ENVIRONMENTAL CONFLICTS:
THE CASE OF ACID RAIN IN EUROPE

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FOREWORD

This paper describes the use of the IIASA RAINS model as a decision-support tool for conflict resolution with respect to the European acid rain issue. It is important that the results of IIASA research be disseminated in peer-reviewed journals, and this reprint is one example of the effective publication program of the Acid Rain Project.

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Abstract

The Acid Rain problem is transboundary in nature: sulfur emissions in one country may lead to desposition of sulfur in a receptor country. A policy conflict may arise in estimating the damage at some receptor due to the various pollutant sources.

This paper first reviews the international policy context that led to the development of the Regional Acidification Informational and Simulation (RAINS) model. The model computes sulfur emissions, transport and deposition which is then transferred into soil and lake acidity. The model is an interactive tool designed to assist policy makers in evaluating the effect of the control measures related to sulfur emissions. A mathematical description of the model is provided followed by a set of objective functions to be introduced within the RAINS model. The current interactive usage of RAINS will be extended with the possibility for the decision maker to progressively define objectives and set constraints in order to obtain an optimal policy.

I. Introduction

International attention concerning the problem of long-range transport of air pollutants started in 1972, just before the United Nations Conference on the Human Environment in Stockholm [17]. In April of that year the Organization for Economic Cooperation and Development (OECD) inaugurated a "Cooperative Technical Program to Measure the Long-Range Transport of Air Pollutants" in which eleven European nations participated. In 1979 a revised publication of the Program's findings was published [12]. It was reported that a substantial part of a country's emissions of SO_2 was transported hundreds of kilometers and deposited in other countries. Emissions originating in the United Kingdom thus affected lakes in Scandinavia, and Austrian deposition levels were increased by emissions in the German Democratic Republic. Although the results of the OECD study carried an uncertainty of a factor of two, many European countries accepted the major conclusions of the report. At the same time it was clear that the geographical scope of OECD was too small to realistically discuss the long-range transport problem. Therefore the discussion of the problem shifted from OECD (with no Eastern European participants) to the United Nations Economic Commission for Europe (ECE), including entire Europe, Canada and the

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United States of America. In 1979 the Convention on Long-Range Transboundary Air Pollution was signed by 32 European countries, the European Economic Community (EEC), Canada and the USA. In the process of formulating the Convention, it turned out that resistance to an agreement did not come from Eastern European countries but from the Federal Republic of Germany (FRC) and the United Kingdom. The British scientists recognized the Scandinavian problems, but objected that it was not certain that these problems were (partly) due to Britain's emissions. The FRC turned into a supporter of reduction policies after it was discovered that large areas of its forests had been damaged by air pollution [17]. Notwithstanding this resistance the Convention was signed in November 1979 and ratified on 16 March 1983 by the required minimum number (24) of the signatories. The Convention entails no binding commitment to undertake measures, but the Contracting Parties endeavour "to limit and, as far as possible, gradually reduce and prevent air pollution, including long-range transboundary air pollution" (article 2). By article 3 the Contracting Parties "shall by means of exchanges of information, consultations research and monitoring develop without undue delay, policies and strategies which shall serve as a means of combating the discharge of air pollutants." Although the Convention covers all types of air pollutants, priority was given to sulfur compounds. At its third meeting, the Executive Body of the Convention (July 1985, Helsinki) established a working group on nitrogen compounds.

Jointly with the World Meteorologic Organization (WMO) the ECE is responsible for the Co-operative Programme for Monitoring and Evaluation of Long-Range Transmission of Air Pollutants in Europe (EMEP). The EMEP sampling network provides a database of concentrations and depositions of air pollutants (mostly sulfur compounds), and in particular provides information for validating the models for long-range transport of air pollutants developed at the Meteorological Synthesizing Centres in Oslo and Moscow [7]. At the end of the second phase of EMEP (1983), 81 monitoring stations in 22 countries were in operation.

The Convention's Working Group on Effects is producing reviews of current knowledge about effects of air pollution, in particular acidification. Also three international cooperative programmes were initiated in 1985/86, namely, Material Exposure Programme, Assessment and Monitoring of Acidification of Rivers and Lakes, and Assessment and Monitoring of Air Pollution Effects on Forests.

