ACID RAIN ABATEMENT IN EUROPE: TWO PROGRESS REPORTS

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FOREWORD

I am pleased to have this opportunity to recognize the important practical contributions being made by Leen Hordijk and his colleagues to the management of the acid rain problem in Europe. This is indeed one of the success stories at the International Institute for Applied Systems Analysis (IIASA).

Examples of the work being undertaken are to be found in the two reprints contained herein, which deal with the IIASA policy-directed computer model RAINS (Regional Acidification Information and Simulation. RAINS is a tool that is already assisting decision makers in the evaluation of emission control strategies. A fixed reduction of 30% in sulphur emissions is only one way of reducing acid rain; RAINS makes it possible to explore many other options quickly and in a user-friendly way.

R.E. MUNN
Leader
Environment Program

T. Schneider (Editor)/*Acidification and its Policy Implications*

ACID RAIN ABATEMENT STRATEGIES IN EUROPE

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ABSTRACT

The paper describes briefly the RAINS (Regional Acidification Information and Simulation) model and presents three alternative abatement strategies for acidification in Europe. These alternatives are: a percentage reduction of emissions per country, reductions based on indicators and targetted emission reductions.

INTRODUCTION

International deliberations on reductions of effects of acid deposition are dominated by the flat-rate-of-reduction paradigm. This is demonstrated by the protocol signed by 21 countries in July 1985 in Helsinki. Article 2 of this protocol reads: "The parties shall reduce their national annual sulphur emissions or their transboundary fluxes by at least 30 percent as soon as possible and at the latest by 1993 using 1980 levels as the basis for calculation of reductions". Based on 1980 emissions the total reduction resulting from the European signatories would amount to roughly 7,500 kilotonnes sulfur, this is 25% of the emissions in Europe.

Although from a political point of view 30% reduction of SO_2 emissions in 21 countries can be considered as a good step forward in abating effects of acidification, one may wonder how effective and how efficient this flat rate policy is. It could well be that another distribution of 7,500 kilotonnes reduction of emissions would be more effective. The problem, however, is to define effectiveness. Ideally one should measure effectiveness in terms of reduced effects of acid deposition on effect categories like lakes, soils, forests, crops, materials, etc. To that end it would be necessary to identify:

1. the dose effect relationships for the effect categories;
2. the location of the lakes, soils, etc., exposed to acid deposition (the stock at risk);
3. the deposition levels; and
4. the link between deposition levels and emissions.

This information is only partially available on the regional scale of Europe. Nevertheless policies to abate acidification are being developed and carried out.

In an attempt to assist these policies, the International Institute for Applied Systems Analysis (IIASA) has started an Acid Rain Project which developed a set of linked computer models describing the bond between human activities and pollution effects.

In this paper we will briefly introduce this model, known as the RAINS (Regional Acidification INformation and Simulation) model. Detailed description of RAINS can be found in Alcamo et al. [ref. 1] and Hordijk [ref. 2]. Furthermore we will show some results of using RAINS. These results are meant to be examples of abatement strategies and do not intend to be policy advices nor do they reflect the view of IIASA or the National Member Organizations that support it.

THE RAINS MODEL

Figure 1 describes the current status of the RAINS model. Starting from the left hand side of the figure the RAINS data bank contains a number of different energy pathways for Europe. These energy pathways have been derived from publications by the Economic Commission for Europe [ref. 3] and the International Energy Agency [ref. 4] for each of 27 larger European countries. The energy use per country is broken down into 8 categories of fuel: hard coal, brown coal, derived coal, light oil, heavy oil, derived oil, gas and others (hydro, nuclear, biomass). The emission producing sectors are conversion (refineries), power plants, industry, domestic, transport and other. The emissions of SO_2 per fuel

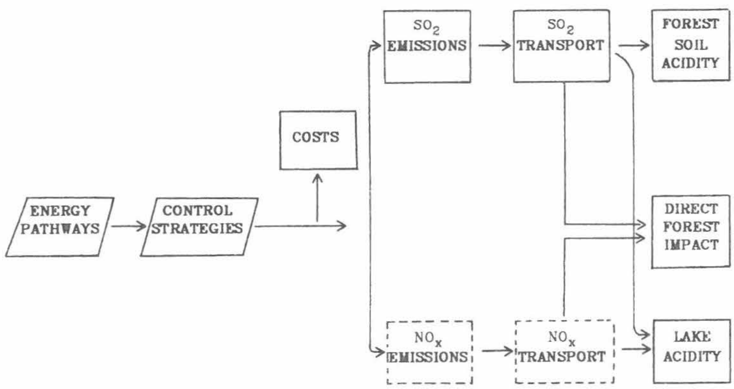

Fig. 1. Current structure of the RAINS model and its submodels. Boxes with dashed lines indicate that the submodel has not yet been implemented.

and per sector have been calculated using sulfur content and heat values of the fuels. These numbers were collected from many different data sources, both international (UN, OECD) and national. The number of energy pathways in RAINS will be extended to include a pathway in which maximal natural gas use is assumed and a pathway reflecting increased efforts in energy conservation throughout Europe. In this way a wide range of possible energy futures will be covered by the RAINS data bank.

The model user has many ways to influence model runs. This begins with the choice of an energy pathway. Since we consider the energy future to be one of the largest uncertainties, we have left the choice of a particular energy future to the user. The next submodel of RAINS, which calculates SO_2 emissions, can also be influenced by the user. The menu of RAINS presents options for abatement strategies: switch to low sulfur fuels, physical or chemical fuel cleaning, desulfurization units on power plants and combustion modified power plants (e.g. fluidized bed combustion). The user can select a combination of strategies for any country or combination of countries and also select the year of implementation and the efficiency of the strategies. The costs of the control policy constructed by the user will then be presented.

