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Critical load of sulfur deposition for ecosystem and its application in China

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Abstract—Current situation of air pollution of China is introduced. Critical loads for 4 types of soil in sensitive areas of China have been calculated using methods of SSMB, Profile Model and Magic Model. Maps of critical load, sulfur deposition of 1990 and exceedance of sulfur deposition over critical load have been made. A case study of applying critical load map for abating acidification has been made for Guizhou Province with respect to four control scenarios. The result showed that evently emission reduction in whole province is not necessary, if critical loads are taken into consideration. Instead, reducing emissions from three big cities or moving LPS from sensitive areas to non-sensitive areas could also meet the requirement of environmental protection.

Keywords: sulfur deposition; critical load; ecosystem.

1 Energy-related air pollution in China

Coal consumption reached 1.05 billion tons in 1990. It is estimated that about 40% were used in cities covering only 10% of the total area of the country. Coal consumption for power generation accounted for about 25% of the total. Therefore, severe air pollution at present mainly occurred in cities, particularly in megacities, i.e. local air pollution. Contribution to air pollution of power sector currently is relatively in a secondary position. Most of the damages to forests and crops mainly happening around cities can be thought as an evidence of the situation.

However, general survey did discover some places far from cities in southern China where soil pH has decreased markedly in 30 or more years (Fig. 1). Obviously, this is consequence of regional air pollution which has been going on silently and has not yet been aware of.

Moreover, projection showed that coal consumption would be 2 billion tons with a share of 40% for power generation by the year 2010. Consequently, SO_2 emission from large point sources at that time will approach the current total emission. It is speculated that in the coming decade regional air pollution will inevitably become a widespread threat to environment.

2. Abatement of air pollution in China

China has a large area with a great variety of topography, vegetation, climate, soil and so on. Under different conditions, detrimental effects brought about by same emission of pollutants could be quite different, heavy in some regional being sensitive to acid deposition, light or negligible in some other regions being non-sensitive.

There have been principles of pollution control in China: all round planning, rational distribution of power plants. Now that some regions are more sensitive to acid deposition, naturally, more emission should be reduced there relative to non-sensitive regions. Let us call this idea as rational reduction.

There must be a criterion for realizing the rational distribution or reduction. This criterion is the well-known critical load of sulfur deposition for ecosystem (Miljorapport, 1988).

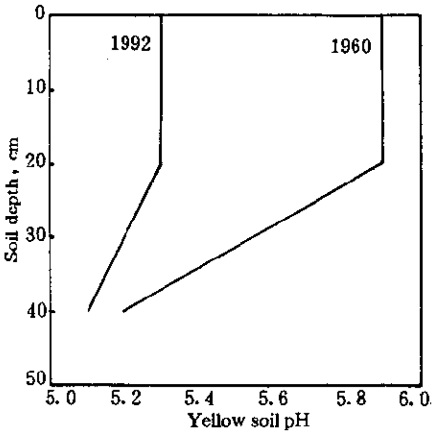


Fig. 1 Decrease of soils pH in 1960 - 1992 at Huitong, Hunan Province (Courtesy of Institute of Applied Ecology)

Even though great efforts having been made, obviously, it is impossible in the near future decreasing emission of air pollutants from energy use significantly in whole China. In this case, cost-effective way is to avoid sitting more power plants and industrial parks at sensitive regions, i.e. regions with low critical loads, or to allocate most of the funds for pollution control to those sources whose emissions mainly deposit at sensitive areas. From the viewpoint of sustainable development, this is one of the key principles that should be taken into consideration when making energy planning together with other economic and political principles.

3 Collection of basic data

Environment is a most complex system and, too, is the process of effect of pollution on ecosystem. Appropriate planning and decision can only be made based on reliable basic data. Unfortunately, it is very often ignored.

In China, in this respect, attention has been paid to collection of basic data in many ways: (1) Collecting specialized maps, atlas, reports, articles. Such as Soil Atlas of China, Meteorological Maps, Agricultural Maps, Provincial Maps of Natural Resources, books on soil, forest, energy, and so on. (2) General survey of forest growth, collecting and analyzing soil samples mainly at sensitive regions. (3) Setting up SO_2 and NO_2 samplers at rural and remote areas. Until now, 12 sampling sites have been set up. (4) Comprehensive study of acidification of soil and surface water. A small catchment of about 1.0 km^2 has been established at suburbs in Guiyang, Guizhou Province with heavy air pollution and acid rain. There are 7 sampling sites for soil water, soil and through fall, one bulk rain collector, one low volume aerosol collector, and SO_2 and NO_2 samplers, a weir for measuring discharge and collecting water samples. Work at this small catchment has been conducted for two years. An interim report has just been completed indicating that it is a successful experiment. This catchment is located at sensitive soil - yellow soil. Carefully gathered data at this site can serve for checking data from other places.

