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Chance–constrained programming (CCP) abatement of SO_2 emission for acid deposition control in Liuzhou City

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Abstract—A deterministic linear programming model which optimizes the abatement of each SO_2 emission source, is extended into a CCP form by introducing equations of probabilistic constrained through the incorporation of uncertainty in the source-receptor-specific transfer coefficients. Based on the calculation of SO_2 and sulfate average residence time for Liuzhou City, a sulfur deposition model has been developed and the distribution of transfer coefficients have been found to be approximately log-normal. Sulfur removal minimization of the model shows that the abatement of emission sources in the city is more effective, while control cost optimization provides the lowest cost programmes for source abatement at each allowable deposition limit under varied environmental risk levels. Finally a practicable programme is recommended.

Keywords: chance-constrained programming; emission source abatement; acid deposition.

BACKGROUND

Acid rain has been found in many regions especially in the south of China, among which Liuzhou is a seriously affected city, where the annually averaged pH value of precipiation is generally below 4.5 and obvious signs of damages can be observed. According to earlier works, the acid rain in China is primarily sulfur characterized (Chinese Research Academy of Environmental Sciences, 1987), and the combustion of coal, especially the high sulfur coal is the main source. Thus, the abatement of SO_2 emission turns to be the chief strategy. Liuzhou City is the largest industrialized city in Guangxi Autonomous Region. In order to use local low-calorific and high-sulfur coal, many fluidized-bed combustors were built which have caused very serious environmental problems.

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Tsinghua University has recently developed a very efficient desulfurization process for fluidized-bed combustion, the sulfur removal efficiency of which is generally by 75–80%. While Beijing Institute of Mining Technology has developed a coal briquet technique with sulfur-fixing binder to reduce sulfur emission by 50% for household and small boiler uses (Zhao Dianwu, 1986). Research on the optimal abatement strategies has become practicable.

For a long time, researchers are worried about the effects of acid deposition on Liuzhou from sources of other cities, especially the effects caused by Heshan Power Plant, which is 525 MW in capacity and 76km away in the southwest of Liuzhou.

DETERMINISTIC ABATEMENT MODEL AND ITS UNCERTAINTY

In fact, any of the strategy should at least meet the following two aims: to restrain serious acid deposition events from exceeding a given frequency and to confine its maximum deposition to certain limit. The current linear programming model can surely deal with the deterministic deposition limits, but unfortunately it can reflect risk levels only via sensitivity analysis.

A deterministic linear programming (LP) model may be written as:

$$\text{minimize:} \quad Z = \sum_{j=1}^{n} C_j * Q_j * X_j, \tag{1}$$

subject to:

$$\sum_{j=1}^{n} Q_j * T_{ji} * (1 - X_j) + \sum_{k=1}^{l} Q_k * T_{ki} + BG_i \leq D_i, \qquad i = 1, \dots, m, \tag{2}$$

$$0 \leq \min X_j \leq X_j \leq \max X_j, \qquad j = 1, \dots, n, \tag{3}$$

where

Z =total cost of emission control;

C_j=marginal cost of SO_2 removal at controllable source $j (j = 1, \dots, n)$; X_j=SO_2 removal level at controllable source $j (j = 1, \dots, n)$, X_j are decision variables;

Q_j=existing SO_2 emission rate at controllable source j;

T_{ji}=transfer coefficient which represents the annual sulfur deposition at receptor i, that transported from a unit emission at source j;

Q_k=existing SO_2 emission rate at noncontrollable source $k (k = 1, \dots, L)$,

BG_i=background sulfur deposition rate;

D_i=maximum allowable sulfur deposition rate;

mixX_j=minimum practicable abatement level;

maxX_j=maximum reachable abatement level.

In fact, the principal elements of the above deterministic model, namely source emission rates, cost-removal functions, transfer coefficients and deposition limits are all random variables. Thus there is great uncertainty in the obtained programmes.

An interesting extension of the deterministic model may be obtained by incorporating uncertainty into the deterministic LP formulation to turn it into a stochastic form, which permits an evaluation of the effects of uncertainty on system performance, and enables the development of nondesiginated-value abatement strategies. The development of such strategies is certainly a highly priority goal. In the following research the uncertainty of transfer coefficients is specifically addressed, because the incorporation of uncertainty into the deterministic LP formulation for random variables other than transfer coefficients is relatively straight forward and perhaps best accomplished through post optimal parametric sensitivity testing and it is anticipated that system performance and reliability will be heavily dependent upon transfer coefficient uncertainty (Ellis, 1985).

The variability or the statistical distributions of transfer coefficients in Liuzhou thus turns to be the most important.

STATISTICAL DISTRIBUTION OF TRANSFER COEFFICIENTS

Average residence time of SO_2 and sulfate is defined as:

$$ET = \int_0^{\infty} G(t)dt, \tag{4}$$

Where $G(t)$ is the probabilistic distribution function of the dry and wet deposition of SO_2 gas and sulfate particulates. ET is in fact the time that the deposition period covers when the amount of total deposition reaches (1–1/e) of the initial emission. The calculation of $G(t)$ depends on the following Lagrangian model schematically shown in Fig. 1(Venkatran, 1982).

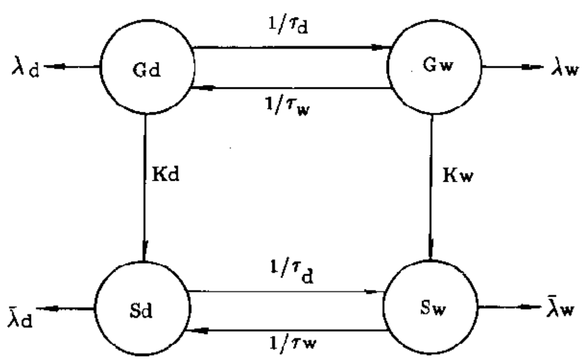


Fig. 1 Schematic diagram of the deposition model

In Fig. 1 SO_2 is denoted by capital letters G and SO_4^{2-} by S. Subscripts d and w refer to dry-and wet-processes respectively, refers to the SO_2 scavenging coefficient, K is the SO_2 to SO_4^{2-} conversion rate, $\bar{\lambda}$ is the SO_4^{2-} scavenging coefficient, τ is the average length of wet or dry period. The following equations for G and S can be immediately write down from the diagram:

$$d(G_d)/dt = -\lambda_d * G_d - K_d * G_d - 1/\tau_d * G_d + 1/\tau_w * G_w, \tag{5}$$

$$d(G_w)/dt = -\lambda_w * G_w - K_w * G_w - 1/\tau_w * G_w + 1/\tau_d * G_d, \tag{6}$$

$$d(S_d)/dt = \bar{\lambda}_d * S_d + K_d * G_d - 1/\tau_d * S_d + 1/\tau_w * S_w, \tag{7}$$

$$d(S_w)/dt = -\bar{\lambda}_w * S_w + K_w * G_w - 1/\tau_w * S_w + 1/\tau_d * S_d, \tag{8}$$

and

$$G(t) = G_d(t) + G_w(t) + S_d(t) + S_w(t). \tag{9}$$

It is found that the calculation of ET has summed up the comprehensive effects of deposition and chemical transformation during both dry and wet processes.

Meteorological data have been analyzed and the differential equations are in turn solved. Results show that the average residence time ET for Liuzhou is approximately 12 hours.

This value of ET indicates that the deposition processes in and around Liuzhou are mainly within the medium-range, i. e. several decade or several hundred kilometers. Fig. 2 shows the emission sources involved. Source ordinal numbers are arranged according to the emission rates from large to small in Fig. 2.

Since every emission source in the city should be considered, this value of ET also suggests that the sulfur deposition model should be the most suitable for the short- or medium-deposition processes there.

