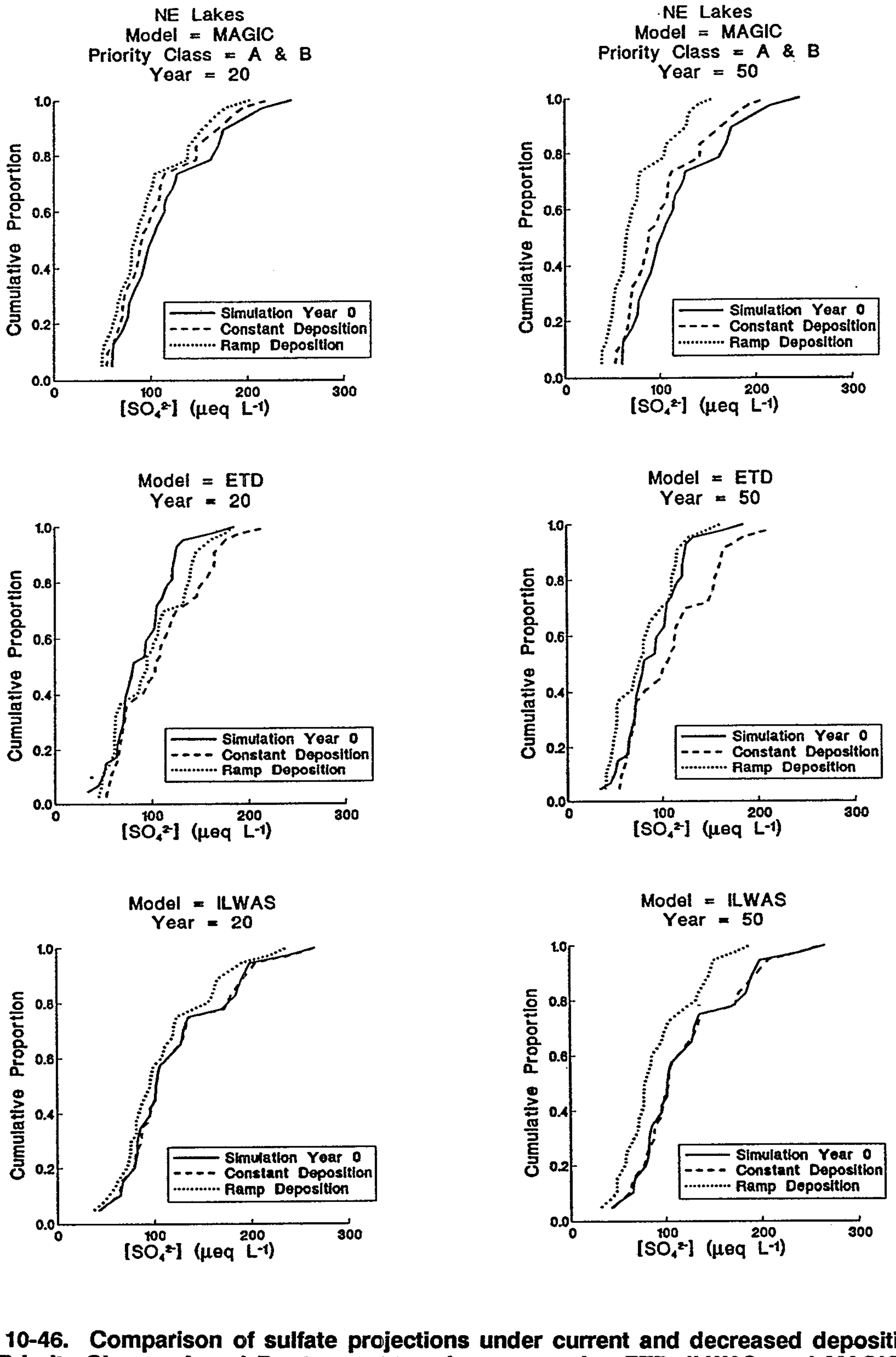


Figure 10-46. Comparison of sulfate projections under current and decreased deposition for NE lakes, Priority Classes A and B, at year 20 and year 50 using ETD, ILWAS, and MAGIC.

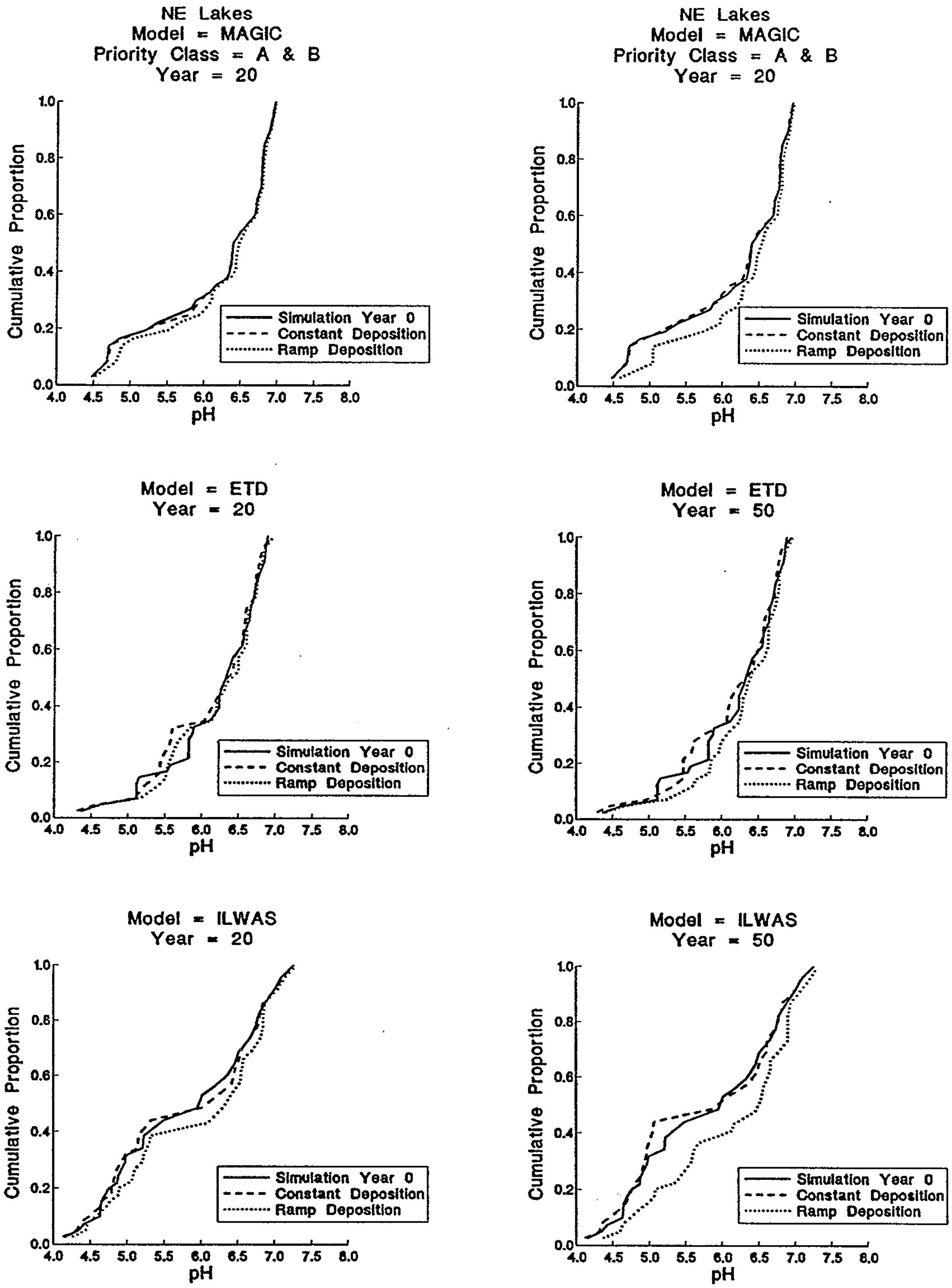


Figure 10-47. Comparison of pH projections under current and decreased deposition for NE lakes, Priority Classes A and B, at year 20 and year 50 using ETD, ILWAS, and MAGIC.

Projections of the number of lakes currently not acidic that might become acidic in the next 50 years under current deposition and a 30 percent decrease in deposition using ETD, ILWAS, and MAGIC were 25 (5 percent), 74 (17 percent), 75 (17 percent) and 25 (5 percent), 25 (5 percent), and 50 (11 percent), respectively. Projections of the number of currently acidic lakes that might chemically improve under current deposition and a 30 percent deposition decrease using ETD, ILWAS, and MAGIC were 27(36 percent), 25 (32 percent), 0 (0 percent), and 52 (68 percent), 25 (32 percent), 13 (16 percent), respectively.

10.11.1.3.2 Rate of change of ANC, sulfate, and pH over 50 years -

The changes in ANC, sulfate, and pH projected over the next 50 years using the three models are shown in box and whisker plots (Figures 10-48 through 10-56). The relative change in the median ANC projected using all three models and assuming current deposition levels was less than 0.1 $\mu eq\ L^{-1}\ yr^{-1}$. The rate of change of median ANC for a 30 percent deposition decrease was about 0.3 $\mu eq\ L^{-1}\ yr^{-1}$ for ILWAS and MAGIC and remained less than 0.1 $\mu eq\ L^{-1}\ yr^{-1}$ for ETD. These rates, while three times greater for ILWAS and MAGIC, are still small and indicate little change in ANC over the 50-year period under either deposition scenario.

The rates of change projected for median sulfate concentrations under current deposition ranged from -0.2 $\mu eq\ L^{-1}\ yr^{-1}$ for MAGIC to less than 0.1 $\mu eq\ L^{-1}\ yr^{-1}$ for ILWAS to 0.4 $\mu eq\ L^{-1}\ yr^{-1}$ for ETD. Assuming a 30 percent deposition decrease, these rates of change in median sulfate concentrations changed sign and magnitude, varying from -0.1 $\mu eq\ L^{-1}\ yr^{-1}$ for ETD to -0.4 $\mu eq\ L^{-1}\ yr^{-1}$ for ILWAS and -0.8 $\mu eq\ L^{-1}\ yr^{-1}$ for MAGIC.

The change in median pH projected over 50 years under current deposition ranged from 0.0 for MAGIC to +0.07 for both ETD and MAGIC. The change in median pH projected over 50 years under decreased deposition ranged from 0.1 for ETD to 0.15 for MAGIC and 0.5 for ILWAS. The variance in pH was greatest for ILWAS and varied overtime (Figure 10-56).

There also was no indication that the rates of change in ANC or sulfate concentrations were functions of the initial ELS-I ANC concentration for either deposition scenario (Table 10-17). Histograms of projected change in median ANC and sulfate concentrations over 40 years using all three models indicate a relatively uniform change among lakes regardless of their initial ANC concentrations (Figures 10-57 through 10-62).

10.11.2 Southern Blue Ridge Province

10.11.2.1 Target Population Projections Using MAGIC

An estimated 1323 streams in the SBRP target population were simulated using MAGIC. This target population included both disturbed and undisturbed watersheds based on chloride concentrations; all watersheds had positive sulfur retention. Three streams (which had NSS Pilot Survey ANC > 400 $\mu eq\ L^{-1}$) were excluded subsequently from this target population, although they were simulated by MAGIC. The MAGIC projections indicated that ANC concentrations in these three systems essentially did not

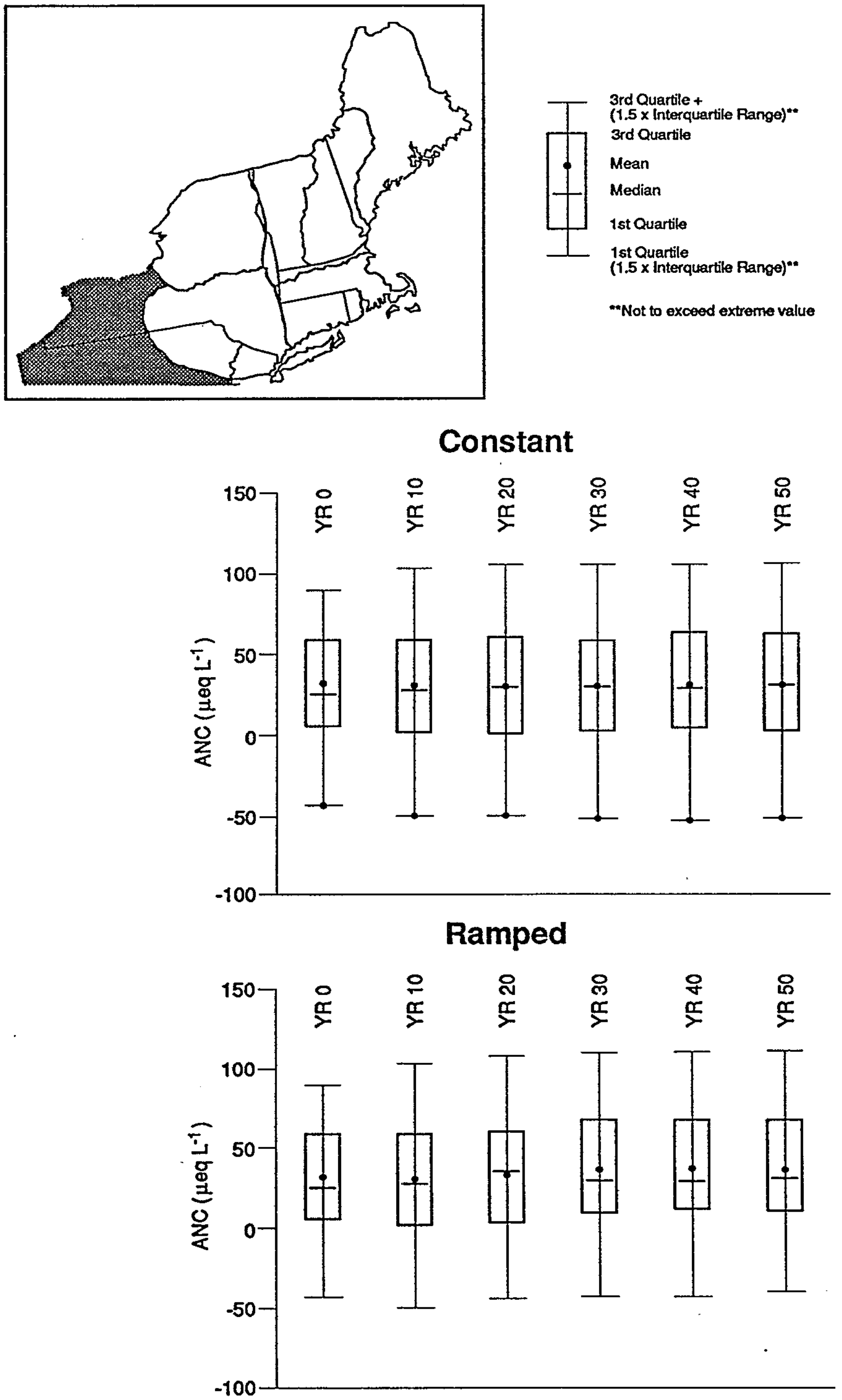


Figure 10-48. Box and whisker plots of ANC distributions in 10-year intervals projected using ETD for NE lakes, Priority Classes A and B.

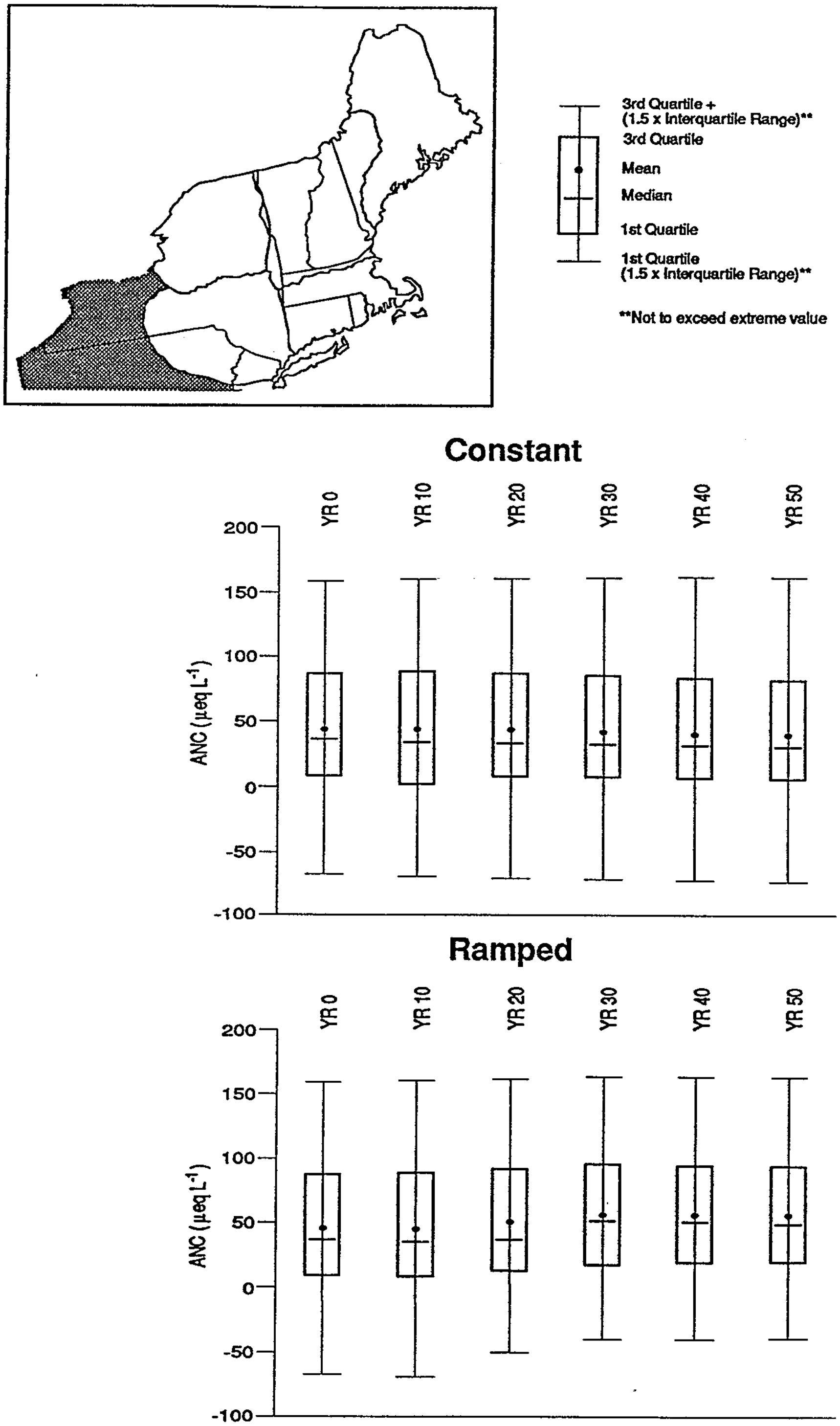


Figure 10-49. Box and whisker plots of ANC distributions in 10-year intervals projected using ILWAS for NE lakes, Priority Classes A and B.

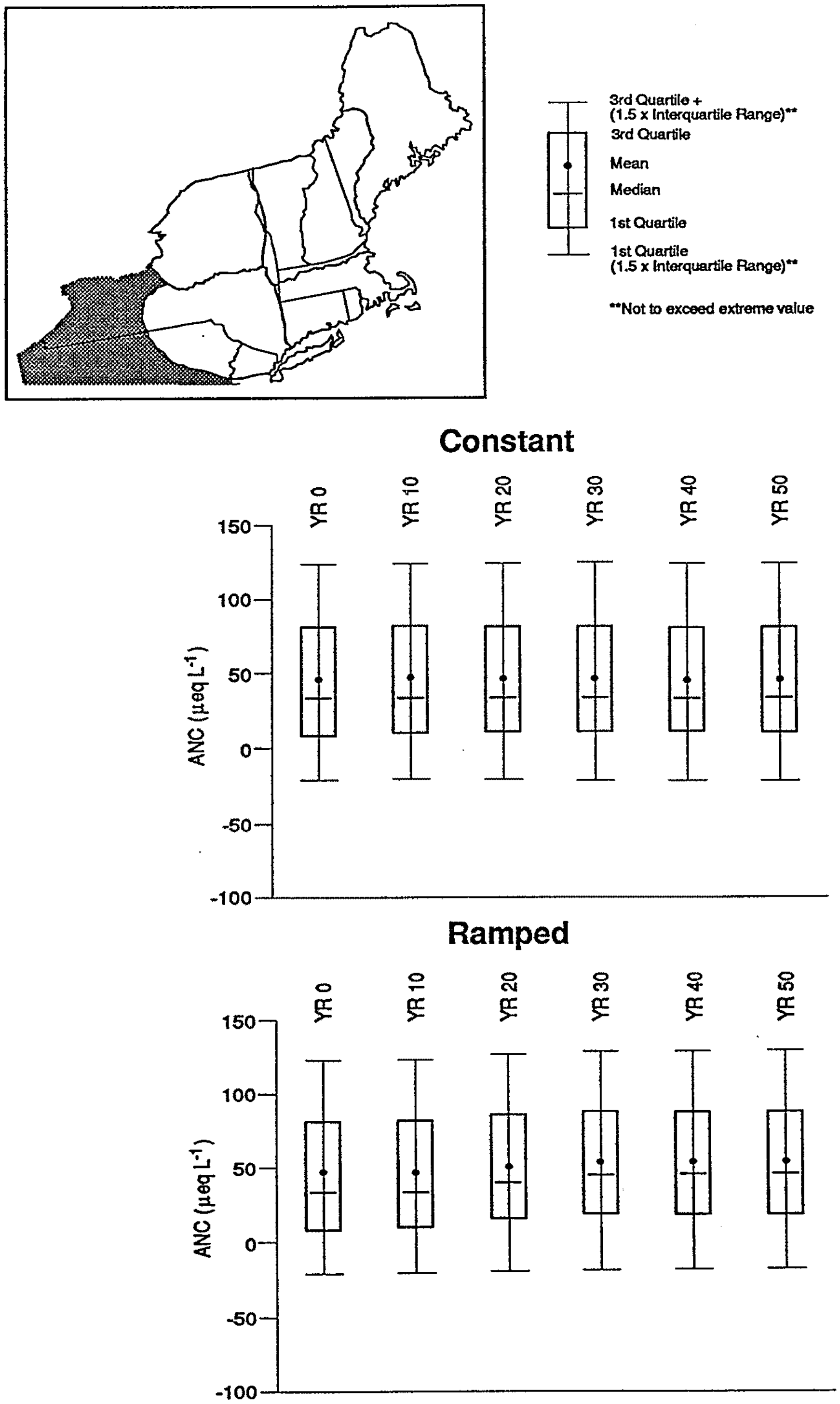


Figure 10-50. Box and whisker plots of ANC distributions in 10-year intervals projected using MAGIC for NE lakes, Priority Classes A and B.

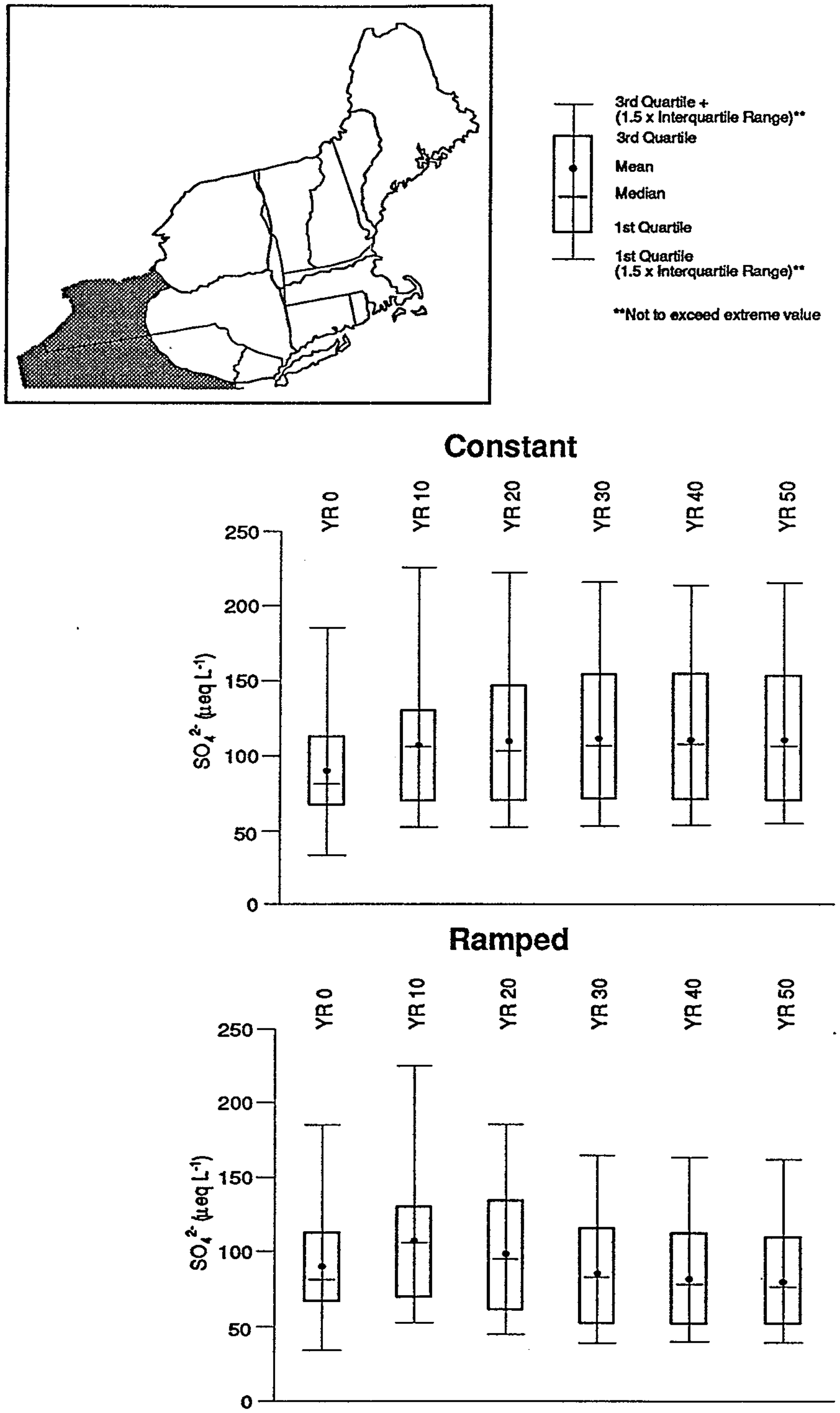


Figure 10-51. Box and whisker plots of sulfate distributions in 10-year intervals projected using ETD for NE lakes, Priority Classes A and B.

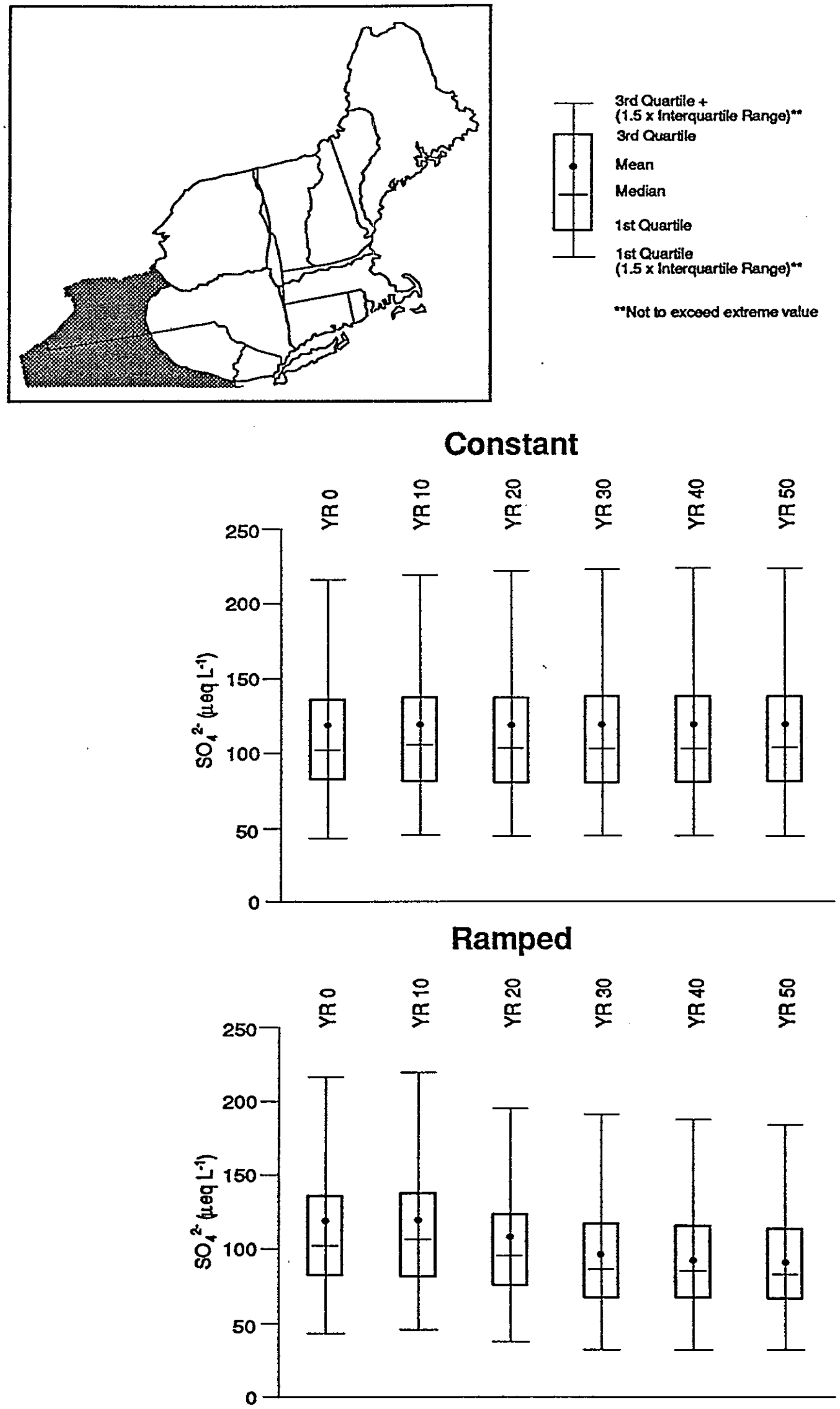


Figure 10-52. Box and whisker plots of sulfate distributions in 10-year intervals projected using ILWAS for NE lakes, Priority Classes A and B.

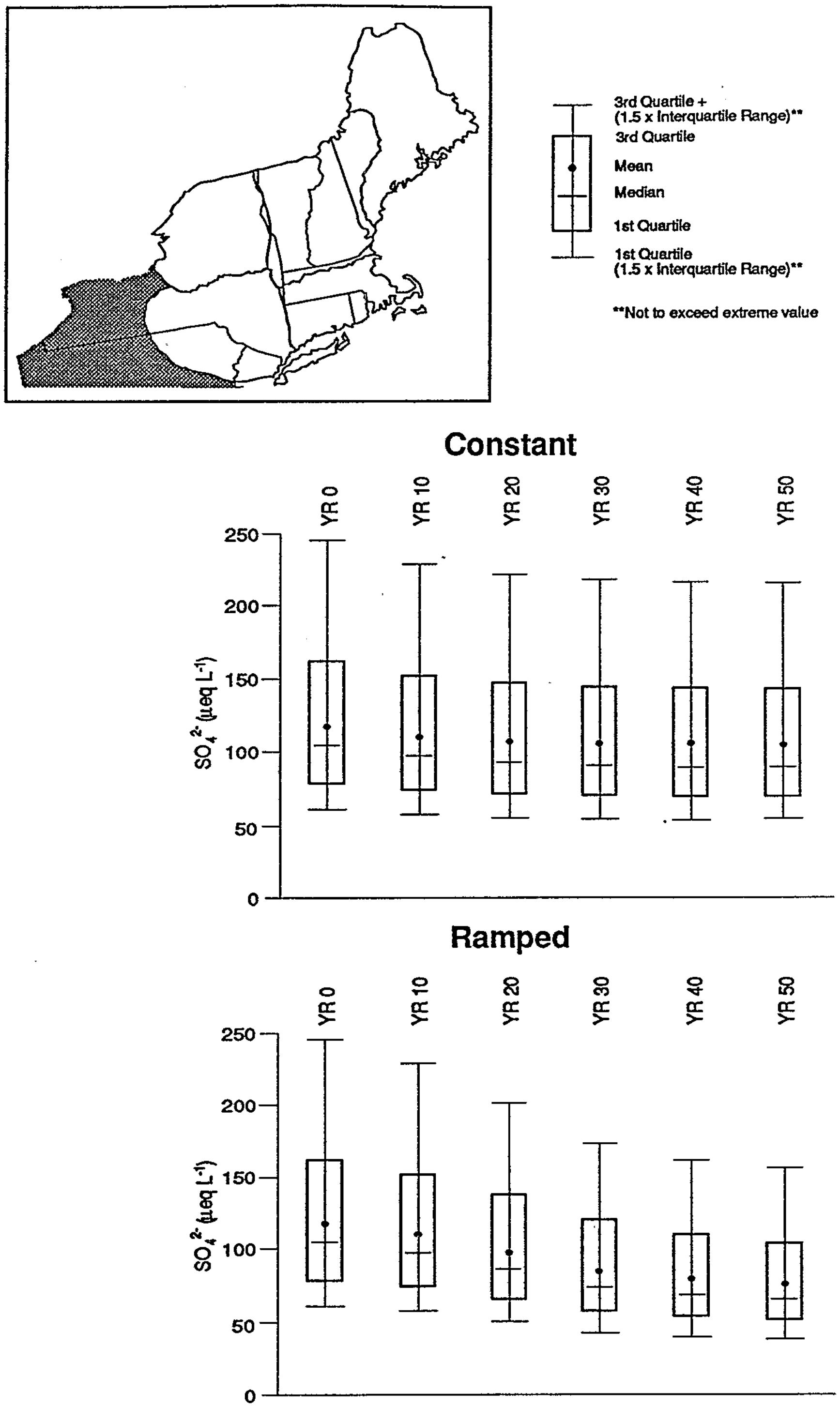


Figure 10-53. Box and whisker plots of sulfate distributions in 10-year intervals projected using MAGIC for NE lakes, Priority Classes A and B.

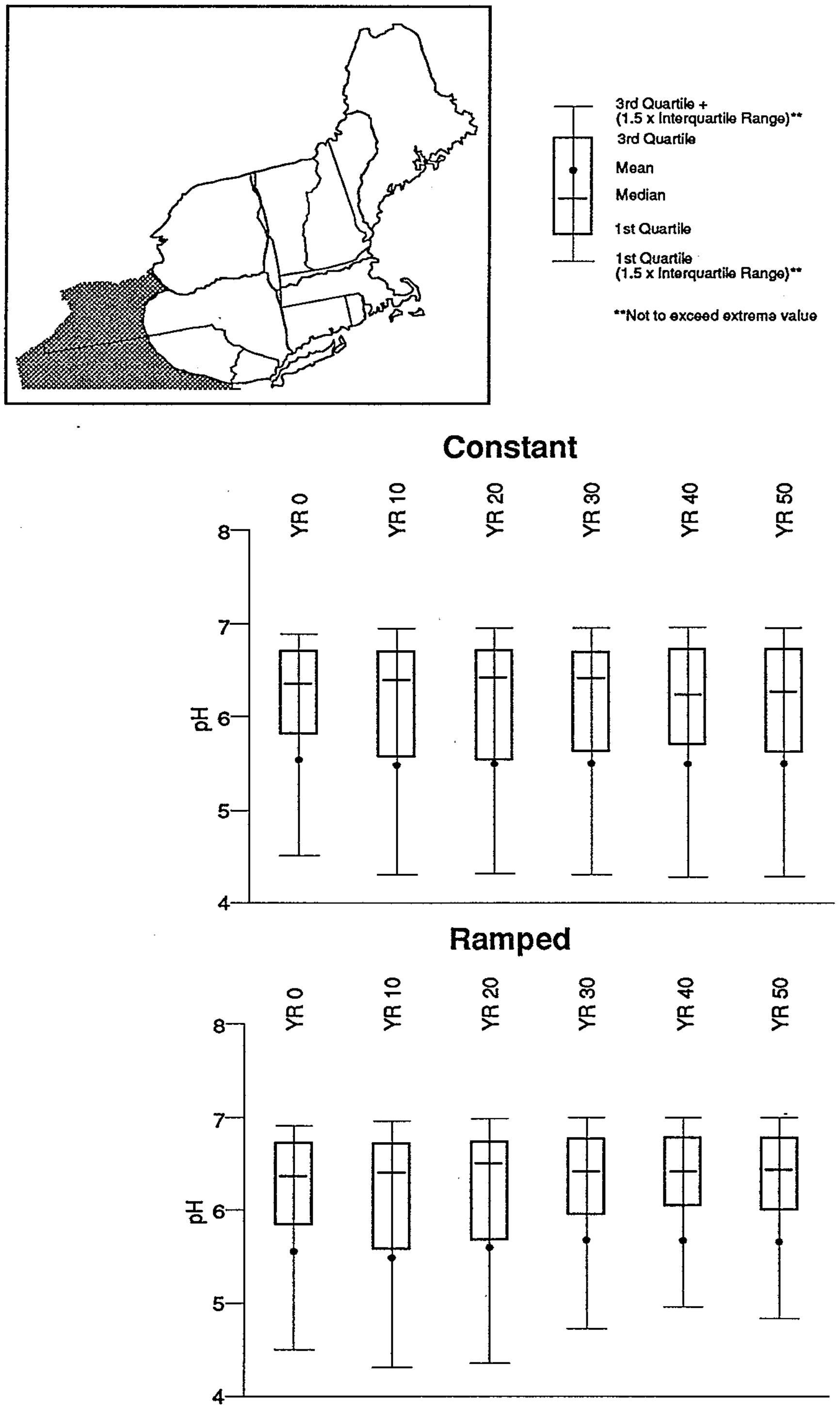


Figure 10-54. Box and whisker plots of pH distributions in 10-year intervals projected using ETD for NE lakes, Priority Classes A and B.

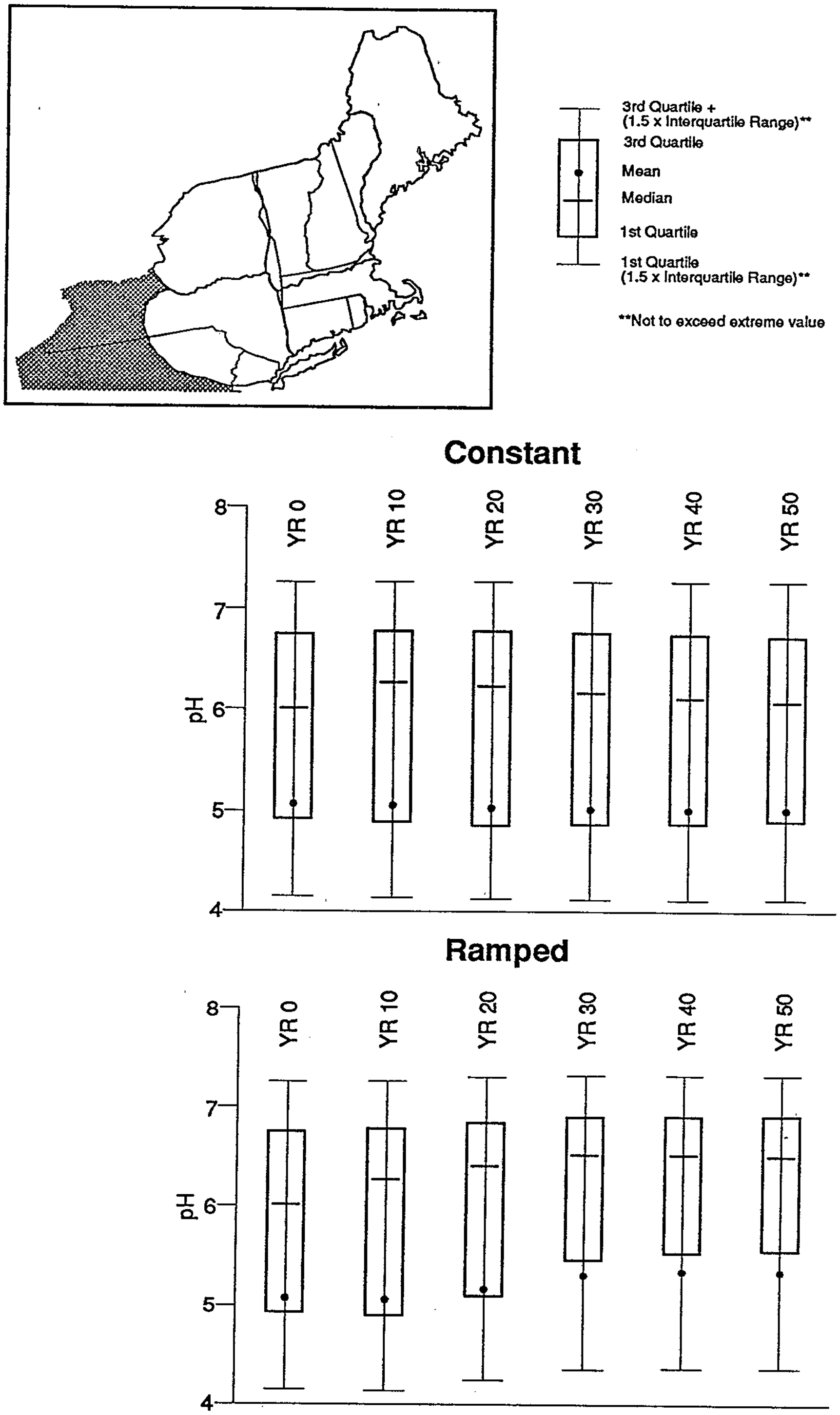


Figure 10-55. Box and whisker plots of pH distributions in 10-year intervals projected using ILWAS for NE lakes, Priority Classes A and B.

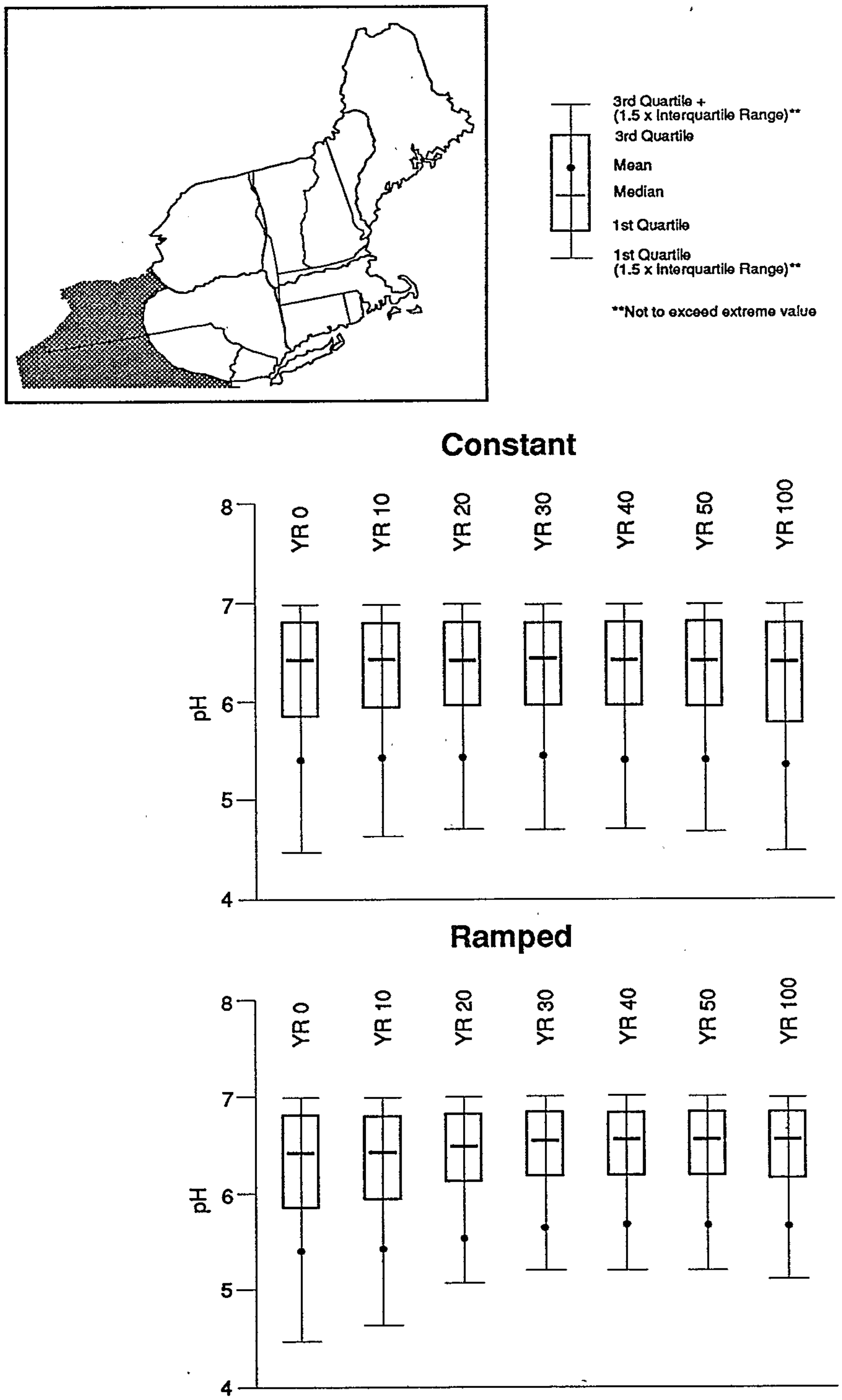
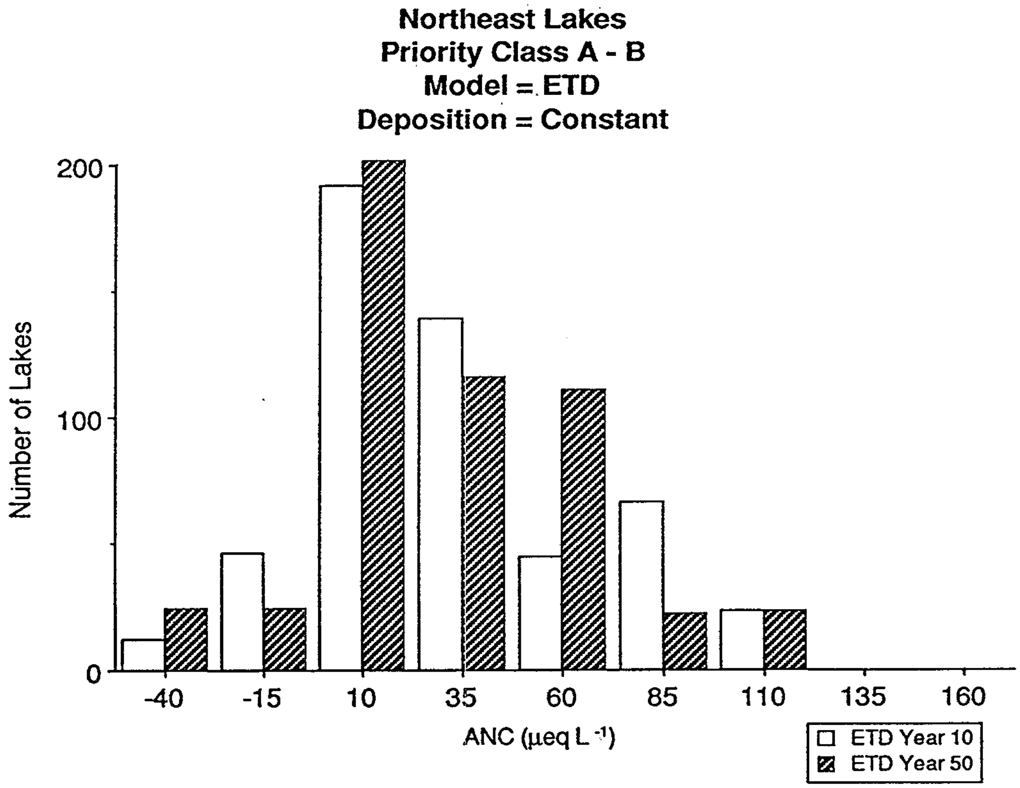


Figure 10-56. Box and whisker plots of pH distributions in 10-year intervals projected using MAGIC for NE lakes, Priority Classes A and B.



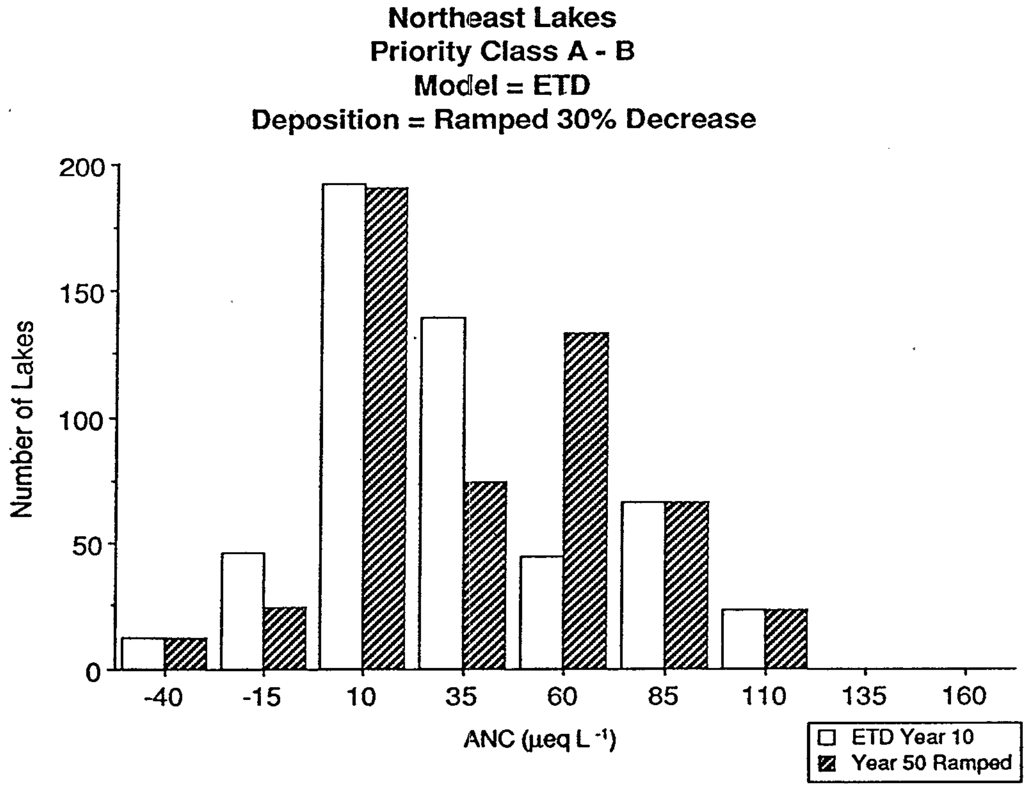
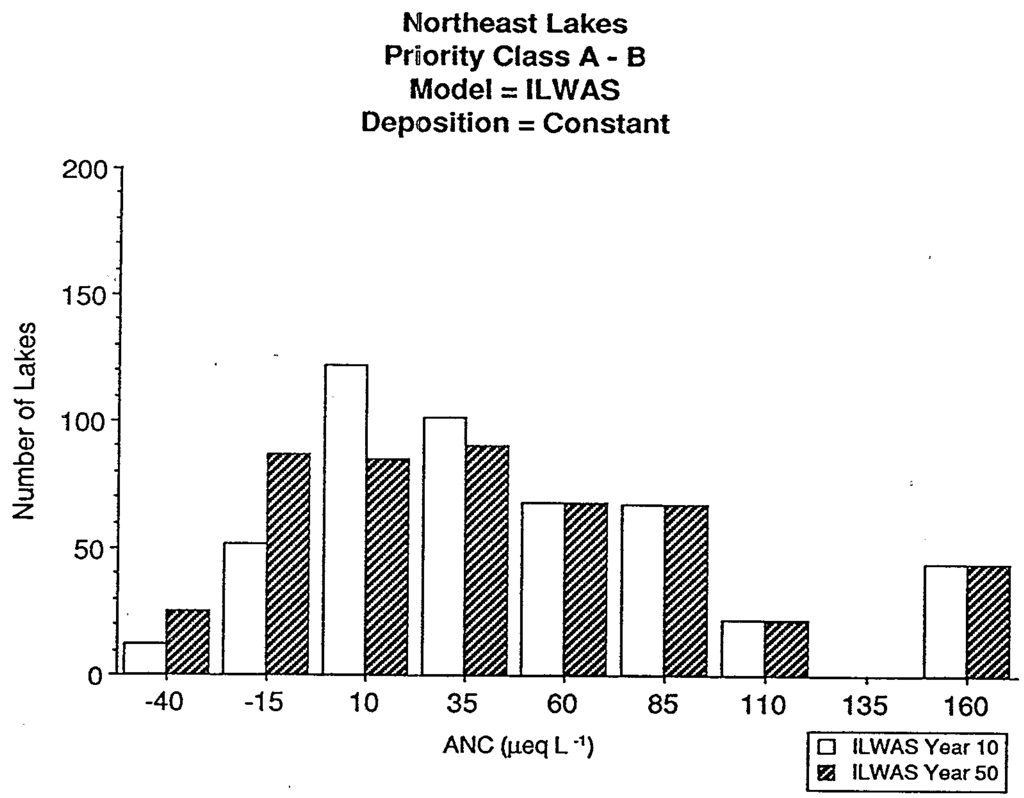


Figure 10-57. ETD ANC population distributions at year 10 and year 50 for current and decreased deposition.