4. Calculation of critical loads

On the basis of basic data collected in China, critical loads were calculated for major sensitive soils in China: yellow, red soils, lateritic soil and latosol using three models: SSMB, profile, magic, and compared with critical load map.

4.1 SSMB method

Steady state modeling approaches assume a time - independent state of chemical interactions involving an equilibrium between the soil solid phase and soil solution. The steady state mass balance (SSMB) method computes the maximum acid input to the system that will not cause exceedance of the critical alkalinity value. The steady mass balance method has been used in Europe to derive critical loads for forest soils(UN - CCE, 1991).

We tried our best to collect actually measured or best estimated data. Weathering data were taken from profile's results. The calculation of critical loads is for four sensitive soil types in southern China(Table 1).

Table 1 Results obtained from SSMB method

Item	Unit	Yellow soil	Red soil	Lateritic red	Latosol
Weathering rate	keq/ha/a	0.593	0.502	0.398	0.351
Deposition	keq/ha/a	1.4	1.31	1.08	0.96
Uptake	keq/ha/a	0.352	0.273	0.3	0.25
Runoff	m	0.6	0.9	1.3	1.6
BC/Al		1.5	1.5	1.5	1.5
pK(gibbsite)		−8.42	−8.45	−8.5	−8.63
Leaching	μeq/L	412	198.8	117.8	47.5
Critical load	keq/ha/a	0.723	0.691	0.664	1.036

4.2 Profile model

Profile is designed to calculate the steady - state chemistry of soil, groundwater recharge as well as surface waters. The soil profile itself is divided into compartments corresponding to the natural soil stratification. In each of the soil compartments, a number of chemical reactions are included, represented either by equilibrium relationships or kinetic equations. The reaction systems considered are soil solution equilibrium reactions, silicate weathering, uptake of nutrients cations, NO_3^- and NH_4^+, nitrification and cation exchange reactions. All processes interact via the soil solution(Warfvinge, 1992).

Table 2 and Table 3 show basic data and basic parameters for calculating critical loads of yellow soil. The soil parameters were based on sampling and analyzing recently carried out in southern provinces. Major results are listed in Table 4.

Table 2 Input data for profile model (Yellow soil in southern China)

Data	Unit	Layer 1	Layer 2	Layer 3	Layer 4
Layer height	m	0.09	0.11	0.35	0.5
Moisture	m^3/m^3	0.2	0.2	0.2	0.2
Bulk density	kg/m^3	800	1110	1450	1550
Specific surface area	m^2/m^3	9.15*E*+05	1.2*E*+06	1.25*E*+06	1.25*E*+06
CO_2	atm	3	5	20	20
Inflow	% of rain	100	80	70	60
Percolation	% of rain	80	70	60	60
Ca, Mg, K uptake	% of max	30	50	20	0
N uptake	% of max	30	40	30	0
DOC	mg/L	2	1	0.5	0.1
Log K gibbsite		7.5	8.4	8.6	8.8
Muscovite	%	9.7	9.7	9.7	9.7
Vermiculite	%	0	0	0	0
Chlorite	%	3.5	3.5	3.5	3.5
K - feldspar	%	4.6	4.6	4.6	4.6

Table 3 Basic parameters for profile model (Yellow soil in southern China)

Parameter	Unit	Value	Parameter	Unit	Value
Soil layer		4	Mg	keq/ha/a	0.2
Precipitation	m/a	1.173	K	keq/ha/a	0.1
Runoff		0.6	Na	keq/ha/a	0.1
Deposition			non - marine		
			fraction	%	95
SO_4	keq/ha/a	2	Max uptake		
NO_3	keq/ha/a	0.08	Ca+Mg+K	keq/ha/a	0.4
NH_4	keq/ha/a	0.22	NO_3+NH_4	keq/ha/a	0.35
Cl	keq/ha/a	0.15	Temperature	℃	17.3
Ca	keq/ha/a	1	Nitrification		
			rate		High