A significant conception is obtained from the reciprocal of the above calculated average resident time. $1/ET$ is in fact an indication of deposition rate. If the concentration in a diffusion plume with the upper edge height of Hm may be considered vertically homogeneous, then Hm/ET is just the deposition velocity at that downwind distance of Hm. Thus the amount of deposition is the product of concentration and the deposition velocity.

$$D(r) = M * R * (Hm/ET) * C * \exp(-r/(ET * U)), \tag{10}$$

where $D(r)$= the amount of deposition at distance r;

r= downwind distance;

M= emission rate;

Hm= upper edge height of diffusion plume;

R= correction to the height Hm, especially in short range;

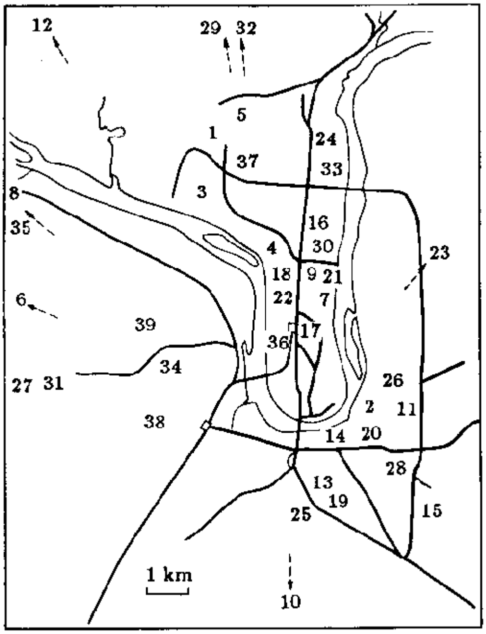
ET= average residence time;

C= reference ground concentration from a unit emission;

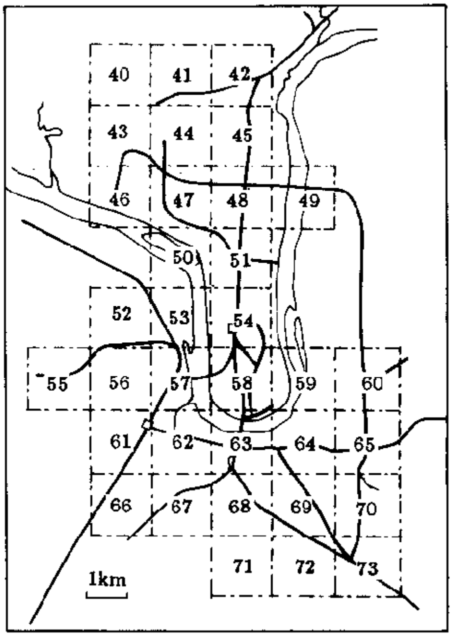
$\exp(-r/(ET * U))$ = decay during deposition process;

U= wind velocity.

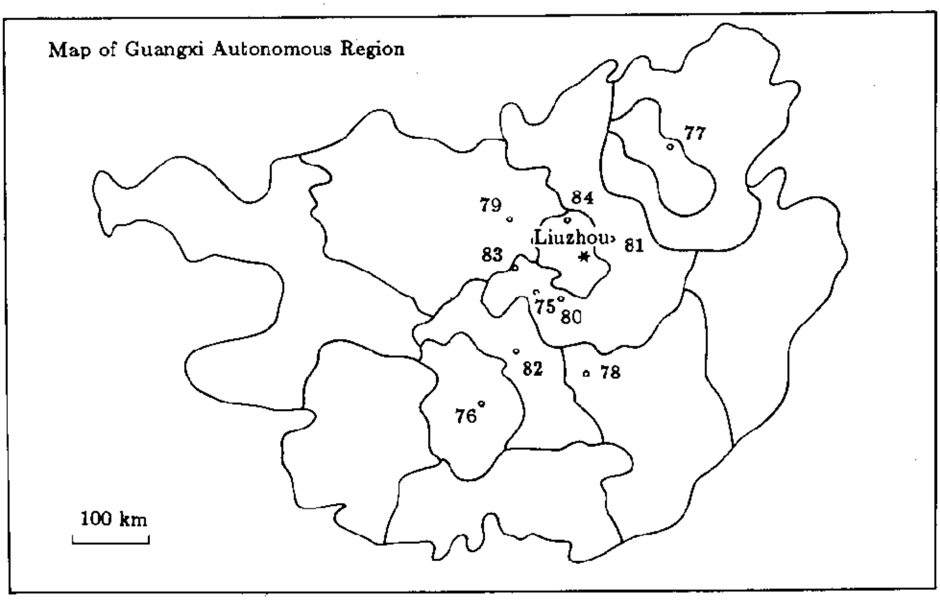
The parameters in the Equation (10) vary with different downwind distance as follows:



a. point sources in the city
n — means that source
No. n is in this direction



b. Area sources in the city
Area source No. 74 (Liu jiang county in the southwest) is omitted



c. City and county sources out of Liuzhou

Fig 2. Emission sources

Usually, $2.15\sigma_z$ is taken as the half width of the diffusion plume (Li Zongkai, 1985), where σ_z is the verticle diffusion parameter taken from the form of city in Brigges (Zeng Peixing, 1987). The height of plume upper edge may be considered as the reference height:

$$Hm = 2.15\sigma_z + H, \tag{11}$$

where

H=effective source height.

When the plume upper edge reaches the average mixing height D, this down-wind distance is noted as r_d. The homogeneous concentration at the distance beyond $r = 2 * r_d$ may be considered (Li Zongkai, 1985). The reference height here is taken as:

$$Hm = D, \qquad r > 2 * r_d, \tag{12}$$

As far as annually averaged deposition is concerned, the crosswind concentration may be considered the same within the downwind deposition area restricted in an angle of 22.5 degrees divided according to the 16 wind directions, assuming the concentration out of that area to be zero (Ma Qianru, 1982). When M = unit:

$$C = \frac{8}{2\pi * r * U * \sigma_z} \sum_{n=1}^{\infty} \{\exp[-\frac{(2n * D - H)^2}{2\sigma_z^2}] + \exp[-\frac{(2n * D + H)^2}{2\sigma_z^2}]\} dy \tag{13}$$

and

$$C = 8/(\pi * r * U * D), \qquad \text{whenever } r > 2 * r_d \tag{14}$$

and the correction

$$R = \exp(-0.5D/(2.15\sigma_z + H)). \tag{15}$$

It has been verified that this deposition model may agree well at $r >> r_d$ with the long distance one (Henning, 1972). The two models simply show:

$$D(r) = 8M * \exp(-r/(ET * U))/(ET * \pi * r * U), \text{ when } r >> r_d. \tag{16}$$

Another test may be obtained from the integration of total deposition upon the whole deposition area restricted by ET. According to the statistical definition of ET, reference Equation (4), these integrations should equalize (1–1/e)=0.632. Tests have shown the validity.

Meteorological data are then analyzed according to different kinds of stabilities, wind directions and wind speeds. Calculations and statistics on these different combinations of meteorological conditions have shown that the transfer coefficients between specific sources and receptors are approximately log-normally distributed, as shown in Fig. 3.

CHANCE-CONSTRAINED PROGRAMMING ABATEMENT MODEL

Chance-constrained programming (CCP) is a way of dealing with stochastic programming problems. The deterministic model of Equations (1), (2) and (3) can be replaced here by a more general probabilistic representation:

$$\text{minimize: } Z = \sum_{j=1}^{n} C_j * Q_j * X_j, \tag{17}$$

$$\text{subject to: } P[\sum_{j=1}^{n} Q_j * \hat{T_{ji}} * (1 - X_j) + \sum_{k=1}^{l} Q_k * \hat{T_{ki}} + BG_i \leq D_i] \geq \alpha_{ij}, \quad i = 1, \ldots, m, \tag{18}$$

$$0 \leq min\ X_j \leq X_j \leq \max X_j, \qquad j = 1, \ldots, n, \tag{19}$$

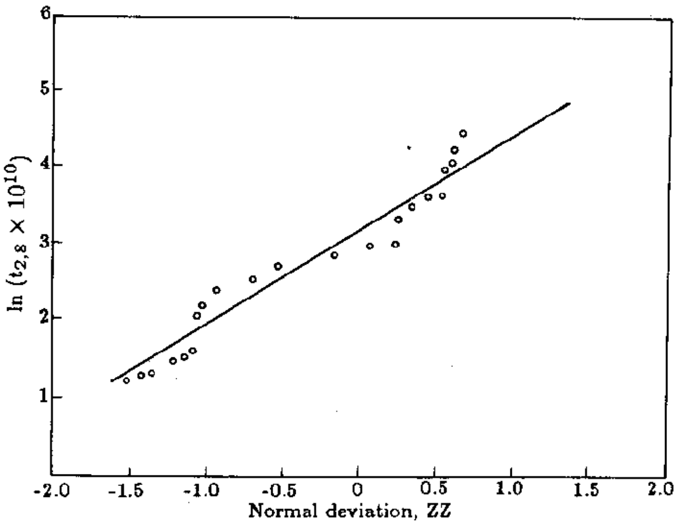


Fig. 3 Transfer coefficient realizations

Constraint (18) is different from constraint (2), where $P[\,]$ represents the probability of the equation within '[ ]' and α_{ij} is a parameter represents security level. Note that $\hat{T_{ji}}$ and $\hat{T_{ki}}$ are probabilistic representations of the transfer coefficients T_{ji} and T_{ki}. The CCP probabilistic constraints clearly indicate that the i-th constraint may be violated no more than $(1 - \alpha_{ij})$ fraction of the time.

As more attention is paid to the anthropogenic emissions and for the sake of unprecisely measured background deposition, BG_i are considered to be zero ($i = 1, \ldots, m$). And for the sake of taking Liuzhou City as a general control point, the same allowable deposition limit D is given at all receptor points.

This CCP technique requires the existence of the deterministic equivalents to the more general probabilistic constraints. The basis for the development of the deterministic equivalents was given by Ben Isreal (Ellis, 1985).