In July 1985 a Protocol was added to the Convention. The Protocol, an internationally binding agreement stating that sulfur emissions or transboundary fluxes will be reduced by at least 30% as soon as possible and at the latest by 1993 (using 1980 levels as the basis for calculation of reductions), has been signed by 21 parties to the Convention. Among countries that did not sign the protocol are large emitters, e.g., the United Kingdom and Poland, and small south European countries like Greece and Portugal. In Eastern Europe only Romania did not sign the Protocol, whereas the Soviet Union's interpretation of the Protocol is in terms of transboundary fluxes rather than in total emissions.

After establishing the Protocol, which by many countries was considered to be a first political step towards reduction of acidification, an international discussion has started about further steps. Important in this discussion are two issues: (1) Can threshold levels of effects be determined? (2) In which way can a flat-rate-of-reduction policy be changed? To answer the first question a large amount of detailed information about acidification effects on lakes, rivers, materials and monuments, forests, crops, soils and groundwater is needed. In

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addition the vulnerable areas in Europe need to be determined. The cooperative programmes of the Convention should provide this information. Together with the knowledge about atmospheric linkages between sources and receptors it should then be possible to derive policies which are different from the current uniform reduction, and which are advantageous in terms of reducing costs and/or increasing environmental production.

Although the results of the EMEP long-range transport of air pollutants model (see [12] and [7]) are generally accepted, one may wonder whether the same will be true for a scientific evaluation of effects of air pollution. It is the authors' belief that long negotiations between Signatories to the Convention will be needed before any agreement other than flat rate reductions can be achieved. First of all, establishing threshold levels will be accompanied with large uncertainties. Second, determination of the vulnerable areas (the stock at risk) will cause intense disputes about the spatial distribution of such areas. For these reasons negotiations might be lengthy, possibly unresolved for ten years or more. Furthermore, investigations into the role of nitrogen compounds have just started, and results will bear influence on the choice of threshold levels and vulnerable areas. Consequently the acid deposition dispute in Europe might continue for some time before further action is taken.

In this paper we will briefly outline an acidification model for Europe which is constructed in order to assist policy makers and their technical advisors. The model has been described inter alia in [1] and is known as the Regional Acidification Information and Simulation (RAINS) model. Next we will present the mathematical form of the model. Finally we formulate some multiobjective optimization problems. But first we will give a short overview of emissions of SO_2 and deposition of sulfur compounds to familiarize the reader with the European situation. In Table 1 the SO_2 emissions in the year 1980 for 27 larger European countries are given. The numbers are given in kilotonnes of sulfur per year.[1]

TABLE 1

EMISSION OF SO_2 IN EUROPEAN COUNTRIES IN 1980 IN KILOTONNES OF SULPHUR (COLUMN 1) AND CURRENT REDUCTION PLANS (COLUMN 2).

Country	(1)	(2)	Country	(1)	(2)
Albania	39	0	Italy	1898	30
Austria	159	50	Luxembourg	20	30
Belgium	432	50	Netherlands	243	60
Bulgaria	508	30	Norway	72	50
Czechoslovakia	1832	30	Poland	1741	0
Denmark	226	50	Portugal	130	0
Finland	294	50	Romania	757	0
France	1657	50	Spain	1879	0
Fed. Rep. Germany	1602	60	Sweden	243	65
German Dem. Rep.	2415	30	Switzerland	67	30
Greece	345	0	Turkey	497	0
Hungary	813	30	United Kingdom	2342	0
Ireland	119	0	USSR (European part)	8588	30
			Yugoslavia	837	0
			Europe	29755	25

[1]To obtain emissions in kilotonnes of sulfur dioxide the numbers have to be multiplied by a factor of 2.

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As described previously, many countries are prepared to reduce their sulfur dioxide emissions by at least 30% based on 1980 levels. The second column of Table 1 shows percentage reductions for the European countries.

