A Game-theoretic Approach to Acid Rain Abatement —Conflict Analysis of Environmental Loads

by

Norio OKADA* and Yoshiko MIKAMI**

*Department of Social Systems Engineering, Tottori University
**IBM Japan, Osaka

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The detrimental impacts of acid rain have become been widely publicized, and effective, and equitable, methods to mitigate the acid rain problem remain to be found. This paper focuses on conflicts involved in allocation of the total emission loads to be reduced to respective pollution sources of acid rain, and proposes a game-theoretic approach to the resolution of the conflict. With an example abstracted from the real-world problem taking place in the North America and Canada, a systematic analysis is performed and policy implications of the results examined to assess the applicability of the proposed model.

Key words : Acid Rain, Environmental Management, Conflict Analysis, Game Theory

1. Introduction

In Europe, North America and even Japan, the detrimental impacts of acid rain have recently been widely publicized and much research work has been conducted to develop effective strategies for acid rain abatement. As a means of quantifying the impacts of alternative management strategies, large-scale linear programming-based screening models have been employed [1],[2],[3].

Nevertheless, effective, and equitable, means to control acid rain emissions at pollution sources remain to be studied. A typical class of problem which involves equitable means of abatement may be termed resolution of acid rain conflicts which in turn involves a highly political decision-making process. McBean and Okada [4] and Hipel and et al. [5] claimed that this decision-making process may be likened to enactment of multi-player 'game' with each player possessing a set of viable options and preferences. Characteristically, the viable options available to each player are qualitatively different and their preferences to be assessed only in terms of order. Metagame analyses were applied and their potential of scientifically examining this type of conflict management strategies demonstrated.

This paper deals with a different type of conflict resolution which is becoming a central issue of policy-makers in acid rain management. The problem is how to assign the target deposites to be reduced in respective receptors to major emission sources which are commonly located quite a distance from the receptors. A conflict arises among receptors; each of them seeks to reduce the target burden of emissions reduction as much as possible while the total amounts of burdens imposed on them are to be fixed. The more one reduces the target level, the less the others. Another aspect of the conflict is how to balance the trade-off relationship between efficient (cost-effective) and fair means of assigning target burdens of emissions reduction to each emission source. The above-stated screening models are capable of selecting effective technical means of acid rain abatement at emission sources but are incapable of explicitly analyzing the resolution of the conflict at stake.

This paper presents a game-theoretic approach to this acid rain abatement conflict, that is, effective and fair allocation of emissions to be reduced to emission sources. We note first that this type of environmental management conflict is categorized as allocation of environmental loads of reduction to pollution sources. Kilgour et al.[10]

tor j. We term this assignment method as 'A' mode of assignment or the proportional assignment method. This mode is mathematically defined as

$$\rho_{ij} = a_{ij} / \sum_i a_{ij} \qquad (a_{ij} \geqq 0) \qquad (2)$$

b) 'EA' mode: The ratio is determined in proportion to the respective transfer coefficients a_{ij} weighted by e_i representing the amounts of emissions at source i. We refer to this as 'EA' mode or the weighted proportional assignment method. This mode is formulated as

$$\rho_{ij} = e_i a_{ij} / \sum_i e_i a_{ij} \qquad (3)$$

c) Max-Min mode: For each receptor j, either of those ratios derived from both 'A' and 'EA' modes is set as either of the upper or lower bound on the range of values, and the ratio is equalized over sources i (=1,..,n) to a maximum extent so that there may not be those sources to which improperly large amounts of loads reduction are allocated. We assume here that each source (player) i may act independently to achieve the most equitable target ratio for itself, given an arbitrary receptor j, or that it may form a group (partial) or grand (entire) coalition to work together, and to achieve the most equitable target ratio for the group per se, given receptor j. This mode is defined as a linear programming problem for each receptor j (=1,..,n), such that

$$\left\{ \begin{array}{ll} & \max \ \varepsilon \\ \text{sub. to} & \rho_{ij} \Delta d_j \geqq \varepsilon \\ & \sum_{i \in S} \rho_{ij} \Delta d_j \geqq |S| \varepsilon \\ & \\ & \text{for all } (i, j) \\ & \text{for any } S \ (\{i\} \subseteq S \subseteq N) \end{array} \right. \qquad (4)$$

where S stands for an arbitrary (group) coalition including both the grand coalition which is formed by all emission sources as players, and the independent sources going alone. $|S|$ denotes the number of members who form the coalition S.