The SO_2 emissions are input to the atmospheric transport submodel. Currently RAINS uses transfer matrices derived from the atmospheric transport model developed at the Meteorological Synthesizing Center-West of the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) in Oslo. This model has been described inter alia in Eliassen and Saltbones [ref. 5] and WMO [ref. 6]. The transfer matrices are used to calculate deposition of sulfur in grid squares of 150 x 150 km all over Europe. A user of RAINS may obtain output in the form of European maps showing selected isolines of deposition or coloured maps showing total deposition patterns.

Output of the atmospheric transport submodel is used in the forest soil and lake acidity submodels. Soil acidification has been described as a decrease in the acid neutralizing capacity of the soil [ref. 7]. Such a decrease may coincide with a decrease in soil pH. The reaction of the soil to the incoming acid stress depends on its buffering properties. In the submodel these buffering properties are described using two variables, one for the gross potential (buffer capacity) and the other for the rate of the reaction (buffer rate). Buffering is assured to be governed by several reactions: carbonate, silicate weathering, cation exchange and aluminum buffering. The data bank for the forest soil submodel contains the spatial distribution of 88 soil types in grids of 1^o longitude by 0.5^o latitude. Model output is provided in maps and graphs for soil pH, Al^{3+} concentration, Ca^{2+}/Al^{3+} ratios and base saturation levels. The forest soil submodel has been described in detail in Kauppi et al. [ref.8], Kämäri et al. [ref.9] and Posch et al. [ref.13].

The lake acidification submodel consists of several modules for meteorology, hydrology, soil chemistry and water quality of lakes. The meteorologic module regulates the input flows of water and deposition to the soil and directly to the lake. The hydrologic and soil chemistry modules together determine the flow of ions leaching from the terrestrial catchment to the lake. New equilibrium concentrations in the lake water are then computed in the lake module. Currently the lake acidity submodel has been implemented for Finland and Sweden. Model output is in the form of maps of these countries showing spring or summer pH classes of lake areas. Documentation of the submodel is provided in Kämäri *et al.* [refs. 10, 11 and 12].

Present work in the RAINS model includes the further development of the cost and direct forest impact submodels, construction of sensitivity maps for groundwater acidification, development of a NO_x emissions submodel and extensive sensitivity and uncertainty analysis [refs.13 and 14].

ABATEMENT OPTIONS IN EUROPE

Three Scenarios

In this section we will present a number of deposition maps representing different abatement policies in Europe. First we will describe these abatement policies.

As was stated in the Introduction 21 countries have pledged a 30% cut in SO_2 emissions. On top of that, several countries have announced higher reduction percentages. Table 1 column (1) presents an overview of those countries and their commitments. Together we have named these commitments Current Reduction Plans. The percentages shown in Table 1 have been derived from several official and unofficial sources.

The SO_2 emissions in 1980 have been calculated in the RAINS model and are shown in Table 2. The same table also shows the effects of the Current Reduction Plans (Column (1)).

As a next step in reducing SO_2 emissions we have looked at three indicators for emission intensity in each country. These indicators are: emissions per inhabitant, emissions per PJ, emissions per m^2. The indicators have been calculated for the year 1995, i.e. the year for which we assume that the Current Reduction Plans have been implemented. Next the median values for the three indicators are found and additional emission reductions are calculated such that values of three indicators are below the original medians for all European countries. Finally the average of the three reduction percentages was calculated and applied to the 1980 emissions of SO_2 in all European countries. We assumed that this scenario, Reductions Based on Indicators, will be implemented such that in the year 2000 the calculated reductions have been reached. Columns (2) of Table 1 and Table 2 present reduction percentages and emission totals, respectively.

TABLE 1

Percentage reduction of SO_2 emission in European countries based on 1980 emissions, for three scenarios.

Country	(1)	(2)	(3)
Albania	-	5	-
Austria	50	50	50
Belgium	50	60	50
Bulgaria	30	42	14
Czechoslovakia	30	71	50
Denmark	50	50	12
Finland	50	50	4
France	50	50	40
Fed. Rep. of Germany	60	40	50
German Dem. Rep.	30	77	40
Greece	-	23	5
Hungary	30	64	50
Ireland	-	8	17
Italy	30	40	49
Luxembourg	30	45	50
Netherlands	60	60	50
Norway	50	50	2
Poland	-	39	46
Portugal	-	4	3
Romania	-	9	33
Spain	-	44	8
Sweden	65	65	7
Switzerland	30	30	47
Turkey	-	11	2
United Kingdom	-	37	50
USSR (European part)	30	31	43
Yugoslavia	-	30	50
European average	25	44	40

(1) Current Reduction Plans

(2) Reductions Based on Indicators

(3) Targetted Emissions Reductions

Another alternative reduction scheme based on targetted deposition levels has been implemented. Since no agreed set of target areas exists in Europe we have taken the ten areas where according to our calculations the deposition in 1980 was the highest. We used a four year (1979-1982) average of EMEP transfer matrices to calculate these depositions. The ten areas are presented in Table 3 and figure 2 presents the spatial distribution of these points and a three dimensional deposition map for 1980.*) Using an algorithm developed and applied by

*) The mapping has been developed by Maximilian Posch and Jean-Paul Hettelingh at IIASA.

