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Integrated assessment models—tools for developing emission abatement strategies for the *Black Triangle* region

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Abstract

International agreements to reduce the long range transport of air pollutants have usually consisted of fixed percentage reductions in the emissions of the signatory countries. Clearly the sensitivity of different ecosystems to certain pollutants varies widely across Europe and so it follows that a more cost-effective way of minimising environmental damage is by selectively reducing the emissions in certain countries and regions. To this end integrated assessment models where used to help formulate the second sulphur protocol [UN–ECE EB.AIR/R.84, 1994] which derived cost-effective strategies for reducing SO_2 emissions from coal-fired power stations across Europe. In this current work similar methodologies where used to derive abatement strategies for the heavily polluted *Black Triangle* region of eastern Europe, i.e. the region contained along the mutual borders of Poland, Germany and the Czech Republic. This work was performed at a much finer resolution than that used during the UN–ECE work, such that specific emission sources could be identified for abatement. The integrated assessment models developed for this work used either critical loads maps, land use maps and population data to identify the ecosystems and people most exposed to air pollution. The models where developed so as to be fully integrated within a geographical information system (GIS), so that data inputs and model results could be easily analysed and displayed. Such a system provides a means whereby policy makers can easily

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devise and compare emission abatement strategies for the *Black Triangle* region.

Keywords: Air pollutants; Ecosystems; Emissions

1. Introduction

Integrated assessment models (IAMs) provide a framework for bringing together disparate information related to a particular environmental problem. As used during the development of the second sulphur protocol this included data on source emissions, atmospheric dispersion and deposition, the capacity of the ecosystem to sustain certain levels of deposition, namely critical loads, and the cost of abating emissions which where represented by national cost curves. Under the UN–ECE work the spatial resolution for much of the input data was 150 km × 150 km, which means that an area such as the heavily polluted *Black Triangle* would be covered by only a few squares. Clearly an area of such strategic importance to the overall success of the protocol required a further study performed at a much finer spatial resolution. As part of the Emission Abatement Strategies and the Environment (EASE) project two IAMs where developed for the *Black Triangle* region, namely Pollution Risk Integrated Model Assessment (PRIMA) [1,2] designed at Warsaw University of Technology and black Triangle Integrated Assessment Model (BTIAM) designed at Imperial College, London. Unlike the sulphur protocol which used national cost curves and aggregated emissions, the IAMs used in this work derived cost-effective abatement strategies which identified individual emission sources for abatement. Moreover, the models made no attempt to derive abatement strategies for the whole of Europe but only to protect the ecosystems within the *Black Triangle*.

Much of the input data and results generated by the IAMs could be displayed and manipulated using maps, showing for example patters of deposition before and after a particular abatement strategy was put in place. Consequently one of the IAMs, namely BTIAM, was itself nested within a GIS (Arc/Info) and a graphical user interface was developed to allow the user to select IAM model parameters, 'map algebra' and displays. Control could be passed from the GIS to the IAM and vice versa automatically, with the interface being intuitive so that a user need have no prior experience of GIS. Such a system would provide a means whereby policy makers could easily devise and compare emission abatement strategies for the *Black Triangle* region.

2. Integrated assessment models developed under the EASE project

2.1. BTIAM

The methodology of BTIAM is similar in many aspects to the ASAM model [3], which was used to help formulate the second sulphur protocol. BTIAM uses critical loads as the ideal deposition that the models should try to attain. It follows then that an *environmental benefit:cost* ratio can be defined simply as a measure of whether the critical loads have been achieved compared to the cost of implementing the abatement measure. In some cases it may be considered that attaining a deposition equal to the critical loads is unrealistic, in which case target loads are used and this provides a practical way of agreeing an intermediate step towards attaining the stricter critical loads some time in the future.

BTIAM can be used for optimised and scenario analysis. In the case of optimised analysis the model takes each source in turn and interrogates the emission control options database to identify the emission reduction and cost of the next available control option. The abatement options are then implemented, and with reference to the source–receptor matrix, a new deposition field is calculated for each source. The *environmental benefit:cost* ratio is then calculated by assuming that the benefit derived from a reduction in the emissions from source i reflects, in a linear sense, the corresponding change in deposition Δd_{ij}, at any receptor j, and the associated contribution that this makes to reducing the overall deposition D_j

$$\text{Benefit}(i) = \sum_{j=1}^{\text{no. of cells}} \frac{D_j - \Delta d_{i,j}}{\text{cl}_j} \tag{1}$$

where cl_j = critical or target loads for receptor j.