Phase 2: Given the constraints as determined in Phase 1, emission sources are assumed to pursue the minimization of the cost burdens to be imposed on themselves. In resolving this conflict, all emission sources who are regarded as the players of the game are assumed to cooperate with a view to forming a grand coalition N; thus they may achieve overall the most efficient (cost-effective) allocation of the actual amounts of loads to be reduced at respective sources. This is based on the supposition that with an increase in size, the total benefits (pay-offs) of forming a coalition and Okada et al.[11],[12] showed that allocation of COD loads to the pollution sources located along a semi-closed water system may well be formulated as a cooperative game theory model. In the following the current paper extends this approach by incorporating the mechanism of the long-range transport of emitted pollutants to receptors.

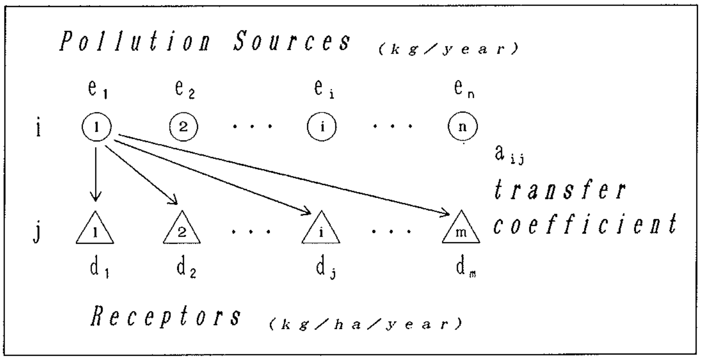

Fig. 1 Model diagram

2. ModelFormulation

2.1 Assumed Hierarchical Process of Load Allocation

The process of allocating the target deposition loads to be reduced to respective emission sources are assumed to take a hierarchical decision making process as illustrated in Fig. 2. The assumed source-receptor relationship is modeled as in Fig. 1.

Phase 1: We assume a decision-making body on federal level. This body sets up the maximum allowable deposites in receptor j, d_{jmax} ($j=1,...m$).In other words, they specify the minimum amounts of emissions to be reduced, $\Delta d_j (>0)$

$$\Delta d_j = d_j - d_{jmax} \qquad (1)$$

Given Δd_j for $j=1,...,m$, we propose three distinct modes of assingning the target loads to respective emission sources, $i=1,..,n$ as follows. The target ratio of assignment of Δd_j to source i, ρ_{ij} is determined by one of the following:

a) 'A' mode: The ratio is determined in proportion to the respective transfer coefficients @ representing the ratio of the amounts of the loads emitted at source i to those transported from there to recep-

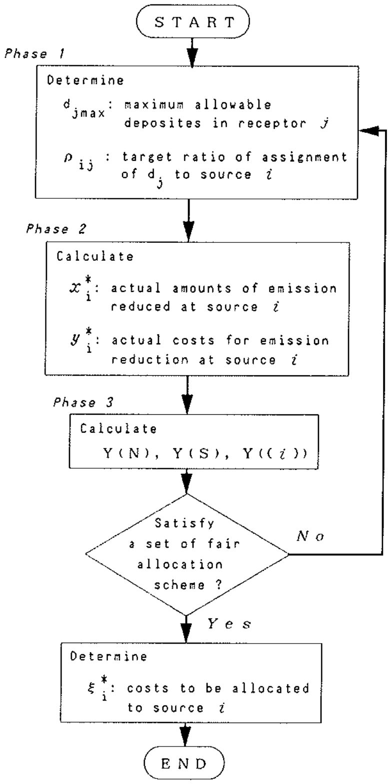

Fig. 2 Load allocation process

increase in terms of reduced costs. To borrow a term from game theory, this assumes the 'law of superadditivity' to hold for increased coalition sizes. Therefore, the problem is formulated as

$$\begin{cases} \min & \sum_{i\in N} f_i(x_i) \\ \text{sub. to} & \sum_{i\in N} a_{ij}x_i \geqq \Delta d_j, \ (j=1,2,\cdots,m), \ 0\leqq x_i\leqq e_i \end{cases} \quad (5)$$