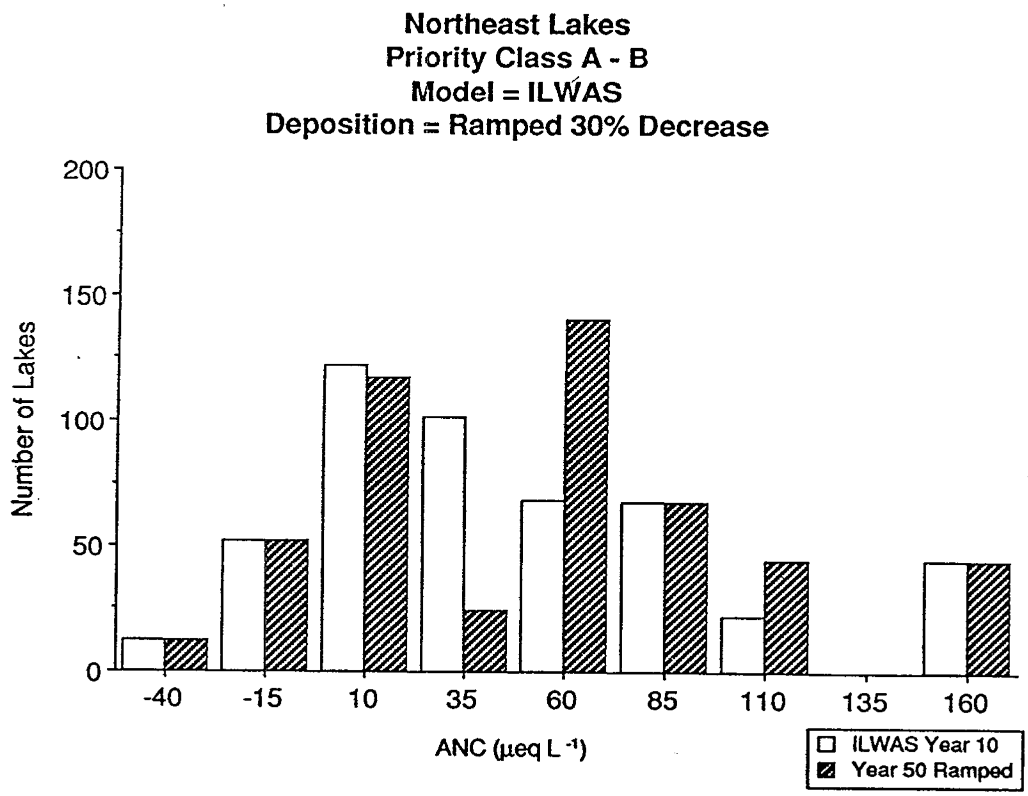
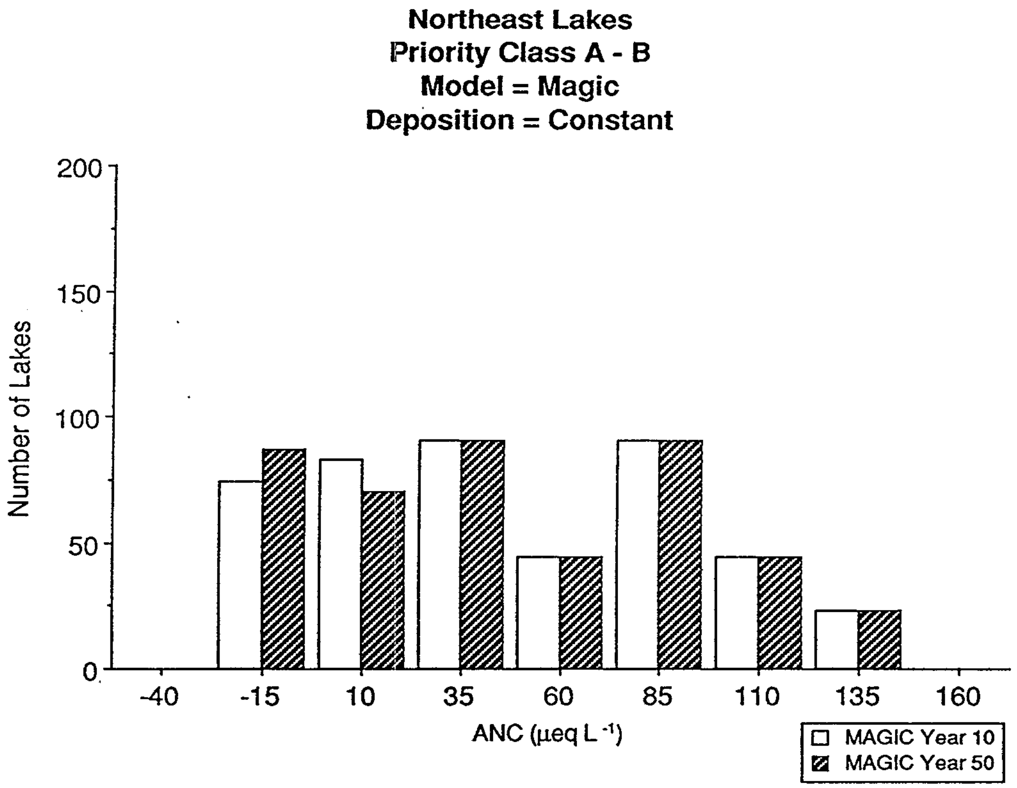


Figure 10-58. ILWAS ANC population distributions at year 10 and year 50 for current and decreased deposition.



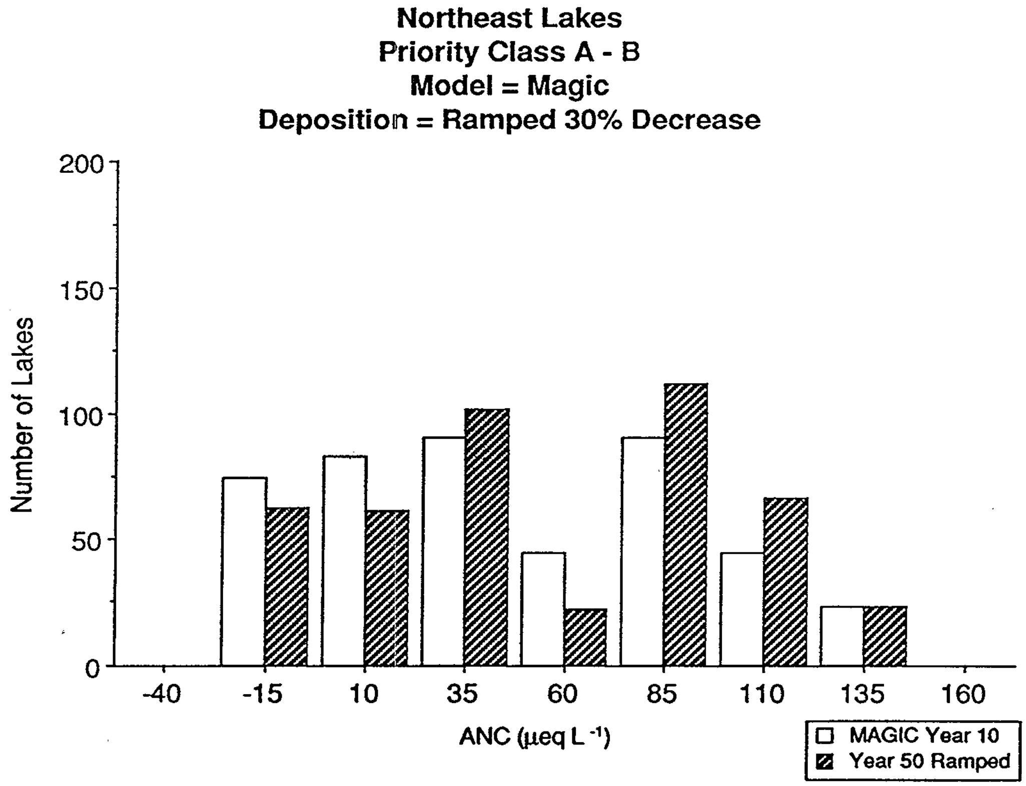


Figure 10-59. MAGIC ANC population distributions at year 10 and year 50 for current and decreased deposition.

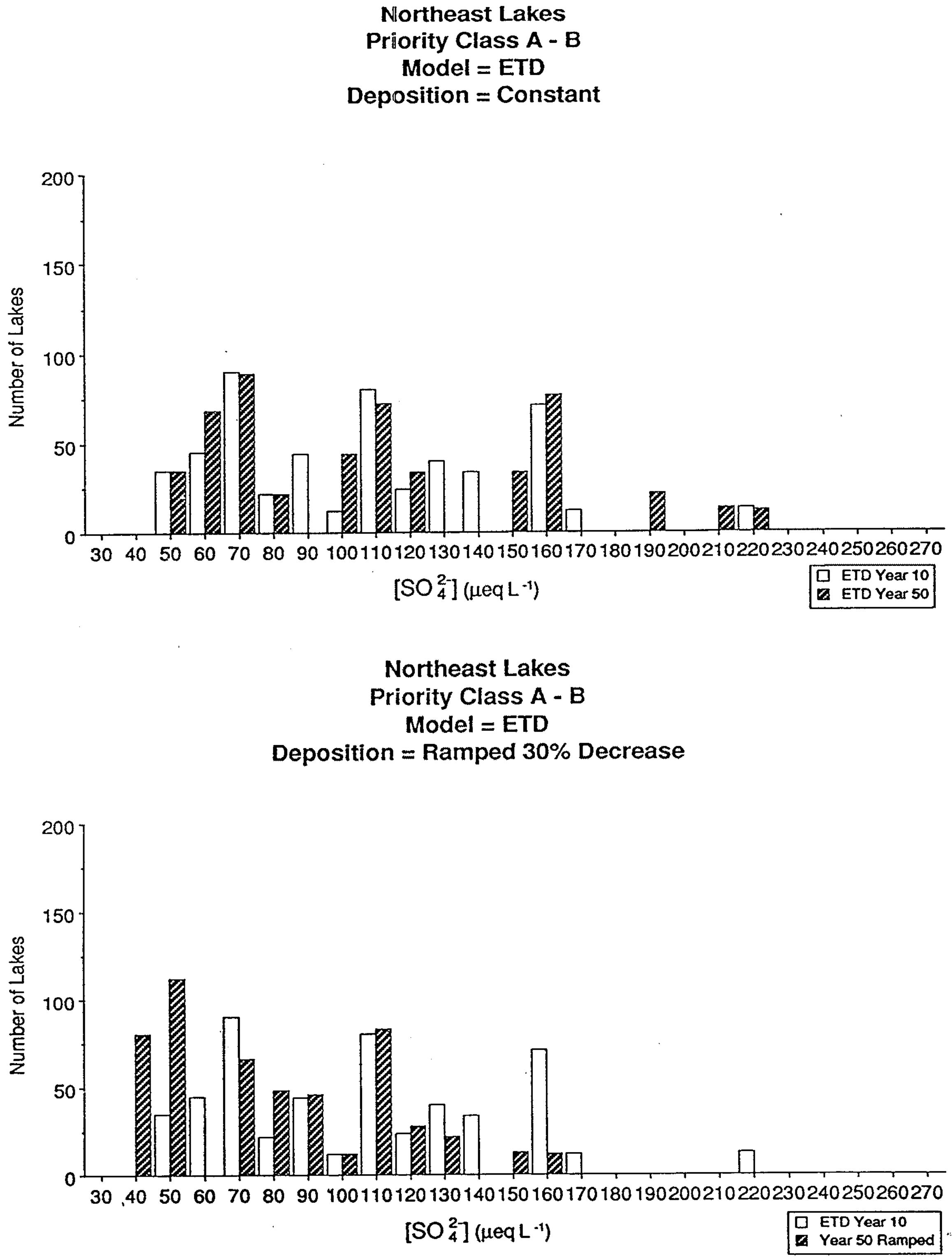
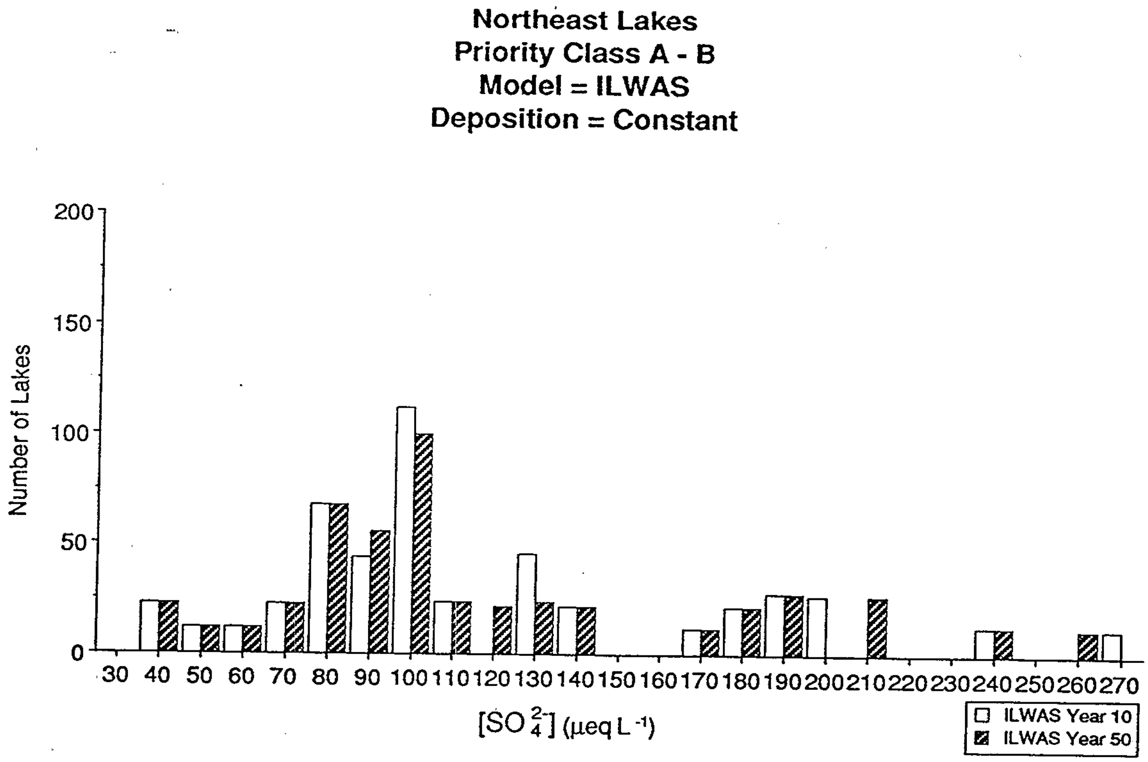


Figure 10-60. ETD sulfate population distributions at year 10 and year 50 for current and decreased deposition.



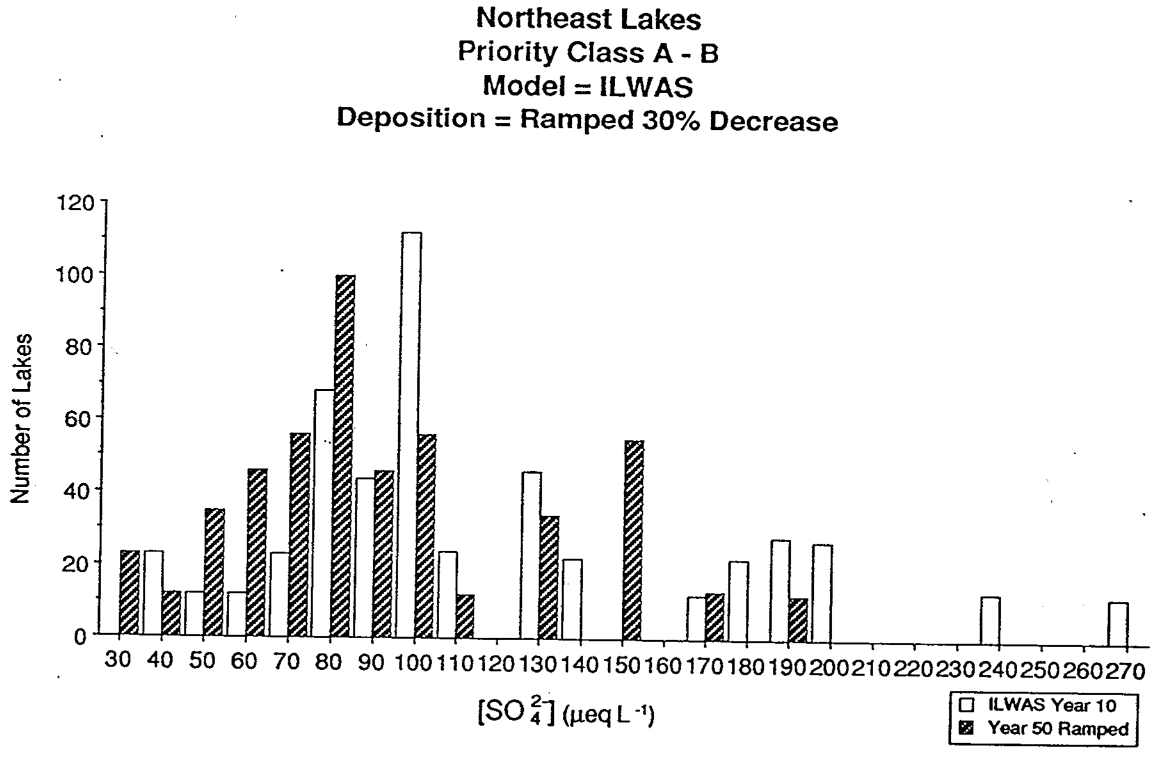
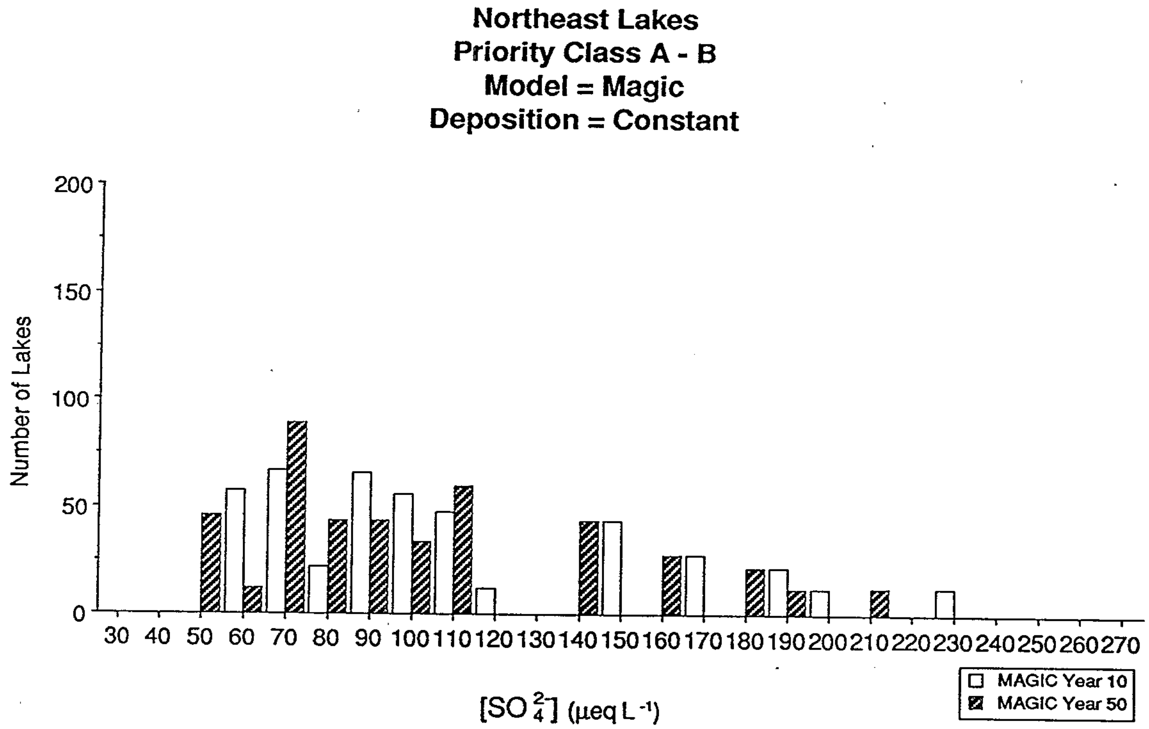


Figure 10-61. ILWAS sulfate population distributions at year 10 and year 50 for current and decreased deposition.



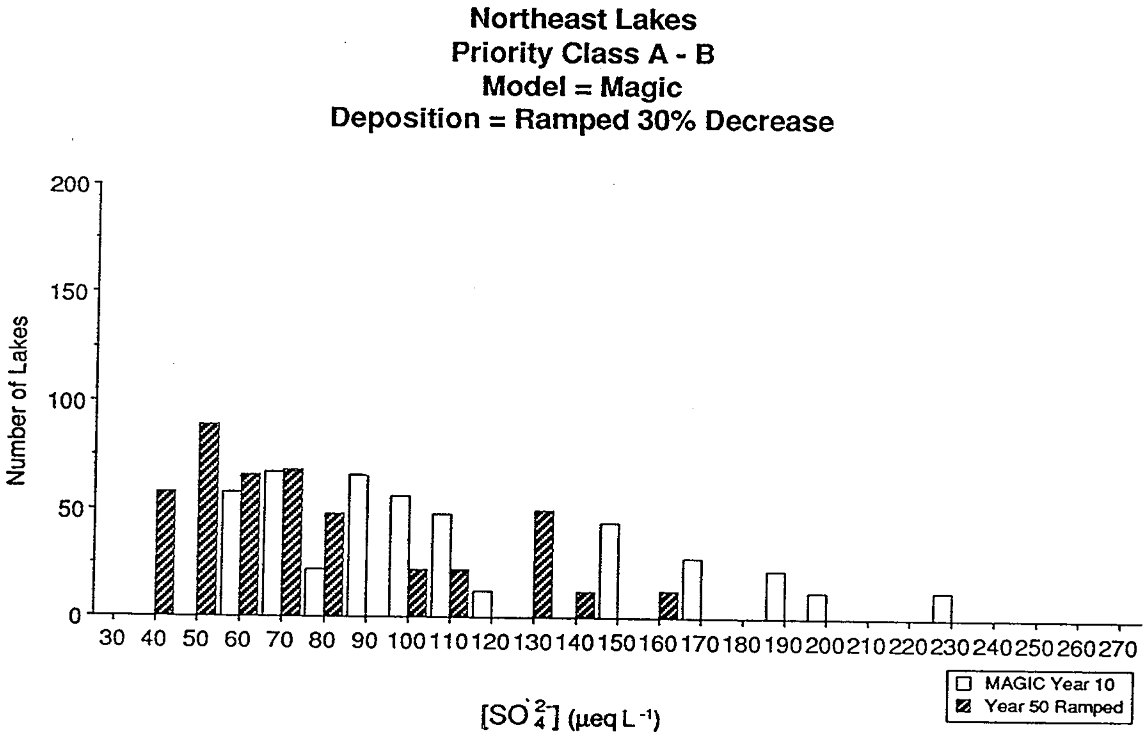


Figure 10-62. MAGIC sulfate population distributions at year 10 and year 50 for current and decreased deposition.

change over the 200-year simulation. Including these streams in the discussion distorts the scales of the ANC figures because two of these streams had ANC concentrations > 1000 μeq L^{-1}. These projections apply only to streams in the SBRP target population and do not necessarily represent southeastern stream responses.

10.11.2.1.1 Deposition scenarios -

There were significant changes in projected ANC and sulfate concentrations and in pH over the 200-year period assuming both current deposition and a 20 percent deposition increase (Figures 10-63 and 10-64). The 200-year time frame was selected to assess changes in surface water chemistry as the watersheds approach sulfate steady state. The time frame is for comparative purposes only and does not represent expected changes over this time frame. Median ANC was projected to decrease from 124 to 78 (-46) μeq L^{-1} over 200 years under current deposition, and from 124 to 59 (-65) μeq L^{-1} assuming increased deposition (Table 10-18). This decrease is greater than the uncertainty bounds on the projections. The median sulfate concentration was projected to increase from 37 to 111 (+74) μeq L^{-1} over the 200-year period under current deposition and from 37 to 133 (+96) μeq L^{-1} over the 200-year period assuming increased deposition (Table 10-18). This increase also is greater than the uncertainty bounds about the projections. The median pH was projected to decrease from 7.0 to 6.75 over the 200-year period under current deposition and from 7.0 to 6.6 with increased deposition. The lower quartile pH, however, was projected to decrease from 6.75 to 6.2 over 200 years under current deposition and from 6.75 to 5.3 under increased deposition. A decrease also was projected for median calcium plus magnesium concentration, with a projected decrease from 115 to 105 (-10) μeq L^{-1} for both current and increased deposition.

Median sulfur retention for the SBRP watersheds at year 0 is about 65 percent. Median sulfur retention projected after 50 years was about 26 percent and after 200 years was about 5 percent for both current and increased deposition. The lower and upper quartile values ranged from less than 1 to about 10 percent after 200 years for both deposition scenarios, indicating the watersheds were approaching sulfate steady state.

Projections of the number of streams that might become acidic after 50, 100, and 200 years assuming current deposition were 129 (9 percent), 159 (11 percent), and 203 (14 percent), respectively. Projections of the number of streams that might become acidic after 50, 100, and 200 years assuming a 20 percent deposition increase were 159 (11 percent), 159 (11 percent), and 337 (24 percent), respectively. For these estimates, the three streams with ANC > 400 μeq L^{-1} were included in the target population, which represented 1429 streams.

10.11.2.1.2 Rate of change of ANC, sulfate, and pH over 200 years -

The projected change in ANC and sulfate concentrations and in pH over the 200-year period for both current and increased deposition are shown in box and whisker plots (Figures 10-65 through 10-67). The projected rates change in median ANC over 200 years assuming current and increased deposition were -0.23 μeq L^{-1} yr^{-1} and -0.32 μeq L^{-1} yr^{-1}, respectively. The relative changes in median ANC projected to occur for the first 50 years, from 50 to 100 years, and from 100 to 200 years were

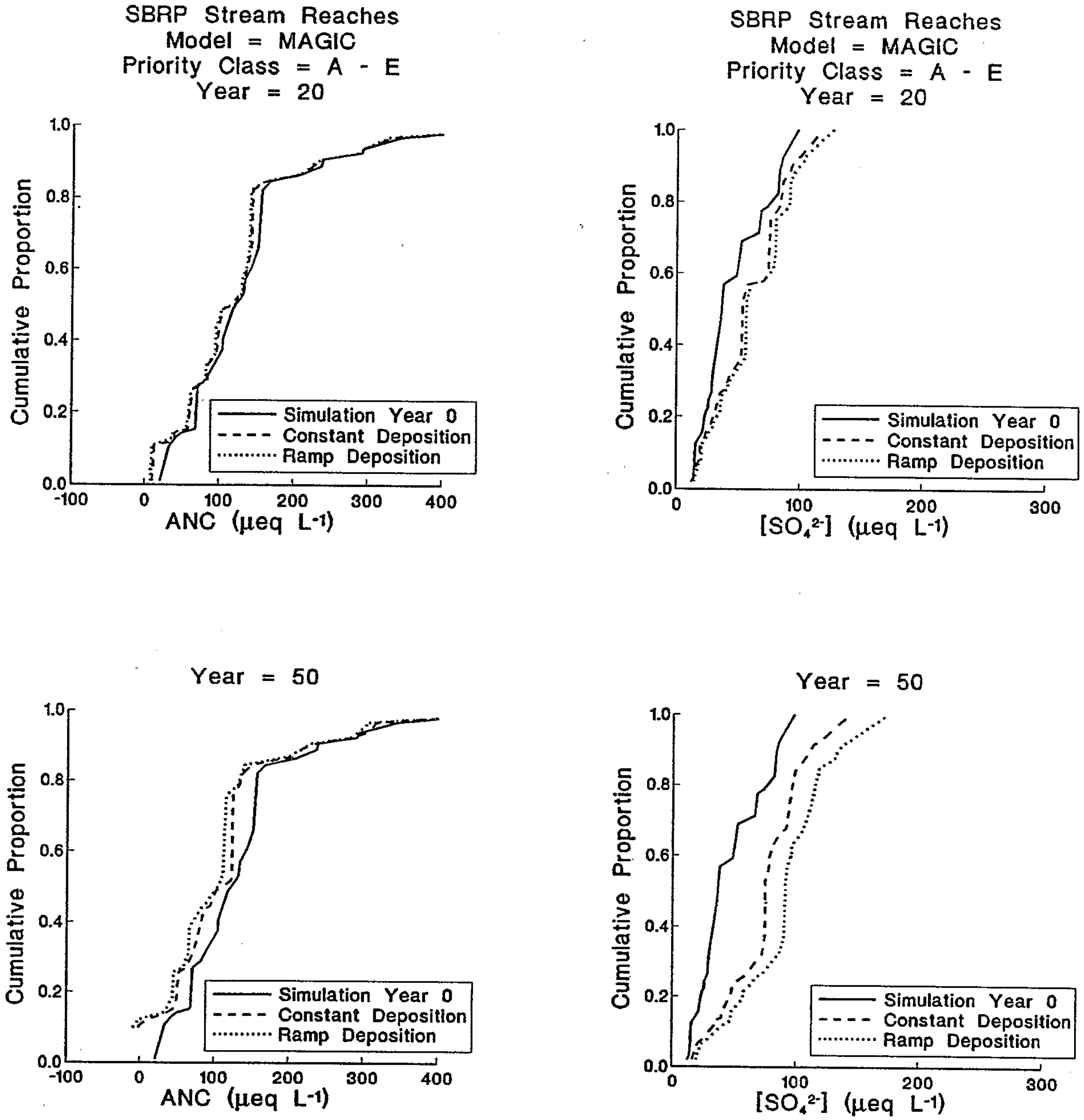


Figure 10-63. MAGIC ANC and sulfate projections for SBRP streams, Priority Classes A - E, at year 20, year 50, year 100, and year 200 under current and increased deposition. (Continued).

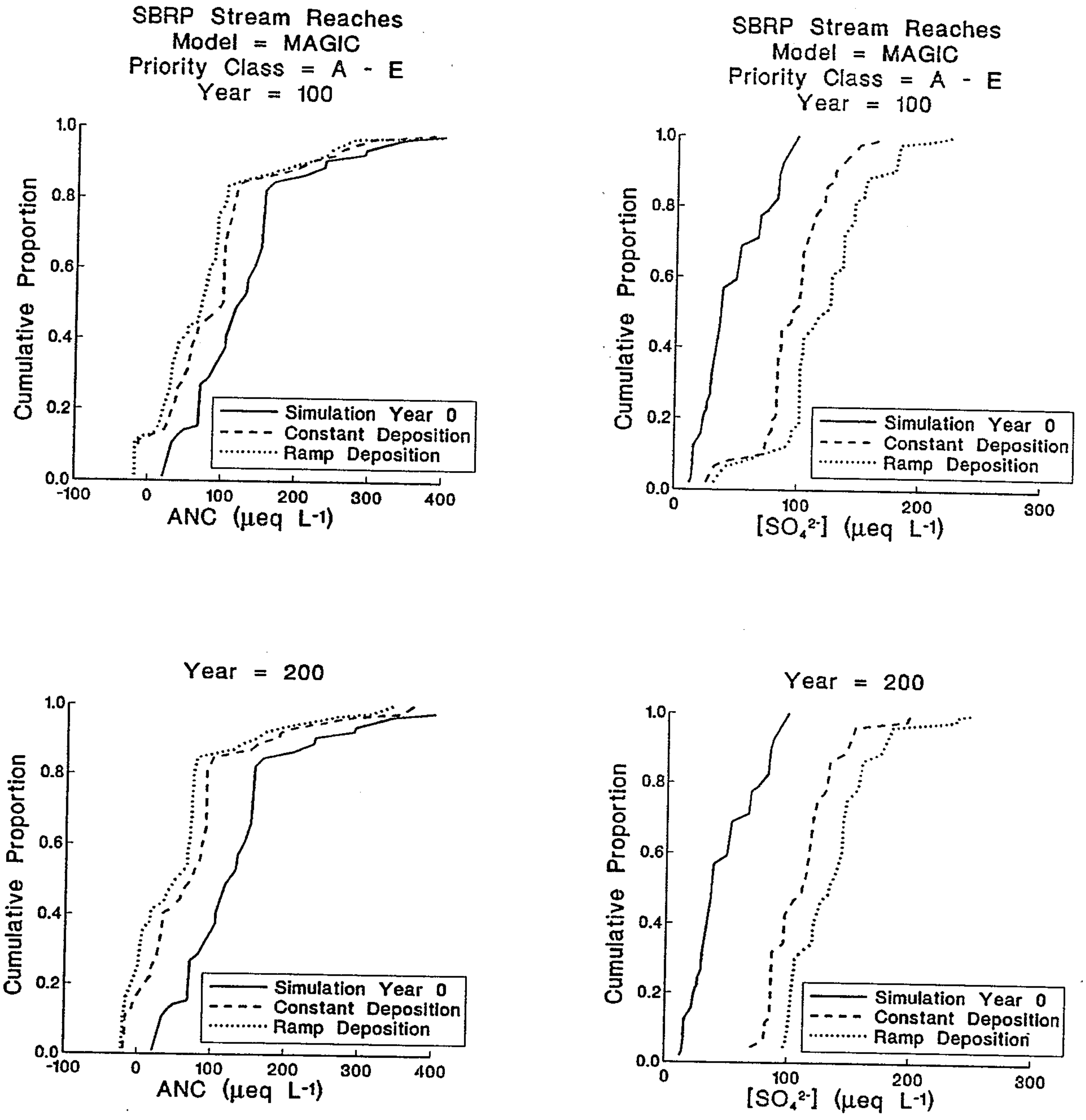
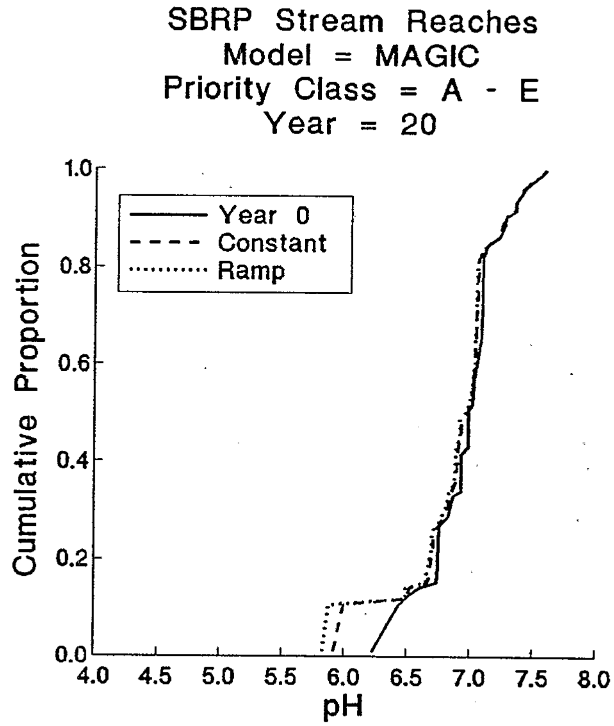


Figure 10-63. (Continued).



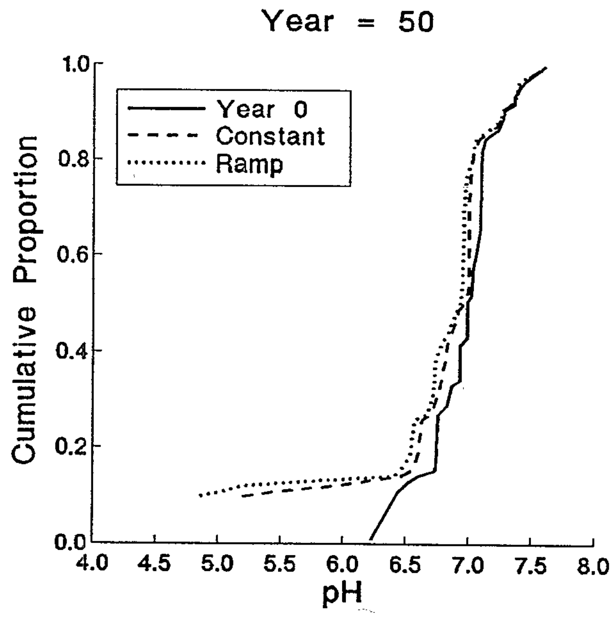


Figure 10-64. MAGIC pH projections for SBRP streams, Priority Classes A - E, at year 20, year 50, year 100, and year 200 under current and increased deposition. (Continued).

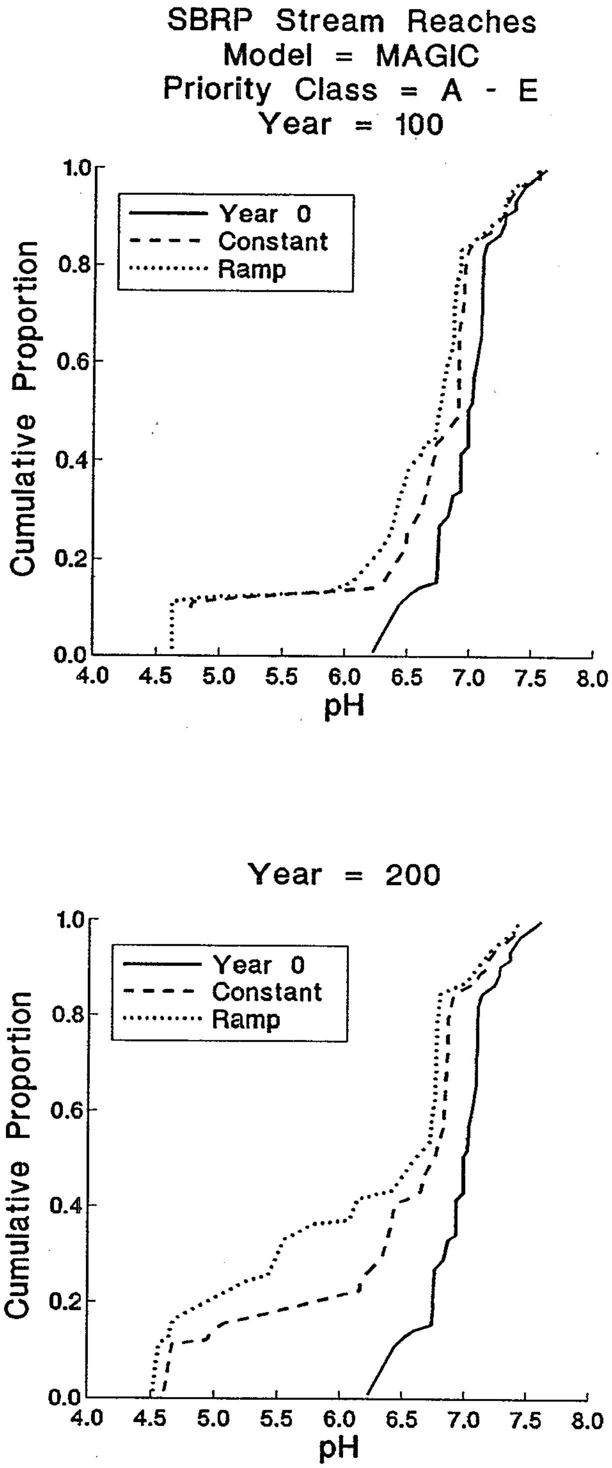


Figure 10-64. (Continued).

Table 10-18. **Descriptive Statistics of Projected ANC, Sulfate, and Percent Sulfur Retention, and Calcium and Magnesium for SBRP Streams in Priority Classes A-E Using MAGIC for Both Current and Increased Deposition**

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			Current Deposition				
MAGIC All, ANC							
Yr 0	139	94	20	71	124	156	510
Yr 20	131	96	10	63	122	144	507
Yr 50	119	99	-3	52	112	125	509
Yr 100	101	97	-13	40	100	111	466
Yr 200	78	85	-19	19	78	91	371
MAGIC All, SO_4^{2-}							
Yr 0	48	26	12	29	37	68	99
Yr 20	60	29	13	35	54	76	118
Yr 50	78	31	16	57	75	99	144
Yr 100	98	29	26	85	97	113	173
Yr 200	112	29	70	87	111	123	209
MAGIC All, pH							
Yr 0	6.87	0.28	6.23	6.76	6.99	7.10	7.60
Yr 20	6.68	0.38	5.92	6.71	6.99	7.06	7.59
Yr 50	6.11	0.59	5.20	6.63	6.96	7.01	7.59
Yr 100	5.68	0.72	4.77	6.50	6.91	6.95	7.55
Yr 200	5.52	0.79	4.61	6.19	6.80	6.86	7.46
MAGIC All, % S Retention							
Yr 0	59	21	24	35	65	78	91
Yr 20	49	23	18	28	48	70	89
Yr 50	34	24	5	21	27	51	85
Yr 100	18	17	1	10	14	18	76
Yr 200	7	8	-2	1	6	10	28
MAGIC All, Ca + Mg							
Yr 0	131	73	50	85	115	140	370
Yr 20	136	73	53	86	121	145	370
Yr 50	139	74	57	102	119	162	382
Yr 100	141	79	57	94	108	155	438
Yr 200	129	74	49	87	105	133	385

continued

Table 10-18. (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			20% Increase in Deposition				
MAGIC All, ANC							
Yr 0	139	94	20	71	124	156	510
Yr 20	128	96	8	62	121	141	507
Yr 50	111	100	-10	46	105	115	507
Yr 100	87	95	-18	29	83	92	443
Yr 200	60	82	-22	0	59	73	344
MAGIC All, SO_4^{2-}							
Yr 0	48	26	12	29	37	68	99
Yr 20	64	31	15	37	57	81	128
Yr 50	94	38	19	68	92	118	175
Yr 100	123	37	32	102	125	146	228
Yr 200	137	33	97	105	133	148	251
MAGIC All, pH							
Yr 0	6.87	0.28	6.23	6.76	6.99	7.10	7.60
Yr 20	6.61	0.41	5.83	6.70	6.99	7.05	7.59
Yr 50	5.79	0.70	4.86	6.57	6.93	6.97	7.59
Yr 100	5.53	0.76	4.63	6.37	6.82	6.88	7.54
Yr 200	5.28	0.91	4.52	5.42	6.68	6.77	7.43
MAGIC All, % S Retention							
Yr 0	59	21	24	35	65	78	91
Yr 20	52	21	25	32	51	73	89
Yr 50	34	24	4	21	26	51	86
Yr 100	15	16	0	6	11	18	76
Yr 200	5	6	-2	0	5	9	17
MAGIC All, Ca + Mg							
Yr 0	131	73	50	85	115	140	370
Yr 20	137	73	54	86	122	145	373
Yr 50	145	75	60	104	123	171	394
Yr 100	147	84	60	98	109	174	472
Yr 200	130	75	48	84	106	135	388

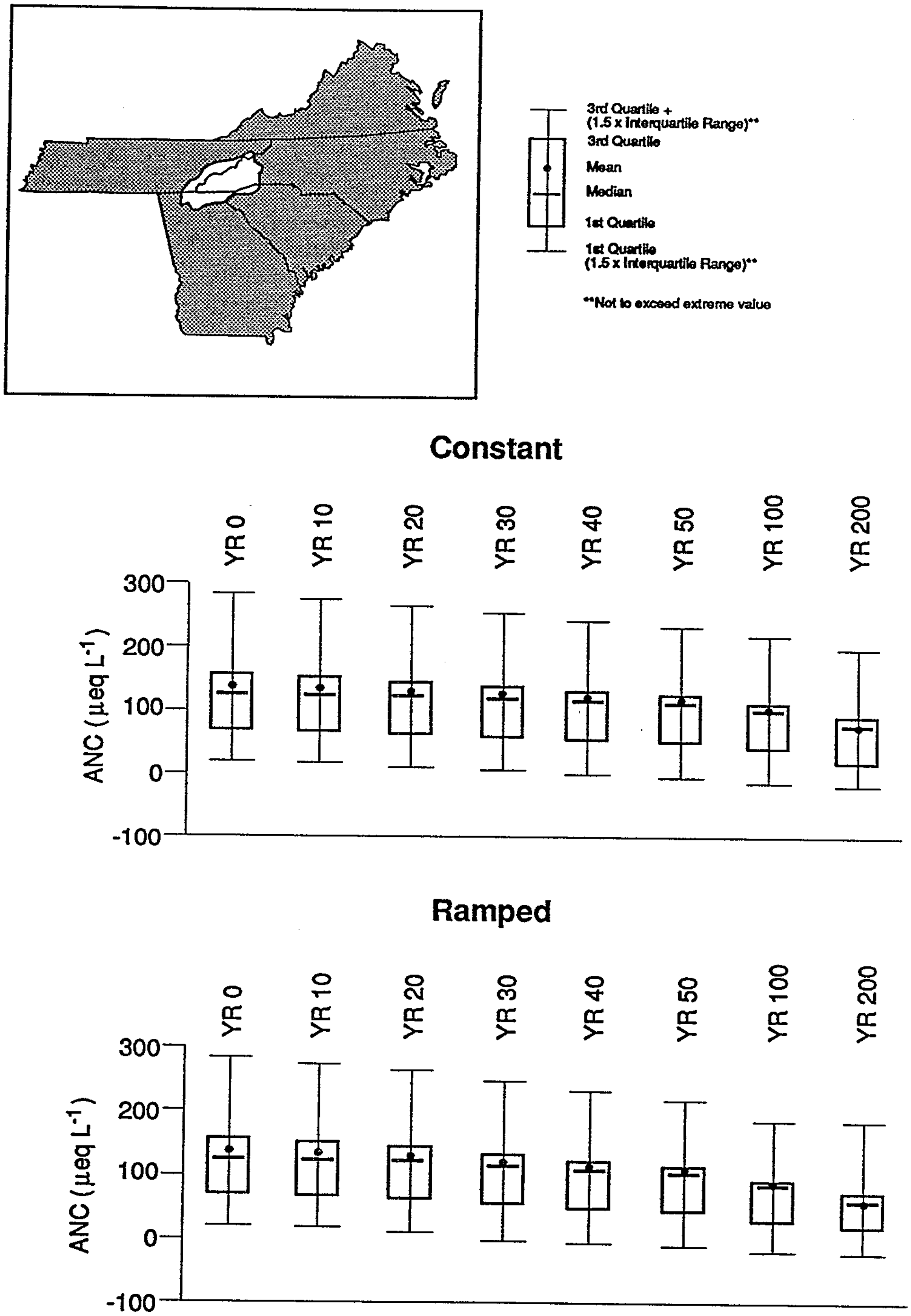


Figure 10-65. Box and whisker plots of ANC distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A - E, for current and increased deposition.

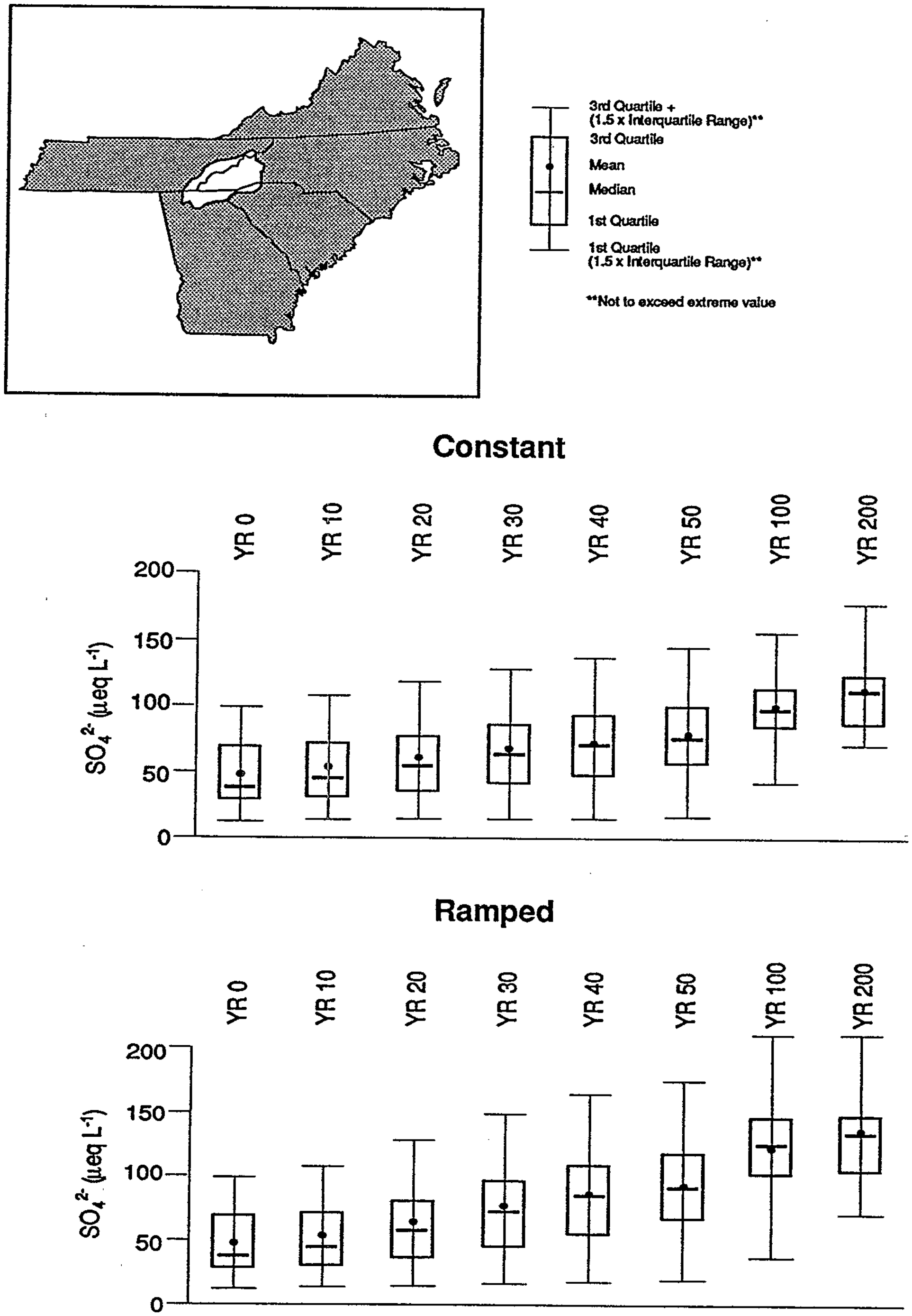


Figure 10-66. Box and whisker plots of sulfate distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A - E, for current and increased deposition.