Figure 1 presents a three-dimensional picture of calculated deposition for 1980. The calculation is based on the EMEP-W model, see [7] for a description of this model. Figure 1 also indicates the ten areas with the highest 1980 deposition levels as calculated by the model. These areas and their locations are presented in Table 2.

TABLE 2

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 degree west of Greenwich

II. The RAINS Model

RAINS consists of four submodels [1], [2]:
1.   The sulfur emissions submodel;
2.   The deposition submodel;
3.   The forest soil acidification submodel;
4.   The lake acidification submodel.

The time span of the model is from 1960 to 2040. It includes all of Europe except for the lake acidification submodel which is currently limited to Finland and Sweden. A user starts with the sulfur emissions submodel by defining a sulfur abatement strategy on one of five energy scenarios or on a previously defined abatement strategy. The sulfur emissions thus computed enter into the deposition submodel where the sulfur deposition in 2473 longitude-latitude grid points is calculated.[2] The soil submodel takes these depositions as a starting point in calculating acidification, measured in H^+ concentrations and uses the dominant forest soil types[3] by means of relevant soil chemistry.

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[2] The European area considered is bound by -12° longitude, 35° latitude and 42° longitude, 74° latitude. The grid size is 1 degree longitude by 0.5 degree latitude.

[3] FAO UNESCO Soil Map of the World, Vol. 1, V, FAO-UNESCO, Paris, 1974.
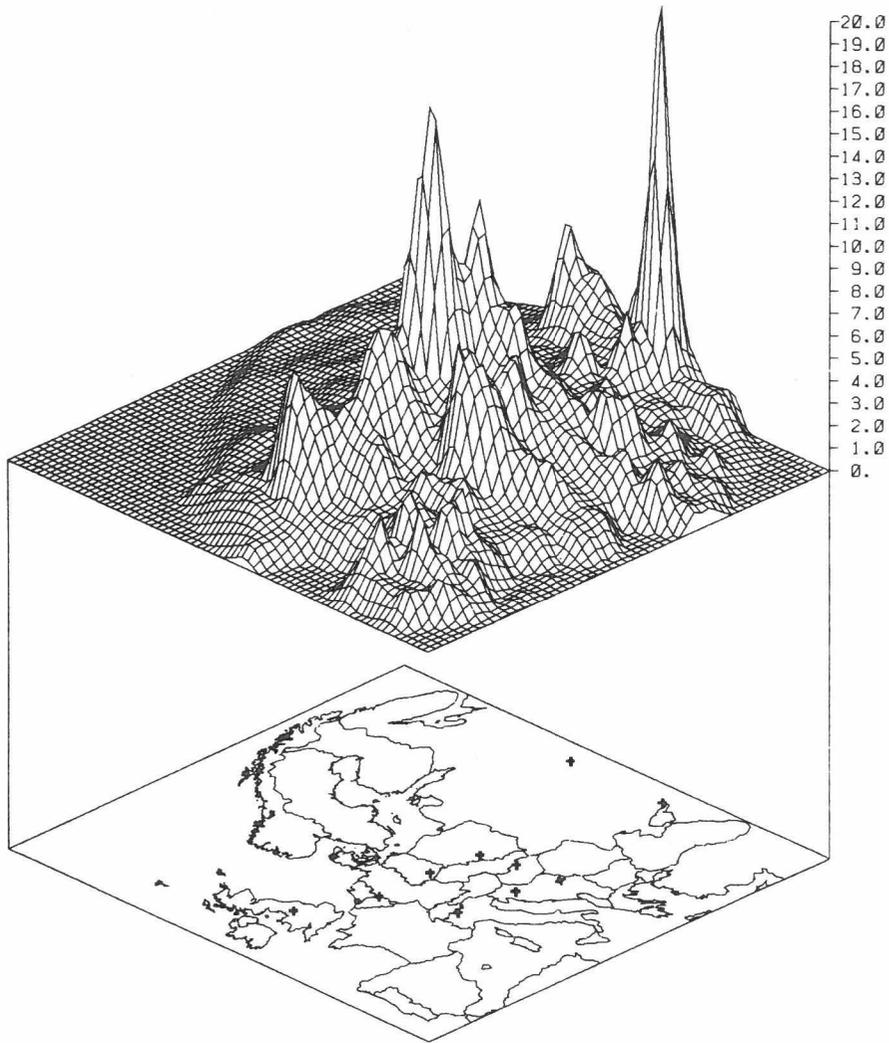
Figure 1. Calculated deposition (gram $S/m^2/yr$) in Europe, 1980. The ten highest deposition areas are indicated on the map.