TABLE 2

Reduced levels of SO_2 emissions in European countries for three scenarios (kilotonnes S per year).

Country	1980	(1)	(2)	(3)
Albania	39	39	37	39
Austria	159	80	80	80
Belgium	432	216	173	216
Bulgaria	508	355	294	436
Czechoslovakia	1832	1282	531	916
Denmark	226	113	113	199
Finland	294	147	188	282
France	1657	829	829	994
Fed. Rep. of Germany	1602	641	641	801
German Dem. Rep.	2415	1691	556	1449
Greece	345	345	266	328
Hungary	813	569	293	406
Ireland	119	119	109	99
Italy	1898	1328	1139	968
Luxembourg	20	14	11	10
Netherlands	243	97	97	122
Norway	72	36	36	80
Poland	1741	1741	1062	940
Portugal	130	130	124	126
Romania	757	757	689	507
Spain	1879	1879	1052	1729
Sweden	243	85	85	226
Switzerland	67	47	47	36
Turkey	497	497	442	487
United Kingdom	2342	2342	1475	1171
USSR (European part)	8588	6012	5926	4895
Yugoslavia	837	837	586	419
Europe	29755	22225	16879	17949

(1) Current Reduction Plans

(2) Reductions Based on Indicators

(3) Targetted Emission Reductions

Shaw and Young [refs. 15 and 16] we derived emission reductions such that deposition throughout Europe will be 4.0 g $S/m^2/yr$ maximum. The maximum allowed emission reduction for all European countries was taken to be 50%. With this constraint it was impossible to reach the target level in the Donetz and Erzgebirge areas. Reduction percentages and emission levels for this scenario (Targetted Emission Reductions) are shown in columns (3) of table 1 and table 2, respectively.

TABLE 3

Ten areas in Europe with the highest calculated deposition levels in 1980.

Area	Approximate longitude/latitude	Country
Donetz	39/47.5	USSR
Erzgebirge	13/51	GDR/CSSR
Katowice	19/50	Poland
Bilo Gora	17/46	Yugoslavia
Lombardy	9/46	Italy
Börzsöny Hills	19.5/48	Hungary
Rhineland	7/51	FRG
West Yorkshire	-2/53*)	United Kingdom
Belgrade	21/45	Yugoslavia
Moscow	39/56	USSR

*) -2 indicates two degrees west of Greenwich

Resulting deposition patterns

The emission reductions calculated above lead to different deposition patterns The RAINS model provides several output modes to show these deposition patterns. Unfortunately it is not possible to reproduce the most illustrative of these modes: a colour map of Europe showing deposition in intervals 0-1, 1-2, 2-4, etc. g $S/m^2/yr$. Two other options of RAINS have been used below.

Figure 3 shows the 3 $g/m^2/yr$ isolines in the year 2000 for two scenarios: Current Reduction Plans and Reductions Based on Indicators. It can be concluded that the area covered by deposition greater than 3 grammes $S/m^2/yr$ isolines will be substantially lower in the case of the second scenario. In table 4 we present an overview of comparisons of the three scenarios.

It can be concluded that the Current Reduction Plans scenario already reduces peaks in deposition substantially. The other two scenarios which require larger emission reductions throughout Europe reduce the peaks even more. In these scenarios depositions greater than 5 g $S/m^2/yr$ have virtually disappeared. At the same time the area where the deposition is greater than 2 g $S/m^2/yr$ decreased by approximately the same percentage as the emission reduction. The major differences between the second and third scenarios are the following. The reduction required in the third scenario is limited to 50% based on 1980 figures whereas the Reduction Based on Indicators scenario points to very high reduction percentages in some Eastern European countries. As a result of this, the deposition pattern of the second scenario looks more flat than the one for the third scenario. The latter scenario shows deposition peaks in the Donetz and Katowice areas only. Figure 4 shows the resulting deposition map for the third scenario.

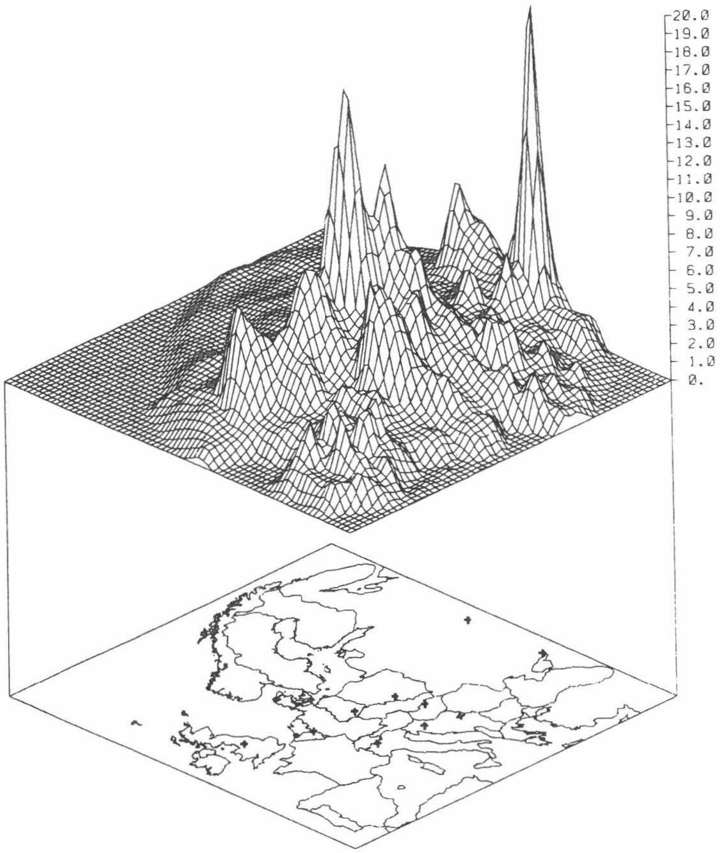

Figure 2. Calculated deposition (gram $S/m^2/yr$) in Europe. The ten highest deposition areas are indicated on the map.

