Environment Protection Engineering

Vol. 32 2006 No. 3

KATARZYNA JUDA-REZLER*

INTEGRATED ASSESSMENT MODELLING OF AIR POLLUTION ON A REGIONAL SCALE

Integrated Assessment Models (IAMs) of Air Pollution were constructed in the ninetieths of the twentieth century as a tool for ambient air and ecosystems quality assessment and management. The IAMs are built as a system of modules, including emission generation, the options and costs of emission control, atmospheric dispersion of pollutants and environmental and/or human sensitivities to pollutants. The modules are linked and include feedback line in the form of an optimisation model. Such an integrated system allows scenario analysis as well as decision support in finding optimal (within objective functions accepted) abatement strategies. This paper outlines the development, structure, capabilities, applications and results of the IAMs for a regional scale.

1. INTRODUCTION

The Integrated Assessment Models (IAMs) of air pollution are developed worldwide in order to build consistent frameworks for the analysis of the emission abatement strategies. They combine scientific findings in various fields relevant to strategy development (economy, technology, data processing, atmospheric and ecological sciences) with relevant databases and mathematical methods. The IAMs comprise modules for current and future emission databases, for emission abatement options and costs, for the matrixes of source–receptor pollutants transition, for matrixes of accepted targets for environmental and/or population health limits/loads and, finally, for an optimisation task. The objectives of IAMs are twofold. Primarily, the impact of the emissions into the ambient air on environment and human health can be assessed by a consistent approach (*scenario analysis mode*). In this mode, the IAMs provide estimates of the costs and environmental/human health benefits of alternative emission control strategies. Secondly, when the targets for environmental/human health to be meet are defined, the costs-optimal allocations of emission reduction in order to achieve specified targets are explored (*optimisation mode*). In most applications, the *cost-effectiveness* scenarios, for which the

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* Institute of Environmental Engineering Systems, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland. E-mail: Katarzyna.Juda-Rezler@is.pw.edu.pl

emission reductions proposed will be justified by actual *environmental* improvements, are looked for. The cost-effectiveness principle aims at the least-cost solution to select given criteria of environmental air quality. This principle implies that more stringent measures are required in ecologically sensitive zones while avoiding over-controls in the areas where the environmental objectives are already met, possibly resulting in an uneven distribution of reduction costs among the emission sources [1]. It is worth mentioning here that the cost-effectiveness principle is essentially different from a *cost-benefit* principle, which allows the severity of emission abatements to be determined by balancing costs between emission control and monetary value of the environmental benefits. There are several reasons why it is difficult to assess the economic damage to society caused by air pollution and the benefits of reducing it. The most important of them is the fact that many of the effects simply have no price tag. For example, there is no price tag of human life or health. Despite this a number of attempts have been made to compare the costs and benefits of various sets of measures. The cost-effectiveness concept is to omit the limitations of the cost-benefit analysis and thus it can be applied in allocating emission reductions as driven by exogenously specified targets for environmental/health sustainability.

The air pollutants are transported with the air mass over long distances, often crossing national borders. The concentration of pollutants and their deposition on the ground in a given area is influenced by a large number of emission sources both from that area and from outside the area. Thus, the strategies for solving air pollution problems have to be – depending on pollutant features, particularly on its atmospheric lifetime – formulated on local, national, regional or global scale. Among IAMs used for regional (continental) applications – the RAINS model [2] developed at IIASA (International Institute of Applied Systems Analysis) is the most important. The RAINS-Europe models have been used in several policy contexts to identify cost-effective allocations of emission reductions in a particular country and to meet European environmental policy targets. An extension of that model, namely the RAINS-Asia IAM for acidification, has been implemented in Asia [3]. As the RAINS model operates in computation grid covering Europe with the grid of coarse resolution (150 km × 150 km), in some countries, including Poland, national IAMs were developed or are currently under development [4], [5], [6]. National IAM computations are performed at a much finer resolution, such that country specific environmental targets could be included as well as specific emission sources could be identified for abatement. The IAMs were also applied in international projects developed for specific areas in Europe, e.g., for implementing abatement strategies in the heavily polluted *Black Triangle* region of eastern Europe, i.e. the region within the boundaries of Poland, Germany and the Czech Republic [7]. Finally, based on the highly successful IA techniques used for transboundary air pollution in Europe and in Asia, the Urban Scale Integrated Assessment Model (USIAM) has been developed to assist in urban air quality management [8].

