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E. KLIMOVA

MODELLING OF TRANSFER AND IMPACT ON ECOSYSTEMS OF EMISSIONS FROM OIL-SHALE POWER PLANTS IN ESTONIA

Impact of Oil-shale Power Plants on Environment in Estonia

North-East region of the Estonian Republic is one of the most polluted areas in the Baltic Sea surrounding countries. In 1990, stationary sources of pollution (power plants and industrial enterprises in Estonia) let into the atmosphere 610.9 thousand tonnes of contaminants including 302.1 thousand tonnes of solid wastes (ashes, dust) and 308.9 thousand tonnes of gaseous wastes [1]. It is about 80 % of the total air pollution in Estonia. Oil-shale power plants are the biggest atmospheric polluters among all stationary sources of pollution in Estonia (Table 1). The problem is redoubled by the fact that mining of oil shale, its burning at two big power plants and consumption in chemical and construction materials industries are concentrated on the same small area.

Table 1. **The biggest air polluters in Estonia [3]**

Enterprise	Emissions, t/year				
	SO_2	CO	NO_x	Gaseous wastes	Solid wastes
Baltic Thermal Power Plant (TPP)	58,788		5,252	64,040	125,069
Estonian TPP	66,056	6,418	6,852	79,410	53,621
Oil-Shale Chemistry Association	5,559	700	359	13,819	941
Kiviôli Plant of Oil-Shale Chemistry	3,007	1,539	117	7,941	951
Kohtla-Järve TPP	3,394		112	3,506	1,277
Iru TTP	12,061		423	12,485	125

The use of oil shale has created serious ecological problems in Estonia. While oil-shale mining causes damage to water system, forestry and agriculture, emissions from power plants pollute the atmosphere and influence soils, forests and waterbodies through the deposition of air pollutants.

As the result, air quality in towns Narva and Kohtla-Järve is beyond the permissible standard as regards concentrations of volatile ash and dust, sulfuric compounds and phenols. Pollution of the atmosphere influences on human health in this region. Due to pollution from power plants and industry average concentrations of some chemical compounds have increased up to several hundred times on peatfields surface, and up to 10 times in lakes [2]. For example, the concentrations of heavy metals (lead and zinc) at the high layer of soil exceed underground level more than 10 times (200-300 mg/kg) [2].

The low but stable level of pollutants at the atmosphere and their accumulation in soils, pollution of surface water and groundwater are factors which cause damaging of the coniferous forests. At present forest lands cover 40.4 % of the Estonian territory [3]. For assessment of the state of Estonian forests a monitoring network was founded in 1988 covering the whole territory of Estonia. The basic criteria of assessment is preservation of needles of different ages and defoliation level. The results of monitoring indicate that on the whole the trees in the North-East Estonia are most damaged. In this region spruce and pine stands practically preserve only 25 % of 2-years-old needles having dropped all older needles. The concentration of sulfur in the needles in this region is 2-5 times higher than in unpolluted areas. The state of coniferous forest is the worst in areas around the industrial centres of North-East Estonia [4].

So, the research on air pollution from oil-shale power plants is the acute and moderate problem, because:

(i) the great amount of pollutants is emitted from the stacks of power plants into the atmosphere;

(ii) pollutants are carried with the wind to the large distances;

(iii) pollutants mix in the atmosphere and get chemical conversions and consequently the deposition on different plots have different chemical compositions, and correspondingly different influence on ecosystems;

(iv) prolonged deposition of air pollutants from the atmosphere lead to their accumulation in ecosystems and to increasing of the level of degradation in these ecosystems;

(v) sometimes the simultaneous action of several contaminants exert the greater pressure upon ecosystems, than their influence by turns (strengthening affect) [5].

All these facts demonstrate that the ecological situation in North-East Estonia and particularly the problem of air pollution require thorough research.

Therefore the modelling of pollutant production impact on environment in Estonia presents undoubted interest.

Modelling Approach

The main goal of this research is to evaluate long range transport and deposition of all air pollutants (dust, SO_2, SO_4^{2-}, CO, NO_x, heavy metals) from oil-shale power plants and enterprises in the region for different initial conditions (climate parameters, number of sources, emission data) and to estimate the composite loading and influence of these contaminants on the ecological systems (forests, soils, waterbodies). Method of simulation modelling as the main method of system analysis was chosen for this complex ecological problem.