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The final submodel, the lake acidification submodel, also uses sulfur deposition as an input variable. In addition a detailed simulation is used for the top soil water flows towards the lake. Those water flows are simulated taking into account precipitation and snowmelt. Separate modules are used for these simulations. In the following mathematical description the first three submodels are formalized. The lake model is described in a non mathematical way. In the description the model the following subscripts are used:

t	=	the time step (generally one year); t = 1960,...,2040
w	=	the season; w = summer, spring
f	=	the fuel type; f = 1,...,6 (the sulfur containing fuels)
s	=	the sectors of final energy use; s = 1,...,6
k,l	=	the European countries; k, l = 1,...,27
i	=	the grid squares

Upper case letters are used to indicate flow and stock variables, lower case letters are used for fractions and per unit variables.

II.1   The Sulfur Emissions Submodel

The basis of this submodel are five energy scenarios to 2040, three being based on published estimates to 2000 from the ECE [6] and two on IEA energy pathways to 2000 [9]. The energy scenarios comprise eight fuel types[4] being used in six sectors[5] of final energy use. For each of the fuel types and each of the sectors, the following computation is done to obtain sulfur emissions for every country for every year.

$$S_{f,s,k,t} = E_{f,s,k,t} \cdot s_{f,s,k,t} \cdot \frac{1}{h_{f,k}} (1-p_{f,s,k,t}) \ (1-r_{f,k}) \tag{1}$$

where
E = energy demand in PJ of fuel type f in sector s, country k and year t
S = sulfur emission
s = sulfur content
h = heat value
p = fraction of sulfur removed by pollution control measures
r = fraction of sulfur retained in ash

Sulfur emissions are obtained after defining pollution control measures, e.g. the use of low sulfur fuel, flue gas desulfurization and combustion modification. The deposition submodel requires the total country emissions obtained as:

$$S_{k,t} = \sum_f \sum_s S_{f,s,k,t} \tag{2}$$

Efforts are being made to introduce in the emissions submodel costs of the pollution control measures for each country in Europe. The cost functions

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[4]The fuel types being distinguished are hard coal, brown coal, derived coal, heavy oil, light oil, crude oil, natural gas and others.
[5]The energy sectors are conversion, conventional power plants, domestic, industry, transport and others.

developed depend on a subset of technological variables (cleaning efficiency, capacity factor, etc.) on a yet to be determined aggregation level. This "medium" aggregation level is feasible but also credible in that it distinguishes country cost estimates in a physically realistic manner. Cost functions developed for each of the 27 countries considered are of the form:

$$C_{k,t}(R_{k,t}) = f \text{ (technological variables)} \tag{3}$$

where   R =   Reduction of emissions in country k
         C =   Cost as function of emission reduction

II.2   The deposition submodel

The primary aim of this submodel is to translate emissions into deposition in each of the European grid squares mentioned earlier. For this purpose a source-receptor matrix is used that is based on a model of long range transport of air pollutants in Europe developed under the Organization of Economic Cooperation and Development (OECD) and the Cooperative Program for the Monitoring and Evaluation of Long Range Transmission of Air Pollutants in Europe (EMEP). This EMEP-W model (see [7] for a description) calculates concentrations of SO_2 and $SO_4^=$ at the center of grid elements. Every 6 hours air trajectories are computed backward from the center of each grid and are followed 96 hours later. The model then solves the mass balance equations along the trajectory. Dry and wet deposition are calculated using the SO_2 and $SO_4^=$ concentrations. The EMEP-W model is too demanding computationally to be used directly as a submodel of RAINS. Therefore a source-receptor matrix has been derived for several years (1978-1982). The elements of this matrix (sometimes referred to as transfer coefficients) represent the deposition per unit area per unit time for one unit emission.