The *environmental benefit:cost* ratio is calculated for each model cell and for each source. The source that produces the highest *environmental benefit:cost* ratio is selected, and its associated control option implemented to produce a new deposition field. The additional cost of the abatement option is added to the running cost. A new source–receptor matrix is then calculated to take into account the reduced contribution that the abated source makes to the total deposition at each cell. The process is then repeated until all the critical or target loads are attained or until the total money available, which is set as initial input to the model, is exhausted.

In the case of scenario analysis the model uses current or predicted reduction plans, with a fixed cost, to calculate new exceedances of the critical or target loads. If required these results can then be compared with the depositions and exceedances obtained from an optimised analysis using the same expenditure. This would indicate whether the optimised analysis suggests any particular strategy which might be advantageous.

2.2. PRIMA

PRIMA can also used for both optimised and scenario analysis and although there are broad similarities in both models, the underlying approach used by PRIMA is different from that adopted by BTIAM. PRIMA allows the policy makers to decide which environmental receptors to protect. Based upon these receptors different model indicators can be used as well as different objective functions for the optimisation model. Taking into account the air pollution problem in the *Black Triangle* region, PRIMA attempted to minimise the exposure to both populations and ecosystems. The model evaluated a population risk level based on the product of SO_2 concentrations and population density. The risk to ecosystems was evaluated through an *area valorisation index*, which estimated a region's sensitivity to pollution based on UN–ECE guideline values for critical levels of SO_2 [4]. The different land classifications given in the land use maps of RIVM provided the source information for the area valorisation index.

3. Model input data

3.1. SO_2 emission source inventories

The official emission inventory for the Czech Republic is given in the REZZO database. There are four main categories in this database, which are: large and medium sized combustion installations (boilers and technology furnaces) with thermal output greater than 5 MW and important industrial plants (REZZO-1); smaller stationary sources with a thermal output between 0.2 and 5 MW as well as other individually monitored industrial plants (REZZO-2); small stationary sources with a thermal output below 0.2 MW (REZZO-3) and mobile sources (REZZO-4). Both PRIMA and BTIAM used data from the REZZO-1,2,3 corresponding to the modelling base year of 1992.

The 1992 emission inventory for Poland came from a database supplied by the Air Pollution Control Department based at the Warsaw University of Technology. There are several categories in this database which includes: public power generation; industrial energy generation and industrial production processes; the municipal sector; small industry and agriculture.

A gridded (10 km × 10 km) emission inventory for eastern Germany was also supplied for the purpose of this work.[1]

3.2. Initial deposition fields and source–receptor matrices

Atmospheric dispersion and deposition models used the emission inventories described above, together with meteorological data from the modelling base year, to provide sulphur deposition maps as input to the IAMs. An Eulerian model POLSOX [5], developed at the Technical University of Warsaw, provided input to PRIMA, whilst a Gaussian puff model DEPOZ [6], developed at Charles University Prague, provided input to BTIAM.

Both models used a source–receptor matrix which was calculated by DEPOZ and defined the annual deposition and air concentration of sulphur at each of the model grid squares *(receptors)* from each emitter *(source)*. The source–receptor matrix in effect represented a 'blame matrix', as it listed the percentage contribution that each source makes to the total deposition and air concentration at each receptor cell. It was assumed that a reduction in emissions from a source would produce a linear reduction in the deposition and air concentrations at the receptor. Thus by reference to the 'blame matrices' the reduction in deposition, resulting from the abatement of a particular source, could be integrated across the model grids.

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[1] R. Friedrich, personal communication, 1995.

3.3. Critical loads and target loads

Critical loads maps of sulphur for the Czech Republic and Poland were provided by the Czech Environmental Institute, and the Institute of Ecology of Industrial Areas respectively. In the case of the Czech Republic a mass balance approach [7] was used to generate a 5-percentile sulphur critical loads map, i.e. where all but the most sensitive 5% of ecosystem area is protected. The critical values of weathering where derived from the Olsson and Melkerud relationship [8]. The results were originally processed on a 37.5 km × 37.5 km subgrid of the European Monitoring and Evaluation Programme (EMEP) projection which had been converted, using GIS, to be consistent with the 10 km × 10 km grid resolution of the IAM grid. In some areas of the Czech Republic critical loads had not been calculated due to insufficient soil chemistry data, in such cases intermediate critical loads values were assigned to these regions.

Similarly for Poland, the mass balance approach was used to derive 5-percentile critical loads maps for sulphur. Critical loads values for elevated sites were calculated in accordance with Sverdrup [9]. The results were originally processed on a longitude/latitude grid of 0.2° × 0.1° resolution which was converted, once again using GIS, into the EASE IAM model grid projection.