Table 4 Results obtained from profile model

Soil	Yellow	Red	Lateritic red	Latosol
Weathering rate	0.593	0.502	0.389	0.351
ANC	−0.524	−0.363	−0.291	−0.091
Uptake of N	0.287	0.205	0.250	0.200
Uptake of cation	0.352	0.273	0.300	0.250
C. L. of potential				
acidity	1.052	0.797	0.639	0.392
C. L of acidity	1.1117	0.865	0.689	0.442

4.3 Magic model

Magic was developed for assessing the long - term acidification of surface water based on the assumption that surface water quality is controlled by atmospheric deposition and some important chemical reactions that take place while the water is in contact with the rock and soils of the terrestrial system. The model uses lumped parameters over a catchment or region and may be used to assess regional responses of soil and water chemistry to changes in patterns of acid deposition. The current version splits the soil profile into two horizontal layers (Cosby, 1986; Zhao, 1991).

Basic data for Magic are carefully measured at a small catchment at Liuchongguan, Guiyang City, Guizhou Province. This small catchment has been working for more than two years and a quite lot of all - round data have been collected. These are the most sufficient and reliable information now we have got. Some of the important parameters are as follows:

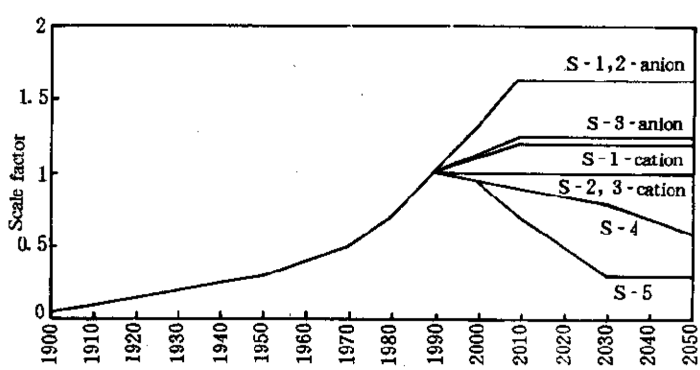
S - wet deposition : 4.0 $gS/m^2/a$; S - dry deposition: 2.1 $gS/m^2/a$; Runoff coefficient: 0.5; Rainfall: 1.173 m/a; Rain chemistry (1992—1993): pH 4.3; SO_4^{2-} 213 μeq/L; NO_3^-: 19.0 μeq/L; Cl^- 11 μeq/L; F^-: 3.3 μeq/L; K^+: 6.5 μeq/L; Na^+: 8.3 μeq/L; Ca^{2-}: 132 μeq/L; Mg^{2+}: 27 μeq/L.

The soil parameters are shown in Table 5.

Table 5 Important soil parameters for Magic

Layer	*CEC*	*BS*	p*K*[Al(OH)$_3$]	Al_i	Al^{3+}	H^+
A	26.19	29.63	8.35	170.5	110.8	79.3
B	17.99	13.59	8.44	140.8	85.2	67.8
C	8.5	13.00	8.80	127.06	71.3	48.2

Five scenarios of SO_2 emissions have been made for calculating using Magic model (Fig. 2).



Scenarios 4,5, anion and cation are the same, others different S - 1 - A, S - 1 - C etc. cation deposition, scenario 1, etc.

Fig. 2 Five scenarios of sulfur deposition in 1900—2050 in Guiyang

Some conclusions could be drawn from results from Magic as follows:

(1) Scenarios 1 - 4, $Al^{3+}/(Ca+Mg)$ of surface layer of soil (soil 1) is greater than 1. Therefore, all these four scenarios are unacceptable (Fig. 3).

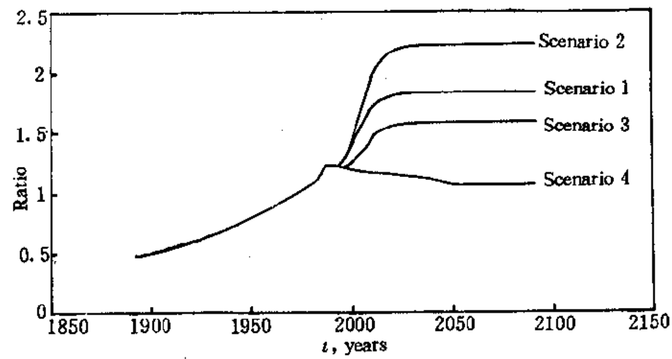


Fig. 3 Change of molar ratio of $Al^{3+}/(Ca+Mg)$

(2)For scenario 5, i.e. 70% reduction. $Al^{3+}/(Ca+Mg)$ for soil 1 and 2 decreases to below 1, Al^{3+} reduces to 150 μeq/L, H^+ of soil water to about 50 μeq/L, and alkalinity goes up to about - 200 μeq/L. Parameters of this levels can meet the demand of environment protection. From this point of view, the deposition of scenario 5 is thus taken as critical load for this area with yellow soil. That is 0.6 keq/ha/a(Fig. 4 and Fig. 5).