CONCLUSION

The RAINS model can be used to evaluate different schemes for SO_2 emission reductions throughout Europe. We have focused on deposition patterns since this is the most advanced part of the RAINS model. Elsewhere we will present the effects of the scenarios presented on indicators for forest soil and lake acidification.

ACKNOWLEDGEMENTS

The author is indebted to the many individuals who have been working with him on the development of the RAINS model at IIASA, to Dr.R.W. Shaw from Bedford Institute of Oceanography, Canada, who provided the optimization algorithm used in this paper, to the World Meteorological Organization and the

TABLE 4.

A comparison of three scenarios with the 1980 situation.

	1980	Scenario (1)	Scenario (2)	Scenario (3)
Emissions (ktonnes S/yr)	29,755	22,225	16,879	17,949
% Reduction based on 1980	-	25	44	40
Area covered by deposition				
> 2 g $S/m^2/yr$	55	43	30	33
> 4 g $S/m^2/yr$	21	10	2	4
> 5 g $S/m^2/yr$	12	5	1	2
> 9 g $S/m^2/yr$	2	1	0	0

(1) Current Reduction Plans

(2) Reductions Based on Indicators

(3) Targetted Emission Reductions

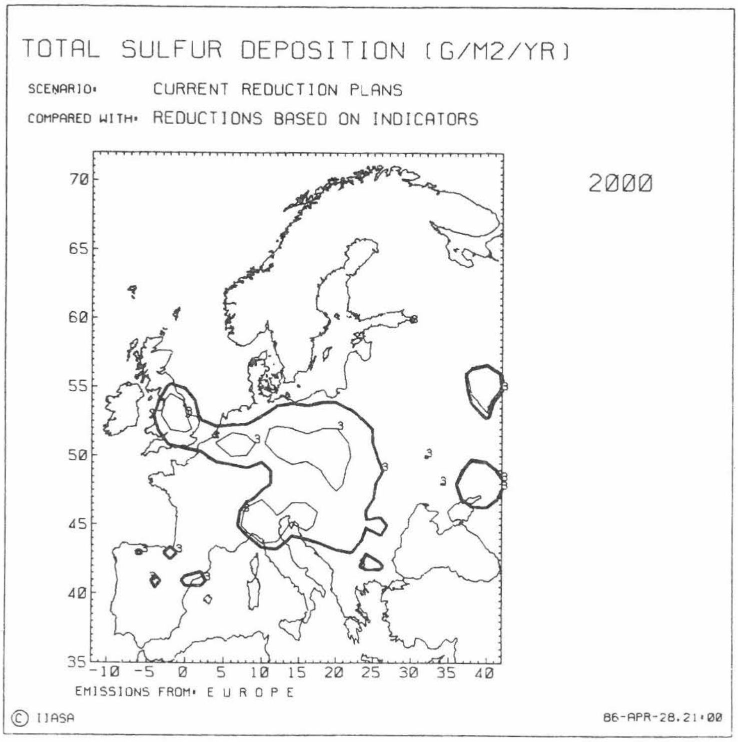

Figure 3. Calculated isolines of 3 g $S/m^2/yr$ for two scenarios in 2000.

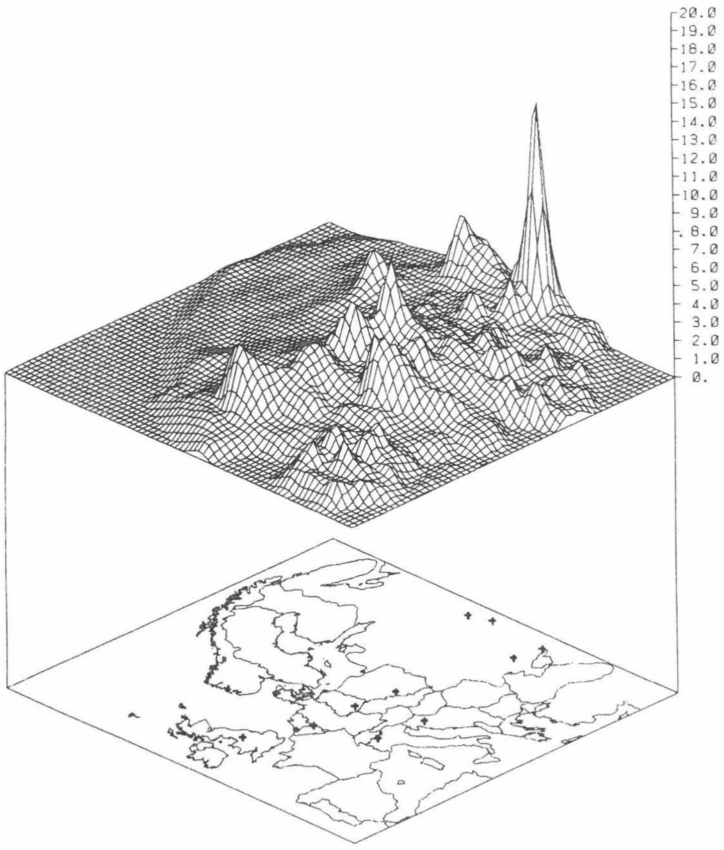

Figure 4. Calculated deposition (grammes $S/m^2/yr$) for Europe in 2000, for the Reduction Based on Indicators scenario.