3.4. Emission control options and costs

Emission control options and their associated costs were compiled for the Czech Republic and Poland [10]. The data generated was based on the emissions from power stations, district heating plants, refineries and other industrial. Parameters such as load factor, fuel sulphur content and boiler size where obtained [11] and these data were used to calculate a theoretical emission for each source. In the case where the calculated emission differed from the observed, the load factor or sulphur content of the fuel was adjusted so that the SO_2 emissions were consistent. In this way the abatement costs could be calculated directly with reference to existing databases.

Costs of the different abatement strategies, such as coal washing, fuel switching, flue gas desulphurisation, etc. were achieved using cost function values [12] as well as data for refineries [13]. These functions include terms for economics of scale, so that abatement technologies for larger plant were more cost-effective. In addition, abatement technologies were applied on a ‘per boiler’ basis and in this way large plants comprising of many small boilers would receive the correct economy of scale. Power stations, district heating plants and refineries were fed individually into the database which produced a list of economical technologies available to that source.

Specific abatement scenarios could be examined using the same costing procedure as that described above, however, in this case all the emission sources and fuel types (e.g. coal, natural gas, nuclear power, etc.) from Poland, the Czech Republic and Germany were included. The scenarios that could be considered include:

(i) *base case*: in which no new plants were constructed and all existing plants were taken at 65% load factor;

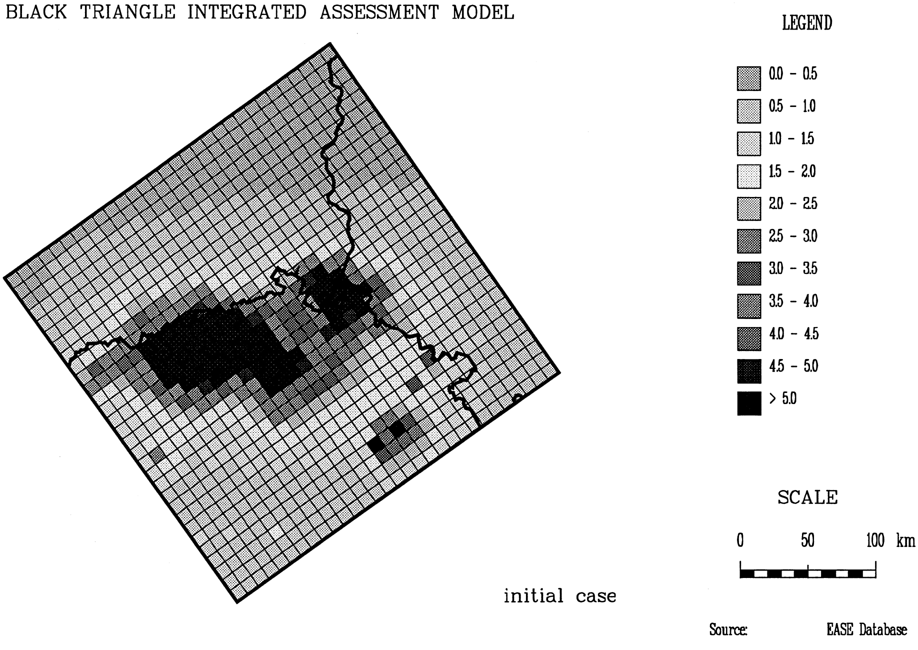
(ii) *business as usual*: a 20% increase in energy demand was predicted over the base year for the year 2010;

(iii) *fuel switching*: the demand for natural gas was increased by 20%, whilst demand for other fuels was reduced pro rata to be consistent with (ii) above. In addition, plants which were currently multi-fuel were changed to burn natural gas;
(iv) *energy efficiency*: which gave a 10% increase in energy efficient practices over the base year for the year 2010; and
(v) *relocation*: where energy demand inside the study area is reduced to 70% of the business as usual scenario, whilst demand outside the study area is increased pro rata to be consistent with (ii) above.

Combinations of the above scenarios are made if the particular characteristics of two or more were required. In addition, 'new emission plants' can be introduced to meet the difference between supply and demand as well as to account for the closing of old plant.

4. An illustrative example of a model run

To illustrate the type of strategies devised by IAMs, BTIAM has been used here to perform an optimised reduction of SO_2 depositions from the 1992 base case level. A map showing the predicted sulphur deposition, resulting from 1992 emissions is given in Fig. 1. In this example, the target loads are taken to be equivalent to the critical loads. As a measure of the cost-effectiveness of the optimised analysis the model will calculate



Source: EASE Database
created by BTIAM / GUI 1997

Fig. 1. Model predicted sulphur deposition resulting from 1992 emissions.