Total deposition per grid is calculated as:

$$D^{tot}_{i,t} = \sum_k S_{k,t}\, a_{k,i}$$

with D^{tot} =   total deposition in grid square i at time t
     a   =   element of the source-receptor matrix from country k to grid square i

II.3   The Forest Soil Acidification Submodel

Soil acidification is defined as a decrease in the acid neutralization capacity of the soil [3]. In order to simulate such decreases, soil chemistry reactions have been classified into five classes of acid buffering reactions [15], [16]. Two buffering variables, buffer capacity and buffer rate, determine the soil's capacity to counteract acidic deposition. The buffer capacity is the total reserve of buffering compounds within one class. The buffer rate is the maximum potential rate of the reaction between the buffering compounds and the hydrogen ions. In Table 3, an incomplete[6] overview is given of the different buffer range classes, the related acidity measure, pH[7] and the buffering variable to be applied.

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[6] A complete table can be found in [11].
[7] $pH = -^{10}\log[H^=]$, $[H^+]$ being the concentration of hydrogen ions.

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TABLE 3

CLASSIFICATION OF THE ACID BUFFERING REACTIONS IN FOREST SOILS

Buffer Range	pH Range	Buffering variable
Carbonate	8.0-6.2	buffer capacity
Silicate	6.2-5.0	buffer rate
Cation exchange	5.0-4.2	buffer capacity
Aluminum	4.2-3.0	buffer rate

Acid deposition results in an input of hydrogen ions, H^+, into the top soil. This process is termed "acid stress." The equations below describe the balance between acid stress and the buffering variables on the portions of the grid squares covered by forests.

The first step towards the calculation of the acidity is to compute the fraction of the total deposition that applies to forest soils only, and translate that into acid stress.

$$as_{i,t} = C \cdot D_{i,t}^{tot} \qquad (5)$$

with as = acid stress in kmol ha^{-1} yr^{-1} in grid square i at time t
D^{tot} = total (wet and dry) deposition
C = constant accounting for the fraction of the total deposition on forest soils and balancing the measurement units.

Next, this acid stress is confronted with the buffer range hierarchy outlined in Table 3. As long as the carbonate buffer range has not been depleted, the pH is kept constant. For the silicate and cation exchange buffer range the following relation holds:

$$BC_{i,t}^{ce} = BC_{i,t-1}^{ce} - (as_t - br^{si}) \qquad (6)$$

with BC^{ce} = buffer capacity in the cation exchange range
br^{si} = buffer rate in the silicate buffer range

For acidity ranging between a pH value of 5.6 and a pH value of 4.0, a non-linear relationship is assumed between the remaining buffer capacity, expressed as percentage of the total buffer capacity, and the silicate, cation exchange and the upper aluminum buffer ranges [13]:

$$pH_{i,t} = 4.0 + 1.6 \, (BC_{i,t}^{ce}/CEC^{tot})^{3/4} \text{ for } pH_{t-1} \geq 4.0 \qquad (7)$$

where pH = measure for acidity (see note 6)
CEC^{tot} = total cation exchange capacity

Once the buffer capacity of the cation exchange range is depleted the aluminum buffer range is simulated to meet equilibrium assumptions between the concentrations of aluminum ions and hydrogen ions. The simulation takes into account the soil thickness, the water contained in the soil layer and the net annual precipitation. Specifying all the equations involved is outside the scope

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of this paper. (Details can be found in [11].) The final equation can be summarized as follows:

$$[H^+]_{i,t} = C_1([H^+]_{i,t-1})^3 + C_2[H^+]_{i,t-1} + C_3(as_{i,t} - br^{si})$$
$$- C_4([H^+]_{i,t})^3 \quad \text{for } pH_{t-1} < 4.0 \tag{8}$$

with $[H^+]$ = concentration of the hydrogen ions
C_1, C_2, C_3, C_4 = constants involving water volume, net precipitation and an equilibrium level at which aluminum may be dissolved or precipitated.