UN Economic Commission for Europe for permission given to use results from the EMEP programme and to the Norwegian Meteorologic Institute for providing the atmospheric transfer matrices used. Errors in this paper are the author's responsibility only.

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TECHNICAL NOTE

TOWARDS A TARGETTED EMISSION REDUCTION IN EUROPE

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Abstract—Currently 20 European countries have stated that they will reduce their SO_2-emissions by at least 30% in the years 1993–1995 based on 1980 emissions. Some countries will reduce more, e.g. France by 50%. Although politically this is an important step, a more or less flat rate of emission reduction throughout Europe is not an efficient solution. The paper describes an alternate emission reduction targetted to those areas where depositions are high and taking into account the source–receptor relationships in Europe. The reductions are calculated by using the model RAINS which is being developed at IIASA. RAINS is a set of linked submodels dealing with energy scenarios, SO_2 emissions, abatement options, long-range transport, deposition, forest soil acidification and lake acidification. For the purpose of this paper an optimization algorithm developed by R. Shaw and J. Young (AES, Canada) has been connected with RAINS. The results show optimal reduction patterns in Europe for a number of different receptor areas and alternative energy scenarios.

Key word index: Acid deposition, emission reduction, optimization.

1. INTRODUCTION

In 1979 a large number of European countries, Canada and the United States of America signed the Convention on Long Range Transboundary Air Pollution. In this Geneva Convention, overseen by the U.N. Economic Commission for Europe, the signatories state in Article 2 that they "... shall endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution." Under the Convention, four major programs are carried out: Air Quality Management, Research and Development, Exchange of Information and the Co-operative Programme for the Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe (EMEP).

In March 1983, the required number of countries had ratified the Geneva Convention and an Executive Body had been established. That same year a number of countries started a campaign to agree on a 30% reduction of SO_2 emissions in countries that ratified the Convention. By March 1984, ministers of nine countries agreed on reducing SO_2 emissions in their countries by 30% in 1993 based on 1980 figures. Later in 1984 at a Minister's meeting in Munich and a meeting of the Executive Body the so-called 30% club extended its membership to include 19 European countries and Canada. The next step was an official protocol signed by these countries in July 1985 in Helsinki.

Although from a political point of view this achievement is very valuable, one may wonder whether a 30% rollback over Europe is an efficient way of reducing the effects of sulfur deposition. From a point of view of atmospheric linkages between a receptor area and the sources of pollution which contribute to deposition in that area, the chances are high that a flat rate reduction is non-optimal. Also from an economic point of view a more cost-efficient solution may be found by varying reductions among countries.

It is obvious that in both cases application of a model describing long-range transport of air pollutants (a so-called LRTAP model) can shed light on the above described optimality problem. Moreover a LRTAP model linked with models describing energy pathways, emission of pollutants, control options and their costs and environmental impact could be of even more use for policy analysis.

In the IIASA Acid Rain Project, work is underway to construct such a set of linked models. The purpose of this RAINS (Regional Acidification INformation and Simulation) model is to provide a tool to assist decision makers in their evaluation of control strategies for acidification in Europe. In this paper we describe briefly the interim state of the model, and show how it could be used when linked with an optimization algorithm.

Detailed information on RAINS can be found in Alcamo *et al.* (1985), Kauppi *et al.* (1985) and Kämäri *et al.* (1984). A description and an application of the optimization algorithm is contained in Young and Shaw (1986) and in Shaw (1984).

2. THE RAINS MODEL

The RAINS model currently consists of three linked compartments: Pollutant Generation, Atmospheric Processes and Environmental Impacts. Though many different submodels can be inserted into these compartments, we have begun with four linked submodels illustrated in Fig. 1.

The Sulfur Emissions submodel computes SO_2 emissions for each of 27 European countries based on a user-selected energy pathway for each country. Currently the RAINS data base contains three energy pathways for each country, based on estimates from the Economic Commission for Europe (ECE, 1983). In each energy pathway, fuels are divided into oil, coal, gas and others and into 11 sectors of energy use. There is an additional sector which accounts for SO_2 emissions from industrial processes. For the reduced emissions the user may specify any combination of the following four pollution control alternatives: (a) fuel cleaning, (b) flue gas control devices, (c) low sulfur power plants (e.g. FBC plants) and (d) low sulfur fuels.

The emissions of SO_2 are then input into the EMEP Sulfur Transport submodel. This model consists of a transfer matrix, which gives the total amount of sulfur (wet and dry) deposited

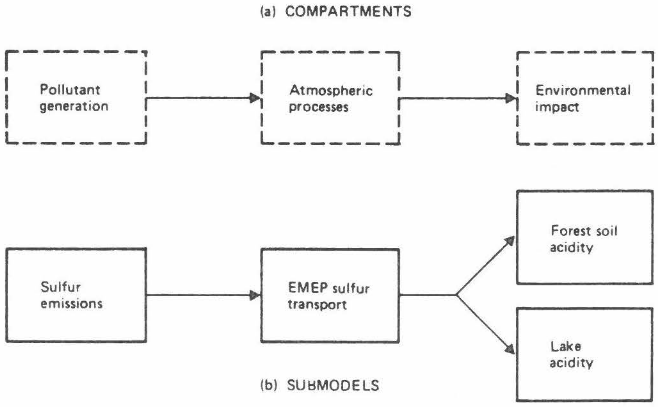

Fig. 1. Schematic diagram of RAINS compartments and submodels.

in a 150 × 150 km grid square due to SO_2 emissions originating from grids in each European country. The transfer matrix is based on the model by Eliassen and Saltbones (1983) and accounts for the effects of wind, precipitation and other meteorological and chemical variables.