The IAMs differ in the scale of their implementation, the number of pollutants concerned and their effect, the target levels/loads accepted, their stringency and the methods of computation, the methods for computing the source–receptor matrices, the methods for calculating the abatement cost curves, and, finally, the methods for optimisation calculations. This paper deals with the methods applied in the regional IAMs, as well as with their goals, applications and results.

2. THE INTERNATIONAL AGREEMENTS FOR AIR POLLUTION PROBLEM

International abatement strategies adopted to control air pollution have been formulated since 1985, when the first protocol for the Convention on Long-Range Transboundary Air Pollution (LRTAP) of the United Nations Economic Commission for Europe (UNECE) was signed. This was the so-called First Sulphur Protocol. This one, and two following protocols for the LRTAP convention – Nitrogen (1988) and Volatile Organic Compounds (VOCs, 1991) – consisted of fixed obligations for controlling emissions derived exclusively on the basis of technical and economic aspects, covering specific types of installations or activities. Such strategies had no direct *quantitative relationship* with the level of air pollution and its effects. Thus, the main motivation for the regional IAMs development was to include the risk that the receptors (e.g. forest, arable land, lakes, human health) will be affected by pollutant in the abatement strategies. The first protocol, formulated based on the results of the IAMs computations and signed in 1994 in Oslo, addressed a single pollutant (sulphur) and a single effect (acidification). This was the so-called *Second Sulphur Protocol*. In 1999, the so-called *multi-pollutant–multi-effect* protocol was signed in Gothenburg. It addresses the emission of SO_2, NO_x, NH_3 and VOCs simultaneously, while considering multiple *ecological* effects, i.e., acidification (by sulphur and nitrogen), eutrophication (by nitrogen) and the formation of tropospheric ozone (by NO_x and VOCs). The scientific support to this protocol required the computation and mapping of multiple critical thresholds (above which a damage may occur), i.e., the critical loads necessary for acidification and eutrophication and critical levels for ozone [9]. By definition, the critical loads (CL) indicate annual levels of the pollutants deposited, and critical levels (CLev) indicate an annual mean concentration of pollutants in ambient air (or exposure to them, e.g. AOT40/AOT60 for ozone), which are sustainable without causing adverse effects. Additionally, the scientific support required computation of source–receptor matrixes for all the pollutants mentioned as well as optimisation of abatement strategies in order to recognize cost-effective European emission reduction strategy which does not allow the critical thresholds of targeted pollutants to be exceeded. In the protocol of 1994, the so-called “gap-closure” approach to the reduction of sulphur deposition was introduced and applied also in 1999 protocol to other pollutants/effects. Because of different sensitivity of species to pollutants, the CL and CLev values vary greatly within Europe and are often unattainable, even by applying the maximum feasible reduction (MFR scenario). Thus, in a majority, the IAMs are searching for the cost-effective abatement strategy, which allows the critical values to be reduced.

3. REGIONAL INTEGRATED ASSESSMENT MODELS

3.1. THE RAINS MODEL

The RAINS (Regional Air Pollution Information and Simulation) model was developed at IIASA as an integrated assessment tool to assist policy advisors in evaluating options for reducing acidification in Europe (see, e.g., [2]). Until today the model has been extended in order to include other pollutants and their effects. At present RAINS takes account of six pollutants: SO_2, NO_x, VOC, NH_3, primary PM2.5 and primary PM10-2.5 (the so-called coarse PM). It can be used to identify the cost-minimal combination of emission control meeting user-supplied air quality targets, taking into account regional differences in the costs of emission control and atmospheric dispersion characteristics [10].