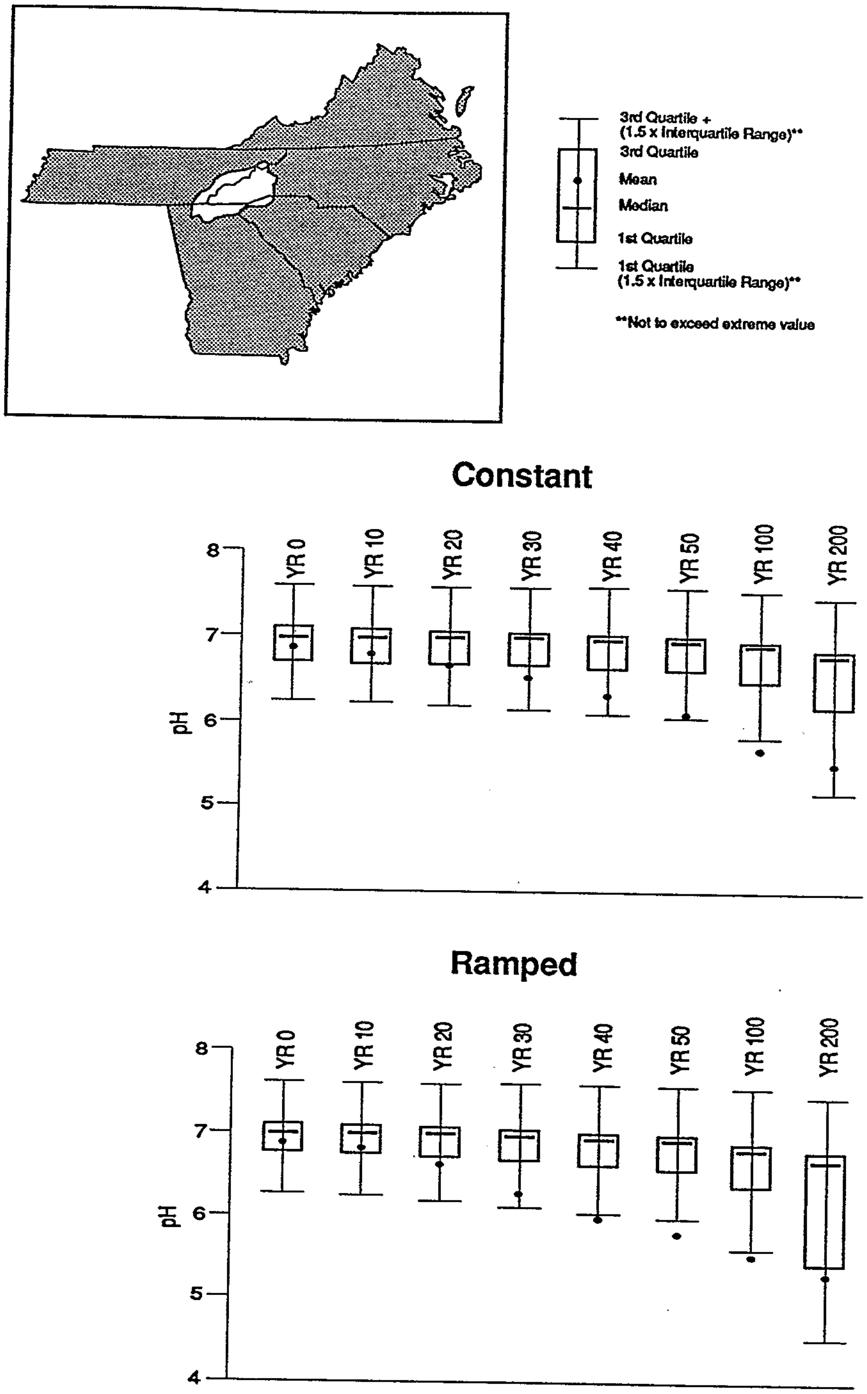


Figure 10-67. Box and whisker plots of pH distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A - E, for current and increased deposition.

11, -12, and -23 $\mu eq\ L^{-1}$, respectively. These projections represent a relatively constant linear decrease in ANC over time assuming current deposition. Assuming a 20 percent deposition increase, the projected changes in median ANC for the first 50 years, from 50 to 100 years, and from 100 to 200 years were -19, -21, and -23 $\mu eq\ L^{-1}$, respectively, indicating a constant relatively linear decrease for the first 100 years and then a slower rate of change over the next 100 years.

The projected change in median sulfate concentration varied over the 200-year simulation period with a relatively linear increase during the first 50 years, asymptotically approaching the 200-year sulfate concentration, 111 $\mu eq\ L^{-1}$ (Table 10-18). The increase for the first 50 years was from 37 to 75(+38) $\mu eq\ L^{-1}$, for 50 to 100 years from 75 to 97 (+22) $\mu eq\ L^{-1}$, and for 100 to 200 years from 97 to 111(+14) $\mu eq\ L^{-1}$ under current deposition. The median sulfate projected for increased deposition was an increase from 37 to 92 (+55) $\mu eq\ L^{-1}$ for the first 50 years; for 50 to 100 years, the increase was from 92 to 125 (+33) $\mu eq\ L^{-1}$; and for 100 to 200 years, the increase was from 125 to 133 (+8) $\mu eq\ L^{-1}$.

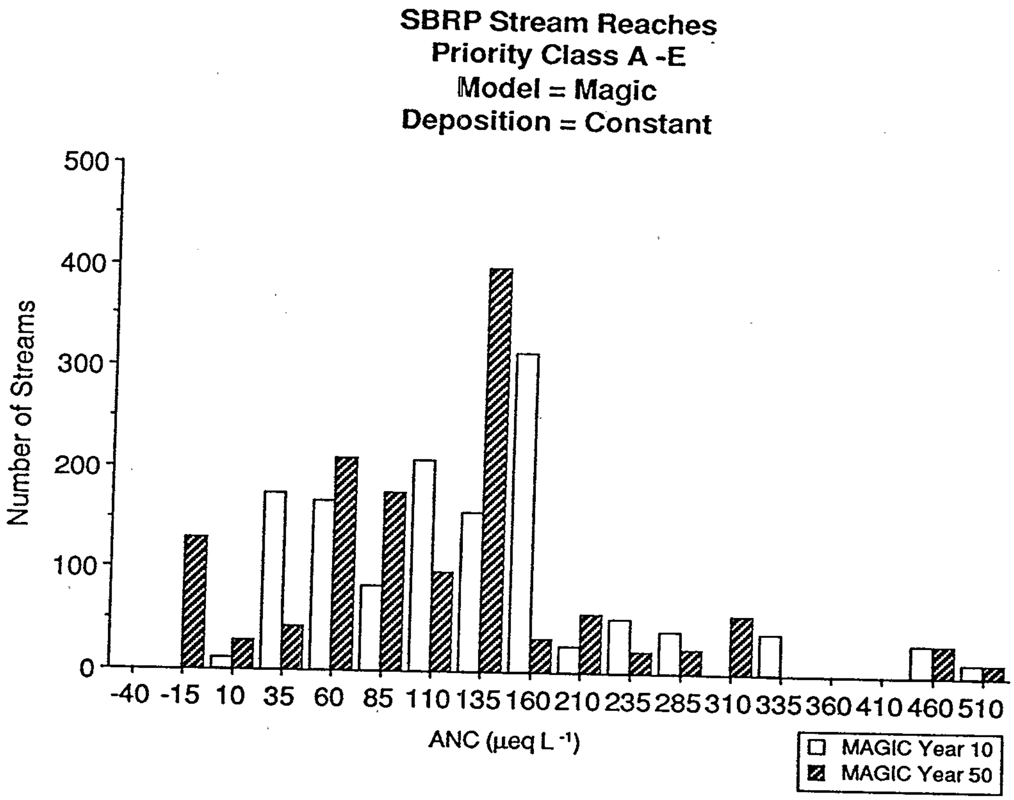
Median pH values were relatively unchanged over the first 50 years under either current or increased deposition and changed about -0.1 units over 100 years (Table 10-18). Over 200 years, the median pH changed -0.25 units under current deposition and -0.4 units with increased deposition. Lower quartile pH values were projected to change about -0.15 units in 50 years under either deposition scenario. The lower quartile pHs changed -0.5 units in 100 years under current deposition and -0.6 units with increased deposition. After 200 years, the lower quartile pH values were projected to change by -0.8 units under current deposition and -1.7 units under increased deposition.

Projected median calcium plus magnesium concentrations increased from 115 to about 123 $\mu eq\ L^{-1}$ during the first 50 years and then decreased to about 108 to 110 $\mu eq\ L^{-1}$ by year 100, with a further decrease to 105 $\mu eq\ L^{-1}$ at year 200 under both current and increased deposition.

There was a differential change projected among streams based on their initial ANC concentrations. Streams with higher initial ANC (based on NSS Pilot Survey data) were projected to have a greater change in ANC than streams with lower initial ANC. This result is illustrated by the change in the frequency intervals of streams in different ANC categories in the histograms (Figures 10-68 and 10-69) and Table 10-15. The projected changes for ANC concentrations in streams with initial ANC between 25 and 100 $\mu eq\ L^{-1}$ and between 100 and 400 $\mu eq\ L^{-1}$ were -14 $\mu eq\ L^{-1}$ versus -24 $\mu eq\ L^{-1}$ over a 40-year period under current deposition. The projected changes for ANC concentrations in streams with initial ANC between 25 and 100 $\mu eq\ L^{-1}$ and 100 to 400 $\mu eq\ L^{-1}$ were -21 versus -34 $\mu eq\ L^{-1}$ over a 40-year period under increased deposition.

10.11.2.2 Restricted Target Population Projections Using ILWAS and MAGIC

An estimated 567 streams in the target population were represented in simulations using both ILWAS and MAGIC. These streams were considered undisturbed based on the chloride concentrations and had NSS Pilot Survey ANC concentrations less than 200 $\mu eq\ L^{-1}$. All the watersheds had positive sulfur retention.



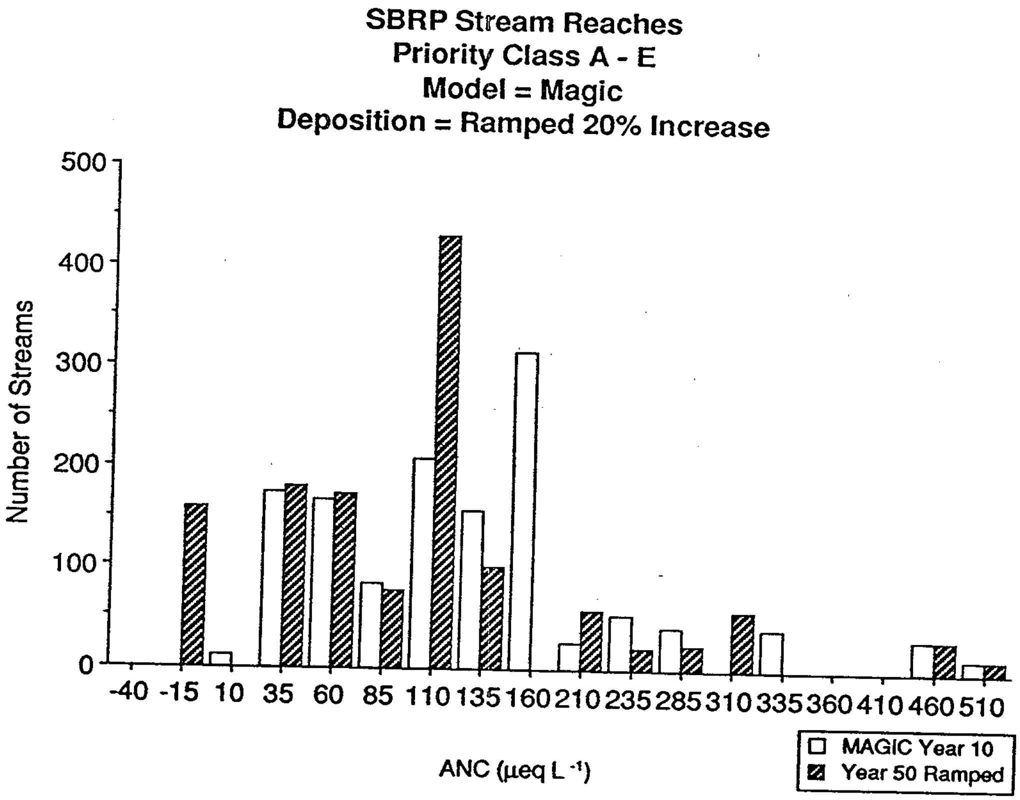
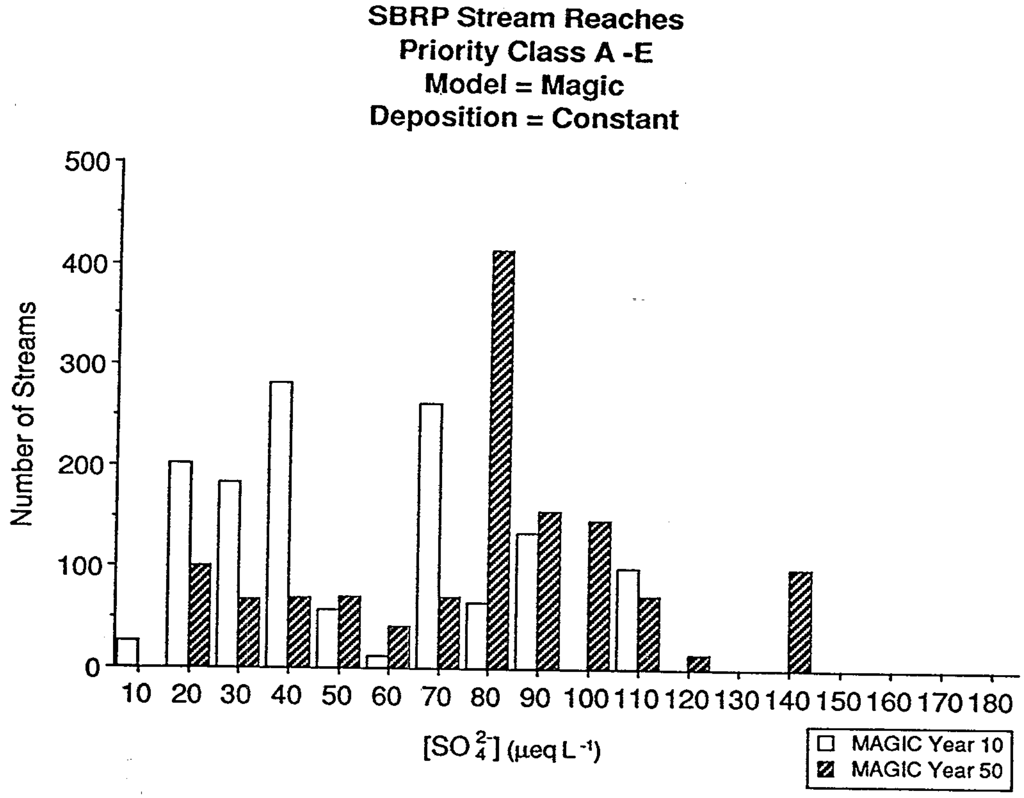


Figure 10-68. **MAGIC ANC population distributions at year 10 and year 50 for current and increased deposition, SBRP streams, Priority Classes A - E.**



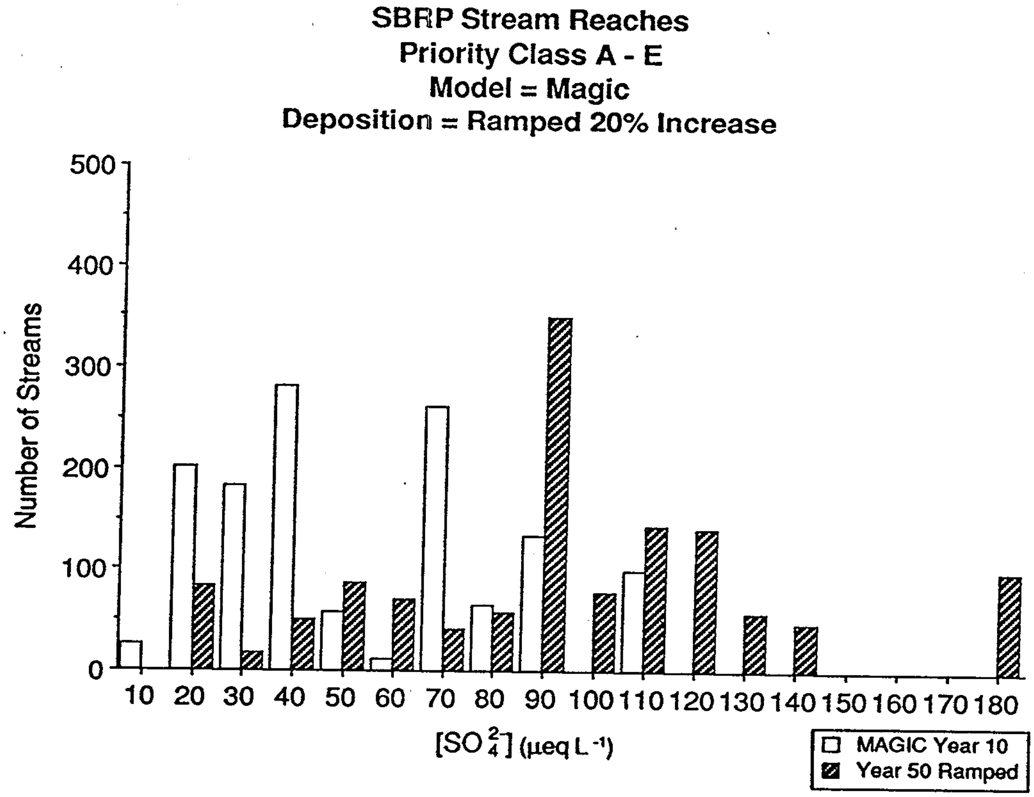


Figure 10-69. MAGIC sulfate population distributions at year 10 and year 50 for current and increased deposition, SBRP streams, Priority Classes A - E.

10.11.2.2.1 Deposition scenarios -

ILWAS and MAGIC projected similar changes in ANC, sulfate, and pH after 50 years. Changes projected for streams with lower initial ANC concentrations using MAGIC were greater than those projected using ILWAS (Figures 10-70 through 10-72). The ILWAS model performed 50-year rather than 200-year simulations, because of time and computational restrictions, and comparisons are therefore made only for this 50-year period.

Median ANC concentrations using the ILWAS model were projected to decrease from 87.4 to 72.4 $\mu eq\ L^{-1}$ (-15.0 $\mu eq\ L^{-1}$) under current deposition and from 87.4 to 71.8 $\mu eq\ L^{-1}$ (-15.2 $\mu eq\ L^{-1}$) for increased deposition (Table 10-19). Median ANC using MAGIC was projected to decrease from 118.1 to 85.5 (-32.6) $\mu eq\ L^{-1}$ for current deposition and from 118.1 to 80.1 (-38.0) $\mu eq\ L^{-1}$ for increased deposition for the 50-year simulation period. Differences between the change projected by the two models were 17.6 $\mu eq\ L^{-1}$ at current deposition and 22.8 $\mu eq\ L^{-1}$ at increased deposition.

Median sulfate concentrations using the ILWAS model were projected to increase from 25.0 to 58.9 (+33.9) $\mu eq\ L^{-1}$ for current deposition and from 25.0 to 69.1 (+44.1) $\mu eq\ L^{-1}$ for increased deposition (Table 10-19). The median sulfate increases projected using MAGIC were from 37.2 to 75.3 (+38.1) $\mu eq\ L^{-1}$ for current deposition and from 37.2 to 91.8 (+54.6) $\mu eq\ L^{-1}$ for increased deposition. Differences between the changes projected using the two models were 4.2 $\mu eq\ L^{-1}$ for current deposition and 10.5 $\mu eq\ L^{-1}$ for increased deposition.

Median pH values using the ILWAS model were projected to decrease from 7.0 to 6.8 (-0.2) for current deposition and 7.0 to 6.8 (-0.2) for increased deposition (Table 10-19). The median pH values projected using MAGIC decreased from 7.0 to 6.9 (-0.1) for current deposition and from 7.0 to 6.8 (-0.2) for increased deposition.

Median calcium plus magnesium concentrations using the ILWAS model were projected to increase from 82.3 to 95.7 (+13.4) $\mu eq\ L^{-1}$ for current deposition and from 82.3 to 103.4 (+21.1) $\mu eq\ L^{-1}$ for increased deposition (Table 10-19). The median calcium plus magnesium concentrations using MAGIC were projected to increase from 115 to 114.8 (-0.2) $\mu eq\ L^{-1}$ for current deposition and from 115 to 120.4 (+5.4) $\mu eq\ L^{-1}$ for increased deposition. Differences between the change projected using the two models were 13.2 $\mu eq\ L^{-1}$ for current deposition and 15.7 $\mu eq\ L^{-1}$ for increased deposition.

Watersheds in the SBRP had an estimated median sulfur retention of 46 percent for current deposition and 48.3 percent for increased deposition (Table 10-19) after 50 years using ILWAS. Median sulfur retention for SBRP watersheds using MAGIC was projected to vary from about 24.5 percent for current deposition to 25 percent for increased deposition.

None of the streams in the SBRP was projected to become acidic within 50 years using the ILWAS model for either current or increased deposition. There were 129 (23 percent) streams that might become acidic at current deposition levels within 50 years using MAGIC and an estimated 159 (28 percent) that might become acidic for increased deposition levels within 50 years.

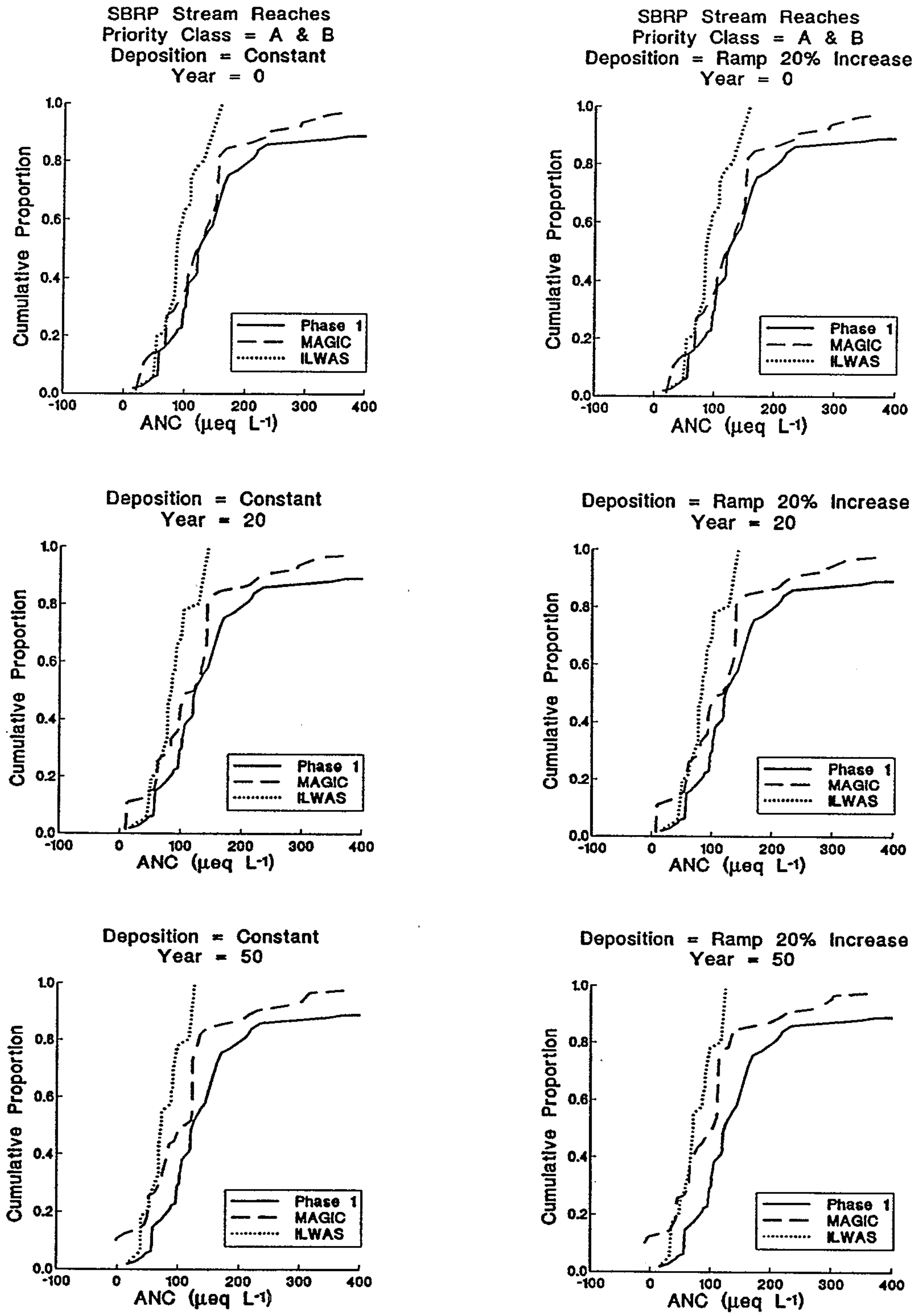


Figure 10-70. Comparison of ILWAS and MAGIC projections for ANC at years 0, 20, and 50 for SBRP streams, Priority Classes A and B, under current and increased deposition.

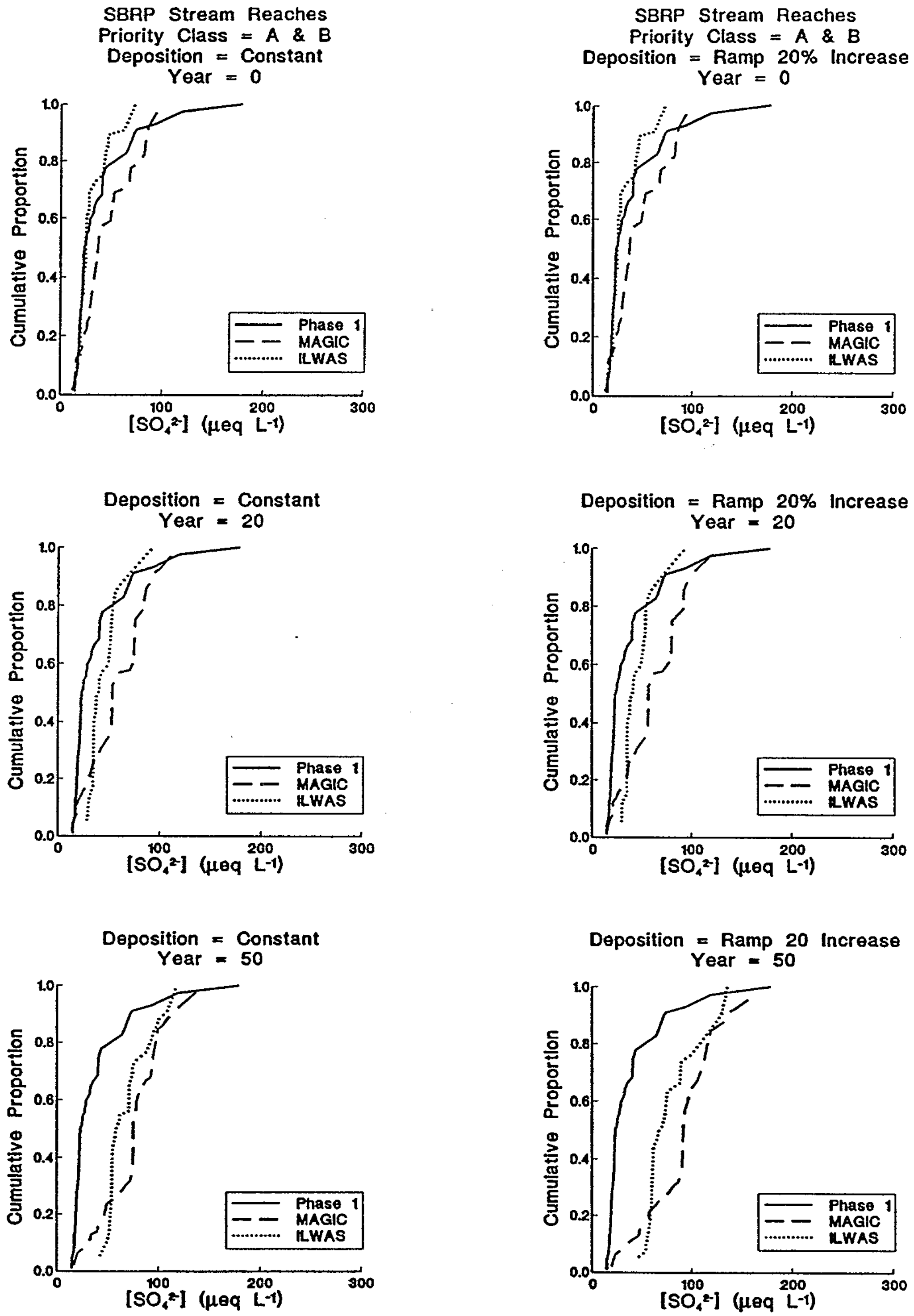


Figure 10-71. Comparison of ILWAS and MAGIC projections for sulfate concentration at years 0, 20, and 50 for SBRP streams, Priority Classes A and B, under current and increased deposition.

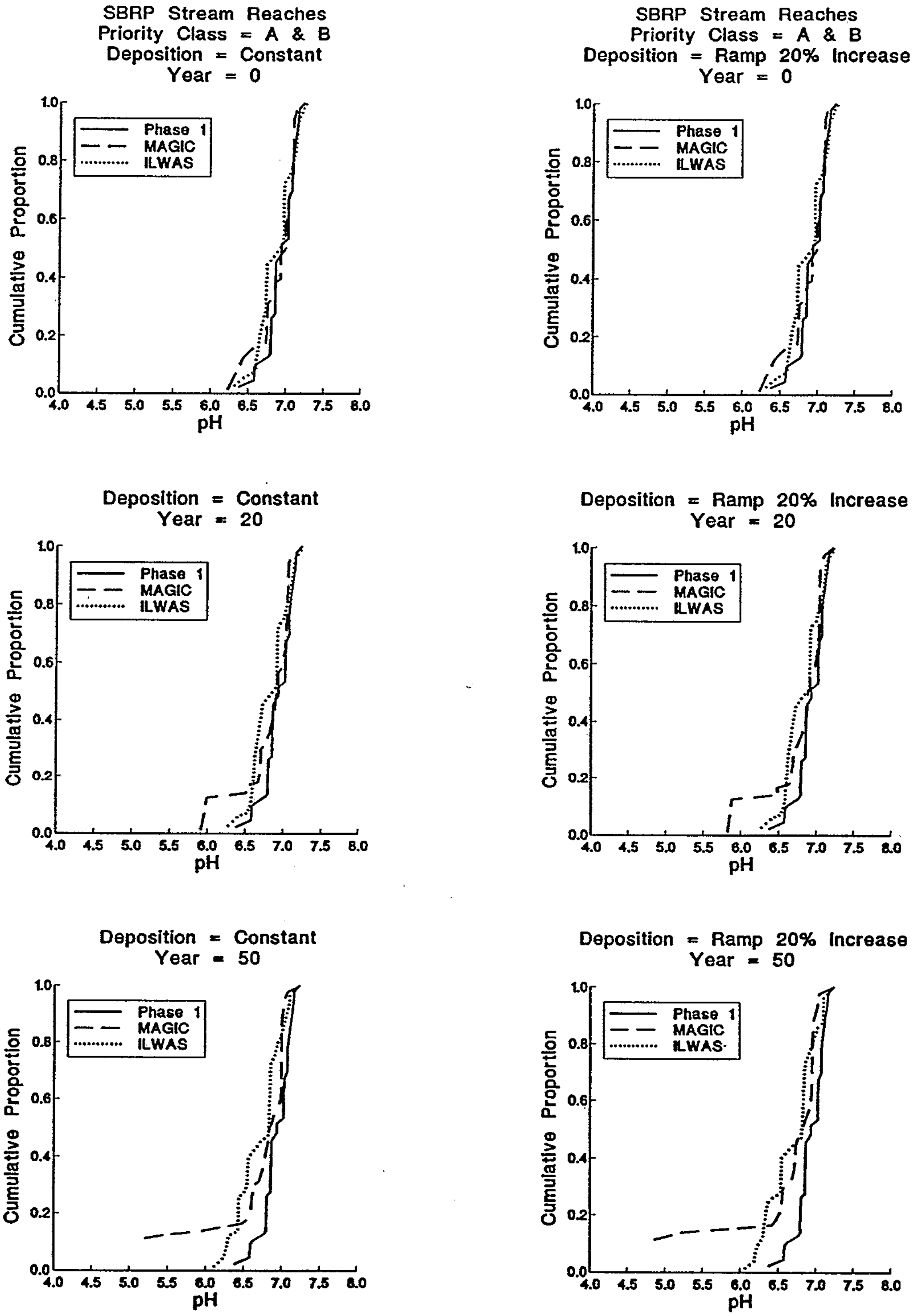


Figure 10-72. Comparison of ILWAS and MAGIC projections for pH at years 0, 20, and 50 for SBRP streams, Priority Classes A and B, under current and increased deposition.

Table. 10-19. Descriptive Statistics of Projected ANC, Sulfate, Percent Sulfur Retention, and Calcium Plus Magnesium for SBRP Streams in Priority Classes A and B Using ILWAS and MAGIC for Both Current and Increased Deposition

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
			Current Deposition				
ANC							
Model Year 0							
ILWAS	98	37	22	83	87	118	159
MAGIC	109	46	20	70	118	152	208
Model Year 20							
ILWAS	91	33	21	78	85	104	145
MAGIC	100	48	10	62	99	142	210
Model Year 50							
ILWAS	79	31	19	53	72	99	126
MAGIC	87	49	-3	52	85	124	215
SO_4^{2-}							
Model Year 0							
ILWAS	31	16	12	21	25	40	73
MAGIC	49	26	12	30	37	68	99
Model Year 20							
ILWAS	47	18	29	35	40	54	93
MAGIC	61	28	13	43	54	76	118
Model Year 50							
ILWAS	71	23	42	55	59	88	118
MAGIC	79	31	16	69	75	95	144
pH							
Model Year 0							
ILWAS	6.82	0.23	6.32	6.71	6.96	7.09	7.27
MAGIC	6.82	0.23	6.23	6.76	6.99	7.09	7.23
Model Year 20							
ILWAS	6.77	0.23	6.27	6.63	6.91	7.05	7.27
MAGIC	6.62	0.34	5.92	6.71	6.91	7.06	7.24
Model Year 50							
ILWAS	6.64	0.28	6.10	6.44	6.84	6.95	7.23
MAGIC	6.05	0.58	5.20	6.63	6.85	7.00	7.25
% S Retention							
Model Year 0							
ILWAS	74	11	37	64	80	80	89
MAGIC	58	21	24	35	65	77	89
Model Year 20							
ILWAS	60	11	29	55	65	66	82
MAGIC	47	22	18	28	48	67	88
Model Year 50							
ILWAS	40	14	20	22	46	49	74
MAGIC	33	22	5	21	24	30	85

continued

Table 10-19 (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
Ca + Mg							
Model Year 0							
ILWAS	88	27	39	64	82	104	128
MAGIC	107	36	50	85	115	127	191
Model Year 20							
ILWAS	90	26	41	62	98	105	132
MAGIC	111	35	53	86	121	128	186
Model Year 50							
ILWAS	94	26	44	73	96	113	143
MAGIC	114	33	57	88	115	134	181
20% Increase in Deposition							
ANC							
Model Year 0							
ILWAS	98	37	22	83	87	118	159
MAGIC	109	46	20	70	118	152	208
Model Year 20							
ILWAS	90	33	21	78	85	104	144
MAGIC	97	48	8	61	95	140	209
Model Year 50							
ILWAS	79	32	19	51	72	100	126
MAGIC	79	49	-10	46	80	114	216
SO_4^{2-}							
Model Year 0							
ILWAS	31	16	12	21	25	40	73
MAGIC	49	26	12	30	37	68	99
Model Year 20							
ILWAS	48	18	30	35	41	54	94
MAGIC	65	30	15	46	57	81	128
Model Year 50							
ILWAS	82	29	46	62	69	100	136
MAGIC	95	38	19	83	92	112	175
pH							
Model Year 0							
ILWAS	6.82	0.23	6.32	6.71	6.96	7.09	7.27
MAGIC	6.82	0.23	6.23	6.76	6.99	7.09	7.23
Model Year 20							
ILWAS	6.77	0.23	6.27	6.63	6.91	7.05	7.27
MAGIC	6.55	0.38	5.83	6.70	6.89	7.05	7.23
Model Year 50							
ILWAS	6.60	0.30	6.06	6.41	6.83	6.96	7.23
MAGIC	5.72	0.69	4.86	6.57	6.82	6.96	7.25

continued

Table 10-19 (Continued)

Model	Mean	Std. Dev.	Min.	P_25	Median	P_75	Max.
% S Retention							
Model Year 0							
ILWAS	74	11	37	64	80	80	89
MAGIC	58	21	24	35	65	77	89
Model Year 20							
ILWAS	64	10	36	60	68	70	84
MAGIC	51	20	25	32	51	69	88
Model Year 50							
ILWAS	42	15	18	26	48	50	77
MAGIC	32	23	4	22	25	29	86
Ca + Mg							
Model Year 0							
ILWAS	88	27	39	64	82	104	128
MAGIC	107	36	50	85	115	127	191
Model Year 20							
ILWAS	90	26	41	61	99	105	133
MAGIC	113	36	53	86	122	130	189
Model Year 50							
ILWAS	101	27	52	79	103	122	149
MAGIC	120	35	60	88	120	147	187

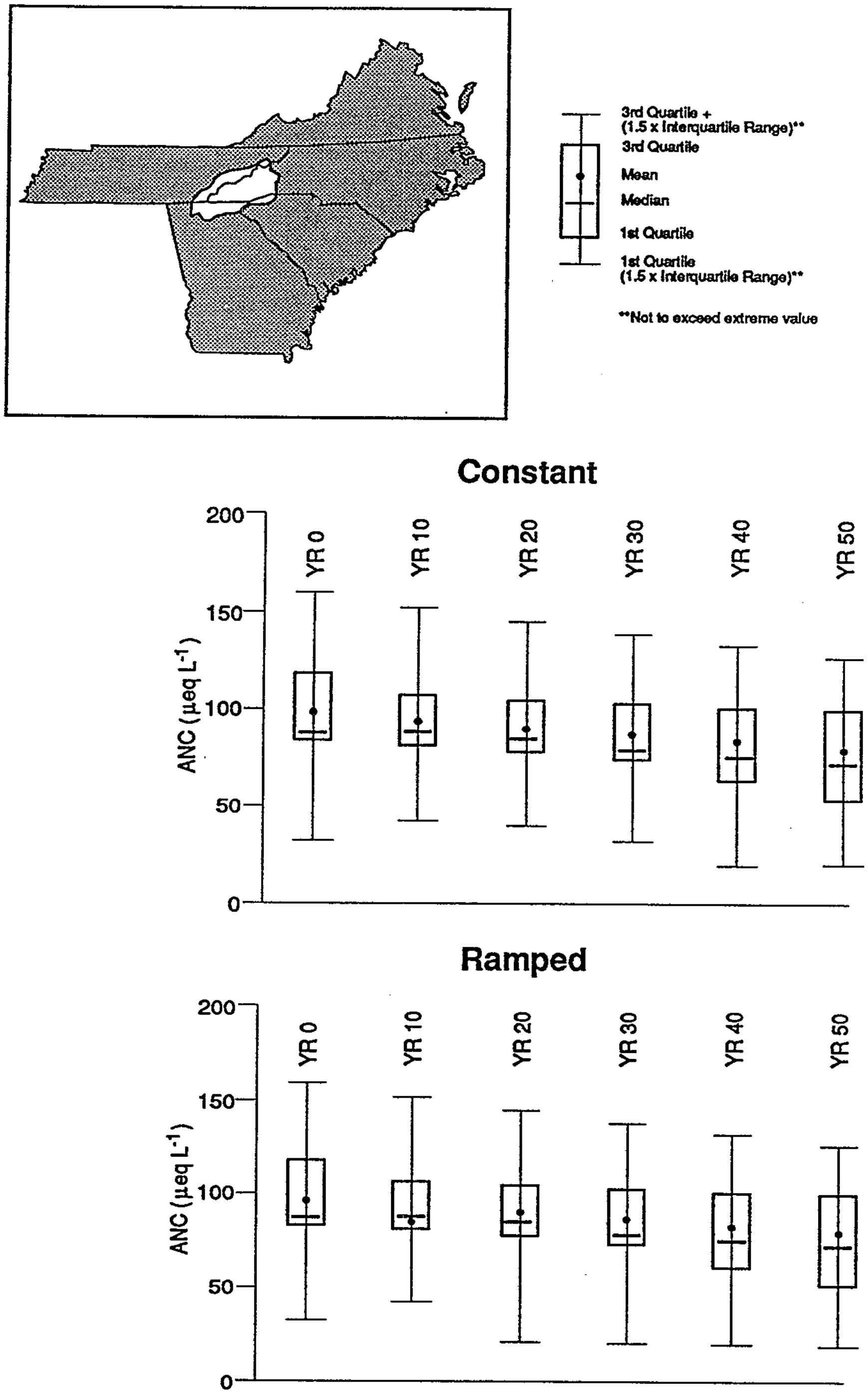


Figure 10-73. Box and whisker plots for ANC distributions in 10-year intervals projected using ILWAS for SBRP streams, Priority Classes A and B, for current and increased deposition.

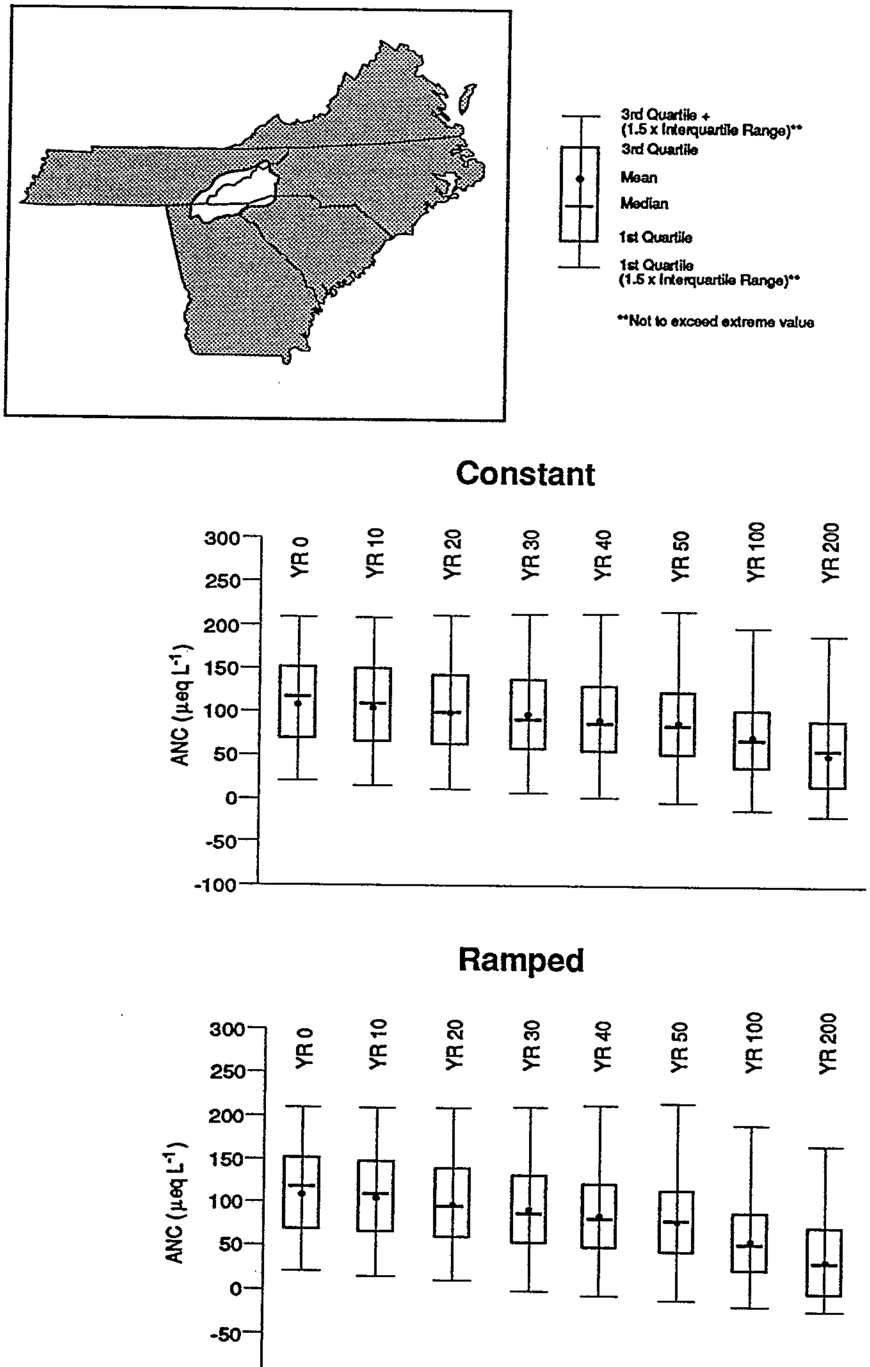


Figure 10-74. Box and whisker plots for ANC distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A and B, for current and increased deposition.

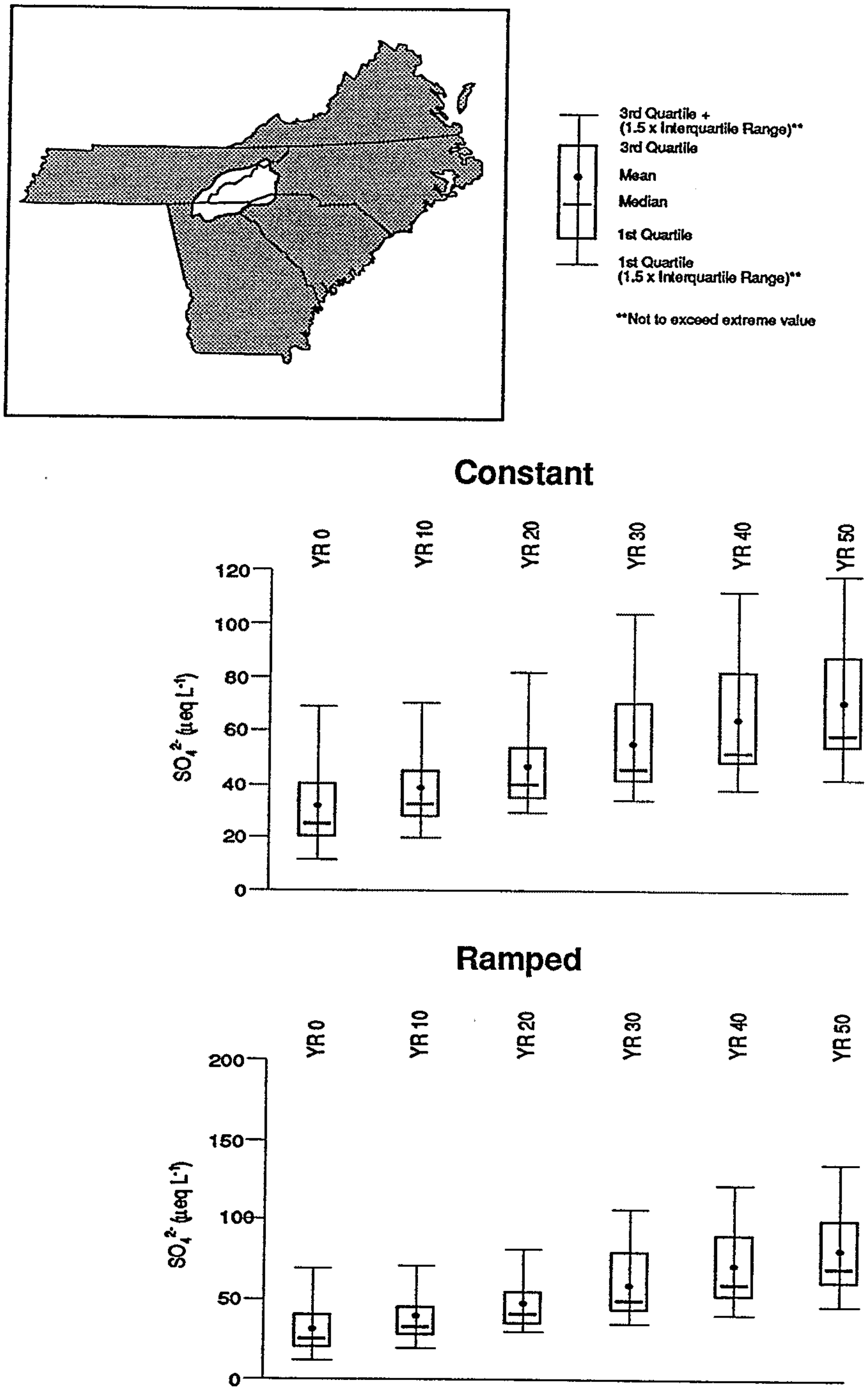


Figure 10-75. Box and whisker plots for sulfate distributions in 10-year intervals projected using ILWAS for SBRP streams, Priority Classes A and B, for current and increased deposition.

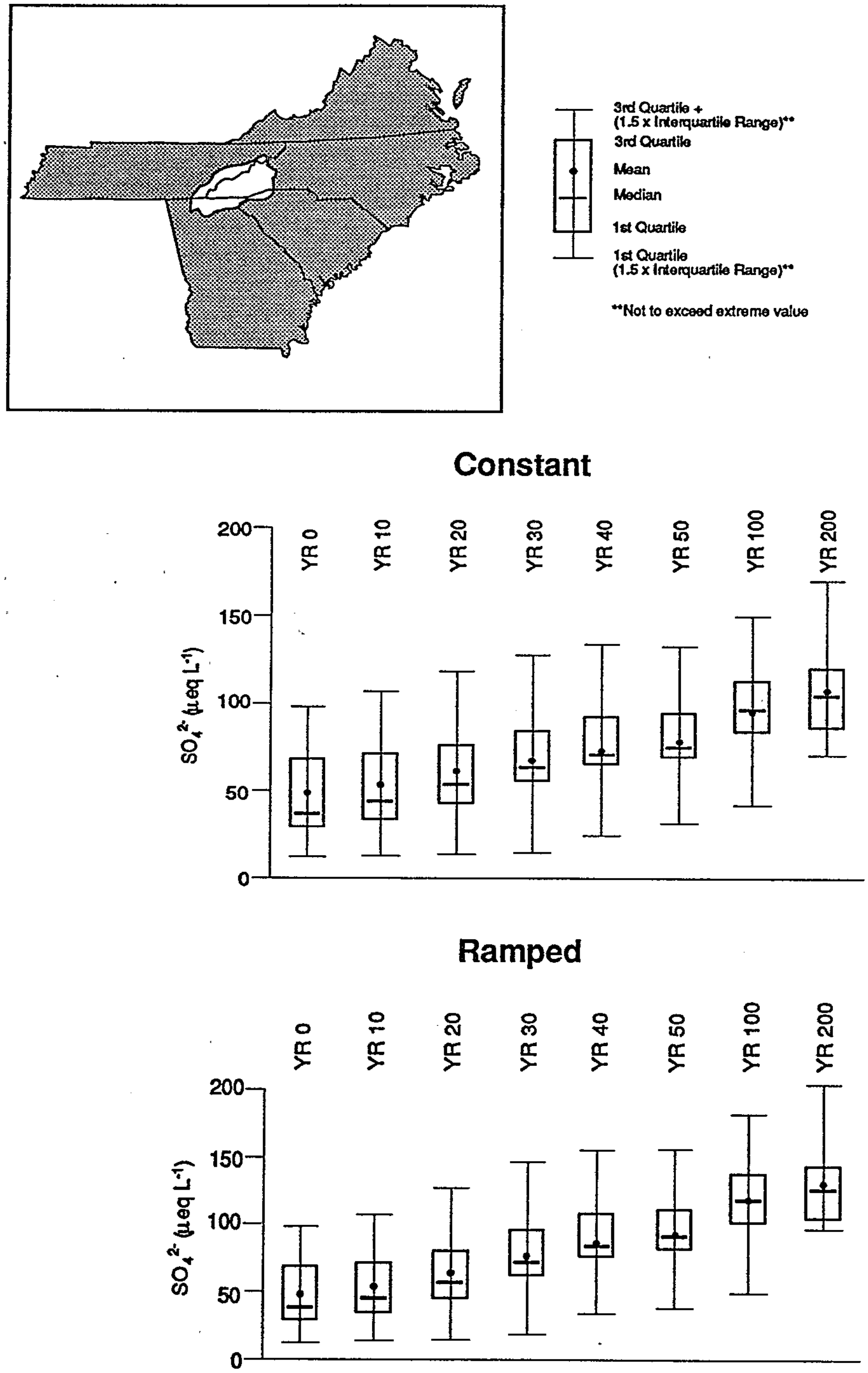


Figure 10-76. Box and whisker plots for sulfate distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A and B, for current and increased deposition.