The sulfur depositions computed by the second submodel is then input to the Forest Soil Acidity submodel. This submodel was based largely on the work of Ulrich and coworkers (Ulrich, 1983) and is reported in detail elsewhere (Kauppi *et al.*, 1985). The submodel is used by assigning buffer capacities and buffer rates to each of 5 buffer ranges and to 80 soil types in Europe. The pH of forest soil is estimated from the buffer ranges and used as an indicator of potential forest impact by acidification. Recently base saturation levels, aluminum concentration and calcium/aluminum ratios have been added to the list of indicators. The geographical unit for this submodel is 1° longitude by 0.5° latitude.

The fourth submodel, Lake Acidity, computes lake acidity levels as a function of catchment characteristics and acid deposition. Details of the model are available from Kämäri *et al.* (1984). Through different modules for meteorology (to account for rain/snow distribution and snowmelt), hydrology (for routing precipitation into quickflow, baseflow and flow between soil layers) and soil chemistry (the same as the Forest Soil Acidity submodel) the lake Response Module calculates the H^+ concentration of the lake based on the ion loads. The change in lake acidity is calculated according to equilibrium reactions of inorganic carbon species. The Lake Acidity submodel has been implemented for Sweden, Finland and Norway.

Other model characteristics are currently the following:

(i) 70-year simulation period (1960–2030),

(ii) month–year time resolution,

(iii) covering all Europe including the European part of the U.S.S.R.,

(iv) interactive with graphical output.

The model can be used by the procedure outlined in Fig. 2.

Research will continue at IIASA until the end of 1987 to improve and apply RAINS. Research efforts include: (a) the model will be enhanced to include NO_x and direct impacts of air pollutants on forest; (b) a cost of control submodel will be added; (c) model testing and uncertainty analysis; (d) implementing optimization algorithms; (e) policy analysis; and (f) distributing RAINS to international and national institutions.

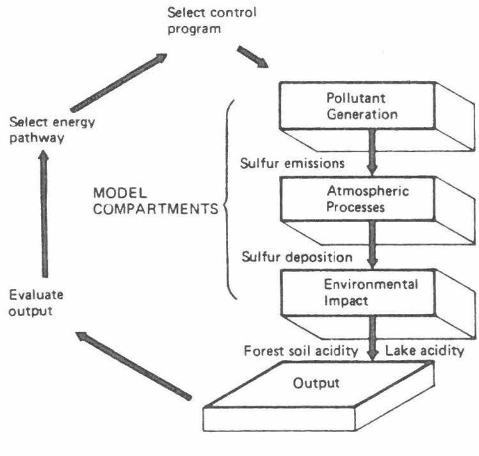

Fig. 2. Model use procedure.

3. AN OPTIMIZATION ALGORITHM

Recently Shaw (1984) described algorithms for optimizing emission reductions and Young and Shaw (1986) and Shaw (1986) described applications to North America.

In short the algorithm of Young and Shaw (YS) works as follows.

As a first step a user should define the receptor areas where reduction of deposition should take place. The user should, furthermore, set the order of treating the receptor areas. Suppose the areas are denoted by j and the deposition in these areas by d_j ($j = 1, \ldots, J$). The deposition d_j is calculated using an atmospheric transfer matrix derived from a long-range transport of air pollutants model. As described earlier, in this paper we use a transfer matrix derived from the EMEP model. The elements of the transfer matrix are called unit transfer coefficients and have the dimension (deposition per unit area per unit time)/(emission per unit time).

In their first method, YS use the unit transfer coefficients to rank emission sources for a predetermined receptor area. The source with the highest coefficient for the receptor area chosen will be reduced first upto a prespecified minimum emission level. If the deposition at the given receptor has to be reduced further, the source with the next highest unit transfer coefficient is chosen for reduction. For the following receptor areas the same procedure is followed, taking into account reductions calculated in foregoing steps.

The second method of YS uses the absolute transfer coefficients, implying that not only the atmospheric linkages between sources and receptors are accounted for but also the strength of the sources.

In their third method, YS do not use a ranking based on atmospheric linkages or sources strength, but instead reduce all sources simultaneously in steps proportional to the source's contribution to the deposition.

It should be noted that the methods of YS do not guarantee a global optimum if one applies either of the methods to a situation where multiple receptors are taken. However, other mathematical programming techniques are available for that purpose (see *inter alia* Barnett *et al.*, 1985; Fortin and McBean, 1983; Morrison and Rubin, 1985).

4. EXAMPLES

Since, contrary to North America, there is no generally accepted set of receptor points in Europe, we have chosen ten receptor areas where the calculated wet and dry deposition (measured in g S m^{-2}) in 1980 rank high. The deposition values in these areas are calculated using the 1980 European emissions as reported to the Economic Commission for Europe (ECE, 1983) and a 4-year (1979–1982) average transfer matrix from the EMEP model. Table 1 presents an overview of the ten selected areas, while Fig. 3 produces their geographical locations.

First we will determine the effects of current reduction plans on deposition in the ten areas. In the meeting referred to in the introduction of this paper and in statements made by ministers and governmental officials several countries have indicated percentages of reduction of SO_2 emissions. In Table 2 we list these current reduction plans (further referred to as CRP) in terms of reduction percentages based on 1980 emissions. If these plans are carried out this would result in a reduction of European SO_2 emissions of 15%.