Modelling approach for air pollution problem is widespread in the world. Among the most well-known models are EMEP model (Norvegian Metrological Institute, Oslo), RAINS model of acidification in Europe (International Institute of Applied

System Analysis in Laxenburg, Austria). In Estonia it is The Mathematical Model for Predicting the Atmospheric Pollution State in the Areas of Local and Regional Scale by prof. K. Laigna. Accumulated experience of those researches was very important and gave me a lead towards creating of the model which was named EMEST.

The EMEST model allows to estimate the level of air pollution in Estonia. Characteristics of sulfur pollution are calculated on the first stage of research, and in future it will be included the computation of pollution estimates by nitrogen, dust and heavy metals.

Estimation of the level of pollution includes:
(i) mapping of emissions;
(ii) calculation of the average annual ground level concentrations of contaminants;
(iii) calculation of the average annual dry and wet depositions of contaminants in the region;
(iv) calculation of average annual transboundary transfer of contaminants;
(v) estimation of air pollution influence on the coniferous forests, soils and waterbodies in Estonia.

The originality of modelling approach which was used in the EMEST model consists in application of medium-scale modelling of transport of air pollutans; use of climatic parameters as long-period average data; possibilities to use changing size of grid square, use of some elements of the GIS-approach for the analysis of input data and for the mapping of obtained results.

Later on the EMEST model as universal remedy can be applied for solving air pollution problems in another regions and countries and first of all in Baltic Republics (Latvia and Lithuania).

The EMEST model is realized as program package for IBM-compatible computers. TurboC++ is used as the programming language.

Structure of the EMEST Model and its Submodels

The EMEST model is an interactive set of submodels with graphical output. The framework of the EMEST model consists of three compartments: Data Base, Transport and Deposition Submodel and Environmental Impact Submodel. Figure 1 depicts the conceptual scheme of the EMEST model and its submodels.

The EMEST model is founded on the Data Base. Data Base includes all the initial data which are needed for calculations and subsequent corrections of the results. There are three main information blocks:
(i) nature-climatic characteristics of the region,
(ii) emissions of pollutants (dust, SO_2, CO, NO_x, heavy metals) from points sources (separately for each source),
(iii) air quality measurements in the region towns.

Meteorological data needed for calculations are considered as average values for the region. Data of air quality measurements are used for verification.

Transfer of pollutants from point sources according to medium scale network is realized in the Transport and Deposition Submodel and is founded on the Lagrangian method for medium-scale models. The application of this method means that concentrations are calculated in the moving coordinate system. Application of the

Lagrangian method in modelling allows to obtain enough accurate estimates of deposition and concentrations, and does not demand a long time period for computations [6].

Sulfur emission is considered as portion emitted by point source at the initial moment. Than this portion is studied at the discrete time moments and the interval between them is equal to the time step value. Coordinate system moves together with the portion. Time step must be such a thing in order to do the uninterrupted current of pollution air (Fig. 2). Climatic wind-rose and average velocity of transfer of the pollutants at the atmosphere are used. Consecutive positions of the centre of portion at the dicrete time moments determine the trajectory of portion movement.

The EMEST model covers the investigated region by grid square network with the resolution of 10×10 km^2 for emissions, atmospheric processes and environmental impacts. On my mind, these grid squares size is optimal for the territory of Estonia, but it may be changed easily in the model. All characteristics of pollution in the EMEST model are calculated as average values for grid elements. Hence, the decrease of grid squares size leads to the increase in results accuracy, but to the increase in the computations times as well. All characteristics are additive. Output data are calculated as annual averages. All main equations used in calculations are presented below in this paper. Mapping of results by grid square network is used to demonstrate the spatial distribution of these characteristics through the territory of Estonia. Estimated sum of deposition may be used as the criterium for minimization of emissions.

The output data of the Transport and Deposition Submodel and some information from Data Base are used in the Environmental Impact Submodel as input data.

Environmental Impact Submodel includes the estimation of the impacts of air pollutants on the coniferous forests, soils and waterbodies. First of all, it is supposed to evaluate impact of sulfur on coniferous forests. This part of research is under development now.