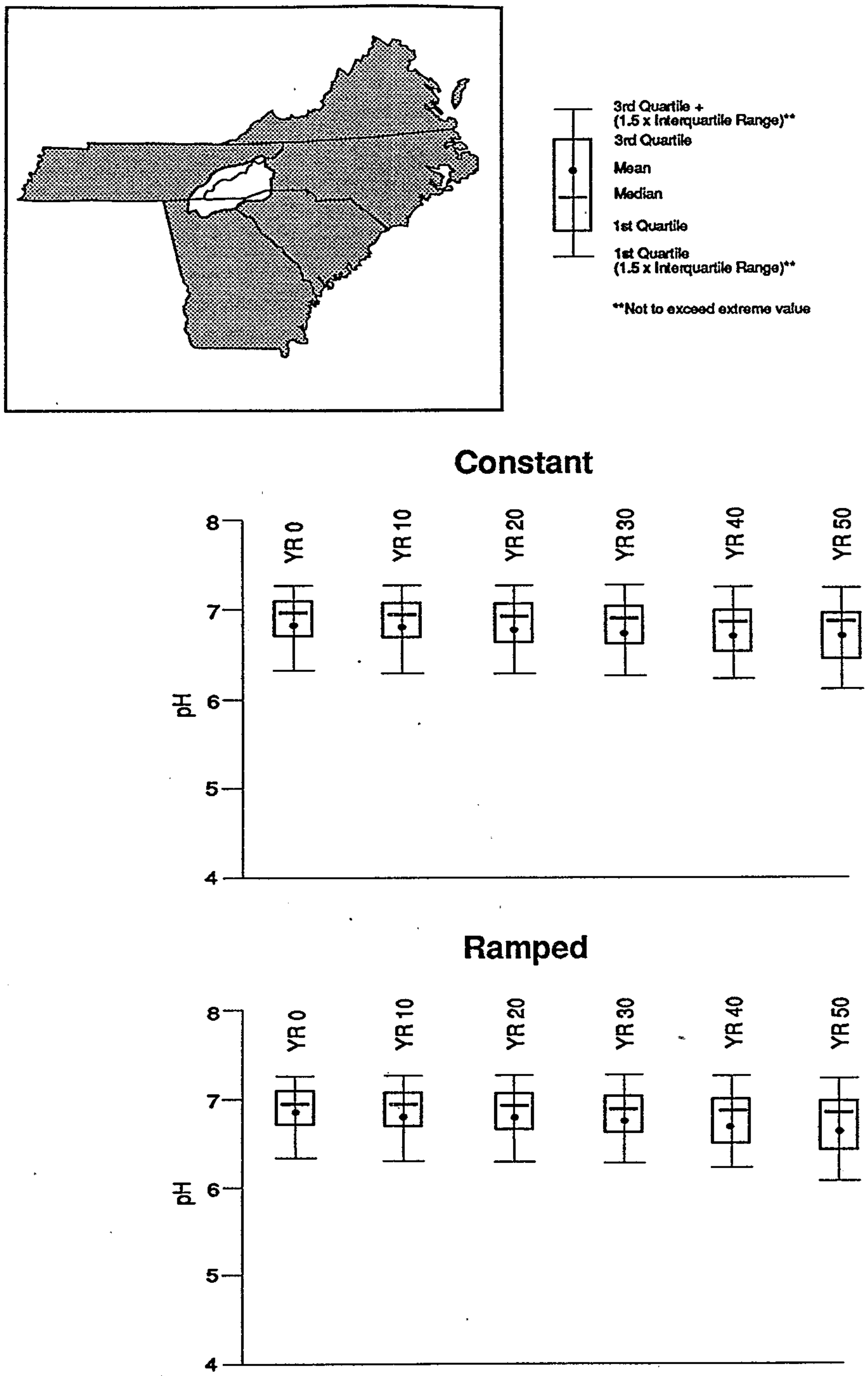


Figure 10-77. Box and whisker plots for pH distributions in 10-year intervals projected using ILWAS for SBRP streams, Priority Classes A and B, for current and increased deposition.

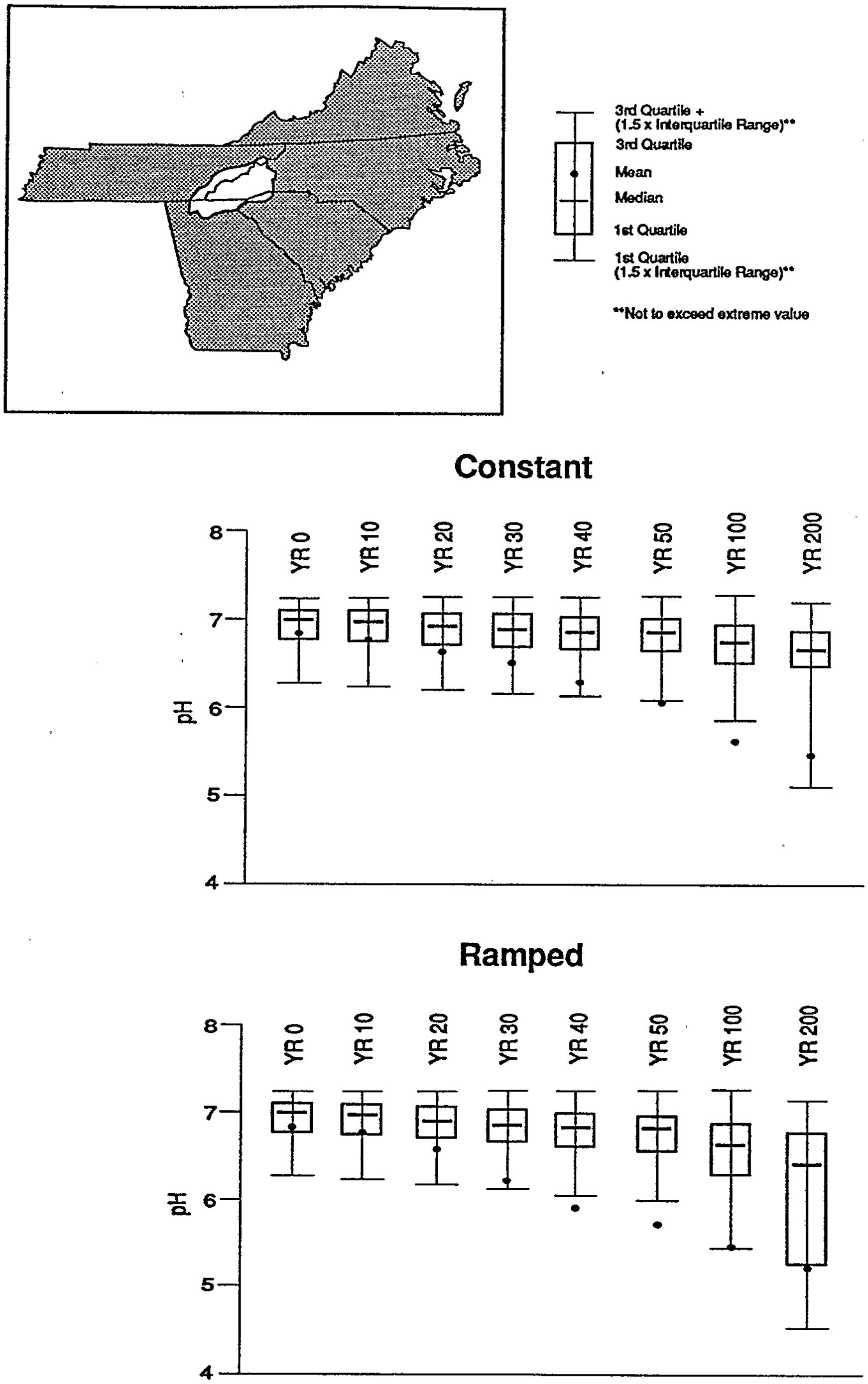


Figure 10-78. Box and whisker plots for pH distributions in 10-year intervals projected using MAGIC for SBRP streams, Priority Classes A and B, for current and increased deposition.

10.11.2.2.2 Rate of change of ANC, sulfate, and pH over 50 years -

The change in median ANC and sulfate concentrations and in pH for streams in the SBRP are shown in box and whisker plots (Figures 10-73 through 10-78). Median ANC was projected to change by about -15 μeq L^{-1} over the 50-year period using the ILWAS model for both current deposition and an increase in deposition. MAGIC projected median changes in ANC of about -33 μeq L^{-1} for current deposition and about -38 μeq L^{-1} for increased deposition (Table 10-19). The change in ANC was relatively small for the first 10 to 20 years and then decreased relatively linearly for the next 30 years.

Median sulfate concentrations, estimated from the ILWAS model, were projected to increase by about 34 μeq L^{-1} over the 50-year period for current deposition and about 44 μeq L^{-1} for increased deposition over the 50 years (Table 10-19). Using MAGIC, the median sulfate concentrations were projected to increase by about 38 μeq L^{-1} for current deposition and about 55 μeq L^{-1} for increased deposition. There was a relatively linear increase in sulfate concentrations over the 50-year period for both models.

Median and lower quartile pH values were projected to change less than 0.2 units for both ILWAS MAGIC over 50 years for either deposition scenario.

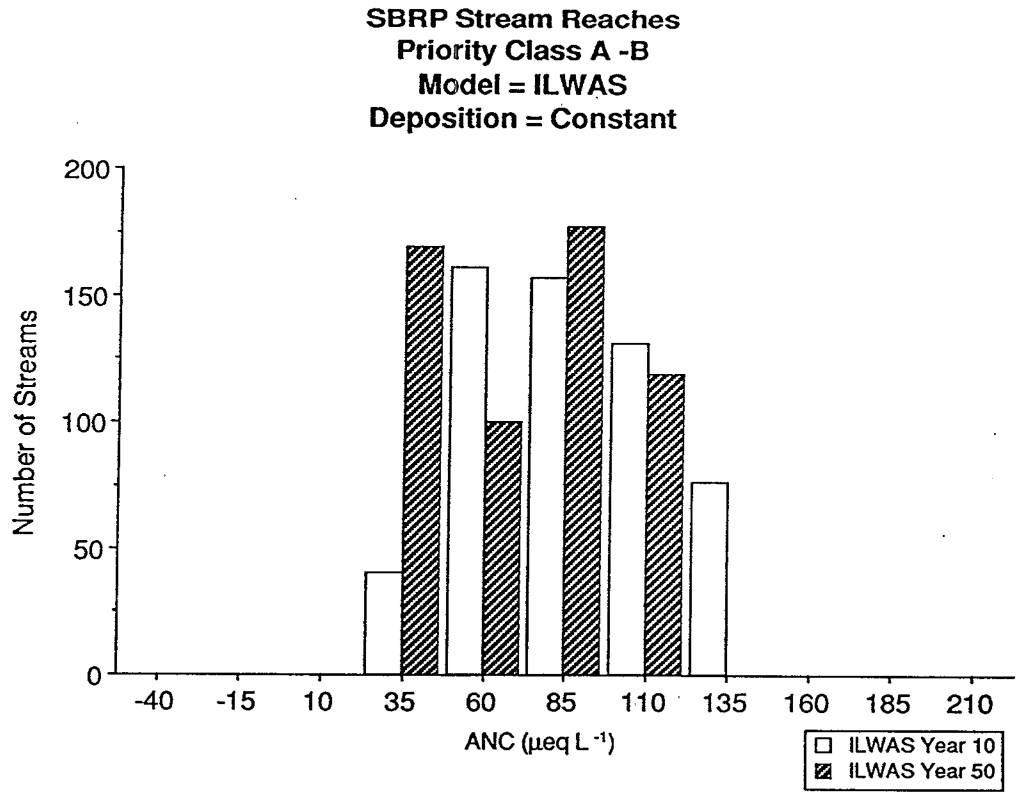
There was an indication that the changes in ANC and sulfate were functions of the initial (NSS - Pilot Survey) ANC using the ILWAS model (Table 10-19). A larger increase in sulfate concentrations and a larger decrease in ANC in the lower ANC groups (i.e., $25 < ANC < 100$ μeq L^{-1}) than in the higher ANC groups (i.e., $100 < ANC < 400$ μeq L^{-1}) were projected with the ILWAS model. Relatively similar changes in ANC and sulfate among ANC groups were projected, however, with MAGIC. This result is indicated in the number of streams that change frequency intervals for distributions of ANC and sulfate concentration over the 40-year period (Figures 10-79 through 10-82).

10.11.3 <u>Regional Comparisons</u>

This section focuses on regional comparisons among the aquatic systems in the NE and the SBRP. Although the representative northeastern systems are lakes and the SBRP systems are streams, it is watershed processes that control projected changes in ANC and sulfate. Comparisons of relationships between ANC and sulfate in these systems, and of changes in pH and calcium plus magnesium with changes in sulfate, can reveal similarities and differences in these processes between the regions.

10.11.3.1 Northeastern Projections of Sulfate Steady State

All three models projected that northeastern lakes would be at sulfate steady state within 50 years at current levels of deposition (Figure 10-83). To examine sulfate steady state in the NE, projected sulfate concentrations are compared with steady-state sulfate concentrations computed using current deposition and mass balance. A 1:1 line indicates perfect agreement between the two values. These sulfate steady-state projections are consistent with the percent sulfur retention of northeastern watersheds presented in Tables 10-14, 10-16 and 10-17. With a 30 percent reduction, the projected sulfate values fall below the 1:1 line, indicating a reduction in lake sulfate concentrations within a 50-year period compared to the



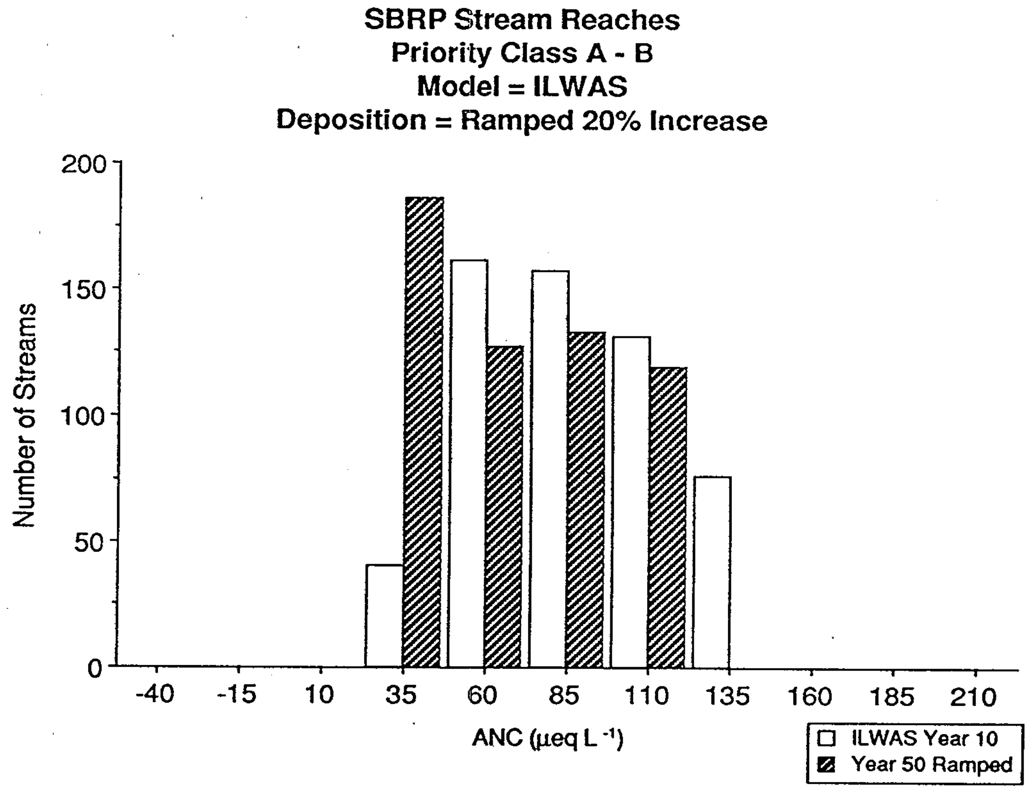


Figure 10-79. ILWAS ANC population distributions at year 10 and year 50 for current and increased deposition, SBRP Priority Class A and B streams.

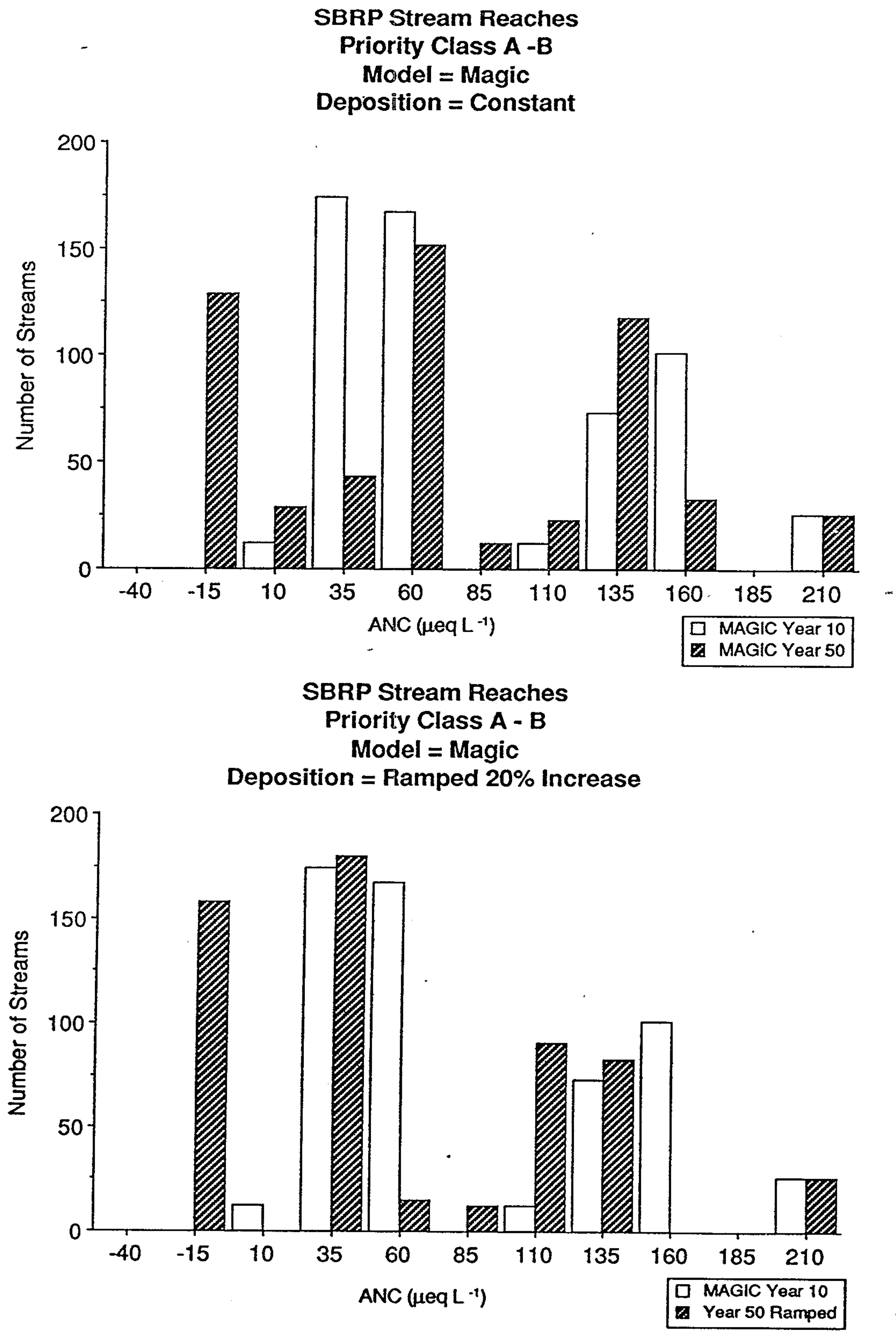


Figure 10-80. MAGIC ANC population distributions at year 10 and year 50 for current and increased deposition, SBRP Priority Class A and B streams.

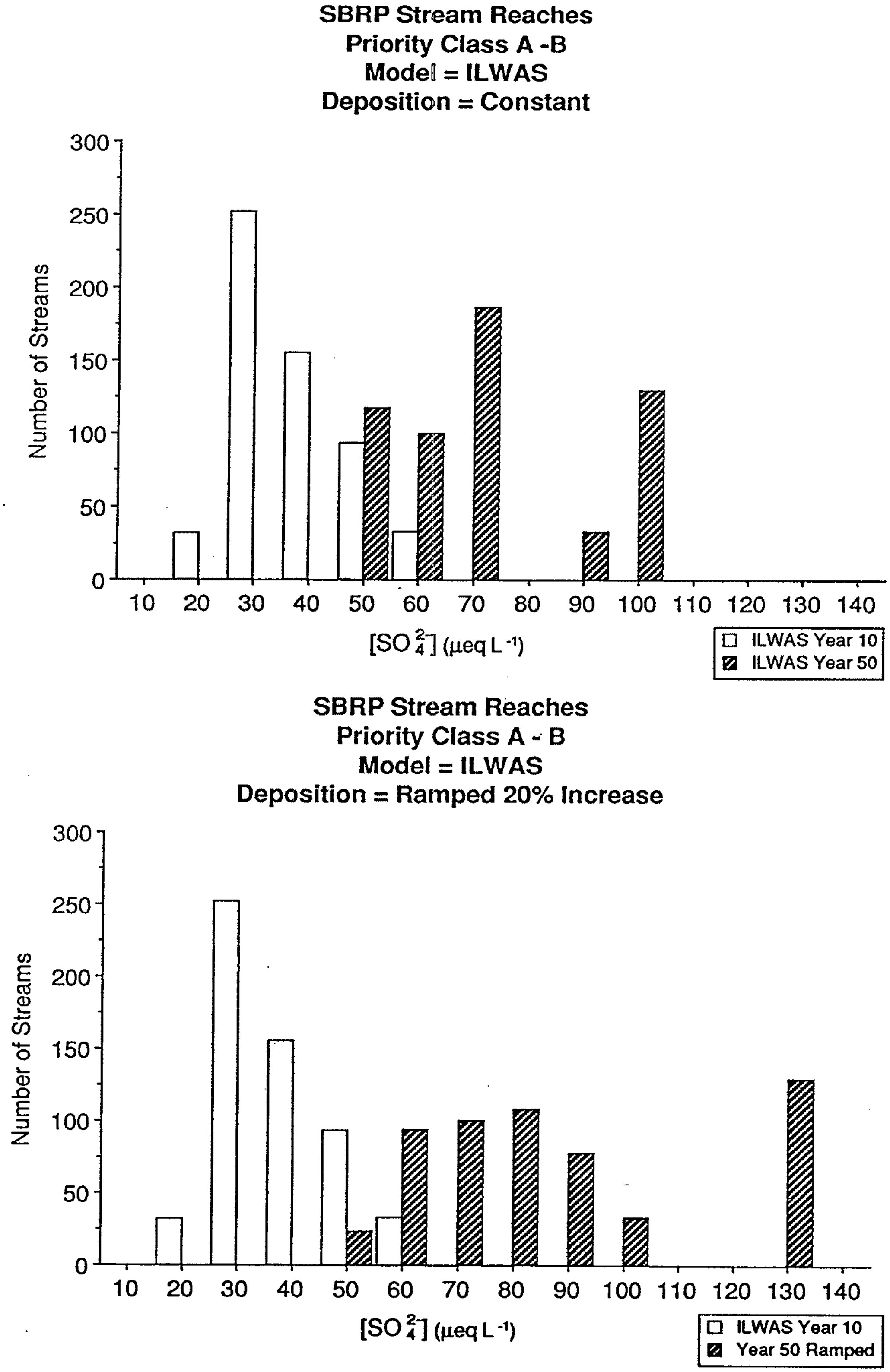
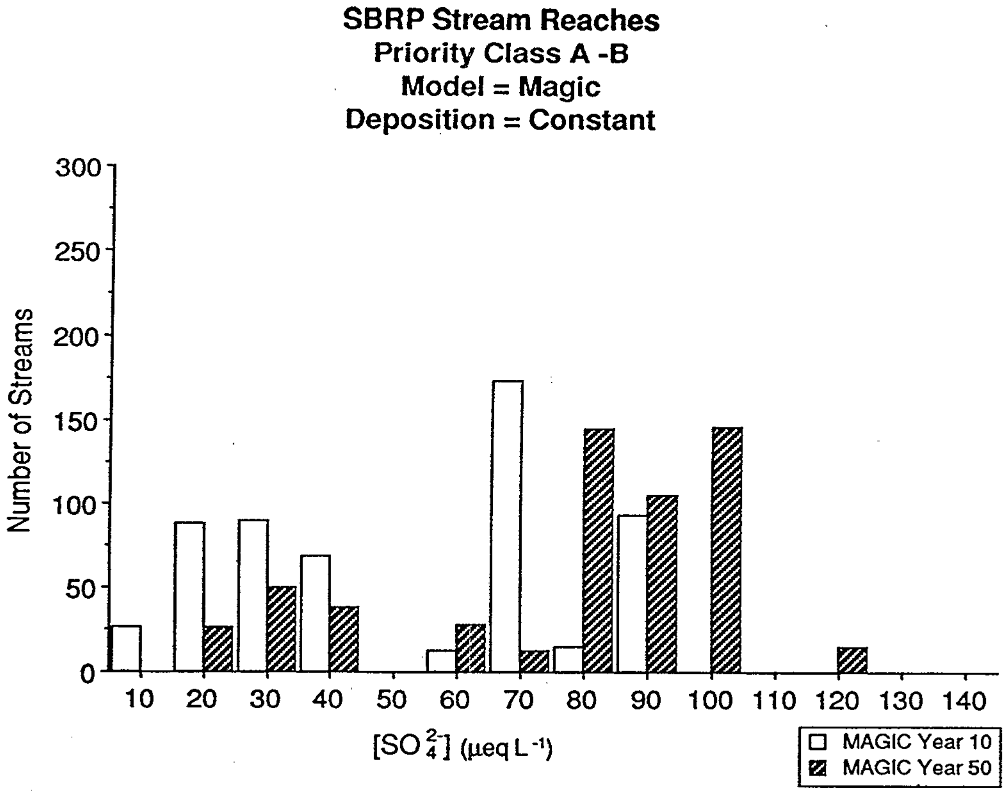


Figure 10-81. ILWAS sulfate population distributions at year 10 and year 50 for current and increased deposition, SBRP Priority Class A and B streams.



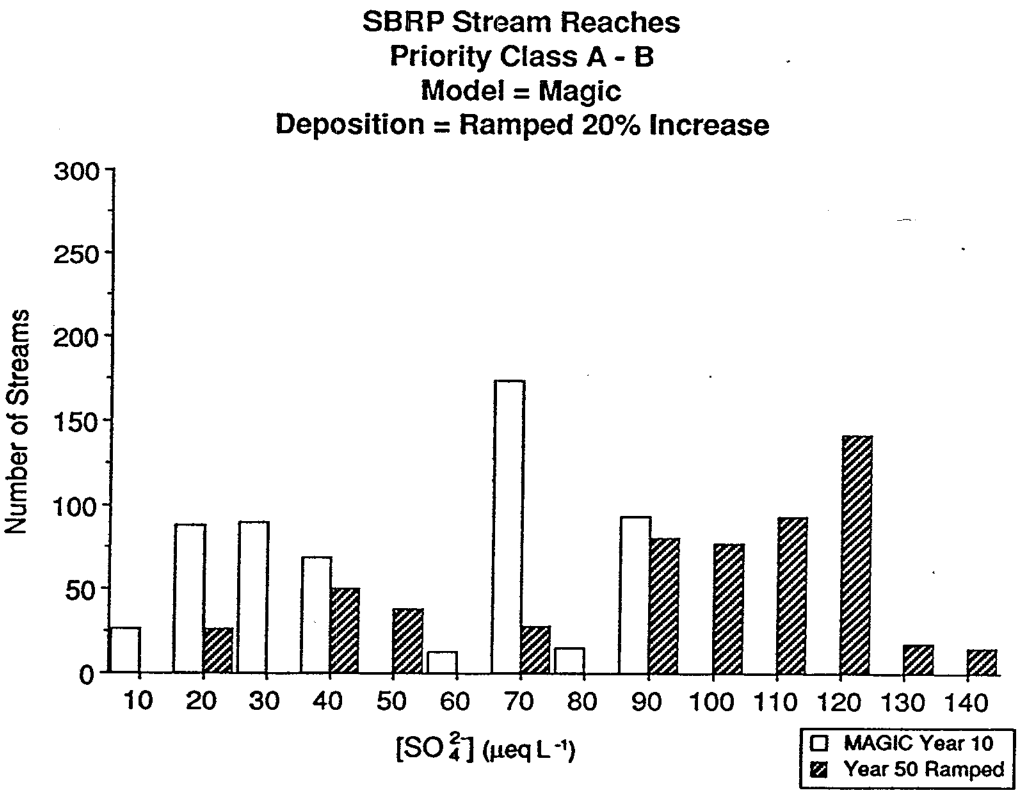


Figure 10-82. MAGIC sulfate population distributions at year 10 and year 50 for current and increased deposition, SBRP Priority Class A and B streams.

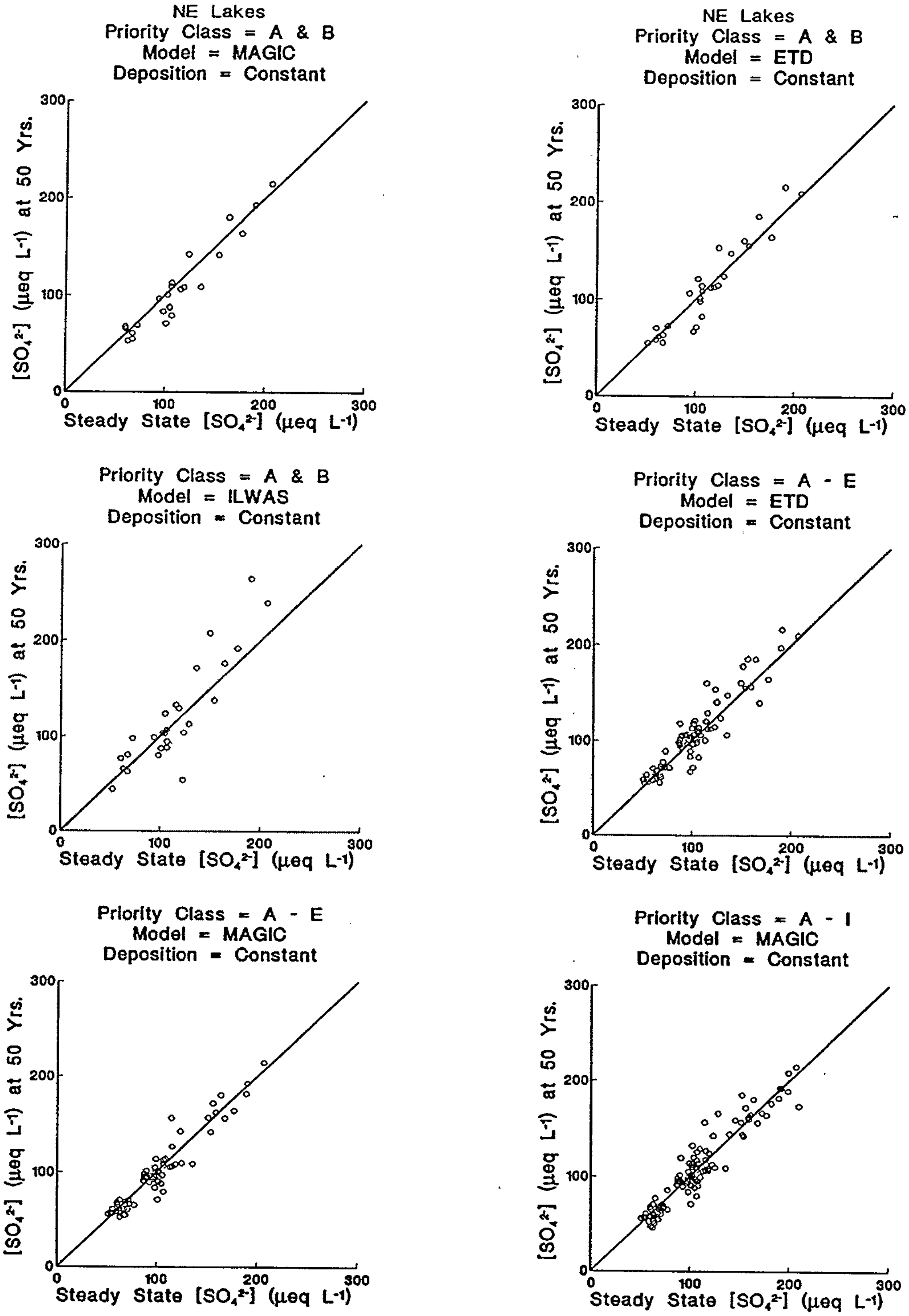


Figure 10-83. Comparison of projected sulfate versus sulfate steady-state concentrations using ETD, ILWAS, and MAGIC for NE lakes.

sulfate concentrations projected for current levels of deposition (Figure 10-84). The watershed sulfur retention values calculated on the basis of sulfur input/output indicate the watersheds are near zero sulfur retention (i.e., near sulfate steady state), after 50 years with a 30 percent deposition decrease. The estimated time to sulfate steady state in the NE is less than 50 years for both current and decreased deposition.

Comparisons of projected sulfate concentrations among models indicates excellent agreement among all models for both current and decreased deposition (Figure 10-85). Fewer data for ILWAS comparisons than for MAGIC and ETD are shown, because only 28 lakes were simulated. The 1:1 relationship among models, however, is evident.

10.11.3.2 Southern Blue Ridge Province Projections of Sulfate Steady State

Projections of sulfate steady state using MAGIC indicate sulfate steady state might be reached in the SBRP within 200 years under current and increased deposition (Figure 10-86). The 1:1 line on the figure indicates agreement between the projected and steady-state sulfate concentrations under current deposition, consistent with the projections of watershed sulfur retention presented in Table 10-19. The relationship between projected sulfate concentrations assuming a 20 percent increase in sulfate deposition indicates these sulfate concentrations lie above the 1:1 line for current deposition, because of the increased sulfate loading and greater sulfate steady-state concentrations. The estimated time to sulfate steady state in the SBRP is about 200 years, compared to less than 50 years in the NE.

10.11.3.3 ANC and Base Cation Dynamics -

All three models projected changes in ANC, sulfate, and pH. Only ILWAS and MAGIC, however, projected changes in base cations. Relationships between changes in ANC and sulfate concentrations and between changes in pH, calcium plus magnesium, and sulfate concentrations are examined in the following sections.

10.11.3.3.1 Northeast -

Comparisons of projected ANC concentrations among models for northeastern watersheds after 50 years are shown in Figure 10-87. The 1:1 line indicates excellent agreement among model projections. The comparisons for ILWAS contain only about 25 data points so the relationships are not as apparent.

The changes in ANC concentrations as functions of change in sulfate concentrations are shown in Figure 10-88 for all three models. For current deposition, the relationships are not apparent because the changes in ANC and sulfate concentrations were projected to be quite small. A negative trend with decreased deposition is apparent for MAGIC and ILWAS because of greater changes in ANC and sulfate concentrations. Given the uncertainty in the projections, however, the indicated trend is not significant.

The pH - ANC relationship for each of the models is compared in Figure 10-89. There is good agreement between the ETD and MAGIC relationships but greater scatter in the ILWAS pH - ANC relationship. The ILWAS ANC - pH relationship is modified by seasonal changes in the pCO_2 function

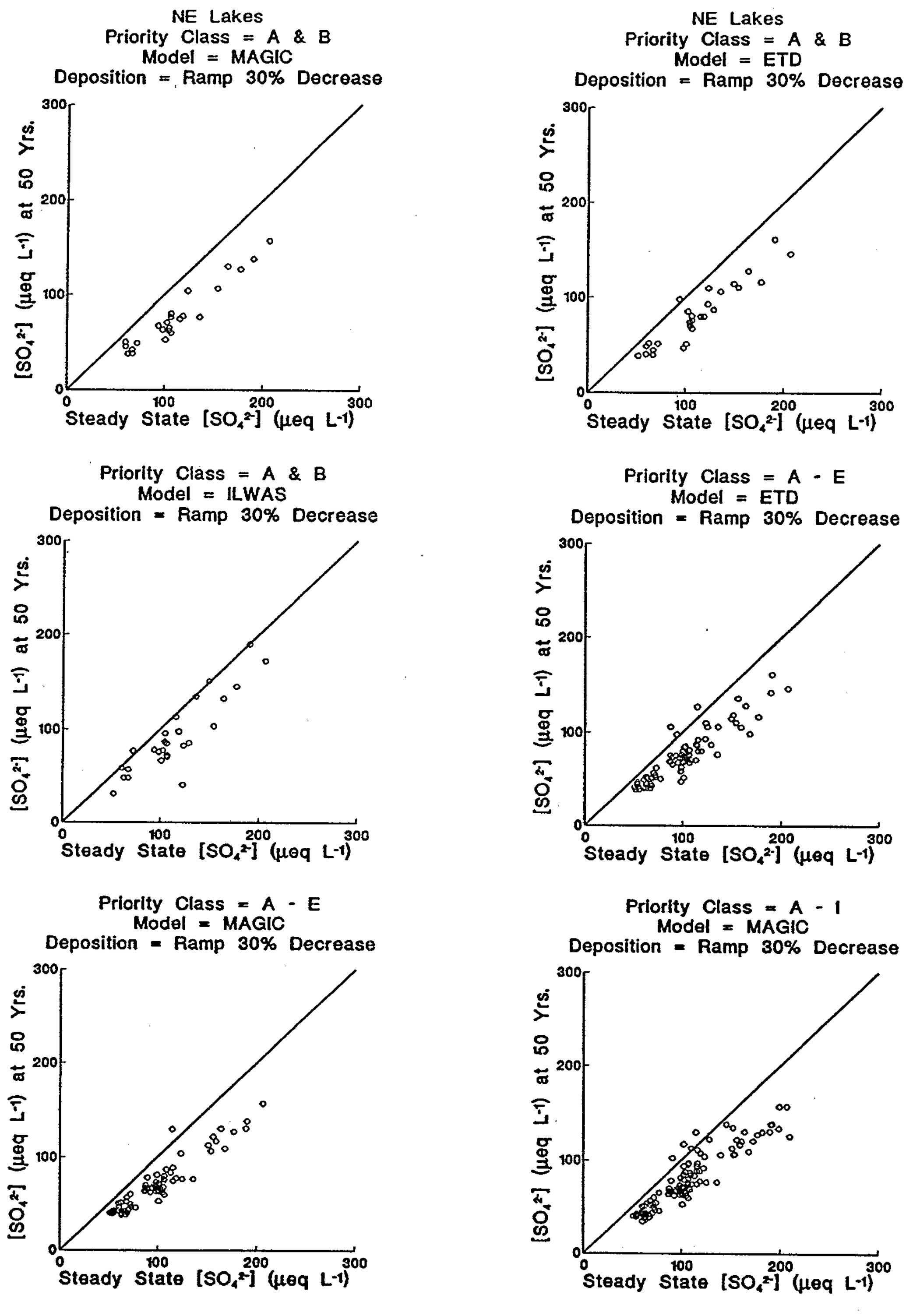


Figure 10-84. Comparison of projected sulfate concentrations under decreased deposition with the current sulfate steady-state concentrations using ETD, ILWAS, and MAGIC for NE lakes.

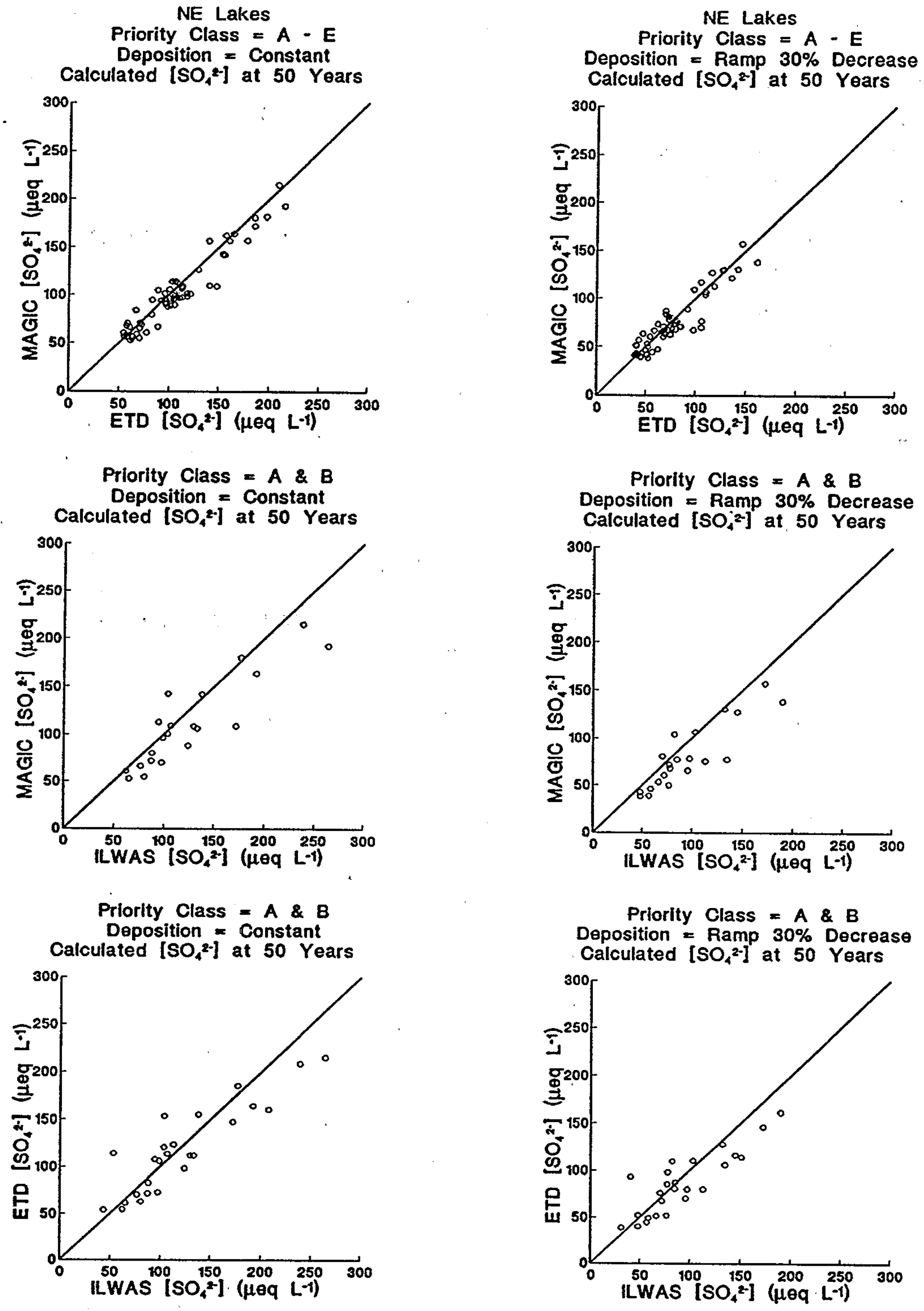


Figure 10-85. Comparison of projected sulfate concentrations between models for NE lakes after 50 years under current and decreased deposition.

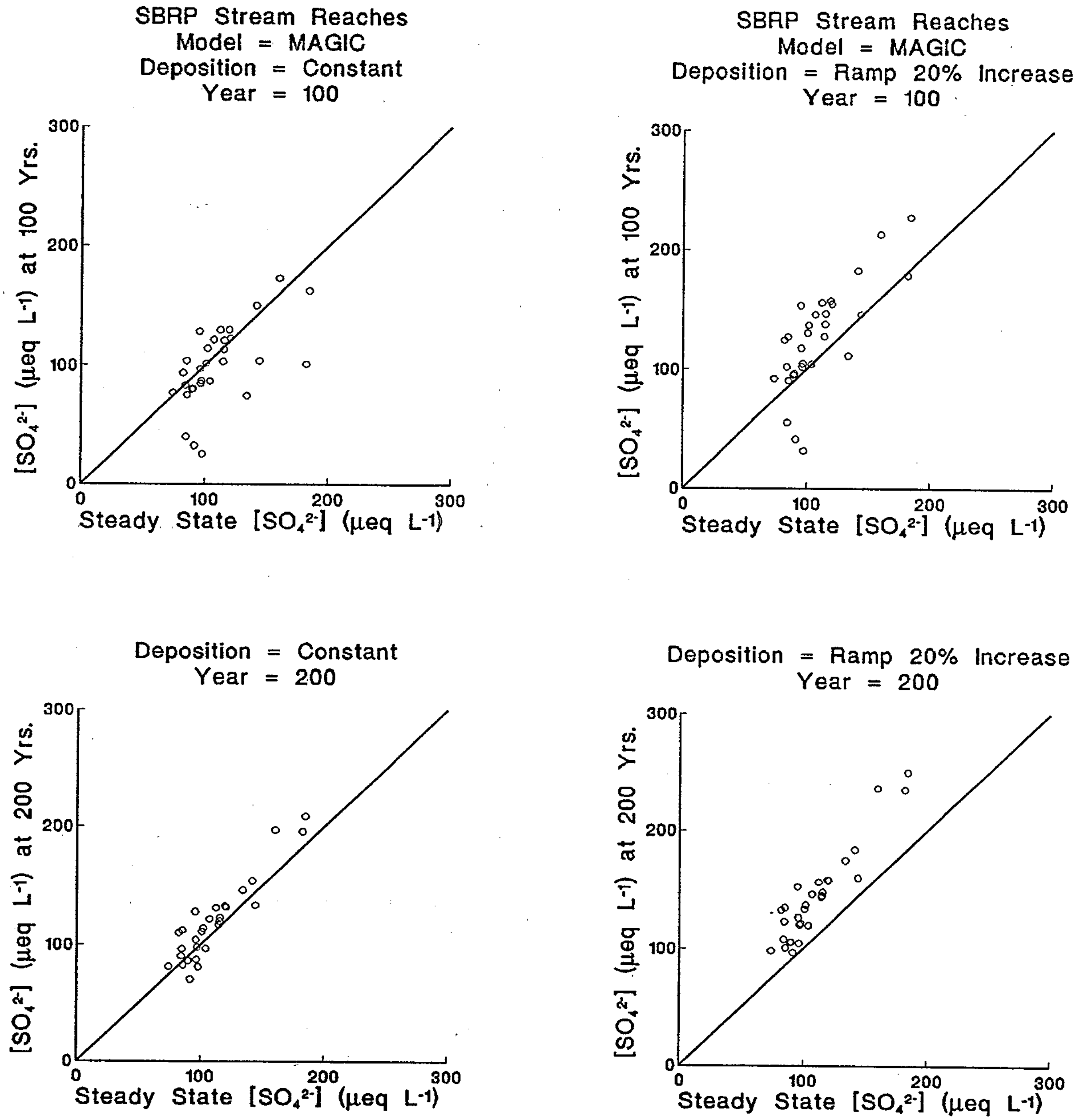


Figure 10-86. Comparison of projected sulfate versus sulfate steady-state concentrations for SBRP streams using MAGIC under both current and increased deposition.

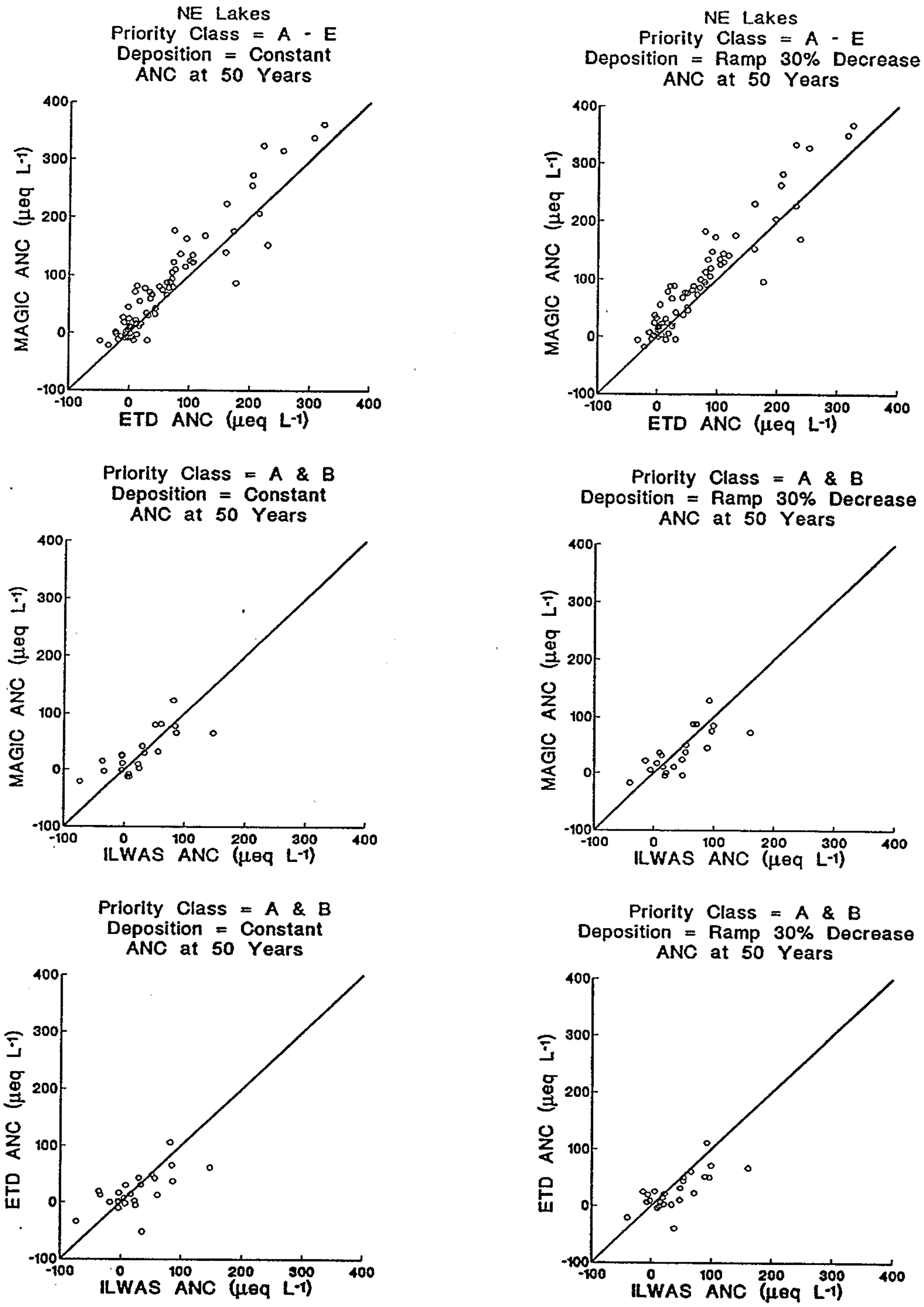


Figure 10-87. Comparison of projected ANC between models in NE lakes after 50 years under current and decreased deposition.