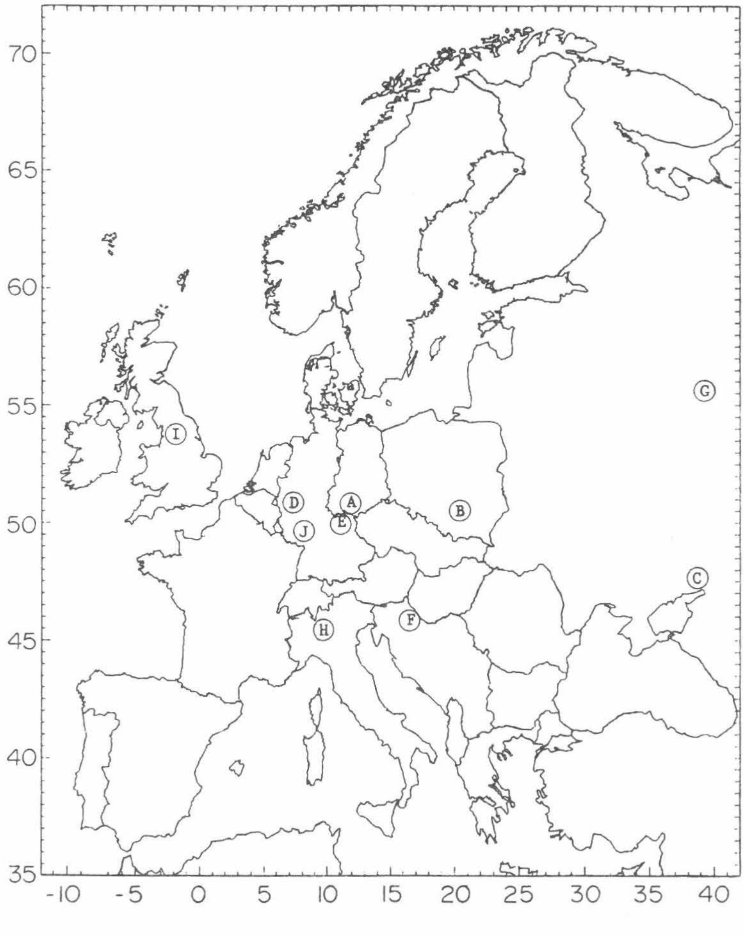

Fig. 3. Location of receptor areas.

Table 1. Overview of receptor areas

	Longitude*	Latitude	Name	Country
A	13	51	Erzgebirge	E Germany / Czechoslovakia
B	19	50	Katowice	Poland
C	38	48	Donetz	U.S.S.R.
D	7	51	Rhineland	W Germany
E	12	50	Fichtel Gebirge	W Germany
F	16.5	46	Bilo Gora	Yugoslavia
G	39	56	Moscow	U.S.S.R.
H	9	46	Lombardy	Italy
I	−2	53	West Yorkshire	U.K.
J	8	49	Black Forest	W Germany

* A minus sign indicates west of the Greenwich 0-line.

Table 2. Current reduction plans

30%	Austria, Belgium, Bulgaria, Czechoslovakia, Finland, E Germany, Hungary, Italy, Luxembourg, Lichtenstein, Switzerland, U.S.S.R.*
40%	Denmark, The Netherlands
50%	France, W Germany, Norway
60%	Sweden

* The U.S.S.R. plans to reduce the transboundary fluxes by 30%. For our calculations we used 5% overall reduction.

In Fig. 4 a map of Europe is presented with the deposition isopleth for 5 g S $m^{-2}a^{-1}$ resulting from CRP and compared with 1980 emissions, using the emissions and sulfur transport submodel of RAINS, together with the graphics of this model.

A flat rate of 30% reduction of emissions will cause another deposition pattern depicted in Fig. 5.

When we now take a look at the target areas described in Table 1 we may compare the deposition reduction achieved by the two reduction schemes. Table 3 presents such a comparison.

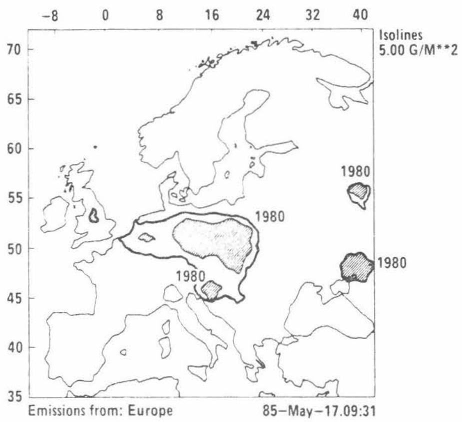

Fig. 4. Total European sulfur deposition in 1980 (heavy line) compared with current reductions plans (shaded area).

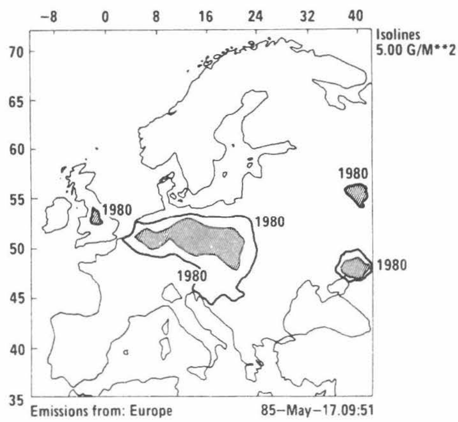

Fig. 5. Total European sulfur deposition in 1980 (heavy line) compared with 30% reductions in all European countries (shaded area).