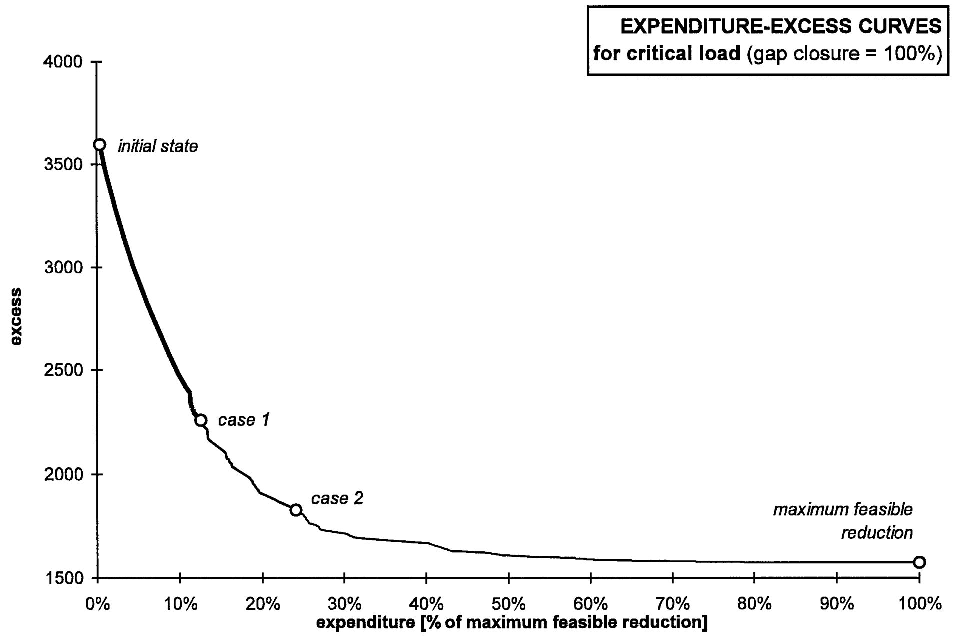


Fig. 2. *Exceedance–expenditure* graph resulting from an optimised reduction of 1992 emissions.

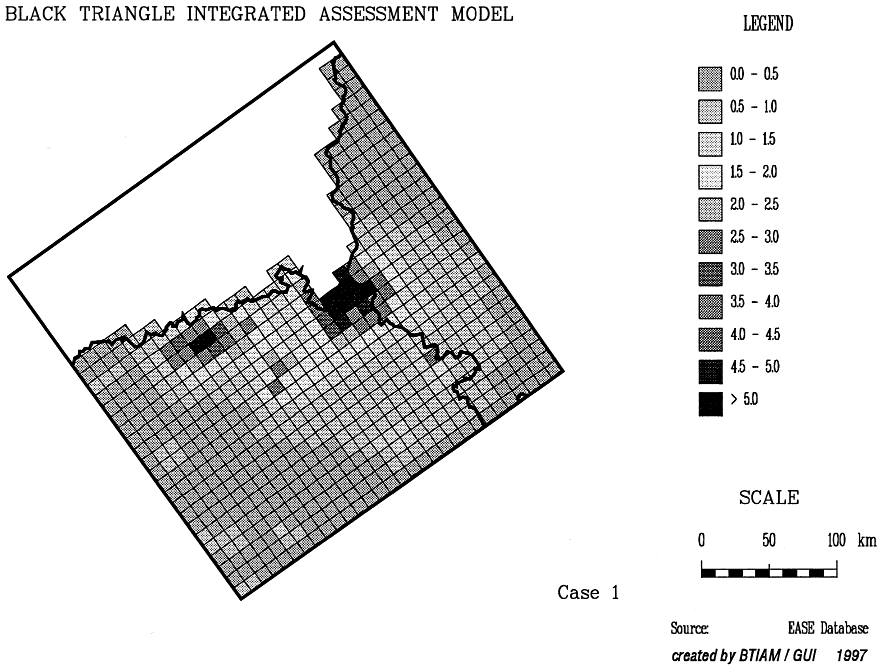


Fig. 3. Predicted sulphur deposition following an expenditure of 200 million ECU, 68% of the maximum feasible reduction.

the total exceedance of critical loads across the model domain, relative to expenditure. Clearly exceedance is given by:

$$\text{exceedance} = \sum_{j=1}^{\text{no. of cells}} \max\left(0, \frac{D_j - \mathrm{cl}_j}{\mathrm{cl}_j}\right) \tag{2}$$