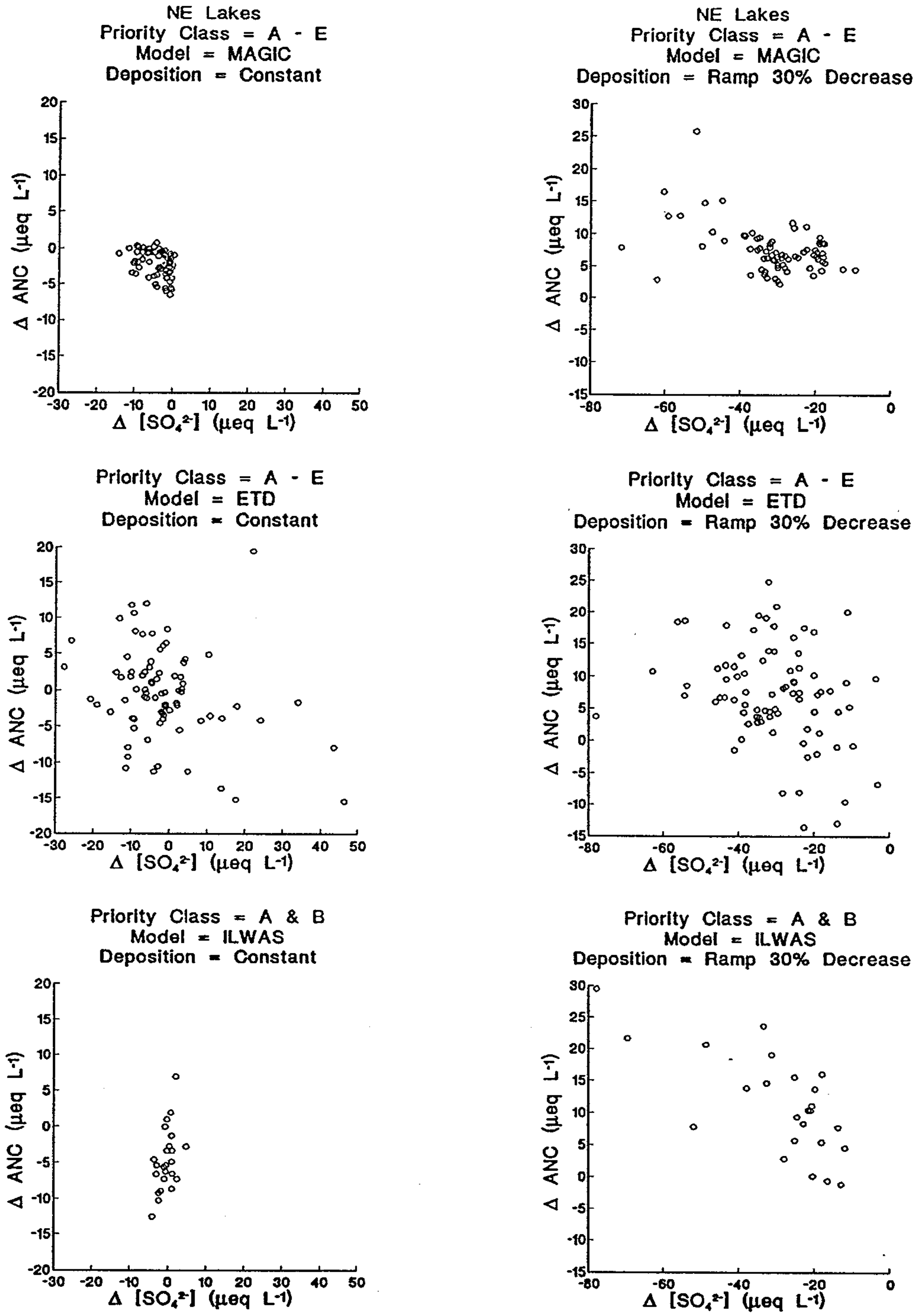
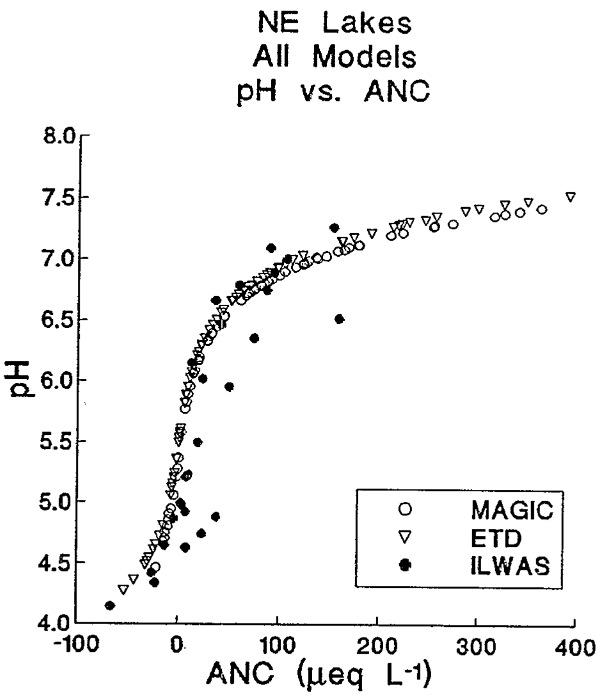


Figure 10-88. Projected changes in ANC as a function of changes in sulfate for NE lakes using ETD, ILWAS, and MAGIC for current and decreased deposition.



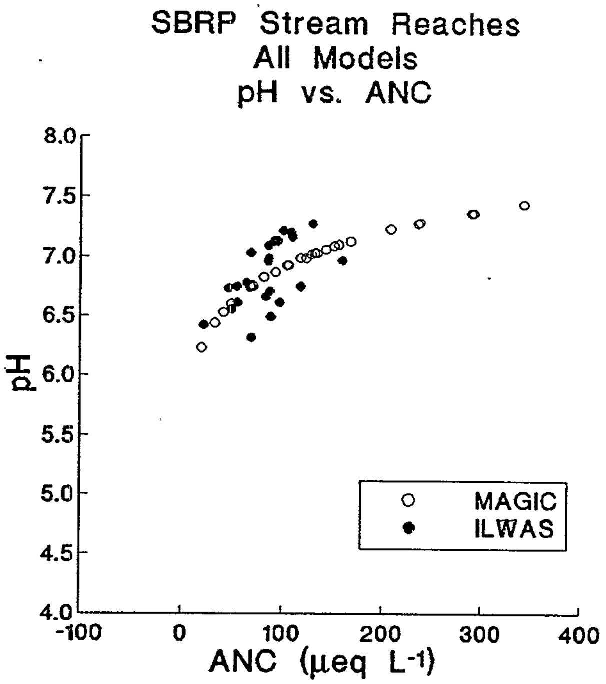


Figure 10-89. Comparison of pH - ANC relationship for each of the models.

and organic acid production/decomposition. Comparisons of projected pH values between models are shown in Figure 10-90. There is greater scatter about the 1:1 line at the lower pH projections for comparisons between all three model pairs with greater convergence on the 1:1 line at higher pH values.

Comparison of changes in calcium plus magnesium concentrations as a function of changes in sulfate concentrations is illustrated in Figure 10-91 for MAGIC and ILWAS. Minimal changes in calcium plus magnesium and sulfate under current deposition resulted in a grouping of lakes in the upper quadrant of the graph about the (0,0) point. The relationship between projected changes in calcium plus magnesium and sulfate concentrations under decreased deposition, however, was relatively linear for both MAGIC and ILWAS.

The projected rate of change for ANC and calcium plus magnesium, although small for the NE, is continuous and does not appear to asymptotically approach steady-state concentrations. This result is illustrated by a plot of the median ANC and calcium plus magnesium concentrations over time for 100 years using the MAGIC results under both current and decreased deposition (Figure 10-92). For current deposition, median ANC remains relatively constant for the first 20 years and then decreases. Median calcium plus magnesium concentrations, however, decrease over the entire 100-year period, although the rate of change slowly decreases. This rate of change is not significant considering the uncertainty in the projections, but the trend is apparent.

The projected change in ANC assuming decreased deposition approaches a peak in 50 years and then declines slightly over the next 50 years (Figure 10-92). The projected change in calcium plus magnesium decreases more rapidly over the 100-year period with decreased deposition than under current deposition. The change over the last 50 years was less than during the first 50 years.

The median sulfate concentration decreases from year 0 and asymptotically approaches a steady-state value by year 50 under current deposition. Median sulfate concentrations were projected to decrease linearly by 22 μeq L^{-1} by year 30 and asymptotically approach steady state by year 50 under decreased deposition.

Median pH is projected to change less than 0.1 unit over 100 years regardless of the deposition scenario. However, if the change in pH is compared with the original calibrated pH at year 0, all three models indicate the greatest change in pH occurs in lakes with initial pH values between about 5.0 and6.5 (Figure 10-93). Under current deposition, those lakes with pH values between 5.0 and 6.0 were projected using ILWAS and MAGIC to have the greatest decrease in pH. The ETD model also projected these lakes might experience the greatest change, but in both the positive and negative directions. Under decreased deposition, all three models projected lakes with initial pH values between 5.0 and 6.0 might have a net increase in pH of from 0.1 to 1.0 pH units.

10.11.3.3.2 Southern Blue Ridge Province -

Comparisons of model-projected ANC, sulfate concentration, and pH for SBRP watersheds after 50 years are shown in Figure 10-94. The 1:1 line indicates an apparent relationship among model projections, but there are relatively few points for inter-model comparison as well as considerable scatter about the 1:1 line.

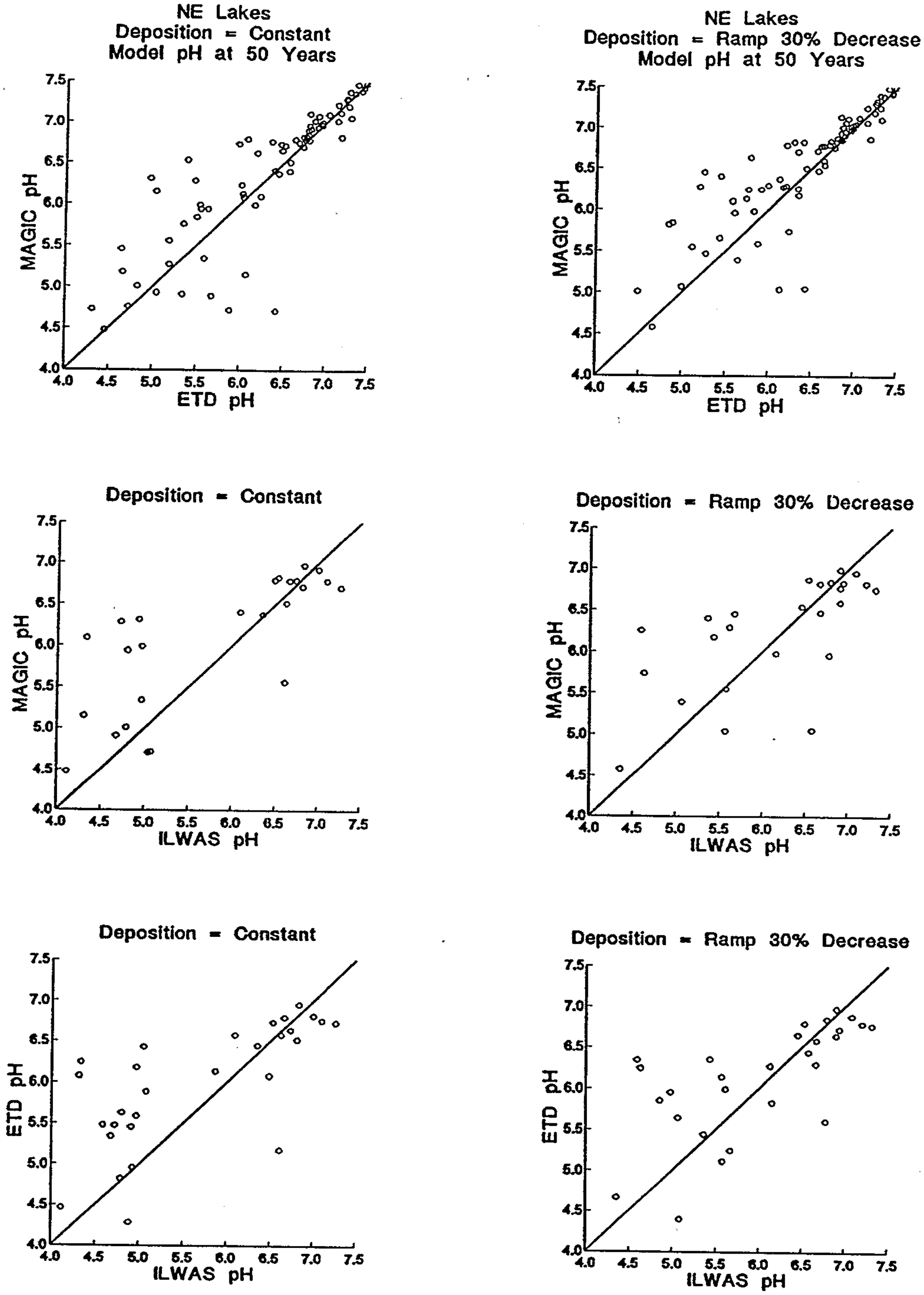


Figure 10-90. Comparison of projected pH values between models for NE lakes after 50 years under current and decreased deposition.

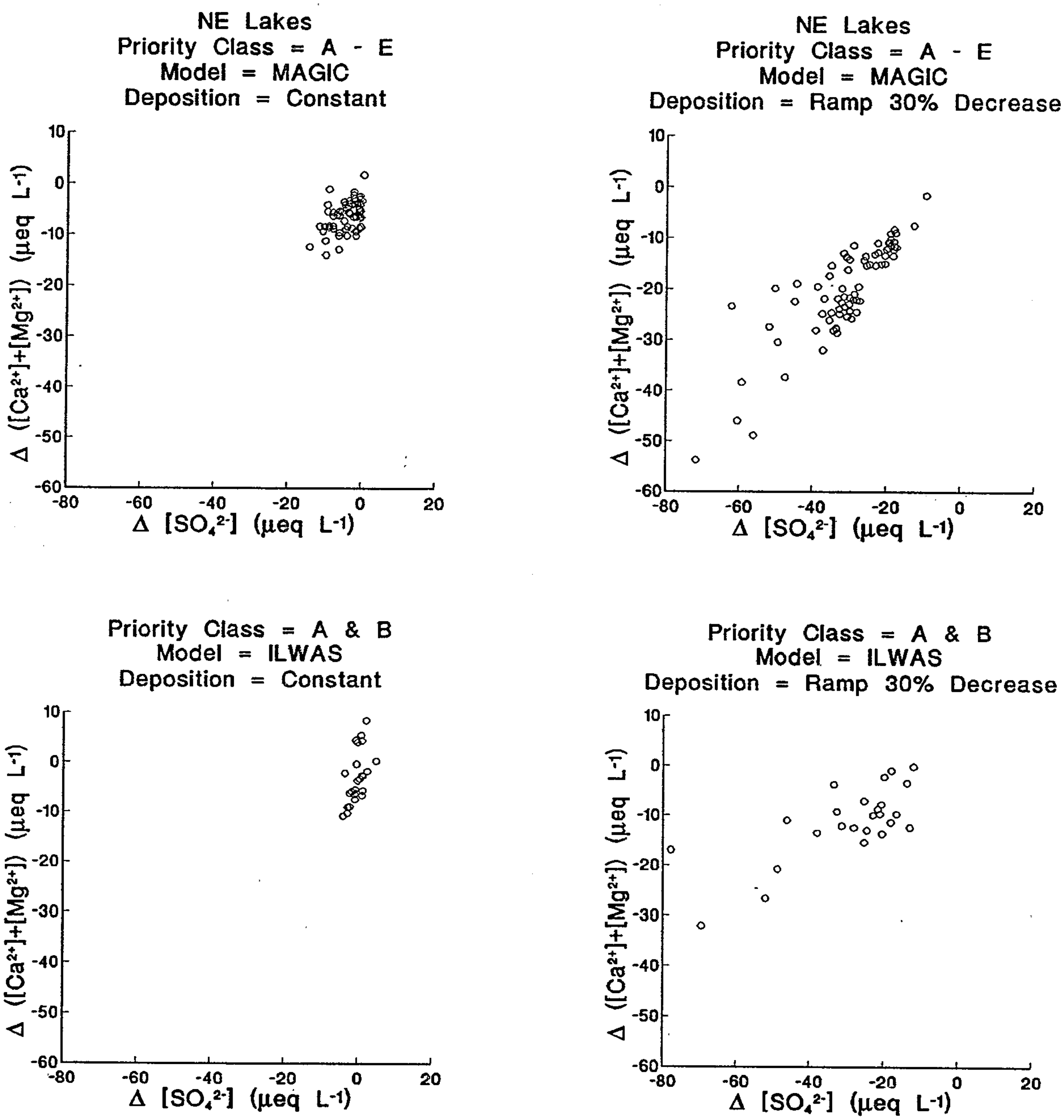


Figure 10-91. Comparison of projected changes in calcium and magnesium versus changes in sulfate using ILWAS and MAGIC for NE lakes.

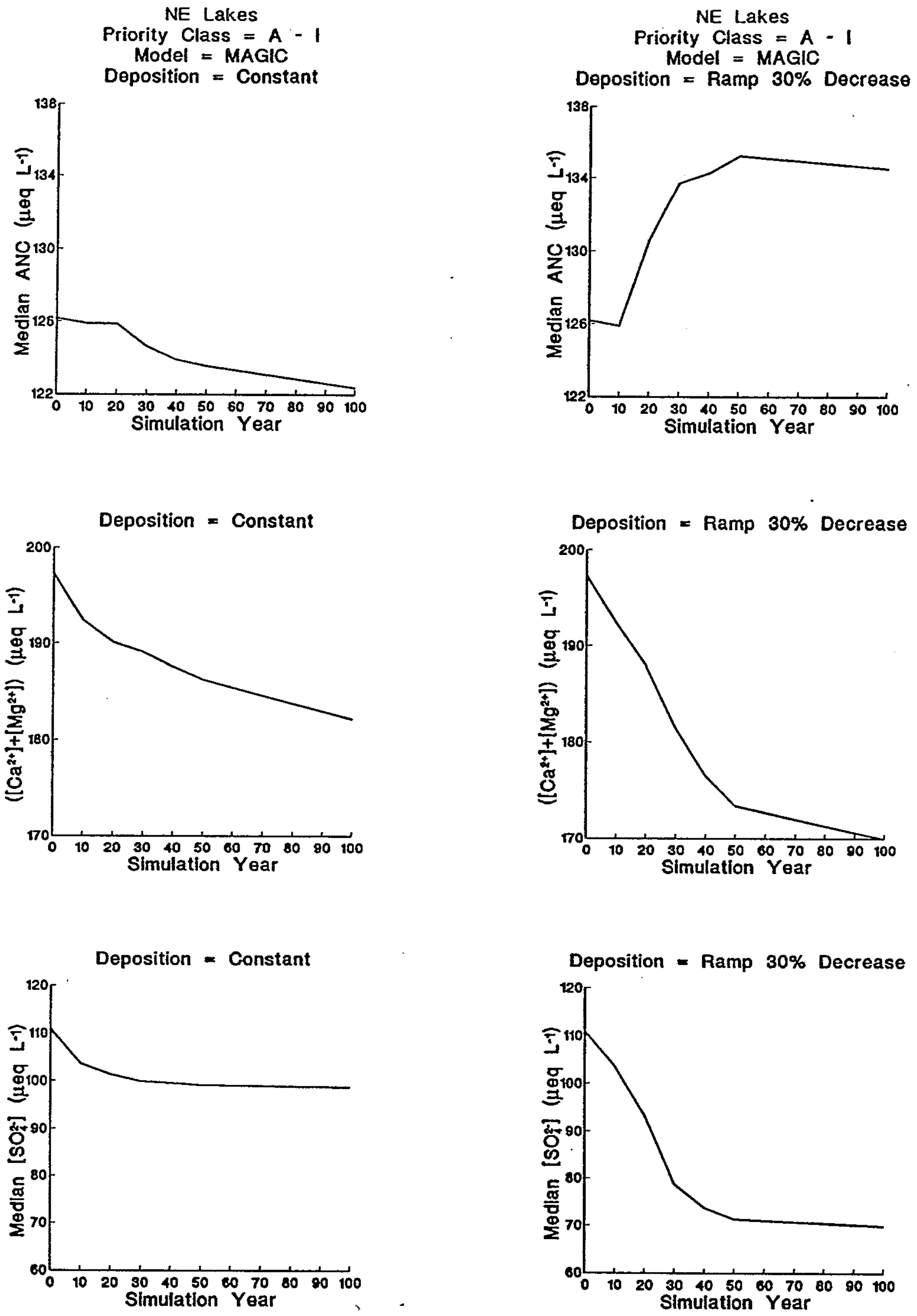


Figure 10-92. Change in median ANC, calcium and magnesium, and sulfate concentrations projected for NE lakes using MAGIC under current and decreased deposition.

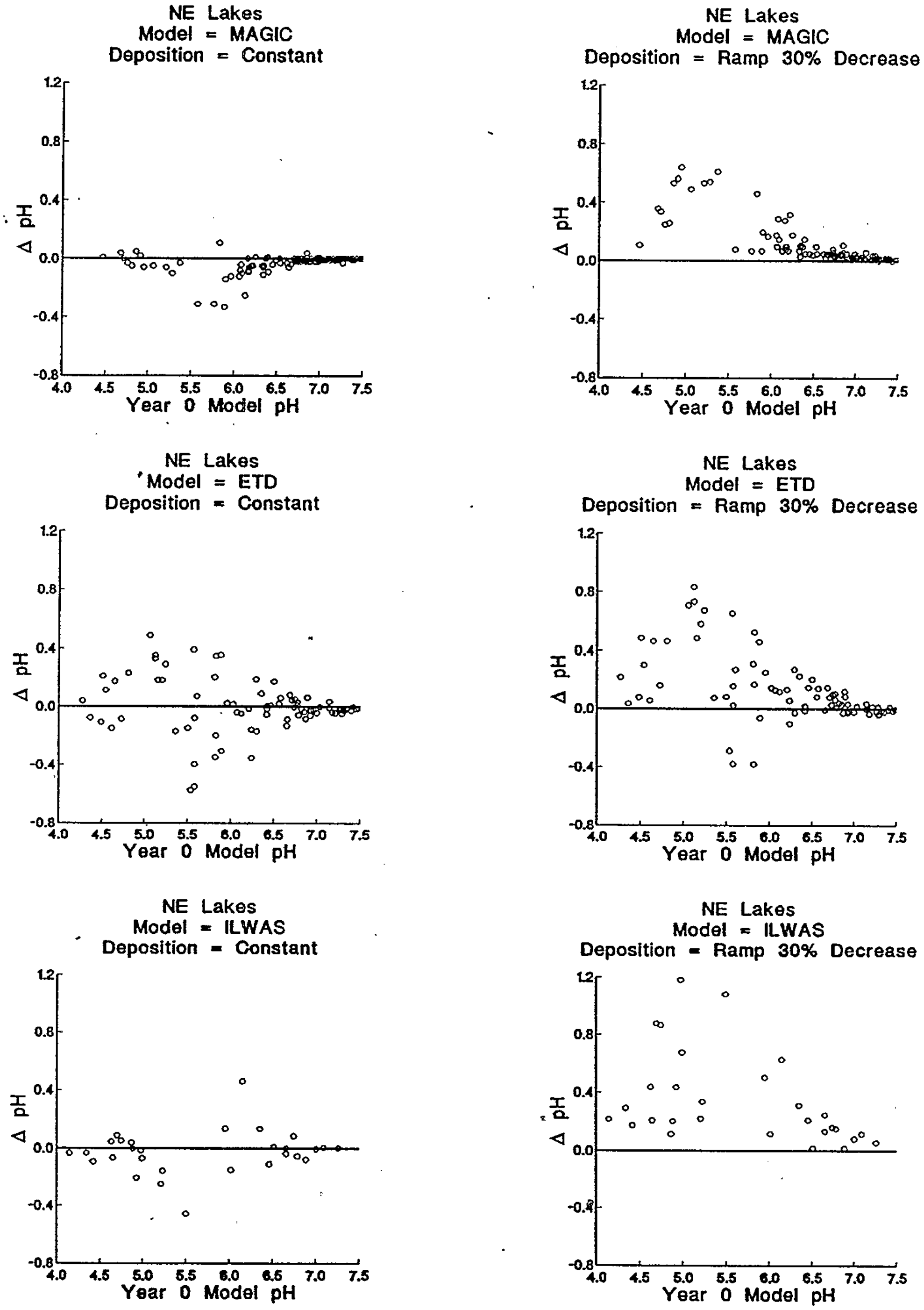


Figure 10-93. Comparison of the change in pH after 50 years as a function of the initial calibrated pH for MAGIC, ETD and ILWAS on northeastern lakes.

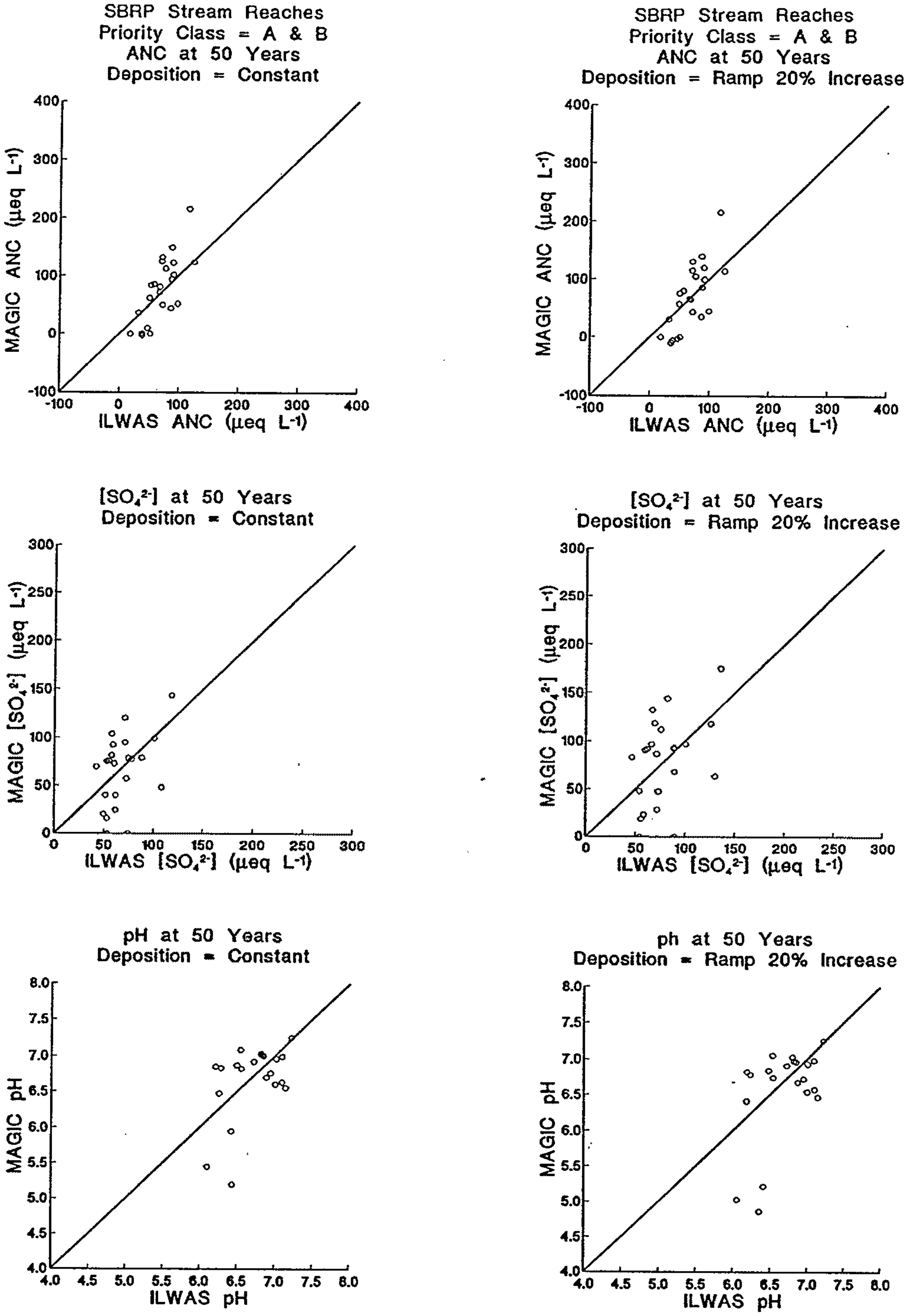


Figure 10-94. Comparisons of projected ANC and sulfate concentrations and pH between ILWAS and MAGIC after 50 years for SBRP streams.

The changes in ANC as functions of change in sulfate concentrations are shown in Figure 10-95 for both ILWAS and MAGIC. A similar figure (Figure 10-96) illustrates the MAGIC projections for all 32 streams simulated in the SBRP, not just the comparable 14 ILWAS watersheds. The projected changes in ANC concentrations were negatively correlated with the projected changes in sulfate concentrations for both current and increased deposition. The relationships between the change in ANC and change in sulfate, computed using a weighted regression for MAGIC were $\Delta ANC = -2.8 - 0.372\ \Delta SO_4^{2-} (r^2 = 0.28)$ for current deposition and $\Delta ANC = -1.05 - 0.441\ \Delta SO_4^{2-}\ (r^2 = 0.42)$ for increased deposition. The changes in calcium plus magnesium concentrations as functions of change in sulfate concentrations are shown in Figure 10-97 for both the ILWAS and MAGIC results under current and increased deposition. Linear regression models assume no error in the independent variable with all the error assumed for the dependent variable. Therefore, a structural regression model is required to compute the slope of the regression line because a structural regression model accounts for error in both the independent and dependent variables. The structural regression model, however, requires additional analyses, which are ongoing. Computing the slope of the relationship of calcium and magnesium versus sulfate using linear regression to estimate an "F" factor (Henriksen, 1982), is not recommended.

Median ANC concentrations were relatively constant for the first 20 years under current deposition, and then were projected to decrease linearly over the remainder of the 200-year period (Figure 10-98). The rate of ANC decrease from year 10 to year 100 was greater under increased deposition (i.e., -0.47 $\mu eq\ L^{-1}\ yr^{-1}$) than for current deposition (i.e., -0.28 $\mu eq\ L^{-1}\ yr^{-1}$). From year 100 to year 200, however, the rate of change in ANC was similar for both deposition scenarios.

Median calcium plus magnesium concentrations were projected to increase until about year 40 and then decrease for the rest of the simulation for both deposition scenarios (Figure 10-98). The rates of change in median calcium plus magnesium concentrations from year 50 to year 100 for current and increased deposition were -0.22 and -0.28 $\mu eq\ L^{-1}\ yr^{-1}$, respectively. The rates of change in calcium plus magnesium concentrations from year 100 to year 200 were -0.03 $\mu eq\ L^{-1}\ yr^{-1}$ for both current and increased deposition.

Median sulfate concentrations were projected to increase at rates of 0.76 $\mu eq\ L^{-1}\ yr^{-1}$ for the first 50 years, 0.43 $\mu eq\ L^{-1}\ yr^{-1}$ from year 50 to year 100, and 0.14 $\mu eq\ L^{-1}\ yr^{-1}$ from year 100 to year 200 under current deposition (Figure 10-98). Under increased deposition, the projected rates of change in median sulfate concentrations were 1.1 $\mu eq\ L^{-1}\ yr^{-1}$ for the first 50 years, 0.66 $\mu eq\ L^{-1}\ yr^{-1}$ from year 50 to year 100, and 0.09 $\mu eq\ L^{-1}\ yr^{-1}$ from year 100 to year 200. Both deposition scenarios resulted in median sulfate concentrations near sulfate steady state after 200 years.

About 44 percent (669 streams) of the DDRP streams in the SBRP had pH values below 7.0 with 17 percent (262 streams) having pH less than 6.75. Comparing the projected change in pH versus the initial pH at year 0, however, indicates that streams with initial pH values less than 6.75 might decrease between -0.5 and -1.0 units within 50 years under current deposition and might have greater than -1.0 unit decrease under increased deposition (Figure 10-99). By year 200, streams with pH less than 7.0 might experience pH decreases between -0.25 and -0.5 under increased deposition with some streams projected to have greater than a -2.0 unit decrease.

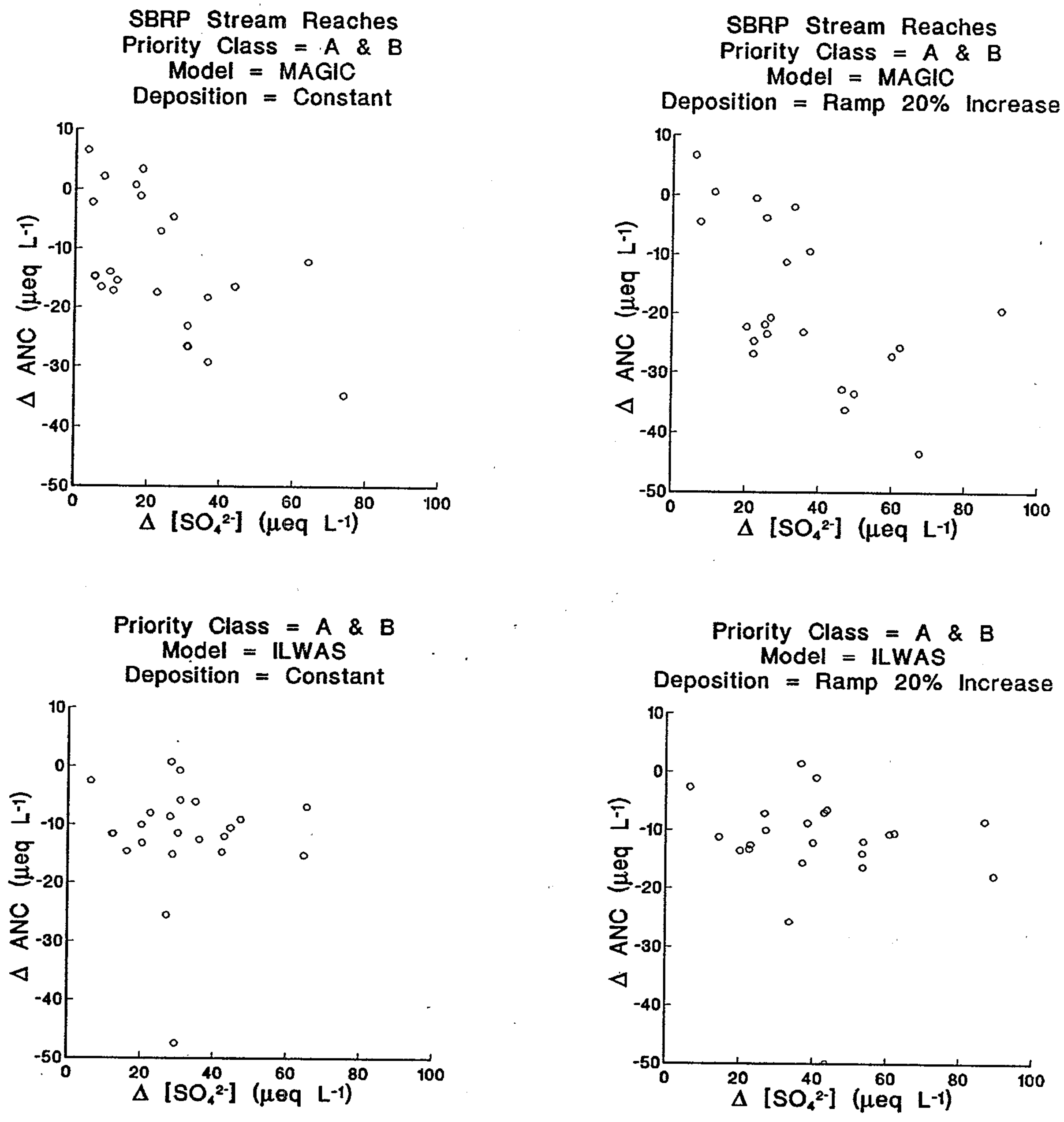


Figure 10-95. Comparison of projected ΔANC and Δsulfate relationships in SBRP Priority Class A and B streams using ILWAS and MAGIC.

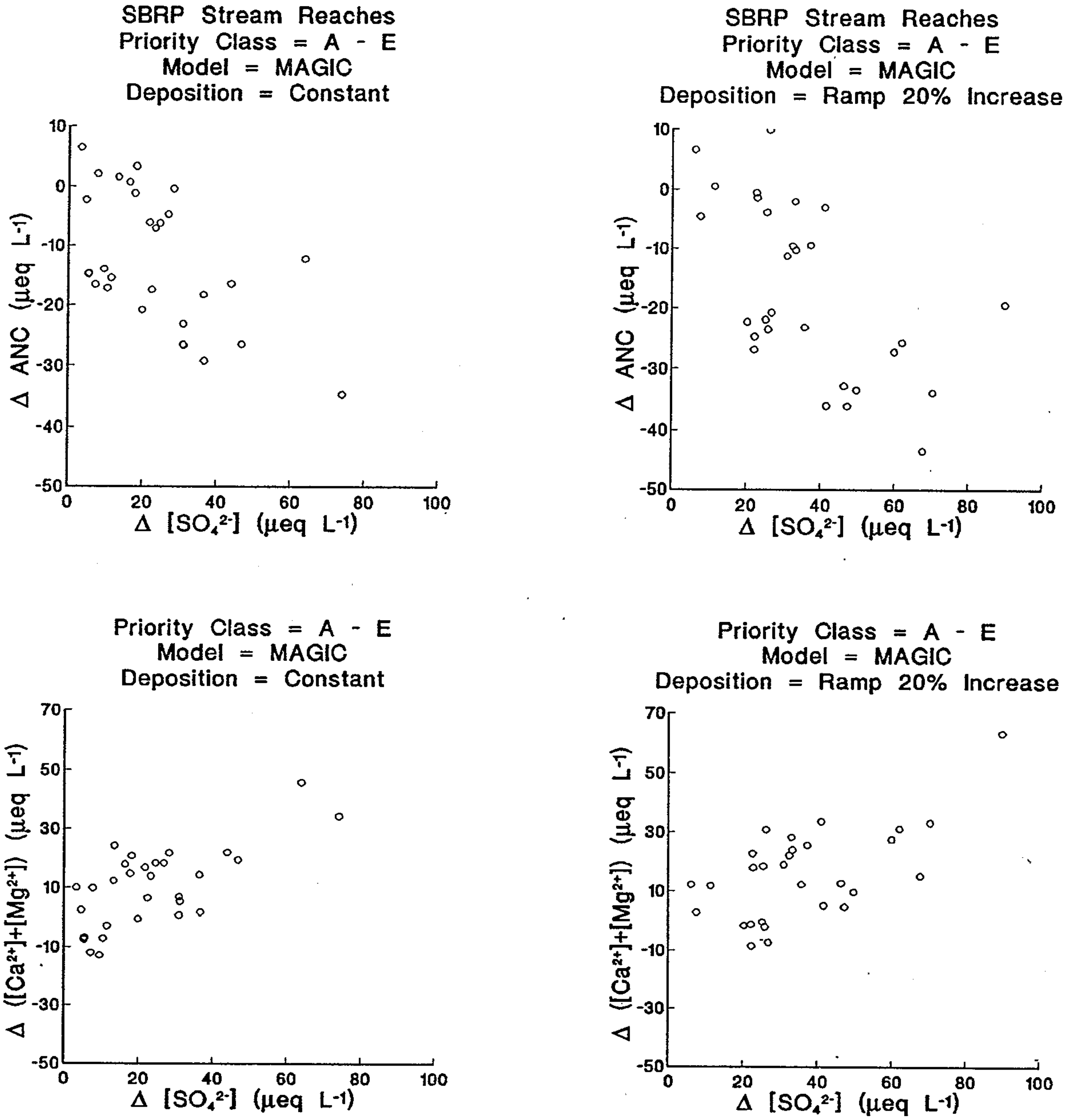


Figure 10-96. Comparison of projected ΔANC and Δsulfate relationships and Δ(calcium and magnesium) and Δsulfate relationships for SBRP Priority Class A - E streams using MAGIC.

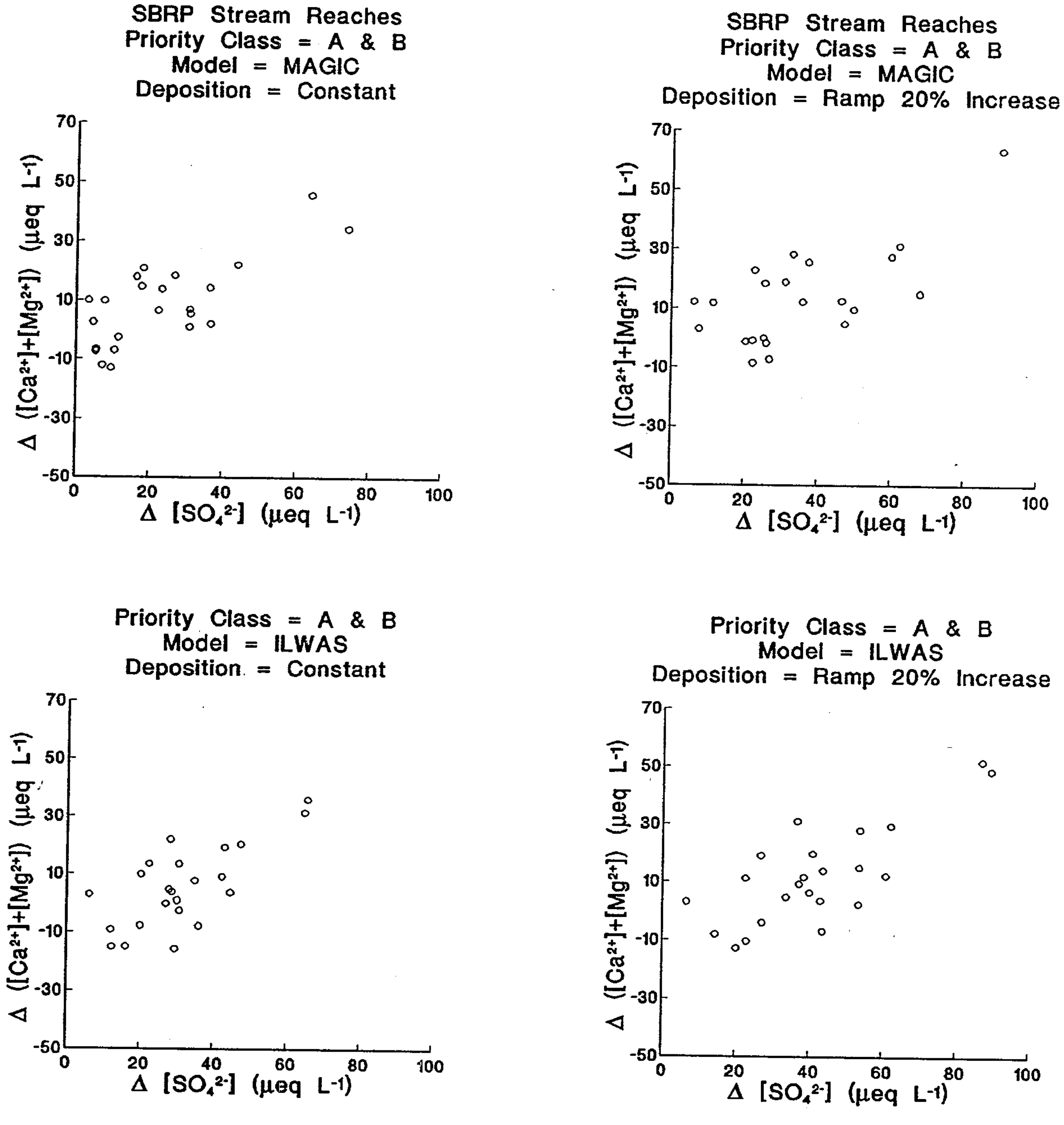


Figure 10-97. Comparison of projected Δ(calcium and magnesium) and Δsulfate relationships for SBRP Priority Class A and B streams using ILWAS and MAGIC.

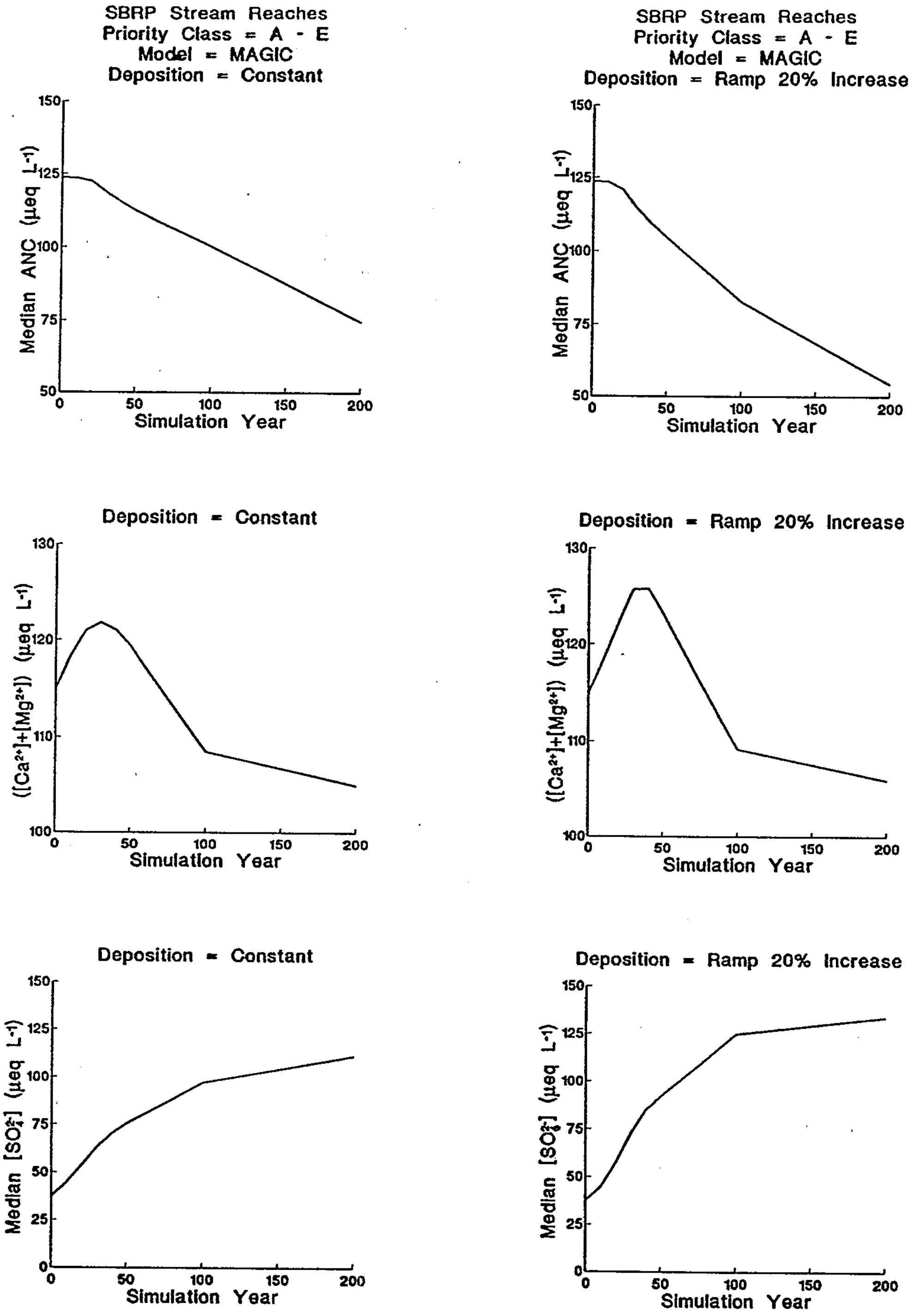


Figure 10-98. Change in median ANC, calcium and magnesium, and sulfate concentrations projected for SBRP streams under current and increased deposition using MAGIC.

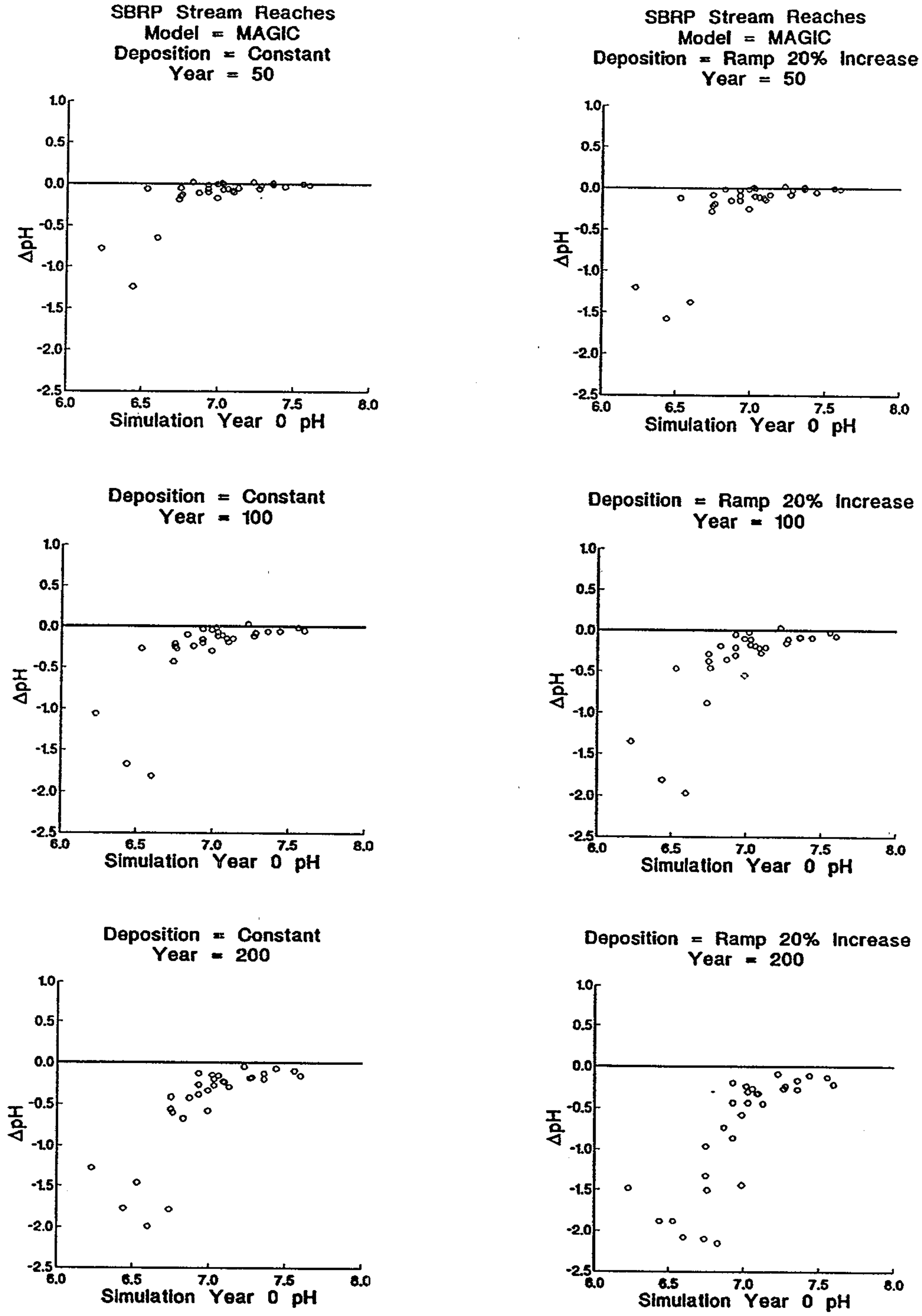


Figure 10-99. Comparison of the change in pH after 200 years as a function of the initial calibrated pH for MAGIC on SBRP streams, Priority Classes A - E.

10.12 DISCUSSION

10.12.1 Future Projections of Changes in Acid-Base Surface Water Chemistry

The Level III Analyses used typical year deposition scenarios to examine the potential effects of alternative deposition levels on future changes in surface water chemistry. The typical year, as discussed in Section 5.6, represents the average meteorology for a 30-year period of record and the average deposition for a 3- to 7-year period of record adjusted for the average meteorological year. Deposition was then estimated for each of the watersheds considered in the Level III Analyses. The typical year scenario enabled each modelling group to use the same input and provided a common basis for comparing changes in surface water chemistry as functions of comparable deposition among all the models. The intent was not to forecast future meteorological or deposition conditions, but rather to have a common basis for comparison among model results. Comparable watershed morphometry, physical and chemical soils data, and surface water chemistry data also were provided to each of the modelling groups, enabling them to assess and contrast the different model formulations and projections. These models integrate much of our knowledge on how watershed processes control surface water acidification, and comparing the output from these models, in part, provides a test of how well we understand these processes. There are different hypotheses on how these processes operate and different philosophies on how to integrate this information in the models (Eary et al., l989; Jenne et al., 1989). These results are not intended, and should not be interpreted, as forecasts of conditions that might be expected over the next 50 to 200 years.