Given the optimal solutions x_i^* to this optimization problem, we get the optimal total costs, Y(N) as

$$Y(N)=\sum_i f_i(x_i^*) \quad (6)$$

<u>Phase 3</u>: Given the optimal-cost information, Y(N) as obtained from the analysis in phase 2, we now turn to allocation of the total costs. This per se is an interesting theme of cooperative game theory. Much research work has been documented in the literature (eg. [13],[14]). The proposed approaches are basically classified into two: one being based on the concept of core as a fair allocation scheme, and another based on other concepts other than the core. A famous and simple scheme of fair allocation to fall under the second category is Shapley Value. The idea is to allocate the total costs for the grand coalition so that the marginal costs of participation in the respective coalition as the last member should be averaged over all possible combinations of coalitions for the particular player (eg. [13],[14]).

The core that underlies the allocation scheme of the first category is mathematically defined as

$$\begin{cases} Y(\{i\}) \geqq \xi_i & (i=1,2,\cdots,n) \\ Y(S) \geqq \sum_S \xi_i & \\ Y(N) \geqq \sum_N \xi_i & \end{cases} \quad (7)$$

where Y (S) for coalition S is obtained for the optimal solutions $\tilde{x}_i$ to the following optimization problem:

$$\begin{cases} \min & \sum_{i\in S} f_i(x_i) \\ \text{sub. to} & \sum_{i\in S} a_{ij}x_i \geqq \sum_{i\in S} \rho_{ij}\Delta d_j \ (j=1,2,\cdots,n), \ 0\leqq x_i\leqq e_i \end{cases} \quad (8)$$

Likewise, Y({i}) for independent player i is obtained for the optimal solutions @ to the optimization problem:

$$\begin{cases} \min & f_i(x_i) \\ \text{sub. to} & a_{ij}x_i \geqq \rho_{ij}\Delta d_j \ (j=1,2,\cdots,n), \ 0\leqq x_i\leqq e_i \end{cases} \quad (9)$$

It is noted that the assumed law of superadditivity is stated as

$$v(N) \geqq v(S) + v(N-S) \quad (10)$$

for any coalition S including {i}, where V(N), V(S) and V({i}) are called the characteristic functions of this cooperative game.

They are defined as

$$v(N)=-Y(N), \ v(S)=-Y(S), \ v(N-S)=-Y(N-S) \quad (11)$$

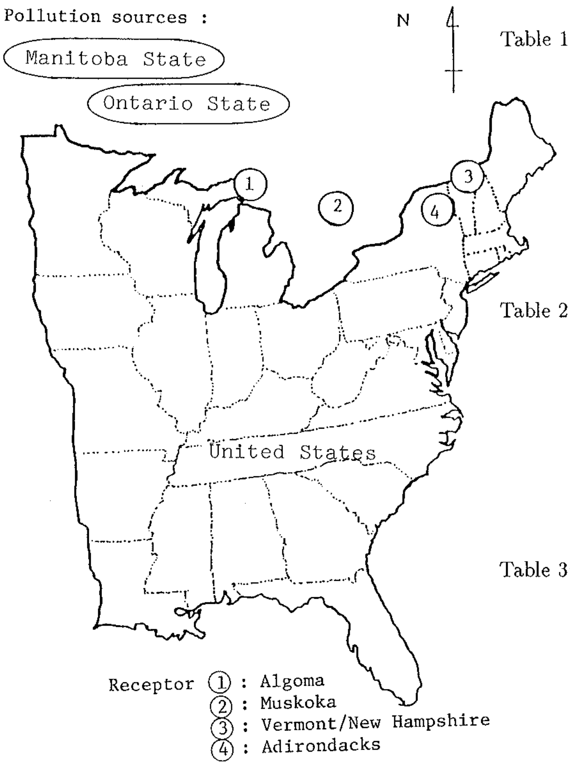

Fig.3 Study area

Table 1: Assumed amounts of enission from source i

i	Place	e_i
1	N. Manitoba	8
2	S. Manitoba	10
3	N. W. Ontario	17
4	N. E. Ontario	7

(10^9 $kg/year$)

Table 2: Assumed amounts of deposites in receptor j

j	Place	d_j
1	Algona	16
2	Muskoka	33
3	Vermont/N. H.	29
4	Adirondacks	31

($kg/ha/year$; Wet Sulfate)

Table 3: Maximum allowable amounts of deposites in receptor j

(Case A to D)

j	Place	d_{jmax}
1	Algona	8.0
2	Muskoka	16.5
3	Vermont/N. H.	14.5
4	Adirondacks	15.5

($kg/ha/year$; Wet Sulfate)

(Case E)

j	Place	d_{jmax}
1	Algona	11.2
2	Muskoka	23.1
3	Vermont/N. H.	20.3
4	Adirondacks	21.7

($kg/ha/year$; Wet Sulfate)

The core as defined above may not always exist. If it exists, there is no guarantee that it has a unique feasible solution. Core-based allocation methods such as Nucleolus, Weak Least Core, Proportional Least Core may be applied to reduce it to a unique one (e.g. [13],[14]).