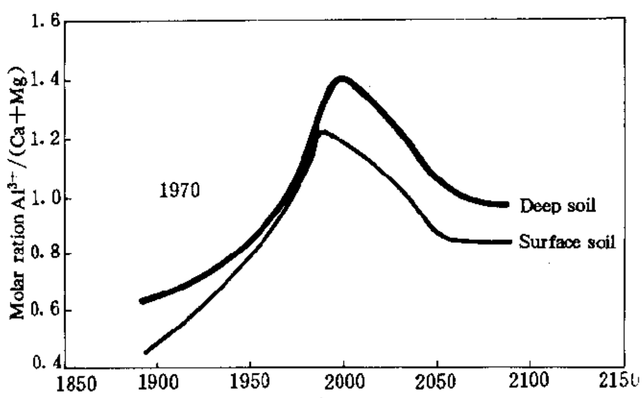


Fig. 4 Change of molar ratio of $Al^{3+}/(Ca+Mg)$ in soil water

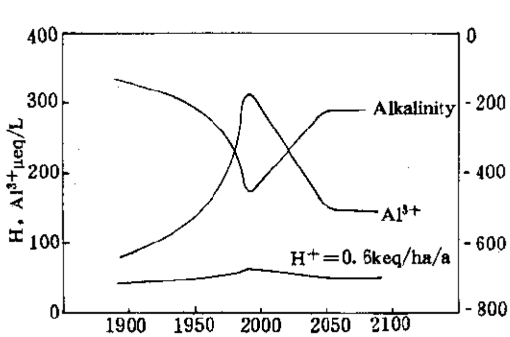


Fig. 5 H^+, Al^{3+} and Al_k concentrations in soil water

A comparison between critical loads from different method can be made(Table 6).

Generally speaking, it seems there is no big difference between results from 3 methods and Rains - Asia Map, except for latosol from SSMB. It is not surprising for this discrepancies, since all calculations are based on not very reliable and sufficient data.

Table 6 Critical loads different method

Unit: keq/ha/a

Method	SSMB	Profile	Magic	Rains - Asia Map
Yellow	0.723	1.052, 1.117	0.6	0.5—1.0
Red soil	0.691	0.797, 0.865	—	0.2—0.5
Lateritic red	0.664	0.639, 0.689	—	0.2—0.5
Latosol	1.036	0.392, 0.442	—	0.2—0.5

Notes: Estimated from map in Rains - Asia (Fig. 6); The first figure of profile is critical of potential acidity, the second critical load of acidity.

5 Maps of critical load, sulfur deposition and exceedance of deposition in China in 1990

Fig. 6 shows map of critical loads of 25 percentile calculated using SSMB. 25 percentile means critical loads in each grid cell which protects 75% of the entire grid cell area (UNECE, 1991). This map has been incorporated into Rains - Asia model, an integrated policy analysis model for Asia.

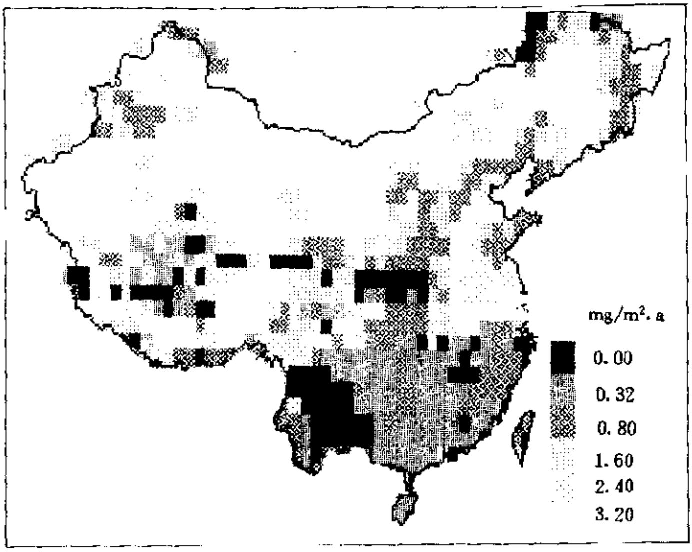


Fig. 6 Critical loads of sulfur for ecosystem in China ($p=25\%$)

Fig. 7 shows sulfur deposition of China in 1990. The total SO_2 emission in 1990 is about 20 MT.