10.12.2 Rate of Future Change

The Panel on Processes of Lake Acidification raised questions on the extent of surface water acidification, the processes that control changes in surface water chemistry (including surface water acidification and chemical improvement), and the rate at which these processes occur. The extent of acidic and low ANC surface waters in the United States was addressed through the NSWS. The processes that control changes in surface water chemistry were discussed in Section 3 and summarized in Galloway et al. (1983a), Church and Turner (1986), Reuss and Johnson (1986), and Martin (1986).

The DDRP was initiated because scientists did not concur on how watershed processes control the rate and magnitude of surface water acidification and how to project such changes in surface water chemistry. A primary area of disagreement among scientists on the Panel was whether future ANC decreases would be gradual over a period of centuries or perceptible over years to decades, i.e., they disagreed about the rate at which acidification might occur. The rates at which changes in sulfate adsorption and base cation supply and surface water acidification and chemical improvement might occur in northeastern lakes and SBRP streams are discussed below.

10.12.2.1 Northeast

Changes that might occur in the NE over the next 100 years (summarized in Figure 10-92) are consistent with various conceptual models of surface water acidification (Galloway et al., 1983a; NAS, 1984; Church and Turner, 1986; Cosby et al., 1985a,b,c; Reuss and Johnson, 1986).

Sulfate deposition in the NE has declined since the 1970s concurrent with declining sulfur emissions in the NE (OTA, 1984; Kulp, 1987). The decline in sulfate concentrations at the start of the projections for the NE under current deposition (Figure 10-92) reflects this deposition decrease as the watersheds approach a sulfate steady-state concentration that is lower than it was in the 1970s. The relatively constant ANC concentrations under current deposition for the first 20 years of the projection occurred primarily because the decline in sulfate concentrations of about 8 $\mu eq\ L^{-1}$ was compensated by a decline of about 8 $\mu eq\ L^{-1}$ in calcium plus magnesium concentrations. Sulfate concentrations asymptotically approached steady state after 20 years, changing by about 2 to 3 $\mu eq\ L^{-1}$ over the next 80 years. A continual depletion of about 8 $\mu eq\ L^{-1}$ in base cation concentrations (calcium plus magnesium) was projected during this 80-year period as sulfate approached steady state, however, which resulted in the continual decline in ANC of about 4 $\mu eq\ L^{-1}$ over this same 80-year period. These results are consistent with observations made in Plastic Lake, Ontario, Canada where ANC concentrations continued to decrease following a reduction in sulfate deposition even though sulfate concentrations remained relatively constant in the lake (Dillon et al., 1987). The ANC decrease in Plastic Lake was attributed to depletion of the available pool of base cations in the watershed (Dillon et al., 1987), although no soil measurements were made. A depletion of the pool of available soil base cations was projected for the northeastern watersheds using both ILWAS and MAGIC and resulted in similar ANC decreases in the northeastern lakes.

All three models projected that northeastern watersheds might be at or near sulfate steady state within 50 years assuming either current or decreased deposition. All three models projected decreased ANC concentrations over 50 years and that additional lakes might become acidic, because of the slow but continual decrease in base cation and ANC concentrations. The lakes currently not acidic that might become acidic over the next 50 to 100 years represented about 3 percent of the 3227 lakes in the MAGIC target population. When compared with the ELS-I target population of 7157 (many of which have ANC concentrations exceeding 400 $\mu eq\ L^{-1}$), this additional percentage of acidic lakes represents less than 1 percent of the population. The ELS-I target population, however, included only lakes larger than 4 ha. Ongoing analyses of small lakes indicates that the ratio of smaller acidic lakes (< 4 ha) to acidic lakes larger than 4 ha is about 2:1 (Sullivan et al., submitted). Considering these small lakes might increase the projected percentage of acidic lakes over the next 50 years to 2 percent. The models, however, support the hypothesis that future ANC decreases in the NE will be gradual over a period of decades to centuries rather than years to decades.

Following the 30 percent decrease in sulfate deposition beginning in year 10, there was a rapid increase in projected ANC over the next 40 years (Figure 10-92). This 11 $\mu eq\ L^{-1}$ increase in ANC occurred because the concurrent projected decrease in median sulfate concentrations of about 22 $\mu eq\ L^{-1}$ occurred with a projected decrease in median base cation concentrations (calcium plus magnesium) of about 11 $\mu eq\ L^{-1}$. This rapid increase in ANC probably occurred because the watersheds were initially near sulfate steady state. A rapid increase in ANC might not be expected if the systems are not at or near sulfate steady state (Cosby et al., 1985a,b,c). All three models projected this rapid increase in ANC following the 30 percent decrease in sulfate deposition. Even though the watersheds were nearly at sulfate steady state within 50 years under decreased deposition, there was a continued decrease in base cations projected from year 50 to year 100, which resulted in a small but continued decrease in ANC concentrations.

Although there was no apparent relationship between the rates of change in ANC and sulfate and the initial ELS-I ANC concentration, the projected rate of change under current deposition in the NE was small. If the majority of the watersheds are near sulfate steady state, then most of these systems might be expected to respond relatively quickly to changes in sulfate concentration regardless of the initial ANC.

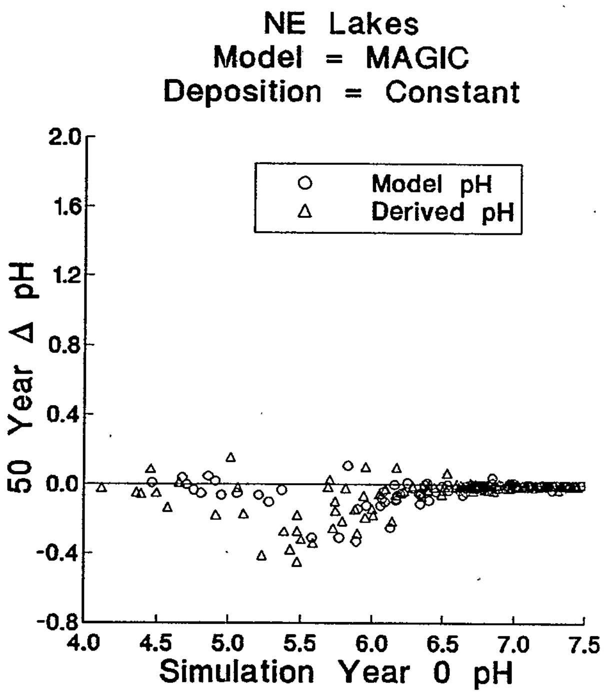
Projections for all three models indicated that as many as 125 currently acidic lakes might chemically improve (increase in ANC) in 50 years assuming a 30 percent deposition decrease. This estimate represents about 77 percent of the estimated 162 currently acidic DDRP target population lakes, but only about 4 percent of the 3277 lakes in the MAGIC target population. The number of lakes estimated to chemically improve was moderated by the continued decrease in ANC from year 50 to year 100: after year 100, the estimated number had decreased to 113 (70 percent).

Differences among model projections were more apparent for Priority Class A and B lakes for three reasons. First, the sample size for this priority class is small and are available for comparison. Second, this priority class includes low ANC systems, which have the greatest variability in terms both of ANC measurements (Linthurst et al., 1986a) and model calibration. The ILWAS and MAGIC models are calibrated on base cations and acid anions and ANC is a computed, not a calibrated value (i.e., ANC = sum base cations - sum acid anions). ELS-I field measurements for many lakes indicate cation or anion deficits that reflect the accepted sampling and measurement error in the analysis. The models, however, require charge balance so the calculated ANC concentrations following calibration might not equal the measured ANC in the lake or stream. This difference between calibrated and measured ANC values for the models was generally greatest at the low ANC concentrations where the relative measurement errors also are greater. The differences between models, however, are well within the uncertainty bounds about the projections. Third, MAGIC performs hindcasts as part of its calibration/projection exercise and, thus, simulates the declining sulfur deposition levels over the past 10 years. These declining sulfur deposition levels continue to exhibit a cumulative effect over the first 10-20 years of the projections. ILWAS and ETD assume historically deposition values are the same as current deposition values and calibrate to them, which also contributes to the differences among models.

The change in pH projected using MAGIC might be underestimated because the initial or calibrated ANC concentrations at year 0 were greater than the ELS-I ANC concentrations. Because of the pH - ANC relationship, the unit change in pH for each unit change in ANC decreases as the ANC increases (i.e., at higher ANC concentrations, pH changes are less). To assess this possible underestimate in pH change, the change in ANC projected using MAGIC was added to the ELS-I ANC, and a derived pH was estimated using the pH - ANC relationship incorporated in MAGIC (Figure 10-100). The change in the derived pH is similar to that in the modelled pH for current deposition, although the maximum change is greater. Under decreased deposition, the estimated change in pH is greater with the derived rather than modelled pH values, but only for a few lakes (Figure 10-100). Because the changes in ANC are both small and not influenced by the initial ANC, the change in pH does not appear to be greatly underestimated.

10.12.2.2. Southern Blue Ridge Province

Projected changes in surface water chemistry that might occur in the SBRP were shown in Figure 10-98. ILWAS and MAGIC projected similar changes in ANC, calcium plus magnesium, and sulfate over



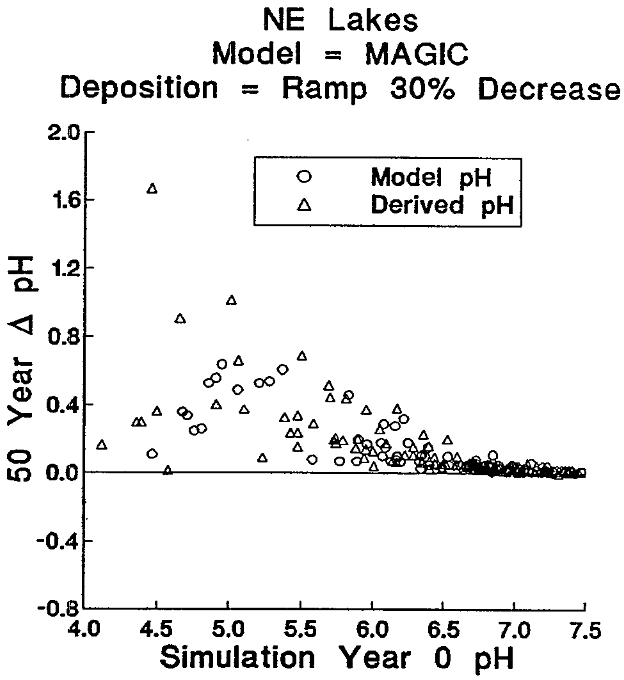


Figure 10-100. Comparison of projected MAGIC change in pH versus derived pH after 50 years for NE lakes.

the 50-year period. MAGIC projections for the SBRP, however, suggest that substantial changes also occur between 50 and 200 years. This discussion, therefore, focuses on the MAGIC projections.

For the first 50 years, both models projected a decrease in ANC and an increase in base cation and sulfate concentrations for both deposition scenarios. The decrease in ANC concentrations over the first 20 years was slight, but a relatively constant linear decrease in ANC after 20 years was projected. Under current deposition, sulfate concentrations increased linearly for the first 50 years from about 37 to 75 μeq L^{-1} while base cations increased from about 110 to 123 μeq L^{-1} by year 30. Increased sulfate concentrations were compensated by increased base cation transport from the watershed and relatively little change in ANC for the first 20 to 30 years. However, when base cations began to decrease, ANC concentrations also decreased from about 122 to 100 μeq L^{-1} from year 20 to year 100, respectively. Over the interval from year 30 to year 100, sulfate concentrations increased by about 35 μeq L^{-1}, base cations declined by about 15 μeq L^{-1}, and ANC decreased by about 20 μeq L^{-1}, projections which are consistent with charge balance requirements and current understanding of soil processes (Reuss and Johnson, 1986; see Sections 3 and 9). Although the rates of sulfate increase and base cation decrease changed from year 100 to year 200 compared with year 50 to year 100, the ratio or relationship between increased sulfate concentrations and decreased base cations remained relatively constant because the rate of change in ANC concentrations was relatively linear from year 30 to year 200. The SBRP watersheds were asymptotically approaching sulfate steady state by year 200, and median watershed sulfur retention had declined to about 5 percent.

The two models differed in the projected number of streams that might become acidic within 50 years under current deposition. The ILWAS model projected no acidic streams while MAGIC projected 130 streams that might become acidic in 50 years assuming current deposition. The estimate of 130 acidic stream reaches, however, is derived from differences in the projections for one SBRP stream with a relatively large weight. This stream's ANC decreased from an initial concentration of about 20 μeq L^{-1} to 3 μeq L^{-1} within 50 years. Given the uncertainty in the projections, 130 is probably the maximum estimated number of streams that might become acidic within 50 years. MAGIC projections also indicated additional streams might become acidic over the next 200 years in the SBRP, with between 12 and 15 percent of the systems potentially becoming acidic by 100 years and 200 years, respectively, under current deposition.

Changes in surface water chemistry projected for the SBRP under increased deposition showed similar patterns to those projected under current deposition (Figure 10-98). The rate at which sulfate asymptotically approached the steady-state concentrations with increased deposition was greater than that under current deposition because of the change in sulfate loading during the first 100 years. The rate of increase in stream sulfate concentrations during the initial phase of approaching steady state is nearly linear and becomes asymptotic as the soil solution sulfate concentration approaches the steady-state sulfate concentration. Higher loadings with the 20 percent increased sulfur deposition scenario resulted in the SBRP soils approaching the new sulfate steady state more quickly on the linear portion of the curve. The rate of change in sulfate from year 100 to year 200 under increased deposition was less than under current deposition because the increased loading over the first 100 years resulted in the watersheds being nearer to sulfate steady state. This increased sulfate loading also resulted in greater base cation depletion rates over the first 100 years. The rate of change in base cations from year 100 to year 200 under increased deposition was slightly greater than under current deposition. Because the rate of change in sulfate under increased deposition was less and the rate of change in base cations was greater than under current deposition, there was a slight decrease in the rate of change in ANC concentrations from year 100 to year 200.

The increased deposition and more rapid increase toward sulfate steady state resulted in a larger number of streams that might become acidic by year 200. The estimated numbers of streams that might become acidic by year 100 and year 200 were 159 (11 percent) and 337 (24 percent) streams.

The models also support the hypothesis that future ANC decreases in the SBRP will be gradual over the period of decades to centuries rather than occur over years to decades. Streams in the SBRP might experience a slow but steady decline in ANC over the next 200 years assuming constant or increased deposition. The stream population in the SBRP typically had higher initial ANC concentration than streams in other geographic regions of the Southeast. Thirty percent of the DDRP SBRP stream population had ANC concentrations between 25 and 100 $\mu eq\ L^{-1}$, and 70 percent of the stream reaches had ANC > 100 $\mu eq\ L^{-1}$. Extrapolating results from the SBRP to the population of other streams in the Southeast, therefore, might not be appropriate because the proportion of streams with lower initial ANC concentrations in other southeastern regions is greater than in the SBRP (Kaufmann et al., 1988). In addition, the projected changes in pH in the SBRP stream accompanying these changes in ANC might range from -0.5 to -1.0 over 50 years and up to -2.0 pH unit changes over 200 years. Other southeastern streams with lower current ANC might exhibit even greater pH changes within 50 years than projected for SBRP streams.

10.12.3 Uncertainties and Implications for Future Changes in Surface Water Acid-Base Chemistry

Uncertainty is defined as intrinsic variability plus error. Intrinsic variability represents the natural variability or noise in the systems that cannot be reduced. The components of error include measurement error, sampling error, model structural error, prediction error, and population estimation error (Beck, 1987). The uncertainty analyses conducted for the Level III models quantitatively estimated many of these error components (although the total error was not partitioned into its respective components) and incorporated this error in the confidence bounds around the model projections. Unknown or poorly understood processes, however, are more difficult to estimate quantitatively but can be qualitatively discussed. The implications of these processes on estimates of future change in ANC and pH are listed in Table 10-20.

10.12.3.1 Deposition Inputs

Analyses were performed to determine the effect of deposition input uncertainty on the model projections (Section 10.10.2). These uncertainty estimates were used to establish confidence intervals about the model projections in Appendix C. Analyses indicated the input uncertainty contributed about half of the total uncertainty in the projections with the other half arising from parameter uncertainty. Uncertainty in dry deposition, particularly of base cations, is certainly a major contributor to deposition input uncertainty. The approaches used to estimate the deposition inputs, however, were reasonable, based on input from the deposition modellers, conversations with technical experts on dry and wet deposition, analyses of existing data, and conventional theory. In part, underestimates or overestimates

Table 10-20. Effects of Critical Assumptions on Projected Rates of Change

Assumptions Resulting in Under-Estimates of ANC and pH Changes	Assumptions Resulting in Over-Estimates of ANC and pH Change
1. Mineral weathering overestimated	1. Mineral weathering underestimated
2. Nitrate assimilation overestimated	2. Organic acids buffer surface water chemistry
3. Total sulfur deposition underestimated	3. Total sulfur deposition overestimated
4. Calibrated ANC greater than observed	4. Calibrated ANC less than observed
5. Watershed land use changed	5. Watershed land use changes
6. Episodic acidification of surface waters	6. Desorption is not the reverse of adsorption-hysteresis-related delays in change
7. Biotic uptake/assimilation reducing available base cation pool	7. Weathering and sulfate adsorption increased by decreased soil pH
8. Effects at distribution extremes over-smoothed through aggregation	

in anion or cation deposition inputs are compensated by increasing or decreasing mineral weathering rates, respectively, of the anion or cation species to match observed surface water chemistry. Watershed exchange pools are tightly coupled with deposition inputs.

This tight coupling of declining base cation concentrations to declining surface water sulfate concentrations was recently reported for Hubbard Brook (Driscoll et al., 1989b). Two mechanisms were indicated that can contribute to this coupling: (1) atmospheric deposition of base cations and (2) release of base cations from mineral weathering or watershed pools of exchangeable base cations (Driscoll et al., 1989b).

For the Level III projections the typical year deposition/precipitation scenario was repeated each year for 50 years, so annual atmospheric deposition was constant for the 50-year period (with daily meteorological variations). For the 30 percent deposition decrease, only sulfate concentrations were reduced in deposition with charge balance maintained by adjusting hydrogen ion concentration. Base cation concentrations were not decreased in either deposition scenario. For these projections, surface water base cation concentrations were tightly coupled with sulfate concentrations through the depletion of soil exchangeable base cations. Depletion of soil exchangeable base cations occurred because sulfate moved through the watersheds as a mobile anion. Under decreased deposition, the reduction in sulfate concentration was compensated by soil base cations and a subsequent increase in ANC. These patterns were consistent with those observed at Hubbard Brook.

While the projected changes in surface water sulfate concentrations are consistent with the depletion of watershed pools of base cations, these processes cannot be decoupled from atmospheric processes in natural watersheds. Atmospheric deposition of base cations clearly is an important process that must be investigated in assessing the effects of sulfate deposition on surface water chemistry. The calibrated models used in the Level III Analyses represent an excellent opportunity for evaluating different hypotheses related to atmospheric deposition and watershed processes. Simulation experimentation on different hypotheses represents one of the most important uses of watershed models.

The deposition inputs, indeed, might be highly inaccurate. The intent, however, was not to forecast but rather to project the effects of alternative sulfur deposition scenarios on future changes in surface water acid-base chemistry. Additional analyses are being proposed as part of the 1990 NAPAP Integrated Assessment but it is likely that this issue will remain beyond 1990.

10.12.3.2 Watershed Processes

Each of the three models has different formulations and different data requirements. If the three models provide similar projections for similar reasons, however, greater confidence can be placed in the conclusions. Questions remain, however, as to whether the models incorporate the key watershed processes affecting surface water acidification and how important the model formulations, operational assumptions, and parameter selection are on the long-term projections.

The key watershed processes incorporated in each model were listed in Table 10-1 and are discussed in detail in Eary et al. (1989) and Jenne et al. (1989). All three models focus on the effects of sulfur deposition on surface water acidification. Each model considers total deposition acidity, including nitrate, but the nitrogen dynamic formulations included in each model, including ILWAS, are rudimentary. Because most of eastern forested watersheds are nitrogen-limited (Likens et al., 1977; Swank and Crossley, 1988), nitrogen inputs are effectively removed from the soil complex. Deposition inputs of nitrate are about twice the ammonium inputs for the eastern United States (Kulp, 1987). Although nitrification has an acidifying effect (Lee and Schnoor, 1988), nitrate assimilation has an alkalizing effect (Lee and Schnoor, 1988). Nitrate concentrations are low in receiving lakes and streams, indicating nitrate is not moving as a mobile anion. Median nitrate concentrations measured during the ELS-I for northeastern lakes were less than 1 μeq L^{-1}. Median nitrate concentrations for SBRP streams were about 10 μeq L^{-1}. This does not preclude soil acidification, however, because biotic processes might influence surface water chemistry. The assumption that nitrogen is not a primary contributor to chronic surface water acidification and, therefore, that nitrogen dynamics do not have to be explicitly modelled represents a limitation of the models, rather than a short-coming in the DDRP design. Nitrate also might be an important component of episodic acidification. The DDRP, however, is not addressing episodic acidification.

Changes in soil pH might influence mineral weathering rates and sulfate adsorption capacities. Plot experiments have indicated these processes can be affected by decreased soil solution pH. Although these effects might occur, median soil solution pH were projected to change less than 0.1 units in the NE and less than 0.2 units in the SBRP.

One of the operational assumptions of the Level III Analyses was that the relationship of organic acids to other chemical species would remain constant. Krug and Frink (1983) hypothesized that reversing surface water acidification by strong mineral acids could result in increased dissociation of humic acids and mobility of organic acids and, therefore, return naturally acidic lakes to their original state. The historical acidic status of the currently acidic lakes is unknown, so the estimated chemical improvement of the 125 currently acidic lakes might be liberal. Historical reconstruction of water chemistry for Adirondack Lakes should be available in the fall of 1989 and might be compared with the DDRP projections of chemical improvement for the same lakes.

Mineral weathering is critical for all long-term projections, but is the process about which little information can be obtained. The mineral weathering parameters are calibration parameters but are not completely unconstrained. The range over which these parameters can vary while maintaining reasonable ranges for other, better characterized parameters (e.g., selectivity coefficients) and still match observed surface water chemistry constituent concentrations (e.g., silica, calcium, sodium, and other base cation concentrations) is bounded. All three models yield similar long-term projections, even though ETD and ILWAS use a fractional order weathering formulation based on hydrogen ion and MAGIC uses a zero order weathering formulation. Long-term projections, however, are sensitive to the mineral weathering parameters in all three models. The sensitivity of the MAGIC and ETD models to changes in the mineral weathering parameters was identified in Table 10-10. Although mineral weathering rates cannot be unequivocally estimated, the model formulations and mass balance approaches used in the models might be analogous to the mass balance approaches used to estimate weathering in watershed studies (Velbel, 1986b; Paces 1973).

Data aggregation might result in underestimates of change in the tails or extremes of the distributions. Soil horizon physical and chemical attributes are averaged (weighted) to Master horizons, Master horizons aggregated to sampling classes, and sampling class attributes aggregated to the watershed values, which are used for model calibration. This averaging or aggregation process will preserve the central tendency in watershed attribute, and subsequent projected effects, but will reduce the variability or extremes in the distribution of soil horizons through watershed attributes. While these extremes represent a small proportion of the target population, the changes in these watersheds might be underestimated so the changes in ANC or pH might be greater than projected.

Although data are not available for model confirmations of long-term projections, short-term calibration and confirmation studies on Woods Lake, Panther Lake, and Clear Pond indicate the RMSEs among the models and the observed standard errors of the data were similar. Identical data were provided to each of the modelling groups in performing the projections; a consistent, methodological approach was used for the sensitivity analyses and the long-term projections; and uncertainty analyses were performed for all three models. The rates of change for different constituents were comparable among models and the processes controlling changes in surface water chemistry under different deposition scenarios and among regions were similar among and between models. Even through there are differences in model structure, process formulations, and temporal and spatial scales, the model projections were remarkably similar. Regardless, long-term projections can be confirmed only with long-term periods of record (Simons and Lam, 1980), which do not exist. Moreover, this study does not establish the adequacy of the formulations representing important watershed processes, the procedures for spatial aggregation of data, or the calibration approaches for long-term acidification projections.

10.13 CONCLUSIONS FROM LEVEL III ANALYSES

Conclusions from the Level III Analyses follow:

- All three models produced comparable results for the northeastern watersheds. ILWAS and MAGIC produced comparable but more variable results for the SBRP.

- All three models projected minimal changes in ANC and sulfate concentrations and pH for lakes in the NE over the next 50 years at current deposition rates. The median changes in ANC, sulfate, and pH over the next 50 years were -1 to -5 μeq L^{-1}, <0.1 pH units, -0.1 to -5 μeq L^{-1}, respectively, each of which is within the projection error of the respective analyses.

- ETD and MAGIC projected about 3 percent and 5 percent, respectively, of the lakes in Priority Classes A - E that are currently not acidic might become acidic within 50 years at current deposition and 2 and 3 percent, respectively, at decreased deposition. ETD estimated about 22 and 46 percent of the currently acidic lakes in Priority Classes A - E might chemically improve (i.e., increase in ANC) in 50 years for current and decreased deposition, respectively. MAGIC estimated about 39 percent and 77 percent, respectively, of the currently acidic lakes might improve in 50 years for the entire target population.

- All three models projected reduced lake sulfate and increased ANC concentrations and pH with a 30 percent reduction in deposition. The median changes in sulfate, ANC, and pH, respectively, were -23 to -28 μeq L^{-1}, +6 to +10 μeq L^{-1}, and 0 to +0.5 pH units over 50 years.

- MAGIC and ILWAS projections of changes in ANC, sulfate concentrations, and pH for SBRP streams over 50 years were similar but there was considerable scatter in the comparisons because of the small sample size.

- For current deposition, MAGIC projections in the SBRP indicated the change in median sulfate after 50, 100, and 200 years was 38, 60, and 74 μeq L^{-1}, respectively. The changes in median ANC after 50, 100, and 200 years were -11, -23, and -46 μeq L^{-1}, respectively. The median percent sulfur retention at 0 years and after 50, 100, and 200 years was 65 percent and 27 percent, 15 percent, and 6 percent, respectively. The changes in median pH after 50, 100, and 200 years were -0.04, -0.09 and -0.20, respectively.

- The percentage of SBRP stream reaches that might become acidic after 50, 100, and 200 years was < 9, 11, and 14 percent, respectively, for current deposition and 11, 11, and 24 percent for increased deposition.

- With a 20 percent increase in deposition, MAGIC projections for the SBRP indicated the changes in median sulfate concentrations after 50, 100, and 200 years, respectively, were 55, 87, and 96 μeq L^{-1}. The changes in median ANC after 50, 100, and 200 years, respectively, were -19, -41, and -64 μeq L^{-1}. The changes in median pH after 50, 100, and 200 years, respectively, were -0.07, -0.12, and -0.32.

- Based on the Level III projections, lakes in the NE might not change significantly over the next 50 years with current deposition.

- Acidic lakes in the NE might improve chemically with a 30 percent reduction in deposition assuming organic acid relationships with other chemical constituents remain constant, although some lakes might continue to acidify.

- Streams in the SBRP might experience a slow but steady decline in ANC and a linear increase in sulfate concentration over the next 50 years assuming current or increased deposition. About 10 percent of the SBRP streams might become acidic within 50 years. The stream population in the SBRP typically had higher initial ANCs than streams in other geographic regions of the Southeast. Thirty percent of the population had ANC concentrations between 25 and 100 μeq L^{-1}, and 70 percent of the stream reaches had ANC > 100 μeq L^{-1}. Care should be taken in extrapolating results from the SBRP to the population of other streams in the Southeast.

SECTION 11

SUMMARY OF RESULTS

11.1 RETENTION OF ATMOSPHERICALLY DEPOSITED SULFUR

11.1.1 Current Retention

On average, watersheds in the Northeast have sulfur budgets near steady state, with negligible net retention of atmospherically deposited sulfur (Section 7). A small proportion of northeastern watersheds have significant net retention, which appears to be controlled by reduction in wetlands or within lakes. In contrast, net retention in stream systems of the Southern Blue Ridge Province is high, averaging about 75 percent. These observations are qualitatively consistent with theory (Galloway et al., 1983a; NAS, 1984) and with site-specific budgets summarized by Rochelle et al. (1987).

The Mid-Appalachian Region is a zone of transition between the NE and SBRP in terms of observed current sulfur retention. Because of the similarities between soils in this region and the SBRP, it is likely that this region at one time retained as much of the elevated sulfur deposition as is now evident in the SBRP (i.e., 70 - 80 percent). It is also likely that continued high sulfur deposition is bringing soils near steady state, leading to reduced sulfur retention, perhaps very dramatically in the westernmost area (Subregion 2Cn of the National Stream Survey, which now has median percent sulfur retention of only 3 percent) (Plate 11-1), and has led to the low ANC and acidic stream reaches (excluding stream reaches affected by acid mine drainage) identified there by the National Stream Survey (Kaufmann et al., 1988). The Mid-Appalachian Region is the subject of additional in-depth soil sampling and analyses now underway within the DDRP.

Results of the sulfur input-output analyses are consistent with results of Level I regression analyses summarized in Section 8. Regression analyses indicate that in the NE, sulfate concentrations are more highly correlated with sulfur deposition than with any watershed characteristic, as would be expected for systems at or near steady state (i.e., systems where sulfur input equals output). Additionally in the NE, percent watershed sulfur retention is correlated with the extent of wetlands and wet soils on watersheds (Section 8.5). This provides empirical support for the hypothesis that, to the limited extent sulfur retention is observed in NE watersheds, reduction in wetlands is the principal retention mechanism.

In the SBRP, sulfate concentrations are correlated principally with edaphic factors. Sulfate concentrations are relatively high in watersheds with high proportions of shallow soils and in catchments having soils with low adsorption capacity. Similarly, percent sulfur retention increases with soil depth and with sulfate adsorption capacity of soils. In both the NE and SBRP, watershed disturbance (e.g., mining activity) is associated with elevated surface water sulfate concentrations.

11.1.2 Projected Retention

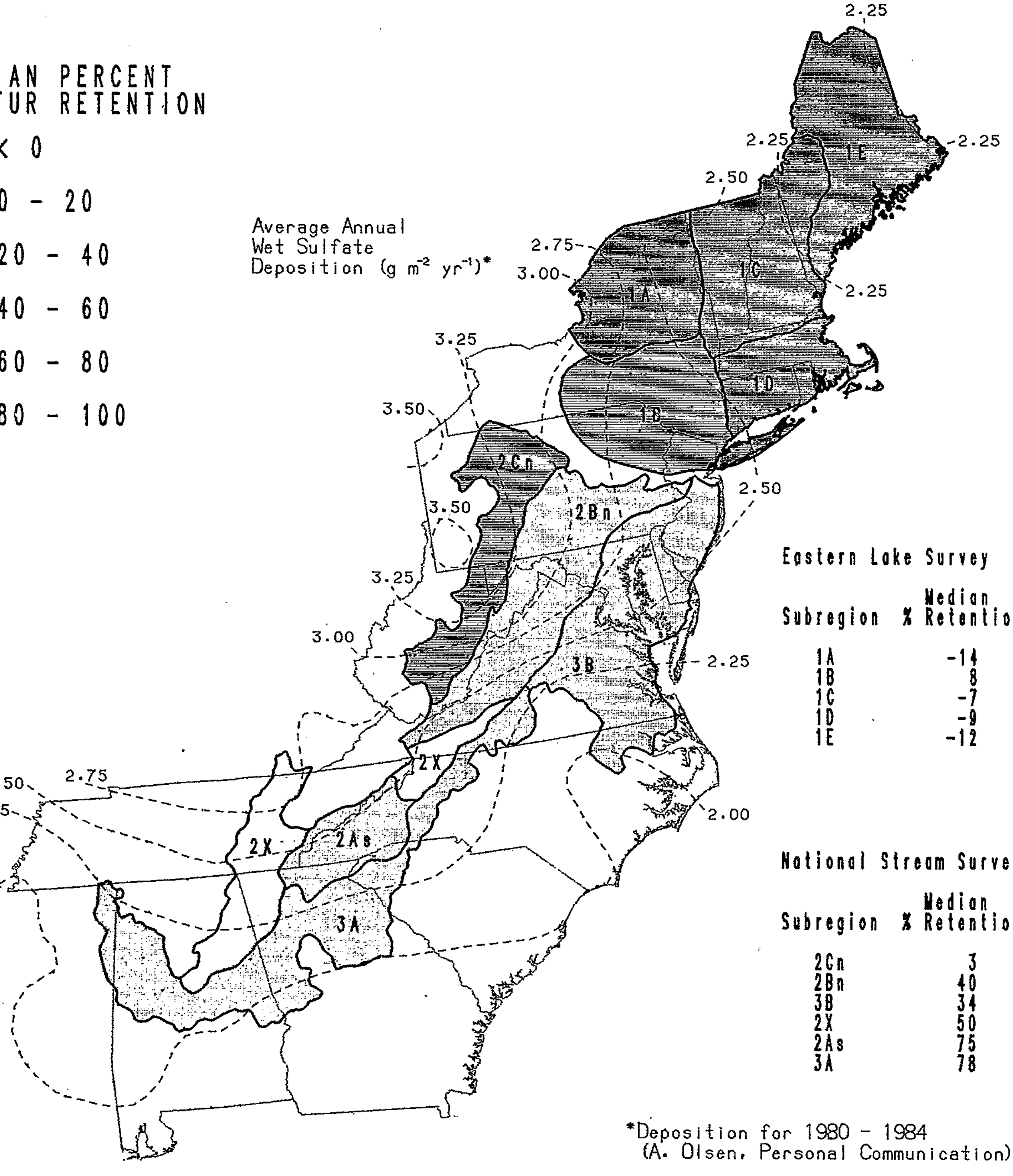
Using deposition scenarios described in Section 5.6, projections were made of future sulfur retention in the NE and SBRP using both a single factor (Level II) adsorption model (Section 9.2) and the three integrated models discussed in Section 10. For the sake of consistency, projections presented graphically

Plate 11-1. Sulfur retention and wet sulfate deposition for National Surface Water Survey subregions in the eastern United States.

NSWS SUBREGIONS
MEDIAN % SULFUR RETENTION
AND WET SULFATE DEPOSITION

MEDIAN PERCENT SULFUR RETENTION

- < 0
- 0 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100



Eastern Lake Survey

Subregion	Median % Retention
1A	-14
1B	8
1C	-7
1D	-9
1E	-12

National Stream Survey

Subregion	Median % Retention
2Cn	3
2Bn	40
3B	34
2X	50
2As	75
3A	78

*Deposition for 1980 - 1984
(A. Olsen, Personal Communication)

in this section are from the Level III MAGIC model. Because different target populations were modelled by the four models (i.e., Level II and three Level III models) and because the projected results vary somewhat among those populations, comparisons will be discussed qualitatively.

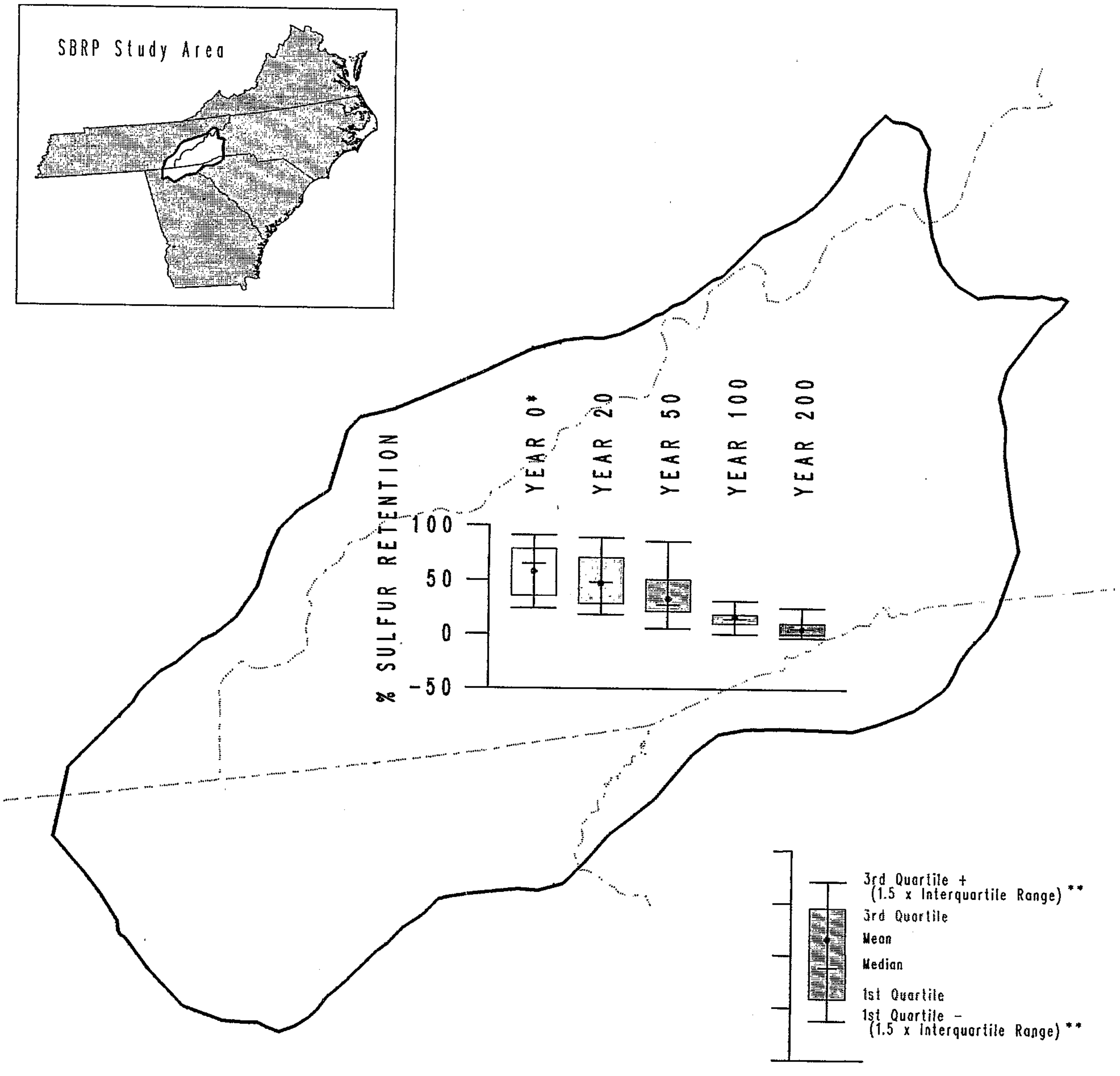
In the NE, median lake sulfate concentrations are already very close to steady state. For the scenario of constant deposition, all of the models thus projected only small changes in median sulfate concentration, and projected those changes to occur relatively rapidly (10 - 20 year lags). Among the Level III models, MAGIC and ETD project small decreases in median sulfate concentration during the next 20 to 50 years, whereas ILWAS projects very small increases. Slight (3 - 5 percent) positive sulfur retention is projected by all three models by year 50, with in-lake reduction as the principal retention mechanism. The differences in the direction of changes for sulfate concentration result from differences in target lake populations, in process representation by the models, and in calibration procedures; absolute differences among projections are minor and are relatively unimportant. For the scenario of decreased sulfur deposition, the models consistently project substantial decreases in median lake sulfate concentration by year 50. MAGIC and ETD project decreases in median sulfate of about 40 μeq L^{-1} in 50 years; ILWAS projects a somewhat slower decrease and a smaller, but still significant decrease of 21 μeq L^{-1} in median lake sulfate.

Changes projected by the Level II sulfate model are very similar to those projected by MAGIC and ETD. The Level II model projects only a small median decrease (7 μeq L^{-1}) in sulfate concentration by year 20 for the constant deposition scenario, and a decrease in median sulfate of 40 μeq L^{-1} by year 50 for the decreased sulfur deposition scenario. The principal difference in projections between the Level II and III models is that the Level II model projects all watersheds to eventually reach exactly steady state, rather than the small positive sulfur retention projected by Level III models. This results from differences in the processes considered by the models; the Level II model considers only sulfate sorption by soils, whereas the Level III models include in-lake reduction, which accounts for the slightly positive retention at long time intervals.

Projected changes in sulfate concentrations for SBRP surface waters occur much more slowly than in the NE, and are much larger in magnitude. Median sulfate retention in SBRP watersheds is currently about 75 percent, but retention is projected to decrease sharply over the next several decades (Plate 11-2). Results were available for the Level II model (Section 9) and two of the Level III models (MAGIC and ILWAS) (Section 10); all three models projected generally similar changes for sulfate in the SBRP. For the constant deposition scenario, the two integrated models project increases in median stream sulfate of roughly 15 μeq L^{-1} in the next 20 years and about 40 μeq L^{-1} in 50 years; median percent retention is projected to decrease by about 40 percent over the 50-year period. For the increased deposition scenario, slightly larger increases in median sulfate concentration, of slightly over 50 μeq L^{-1}, are projected by year 50. The Level II model projects somewhat faster increases for sulfate, with increases of 31 and 56 μeq L^{-1} in median sulfate concentration at 20 and 50 years, respectively. The Level II model and MAGIC both project that rates of increase in sulfate concentration will decrease by year 100 as SBRP watersheds approach steady state (ILWAS projections were not made beyond 50 years) (Section 10). The cumulative increases projected for median sulfate at 100 and 200 years are 60 and 74 μeq L^{-1} for MAGIC and 66 and 81 μeq L^{-1} for Level II. The differences among the models at 20 and 50 years are attributable to differences in hydrologic routing in the models and to assumptions about the chemistry of deep subsoils. The 20- and 50-year projections

Plate 11-2. Changes in sulfur retention in the Southern Blue Ridge Province as projected by MAGIC for constant sulfur deposition.

% SULFUR RETENTION
Model = MAGIC
Deposition = Constant



*YEAR 0 = NSS Sample

** Not to exceed extreme value.

occur during the period when the models project the most rapid changes in sulfate concentration, and can be regarded as a measure of uncertainty in the projections. In terms of the most important aspects of sulfur dynamics, the three models are consistent. All project that under the deposition scenarios simulated, the delayed response phase of SBRP watersheds would end for sulfate, and that there would be substantial increases in sulfate concentration in the next 20 to 50 years. Such changes would be accompanied by decreases in surface water ANC to a degree dependent upon the relative leaching of acids and base cations from watershed soils.

The results of the various sulfate analyses are all internally consistent. Level II projections of base year sulfate in watersheds of the NE and SBRP are consistent with, and provide a mechanistic explanation for, analyses by Rochelle and Church (1987), summarized in Section 7.3, showing watersheds in the northeastern United States to be at or near steady state for sulfur and watersheds in the SBRP to have high net sulfur retention. The very short sulfate response times projected for the NE are also consistent with results of regression analyses in Sections 7 and 8, which indicate that deposition is the principal control on surface water sulfate in the NE, and that significant sulfur retention (where observed), is probably attributable to sulfate reduction in lakes and/or wetlands rather than to sorption. Similarly, the long response times predicted by dynamic models for the SBRP are consistent with results of the Level I regression analyses, which found sulfate concentration and percent sulfur retention to be correlated with soil variables directly affecting adsorption capacity of soils (i.e., soil thickness and isotherm parameters).

11.2 BASE CATION SUPPLY

11.2.1 Current Control

Base cations are supplied from watersheds to surface waters by two processes acting in concert. The initial source is mineral weathering, which is a slow process that supplies base cations to the soil exchange complex. Equilibrium between the exchange complex and soil water (and thus waters delivered to lakes and streams) is reached quickly. It is generally accepted that weathering rates are likely to change negligibly or increase only slightly due to the effects of acidic deposition since only slight decreases in soil pH are likely. If weathering supplies base cations to surface waters at rates equal to or greater than rates of acid anion deposition, then systems would be relatively "protected". If weathering rates are low and cation exchange dominates base cation supply rates, then the rate of depletion of base cations from the exchange complex becomes an important determinant of rates of surface water acidification. Our analyses indicate that surface water ANCs >100 $\mu eq\ L^{-1}$ cannot be explained by the cation exchange model of Reuss and Johnson (1986); thus, ANC generation appears to be dominated by weathering in these systems and they, presumably, are relatively protected against loss of ANC (Section 9). Surface waters with ANCs <100 $\mu eq\ L^{-1}$ are likely controlled by a mix of weathering and cation exchange. The exact proportion of the mix is difficult to determine.

11.2.2 Future Effects

Single factor base cation analyses, using the models of Reuss and Johnson (1986) and of Bloom and Grigal (1985), were developed as a "worst-case" analysis by (1) considering only processes occurring in the top 1.5 - 2 meters of the regolith and (2) setting mineral weathering rates to zero (i.e., assuming that the supply of base cations was totally controlled by cation exchange). This analysis indicated that depletion of base cations from the exchange complex would occur under the sulfur deposition scenarios simulated. The effect on surface water ANCs was initially slight but was not negligible. The magnitude of soil base cation depletion was projected to accelerate in the future. At current levels of deposition, about 15 percent of the lakes in the ELS target population are potentially susceptible to significant depletion of exchangeable cations and, thus, depletion of associated surface water ANCs. The greatest portion of such changes is projected to occur on a time scale of about 50 years. In the SBRP, a greater percentage of systems are projected to be susceptible to adverse effects, but at longer time scales (i.e., about 100 years) than northeastern systems.

Any effects of base cation depletion would be superimposed upon effects resulting from changes in sulfate mobility in soils. The combined effects were simulated using the Level III watershed models and are summarized in the next section.

11.3 INTEGRATED EFFECTS ON SURFACE WATER ANC

The three Level III watershed models (Section 1.3.4) were used to project the integrated watershed and surface water responses to the sulfur deposition scenarios. Results among the models were remarkably comparable. For example, within modelling Priority Classes A and B in the NE (Section 10) and for the decreased sulfur deposition scenario, the MAGIC, ETD, and ILWAS models project changes (at 50 years) in the median target population ANC for ANC groups <0 and 0 - 25 μeq L^{-1} within 2 μeq L^{-1} (5 - 7 μeq L^{-1}) and 3 μeq L^{-1} (10 - 13 μeq L^{-1}), respectively. For the ANC group 25 - 100 μeq L^{-1} the ILWAS and MAGIC models project increases in median ANC within 1 μeq L^{-1} (5.4 - 6.3 μeq L^{-1}). Increases in the median ANC of this group (25 - 100 μeq L^{-1}) under these conditions projected by the ETD model are quite a bit greater (i.e., $\sim$14μeq L^{-1} vs. $\sim$6 μeq L^{-1}).

The greatest disagreement among the model projections (at 50 years) is for the increased sulfur deposition scenario in the SBRP. For modelling Priority Classes A and B and ANC group 100 - 400 μeq L^{-1}, the ILWAS model projects a decrease in median ANC of 7 μeq L^{-1}, whereas the MAGIC model projects a decrease of 24 μeq L^{-1}. Otherwise, comparative results among the models are remarkably uniform, especially among the lower ANC groups of systems that are of the greatest concern.

Results from MAGIC are presented here because this model was successfully calibrated to the largest number of watershed systems in the two regions (i.e., 123 of the 145 DDRP sample watersheds, representing a target population of 3,227 systems in the NE; and 30 of the 35 DDRP sample watersheds, representing a target population of 1,323 stream reaches in the SBRP).

As discussed in Section 10, the watershed modelling analyses make use of watershed soil representations as aggregated from the DDRP Soil Survey. Because of the focus of the DDRP on regional characteristics and responses, soils data were gathered and aggregated so as to capture the most important central tendencies of the study systems. As a result, extremes of individual watershed responses probably are not fully captured in the analyses presented here (see discussion in Sections 8 and 10). Those systems that are projected to respond to the greatest extent or most quickly to current or altered levels of sulfur deposition might, in fact, be expected to respond even more extensively or more quickly than indicated here. This should be kept in mind when reviewing the simulation results presented in this Section.

11.3.1 Northeast Lakes

Results of the projections for both deposition scenarios are presented in a couple of ways. Plate 11-3 and Table 11-1 illustrate the projected change in the median ANC at 50 years for lakes classified into four ANC groups (i.e., <0 μeq L^{-1}, 0 - 25 μeq L^{-1}, 25 - 100 μeq L^{-1}, and 100 - 400 μeq L^{-1}). These projections indicate a general, very slight decline in ANC over the 50-year period under the current deposition scenario and an increase of roughly 5 - 15 μeq L^{-1} in ANC for all groups under the decreased sulfur deposition scenario. Plates 11-4 and 11-5 illustrate the overall projected ANCs for the target population at 20, 50 and 100 years for the constant and decreased deposition scenarios, respectively.

Table 11-2 presents the population estimates (with 95 percent confidence intervals) of northeastern lakes having values of ANC <0 μeq L^{-1} and <50 μeq L^{-1} at 20 and 50 years as projected by the MAGIC model for the two deposition scenarios. The ANC = 0 μeq L^{-1} value is used to define acidic systems, and the ANC value of 50 μeq L^{-1} (for index values as sampled in the NSWS, see Section 5.3) has recently been suggested as useful in approximating the level at or below which systems are susceptible to severe episodic acidification (i.e., brief periods of ANC depression to very low or negative values) (Eshleman, 1988) with consequent adverse effects on biota. It is extremely important to keep in mind that these values only serve as indices in an otherwise smooth continuum of surface water chemistry conditions and responses to acidic deposition. It is also important to remember that adverse biological effects occur at higher ANCs (i.e., greater than 50 μeq L^{-1}) in systems that previously (i.e., prior to the advent of acidic deposition) were adapted to more circumneutral conditions (Schindler, 1988).

As indicated in Table 11-2, under the constant deposition scenario, the number of lakes with ANC <0 μeq L^{-1} increases at 50 years whereas the number of lakes with ANC <50 μeq L^{-1} remains essentially constant. For the scenario of decreased sulfur deposition, a marked decrease is projected in the number of systems with ANC <0 and ANC <50 μeq L^{-1}. Plate 11-6 shows the changes in pH for northeastern lakes at 50 years as projected by MAGIC. MAGIC projects the greatest change for the lowest ANC group. For this group the change projected by ILWAS is virtually identical to that projected by MAGIC. Projections by ILWAS and ETD for the higher ANC groups are somewhat greater than projections by MAGIC (see Section 10).

Model projections indicate a mixed response of northeastern lake systems at current levels of sulfur deposition. Slight decreases in median ANCs are projected for all ANC groups, along with a slight increase in the number of systems with ANC < 0 μeq L^{-1}. The number of systems having ANC < 50 μeq L^{-1} (and thus potentially susceptible to episodic acidification), however, is not projected to change appreciably. Projected responses to decreased sulfur deposition show a clearer pattern; MAGIC projects surface water ANCs to increase and the number of lakes with ANC <0 μeq L^{-1} and ANC <50 μeq L^{-1} to decrease. Such a response would be consistent qualitatively with reported changes in the chemistry of lakes near Sudbury, Ontario, following reductions of sulfur dioxide emissions from the Sudbury smelter (Dillon et al., 1986; Hutchinson and Havas, 1986; Keller and Pitbaldo, 1986).

Plate 11-3. Change in median ANC of northeastern lakes at 50 years as projected by MAGIC (see Section 1.3.4 for definition of the deposition scenarios used).