3. Case Study: Model Applications

3.1 Study Area

The study area which represents a real-world acid rain conflcit in North America and Canada is selected as illustrated in Fig. 3. The data were collected basically from Gibian [6], Streets [7], Webber [8] and Crandall [9].

Table 4 Assumed values for transfer coefficients

(1)

Case A	Receptor			
Source	1	2	3	4
1	0.45	0.25	0.20	0.29
2	0.77	0.77	0.00	0.00
3	1.67	1.67	1.67	1.67
4	2.99	0.91	1.43	1.04

(unit: $kg \cdot sulfate/ha/10^9 kg/year$)

(2)

Case B	Receptor			
Source	1	2	3	4
1	0.45	0.25	0.20	0.29
2	0.77	0.77	0.10	0.10
3	1.67	1.67	1.67	1.67
4	2.99	0.91	1.43	1.04

(3)

Case C	Receptor			
Source	1	2	3	4
1	0.45	0.25	0.20	0.29
2	0.77	0.77	0.00	0.00
3	2.00	2.00	2.00	2.00
4	2.99	0.91	1.43	1.04

(4)

Case D	Receptor			
Source	1	2	3	4
1	0.45	0.25	0.20	0.29
2	0.77	0.77	0.00	0.00
3	1.34	1.34	1.34	1.34
4	2.99	0.91	1.43	1.04

(5)

Case E	Receptor			
Source	1	2	3	4
1	0.45	0.25	0.25	0.29
2	0.77	0.77	0.00	0.00
3	1.67	1.67	1.67	1.67
4	2.99	0.91	1.43	1.04

Table 5 Cases of anlysis

Case	Remarks (Differences from Standard)
Case A	Standerd Case
Case B	Replace zero entries with 0.1 in a_{ij}.
Case C	Increase each of a_{ij} for source $i = 3$ by 20 *percent*.
Case D	Decrease of each a_{ij} for source $i = 3$ by 20 *percent*.
Case E	Upgrade target reduction ratio for each receptor from 50 to 70 *percent*.

Table 6: Target ratios of load assignment (ρ_{ij}) for Case A

A mode	Receptor			
Source	1	2	3	4
1	0.08	0.07	0.06	0.10
2	0.13	0.22	0.00	0.00
3	0.28	0.46	0.51	0.55
4	0.51	0.25	0.43	0.35

EA mode	Receptor			
Source	1	2	3	4
1	0.06	0.05	0.04	0.06
2	0.13	0.17	0.00	0.00
3	0.47	0.64	0.71	0.75
4	0.34	0.14	0.25	0.19

MAX-MIN mode	Receptor			
Source	1	2	3	4
1	0.08	0.05	0.04	0.06
2	0.13	0.17	0.00	0.00
3	0.395	0.53	0.53	0.59
4	0.395	0.25	0.43	0.35

It is noted, however, that the application model thus specified may not precisely reflect the real world problem. It is rather a hypothetical model which abstracts the essence of the actual conflict.

The cost function with respect to x_i, the amounts of emissions reduced is identified as

$$f_i(x_i) = 0.590255(\exp(0.0927209 \cdot x_i) - 1) \qquad (i=1,2,\cdots,n) \qquad (12)$$

which is assumed to be identical for all emission sources. Because of its convexity, piece-wise linear programming approach is used in solving the optimization problems. Other parameters are set as listed in Tables 1 to 4.

Table 7: Caluculated emissions reduced and needed for a set of coalition types (Case A).