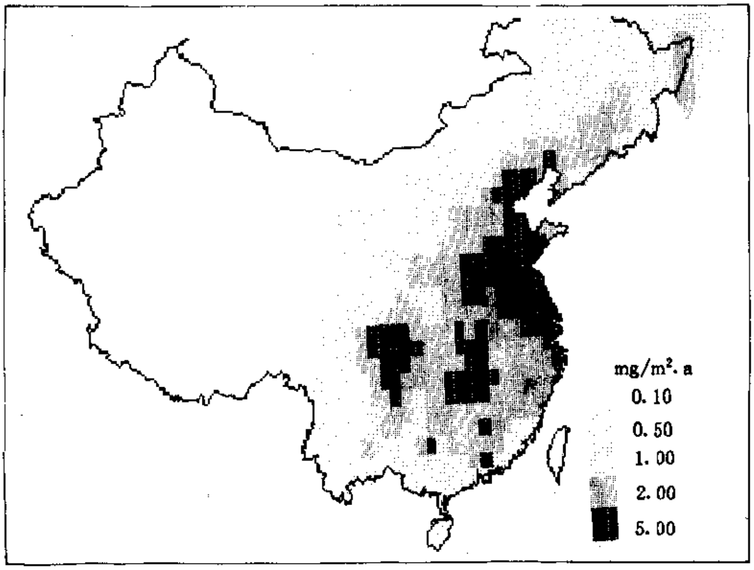


Fig. 7 Total sulfur deposition of China in 1990

Fig. 8 shows exceedance of critical loads of sulfur. Exceedance is defined as the excess of deposition in certain year over critical load. This map gives an idea of ecosystem in which regions is at risk and deposition in those regions should be reduced.

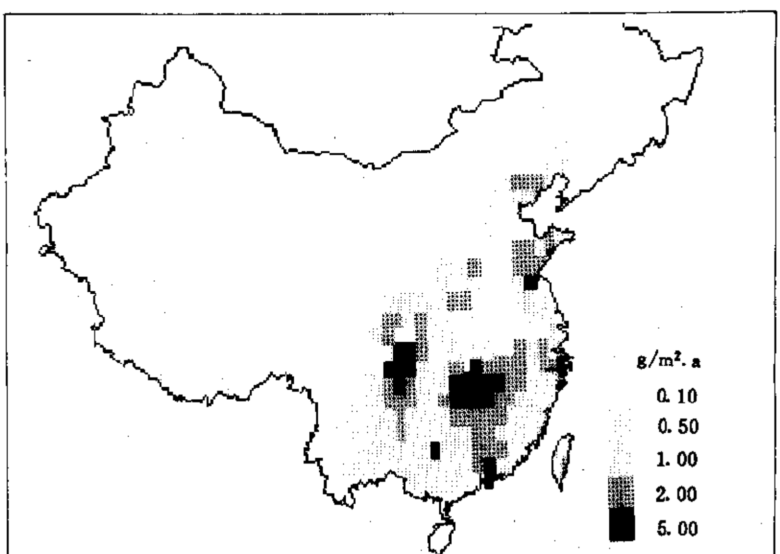


Fig. 8 Exceedance of sulfur deposition over critical load in 1990

6 A case study —application of critical loads in Guizhou Province

Guizhou Province is located in southwest China. Due to being situated in a basin surrounding by mountains with unfavorable meteorological condition for air pollutants to disperse, and rich in high sulfur coal, air pollution and acid rain are among the most severe in China. In the central part of this province, three big cities, Guiyang, Zunyi and Anshun are relatively industrialized and densely populated. Sulfur content of coal mined and used there can be as high as 3%—5%. In the western part, Liupanshui region, is another industrial park. Fortunately, coal sulfur content generally is below 1%. Eastern park, particularly southeastern part, is an undeveloped region with few small industry. The whole province mainly covers with sensitive yellow soil, most sensitive soil spreads in southeastern part. Fig. 9 shows critical load map of Guizhou Province.