Coniferous forests occupy a considerable part of the territory of Estonia. It is established fact that air pollution causes damage forests and forest soils. In this connection it is necessary to consider some important aspects which will be included in the EMEST model.

It is well known that the mechanisms of damage of the forests are based on direct impact of air pollutants on the foliage, and the injurios effects of polluted soils on the root system. But in both cases the damaging effect is determinated by the values of concentrations and depositions of pollutants and by the duration of influence.

In high concentrations (>100 mg/m^3) the foliar effect of SO_2 is easily detectable as a red-broun needles in coniferous trees [7]. At low and moderate concentrations the symptoms of damage develop over a longer period of time. However such concentrations during a long period of time may lead to the considerable damaging of forests. A mechanism of negative impact of the moderate concentrations on ecosystems consists in the effect of accumulative dose [7].

As obtaining of the accurate estimates of sulfur deposition and concentrations and their influence on the coniferous forests is the target for this research, it has been considered necessary to include the filtering effect in the Environmental Impact Submodel. It is known from the literature, that the deposition on a forest area, is ϕ times larger than the deposition on open land [8]. This effect, usually termed the filtering effect of vegetation [9], is a function of the aerodynamic and surface

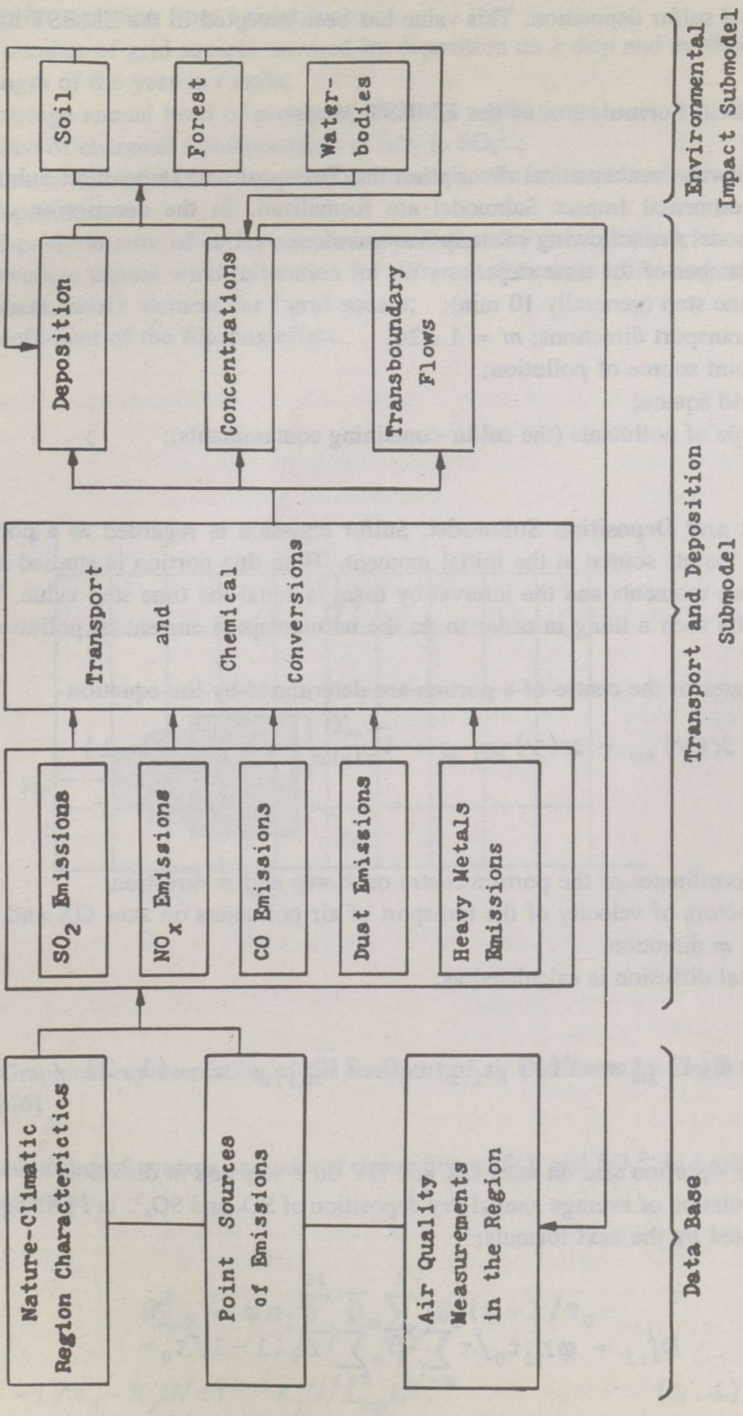

Fig. 1. Structure of the EMEST model and its submodels

characteristics of vegetation [8]. An average factor of $\phi=2$ for total sulfur deposition has been used for the whole of Europe [10]. We assume that in Estonia with high precipitation rates the ϕ value can be, in reality, a little smaller and may be equal 1.8 for total sulfur deposition. This value has been accepted in the EMEST model.

Mathematical Formulation of the EMEST Model

In the following mathematical description the Transport and Deposition Submodel and Environmental Impact Submodel are formalized. In the description of the EMEST model the following subscripts are used:

k - the number of the time step;
t - the time step (generally 10 min);
m - the transport directions; *m* = 1...24;
i - the point source of pollution;
l - the grid square;
j - the type of pollutants (the sulfur-containing contaminants);

Transport and Deposition Submodel. Sulfur emission is regarded as a portion, emitted by points source at the initial moment. Than this portion is studied at the discrete time moments and the interval by them is equal the time step value. Time step must be such a thing in order to do the uninterrupted current of pollution air (Fig. 2).

Coordinates of the centre of a portion are determined by the equation

$$x(y)_{km} = x(y)_{k-1,m} + \overline{V}_{x(y)m} \qquad (1.1)$$

where

$x(y)_{km}$ - coordinates of the portion centre on *k* step and *m* direction;
$\overline{V}_{x(y)m}$ - vectors of velocity of the transport of air pollutants on axes OX and OY, in *m* direction.

Horisontal diffusion is calculated as:

$$X(Y)_{km} = X(Y)_{k-1,m} + 0.2\overline{V}_{x(y)m} \qquad (1.2)$$

where *X(Y)* - portion size on axes OX and OY on *k* step and *m* direction.

The calculation of average annual dry deposition of SO_2 and SO_4^{2-} in *l* grid square are conducted by the next formula:

$$D^{l}_{i,j} = \varphi n_l \tau_0/\tau \sum_{m=1}^{24} \overline{\beta}_m \sum_{k=1}^{k} E_i (1-1/\tau_0 - -1/\tau_j - K_j U/\tau)^{k-1}/L_{km}L^2; \qquad (1.3)$$

where
D^l - average annual dry deposition of sulfur contaminants in l grid square and from i point source;
E_i - sulfur emission from i point source;
L_{km} - number of grid squares covered by deposition on k step and m direction;
τ - length of the year in t units;
U - average annual level of precipitation in the region;
τ_0 - time of chemical transformation of SO_2 in SO_4^{2-};
τ_j - time of life of sulfur-containing pollutants in the atmosphere before dry deposition;
K_j - deposition ratio of sulfur-containing pollutants by precipitation;
β_m - average annual wind reiteration for different directions in mixing layer;
n_l - forest matrix element for l grid square;
φ - coefficient of the filtering effect.

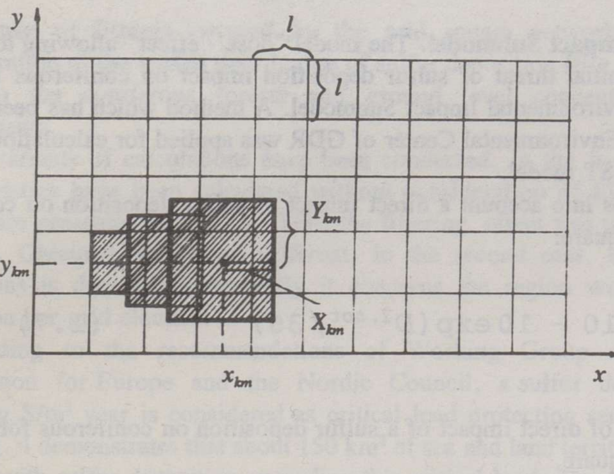

Fig. 2. Graphical representation of the transport of air pollutants by Lagrange method [6]