Since transfer coefficients are log-normally distributed as shown above, under complete colinearity assumption the non-linear transformation functions may be written as:

$$\hat{T_{ji}} = \exp(\overline{ln(T_{ji})} + ZZ * \sigma_{ji}),$$
$$\hat{T_{ki}} = \exp(\overline{ln(T_{ki})} + ZZ * \sigma_{ki}), \quad (20)$$

where

$\overline{ln(T_{ji})}, \overline{ln(T_{ki})}$= expected value of T_{ji} and T_{ki},

σ_{ji}, σ_{ki}= standard deviation of T_{ji} and T_{ki}.

ZZ= a factor to denote probability of constraint violence which is determinated by security level (Ellis, 1986),

$$e.g. \int_{ZZ}^{\infty} \exp(-t^2/2)dt = 1 - \alpha, \quad (21)$$

while random variable t is normally distributed $N(0, 1)$.

Complete colinearity here means strict dependence between all transfer coefficients in the abatement optimization, i. e. there is always only one predominant meteorological condition which governs pollutant transfer between each source-receptor pair in the control region and this in turn results in transfer coefficient realizations with constant security level, α. Since the calculation of ET has showed that the average deposition range is mainly within several ten or several hundred kilometers, it is obvious that the above assumption is reasonable.

Therefore, the deterministic equivalent to constraint (18) may be expressed as:

$$\sum_{j=1}^{n} Q_j * T_{ji} * (1 - X_j) + \sum_{k=1}^{l} Q_k * T_{ki} \leq D, \quad i = 1, \ldots, m. \quad (22)$$

SULFUR REMOVAL MINIMIZATION

First, consider all the sources as controllable and have cost coefficients C_j=unit ($j = 1, \ldots, n$) in the abatement model Equation (17). The model thus becomes:

$$\text{minimize: } Z = \sum_{j=1}^{n+l} Q_j * X_j \,, \quad (23)$$

$$\text{subject to: } P[\sum_{j=1}^{n+l} Q_j * T_{ji} * (1 - X_j) \leq D] \geq \alpha, \quad i = 1, \ldots, m, \quad (24)$$

$$0 \leq X_j \leq 1, j = 1, \ldots, n + L. \quad (25)$$

This is in fact an optimization for the least sulfur removal in the abatement plan. This simplified model has its specific meaning at least in two phases:

(1) To optimize least sulfur removal at relaxed high allowable deposition limits, one may readily find the most effective sources to be controlled. These sources, controllable or uncontrollable, are the most serious pollution sources to Liuzhou, thus emphases should be paid to these sources. If there are some uncontrollable sources at present, this procedure will lead to consider at first the development of such techniques as for control of these sources, or it will guide the decision-maker to adopt measures such as shut down some plants or move them to other places to adjust the distribution of the city industry.

(2) Optimizing under strict low allowable deposition limits, it may be found that other sets of sources are still of no concern. These may help to find out the unimportant sources to the sulfur deposition in Liuzhou and they can be deleted out from the optimization process to make it more efficient.

Optimizing under security level of 80% and 50% (50% security level here indicates expected value in the statistical sense), the results are summarized in Table 1 and Table 2 respectively. It is shown that the sources of No. 4, 7, 9, 16, 30, 47, 48, 50 and 51 are the main sources to be concerned. The abatement emission is less than 11% of the total emission in Liuzhou only, but may results in nearly 30% decrease of the highest deposition. More runs have shown sources No. 7 and 51 in the city are of the most importance, but source No. 7 is stove-emission and difficult to control with current practical technology. The government of the city should pay attention to rationalize the distribution of Liuzhou industry according to the above viewpoint.

Other runs are performed under strict deposition limits and they also yield important results. Even at a large abatement scale of the highest deposition, the sources out of the city (sources No. 75 to No. 84, shown in Fig. 3(c)) are still not involved in the abatement. Thus the contribution of sources out of Liuzhou on the annual sulfur deposition in the city is relatively small.

The effects of sources out of Liuzhou and the effects caused by Heshan Power Plant were calculated under different security levels and the results are given in Table 3.

Table 1 SO_2 removal minimization under security level of 80%

Deposition limit abatement 29%; Least SO_2 removal: 5981.84t $(SO_2)/a$.

Emission abatement at each source:

X(1)= .000	*X*(2)= .000	*X*(3)= .000	*X*(4)= .671
X(5)= .000	*X*(6)= .000	*X*(7)= .833	*X*(8) .000
X(9)= .000	*X*(10)= .000	*X*(11)= .000	*X*(12)= .000
X(13)= .000	*X*(14)= .000	*X*(15)= .000	*X*(16)= .000
X(17)= .000	*X*(18)= .000	*X*(19)= .000	*X*(20)= .000
X(21)= .000	*X*(22)= .000	*X*(23)= .000	*X*(24)= .000
X(25)= .000	*X*(26)= .000	*X*(27)= .000	*X*(28)= .000
X(29)= .000	*X*(30)= .000	*X*(31)= .000	*X*(32)= .000
X(33)= .000	*X*(34)= .000	*X*(35)= .000	*X*(36)= .000
X(37)= .000	*X*(38)= .000	*X*(39)= .000	*X*(40)= .000
X(41)= .000	*X*(42)= .000	*X*(43)= .000	*X*(44)= .000
X(45)= .000	*X*(46)= .000	*X*(47)= .000	*X*(48)= .000
X(49)= .000	*X*(50)=1.000	*X*(51)=1.000	*X*(52)= .000
X(53)= .000	*X*(54)= .000	*X*(55)= .000	*X*(56)= .000
X(57)= .000	*X*(58)= .000	*X*(59)= .000	*X*(60)= .000
X(61)= .000	*X*(62)= .000	*X*(63)= .000	*X*(64)= .000
X(65)= .000	*X*(66)= .000	*X*(67)= .000	*X*(68)= .000
X(69)= .000	*X*(70)= .000	*X*(71)= .000	*X*(72)= .000
X(73)= .000	*X*(74)= .000	*X*(75)= .000	*X*(76)= .000
X(77)= .000	*X*(78)= .000	*X*(79)= .000	*X*(80)= .000
X(81)= .000	*X*(82)= .000	*X*(83)= .000	*X*(84)= .000

Table 2 SO_2 removal minimization at expected value

Deposition limit abatement 30%; Least SO_2 removal: 9725.16t $(SO_2)/a$.

Emission abatement at each source:

X(1)= .000	*X*(2)= .000	*X*(3)= .000	*X*(4)=1.000
X(5)= .000	*X*(6)= .000	*X*(7)=1.000	*X*(8)= .000
X(9)= .479	*X*(10)= .000	*X*(11)= .000	*X*(12)= .000
X(13)= .000	*X*(14)= .000	*X*(15)= .000	*X*(16)=1.000
X(17)= .000	*X*(18)= .000	*X*(19)= .000	*X*(20)= .000
X(21)= .000	*X*(22)= .000	*X*(23)= .000	*X*(24)= .000
X(25)= .000	*X*(26)= .000	*X*(27)= .000	*X*(28)= .000
X(29)= .000	*X*(30)=1.000	*X*(31)= .000	*X*(32)= .000
X(33)= .000	*X*(34)= .000	*X*(35)= .000	*X*(36)= .000
X(37)= .000	*X*(38)= .000	*X*(39)= .000	*X*(40)= .000
X(41)= .000	*X*(42)= .000	*X*(43)= .000	*X*(44)= .000
X(45)= .000	*X*(46)= .000	*X*(47)= .925	*X*(48)=1.000
X(49)= .000	*X*(50)= .886	*X*(51)=1.000	*X*(52)= .000
X(53)= .000	*X*(54)= .000	*X*(55)- .000	*X*(56)= .000
X(57)= .000	*X*(58)= .000	*X*(59)= .000	*X*(60)= .000
X(61)= .000	*X*(62)= .000	*X*(63)= .000	*X*(64)= .000
X(65)= .000	*X*(66)= .000	*X*(67)= .000	*X*(68)= .000
X(69)= .000	*X*(70)= .000	*X*(71)= .000	*X*(72)= .000
X(73)= .000	*X*(74)= .000	*X*(75)= .000	*X*(76)= .000
X(77)= .000	*X*(78)= .000	*X*(79)= .000	*X*(80)= .000
X(81)= .000	*X*(82)= .000	*X*(83)= .000	*X*(84)= .000

Table 3 Effects of sources out of Liuzhou

Security level, %	80			50		
Sources	Total $g/m^2.a$	Heshan $g/m^2.a$	%	Total $g/m^2.a$	Heshan $g/m^2.a$	%
Average deposition effect	0.24	0.12	50	0.16	0.08	50

CONTROL COST MINIMIZATION

For the sake of relatively smaller contribution derived above, sources out of Liuzhou are called off from the optimization processes and considered as uncontrollable sources. Such a procedure may not only simplify the optimization process but also make it possible for Liuzhou government to form its own abatement strategy, so that it can be carried out more efficiently.