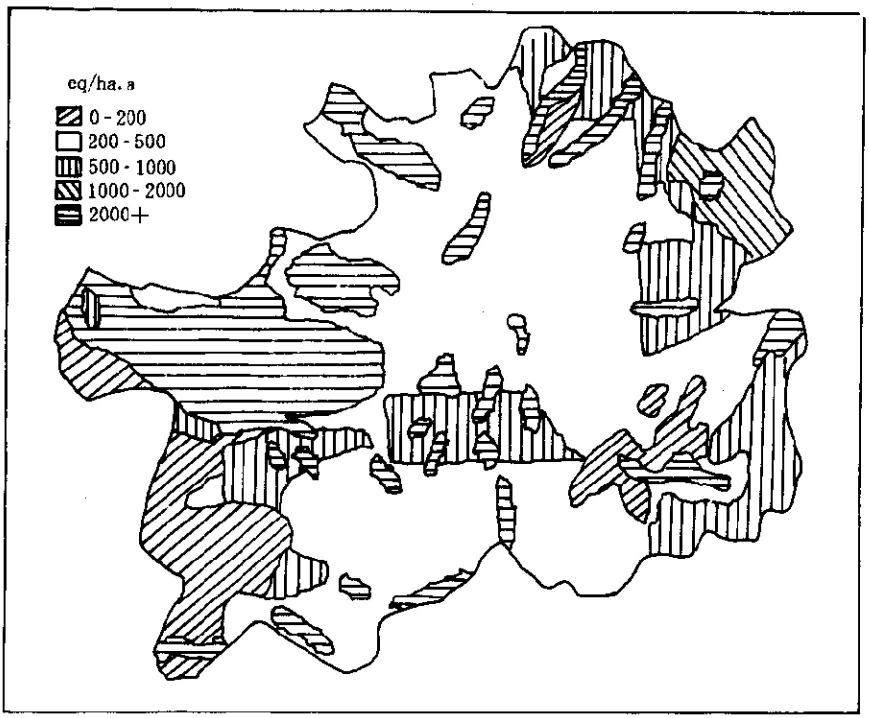


Fig. 9 Map of critical loads of sulfur deposition of Guizhou Province

Research on acid rain and air pollution have been conducted for more than ten years and, naturally, a lot of basic data have been gathered. For this reason, it is believed that this is a suitable area for carrying out a case study of applying critical loads for the purpose of energy planning. Taking 1992 as base, 2010 as target year. Four control scenarios have been made(Table 7).

Maps of exceedance of deposition over critical load for 1992 and 4 scenarios are shown in Fig. 10 - 14. From these maps some conclusions can be drawn up: (1) In 1992, regions with deposition exceeding critical load are Guiyang City and Zunyi City and surroundings area(Fig. 10). (2) In 2010, the region with deposition exceeding critical load expands significantly, and what is more, it merges with region exceeding critical load around Chongqing City, Sichuan Province (Fig. 11).

Table 7 SO_2 emission of 4 scenarios in Guizhou Province

(Unit: 10^4ton)

Area	1992		2010(BAU)		2010(-50% reduction, whole province)		2010 (-50% reduction at 3 areas *)		2010(3 LPS moved)	
	Areal	LPS	Areal	LPS	Areal	LPS	Areal	LPS	Areal	LPS
Guiy	10.63	3.83	18.67	11.50	9.34	5.75	9.34 *	5.75	18.67	moved to Bij
Liu	6.68	1.1	10.62	2.51	5.31	1.26	10.62	2.51	10.62	35.31
Gui S	6.47	—	10.93	—	5.47	—	10.93	—	10.93	—
Bij	4.56	0.12	7.90	—	3.95	—	7.90	—	7.90	—
Zunyi	5.0	4.73	15.65	0.78	7.83	0.39	7.83	0.39 *	7.83 * half moved to Bij	0.39 half moved to Bij
Tong	1.23	0.3	2.58	—	1.29	—	2.58	—	2.58	—
G—SW	1.91	0.29	3.71	—	1.86	—	3.71	—	3.71	—
Ans	4.79	16.5	19.44	33.0	9.72	16.5	9.72 *	16.5 *	19.44	moved to Liu
G—SE	2.24	0.86	5.23	—	2.62	—	5.23	—	5.23	—
sub—T	43.51	27.73	94.73	47.79	47.39	23.9	67.86	25.15	86.91	55.62
Total	71.24		142.52		71.29		93.01		142.52	

Notes: Guiy—Guiyang; Liu—Liupanshui; Gui S—Southern Guizhou; Bij—Bijie; Ton—Tongren; G—SW—Southwestern Guizhou; Ans—Anshun; G—SE—Southeastern Guizhou