The estimates of average annual wet deposition of SO_2 and SO_4^{2-} in l grid square are obtained as:

$$W^l_{i,j} = \varphi n_l \sum_{m=1}^{24} \overline{\beta}_m \sum_{k=1}^{k} E_i (1 - 1/\tau_0 - -1/\tau_j - K_j U/\tau)^{k-1} K_j U / L_{km} L^2 . \qquad (1.4)$$

Total sulfur deposition per grid is calculated as:

$$D^{l,tot} = D^l_{i,j} + W^l_{i,j} \qquad (1.5)$$

where $D^{l,tot}$ - total sulfur deposition in l grid square.

The average annual estimate of the ground level concentration of SO_2 and SO_4^{2-} in l grid square is calculated as:

$$C^l_{i,j} = D^l_{i,j} / V_j \tau \qquad (1.6)$$

where

$C_{i,j}^l$ - ground level concentration of sulfur-containing pollutants in l grid square and from i point source;

V_j - dry deposition velocity for sulfur-containing pollutants.

Environmental Impact Submodel. The model "dose - effect" allowing to account the index of potential threat of sulfur deposition impact on coniferous forests is realized in the Environmental Impact Submodel. A method which has been elaborated in the Environmental Center of GDR was applied for calculations of this index in the EMEST model.

This index takes into account a direct impact of sulfur deposition on coniferous forests in l grid square:

$$d^l = 10 - 10\exp(D^{l,tot}/36) \qquad (1.7)$$

where d^l - index of direct impact of a sulfur deposition on coniferous forests in l grid square.

If $d^l >= P$ (P is the threshold value of coniferous forests sensitivity on sulfur deposition), it is considered as dangerous for forest ecosystems. Value of $P = 0.2$ has been used in the EMEST model.

Results

On the first stage of research, the EMEST model has been used for calculations of the characteristics of sulfur pollution and its influence on the coniferous forests in Estonia and the first results have been obtained. Stationary sources of sulfur emissions such as Baltic Thermal Power Plant (TPP), Estonian TTP, Kohtla-Järve TPP, Ahtme TPP, Kiviôli Plant of Oil-Shale Chemistry, Oil-Shale Chemistry Association, has been taken into account.

Estimates of dry and wet sulfur depositions and ground level concentrations of

SO_2 and SO_4, estimate of transboundary sulfur transfer and indexes of the threat to the coniferous forests have been obtained as the results of the model calculations. Some summarized output estimates for the investigated region are presented in Table 2.

Table 2. **Summarized model outputs for investigated region**

Characteristic	Value
Sum of SO_2 emissions	140,197 t S/year
Sum of sulfur deposition	108,857 t S/year
Sum of dry sulfur deposition	84,500 t S/year
Sum of wet sulfur deposition	24,357 t S/year
Sum of SO_2 dry deposition	84,471 t S/year
Sum of SO_4^{2-} dry deposition	29 t S/year
Sum of SO_2 wet deposition	24,108 t S/year
Sum of SO_4^{2-} wet deposition	249 t S/year
Sum of transboundary flows	30,358 t S/year
Average index of the threat to the coniferous forests	0.45

The map of Estonia covered by the grid square network is used for the demonstration of the spatial distribution of sulfur deposition (Fig. 3), indexes of the threat to the coniferous forests and ground level concentrations of sulfur contaminants.

Two variants of calculations have been conducted. In the first case, all output characteristics have been calculated without consideration of filtering effect. The results are presented on Fig. 3. Then the filtering effect was taken into account (Fig. 4). Obtained results are different. In the second case, the area of sulfur depositions is decreased; especially it concerns the region with the low sulfur deposition per grid element.

According to the recommendations of Working Group of the Economic Commission for Europe and the Nordic Council, a sulfur deposition level of 1,000 mg S/m^2 year is considered as critical load protecting sensitive ecosystems [10]. Fig. 4 demonstrates that about 150 km^2 of sea and land territory of Estonia are covered with sulfur deposition exceeding this critical load. The most polluted area is situated near Narva where the level of sulfur deposition is more than 10,000 mg S/m^2 year.