CHANGE IN MEDIAN ANC
Year 10 to Year 50
Model = MAGIC

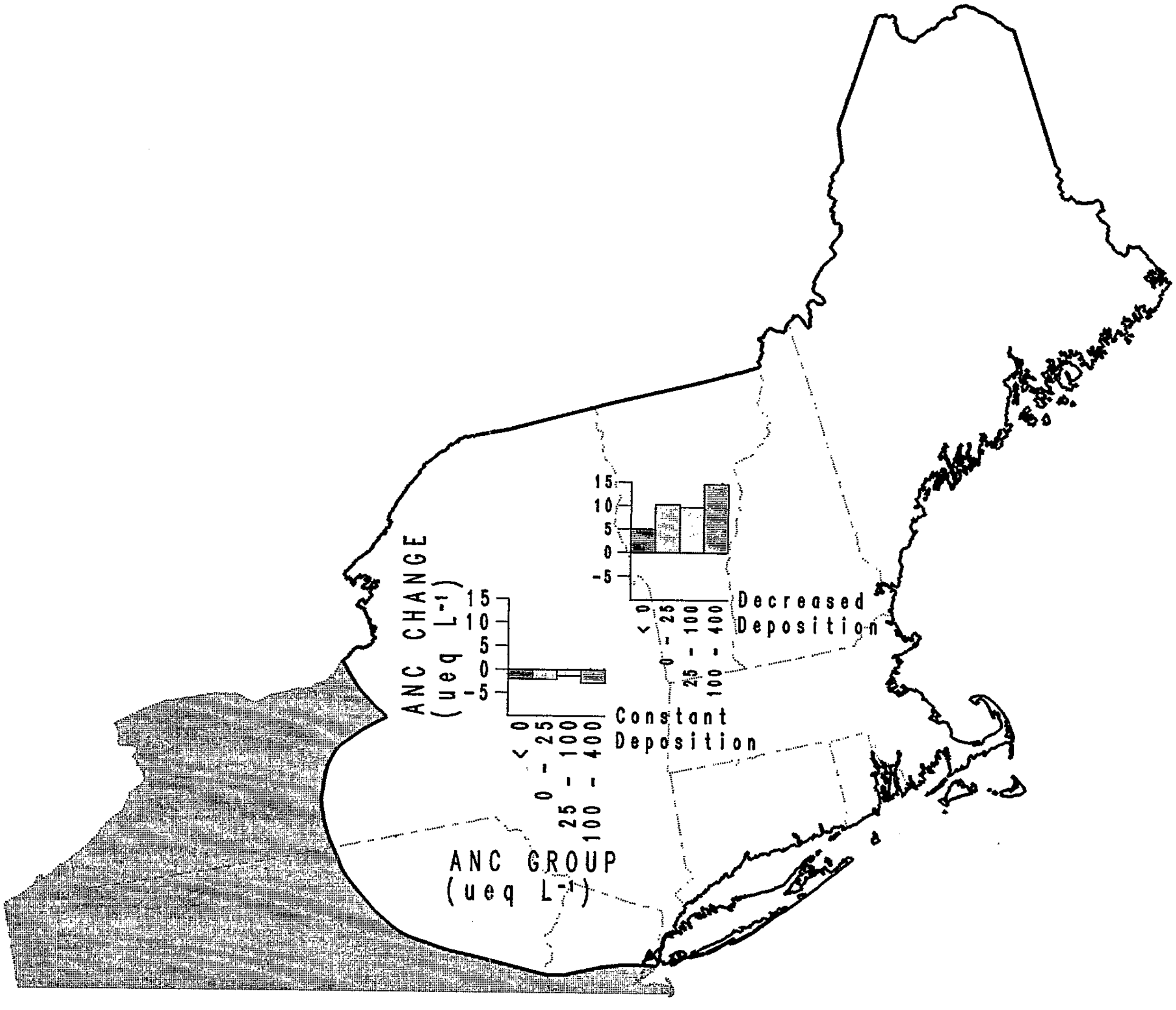


Table 11-1. Weighted Median Projected Change in ANC at 50 Years for Northeastern DDRP Lakes

	ANC Group (μeq L^{-1})			
	<0	0-25	25-100	100-400
Target Population	162	398	1054	1612
Change in Median (μeq L^{-1}) (deposition = constant)[a]	-2	-2	-1	-3
Change in Median (μeq L^{-1}) (deposition = decreased)	5	10	10	15

[a] See Section 1.3.4 for definition of the deposition scenarios used.

Plate 11-4. ANCs of northeastern lakes versus time, as projected by MAGIC for constant sulfur deposition.

ANC vs. TIME
Model = MAGIC; Deposition = Constant
ANC Group(s) = All

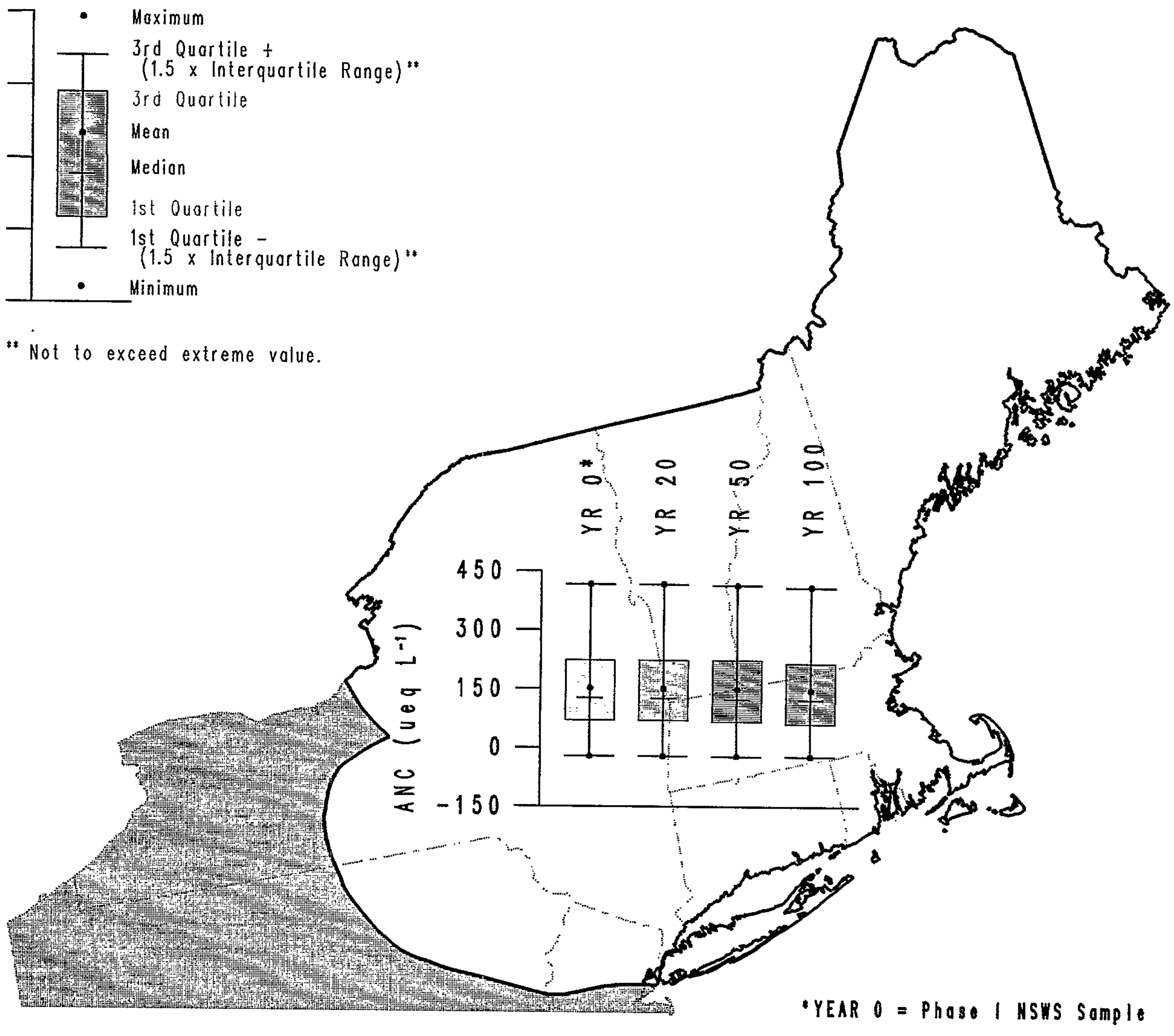


Plate 11-5. ANCs of northeastern lakes versus time, as projected by MAGIC for decreased sulfur deposition.

ANC vs. TIME
Model = MAGIC; Deposition = Decreased
ANC Group(s) = All

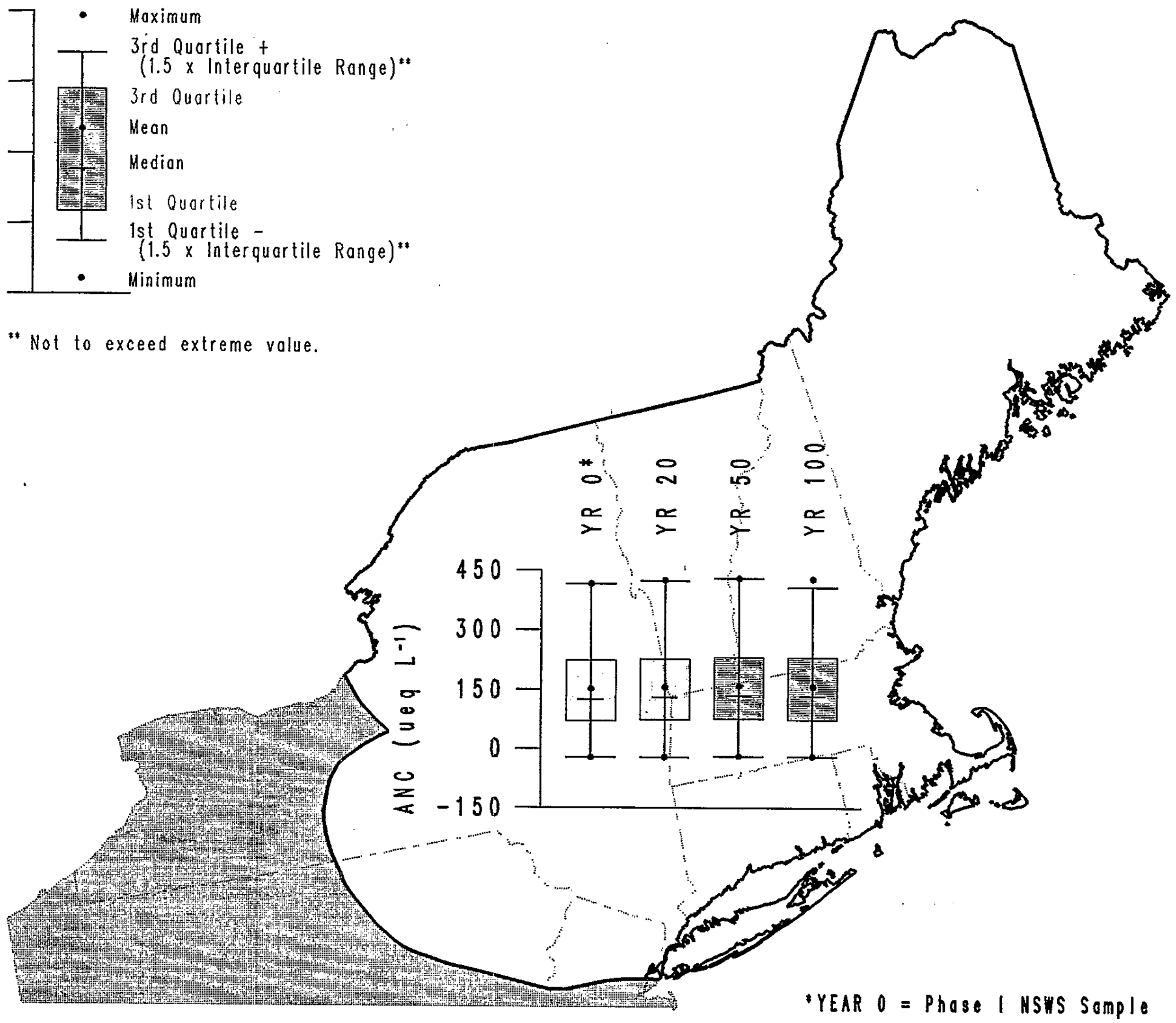


Table 11-2. Lakes in the NE Projected to Have ANC Values <0 and <50 $\mu eq\ L^{-1}$ for Constant and Decreased Sulfur Deposition[a,b]

Time from Present (yr)		Constant Deposition		Decreased Deposition	
		ANC <0	ANC <50	ANC <0	ANC <50
0_{NSWS}	#[c]	162[d]	880[d]	162[d]	880[d]
	%	5	27	5	27
$0_{calibrated}$	#[e]	161[e]	648[e]	161[e]	648[e]
	%	5	20	5	20
20	#	161 (245)	648 (319)	136 (230)	621 (313)
	%	5 (8)	20 (10)	4 (7)	19 (10)
50	#	186 (251)	648 (329)	87 (237)	586 (331)
	%	6 (8)	20 (10)	3 (7)	18 (10)

[a] Projections are based on 123 lake/watersheds successfully calibrated by MAGIC. Projections at 20 and 50 years are based on the MAGIC calibrated values at year 0. The calibrated values at year 0 can vary from the values observed by the NSWS (see footnote "e" this table and also Figure 10-42). If modelled changes in ANC are combined with observed NSWS ANC values at year 0 (rather than with model-calibrated ANC at year 0), resulting projections of ANC in years 20 and 50 are obtained that sometimes differ from the values given here (for example, 248 lakes [rather than 186] would be projected to be acidic at year 50 under current levels of deposition). Projections presented in this table, therefore, are best used to indicate the direction and relative magnitude of potential changes rather than absolute numbers of systems with ANC values less than 0 or 50 $\mu eq\ L^{-1}$.

[b] See Section 1.3.4 for definition of the deposition scenarios used.

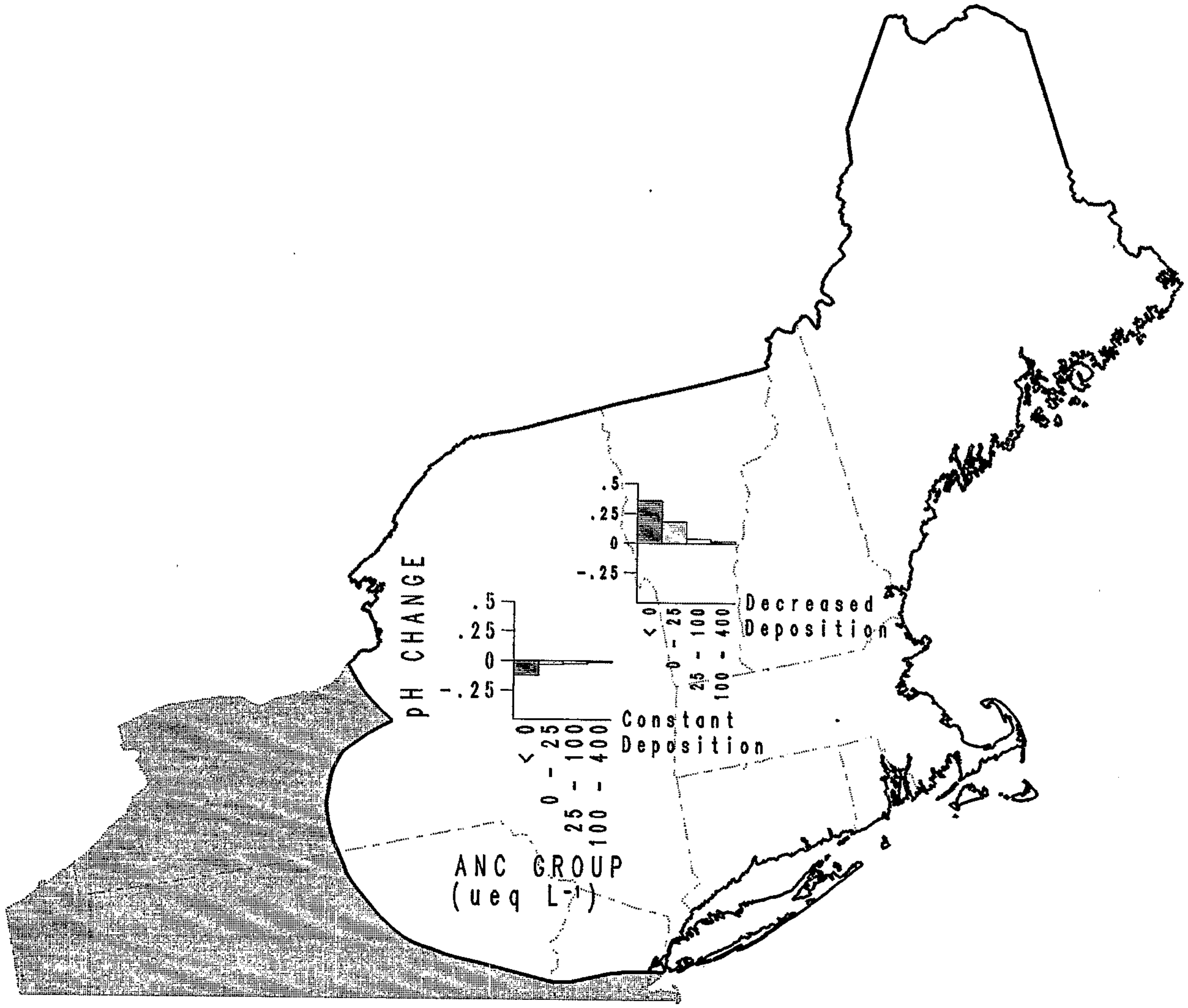
[c] # is the number of lakes; % is percent of the target population of 3,227 lakes; ( ) indicate 95 percent confidence estimates relative to NSWS estimates at year 0.

[d] Indicates estimate from NSWS Phase I sample for the same 123 lakes; target population = 3,227 lakes.

[e] # is the number of lakes and % is the percent of target population of 3,227 lakes as estimated from the MAGIC calibration to the NSWS Phase I sample.

Plate 11-6. Changes in median pH of northeastern lakes at 50 years as projected by MAGIC (see Section 1.3.4 for definition of the deposition scenarios used).

CHANGE IN MEDIAN pH
Year 10 to Year 50
Model = MAGIC



Because of the highly organic nature of some soils in the NE, the exact nature of chemical "recovery" of northeastern lakes is uncertain. To our knowledge, there are no field studies in that region that carefully document such a situation over a sufficient time period to cast much light upon this subject. As discussed in Section 1, it has been hypothesized that leaching of organic acids could be controlled by changes in soil water pH (e.g., as caused by acidic deposition) and that this, in turn, could have important effects on surface water pH values (Krug and Frink, 1983; Krug, 1989). In this hypothesis, a decrease in precipitation acidity would result in an increase in leaching of organic acids to surface waters, partially offsetting (i.e., toward lower pH) pH increases associated with the "improved" chemical quality of the atmospheric deposition. Recently, Wright et al. (1988) noted such an effect in a stream catchment in Norway where acidic deposition was excluded and reconstituted, more circumneutral waters were substituted as "rain". The catchment studied by Wright et al. (1988) has extremely thin, organic soils and, thus, is a site almost ideally suited to the observation of such an effect. Wright et al. (1988) noted that in other areas of Norway having soils of a more mineral nature (and probably much more similar to soils of the type found on DDRP northeastern study sites) the potential for enhanced mobilization of organic anions would likely be much suppressed and minor relative to the effects of decreasing sulfur deposition.

Even if there was an appreciable increase in organic acid leaching as a response to reduced deposition acidity, the net effect would be beneficial to aquatic biota inasmuch as it would most likely be accompanied by reductions in surface water concentrations of inorganic monomeric aluminum, which is highly toxic to fish (Baker and Schofield, 1982).

Thus, although the exact chemical response of the northeastern DDRP systems is unknown, projections indicate an improvement in surface water quality as a consequence of reduced sulfur deposition in the region.

11.3.2 Southern Blue Ridge Province

Plate 11-7 and Table 11-3 illustrate the projected changes (MAGIC model) in median ANC at 50 years for stream reaches in the SBRP. The MAGIC model used in this analysis was successfully calibrated to 32 of the 35 DDRP SBRP stream reach watersheds. Two stream reaches had ANC > 1000 μeq L^{-1} and were dropped from this presentation. The remaining 30 stream reaches had ANC > 25 μeq L^{-1} and < 400 μeq L^{-1} and represent a target population of 1,323 stream reaches in the SBRP. The projected changes in median ANCs have been computed for the same ANC groups (25 - 100 μeq L^{-1} and 100 - 400 μeq L^{-1}) as for the NE (Plate 11-3). Plates 11-8 and 11-9 illustrate the overall projected ANCs for the target population at 20, 50, 100, and 200 years for the current and increased deposition scenarios, respectively.

Table 11-4 presents the population estimates (with 95 percent confidence intervals) of SBRP stream reaches having ANC <0 μeq L^{-1} and <50 μeq L^{-1} at 20 and 50 years as projected by the MAGIC model for the two deposition scenarios. The 95 percent confidence intervals about these projections are broad but understandable, given the low number of systems available for simulation (30) and the inherent uncertainties involved in such a complex simulation of environmental response.

Plate 11-7. Change in median ANC of Southern Blue Ridge Province stream reaches at 50 years as projected by MAGIC (see Section 1.3.4 for definition of the deposition used).

CHANGE IN MEDIAN ANC

Year 10 to Year 50

Model = MAGIC

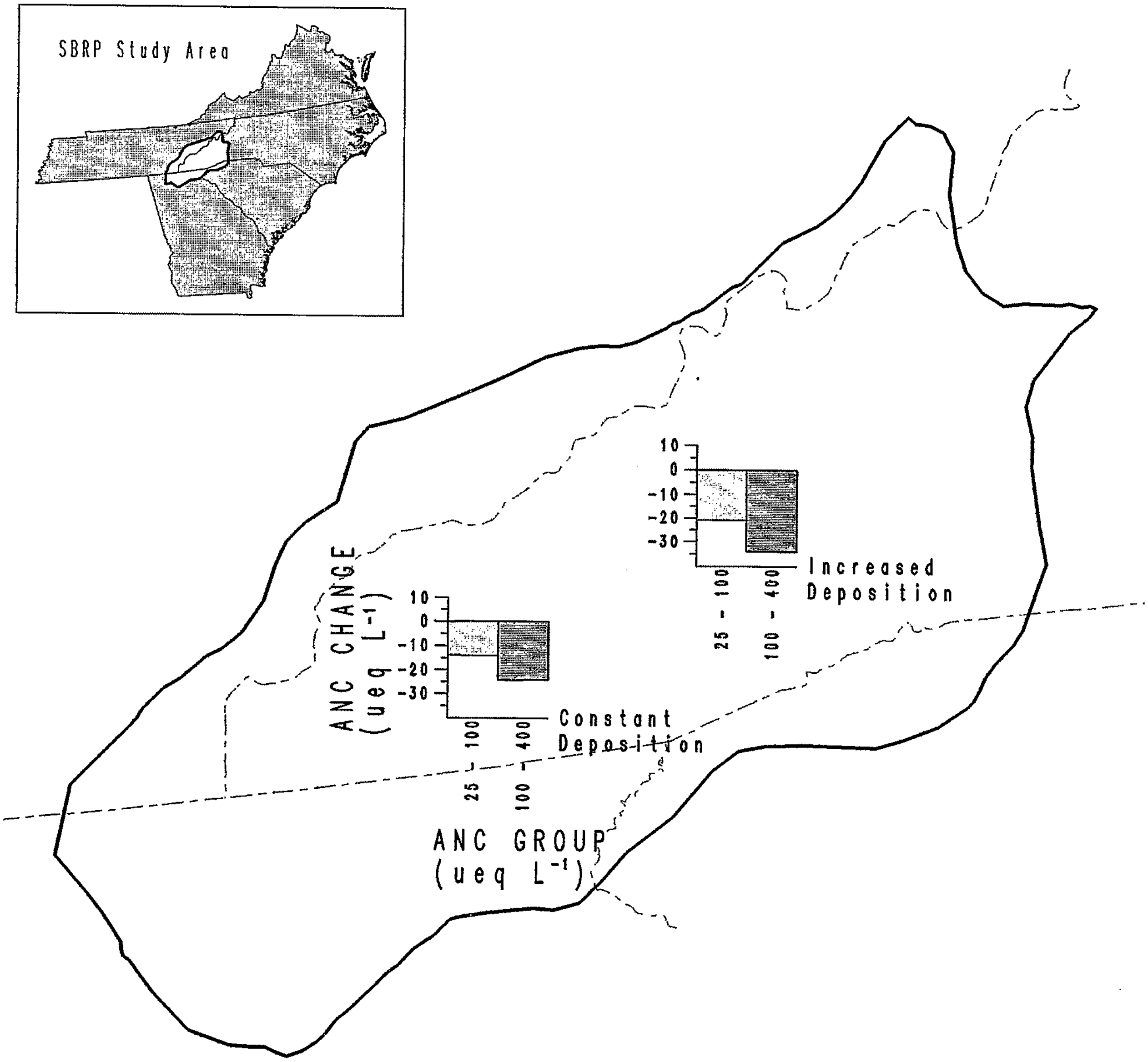


Table 11-3. Weighted Median Projected Change in ANC at 50 Years for DDRP SBRP Stream Reaches

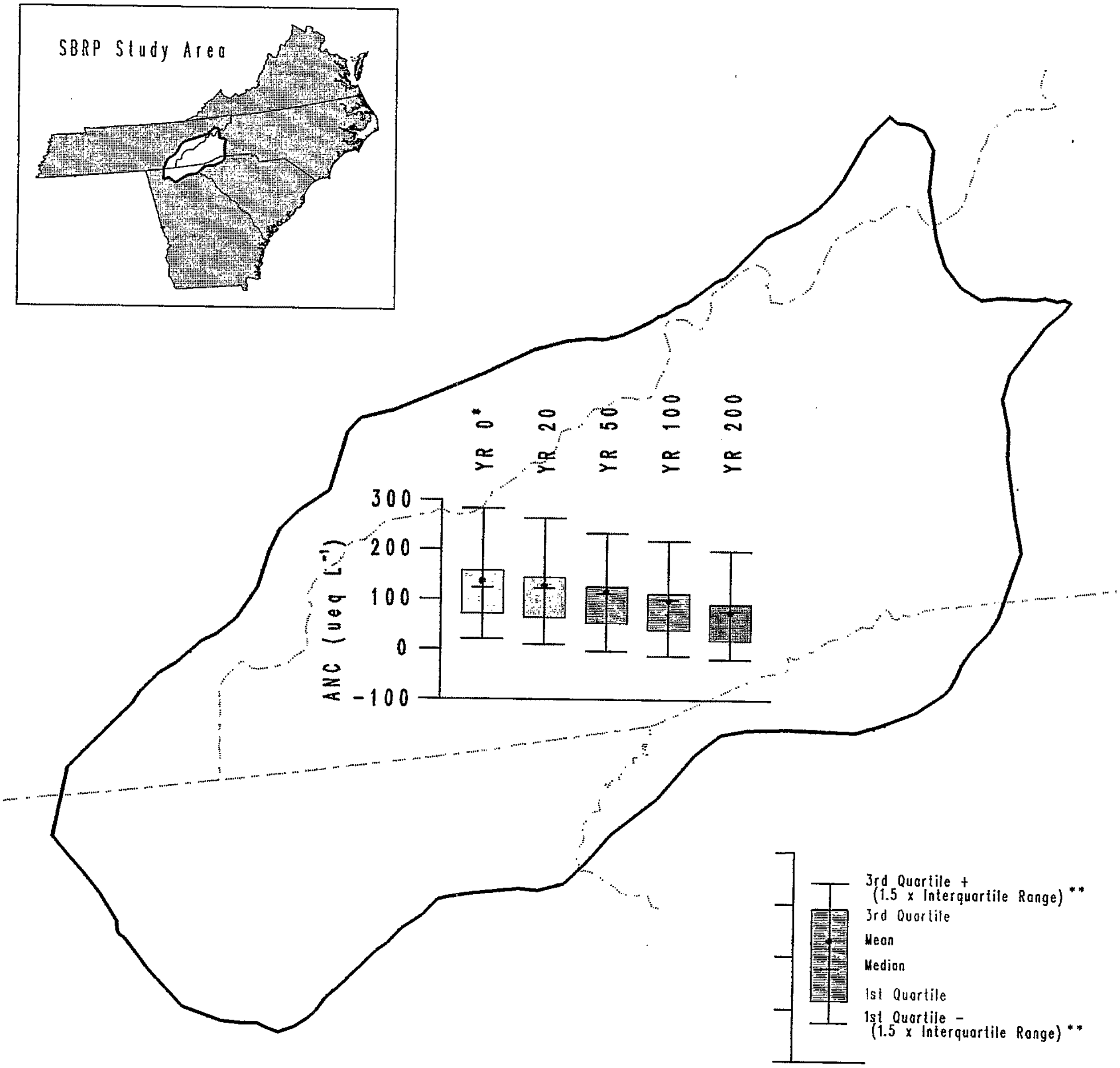
	ANC Group (μeq L^{-1})	
	25-100	100-400
Target Population	407	916
Median Change (μeq L^{-1}) (deposition = constant)[a]	-14	-24
Median Change (μeq L^{-1}) (deposition = increased)	-20	-34

[a]See Section 1.3.4 for definition of the deposition scenarios used.

Plate 11-8. ANCs of Southern Blue Ridge Province stream reaches versus time, as projected by MAGIC for constant sulfur deposition (see Section 1.3.4 for definition of the deposition scenarios used).

ANC vs. TIME

Model = MAGIC; Deposition = Constant
ANC Group(s) = <400 ueq L^{-1}

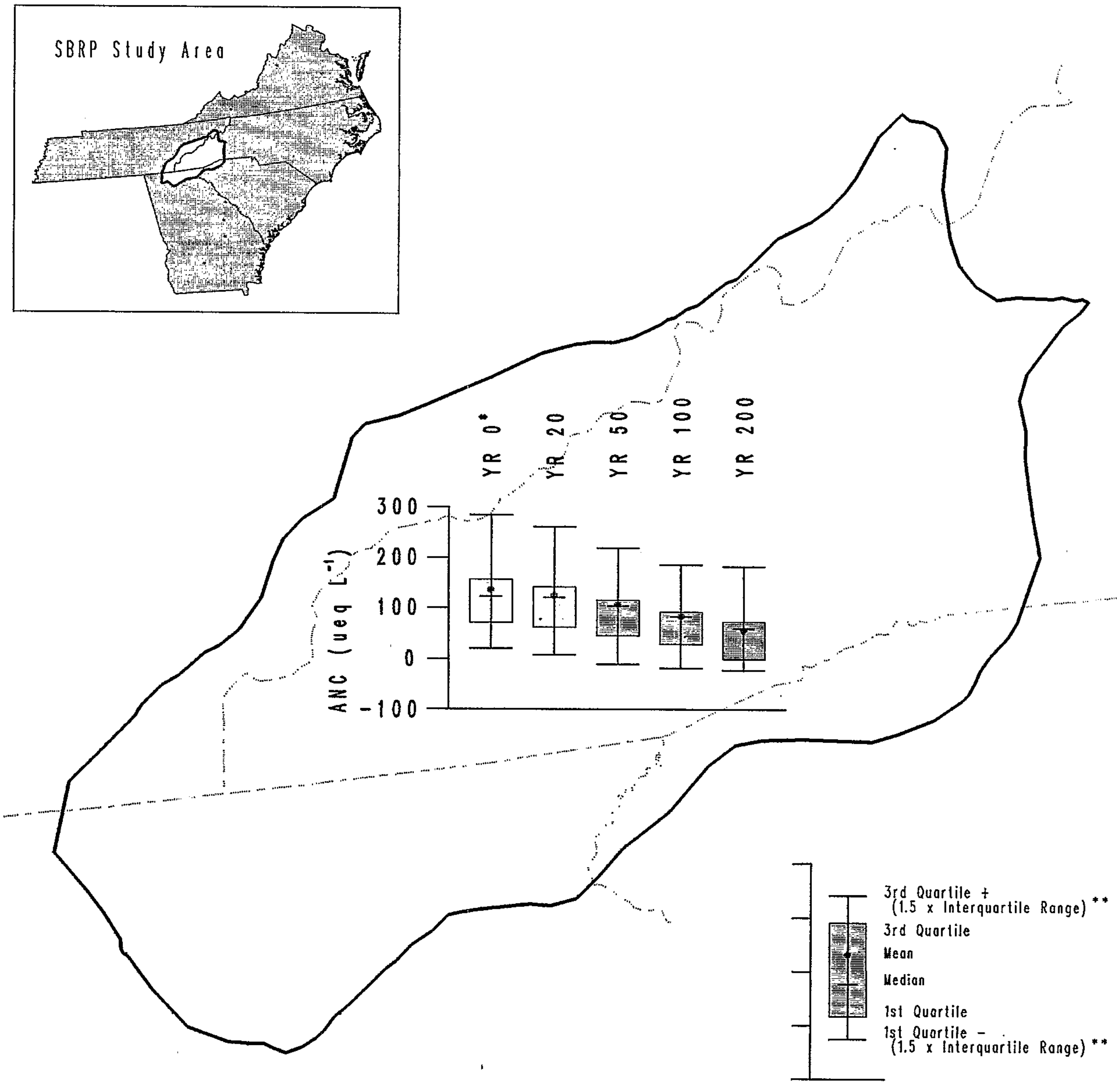


*YEAR 0 = NSS Sample

** Not to exceed extreme value.

Plate 11-9. ANCs of Southern Blue Ridge Province stream reaches versus time, as projected by MAGIC for increased sulfur deposition (see Section 1.3.4 for definition of the deposition scenarios used).

ANC vs. TIME
Model = MAGIC; Deposition = Increased
ANC Group(s) = <400 ueq L^{-1}



*YEAR 0 = NSS Sample

** Not to exceed extreme value.

Table 11-4. SBRP Stream Reaches Projected to Have ANC Values <0 and <50 μeq L^{-1} for Constant and Increased Sulfur Deposition[a,b]

Time from Present (yr)		Constant Deposition		Increased Deposition	
		ANC <0	ANC <50	ANC <0	ANC <50
0_{NSWS}	#[c]	0[d]	58[d]	0[d]	58[d]
	%	0	4	0	4
$0_{calibrated}$	#[e]	0[e]	187[e]	0[e]	187[e]
	%	0	14	0	14
20	#	0	187 (310)	0	187 (314)
	%	0	14 (23)	0	14 (24)
50	#	129 (295)	203 (333)	159 (291)	340 (359)
	%	10 (22)	15 (25)	12 (22)	26 (27)

[a] Projections are based on 30 stream/watersheds successfully calibrated by MAGIC. Projections at 20 and 50 years are based on the MAGIC calibrated values at year 0. The calibrated values at year 0 can vary from the values observed by the NSWS (see footnote "e" this table and also Figure 10-70). If modelled changes in ANC are combined with observed NSWS values at year 0 (rather than with model-calibrated ANC at year 0), resulting projections of ANC in years 20 and 50 are obtained that sometimes differ from the values given here (for example, zero stream reaches [rather than 129] would be projected to become acidic by year 50 under current levels of deposition; also, although projections from the ILWAS model for median regional decreases in ANC over 50 years are comparable to those projected by MAGIC for the same watersheds [see Table 10-15], ILWAS does not project any SBRP watersheds to become acidic by year 50). Projections presented in this table, therefore, are best used to indicate the direction and relative magnitude of potential changes rather than absolute numbers of systems with ANC values less than 0 or 50 μeq L^{-1}.

[b] See Section 1.3.4 for definition of the deposition scenarios used.

[c] # is the number of stream reaches; % is percent of the target population of 1,323 stream reaches; ( ) indicate 95 percent confidence estimates relative to NSWS estimates at year 0.

[d] Indicates estimate from NSWS Pilot Stream Survey sample for the same 30 stream reaches; target population = 1,323 stream reaches.

[e] # is the number of stream reaches and % is the percent of the target population of 1,323 stream reaches as estimated from the MAGIC calibrations to the NSWS Pilot Stream Survey sample.

Plates 11-10 and 11-11 show decreases in pH of SBRP stream reaches as projected by *MAGIC* and ILWAS, respectively, for the increased sulfur deposition scenario. Changes projected by the two models are highly comparable.

Model projections for the SBRP stream reaches indicate decreased surface water quality under scenarios of either current or increasing sulfur deposition. As noted in Sections 9 and 10, responses to changes in sulfur deposition levels in the SBRP are projected to be slower than those in the NE; i.e., there is a considerable lag in the response of the systems due to the storage of sulfur in the soils. The result is that there is a delay not only in the acidification of surface waters in the region, but also in any potential recovery if sulfur deposition were to be decreased. Due to the fact that soils in this region are much less organic in nature than those in the NE (e.g., wetlands in the SBRP are virtually non-existent; mean stream DOC at lower nodes was <1 mg L^{-1}), these model projections are uncomplicated by potential effects of organic acid leaching.

Projections of stream water quality response for the DDRP SBRP target population clearly indicate future adverse effects of sulfur deposition at increased or current levels.

11.4 SUMMARY DISCUSSION

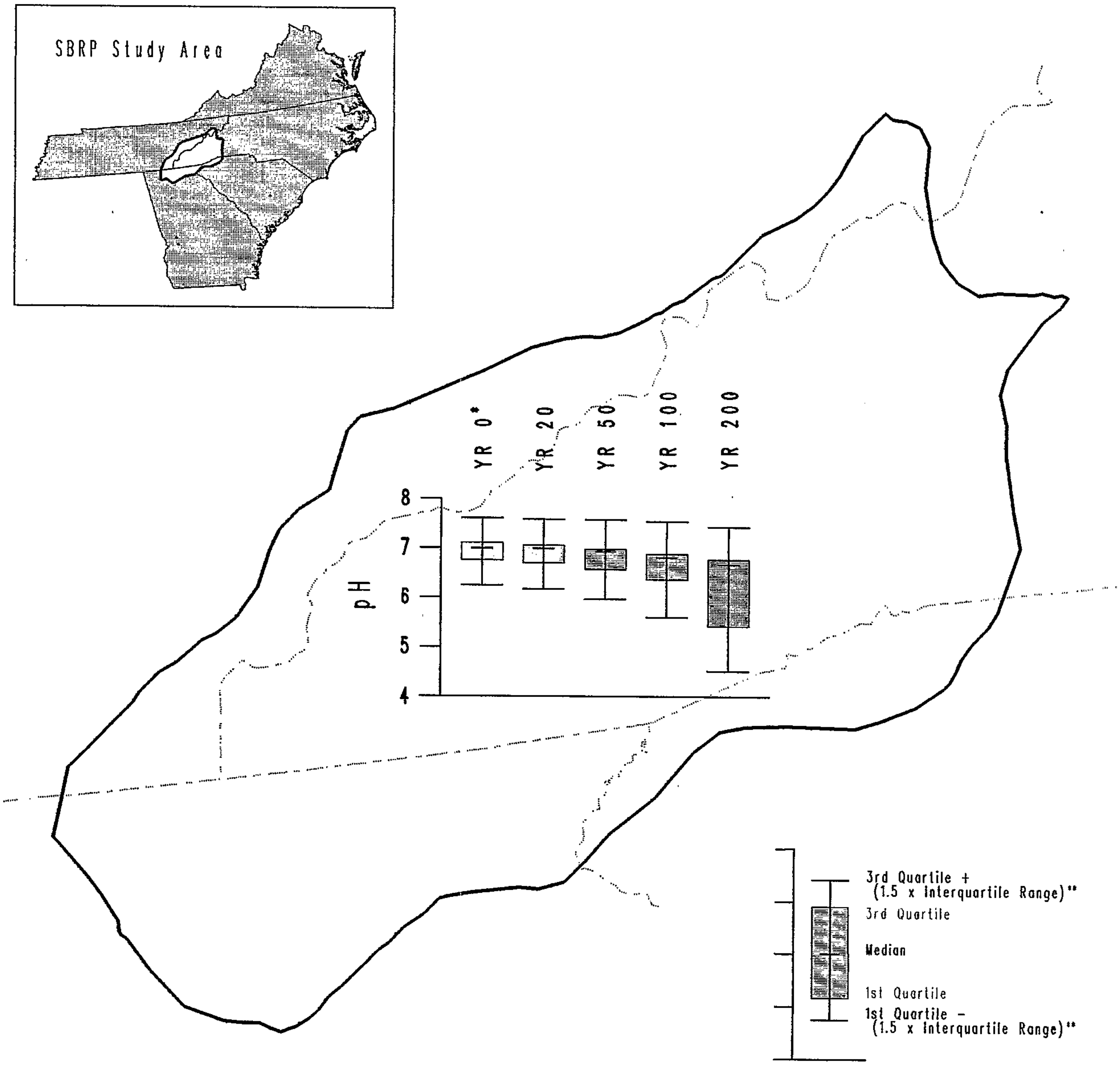
The NE is currently at sulfur steady state and sulfate concentrations in surface waters would respond relatively rapidly to decreases in sulfur deposition. Associated with these changes would be increases in surface water ANC. Continued sulfur deposition at current levels is gradually depleting the cation exchange pool in northeastern soils with consequent decreases in surface water ANC. Such changes are relatively slow and minor, however, relative to direct effects of increased anion mobility in watersheds on surface water chemistry.

Watersheds in the SBRP are currently retaining nearly three-quarters of the atmospherically deposited sulfur on the average but soils are projected as becoming more saturated with regard to sulfur. Sulfate concentrations are projected to be increasing in the surface waters of the region. This response is projected to be marked over the next 50 years at either current or increased levels of sulfur deposition, as are decreases in stream water ANC. Superimposed upon this effect is a relatively minor acidification effect of base cation depletion.

Results from all level of DDRP analyses are (1) consistent internally, (2) consistent with theory (Galloway et al., 1983a) and (3) consistent with recent observations of lakes monitored during changing sulfur deposition regimes (Dillon et al., 1986; Hutchinson and Havas, 1986; Keller and Pitbaldo, 1986).

Plate 11-10. Changes in pH of SBRP stream reaches as projected by MAGIC (see Section 1.3.4 for definition of the deposition scenarios used).

pH vs. TIME
Model = MAGIC; Deposition = Increased
ANC Group(s) = <400 ueq L^{-1}



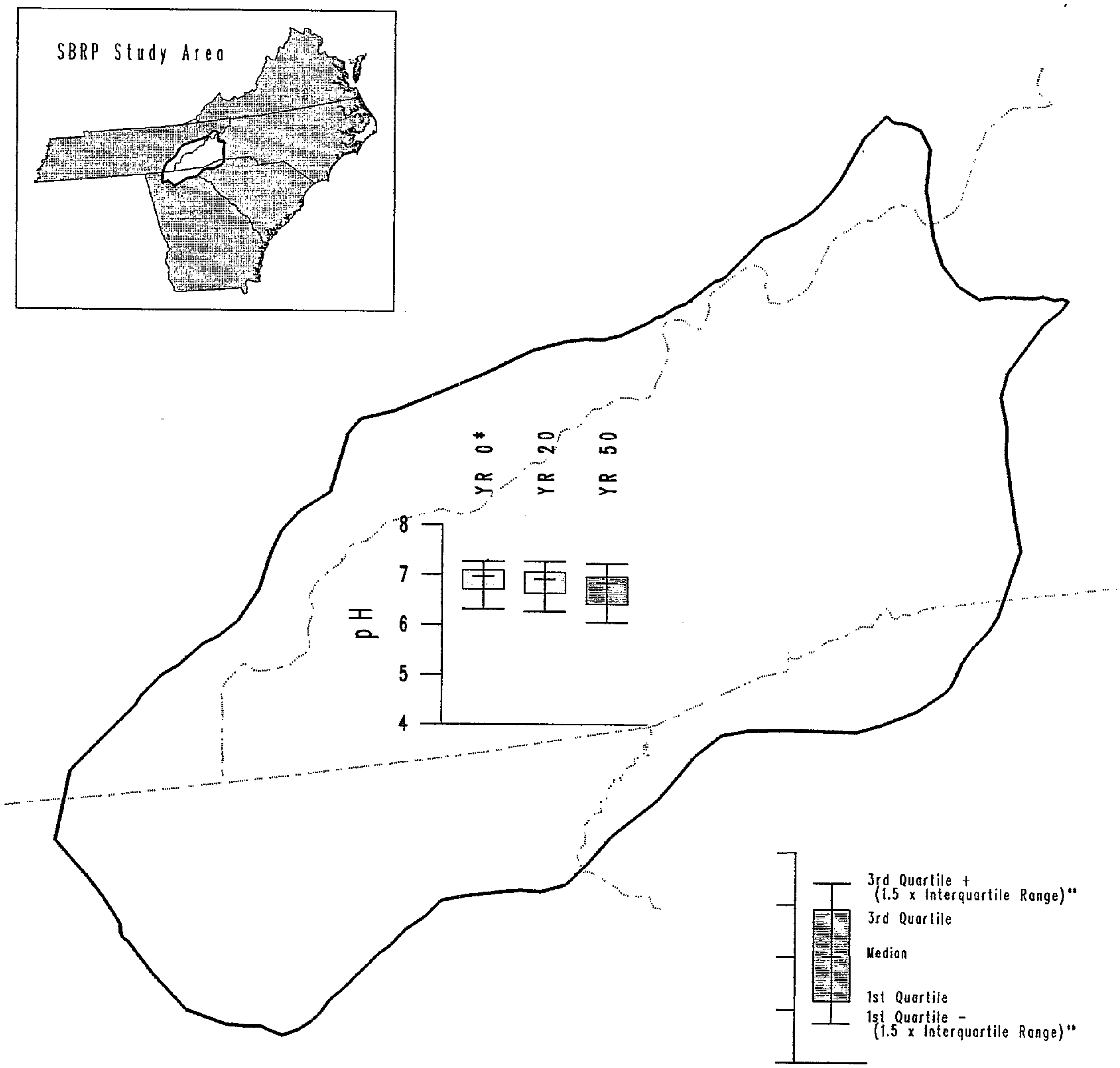
*YEAR 0 = Model Year 0

** Not to exceed extreme value.

Plate 11-11. Changes in pH of SBRP stream reaches as projected by ILWAS (see Section 1.3.4 for definition of the deposition scenarios used).

pH vs. TIME

Model = ILWAS; Deposition = Increased
ANC Group(s) = <400 ueq L^{-1}



*YEAR 0 = Model Year 0

** Not to exceed extreme value.

SECTION 12

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SECTION 13

GLOSSARY

13.1 ABBREVIATIONS AND SYMBOLS

13.1.1 Abbreviations

ADS	--	Acid Deposition System
AERP	--	Aquatic Effects Research Program
ANC	--	Acid neutralizing capacity
AREAL-RTP	--	USEPA Atmospheric Research and Exposure Assessment Laboratory - Research Triangle Park
CDF	--	Cumulative distribution function
CI	--	Confidence interval
CIR	--	Color infrared photography
DDRP	--	Direct/Delayed Response Project
DEM	--	Digital elevation models
DOC	--	Dissolved organic carbon
DQO	--	Data quality objective
ELS-I	--	Eastern Lake Survey-Phase I
EMSL-LV	--	USEPA Environmental Monitoring and Systems Laboratory - Las Vegas
EPA	--	U.S. Environmental Protection Agency
EPRI	--	Electric Power Research Institute
ERL-C	--	USEPA Environmental Research Laboratory - Corvallis
ERP	--	Episodic Response Project
ETD	--	Enhanced Trickle Down Model
GIS	--	Geographic Information System
IBM PC	--	International Business Machines Corporation - personal computer
ILWAS	--	Integrated Lake/Watershed Acidification Study
IQR	--	Interquartile range
LAI	--	Leaf area index
LTA	--	Long-term annual average deposition

MAGIC	--	Model for Acidification of Groundwater in Catchments
MLRA	--	Major land resource areas
NAS	--	National Academy of Sciences
NADP/NTN	--	National Acid Deposition Program/National Trends Network
NAPAP	--	National Acid Precipitation Assessment Program
NCDC	--	National Climatic Data Center
NE	--	Northeast Region
NHAP	--	National High Altitude Photography
NOAA	--	National Oceanographic and Atmospheric Administration
NRC	--	National Research Council
NSS-I	--	National Stream Survey-Phase I
NSWS	--	National Surface Water Survey
ORNL	--	Oak Ridge National Laboratory, Tennessee
OTA	--	Office of Technology Assessment
PCA	--	Principal component analysis
PNL	--	Battelle-Pacific Northwest Laboratories
QA	--	Quality assurance
QC	--	Quality control
RADM	--	Regional Acid Deposition Model
RELMAP	--	Regional Lagrangian Model of Air Pollution
RCC	--	Regional Coordinator/Correlator
RILWAS	--	Regional Integrated Lake/Watershed Acidification Study
RMSE	--	Root mean square error
RSD	--	Relative standard deviation
SAB	--	Science Advisory Board
SAS	--	Statistical Analysis System
SBR	--	Southern Blue Ridge
SBRP	--	Southern Blue Ridge Province
SCS	--	Soil Conservation Service
SE	--	Standard error
SOBC	--	Sum of base cations
SOEBC	--	Sum of exchangeable base cations
SUNY-P	--	State University of New York, Plattsburgh
TMY	--	Typical meteorological year

UMW	--	Upper Midwest
UDDC	--	Unified Deposition Database Committee
USDA	--	U.S. Department of Agriculture
USDOI	--	U.S. Department of Interior
USFS	--	U.S. Forest Service
USGS	--	U.S. Geological Survey
UTM	--	Universal Transverse Mercator
WA	--	Watershed area
WBA	--	Watershed Based Aggregation

13.1.2 Symbols

2As	--	Southern Blue Ridge subregion (NSS Pilot Survey)
2Bn	--	Valley and Ridge subregion (NSS Pilot Survey)
2Cn	--	Northern Appalachians subregion (NSS Pilot Survey)
2X	--	Southern Appalachians subregion (NSS Pilot Survey)
3A	--	Piedmont subregion (NSS Pilot Survey)
3B	--	Mid-Atlantic Plain subregion (NSS Pilot Survey)
A	--	acid that is leached out of the soil
AC_BaCl	--	barium chloride triethanolamine exchangeable acidity
A_H	--	area of all open water bodies in drainage basin, in kilometers squared
A_L	--	area of primary lake, in kilometers squared
Al_AO	--	aluminum, acid oxalate extractable
Al_CD	--	aluminum, citrate dithionite extractable
Al_PYP	--	aluminum, pyrophosphate extractable
Al^{3+}	--	aluminum ion
ALPOT	--	aluminum potential (pH - 1/3pAl)
ANN_AVG	--	flow-weighted annual average sulfate concentration
AVG_EL	--	average elevation; (MAX_ELEV + MIN_ELEV)/2, in meters
A_w	--	total watershed area, in kilometers squared
B_CENT	--	drainage basin centroid expressed as an X,Y coordinate
B_LEN	--	length of drainage basin: air-line distance from basin outlet to farthest upper point basin, in kilometers
B_PERIM	--	the length of the line which defines the surface divide of the drainage basin, in kilometers
B_SHAPE	--	basin shape ratio; B_LEN^2/WS_AREA

B_WIDTH	--	average basin width; WS_AREA/B_LEN, in kilometers
BS_Cl	--	base saturation calculated from unbuffered 1N ammonium chloride CELod exchangeable bases
C	--	correction factor for the decrease in acidity due to the protonation of bicarbonate
C_TOT	--	carbon total
Ca+Mg-DRY	--	the annual loading of Ca plus Mg in dry deposition
Ca+Mg-WET	--	the annual loading of Ca plus Mg in wet deposition
Ca_Cl	--	exchangeable calcium in unbuffered 1N ammonium chloride
Ca^{2+}	--	calcium ion
$CaCl_2$	--	calcium chloride
CEC_Cl	--	unbuffered 1N ammonium chloride cation exchange capacity
Cl^-	--	chloride ion
CO_2	--	carbon dioxide
COMPACT	--	compactness ratio; ratio of perimeter of basin to the perimeter of a circle with equal area; $(PERIM)/(2 * (* A_w)^5)$
DDENSITY	--	drainage density; TOTSTRM/WS_AREA
ELONG	--	elongation ratio; (4 * WS_AREA)/L_BEN
FRAG	--	fragments > 2 mm diameter
H^+	--	hydrogen ion
H^+_{total}	--	total effective acidity $(H^+ + NH_4^+ - NO_3^-)$
H20_WS	--	ratio of open water bodies area to total watershed area; H20_AREA/ws_area
H_2O	--	water
H_2SO_4	--	sulfuric acid
H5up	--	the percent of a watershed covered by bedrock with sensitivity codes of 5 and 6
ha	--	hectare (2.47 acres or ten thousand square meters)
HCO_3^-	--	bicarbonate ion
H-DRY	--	annual hydrogen ion loading in dry deposition
H-WET	--	annual hydrogen ion loading in wet deposition
I	--	amount of effective acidity in deposition
IND_AVG	--	flow-weighted average sulfate concentration for the index sample time frame (spring or fall)
INT	--	total length of intermittent streams as defined from USGS topographic maps of aerial photos, in kilometers
K	--	hydraulic conductivity

K^+	--	potassium ion
K_Cl	--	exchangeable potassium in unbuffered 1N ammonium chloride
Keq ha^{-1}	--	Kiloequivalent per hectare
kg	--	kilogram
km	--	kilometer
k_{so4}	--	sulfate mass transfer coefficient (m yr^{-1})
L_CENT	--	primary lake centroid expressed as X,Y coordinates
L_PERIM	--	perimeter of primary basin lake, in kilometers
LIMEPOT	--	lime potential (pH - 1/2pCa)
ln(a/TanB)	--	an index of flowpath partitioning used in the TOPMODEL hydrologic model
ln(a/KbTanB)	--	an index of flowpath partitioning used in the TOPMODEL hydrologic model
LTA-rbc	--	long-term annual average, reduced dry base cation
LTA-zbc	--	long-term annual average, zero dry base cation
M_PATH	--	estimate of mean flowpath, in meters
M04	--	miscellaneous land area mapped as quarry pits
MAX_EL	--	elevation at approximately highest point, in meters
MAX_REL	--	maximum relief; MAX_ELEV - MIN_ELEV, in meters
μeq L^{-1}	--	microequivalents per liter, unit of concentration
mg	--	milligram
Mg_Cl	--	exchangeable magnesium in unbuffered 1N ammonium chloride
Mg^{2+}	--	magnesium ion
MIN_EL	--	elevation of primary lake, in meters
Na^+	--	sodium ion
Na_Cl	--	exchangeable sodium in unbuffered 1N ammonium chloride
NECMPON	--	data file with soil and miscellaneous area components of map units for the DDRP Northeast region
NECMPOS	--	map unit composition data file for the DDRP Northeast region
NEIDLGD	--	identification legend data file for the DDRP Northeast region
NH_4^+	--	ammonium ion
NO_3^-	--	nitrate ion
OH^-	--	hydroxide ion

pCO_2	--	partial pressure of carbon dioxide
PER_DD	--	drainage density calculated from perennial streams only; PERIN/WS_AREA
PERIMRAT	--	ratio of the lake perimeter to the watershed perimeter; Lake Perimeters/B_PERIM
PERIN	--	total perennial stream length as defined from USGS topographic maps and aerial photos, in kilometers
PH_01M	--	pH (0.01M $CaCl_2$)
PH_H2O	--	pH (deionized water)
R	--	runoff estimate (length $time^{-1}$) Average annual runoff; interpolated to each site from Krug et al. (in press) runoff map, in centimeters
r	--	correlation coefficient
R^2	--	coefficient of determination, the proportion of variability explained by a regression model
REL_RAT	--	relief ratio; (MAX_ELEV-MIN_ELEV)/B_LEN
ROTUND	--	rotundity ratio; $(B\_LEN)^2/(4 * WS\_AREA)$
RT_R	--	lake retention time, in years
S	--	sum of base cations
SBC_CI	--	sum of base cations as measured in unbuffered 1N ammonium chloride
S_d	--	dry sulfur deposition (mass $length^{-2}$ $time^{-1}$)
SE_MP_CM	--	map unit composition data file for the DDRP Southern Blue Ridge region
SE_MP_UN	--	map unit identification legend data file for the DDRP Southern Blue Ridge region
SECMPNT	--	data file with soil and miscellaneous area components of map units for the DDRP Southern Blue Ridge region
SEDBMNT	--	Southern Blue Ridge Mapping Database Management System
SiO_2	--	silicon dioxide
SO4_B2	--	half saturation constant
SO4_EMX	--	adsorption asymptote
SO4_H2O	--	sulfate, water extractable
SO4_PO4	--	sulfate, phosphate extractable
SO4_SLP	--	slope of sulfate adsorption isotherm at zero net adsorption
SO4_XIN	--	zero net adsorption concentration for sulfate, determined from adsorption isotherms
SO_4^{2-}	--	sulfate
SO4-DRY	--	annual loading of sulfate in dry deposition
SO4-WET	--	annual loading of sulfate in wet deposition
$[SO_4^{2-}]^{ss}$	--	steady state sulfate concentration
SOILDEN	--	soil bulk density

S_s	--	surface water sulfur (mass length^{-3})
STRMORDER	--	maximum stream order (Horton) of streams in the watershed
SUB_BAS(n)	--	area of each subcatchment in the drainage basin, in kilometers squared
S_w	--	wet sulfur deposition (mass length^{-2} time^{-1})
THKA	--	soil thickness, adjusted for FRAG
TOT_DD	--	estimated drainage density based on crenulations identified on topographic map
TOTSTRM	--	total stream length; combination of perennial and intermittent, in kilometers
t_w	--	hydraulic residence time, in years
T_w	--	hydrologic retention time, in years
V^6	--	volume of primary lake, $10^6 m^3$
WA:LA	--	watershed area to lake area ratio
WM_PATH	--	estimate of weighted mean flowpath, in meters
WS_AREA	--	total watershed area, in kilometers squared
WS_LA	--	ratio of the total watershed area to the area of the primary lake

13.2 DEFINITIONS

ACCURACY - the difference between the approximate solution obtained using a numerical model and the exact solution of the governing equations (or a known standard concentration), divided by the exact solution (or known standard concentration).