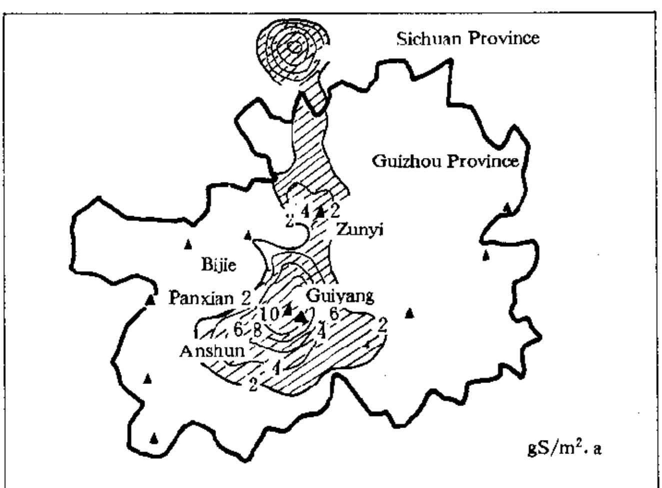


Fig. 10 Exceedance of sulfur deposition over critical load in 1992 in Guizhou

(3) Fig. 12 shows exceedance area after emission of the whole province being reduced by 50%. Then the exceeding areas only around three big cities, Guiyang, Anshun and Zunyi. The highest value of exceedance decreases from 10 to 6 $g/m^2/a$. (4) If only reduce emission of three big citics, Guiyang, Zunyi and Anshun, the highest exceeding value also decreases from 10 to 6,

even though the exceedance area is a region including all these three cities. In fact, there is no big difference between reducing all provincial emission and only three big cities's(Fig. 13). (5) Fig. 14 demonstrates the result of moving 3 LPS in sensitive areas to less sensitive area with less emissions. The exceedance area splits into 4 areas, but the situation is again about the same as those of scenarios with emission reduction.

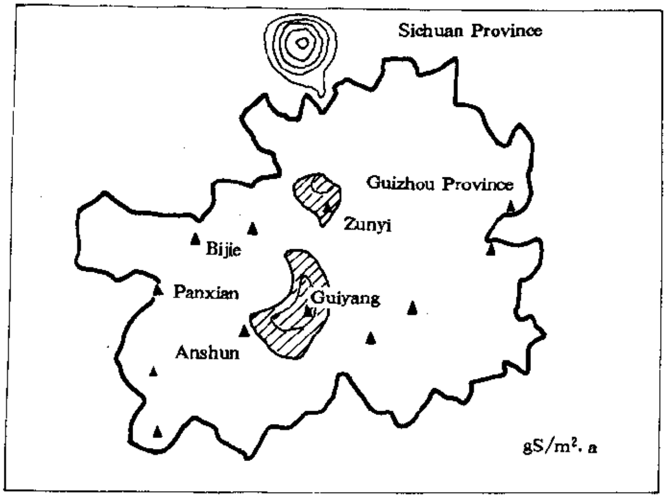


Fig. 11 Exceedance of sulfur deposition for BAU of 2010

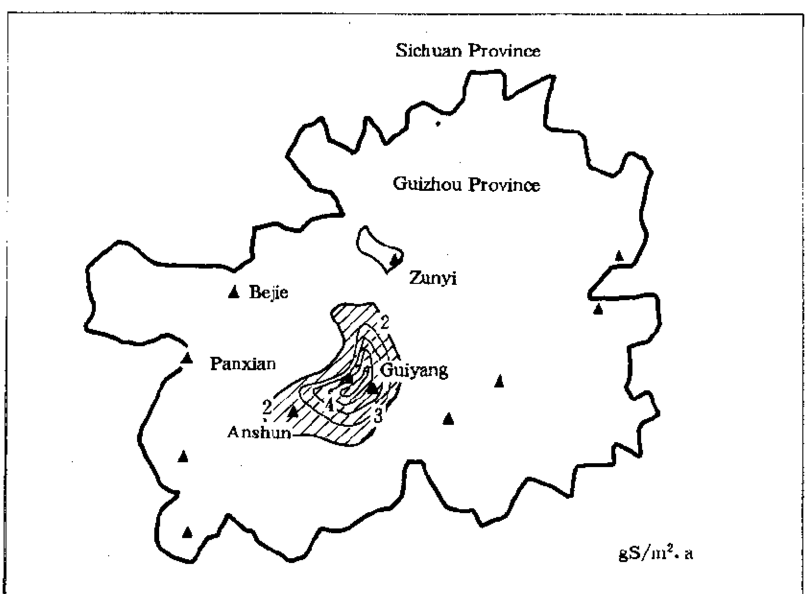


Fig. 12 Exceedance for 50% reduction of sulfur deposition in whole province in 2010

The conclusion is that the best way is, if possible, to move LPS to less sensitive area with relatively less emission or only reduce emissions from a few industrialized big cities located in sensitive area. It is likely that evenly lower down emission from whole province is not a cost - effective option.