By substituting equations (5) and (6) into equation (7) the soil acidification at time t is computed under the condition that the soil acidity at time t-1 was greater than or equal to 4.0. Otherwise the soil acidification is simulated using equation (8). This equation can be solved recursively.[8] The simulation is done for every grid square and soil type in Europe.

II.4 The Lake Acidification Submodel

The lake acidification submodel consists of four modules for meteorology, hydrology, soil chemistry and lake acidity. Thi submodel is described in detail in [10]. The simulation is done for a monthly time step finally resulting in an average spring- and summer-acidity level for each year. Since a detailed mathematical description of each of the modules is outside the scope of this paper, only the purpose of each of the modules is described.

The meteorologic module determines the precipitation and the sulfur deposited on the area considered to be relevant for describing waterflows to the lake area concerned. This area is called the terrestrial catchment area.

Total precipitation, divided into rain and snow using threshold temperatures, is computed in order to determine the part of sulfur deposition that is accumulated in the snowpack and the part that is released in the snowmelt. The final output variable of this module is the acid stress:

$$as_t = D^{tot} - D_t + D_t \tag{9}$$

with as = acid stress
D^{tot} = total sulfur deposition
D^s = deposition accumulated in the snowpack
D^m = deposition released from the snowpack.

This variable is used in the soil chemistry module. For this purpose a description is needed of the flows of rain and snowmelt water towards the lake. This is done in the hydrologic module. In this module, the catchment area is vertically segmented in two soil layers, called the A- and B reservoirs. The A reservoir is defined as the upper 0.5 meter soil layer. Physically, the flow from the upper reservoir can be thought of as quickflow, which drains down the hillsides and enters the brooks directly. A part of the content of the A reservoir enters the B

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[8]In fact $C_1 = C_2 \times C_4$ so that recursion can easily be implemented. The final third order equation may then be solved using Cardanno's rule resulting in a single real root for the concentration of hydrogen ions.

reservoir. This depends on the percolation rate, the water volume in the A reservoir and the space left in the B reservoir. The latter reservoir provides the baseflow coming from deeper soil layer [5]. The rate with which the water is discharged from the B reservoir to streams and lakes is limited by hydraulic conductivity, surface slope, soil moisture, catchment width and terrestrial catchment area. The volumes of A- and B reservoir are used in the soil chemistry module to compute the acid stress within the two reservoirs. The soil chemistry module resembles equations (5) to (8) with the difference that two soil layers are used. The acid stress in the A layer is defined by equation (5) while the acid stress in the B-layer is defined as a function of both the acid stress in the A layer and the percolation rate from the A to the B reservoir.

The final output of the soil chemistry module is the quantity of acidity and the quantity of alkalinity. Alkalinity expresses the total buffer capacity of the lake water. In the lake module the output variables of the soil chemistry module, are used to compute the concentration of H^+ ions. The results presented to the user of RAINS are average pH levels in the spring and in the summer. In the remainder of this paper the outcome of the lake submodel will have the following notation:

$$[H^+]w, t = \quad \text{lake } H^+ \text{ concentration in season w (summer or spring) of year t} \qquad (10)$$

III. Multiple Objective Decision Making in RAINS

In order to tackle environmental problems in general, a multidisciplinary approach is most appropriate [4]. As illustrated by the discussion of the RAINS model above, the acidification problem is multidisciplinary; economic, energy and environmental aspects must be modeled. The use of multiple objective decision making (MODM) in a multidisciplinary context is not new [14]. Such an application of MODM using the RAINS framework is suggested below. The approach is under development within RAINS and consequently the following discussion is tentative.

Variables and indicators modeled with RAINS that may be of interest to the decision makers (DM) include;

$S_{k,t}$ = sulfur emissions in country k at year t (equation (2))
$R_{k,t}$ = the emission reduction in country k at year t
$C_{k,t}(R_{k,t})$ = the cost of emission reduction in country k at year t (equation (3))
$D_{i,t}^{tot}$ = total deposition in grid square i at year t (equation (4))

$[H^+]i, t$ = concentration of H^+ ions in forest soils of grid square i at year t (equations (7) and (8))
$[H^+]_{w,t}^l$ = concentration of H^+ ions in lakes in season w of year t (equation 10))

Several MODM will be formulated and discussed which used these variables and indicators of economic and environmental impacts. Only a few examples are given; other formulations are possible, especially considering the large temporal and spatial scales of RAINS and the adverse impacts of acid rain in Europe.