Sixty runs were performed to assess the effects of the system risk level $1-\alpha$, on overall system cost $Z_{\min}$ and receptor deposition to span the complete range of stipulated maximum allowable receptor deposition level D. That range is lower-bounded by infeasible values of D, i. e.

$$\sum_{j=1}^{n} Q_j * (1-X_j) * T_{ji} + \sum_{k=1}^{l} Q_k * T_{ki} \geq D, \quad i-1,\ldots,m \tag{26}$$

$$X_j = \max X_j, \qquad j=1,\ldots,n \tag{27}$$

$$\sum_{j=1}^{n} Q_j * (1-X_j) * T_{ji} + \sum_{k=1}^{l} Q_k * T_{ki} \leq D, \quad i=1,\ldots,m \tag{28}$$

$$X_j = 0 \qquad j=1,\ldots,n \tag{29}$$

These two bounds and the intermediate lowest cost curves were drawn up in Fig. 4 based on these runs.

Fig. 4 is the most significant contribution of stochastic programming to ordinary deterministic programming in the sense that it provides not only the whole degree of deposition limits but also the risk levels or security levels to meet these limits at any acceptable control cost. Finally, Fig. 4 and a complete set of corresponding minute descriptions of each source abatement level of the 60 runs as an appendix are provided to Liuzhou government. All these will surely benefit in reaching the final goal of Liuzhou acid deposition abatement.

Table 4 Sub-optimal abatement recommended under security level of 80%

Deposition limit abatement: 50%; Lowest control cost:11.48 million yuan (RMB)/a; Total amount of SO_2 removal:30939.02t(SO_2)/a; Emission abatement at each source:

X(1)= .600	X(2)= .197	X(3)= .800	X(4)= .800
X(5)= .000	X(6)= .000	X(7)= .000	X(8)= .000
X(9)= .800	X(10)= .000	X(11)= .800	X(12)= .000
X(13)= .800	X(14)= .000	X(15)= .000	X(16)= .800
X(17)= .800	X(18)= .800	X(19)= .000	X(20)= .000
X(21)= .800	X(22)= .000	X(23)= .000	X(24)= .800
X(25)= .000	X(26)= .400	X(27)= .000	X(28)= .000
X(29)= .000	X(30)= .800	X(31)= .000	X(32)= .000
X(33)= .800	X(34)= .000	X(35)= .000	X(36)= .800
X(37)= .800	X(38)= .000	X(39)= .000	X(40)= .400
X(41)= .400	X(42)= .400	X(43)= .400	X(44)= .400
X(45)= .400	X(46)= .400	X(47)= .400	X(48)= .400
X(49)= .400	X(50)= .400	X(51)= .400	X(52)= .400
X(53)= .400	X(54)= .400	X(55)= .400	X(56)= .400
X(57)= .400	X(58)= .400	X(59)= .400	X(60)= .400
X(61)= .400	X(62)= .400	X(63)= .400	X(64)= .400
X(65)= .400	X(66)= .400	X(67)= .400	X(68)= .400
X(69)= .400	X(70)= .400	X(71)= .400	X(72)= .400
X(73)= .400	X(74)= .400		

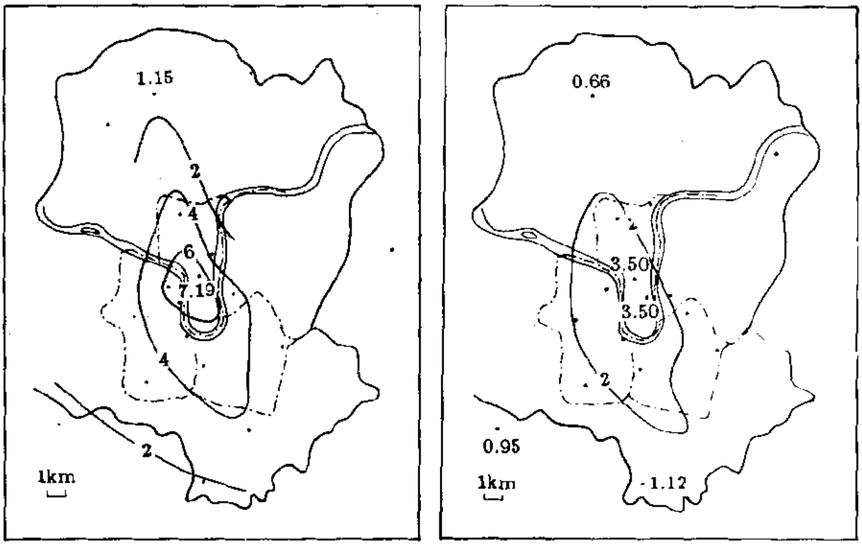
Table 5 Sub-optimal abatement recommended at expected value

Deposition limits abatement: 50%; Lowest control cost:11.92 million Yuan(RMB)/a; Total amount of SO_2 removal:34868.82 (SO_2)/a; Emission abatement at each source:

X(1)= .600	X(2)= .800	X(3)= .800	X(4)= .800
X(5)= .000	X(6)= .000	X(7)= .000	X(8)= .000
X(9)= .800	X(10)= .000	X(11)= .800	X(12)= .000
X(13)= .614	X(14)= .533	X(15)= .000	X(16)= .800
X(17)= .800	X(18)= .800	X(19)= .000	X(20)= .000
X(21)= .800	X(22)= .000	X(23)= .000	X(24)= .800
X(25)= .000	X(26)= .000	X(27)= .000	X(28)= .000
X(29)= .000	X(30)= .800	X(31)= .000	X(32)= .000
X(33)= .800	X(34)= .000	X(35)= .000	X(36)= .800
X(37)= .800	X(38)= .000	X(39)= .000	X(40)= .400
X(41)= .400	X(42)= .400	X(43)= .400	X(44)= .400
X(45)= .400	X(46)= .400	X(47)= .400	X(48)= .400
X(49)= .400	X(50)= .400	X(51)= .400	X(52)= .400
X(53)= .400	X(54)= .400	X(55)= .400	X(56)= .400
X(57)= .400	X(58)= .400	X(59)= .400	X(60)= .400
X(61)= .400	X(62)= .400	X(63)= .400	X(64)= .400
X(65)= .400	X(66)= .400	X(67)= .400	X(68)= .400
X(69)= .400	X(70)= .400	X(71)= .400	X(72)= .400
X(73)= .400	X(74)= .400		

It is found that the most important sources are fluidized-bed combustors except source No. 1 (power plant emission) and source No. 26 (small boiler). Liuzhou should encourage the use of FBC desulfurization approach.

The deposition isopleth map after the recommended abatement is drawn up in Fig. 5(b) at the expected value, Fig. 5(a) is its initial deposition used for reference.



a. Initial deposition   b. After recommended abatement

Fig. 5 Deposition isopleth map at expected value

CONCLUSION

A deterministic model for development of acid deposition abatement strategies of Liuzhou was extended into a probabilistic form by the incorporation of uncertainty associated with pollutant transport and deposition processes. Transfer coefficients between each source-receptor pair was specified as a vital stochastic parameter. Average residence time of SO_2 and sulfate for Liuzhou was calculated to be 12 hours which has summed up the comprehensive effects of pollutant transport, transformation and deposition during dry and wet processes. The value of ET indicates that the deposition in Liuzhou is mainly within the medium-range and this in turn calls for the establishment of single source deposition model which is most applicable to the atmospheric environment around Liuzhou. Tests were conducted to show the validity of the model. Calculations and statistics of variable meteorological conditions show that the probabilistic distribution of transfer coefficients is log-normal.

Chance-constrained programming was introduced to meet two kinds of optimization: SO_2 removal minimization and control cost minimization. Lowest control costs were obtained at each allowable deposition limit under different security levels and the map of isopleth cost curves of Liuzhou was drawn. Based on the careful analysis of the emissions to be cut down, a more practical abatement plan is recommended, which urges the full control of all area emissions and encourages to adopt the advanced FBC desulfurization technique according to the sources shown in Table 4 and Table 5, to cut down the highest annual sulfur deposition to one half.

It is worth while to note that the total contribution of emissions out of Liuzhou is relatively unimportant to the annual sulfur deposition in the city, though the influence of Heshan Power Plant makes half of their contribution. Serious emissions to be concerned are mainly in the city, especially the point source No. 4, 7, 9, 16, 30 and area emission just at the north center of the city, i. e. source No. 47, 48, 50 and 51. Liuzhou government should pay more attention to rationalize the distribution of city industry and residential areas.

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Tsinghua University has recently developed a very efficient desulfurization process for fluidized-bed combustion, the sulfur removal efficiency of which is generally by 75–80%. While Beijing Institute of Mining Technology has developed a coal briquet technique with sulfur-fixing binder to reduce sulfur emission by 50% for household and small boiler uses (Zhao Dianwu, 1986). Research on the optimal abatement strategies has become practicable.