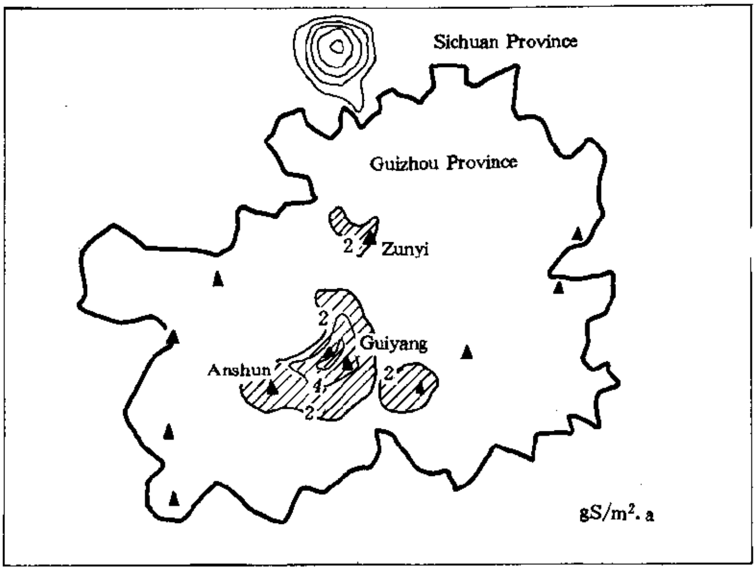


Fig. 13 Exceedance for 50% reduction of sulfur deposition in 3 megacities in 2010

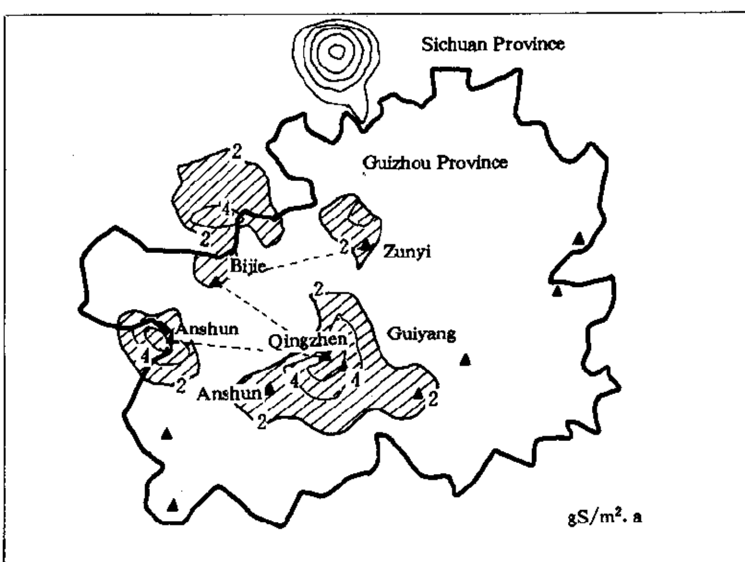


Fig. 14 Exceeedance for 3 large power plants re - located

7 Conclusion remarks

Map of critical loads is an useful tool helping decision - makers to achieve cost - effective rational distribution of LPS or rational reduction of emissions. This has already been proved by European experience. The case study in this paper seems to support this idea.

Without mentioning, maps of the kind should be reliable. Reliability of results comes from reliable basic data. Carefully collecting enough and representative basic data is of course of crucial importance.

It is suggested that several methods be used simultaneously, in order to cross check the final results.

For policy analysis of energy planning or economic planning, obviously, maps of critical loads are not enough. Together with critical load calculation, cost - benefit analysis should also be carried out when making energy planning.

References

Cosby BJ, Hornberger GM, Wright RF and Galloway JN. Water Resources Research, 1986; 22:1283

Miljorapport. Critical loads for sulfur and nitrogen . Workshop held at Skokloster, Sweden. 1988:19

UN - CCE. Mapping critical loads for Europe. CCE Technical report No. 1, 1991

Warfvinge P, Sverdrup H. Water, Air and Soil Pollution, 1992; 63:119

Zhao Dianwu, Hans Martin Seip. Water, Air and Soil Pollution, 1991; 60:83

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