ACID ANION - negatively charged ion that combines with hydrogen ion to form an acid.

ACID CATION - hydrogen ion or other metal that can hydrolyze water to produce hydrogen ions, e.g. Al, Mn, Fe.

ACID CRYSTALLINE - in the Southern Blue Ridge Province, rocks or bedrock which, upon weathering, form secondary phases including HIV clays.

ACID DEPOSITION SYSTEM (ADS) - a national database of precipitation amount and chemistry maintained at Battelle-Pacific Northwest Laboratories.

ACID MINE DRAINAGE - runoff with high concentration of metals, sulfate, and acidity resulting from the OXIDATION of sulfide minerals that have been exposed to air and water (usually from mining activities).

ACID NEUTRALIZING CAPACITY - the total acid-combining capacity of a water sample determined by titration with a strong acid to a preselected equivalence point pH: an integrated measure of the ability of an aqueous solution to neutralize strong acid inputs. Acid neutralizing capacity includes strong bases (e.g., hydroxide) as well as weak bases (e.g., borates, carbonates, dissociated organic acids, alumino-hydroxyl complexes).

ACIDIC DEPOSITION - rain, snow, or dry fallout containing high concentrations of sulfuric acid, nitric acid, or hydrochloric acid, usually produced by atmospheric transformation of the by-products of fossil fuel combustion (power plants, smelters, autos, etc.). Precipitation with a pH of less than 5.0 is generally considered to be unnaturally acidic, i.e., altered by ANTHROPOGENIC activities.

ACIDIC EPISODE - an episode in a water body in which ACIDIFICATION of SURFACE WATER to an ACID NEUTRALIZING CAPACITY less than or equal to 0 μeq L^{-1} occurs.

ACIDIC LAKE OR STREAM - an aquatic system with an ACID NEUTRALIZING CAPACITY less than or equal to 0 μeq L^{-1}.

ACIDIFICATION - any temporary or permanent loss of ACID NEUTRALIZING CAPACITY in water or BASE SATURATION in soil by natural or ANTHROPOGENIC processes.

ACIDIFIED - a natural water that has experienced any temporary or permanent loss of ACID NEUTRALIZING CAPACITY or a soil that has experienced a reduction in BASE SATURATION.

ACTIVITY COEFFICIENTS - empirically derived coefficients used to transform concentration data to salt or ion activities.

ADJUSTED R^2 - the standard R^2 of regression analysis, modified to balance increasing the R^2 against increasing the number of explanatory variables.

AFFORESTATION - the natural process through which non-forested lands become forested.

AGGRADING FORESTS - forests in which there is a net annual accumulation of biomass.

AGGREGATION - a method for statistically reducing a set of data to a single calculated or index value for each parameter (e.g., a weighted average).

AKAIKE'S INFORMATION CRITERION - a criterion for selecting one of a sequence of regression models, based on formulae from information theory.

ALFISOLS - in Soil Taxonomy, the ORDER of mineral soils with an argillic horizon with at least 35 percent base saturation.

ALIASING - occurrence of an apparent shift in frequency of a periodic phenomenon. It arises as the consequence of the choice of discrete space or time sampling points to represent a continuous process. The choice may introduce a spurious periodic solution or mask a real periodic phenomenon.

ALKALINITY - the titratable base of a sample containing hydroxide, carbonate, and bicarbonate ions, i.e., the equivalents of acid required to neutralize the basic carbonate components.

ALKALINITY MAP CLASS - a geographic area defined by the expected ALKALINITY of SURFACE WATERS (does not necessarily reflect measured alkalinity); used as a STRATIFICATION FACTOR in ELS-I design.

ALLOPHANE - an amorphous to cryptocrystalline alminosilicate mineral, commonly thought to be a precursor phase to kaolinite.

ALUMINUM BUFFERING - a chemical process in which hydrogen ion activities are buffered by the precipitation/dissolution of aluminum hydroxides.

ALUMINUM BUFFER RANGE - pH 4.2 - 2.8

AMPHOTERIC - a substance capable of acting as either an acid or a base; positively charged at high pH and with an OH^- functional group at low pH.

ANAEROBIC - without free oxygen (e.g., hypolimnetic lake waters, sediments, or poorly drained soils).

ANALYTE - a chemical species that is measured in a water soil, or tissue sample.

ANALYTICAL CHARACTERIZATION - physical and chemical properties of water soil, or samples measured in the laboratory.

ANALYTICAL DUPLICATE - a QUALITY CONTROL sample made by splitting a sample.

ANION - a negatively charged ion.

ANION CATION BALANCE - a method of assessing whether all CATIONS and ANIONS have been accounted for and measured accurately; in an electrically neutral solution, such as water, the total charge of positive ions (cations) equals the total charge of negative ions (anions).

ANION EXCHANGE/ADSORPTION - a reversible process occurring in soil in which ANIONS are adsorbed and released.

ANTHROPOGENIC - of, relating to, derived from, or caused by human activities or actions.

APPARENT SOLUBILITY PRODUCT - an approximate form of an equilibrium constant calculated using solution concentration data instead of activities.

AQUEOUS SPECIES - any dissolved ionic or nonionic chemical entity.

AQUIC - a moisture regime of soils in which a water table and reducing conditions occur near the surface.

AQUIFERS - below-ground stratum capable of producing water as from wells or springs.

AQUO LIGAND - a water molecule held to Fe or Al in a clay edge or hydrous oxide by ligand exchange.

ARC - represents line features and borders of area features. One line feature may be made up of many arcs. The arc is the line between two nodes.

ARC/INFO - a commercial geographic information system (GIS) software used to automate, manipulate, analyze, and display geographic data in digital form.

ATTRIBUTE - the class, characteristics or other properties associated with a specific feature, area on a map, lake or stream.

AVAILABLE TRANSECT - a transect identified to represent a map unit and listed for random selection.

BASE CATION - a nonprotolytic CATION that does not affect ACID NEUTRALIZING CAPACITY; consists principally of calcium, magnesium, sodium, and potassium.

BASE CATION EXCHANGE - the process by which BASE CATIONS (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are adsorbed or released from negatively charged sites on soil particles from or to, respectively, soil solutions. Such exchange processes are instrumental in determining pH of soil solutions.

BASE CATION SUPPLY - (1) the pool of BASE CATIONS (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) in a soil available for exchange with hydrogen ions (H^{+}). The base cation pool is determined by the CATION EXCHANGE CAPACITY of the soil and the percentage of exchange sites occupied by BASE CATIONS.

BASE SATURATION - the percentage of total soil CATION EXCHANGE CAPACITY that is occupied by exchangeable cations other than hydrogen and aluminum, i.e., the base cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}.

BEDROCK - solid rock exposed at the surface of the earth or overlain by unconsolidated material.

BEDROCK GEOLOGY - the physical and chemical nature and composition of solid rock at or near the earth's surface.

BEDROCK LITHOLOGY - see LITHOLOGY.

BEDROCK SENSITIVITY SCORES - a six point scale, developed for DDRP, designed to distinguish the relative reactivities of different lithologies.

BEDROCK UNITS - the smallest homogenous entity depicted on a bedrock map.

BIAS - a systematic error in a method caused by artifacts or idiosyncracy of the measurement system.

BIOMASS - the quantity of particulate organic matter in units of weight or mass.

BIOMASS ACCRETION - net accumulation of plant mass in a growing, or aggrading, ecosystem; also refers to net accumulation of an individual nutrient associated with accumulation of biomass.

BLOOM-GRIGAL MODEL - a numerical model used to investigate the evolution of soil exchange characteristics under various H^+ ion deposition SCENARIOS. The code is based on mass balance consideration with empirical functions used to describe the pH-base saturation relationships.

BONFERRONI INEQUALITY - an inequality from probability theory that is used to carry out multiple simultaneous statistical comparisons.

BOXPLOT - a graph of data with a box drawn from the 25th percentile to the 75th percentile; lines extending from the box as far as the data extend to a distance of at most 1.5 times the INTERQUARTILE RANGE, and more extreme observations marked individually.

BUFFERING CAPACITY - the quantity of acid or base that can be added to a water sample with little change in pH.

BULK DENSITY - the integrated density of a volume of soil, including solid matter, soil solutions, voids, roots, etc.

Ca/Al EXCHANGE REACTION - the reaction describing the distribution of Ca and Al between the soil exchange complex and the soil solution.

CALCITE - a mineral with the formula $CaCO_3$. A carbonate mineral.

CALIBRATION - process of checking, adjusting, or standardizing operating characteristics of instruments and model appurtenances on a physical model or coefficients in a mathematical model with empirical data of known quality. The process of evaluating the scale readings of an instrument with a known standard in terms of the physical quantity to be measured.

CALIBRATION BLANKS - a zero-concentration QUALITY CONTROL standard that contains only the matrix of the CALIBRATION standard.

CAPACITY FACTOR - a chemical property of a system defined as a function of the quantity or size of that system.

CAPACITY-LIMITED PROCESS - A mechanism (e.g., sulfate adsorption or cation exchange) for which the long-term ability to supply or consume cations or anions is constrained by the size of a watershed pool or capacity (e.g., pool of exchangeable bases and sulfate adsorption capacity) rather than by reaction kinetics.

CARBON-BONDED SULFUR - a reduced form of organic sulfur, characterized by C-S bonds.

CARBONIC ACID - a weak acid, H_2CO_3, formed by dissolution of carbon dioxide in water. Dissociation of carbonic acid (to H^+ and HCO_3^-) and subsequent consumption of H^+ by exchange or weathering reactions generates ANC in the form of bicarbonate ions.

CATCHMENT - see WATERSHED.

CATION - a positively charged ion.

CATION DEPLETION - a process through which base cations on a soil exchange site are progressively replaced by ACID CATIONS at rates higher than those expected during normal pedogenesis.

CATION EXCHANGE - a reversible process occurring in soil and/or sediment in which ACIDIC CATIONS (e.g., hydrogen ions) are adsorbed and BASE CATIONS are released.

CATION EXCHANGE CAPACITY - the sum total of exchangeable cations that a soil can absorb.

CATION (OR ANION) LEACHING - movement of cations (or anions) out of soil, in conjunction with mobile anions in soil solution.

CATION RETENTION - the physical, biological, and geochemical processes by which cations in watersheds are held, retained, or prevented from reaching receiving SURFACE WATERS.

CHRONIC ACIDIFICATION - see LONG-TERM ACIDIFICATION.

CIRCUMNEUTRAL - close to neutrality with respect to pH (pH = 7); in natural waters, pH 6 - 8.

CLAY - a soil separate consisting of particles with an equivalent diameter less than 0.002 mm; also a soil textural class containing $\geq$ 40 percent clay-sized material, < 45 percent sand and < 40 percent silt.

CLAY MINERALS - any of a series of sheet silicate minerals formed in a soil or low-temperature diagenetic environment.

CLOSED LAKES - a lake with a surface water inlet but no surface water outlet.

CLUSTER ANALYSIS - a multivariate classification technique for identifying similar (or dissimilar) groups of observations.

COARSE PARTICLE DRY DEPOSITION - atmospheric DRY DEPOSITION of particles greater than 2 microns in effective diameter.

COLLINEAR - see MULTICOLLINEARITY.

COMBINATION BUFFER - land area surrounding a lake including area within a 40-foot elevation contour, area within a linear buffer adjacent to perennial streams, and area around contiguous wetlands.

COMPLEX - a map unit consisting of two or more dissimilar soil components or miscellaneous areas occurring in a regularly repeating pattern.

COMPONENTS - see MAJOR COMPONENTS, MINOR COMPONENTS, and MAP UNIT COMPOSITION.

CONSOCIATION - a map unit dominated by a single soil taxon (or miscellaneous area) and similar soils.

CONTOUR LINE - a line connecting the points on the land surface that have the same elevation.

CONVERGENCE - state of tending to a unique solution. A given scheme is convergent if an increasingly finer computational grid leads to a more accurate approximation of the unique solution. Note that a numerical method may sometimes converge on a wrong solution.

COOK'S D - a regression statistic designed to indicate LEVERAGE POINTS.

COVERAGE - a digital analog of a single map sheet; forms the basic unit of data storage in ARC/INFO.

CUMULATIVE DISTRIBUTIVE FUNCTION - a function, F(x), such that for any reference value X, F(x) is the estimated proportion of individuals (lakes, streams, estuaries, coastal waters) in the population having a value $x \leq X$.

DARCY'S LAW - An equation to predict the flux of water through a porous medium, of the form $Q = K * A * S$, where Q =lateral water flux, K = saturated hydraulic conductivity, A = cross sectional area, and S = hydraulic gradient.

DATABASE FILE - a collection of records that share the same format.

DEPOSITIONAL FLUXES - the mass transfer rate to the earth's surface of any of a number of chemical species.

DEPTH TO BEDROCK - depth to solid, fixed, unweathered rock underlying soils.

DEPTH TO A SLOWLY PERMEABLE OR IMPERMEABLE LAYER - depth to a layer in soils or underlying soils that restricts the downward flow of water (e.g., bedrock, dense till or fragipan).

DETECTION LIMIT QC CHECK SAMPLE - a QUALITY CONTROL sample that contains the ANALYTE of interest at two to three times the contract required detection limit.

DIAZO - a photocopy whose production involves the use of a coating of a diazo compound.

DIGITIZATION - the process of entering lines or points into a GEOGRAPHIC INFORMATION SYSTEM.

DIGITIZED COORDINATES - lines or points that have been entered into a GEOGRAPHIC INFORMATION SYSTEM.

DISSIMILATORY REDUCTION - a process in which an oxidized chemical species (e.g., SO_4 - S) is utilized by an organism as an electron acceptor in the absence of free oxygen and released in a reduced form (e.g., S^{2-}) rather than assimilated.

DISSOCIATION - separation of an acid into free H^+ and the conjugate base of that acid (e.g., H_2CO_3 -> H_+ + HCO_3^-), or separation of a base into a free hydroxyl and the conjugate acid of the base (e.g., NH_4OH --> NH_4^+ + OH^-).

DISSOLUTION RATES - the rate at which a mineral is transformed to aqueous species or secondary minerals in an aqueous environment.

DISSOLVED ORGANIC CARBON - a measure of organic (nonorganic) fraction of carbon in a water sample that is dissolved or unfilterable.

DOLOMITE - a mineral with the chemical formula $CaMg(CO_3)_2$. A carbonate mineral.

DOWNSTREAM REACH NODE - see LOWER NODE.

DRAINAGE - the frequency and duration of periods when the soil is free of saturation or partial saturation and the depth to which saturation commonly occurs.

DRAINAGE BASIN - see WATERSHED.

DRAINAGE CLASS - any of the seven classes that characterize the frequency and duration of soil saturation.

DRAINAGE LAKE - a lake with SURFACE WATER outlet(s) or with both inlets and outlets.

DRY DEPOSITION - for the purposes of DDRP analysis, atmospheric deposition of materials to watersheds in any form other than rain or snow.

DRY DEPOSITION VELOCITY - an effective velocity used with airborne concentrations to compute dry depositional flux of materials to surfaces or watersheds.

EIGENVALUE - the eigenvalues of a square matrix A are the roots c of the polynomial equation det(A-cI) = 0, where det(.) is the determinant and I is an identity matrix.

ELECTRON ACCEPTOR - an oxidized (or at least partially oxidized) chemical species capable of undergoing a reduction reaction by addition of an electron.

ELEVATIONAL BUFFER - land area around a lake bounded by a topographic contour.

ELS PHASE I LAKES - the population of lakes sampled during phase I of the Eastern Lake Survey of the EPA's National Surface Water Survey.

EMPIRICAL MODEL - representation of a real system by a mathematical description based on experimental data rather than on general physical laws.

ENTISOLS - in Soil Taxonomy, the ORDER of mineral soils with no or very poorly developed genetic horizons.

EPISODE - a short-term change in stream pH and ACID NEUTRALIZING CAPACITY during storm flows or snowmelt runoff.

EQUIVALENT - unit of ionic concentration; the quantity of a substance that either gains or loses one mole of protons or electrons.

ESTER SULFATE - an oxidized form of sulfur in soil organic matter, characterized by C-O-SO_3 or N-O-SO_3 linkages.

EVAPORITE - a mineral formed from solution phase due to supersaturation and chemical precipitation resulting from evapoconcentration of the solution; sulfate, chloride, and many carbonate minerals form in this manner.

EVAPOTRANSPIRATION (%ET) - the amount or proportion of precipitation that is returned to the air through direct evaporation or by transpiration of vegetation.

EXCHANGE POOL - the reservoir of BASE CATIONS in soils available to participate in exchange reactions.

EXTENSIVE PARAMETERS - variables that depend on the size (extent) of the system.

EXCHANGE REACTIONS - any of a number of reactions that describe the partitioning of two chemical species between a solution and soil exchange complex.

FELDSPARS - a group of tectosilicate minerals that are the most abundant group in the earth's crust.

FIELD REVIEW - a review of soil surveys made in the field by supervisory soil scientists to help field soil scientists maintain standards that are both adequate for the objectives of the survey and consistent with those of other surveys. Samples of the fieldwork are examined for soil identification, placement of boundaries, and map detail in relation to survey objectives.

FINE PARTICLE DRY DEPOSITION - atmospheric DRY DEPOSITION of particles of size less than 2 microns in effective diameter.

FIRST-ORDER REACTION - a chemical reaction, the rate of which is proportional to the concentration of the limiting reactant.

FOREST COVER TYPE - a descriptive classification of forest land based on present occupancy of an area by tree species. (The term "vegetation" implies total forest community, whereas the focus here is on trees defining type. Whenever the term "vegetation" is used in this report it should be construed as FOREST COVER TYPE.)

FREUNDLICH ISOTHERM - an exponential adsorption isotherm of the form $E_c = aC^b$, where: E_c = concentration of adsorbed species (per unit mass adsorbent), C = dissolved concentration of species being adsorbed, and a and b are derived coefficients.

FULVIC ACID - a family of naturally-occurring weak organic acids found in soils and surface waters; fulvic acids are operationally defined as the acid-soluble (pH = 1.0) fraction of an alkali-soluble soil extract; pK is roughly 3.5.

GAINES THOMAS FORMULATION - a formulation used to describe exchange processes.

GAPON - a formulation used to describe exchange processes.

GENERIC BEDROCK TYPE - see GENERIC ROCK TYPE.

GENERIC ROCK TYPE - a general classification of different BEDROCK UNITS into groups according to the primary LITHOLOGY.

GEOGRAPHIC INFORMATION SYSTEM (GIS) - a computerized system designed to store, process, and analyze data.

GEOLOGY - see BEDROCK GEOLOGY.

GEOMORPHIC POSITION - the relative location in the landscape described by hillslope elements (cross section view) and slope components (plane view), e.g., sideslope footslope.

GIBBSITE - a mineral with the chemical formula $Al(OH)_3$.

GIS BUFFERS - land area surrounding a lake, stream, or wetland, delineated using a GIS. See COMBINATION BUFFER and LINEAR BUFFER.

GLACIAL TILL - see TILL.

GLACIOFLUVIAL - a material that has been deposited by glaciers and sorted by meltwater.

GLEY SOIL - a soil developed under conditions of poor drainage, characterized by oxygen depletion and reduction of iron and other metals (Mn), resulting in gray colors and mottles.

GRAN ANALYSIS - a mathematical procedure used to determine the equivalence points of a TITRATION CURVE for acid and base neutralizing capacity.

GREAT GROUP - in Soil Taxonomy, the level of classification just below SUBORDER, e.g., Haplorthods.

GROUNDWATER - water in the part of the ground that is completely saturated.

HETEROSCEDASTIC - referring to a statistical situation in which variances are not all equal.

HEURISTIC MODEL - representation of a real system by a mathematical description based on reasoned, but unproven argument, intended for use as an aid to studying and exploratory analysis of the system being modelled.

HINDCAST - to estimate some prior event or condition as a result of a rational study and analysis of available pertinent current and historical data.

HISTIC SOILS - organic-rich soils.

HISTOSOLS - in Soil Taxonomy, the ORDER of soils formed from organic PARENT MATERIAL.

HOMOSCEDASTIC - referring to a statistical situation in which the variances may all be considered.

HORIZON - a horizontal layer of soil with distinct physical and/or chemical characteristics. Genetic horizons are the result of soil-forming process.

HORNBLENDE - a common amphibole mineral with the approximate chemical formula $(Ca,Na)_3(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$.

HYDRAULIC HEAD - hydrostatic pressure created by a difference in height of water columns in different portions of a connected aquifer.

HYDRAULIC RESIDENCE TIME - a measure of the average amount of time water is retained in a lake basin. It can be defined on the basis of inflow/lake volume, represented as RT, or on the basis of outflow/lake volume and represented as T_w. The two definitions yield similar values for fast flushing lakes, but diverge substantially for long residence time SEEPAGE LAKES.

HYDROLOGIC FLOW PATHS - the distribution and circulation of water deposited by precipitation on the surface of the land, in the soil, and underlying rocks within a WATERSHED.

HYDROLOGIC RETENTION TIME - see HYDRAULIC RESIDENCE TIME.

HYDROUS OXIDE - a collective term referring to any of a group of amorphous or crystalline species of iron or aluminum that are partially or fully hydrated (e.g., MO(OH), $M(OH)_3$).

HYPOLIMNION - in a thermally-stratified lake, the portion in a lake at depths below the thermocline; these waters are isolated from reaeration at the surface and oxygen is likely to be depleted, leading to mobilization of reduced chemical species.

IMMOBILIZATION REACTION - conversion of an inorganic form of a nutrient (especially S or N) to organic matter.

IMPOUNDMENT - a man-made lake created by construction of a dam; also applied to natural lakes whose level is controlled by a man-made spillway.

INCEPTISOLS - in Soil Taxonomy, the ORDER of soils with at least one diagnostic horizon, but with no horizon strongly enough developed to place them in another ORDER.

INCLUSIONS - see MINOR COMPONENTS.

INDEX OF CONTACT TIME - the theoretical maximum potential of contact between runoff and the soil matrix. The index is calculated by dividing the soil water flow rate (obtained using Darcy's law) by average annual runoff.

INDEX SAMPLE - in NE lakes, one sample per lake, used to represent chemical conditions on that lake. In streams, any sample (or the average of one to three samples) collected at a stream NODE during the SPRING BASEFLOW INDEX PERIOD, used to represent chemical conditions in the stream.

INFO - a database management system that stores, maintains, manipulates, and reports information associated with geographic features in ARC/INFO.

INITIAL CONDITIONS - given values of DEPENDENT VARIABLES or relationship between dependent and independent variables at the time of start-up of the computation in a mathematical model.

IN-LAKE SULFUR RETENTION - net retention of sulfur within a lake, occurring principally by reduction within sediments.

INTENSITY FACTOR - a variable with properties defined by concentration or a surface and/or in solution, and therefore independent of the quantity or size of the system.

INTENSIVE PARAMETERS - variables whose values are independent of the size or extent of the system, e.g., temperature and pH.

INTERQUARTILE RANGE - the difference between the 75th and the 25th percentiles.

IONIC STRENGTH - a measure of the interionic effect resulting from the electrical attraction and repulsion between various ions. In very dilute solutions, ions behave independently of each other and the ionic strength can be calculated from the measured concentrations of ANIONS and CATIONS present in the solution.

ISOTHERM - a linear or nonlinear function describing partitioning of an absorbent between solid and sorbed phases. Such isotherms were originally used to characterize (nearly) ideal processes (e.g., the Langmuir equation was developed to describe adsorption of a gas by a solid), but are often empirically defined for adsorption of anions or organic compounds on soils because they provide a convenient shorthand to describe partitioning.

KAOLINITE - a two-layer clay mineral with the chemical formula $Al_2Si_2O_5(OH)_4$.

KINETIC MODELS - any of a family of numerical models that use kinetic considerations as the unifying principle in describing natural processes.

KRIGING - a technique for spatial interpolation.

LABEL - represents point features or is used to assign identification numbers to POLYGONS.

LAKE TYPE - a classification of lakes based on the presence or absence of inlets, outlets, and dams as represented on LARGE-SCALE MAPS.

LAND COVER - see FOREST COVER TYPE.

LAND USE - the dominant use of an area of land (e.g., crop land).

LANDFORM SEGMENT - a small part of the local landform that is uniquely related to landscape processes.

LANGMUIR ISOTHERM - a hyperbolic adsorption isotherm (used in this project for sulfate) of the form $E_c = (B_1 * C)/(B_2 + C)$, where: E_c = net adsorbed sulfate, C = dissolved sulfate, and B_1 and B_2 are empirically derived coefficients. When appropriate, the isotherm can be "extended" by addition of a third coefficient to describe a non-zero Y-intercept.

LARGE-SCALE MAPS - 1:24,000, 1:25,000, or 1:62,500 scale U.S. Geological Survey topographical maps.

LEACHING - the transport of a solute from the soil in the soil solution.

LEVERAGE POINT - a data point that strongly influences the parameter estimates in a regression.

LIGAND EXCHANGE - a mechanism of bond formation between an oxyanion and a soil mineral bearing hydroxyl groups. The exchange involves formation of inner sphere complexes of anions to Lewis acid sites, following replacement of water from the Lewis acid site by the oxyanion.

LIMESTONE - a rock type consisting primarily of CALCITE.

LINEAR BUFFER - land area within a set distance of a lake or stream.

LITHOLOGY - the physical characteristics of a rock or mapped BEDROCK UNIT. Generally relates to mode of formation, mineralogy, and texture.

LITTERFALL - fresh organic detritus, usually leaves, needles, twigs, etc., that compose the bulk of the forest floor.

LOCAL LANDFORM - a subdivision of the regional landform that is the result of localized landscape processes.

LONG-TERM ACIDIFICATION - a long-term partial or complete loss of ACID NEUTRALIZING CAPACITY from a lake or stream.

LONG-TERM ANNUAL AVERAGE DEPOSITION (LTA) - a dataset of atmospheric deposition representing atmospheric deposition during the early-to-mid 1980s for the purposes of the DDRP.

LOWER NODE - the downstream NODE of a STREAM REACH.

MAJOR LAND RESOURCE AREA - a geographic area characterized by a particular pattern of soils, climate, water resources, and LAND USE.

MAJOR COMPONENTS - soil components or miscellaneous areas that are identified in the name of a map unit.

MALLOWS' C_P - a criterion for selecting one of a sequence of regression models.

MAP COMPILATION - the process of checking and measuring soil map unit data.

MAPPING PROTOCOLS - instructions that guide the field mapping and provide for quality control.

MAP SYMBOL - a symbol used on a map to identify map units.

MAPPING TASK LEADER - the person responsible for field mapping activities.

MAP UNIT - see SOIL MAP UNIT.

MAP UNIT COMPOSITION - the relative proportion (expressed in percent) of all soil components and miscellaneous areas in a map unit.

MAP UNIT COMPOSITION FILE - a DATABASE FILE that contains all components and their relative proportion for each map unit in the survey area (components are identified by an assigned code, i.e., SCODE).

MAP UNIT CORRELATION - see SOIL CORRELATION.

MAP UNIT DELINEATION - an area on a map uniquely identified with a symbol. A delineation of a soil map has the same major components as identified and named in the map unit.

MAP UNIT NAME - the title of a map unit identified by the major soil components or miscellaneous areas followed by appropriate phase terms.

MASS ACTION MODELS - any of a family of numerical models that use equilibrium-based principles as the central unifying theme.

MASS BALANCE MODELS - any of a family of numerical models that use conservation-of-mass principles as the central unifying theme.

MASS TRANSFER COEFFICIENTS - a removal or rate constant used in models of in-lake alkalinity generation (and elsewhere) to quantify the average removal rate of a reactant from solution. Specific reference in this project is transfer from solution to sediment by all processes, including sedimentation and diffusion. In many systems, the mass transfer coefficient for sulfur is essentially a diffusion constant for sulfate across the water-sediment interface; for nitrate a biological uptake/sedimentation rate.

MASTER HORIZONS - the most coarsely based delineations within a pedon. Usually, A/E horizons denote zones of net mass depletion; B horizons are zones of net accumulation, and C horizons indicate minimal pedogenic evolution.

MATRIX SPIKE - a QUALITY CONTROL sample made by adding known quantity of an ANALYTE to a sample aliquot.

MAX - the maximum sensitivity code observed on a WATERSHED.

MEAN - the weighted average of sensitivity codes for a WATERSHED.

MEDIAN (M) - the value of x such that the cumulative distribution function $F(x) = 0.5$; the 50th percentile.

METASEDIMENTARY - rocks or bedrock formed from metamorphosis of sedimentary rocks.

MICAS - a group of primary phylosilicate minerals, frequently including biotite and muscovite.

MID-APPALACHIAN REGION - one of the three geographic regions considered by the DDRP, consisting of upland areas (subregions 2Bn and 2Cn) of the Mid-Atlantic region (MD, PA, VA, WV) defined by the National Stream Survey.

MINERAL WEATHERING - dissolution of rocks and minerals by erosive forces.

MINERALIZATION - microbially-mediated conversion of nutrients from an organically bound (especially N and S) to an inorganic form.

MINOR COMPONENTS - soil components or miscellaneous areas that are not identified in the name of the map unit. Many areas of these components are too small to be delineated separately.

MISCELLANEOUS AREA - land areas that have no soil and thus support little or no vegetation without major reclamation. Rock outcrop is an example.

MISCELLANEOUS LAND AREAS - see MISCELLANEOUS AREA.

MOBILE ANION - an anion that remains in solution and passes through a soil without significant delays due to biological or chemical processes; also a model or paradigm for cation leaching from soils, based on the premise that the rate of cation leaching from a soil is controlled by the sum of mobile anions (which are regulated by a suite of more-or-less independent processes).

MONTE CARLO METHOD - technique of STOCHASTIC sampling or selection of random numbers to generate synthetic data.

MOTTLING - spots or blotches of different color in a soil, including gray to black blotches in poorly drained soils due to presence of reduced iron and other metals.

MULTICOLLINEARITY - when one of the explanatory variables can be reproduced as a linear combination of the other explanatory variables. In such a case, the usual regression estimates cannot be computed.

NITROGEN TRANSFORMATION - biochemical processes through which nitrogen deposited in an environment is converted to other forms.

NODE - the points identifying either an upstream or downstream end of a REACH.

NONPARAMETRIC - referring to a statistical procedure that does not make the classical distributional assumptions.

NON-SILICATE IRON AND ALUMINUM - soil iron and/or aluminum occurring in the soil as an amorphous or a (hydrous) oxide phase rather than as an ion incorporated within a silicate mineral lattice.

OFFICIAL SOIL SERIES DESCRIPTION - a record of the definitions of a soil series and other relevant information about each series. These definitions are the framework within which most of the detailed information about soils of the United States is identified with soils at specific places. These definitions also provide the principal medium through which detailed information about the soil and its behavior at one place is projected to similar soils at other places.

ORDER - in Soil Taxonomy, the highest level of classification, e.g., SPODOSOLS.

ORGANIC ACID - organic compound possessing an acidic functional group; includes fulvic and humic acids.

ORGANIC ANION - an organic molecule with a negative net ionic charge.

ORGANIC "BLOCKING" - a reduction in the sulfate (or other anion) adsorption capacity of a soil resulting from preferential sorption of organic acids by the soil.

ORGANIC HORIZONS - any identifiable soil horizon containing in excess of 20 percent organic matter by weight.

OUTLIER - observation not typical of the population from which the sample is drawn.

OXIDATION - loss of electrons by a chemical species, changing it from a lower to a higher oxidation state (e.g., Fe^{2+} to Fe^{3+} or S^{-2} to S^{+6}, with intermediates).

PARAMETER - (1) a characteristic factor that remains at a constant value during the analysis, or (2) a quantity that describes a statistical population attribute.

PARENT MATERIAL - the material from which soils were formed.

PARTIAL PRESSURE - the pressure of a gaseous sample that is attributable to one particular component.

PEDON - the smallest block of soil that contains all the characteristics of a soil (usually about 1 m^2); a soil individual.

PERCENT COARSE FRAGMENTS - the percentage of soil, by volume, that is composed of rock fragments unable to pass through a 2-mm sieve.

PERMEABILITY - the ease with which gases, liquids, or plant roots penetrate or pass through a bulk mass of soil or a layer of soil.

pH - the negative logarithm of the hydrogen ion activity. The pH scale runs from 0 (most acidic) to 14 (most alkaline); a difference of 1 pH unit indicates a tenfold change in hydrogen activity.

POLYGON - represents area features.

PRECISION - a measure of the capacity of a method to provide reproducible measurements of a particular ANALYTE (often represented by variance).

PRIMARY MINERAL WEATHERING - the natural process by which thermodynamically unstable minerals are converted to more stable phases under earth surface conditions.

PRINCIPAL COMPONENT ANALYSIS - a statistical analysis concerned with explaining the variance-covariance structure through the use of PRINCIPAL COMPONENTS.

PRINCIPAL COMPONENTS - particular linear combinations of the original data, which geometrically represent a new coordinate system with axes in the directions of maximum variability.

PROBABILITY SAMPLE - a sample in which each unit has a known probability of being selected.

QC CHECK SAMPLE - a QUALITY CONTROL sample that contains the ANALYTE of interest at a concentration in the mid-calibration range.

QUALITY ASSURANCE - steps taken to ensure that a study is adequately planned and implemented to provide data of known quality, and that adequate information is provided to determine the quality of the database resulting from the study.

QUALITY CONTROL - steps taken during a study to ensure that data quality meets the minimum standards established by the quality assurance plan.

QUARTILE - any of three values (Q_1, Q_2, Q_3) that divide a population into four equal classes, each containing one-fourth of the population.

QUARTZ - a crystalline form of silicon dioxide (SiO_2).

QUARTZITES - a metamorphic rock-type composed of primarily QUARTZ.

QUINTILE - any of the four values (Q_1 , Q_2 , Q_3 , Q_4) that divide a population into five equal classes, each representing 20 percent of the population; used to provide additional values to compare characteristics among populations of lakes and streams.

RATE-LIMITED REACTION - a process (e.g., mineral weathering) for which the long-term ability to supply reaction products (e.g., base cations) is constrained by reaction or transport kinetics.

RCC TRANSECTS - transects conducted by the Regional Coordinator/Correlator (RCC).

REACH - segments of the stream network represented as blue lines on 1:250,000-scale U.S. Geological Survey maps. Each reach (segment) is defined as the length of stream between two blue-line confluences. In the NSS-I, stream reaches were the sampling unit.

REACTION ORDER - the relationship between the rate of a chemical reaction and the concentration of a reaction substrate, defined by the value of the exponent of that substrate.

REACTIVITY SCALE - any of a number of relative scales designed to categorize the general "weatherability" of different LITHOLOGIES.

REACTIVITY SCORE - see REACTIVITY SCALE.

REAGENT BLANK - a QUALITY CONTROL sample that contains all the reagents used and in the same quantities used in preparing a soil sample for analysis.

REDUCTION/OXIDATION - chemical reaction in which substances gain or lose electrons.

REGION - a major area of the conterminous United States where a substantial number of streams with ALKALINITY less than 400 $\mu eq\ L^{-1}$ can be found.

REGIONAL LANDFORM - physiographic areas that reflect a major land-shaping process over a long period of time.

REGIONAL SOILS LEGEND - a correlated and controlled legend for an entire region (see SOIL IDENTIFICATION LEGEND).

RELMAP - a source-receptor model designed to estimate dry deposition of sulfur; not used directly in the DDRP.

REPORTS - relative to GIS activities, a format designed by the user for printing out information containing the data files.

RESERVOIR - a body of water collected and stored for future use in a natural or artificial lake.

RESIDUAL - in regressions, the difference between the observed dependent variable and the value predicted from the regression fit.

REUSS MODEL - a numerical model used to describe exchange processes in a soil environment.

RIPARIAN - a zone bounding and directly influenced by SURFACE WATERS.

ROBUST - a statistical procedure that is insensitive to the effect of OUTLIERS.

ROUTINE TRANSECTS - transects conducted by field soil scientists responsible for the mapping.

SALT EFFECT - the process by which hydrogen ions are displaced for the soil exchange complex by BASE CATIONS (from neutral salts). The result is a short-term increase in the acidity of associated water.

SAMPLING CLASS - see SOIL SAMPLING CLASS.

SAMPLING CLASS CODE - a three-character code assigned to each SOIL SAMPLING CLASS.

SAMPLING CLASS COMPOSITION - the relative proportion of sampling classes in a map unit.

SAND - a soil separate between 0.05 and 2.0 mm in diameter; also a soil texture class containing at least 85 percent sand, and whose percentage of silt, plus 1.5 times the percent clay, does not exceed 15.

SATURATION INDEX - the ratio of the ion activity product (of dissolved ions) to the solubility product for a solid phase; if the saturation index (SI) exceeds 1.0, the solution is supersaturated with respect to that phase; if SI = 1.0, the solution is at equilibrium, if SI < 1.0, the solution is undersaturated with respect to that solid phase.

SCENARIO - one possible deposition sequence following implementation of a control or mitigation strategy and the subsequent effects associated with this deposition sequence.

SECONDARY MINERALS - any inorganic mineral phase formed by transformation of another mineral or by precipitation from an aqueous phase.

SEEPAGE LAKE - a lake with no permanent SURFACE WATER inlets or outlets.

SELECTIVITY COEFFICIENT - the apparent constant used to describe the partitioning of species in an exchange reaction.

SENSITIVITY ANALYSIS - test of a model in which the value of a single variable or parameter is changed, and the impact of this change on the DEPENDENT VARIABLE is observed.

SENSITIVITY CODES - see BEDROCK SENSITIVITY SCORES.

SIGNIFICANCE LEVEL - the conditional probability that a statistical test will lead to rejection of the null hypothesis, given that the null hypothesis is true.

SILICA - the dissolved form of silicon dioxide (SiO_2).

SILT - a soil separate consisting of particles between 0.05 and 0.002 mm in equivalent diameter; also a soil texture class containing at least 80 percent silt and < 12 percent clay.

SILVICULTURAL PRACTICES - forest management practices to increase wood yields: thinning, pruning, fertilization, spraying with herbicides/insecticides, and irrigating.

SIMULATION - replication of the prototype using a model.

SKELETAL SOILS - soils with at least 35 percent rock fragments in the control section.

SLOPE PHASE - the slope gradient of a soil map unit or taxonomic unit expressed in percent.

SLOPE SHAPE ACROSS - shape of the surface parallel to the contours of the landscape (e.g. concave, convex, plane).

SLOPE SHAPE DOWN - shape of the land surface at right angles to the contours of the landscape.

SMALL-SCALE MAP - 1:250,000-scale U.S. Geological Survey map.

SMECTITES - a family of three-layer clay minerals.

SOIL - unconsolidated material on the surface of the earth that serves as a natural medium for the growth of plants.

SOIL ACIDIFICATION - a process through which BASE CATIONS are removed from the soil and are replaced by ACID CATIONS.

SOIL BUFFERING CAPACITY - the capacity of a soil to resist changes in pH with the addition of acids to the system.

SOIL COMPONENT CODE - four-character code assigned to each soil or miscellaneous area component of map units in a survey area. Codes were used to link data files.

SOIL COMPONENTS FILE - a computer data file that contains all the soil and miscellaneous area components in a survey area and identified with a code (i.e., SCODE).

SOIL CORRELATION - the process of maintaining consistency in naming, classifying, and interpreting kinds of soils and of the units delineated on maps.

SOIL EXCHANGE COMPLEX - all components of a soil that contribute to the absence of exchange properties of that soil.

SOIL FAMILY - next to the lowest category in Soil Taxonomy in which classes are separated mainly on particle size, temperature, and mineralogy.

SOIL IDENTIFICATION LEGEND - a map legend that lists the symbols used to identify SOIL MAP UNITS and the names of the map units.

SOIL LEGEND - see SOIL IDENTIFICATION LEGEND.

SOIL MAP UNIT - a collection of areas defined and named in terms of their soil components or miscellaneous areas or both. Each map unit differs in some respect from all others in a survey area and is uniquely identified on a soil map.

SOIL SAMPLING CLASS - an arbitrary grouping of soils either known or expected to have similar physical and/or chemical effects on drainage waters with respect to effects of acidic deposition.

SOIL SERIES - the most homogenous category in the taxonomy used in the United States. A group of soils that have horizons similar in arrangement and in differentiating characteristics.

SOIL SOLUTIONS - those aqueous solutions in contact with soils.

SOIL TAXONOMIC CLASS - the soil members within limits of ranges set by Soil Taxonomy. Taxonomic units are members of the taxonomic class.

SOIL TAXONOMIC UNIT - a kind of soil described in terms of ranges in soil properties of the polypedons referenced by the taxonomic unit in the survey area.

SOIL TEXTURE - the relative proportion by weight, of the several soil particle size classes finer than 2 mm in equivalent diameter (e.g., sandy loam).

SOIL TEXTURE MODIFIER - suitable adjectives added to soil texture classes when rock fragments exceed about 15 percent by volume, for example, gravelly loam. The terms "very" and "extremely" are used when rock fragments exceed about 35 and 60 percent by volume, respectively.

SOIL TRANSECT - a distance on the surface of the earth represented by a line on a map. Transects can be straight, dogleg, or zigzag.

SOLID PHASE EXCHANGERS - those components of soils, primarily organic matter, clay minerals and mineral oxides, that serve as the sites for exchange reactions.

SOLUM - soil layers that are affected by soil formation.

SPECIATION MODEL - a numerical model used to describe the distribution of aqueous species among various possible complexes and ion pairs; usually for the purpose of estimating single ion activities.

SPECIFIC ADSORPTION - adsorption of sulfate by ligand exchange, often involving exchange of two ligands and formation of a bridged ($M-O-SO_2-O-M$) structure.

SPODIC HORIZONS - a soil horizon in which iron oxides, aluminum oxides, and organic matter have accumulated from higher horizons.

SPODOSOLS - in Soil Taxonomy, the ORDER of mineral soils with well-developed SPODIC HORIZONS.

SPRING BASEFLOW INDEX PERIOD - a period of the year when streams are expected to exhibit chemical characteristics most closely linked to ACIDIC DEPOSITION. The time period between snowmelt and leafout (March 15 to May 15 in the NSS-I) when NSS-I stream reaches were visited coinciding with expected periods of highest geochemical and assessment interest (i.e., low seasonal pH and sensitive life stages of biota).

STABILITY (NUMERICAL OR COMPUTATIONAL) - ability of a scheme to control the propagation or growth of small perturbations introduced in the calculations. A scheme is unstable if it allows the growth of error so that it eventually obliterates the solution.

STANDARD DEVIATION - the square root of the variance of a given statistic.

STEADY-STATE - the condition that occurs when a property (e.g., mass, volume, concentration) of a system does not change with time. This condition requires that sources and sinks of the property are in balance (e.g., inputs equal outputs; production equals consumption).

SULFATE RETENTION - the physical, biological, and geochemical processes by which sulfate in WATERSHEDS is held, retained, or prevented from reaching receiving SURFACE WATERS.

SULFIDE - an ion consisting of reduced sulfur (S^{2-}) or a compound containing sulfide, e.g., hydrogen sulfide (H_2S) or the iron sulfide pyrite (FeS_2).

SULFIDE OXIDATION - chemical reaction in which a sulfide loses electrons and assumes a higher oxidation state; sulfate is the completely oxidized end product.

SULFITIC - containing sulfide minerals, usually pyrite.

SULFUR INPUT/OUTPUT BUDGET - an approach to describing sulfur mobility in a watershed by comparing fluxes of sulfur to and from the watershed (as the difference between input and output or as a ratio).

SURFACE WATER - streams and lakes.

SURFACE WATER RUNOFF - precipitation that flows overland to reach SURFACE WATERS.

SURFICIAL GEOLOGY - characteristics of the earth's surface, especially consisting of unconsolidated residual, colluvial, or glacial deposits lying on the BEDROCK.

SYNOPTIC - relating to or displaying conditions as they exist at a point in time over a broad area.

SYSTEMATIC ERROR - a consistent error introduced in the measuring process. Such error commonly results in biased estimations.

TARGET POPULATION - a subset of a population explicitly defined by a given set of exclusion criteria to which inferences are to be drawn from the sample attributes.

THERMODYNAMIC CONSTANTS - an empirically derived constant used to describe the relative distribution of chemical species in a specified reaction when at equilibrium.

THROUGHFALL - precipitation that has interacted with a forest canopy, the chemistry of which is thus modified from that of incident precipitation due to wash off of dry-deposited material and leaf exudates as well as by ion exchange and uptake by leaf surfaces.

TICS - registration or geographic control points for a COVERAGE.

TILL - unstratified material deposited by glaciers.

TITRATION CURVES - a loci of points describing some solution property, usually pH, as a function of the sequential addition of a strong acid (or base) to the system.

TOPMODEL - topographically based, variable source area hydrologic model.

TOPOGRAPHIC MAP - a map showing contours of surface elevation.

TRANSECT - see SOIL TRANSECT.

TRANSECTING - a field activity involving the collection of data at points along a designated line (see TRANSECT POINTS).

TRANSECT POINTS - locations along a TRANSECT where data are collected.

TRANSECT SEGMENT UNION - all transect stops in the same map unit on a WATERSHED.

TRANSECT STOPS - see TRANSECT POINTS.

TRANSFORMATION ERROR - calculates the residual mean square error of the digitized TIC locations and the existing TICs.

TRAVERSING - a field activity that involves observation at uncontrolled representative locations in the landscape.

TYPICAL YEAR (TY) DEPOSITION DATA - a dataset of atmospheric deposition developed within the DDRP for specific use with the integrated watershed models.

UNCERTAINTY ANALYSIS - the process of partitioning modelling error or uncertainty to four sources: intrinsic natural variability, prior assumptions/knowledge, model identification, and prediction error.

UNIVERSAL TRANSVERSE MERCATOR (UTM) PROJECTION - a standard map projection used by the U.S. Geological Survey.

UPPER NODE - the upstream NODE of a STREAM REACH.

UPSTREAM REACH NODE - see UPPER NODE.

UTM COORDINATES - lines or points as represented in a UNIVERSAL TRANSVERSE MERCATOR PROJECTION.

VALIDATION - comparison of model results with a set of prototype data not used for verification. Comparison includes the following: (1) using a dataset very similar to the verification data to determine the validity of the model under conditions for which it was designed; (2) using a dataset quite different from the verification data to determine the validity of the model under conditions for which it was not designed but could possibly be used; and (3) using post-construction prototype data to determine the validity of the predictions based on model results.

VANSELOW EXCHANGE FORMULATION - a formulation used to describe soil exchange reactions.

VARIABLE - a quantity that may assume any one of a set of values during the analysis.

VARIABLE SOURCE AREA - A topographically convergent, low transmissivity area within a watershed that tends to produce saturation excess overland flow during storm runoff periods.

VEGETATION - see FOREST COVER TYPE.

VERIFICATION - check of the behavior of an adjusted model against a set of prototype conditions.

WATERSHED - the geographic area from which SURFACE WATER drains into a particular lake or point along a stream.

WATERSHED STEADY STATE - a condition in which inputs of a constituent to a WATERSHED equal outputs.

WATERSHED SULFUR RETENTION - retention of sulfur by any of a number of mechanisms within a WATERSHED.

WEATHERED BEDROCK - soft or partly consolidated BEDROCK that can be dug with a spade.

WEATHERING - physical and chemical changes produced in rocks at or near the earth's surface by atmospheric agents with essentially no transport of the altered materials.

WEIGHT - the inverse of a sample's inclusion probability; each sample site represents this number of sites in the TARGET POPULATION.

WET DEPOSITION - for the purposes of the DDRP, atmospheric deposition of materials via rain or snow.

WETLAND - an area, generally with hydric soils, that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper soil horizons and that is capable of supporting the growth of hydrophitic vegetation.

ZERO-ORDER REACTION - a chemical reaction, the rate of which is independent of reactant concentration.