The implementation of the RAINS model integrates emission databases for 38 regions in Europe. The time horizon extends from the year 1990 to the year 2010. For emission control options and costs, the RAINS model recognizes a limited list of characteristic methods of emission abatement for each of its application areas (e.g., the categories of emission sources). The databases on emission control costs have been constructed on the basis of the actual operating experience of various emission control options documented in a number of national and international studies. For sulphur and nitrogen compounds the atmospheric transfer matrices are calculated based on source–receptor matrices derived from a Lagrangian model of long-range transport of air pollutants in Europe, developed by the Cooperative Programme for Monitoring and Evaluation of LRTAP Convention (EMEP). In order to capture the interannual meteorological variability, the model runs have been performed for 11 years (1985–1995); for each of these years the transfer of pollutants from sources (aggregated to entire countries) to each of the grid element (150 km × 150 km) of the computational grid covering Europe was calculated. These annual source–receptor matrices were averaged over 11 years and rescaled to provide the spatial distribution of one unit of emission. For ozone, the RAINS model expresses changes in long-term levels at a given receptor site (over a six-month period) as a function of the precursor emissions (NO_x and VOCs). Most of the ozone models are highly sophisticated and contain a huge number of details about chemical mechanisms and meteorological factors relevant to ozone formation; in consequence, their computational complexity makes it impossible to use them directly within the framework of the IAM. Therefore, in describing ozone formation, the RAINS model uses a 'reduced-form' model derived by a statistical analysis of a large sample of scenarios calculated with the comprehensive EMEP photooxidants model. The reduced-form model captures the response of the regional long-term ozone levels expressed by AOT40 and/or AOT60 to the changes in annual emissions of the precursor emissions of NO_x and VOC in the European countries [1].

Next the RAINS model incorporates databases of critical loads and critical levels compiled in the Coordination Center for Effects (CCE) at the National Institute for Public Health and Environmental Protection (RIVM) in the Netherlands [9]. The *gap-closure* approach is applied to formulating the environmental targets.

Finally, in the RAINS model, three solvers of optimisation problems are applied, namely CFSQP, CONOPT and MINOS [11]. CFSQP implements two algorithms based on sequential quadratic programming (SQP): monotone linear search and non-monotonic linear search. CONOPT is based on generalized reduced gradient (GRG), optimised for sparse matrices. MINOS, the most general of them, uses separate approaches for linear optimization (primal simplex method), for optimization with non-linear target function (GRG coupled with Newton method) and for non-linear target function with non-linear constraints (projected augmented Lagrangian algorithm, where the non-linear constraints are locally replaced by linearized ones for each single step).

Optimisation results of the RAINS model were used to conduct international environmental negotiations for the LRTAP Convention, i.e.: the Oslo (1994) [12] and the Gothenburg (1999) [2] Protocols as well as the EU's Directive on National Emission Ceilings from 2001 [1].

An extension of the RAINS-Asia IAM to acidification was implemented in Asia [3]. The model addressed a single pollutant (SO_2) and two effects (acidification and impact of ambient SO_2 on health). The optimisation mode of the RAINS-Asia model was used to identify cost-effective emission control strategies that achieve single (deposition or concentration) or combined (deposition and concentration) targets at least costs. The scenarios with combined targets were found to be attractive. The combined scenario reduces not only ambient SO_2 concentrations below the WHO guideline value (for additional 22% of Asian population), but at the same time also the area of ecosystems unprotected against acidification. This reduction reaches 60% compared to that recommended by a current legislation scenario. Although the cost of this scenario is approximately the same as the cost of reducing the emissions in Asia to the level of emissions in 1995 (and amounts to only 37% of the cost of a full implementation of the best available control technologies), the environmental effects are much stronger.

In 2004, the RAINS model undergoes extensive review procedures in order to establish its scientific credibility and to determine its fitness for the purpose of policy analysis in the context of the EU's Clean Air for Europe (CAFE) programme. The main goal of the IAM under CAFE programme was to perform scenario analysis of the *human health impacts* of the ozone and PM2.5 emissions into ambient air. According to RAINS computations current levels of these pollutants cause severe health impacts in the EU, resulting in some 370,000 premature deaths each year. Additionally, there is a widespread and significant damage to ecosystems, agricultural crops, modern materials, and cultural heritage. In the year 2000, the annual cost of the impact that PM2.5 and ozone have on human health was estimated to be between 276 and 790 billion euro [13].