(emissions: $10^9 kg/year$; costs: $dollar/year$)

Coalition		A mode		EA mode		MAX-MIN mode	
Grand		x^*	$Y(N)$	x^*	$Y(N)$	x^*	$Y(N)$
N	1	0.0000	0.8653	0.0000	0.8653	0.0000	0.8653
	2	0.0000		0.0000		0.0000	
	3	9.0000		9.0000		9.0000	
	4	1.6154		1.6154		1.6154	
Group		$\tilde{x}$	$Y(S)$	$\tilde{x}$	$Y(S)$	$\tilde{x}$	$Y(S)$
S	1	0.0000	0.5837	0.0000	0.7103	0.0000	0.5837
	2	0.0000		0.0000		0.0000	
	3	7.4102		8.4970		7.4102	
	1	0.0000	0.7510	0.0000	0.4502	0.0000	0.6298
	2	3.6453		2.3961		2.8498	
	4	6.7067		4.5000		6.1106	
	1	0.0000	0.7728	0.0000	0.7728	0.0000	0.7728
	3	7.5000		7.5000		7.5000	
	4	2.8606		2.8606		2.8606	
	2	0.0000	0.7836	0.0000	0.8068	0.0000	0.8068
	3	8.3713		8.5689		8.5689	
	4	1.5000		1.5000		1.5000	
	1	3.2069	0.5709	3.2069	0.4468	3.2069	0.4468
	2	5.1731		3.6731		3.6731	
	1	0.0000	0.4427	0.0000	0.5950	0.0000	0.4427
	3	6.0329		7.5180		6.0329	
	1	0.0000	0.5117	0.0000	0.2456	0.0000	0.4506
	4	6.7067		3.7260		6.1106	
	2	0.0000	0.5129	0.0000	0.6521	0.0000	0.5331
	3	6.7186		8.0030		6.9162	
	2	3.0000	0.6271	1.5000	0.3822	2.8352	0.5476
	4	5.9835		4.3517		5.2164	
	3	7.4192	0.6727	7.5000	0.7125	7.5000	0.7125
	4	1.5000		1.9664		1.9664	
Single		$\hat{x}$	$Y(\{i\})$	$\hat{x}$	$Y(\{i\})$	$\hat{x}$	$Y(\{i\})$
i	1	5.3448	0.3809	3.3000	0.2126	3.3000	0.2126
	2	4.7143	0.3247	3.6429	0.2391	3.6429	0.2391
	3	5.1048	0.3595	6.9611	0.5377	5.4761	0.3926
	4	5.2164	0.3695	2.8317	0.1779	5.2164	0.3695

x^*: Emissions reduced, $Y(N)$: Costs needed, for grand coalition
$\tilde{x}$: Emissions reduced, $Y(S)$: Costs needed, for group coalition
$\hat{x}$: Emissions reduced, $Y(\{i\})$: Costs needed, for single coalition

3.2 Study Cases

The study cases of analysis are set up as listed in Table 5, where Case A corresponds to the standard case and other cases to its variants.

3.3 Model Calculations

1) Analysis of Standard Case (Case A)

Application of the Phase 1 model gives the target ratios of load assignment calculated as listed in Table 6. Analysis of this table indicates:

(1) Application of the EA mode results in the values of the target ratios evaluated basically halfway between those obtained from the A mode and those from the Max-Min mode assignment. This is a typical analytical property built in the assumed modes of assignment.

(2) Rigorously, this is not true of the values for Source 3. The calculated ratio is highest for the EA mode's application. The reason

is that the amounts of emission at this source are estimated to be highest and that the proportional assignment as weighted by this index pushes up the target ratio for this source to the highest value.

By applying the phase 2 model to Case A, we obtain the results as listed in Table 7. Proceeding to the Phase 3 analysis by use of Shapley Value and Nuleolus results in the cost allocations as shown in Tables 8 and 9, respectively. Scrutiny of these results shows that:

Table 8: Caluculated costs to be allocated (by Shapley Value).