Decision making in acid rain abatement can be considered at national,

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bilateral and multilateral levels. At the national level a country considers only its own costs and effects. At the bilateral level a country aims at optimizing its abatement strategy considering deposition and environmental effects in one other country. Finally, a multilateral approach can be taken: all European countries together try to optimize their efforts in order to reach specified deposition and effect levels.

At the national level the objective for a country (irrespective of adverse effects outside that country), could be cost minimization subject to meeting required of national emission standards:

$$\min C_{k,t}(R_{k,t}) \tag{11}$$

$$\text{s. t. } S_{k,t} - R_{k,t} \leq \overline{S}_{k,t}$$

$$R_{k,t} \geq 0$$

with $\overline{S}_{k,t}=$ sulfur emission standard, representing, for example, the 30% reduction agreed to by many countries in 1985.

This optimization problem can be extended by including standards for deposition in (certain areas of) the country and targets for environmental effects:

$$\min C_{k,t}(R_{k,t}) \tag{12}$$

$$\text{s.t. } \sum_i w_i(S_{k,t} - R_{k,t}) a_{k,i} \leq \overline{D}_{k,t}$$

$$\text{or } \sum_i w_i[H^+]_{i,t} \geq \overline{[H^+]}_{k,t}$$

$$R_{k,t} \geq 0$$

with D   =   deposition standard in country k at time t due to
                                     emissions of country k in grid square i of country k.
        $\overline{[H^+]}$ =   soil acidification standard
        w   =   weight representing spatial factors, e.g. vulnerability of
                                     ecosystems

In a bilateral framework the MODM problems can be formulated as:

$$\min C_{k,t}(R_{k,t}) \tag{13}$$

$$\text{s.t } \sum_i w_i (S_{k,t} - R_{k,t}) a_{k,t} \leq \overline{D}_{1,t}$$

$$\text{or } \sum_i w_i [H^+]_{i,t} \leq \overline{[H^+]}_{1,t}$$

$$R_{k,t} \geq 0$$

with 1 referring to the country where the effects in grid square i of emissions of country k are to be reduced.

The most interesting case is the multilateral problem of acid rain abatement. Before formulating some MODM problems, several observations of a technical and political nature will be made. Currently the common policy in

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Europe is a source reduction policy; the Helsinki protocol (see section I) requires a 30% reduction of emissions. An alternative approach would be to aim at targeted levels of deposition (or soil or lake acidification). As mentioned at the outset, such environmental criteria will be difficult to determine. However, the uncertainty of appropriate thresholds will reduce in time with additional research. A drawback of the targeted reduction approach is that for some participating countries the costs of control policies will be much lower than the benefits. Some countries could be unwilling to contribute to better environmental conditions in other countries, if this would imply high costs to them. In fact there are countries where the economic circumstances are such, that one cannot expect substantial investments in pollution control for years to come. Furthermore, one has to consider technological constraints. A country might argue that the structure of its electricity producing sector does not allow a rapid implementation of new (abatement) technologies. In some cases reduction resulting from optimization might be achieved a decade later than required. Altogether these economic, technologic and political observations indicate a difficult environment to negotiate a common European policy for reducing adverse effects of acid rain. A technical way out of this situation could be an agreement that allows for cost sharing via a European fund for the abatement of air pollution. Such a policy would imply abandoning the "polluters pay principle" which is currently generally accepted throughout the continent.