According to the EMEST model calculations, the average annual ground level concentrations of SO_2 (emitted from observed point sources only) in this region are not large and vary from 0.003 mg/m^3 to 0.037 mg/m^3 (near Narva). It is below maximum permissible concentration 0.050 mg/m^3. The observed value of average annual concentration in Narva in 1989 has been equal 0.050 mg/m^3 [4].

The calculated indexes of the threat to the coniferous forests in this region are ranged from 2 to 7.

So, the results obtained suggest that emissions from oil-shale power plants have considerable impact on the coniferous forests in Estonia in the region where according to Fig. 4 the level of sulfur deposition exceeds 1,000 mg S/m^2 year.

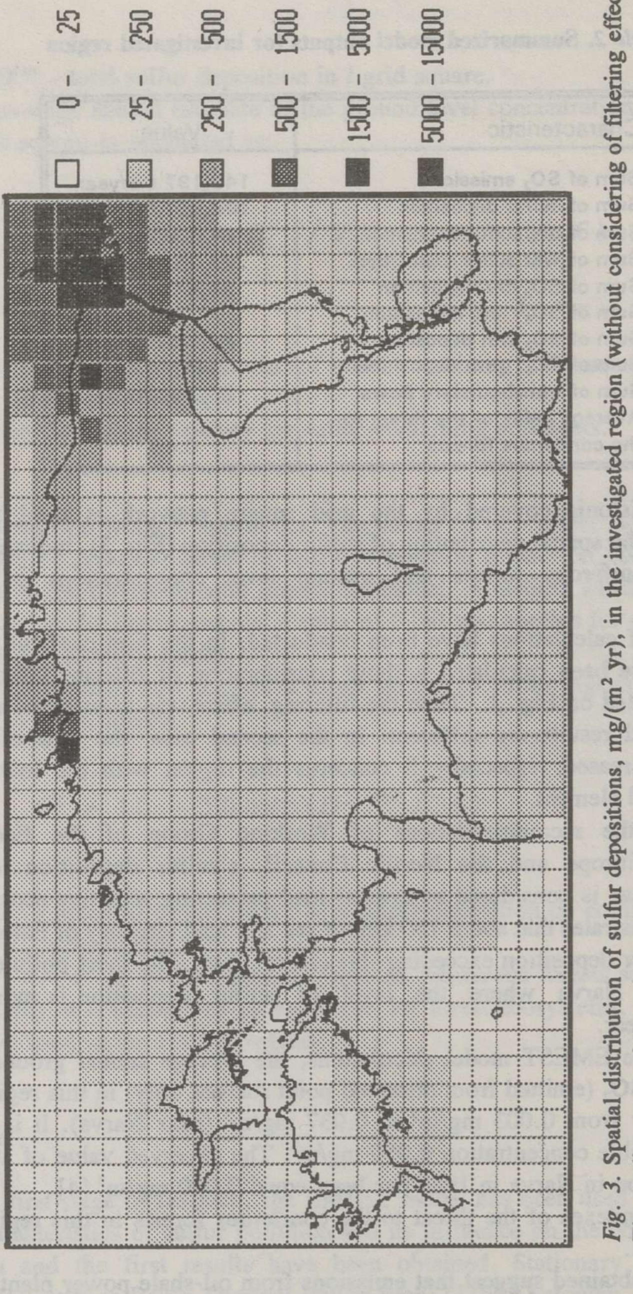

Fig. 3. **Spatial distribution of sulfur depositions, mg/(m² yr), in the investigated region (without considering of filtering effect). The outline map of Estonia has been obtained from the Estonian Nature Managment Centre**