For a long time, researchers are worried about the effects of acid deposition on Liuzhou from sources of other cities, especially the effects caused by Heshan Power Plant, which is 525 MW in capacity and 76km away in the southwest of Liuzhou.

DETERMINISTIC ABATEMENT MODEL AND ITS UNCERTAINTY

In fact, any of the strategy should at least meet the following two aims: to restrain serious acid deposition events from exceeding a given frequency and to confine its maximum deposition to certain limit. The current linear programming model can surely deal with the deterministic deposition limits, but unfortunately it can reflect risk levels only via sensitivity analysis.

A deterministic linear programming (LP) model may be written as:

$$\text{minimize:} \quad Z = \sum_{j=1}^{n} C_j * Q_j * X_j, \tag{1}$$

subject to:

$$\sum_{j=1}^{n} Q_j * T_{ji} * (1 - X_j) + \sum_{k=1}^{l} Q_k * T_{ki} + BG_i \leq D_i, \qquad i = 1, \ldots, m, \tag{2}$$

$$0 \leq \min X_j \leq X_j \leq \max X_j, \qquad j = 1, \ldots, n, \tag{3}$$

where

Z =total cost of emission control;

C_j=marginal cost of SO_2 removal at controllable source $j (j = 1, \ldots, n)$; X_j=SO_2 removal level at controllable source $j (j = 1, \ldots, n)$, X_j are decision variables;

Q_j=existing SO_2 emission rate at controllable source j;

T_{ji}=transfer coefficient which represents the annual sulfur deposition at receptor i, that transported from a unit emission at source j;

Q_k=existing SO_2 emission rate at noncontrollable source $k (k = 1, \ldots, L)$,

BG_i=background sulfur deposition rate;

D_i=maximum allowable sulfur deposition rate;

mixX_j=minimum practicable abatement level;

maxX_j=maximum reachable abatement level.

In fact, the principal elements of the above deterministic model, namely source emission rates, cost-removal functions, transfer coefficients and deposition limits are all random variables. Thus there is great uncertainty in the obtained programmes.

An interesting extension of the deterministic model may be obtained by incorporating uncertainty into the deterministic LP formulation to turn it into a stochastic form, which permits an evaluation of the effects of uncertainty on system performance, and enables the development of nondesiginated-value abatement strategies. The development of such strategies is certainly a highly priority goal. In the following research the uncertainty of transfer coefficients is specifically addressed, because the incorporation of uncertainty into the deterministic LP formulation for random variables other than transfer coefficients is relatively straight forward and perhaps best accomplished through post optimal parametric sensitivity testing and it is anticipated that system performance and reliability will be heavily dependent upon transfer coefficient uncertainty (Ellis, 1985).

The variability or the statistical distributions of transfer coefficients in Liuzhou thus turns to be the most important.

STATISTICAL DISTRIBUTION OF TRANSFER COEFFICIENTS

Average residence time of SO_2 and sulfate is defined as:

$$ET = \int_0^{\infty} G(t)dt, \tag{4}$$

Where $G(t)$ is the probabilistic distribution function of the dry and wet deposition of SO_2 gas and sulfate particulates. ET is in fact the time that the deposition period covers when the amount of total deposition reaches $(1\text{–}1/e)$ of the initial emission. The calculation of $G(t)$ depends on the following Lagrangian model schematically shown in Fig. 1(Venkatran, 1982).

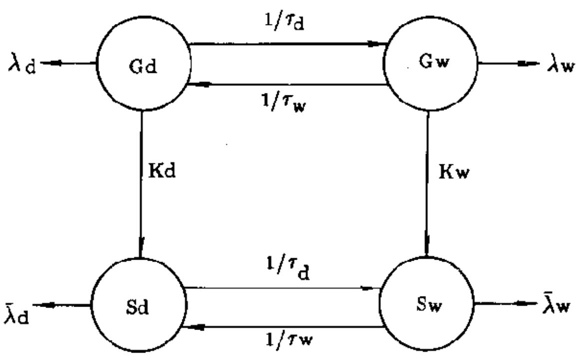


Fig. 1 Schematic diagram of the deposition model

In Fig. 1 SO_2 is denoted by capital letters G and SO_4^{2-} by S. Subscripts d and w refer to dry-and wet-processes respectively, refers to the SO_2 scavenging coefficient, K is the SO_2 to SO_4^{2-} conversion rate, $\bar{\lambda}$ is the SO_4^{2-} scavenging coefficient, τ is the average length of wet or dry period. The following equations for G and S can be immediately write down from the diagram:

$$d(G_d)/dt = -\lambda_d * G_d - K_d * G_d - 1/\tau_d * G_d + 1/\tau_w * G_w, \tag{5}$$

$$d(G_w)/dt = -\lambda_w * G_w - K_w * G_w - 1/\tau_w * G_w + 1/\tau_d * G_d, \tag{6}$$

$$d(S_d)/dt = \bar{\lambda}_d * S_d + K_d * G_d - 1/\tau_d * S_d + 1/\tau_w * S_w, \tag{7}$$

$$d(S_w)/dt = -\bar{\lambda}_w * S_w + K_w * G_w - 1/\tau_w * S_w + 1/\tau_d * S_d, \tag{8}$$

and

$$G(t) = G_d(t) + G_w(t) + S_d(t) + S_w(t). \tag{9}$$

It is found that the calculation of ET has summed up the comprehensive effects of deposition and chemical transformation during both dry and wet processes.

Meteorological data have been analyzed and the differential equations are in turn solved. Results show that the average residence time ET for Liuzhou is approximately 12 hours.

This value of ET indicates that the deposition processes in and around Liuzhou are mainly within the medium-range, i. e. several decade or several hundred kilometers. Fig. 2 shows the emission sources involved. Source ordinal numbers are arranged according to the emission rates from large to small in Fig. 2.

Since every emission source in the city should be considered, this value of ET also suggests that the sulfur deposition model should be the most suitable for the short- or medium-deposition processes there.

A significant conception is obtained from the reciprocal of the above calculated average resident time. $1/ET$ is in fact an indication of deposition rate. If the concentration in a diffusion plume with the upper edge height of Hm may be considered vertically homogeneous, then Hm/ET is just the deposition velocity at that downwind distance of Hm. Thus the amount of deposition is the product of concentration and the deposition velocity.

$$D(r) = M * R * (Hm/ET) * C * \exp(-r/(ET * U)), \tag{10}$$

where $D(r)$= the amount of deposition at distance r;

r= downwind distance;

M= emission rate;

Hm= upper edge height of diffusion plume;

R= correction to the height Hm, especially in short range;

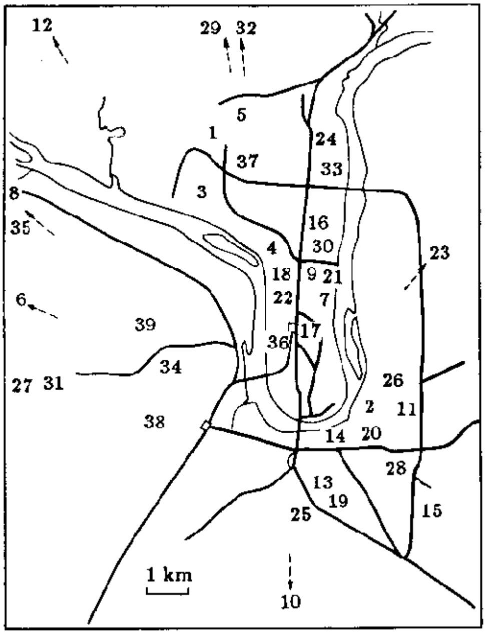
ET= average residence time;

C= reference ground concentration from a unit emission;

$\exp(-r/(ET * U))$ = decay during deposition process;

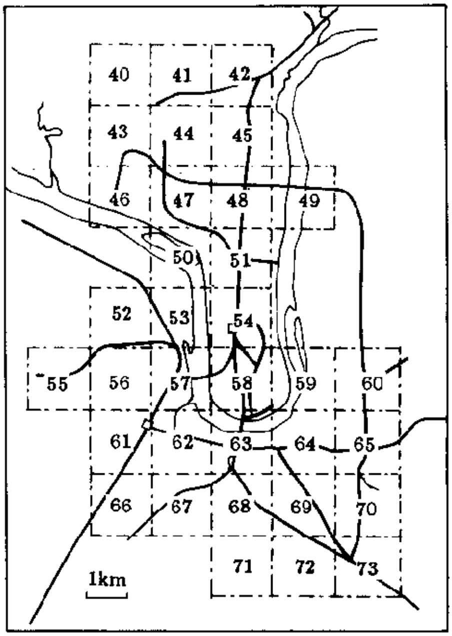
U= wind velocity.