3.2. OTHER MODELS

During preparations of the Oslo Protocol for the LRTAP Convention, besides RAINS, two other regional IAMs were used. These include the Abatement Strategies Assessment Model (ASAM) developed at Imperial College of Science, Technology and Medicine in London, UK, [14] and the Co-ordinated Abatement Strategy Model (CASM) developed at the Stockholm Environment Institute in York (SEI-Y), UK [15].

Despite the fact that the three models contributed to the negotiation process, each submitting results for all the scenarios requested, the final agreed strategy was generally certified to the RAINS model. As the RAINS model was developed at an international institute, unlike the two other models, it was not seen as being subject to the influence of an individual party on the Convention. The structure of each of the three models is almost identical, differences between them lie in some of the data sources and the approaches offered for optimising abatement strategies. The data sets involved are the same; moreover, each model requires that input data are linear. Effect-oriented cost-effective SO_2 emission reduction strategies were explored using linear programming optimisation techniques.

The CASM model is not in operation any more. The ASAM model has been substantially adapted to address the multi-pollutant, multi-effect problem. Simultaneously, the extensive work was undertaken with ASAM model to address uncertainties in integrated assessment modelling [16], [17]. Much of the uncertainty analysis undertaken with ASAM conforms with the principles of a systematic risk assessment. The uncertainties study demonstrated a large degree of robustness of derived abatement strategies to uncertainties in the IAMs input data sets: critical loads, meteorological data and abatement cost information.

4. SUMMARY AND CONCLUSIONS

A great deal of information have to be considered in policy-making process concerning the air pollution problems, thus Integrated Assessment Models have been developed as one way to link this information. The IAMs without doubt contains many uncertainties and assumptions in the data used and in the modelling itself. Moreover, the emission controls suggested in an optimised scenario of IAMs are critically determined by the economic, demographic and environmental situation in an area under consideration as well as by the type and stringency of an accepted environmental/human health targets. Nevertheless, the results obtained are showing the way for finding the cost effective emission reduction strategies which are targeted for protecting human health and vegetation from adverse effect of air pollutants. Currently, the strategies for multi-pollutant–multi-effect issue are addressed by regional scale IAMs. However, as regional models are operating in computation grid with coarse resolution, and thus they contain necessary simplifications, the *national IAMs* should be developed. They could incorporate country specific conditions and provide support for national evaluation of European emission reduction strategies. Since such integrated modelling is quite complex and requires a sound scientific contribution, these activities should be encouraged and supported by sufficient national resources.

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ZINTEGROWANE MODELOWANIE OCENY ZANIECZYSZCZENIA ATMOSFERY W SKALI REGIONALNEJ

Komputerowe modele zintegrowanej oceny zanieczyszczenia atmosfery (*Integrated Assessment Models*, *IAMs*) zaczęły powstawać na początku lat dziewięćdziesiątych ubiegłego stulecia jako narzędzia wspomagania decyzji w procesie zarządzania jakością środowiska. Systemy IAM łączą modele emisji zanieczyszczeń, rozprzestrzeniania się zanieczyszczeń w atmosferze, wrażliwości poszczególnych elementów środowiska i zdrowia ludzkiego na zanieczyszczenia, opcji ochronnych i kosztów redukcji emisji z modelem optymalizacji. Systemy IAM umożliwiają nie tylko ocenę stanu zanieczyszczenia środowiska i wynikających z niego zagrożeń, ale także wybór optymalnych – pod względem kosztów – strategii redukcji emisji zanieczyszczeń, zorientowanych na poprawę stanu środowiska przyrodniczego i ochronę zdrowia ludzi. Artykuł przedstawia rozwój, strukturę, możliwości, zastosowania i wyniki modeli zintegrowanych opracowanych dla skali regionalnej (europejskiej).