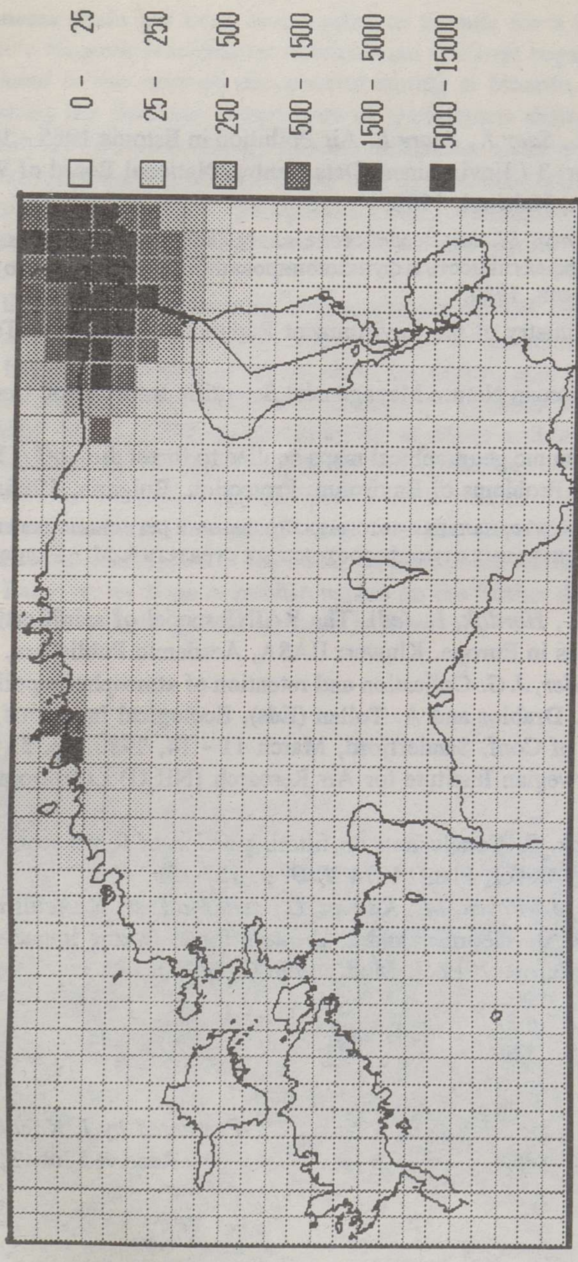

Fig. 4. Spatial distribution of sulfur depositions, mg/(m^2 yr), in the investigated region (with considering of filtering effect)

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REFERENCES

1. *Kallaste T., Roots O., Saar J., Saare L.* Air Pollution in Estonia 1985 - 1990 // Environmental Report 3 / Environment Data Centre, National Board of Waters and the Environment, Helsingi, 1992.
2. *Липпмаа Э. Т., Мытус М. М.* Воздействие сланцевой энергетики на окружающую среду // Эффективность и функционирование энергетического комплекса региона. Таллинн, 1989.
3. Environment '90. Ministry of the Environment Republic of Estonia. - Tallinn, 1991.
4. Environment '89. Estonian Nature Management Scientific Information Center. - Tallinn, 1990.
5. *Crossmann W.D.* Dynamic geographical maps applied to forest die - off // Papers of Int. Symp. on the Problems of Environm. Protection. Bulgaria, 1986.
6. *Литвин В. А.* Многокритериальная автоматизированная региональная система моделирования эффективных атмосфероохранных стратегий. М. : Гидрометеоиздат, 1988.
7. *Alcamo, I., Shaw, R., Hordijk, L. (ed).* The RAINS model of acidification. Science and Strategies in Europe. Kluwer: IIASA, Academic Publishers, 1990.
8. *Miller, H.G. and Miller, J.G.* Collection and retention of atmospheric pollutants by vegetation, in D. Drablos and A. Tollan (Eds), Ecological Impact of Acid Precipitation, Proc. of Conf. Sanderfjord, March 11 - 14, 1980, pp. 33 - 40, SNSF - project Norwegian Institute for Air Research (NILU) Lillestrom Norway, 1980.
9. *Mayer, R. and Ulrich, B.* Conclusions on filtering action of forest from ecosystem analysis // Oecol. Plant. 1974 V. 9. p. 157-168.
10. *Kauppi, P., Kamary, J., Posch, M., Kauppi, L., and Matzner, E.* Acidification of forest soils: model development and application for analyzing impacts of acidic deposition in Europe // Ecol. Mod., 1986 (in press).

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Estonian Academy of Sciences,
Institute of Economics
Tallinn, Estonia