The parameters in the Equation (10) vary with different downwind distance as follows:



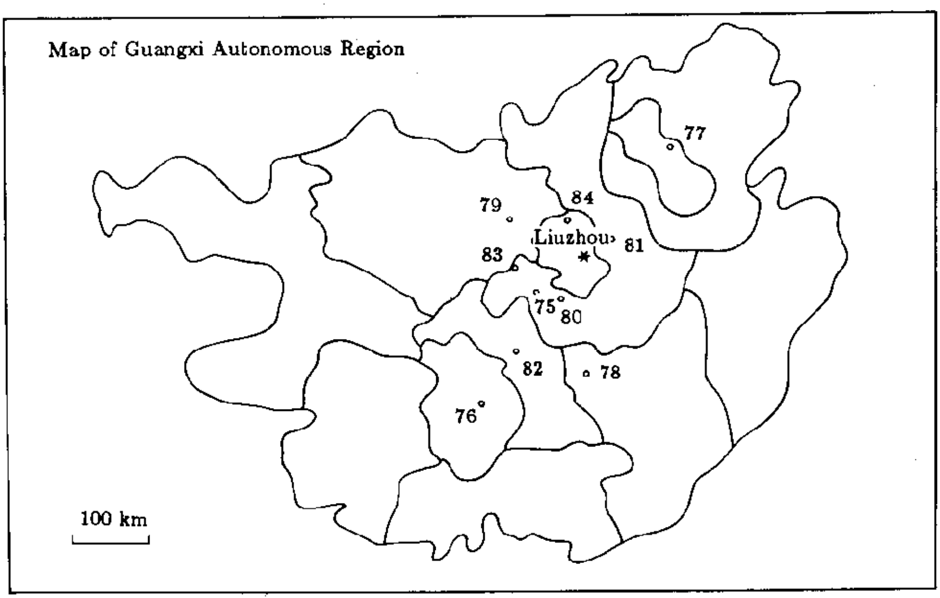
a. point sources in the city

n — means that source No. n is in this direction



b. Area sources in the city

Area source No. 74 (Liu jiang county in the southwest) is omitted



c. City and county sources out of Liuzhou

Fig 2. Emission sources

Usually, $2.15\sigma_z$ is taken as the half width of the diffusion plume (Li Zongkai, 1985), where σ_z is the verticle diffusion parameter taken from the form of city in Brigges (Zeng Peixing, 1987). The height of plume upper edge may be considered as the reference height:

$$Hm = 2.15\sigma_z + H, \tag{11}$$

where

H=effective source height.

When the plume upper edge reaches the average mixing height D, this down-wind distance is noted as r_d. The homogeneous concentration at the distance beyond $r = 2 * r_d$ may be considered (Li Zongkai, 1985). The reference height here is taken as:

$$Hm = D, \qquad r > 2 * r_d, \tag{12}$$

As far as annually averaged deposition is concerned, the crosswind concentration may be considered the same within the downwind deposition area restricted in an angle of 22.5 degrees divided according to the 16 wind directions, assuming the concentration out of that area to be zero (Ma Qianru, 1982). When M = unit:

$$C = \frac{8}{2\pi * r * U * \sigma_z} \sum_{n=1}^{\infty} \{\exp[-\frac{(2n * D - H)^2}{2\sigma_z^2}] + \exp[-\frac{(2n * D + H)^2}{2\sigma_z^2}]\} dy \tag{13}$$

and

$$C = 8/(\pi * r * U * D), \qquad \text{whenever } r > 2 * r_d \tag{14}$$

and the correction

$$R = \exp(-0.5D/(2.15\sigma_z + H)). \tag{15}$$

It has been verified that this deposition model may agree well at $r >> r_d$ with the long distance one (Henning, 1972). The two models simply show:

$$D(r) = 8M * \exp(-r/(ET * U))/(ET * \pi * r * U), \text{ when } r >> r_d. \tag{16}$$

Another test may be obtained from the integration of total deposition upon the whole deposition area restricted by ET. According to the statistical definition of ET, reference Equation (4), these integrations should equalize $(1-1/e)=0.632$. Tests have shown the validity.

Meteorological data are then analyzed according to different kinds of stabilities, wind directions and wind speeds. Calculations and statistics on these different combinations of meteorological conditions have shown that the transfer coefficients between specific sources and receptors are approximately log-normally distributed, as shown in Fig. 3.

CHANCE-CONSTRAINED PROGRAMMING ABATEMENT MODEL

Chance-constrained programming (CCP) is a way of dealing with stochastic programming problems. The deterministic model of Equations (1), (2) and (3) can be replaced here by a more general probabilistic representation:

$$\text{minimize: } Z = \sum_{j=1}^{n} C_j * Q_j * X_j, \tag{17}$$

$$\text{subject to: } P[\sum_{j=1}^{n} Q_j * \hat{T_{ji}} * (1 - X_j) + \sum_{k=1}^{l} Q_k * \hat{T_{ki}} + BG_i \leq D_i] \geq \alpha_{ij}, \quad i = 1, \ldots, m, \tag{18}$$

$$0 \leq min\ X_j \leq X_j \leq \max X_j, \qquad j = 1, \ldots, n, \tag{19}$$

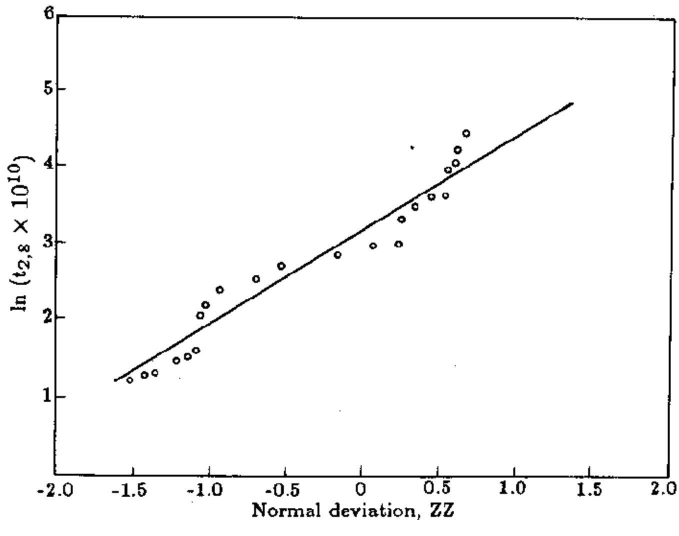


Fig. 3 Transfer coefficient realizations

Constraint (18) is different from constraint (2), where $P[\,]$ represents the probability of the equation within '[ ]' and α_{ij} is a parameter represents security level. Note that $\hat{T_{ji}}$ and $\hat{T_{ki}}$ are probabilistic representations of the transfer coefficients T_{ji} and T_{ki}. The CCP probabilistic constraints clearly indicate that the i-th constraint may be violated no more than $(1 - \alpha_{ij})$ fraction of the time.

As more attention is paid to the anthropogenic emissions and for the sake of unprecisely measured background deposition, BG_i are considered to be zero $(i = 1, \ldots, m)$. And for the sake of taking Liuzhou City as a general control point, the same allowable deposition limit D is given at all receptor points.

This CCP technique requires the existence of the deterministic equivalents to the more general probabilistic constraints. The basis for the development of the deterministic equivalents was given by Ben Isreal (Ellis, 1985).

Since transfer coefficients are log-normally distributed as shown above, under complete colinearity assumption the non-linear transformation functions may be written as:

$$\hat{T_{ji}} = \exp(\overline{ln(T_{ji})} + ZZ * \sigma_{ji}), \\ \hat{T_{ki}} = \exp(\overline{ln(T_{ki})} + ZZ * \sigma_{ki}), \tag{20}$$

where

$\overline{ln(T_{ji})}, \overline{ln(T_{ki})}$= expected value of T_{ji} and T_{ki},

σ_{ji}, σ_{ki}= standard deviation of T_{ji} and T_{ki}.

ZZ= a factor to denote probability of constraint violence which is determinated by security level (Ellis, 1986),

$$e.g. \int_{ZZ}^{\infty} \exp(-t^2/2)dt = 1 - \alpha, \tag{21}$$

while random variable t is normally distributed $N(0, 1)$.

Complete colinearity here means strict dependence between all transfer coefficients in the abatement optimization, i. e. there is always only one predominant meteorological condition which governs pollutant transfer between each source-receptor pair in the control region and this in turn results in transfer coefficient realizations with constant security level, α. Since the calculation of ET has showed that the average deposition range is mainly within several ten or several hundred kilometers, it is obvious that the above assumption is reasonable.