Fig. 2 gives the *exceedance–expenditure* graph for this model simulation and shows a rapid improvement in the environment as initial cost-effective abatement strategies are phased in. The rate of environmental improvement reduces as the model approaches diminishing returns for excessive expenditure. In this example the initial exceedance function is 3696, summed over Poland and the Czech Republic. From the cost curves the maximum feasible reduction (mfr) is reached at an annualised cost of 1660 million ECU, producing a much reduced exceedance of 1576 units. However, *case 2* shows that with a much lower investment of only 24% of the maximum, equivalent to 400 million ECU, an exceedance value of 1832 units is attained which is 88% of the mfr. An even more modest investment of 200 million ECU, which is 13% of the maximum possible investment, will produce an exceedance value of 2260 units, which is 68% of the mfr, which represents *case 1*. The resulting deposition fields resulting from the implementation of cases 1 and 2 are given in Figs. 3 and 4, respectively. It should be noted that deposition fields, and abatement strategies for Germany have not been evaluated due to the lack of input data from this country.

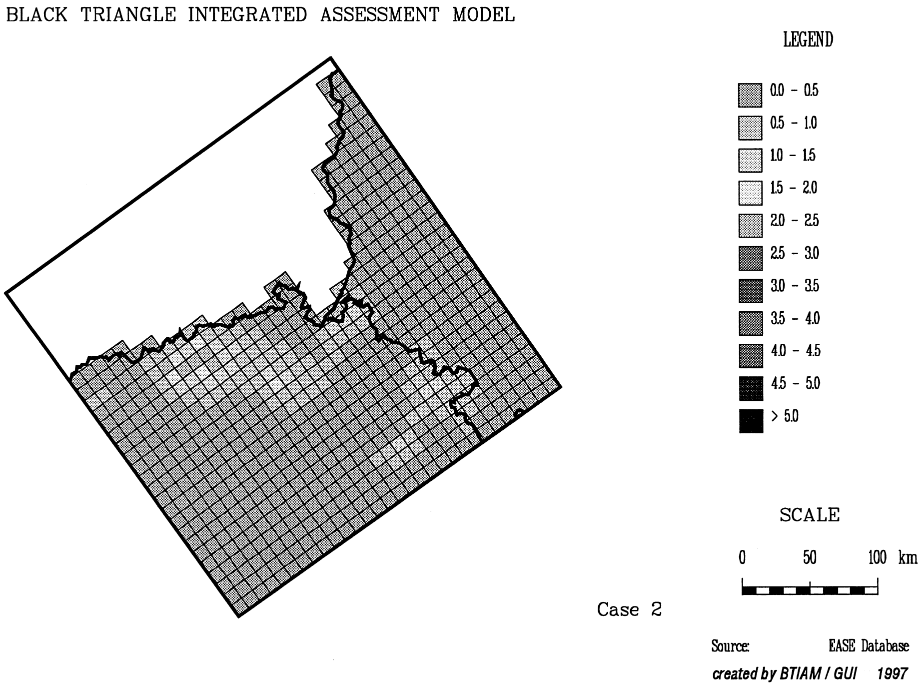


Fig. 4. Predicted sulphur deposition following an expenditure of 400 million ECU, 88% of the maximum feasible reduction.

5. Model sensitivity

Test have shown that the model results can be very sensitive to the geographical area covered by the model domain. In the above example, abatement strategies where derived for sources (s_i) that were within the *Black Triangle* region as well as those sources (s_o) that were outside the region but contributed to the region's deposition field. By extending the model domain to include the s_o sources the abatement strategies changed as emphasis now shifts to reducing localised pollution problems.

The model was also sensitive to the cost curves data, and in particular the dependence of abatement costs on the time of implementation as well as the lifetime of the emission source. The model's sensitivity to cost curves is not unexpected and underlines the need to produce a detailed study of the abatement options.

6. Conclusion

This paper has described how IAMs may be used to draw together disparate information necessary to address a particular environmental problem. Although the models developed for this work were used to formulate abatement strategies for a particularly polluted region of Europe, there is no reason why similar methodologies could not be used to address any number of environmental problems. Moreover, when the IAMs are nested within a GIS, as in this case, such integrated systems have the ability to manipulate, overlay, and display a wide range of thematic datasets. This allows populations and ecosystems that are most at risk to be easily identified. Moreover, such systems can provide a means whereby policy makers can easily devise and compare appropriate environmental strategies.

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