Table 3. Deposition in target areas for different scenarios

Site	Deposition g S $m^{-2}a^{-1}$ 1980	CRP	30%
A	16.8	11.7	11.8
B	12.7	11.4	8.9
C	11.9	11.2	8.4
D	9.2	5.3	6.4
E	8.8	5.9	6.1
F	7.8	6.8	5.5
G	7.3	6.8	5.2
H	6.2	4.4	4.4
I	5.8	5.6	4.0
J	5.0	2.9	3.5
Total emission reduction (kton S)	—	5280	9490

Obviously those areas located in countries which do not participate in the CRP benefit more from the 30% scheme. Examples of those areas are Katowice, Donetz and Bilo Gora. Areas where the deposition is influenced to a large degree by countries which aim at a higher reduction percentage than 30 benefit more from the CRP scheme. Examples are the Rhineland area and the Black Forest.

Let us now turn our attention to optimization. At this point we would like to stress that our results are to be viewed as examples and certainly not as directions for European policies.

The receptor points in the U.S.S.R., Donetz and Moscow receive their deposition for nearly 100% from emission sources in the U.S.S.R. Since we are using a country to grid square transfer matrix an x% deposition reduction, any of the U.S.S.R. receptor points will be reached by an x% reduction of the U.S.S.R. emissions. Therefore optimization is impossible for these areas.

With CRP the deposition in the Ezgebirge amounts to $11.7\ g\ S\ m^{-2}a^{-1}$, which is a reduction of 30% compared with the 1980 deposition level. Another, more optimal way, to achieve this 30% reduction is to reduce emissions in the German Democratic Republic by 49%. Instead of the required 5280 kt reduction of SO_2 emissions resulting from CRP it is enough to reduce G.D.R. emissions by 1210 kt to reach the same level of deposition in this receptor area.

A flat rate of 30% reduction for all European countries will reduce emissions in the Black Forest from 5 to $3.5\ g\ S\ m^{-2}a^{-1}$. This 30% rollback equals a 9500 kt reduction of emissions. If 70% were the maximum reduction percentage for all European countries it is possible to reach a lower level of deposition in this target area. Aiming at $3\ g\ S\ m^{-2}a^{-1}$ would require a 70% reduction of emissions in W Germany and Luxembourg and 25% reduction in France. The total reduction in Europe would be 1800 kt SO_2. Should we take the CRP as our starting point, the gross reduction of European emissions would be 2530 kt SO_2. Countries involved are in this case Belgium, France, W Germany, Luxembourg, the Netherlands and Switzerland, each at their maximum reduction level in the CRP and E Germany with 20% reductions. In this case 40% reduction in deposition could be achieved by 8% reduction in emissions.

Since the United Kingdom is not a participant in CRP the deposition in the West Yorkshire area could only be reduced slightly to $5.6\ g\ S\ m^{-2}a^{-1}$. However, a 30% emission reduction in the U.K. would bring this level down to 4.5 g. Approximately 600 kt reduction of emissions from U.K. sources would be enough. As can be expected the effects of this U.K. effort would have only marginal influence in the other receptor areas.

To reduce the deposition in the Lombardy area by 30% in the context of CRP, a total of 2200 kt emission reduction is required. Austria, Czechoslovakia, Italy and Switzerland would all have to reduce their SO_2 emissions by 30%, while France would achieve its maximum reduction of 50% and W Germany's emissions should come down with 20%. A more efficient way of reduction can be achieved by allowing higher reduction percentages than foreseen under the CRP scheme. A total of 580 kt SO_2 (i.e. only 2% of all European emissions) mainly from Italy, the F.R.G. and Luxembourg will also reduce the deposition level in the Lombardy area to $4.5\ g\ S\ m^{-2}a^{-1}$. Of course, deposition levels in other target areas will be higher than under the CRP regime.

5. CONCLUSIONS

In this paper we linked parts of the RAINS model with an optimization algorithm. We focused our attention on 10 receptor areas with high deposition values in 1980. These areas should not be considered to represent European areas where impacts from acid deposition would be very strong. Currently there is no such set of environmentally sensitive areas available for Europe. It would be of value to international deliberations if the scientific community could identify a limited number of these areas. The results achieved under the U.S.A.–Canada Memorandum of Intent could serve as an example (MOI, 1983).

The deposition levels chosen are different for different receptor areas. The reason for this difference is that for each region another starting point was taken. In some cases we looked at the CRP and the possible reduction in a target area, in other cases we started with a 30% rollback over Europe. Consequently, the target values do not represent no-damage levels. In general one may conclude that for the target areas chosen, more optimal ways of deposition reduction can be found than those currently discussed in international meetings. The reader should, however, bear in mind the following caveats:

(i) The single receptor oriented approach taken in this paper does not evaluate deposition reductions in other areas than the single receptor chosen. Future research will be directed towards a multi-receptor approach.

(ii) For a different set of target areas different results than those reported here will emerge.

(iii) The transfer matrix is a crucial element in the analysis. It is clear from the literature that sensitivities and uncertainties of atmospheric models need further research. Joint research under the EMEP programme and at IIASA aims at establishing the uncertainties of the transfer matrix used in this paper. This work includes an assessment of year-to-year meteorological variability (see Alcamo and Bartnicki, 1985).

(iv) The results of this paper should be regarded only as illustrations of an alternative approach than a 30% flat rate reduction. However, it is clear that science can produce tools that can serve in policy making and evaluation.

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