Therefore, the deterministic equivalent to constraint (18) may be expressed as:

$$\sum_{j=1}^{n} Q_j * T_{ji} * (1 - X_j) + \sum_{k=1}^{l} Q_k * T_{ki} \leq D, \quad i = 1, \ldots, m. \tag{22}$$

SULFUR REMOVAL MINIMIZATION

First, consider all the sources as controllable and have cost coefficients C_j=unit ($j = 1, \ldots, n$) in the abatement model Equation (17). The model thus becomes:

$$\text{minimize: } Z = \sum_{j=1}^{n+l} Q_j * X_j , \tag{23}$$

$$\text{subject to: } P[\sum_{j=1}^{n+l} Q_j * T_{ji} * (1 - X_j) \leq D] \geq \alpha, \quad i = 1, \ldots, m, \tag{24}$$

$$0 \leq X_j \leq 1, j = 1, \ldots, n + L. \tag{25}$$

This is in fact an optimization for the least sulfur removal in the abatement plan. This simplified model has its specific meaning at least in two phases:

(1) To optimize least sulfur removal at relaxed high allowable deposition limits, one may readily find the most effective sources to be controlled. These sources, controllable or uncontrollable, are the most serious pollution sources to Liuzhou, thus emphases should be paid to these sources. If there are some uncontrollable sources at present, this procedure will lead to consider at first the development of such techniques as for control of these sources, or it will guide the decision-maker to adopt measures such as shut down some plants or move them to other places to adjust the distribution of the city industry.

(2) Optimizing under strict low allowable deposition limits, it may be found that other sets of sources are still of no concern. These may help to find out the unimportant sources to the sulfur deposition in Liuzhou and they can be deleted out from the optimization process to make it more efficient.

Optimizing under security level of 80% and 50% (50% security level here indicates expected value in the statistical sense), the results are summarized in Table 1 and Table 2 respectively. It is shown that the sources of No. 4, 7, 9, 16, 30, 47, 48, 50 and 51 are the main sources to be concerned. The abatement emission is less than 11% of the total emission in Liuzhou only, but may results in nearly 30% decrease of the highest deposition. More runs have shown sources No. 7 and 51 in the city are of the most importance, but source No. 7 is stove-emission and difficult to control with current practical technology. The government of the city should pay attention to rationalize the distribution of Liuzhou industry according to the above viewpoint.

Other runs are performed under strict deposition limits and they also yield important results. Even at a large abatement scale of the highest deposition, the sources out of the city (sources No. 75 to No. 84, shown in Fig. 3(c)) are still not involved in the abatement. Thus the contribution of sources out of Liuzhou on the annual sulfur deposition in the city is relatively small.

The effects of sources out of Liuzhou and the effects caused by Heshan Power Plant were calculated under different security levels and the results are given in Table 3.

Table 1 SO_2 removal minimization under security level of 80%

Deposition limit abatement 29%; Least SO_2 removal: 5981.84t $(SO_2)/a$.

Emission abatement at each source:

X(1)= .000	X(2)= .000	X(3)= .000	X(4)= .671
X(5)= .000	X(6)= .000	X(7)= .833	X(8)= .000
X(9)= .000	X(10)= .000	X(11)= .000	X(12)= .000
X(13)= .000	X(14)= .000	X(15)= .000	X(16)= .000
X(17)= .000	X(18)= .000	X(19)= .000	X(20)= .000
X(21)= .000	X(22)= .000	X(23)= .000	X(24)= .000
X(25)= .000	X(26)= .000	X(27)= .000	X(28)= .000
X(29)= .000	X(30)= .000	X(31)= .000	X(32)= .000
X(33)= .000	X(34)= .000	X(35)= .000	X(36)= .000
X(37)= .000	X(38)= .000	X(39)= .000	X(40)= .000
X(41)= .000	X(42)= .000	X(43)= .000	X(44)= .000
X(45)= .000	X(46)= .000	X(47)= .000	X(48)= .000
X(49)= .000	X(50)=1.000	X(51)=1.000	X(52)= .000
X(53)= .000	X(54)= .000	X(55)= .000	X(56)= .000
X(57)= .000	X(58)= .000	X(59)= .000	X(60)= .000
X(61)= .000	X(62)= .000	X(63)= .000	X(64)= .000
X(65)= .000	X(66)= .000	X(67)= .000	X(68)= .000
X(69)= .000	X(70)= .000	X(71)= .000	X(72)= .000
X(73)= .000	X(74)= .000	X(75)= .000	X(76)= .000
X(77)= .000	X(78)= .000	X(79)= .000	X(80)= .000
X(81)= .000	X(82)= .000	X(83)= .000	X(84)= .000

Table 2 SO_2 removal minimization at expected value

Deposition limit abatement 30%; Least SO_2 removal: 9725.16t $(SO_2)/a$.

Emission abatement at each source:

X(1)= .000	X(2)= .000	X(3)= .000	X(4)=1.000
X(5)= .000	X(6)= .000	X(7)=1.000	X(8)= .000
X(9)= .479	X(10)= .000	X(11)= .000	X(12)= .000
X(13)= .000	X(14)= .000	X(15)= .000	X(16)=1.000
X(17)= .000	X(18)= .000	X(19)= .000	X(20)= .000
X(21)= .000	X(22)= .000	X(23)= .000	X(24)= .000
X(25)= .000	X(26)= .000	X(27)= .000	X(28)= .000
X(29)= .000	X(30)=1.000	X(31)= .000	X(32)= .000
X(33)= .000	X(34)= .000	X(35)= .000	X(36)= .000
X(37)= .000	X(38)= .000	X(39)= .000	X(40)= .000
X(41)= .000	X(42)= .000	X(43)= .000	X(44)= .000
X(45)= .000	X(46)= .000	X(47)= .925	X(48)=1.000
X(49)= .000	X(50)= .886	X(51)=1.000	X(52)= .000
X(53)= .000	X(54)= .000	X(55)= .000	X(56)= .000
X(57)= .000	X(58)= .000	X(59)= .000	X(60)= .000
X(61)= .000	X(62)= .000	X(63)= .000	X(64)= .000
X(65)= .000	X(66)= .000	X(67)= .000	X(68)= .000
X(69)= .000	X(70)= .000	X(71)= .000	X(72)= .000
X(73)= .000	X(74)= .000	X(75)= .000	X(76)= .000
X(77)= .000	X(78)= .000	X(79)= .000	X(80)= .000
X(81)= .000	X(82)= .000	X(83)= .000	X(84)= .000

Table 3 Effects of sources out of Liuzhou

Security level, %	80			50		
Sources	Total g/m^2.a	Heshan g/m^2.a	%	Total g/m^2.a	Heshan g/m^2.a	%
Average deposition effect	0.24	0.12	50	0.16	0.08	50

CONTROL COST MINIMIZATION

For the sake of relatively smaller contribution derived above, sources out of Liuzhou are called off from the optimization processes and considered as uncontrollable sources. Such a procedure may not only simplify the optimization process but also make it possible for Liuzhou government to form its own abatement strategy, so that it can be carried out more efficiently.

Sixty runs were performed to assess the effects of the system risk level $1-\alpha$, on overall system cost $Z_{\min}$ and receptor deposition to span the complete range of stipulated maximum allowable receptor deposition level D. That range is lower-bounded by infeasible values of D, i. e.

$$\sum_{j=1}^{n} Q_j * (1-X_j) * T_{ji} + \sum_{k=1}^{l} Q_k * T_{ki} \geq D, \quad i-1,\ldots,m \tag{26}$$

$$X_j = \max X_j, \qquad j=1,\ldots,n \tag{27}$$

$$\sum_{j=1}^{n} Q_j * (1-X_j) * T_{ji} + \sum_{k=1}^{l} Q_k * T_{ki} \leq D, \quad i=1,\ldots,m \tag{28}$$

$$X_j = 0 \qquad j=1,\ldots,n \tag{29}$$

These two bounds and the intermediate lowest cost curves were drawn up in Fig. 4 based on these runs.

Fig. 4 is the most significant contribution of stochastic programming to ordinary deterministic programming in the sense that it provides not only the whole degree of deposition limits but also the risk levels or security levels to meet these limits at any acceptable control cost. Finally, Fig. 4 and a complete set of corresponding minute descriptions of each source abatement level of the 60 runs as an appendix are provided to Liuzhou government. All these will surely benefit in reaching the final goal of Liuzhou acid deposition abatement.