There are many ways to formulate a MODM problem that takes into account the above observations. Two alternative formulations for the international problem are proposed. In the first formulation the target is to minimize the sum of reductions in all countries under two constraints. The first constraint sets upper bounds on deposition levels in a number of selected grid elements. The second constraint represents a European fund for acid rain abatement. The origin and amount of the fund are left open in this formulation. Depending on the selection of target areas the solution of this optimization problem could include a number of countries where no emission reductions are required. To avoid this a lower bound on reductions could be added, either in terms of tonnes of reduction implemented or planned reductions or in money terms (based, for example, on already decided reductions). The MODM formulation of this problem is as follows:

$$\min \quad \sum_k R_{k,t} \tag{14}$$

$$\text{s.t.} \quad \sum_k (S_{k,t} - R_{k,t}) a_{k,i} \leq \overline{D}_{i,t}$$

$$\sum_k C_{k,t} (R_{k,t}) \leq \overline{C}_t$$

$$R_{k,t} \geq \dot{Q}_{k,t}$$

$$R_{k,t} \leq S_{k,t}$$

with D = maximum deposition in grid i
      C = available funds
      Q = reductions already agreed upon

In a second formulation deposition is minimized subject to budget constraints. Several budget constraints can be considered. In the case where countries already have agreed upon reductions the total amount of money

involved in these reductions could be considered as the minimum available budget. In addition to this limit to total European spending there might be a budget per country as well. Governments may state that they cannot spend more than a certain amount above the costs of the already agreed upon reductions. Alternatively a percentage of the gross domestic product might be used as a threshold.

$$\min \; \sum_k \sum_i w_i \, (S_{k,t} - R_{k,t}) a_{k,i} \tag{15}$$

$$\text{s.t.} \; R_{k,t} \le S_{k,t}$$

$$\gamma_k^v C_{k,t} \, (Q_{k,t}) \le C_{k,t} \, (R_{k,t}) \le \gamma_k^u \, (C_{k,t} \, (Q_{k,t})$$

or

$$\beta_k^v \, GDP_{k,t} \le C_{k,t} \, (R_{k,t}) \le \beta_k^u \, GDP_{k,t}$$

with

w	=	weight factors for chosen deposition (target areas i)
$\gamma^u \, \gamma^u$	=	multiplication factors to define lower and upper bounds for country budgets, relating to already agreed upon reductions
GDP	=	gross domestic product
$\beta^u \beta^u$	=	multiplication factors to define lower and upper bounds for country budgets, relating to GDP.

Target function (15) can be simplified by omitting the constants:

$$\max \; \sum_k \sum_i w_i R_{k,t} \, a_{k,t} \tag{15a}$$

The weights w_i can be formulated as a non linear increasing function of the deposition in target areas i. This would invoke larger reductions in areas with originally high depositions. The lower bounds on country budgets are added to avoid that countries with relatively low contributions to depositions in target areas would be assigned zero (or very low) reductions. Although such a low reduction would be optimal in an economic and atmospheric transport sense, it might be undesirable from a political point of view.

In the MODM formulations (14) and (15) deposition levels have been chosen as constraints respectively targets. Alternatively, soil and lake H^+ concentration levels could be used.

In the foregoing objective functions were formulated taking into account uni-, bi- and multilateral policy frameworks. An implicit assumption behind the suggested policy objectives was for these to be evaluated for every time step t. An optimization of the time span within which a policy should be realized was left out of the discussion, since such an addition would not have added to a better understanding of possible policy conflicts as described in this paper. Finally, it should be noted that solutions to some multiple objective policies may be infeasible due to conflicting constraints in bi- and multilateral policy frameworks.

IV. Conclusions

International deliberations on reduction of emissions in Europe until 1985 focussed on SO_2. As of 1985 the second acidifying compound nitrogen oxides

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(NO_x) has been discussed. The model RAINS will be extended by taking into account emissions transport, deposition and effects of NO_x. This will make RAINS more complex, since it is known that a long-range transport model for NO_x cannot easily be translated into a linear source-receptor matrix. It is assumed that negotiations on NO_x reductions might take longer than the rapidly agreed 30% reductions for SO_2. In collaboration with the UN Economic Comission for Europe RAINS will be further developed to a tool which could assist in these negotiations.

The MODM problems formulated in this paper can be extended to include NO_x targets. Also other constraints, like emissions per capita, per km^2 or per PJ energy input will be considered. The introduction of the MODM concept in RAINS can make it a tool that changes its current setup into one that is part of the MODM methods for Progressive Articulation of Preference Information Given [8, p. 102].

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