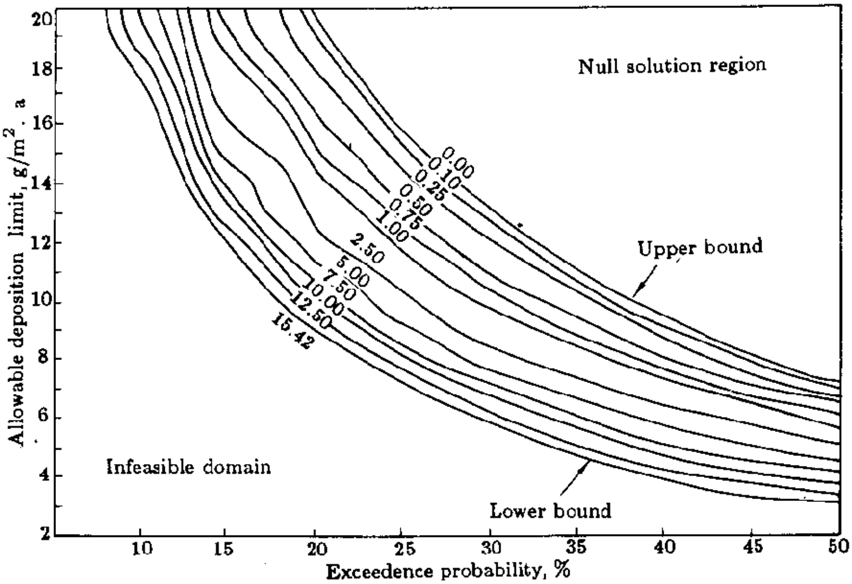


Fig. 4 Liuzhou emission control cost response surface (unit: million Yuan(RMB))

RECOMMENDED ABATEMENT PLAN

From the detailed analysis of the abatement sources resulted from the control cost minimization, it was found that most of the area emissions should be cut down whenever a strict deposition limit is to be kept. Area emissions, which are different from point sources, are difficult to control according to each geometry net in the minimization (Fig. 2b), and they are the most serious pollution sources of ground level SO_2 concentration, so it is suggested that Liuzhou should spread the use of coal briquet to control all the area SO_2 emissions in the city. Based on this suggestion, a series of control cost minimizations are performed among all controllable point sources. Two final results are listed in Table 4 and Table 5. It is recommended that the best decision should roll back the maximum deposition by approximately 50%. If the expected deposition limit is too lax, the abatement of all area sources will become meaningless. If it is too strict, the cost of control will increase rapidly to an extent that Liuzhou can not afford.

Table 4 Sub-optimal abatement recommended under security level of 80%

Deposition limit abatement: 50%; Lowest control cost:11.48 million yuan (RMB)/a; Total amount of SO_2 removal:30939.02t(SO_2)/a; Emission abatement at each source:

X(1)= .600	X(2)= .197	X(3)= .800	X(4)= .800
X(5)= .000	X(6)= .000	X(7)= .000	X(8)= .000
X(9)= .800	X(10)= .000	X(11)= .800	X(12)= .000
X(13)= .800	X(14)= .000	X(15)= .000	X(16)= .800
X(17)= .800	X(18)= .800	X(19)= .000	X(20)= .000
X(21)= .800	X(22)= .000	X(23)= .000	X(24)= .800
X(25)= .000	X(26)= .400	X(27)= .000	X(28)= .000
X(29)= .000	X(30)= .800	X(31)= .000	X(32)= .000
X(33)= .800	X(34)= .000	X(35)= .000	X(36)= .800
X(37)= .800	X(38)= .000	X(39)= .000	X(40)= .400
X(41)= .400	X(42)= .400	X(43)= .400	X(44)= .400
X(45)= .400	X(46)= .400	X(47)= .400	X(48)= .400
X(49)= .400	X(50)= .400	X(51)= .400	X(52)= .400
X(53)= .400	X(54)= .400	X(55)= .400	X(56)= .400
X(57)= .400	X(58)= .400	X(59)= .400	X(60)= .400
X(61)= .400	X(62)= .400	X(63)= .400	X(64)= .400
X(65)= .400	X(66)= .400	X(67)= .400	X(68)= .400
X(69)= .400	X(70)= .400	X(71)= .400	X(72)= .400
X(73)= .400	X(74)= .400		

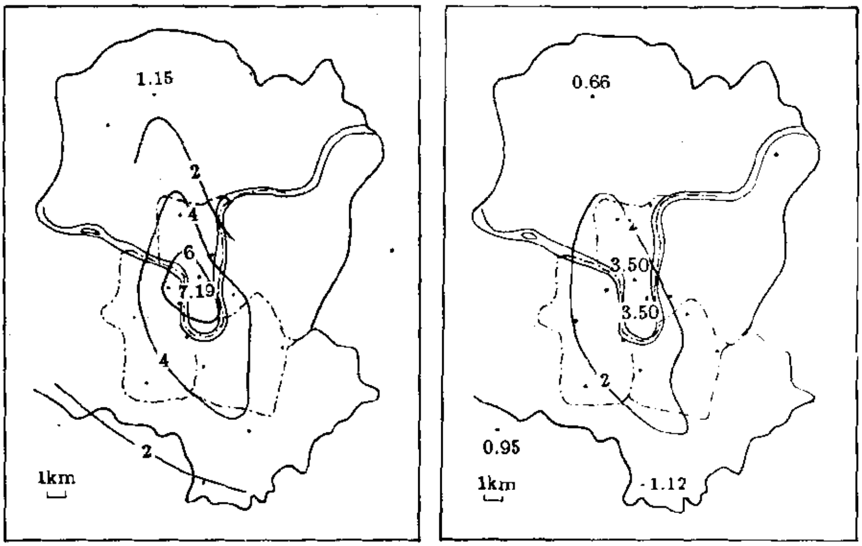
Table 5 Sub-optimal abatement recommended at expected value

Deposition limits abatement: 50%; Lowest control cost:11.92 million Yuan(RMB)/a; Total amount of SO_2 removal:34868.82 (SO_2)/a; Emission abatement at each source:

X(1)= .600	X(2)= .800	X(3)= .800	X(4)= .800
X(5)= .000	X(6)= .000	X(7)= .000	X(8)= .000
X(9)= .800	X(10)= .000	X(11)= .800	X(12)= .000
X(13)= .614	X(14)= .533	X(15)= .000	X(16)= .800
X(17)= .800	X(18)= .800	X(19)= .000	X(20)= .000
X(21)= .800	X(22)= .000	X(23)= .000	X(24)= .800
X(25)= .000	X(26)= .000	X(27)= .000	X(28)= .000
X(29)= .000	X(30)= .800	X(31)= .000	X(32)= .000
X(33)= .800	X(34)= .000	X(35)= .000	X(36)= .800
X(37)= .800	X(38)= .000	X(39)= .000	X(40)= .400
X(41)= .400	X(42)= .400	X(43)= .400	X(44)= .400
X(45)= .400	X(46)= .400	X(47)= .400	X(48)= .400
X(49)= .400	X(50)= .400	X(51)= .400	X(52)= .400
X(53)= .400	X(54)= .400	X(55)= .400	X(56)= .400
X(57)= .400	X(58)= .400	X(59)= .400	X(60)= .400
X(61)= .400	X(62)= .400	X(63)= .400	X(64)= .400
X(65)= .400	X(66)= .400	X(67)= .400	X(68)= .400
X(69)= .400	X(70)= .400	X(71)= .400	X(72)= .400
X(73)= .400	X(74)= .400		

It is found that the most important sources are fluidized-bed combustors except source No. 1 (power plant emission) and source No. 26 (small boiler). Liuzhou should encourage the use of FBC desulfurization approach.

The deposition isopleth map after the recommended abatement is drawn up in Fig. 5(b) at the expected value, Fig. 5(a) is its initial deposition used for reference.



a. Initial deposition b. After recommended abatement

Fig. 5 Deposition isopleth map at expected value

CONCLUSION

A deterministic model for development of acid deposition abatement strategies of Liuzhou was extended into a probabilistic form by the incorporation of uncertainty associated with pollutant transport and deposition processes. Transfer coefficients between each source-receptor pair was specified as a vital stochastic parameter. Average residence time of SO_2 and sulfate for Liuzhou was calculated to be 12 hours which has summed up the comprehensive effects of pollutant transport, transformation and deposition during dry and wet processes. The value of ET indicates that the deposition in Liuzhou is mainly within the medium-range and this in turn calls for the establishment of single source deposition model which is most applicable to the atmospheric environment around Liuzhou. Tests were conducted to show the validity of the model. Calculations and statistics of variable meteorological conditions show that the probabilistic distribution of transfer coefficients is log-normal.

Chance-constrained programming was introduced to meet two kinds of optimization: SO_2 removal minimization and control cost minimization. Lowest control costs were obtained at each allowable deposition limit under different security levels and the map of isopleth cost curves of Liuzhou was drawn. Based on the careful analysis of the emissions to be cut down, a more practical abatement plan is recommended, which urges the full control of all area emissions and encourages to adopt the advanced FBC desulfurization technique according to the sources shown in Table 4 and Table 5, to cut down the highest annual sulfur deposition to one half.

It is worth while to note that the total contribution of emissions out of Liuzhou is relatively unimportant to the annual sulfur deposition in the city, though the influence of Heshan Power Plant makes half of their contribution. Serious emissions to be concerned are mainly in the city, especially the point source No. 4, 7, 9, 16, 30 and area emission just at the north center of the city, i. e. source No. 47, 48, 50 and 51. Liuzhou government should pay more attention to rationalize the distribution of city industry and residential areas.

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