(10^9 *dollar/year*)

Case	A mode		EA mode		MAX-MIN mode	
Case A	Source	Costs	Source	Costs	Source	Costs
	1	0.1795	1	0.1114	1	0.1121
	2	0.1953	2	0.1638	2	0.1635
	3	0.2004	3	0.4493	3	0.2891
	4	0.2901	4	0.1408	4	0.3005
Case B	Source	Costs	Source	Costs	Source	Costs
	1	0.1715	1	0.1062	1	0.1075
	2	0.2211	2	0.2005	2	0.2009
	3	0.1933	3	0.4314	3	0.2709
	4	0.2795	4	0.1272	4	0.2860
Case C	Source	Costs	Source	Costs	Source	Costs
	1	0.1574	1	0.0841	1	0.0858
	2	0.1719	2	0.1327	2	0.1322
	3	0.1296	3	0.3454	3	0.2209
	4	0.2222	4	0.1190	4	0.2422
Case D	Source	Costs	Source	Costs	Source	Costs
	1	0.2200	1	0.1340	1	0.1361
	2	0.2433	2	0.2054	2	0.2083
	3	0.2880	3	0.5839	3	0.3853
	4	0.3406	4	0.1686	4	0.3622
Case E	Source	Costs	Source	Costs	Source	Costs
	1	0.3054	1	0.1740	1	0.1780
	2	0.3246	2	0.2553	2	0.2571
	3	0.3188	3	0.7550	3	0.4810
	4	0.4449	4	0.2095	4	0.4777

(i) The outlined patterns of cost allocations are identical. In the Shapley Value case, for instance, those sources which have large values for their related transfer coefficients and emission amounts tend to share the highest costs for any mode assignment. Surce 3 which emits the largest amounts of pollutants among all sources, is a typical example of this, which is allocated the highest costs when the EA mode is applied, and the second highest when either of the A mode or Max-Min mode is applied. Likewise, Source 4 is found to contribute a great deal to the long-range transport of pollutants to the receptor areas since it has relatively large values for ts related transfer coefficients. Consequently it shares the highest allocated costs by the A mode and Max-Min mode assignments. On the contrary, other sources such as Sources 1 and 2 are found to share less costs.

(ii) The Max-Min mode tends to help equalize the way the total costs are shared by the sources.

(iii) The same tendencies may be observed for the results when Nucleouls, a typical core-based fair allocation method, is employed (see Table 9).

2) Comparative and Sensitivity Analyses of Cases B to E

Table 9: Caluculated costs to be allocated (by Nucleolus).

(10^9 *dollar/year*)

Case	A mode		EA mode		MAX-MIN mode	
Case A	Source	Costs	Source	Costs	Source	Costs
	1	0.1422	1	0.0692	1	0.0953
	2	0.1410	2	0.2046	2	0.1792
	3	0.2566	3	0.4258	3	0.2723
	4	0.3255	4	0.1657	4	0.3185
Case B	Source	Costs	Source	Costs	Source	Costs
	1	0.1190	1	0.0650	1	0.0904
	2	0.2709	2	0.2143	2	0.2006
	3	0.1565	3	0.4246	3	0.2607
	4	0.3189	4	0.1614	4	0.3135
Case C	Source	Costs	Source	Costs	Source	Costs
	1	0.1196	1	0.0557	1	0.0848
	2	0.1153	2	0.1848	2	0.1599
	3	0.1853	3	0.3024	3	0.1847
	4	0.2611	4	0.1382	4	0.2518
Case D	Source	Costs	Source	Costs	Source	Costs
	1	0.1654	1	0.0901	1	0.1067
	2	0.1928	2	0.2268	2	0.1927
	3	0.3466	3	0.5794	3	0.4066
	4	0.3872	4	0.1955	4	0.3860
Case E	Source	Costs	Source	Costs	Source	Costs
	1	0.2495	1	0.1126	1	0.1572
	2	0.2456	2	0.3121	2	0.2660
	3	0.3904	3	0.7255	3	0.4686
	4	0.5083	4	0.2434	4	0.5018

Calculations are conducted to operationally analyze several variants of Case A. From Tables 8 and 9, we may conclude that:

(1) Case B is different from Case A merely in that all the zero entries are changed to 0.1 for Source 2. Obviously, the result is the increased costs imposed on Source 2, which well reflects the increased obligations of emissions reduction for this source when group coalitions or independent cases are examined in Phase 2, thus explicitly assessing its bargainability in the cost allocation game to follow. In contrast, precisely the same calculation result is obtained for the grand coalition in the Phase 2 analysis. The above fact is always the same for whatever mode of target ratio assignment is applied or whichever method of cost allocation is employed. Otherwise, the same tendencies are observed as those for the standard case.

(2) Case C is different from Case A in that those transfer coefficients related to Source 3 are assumed to take increased values by 20 percent, with an implication that the source that emits the largest amounts of pollutants is now assumed to affect the receptors even more so. This results in an increased efficiency and effectiveness of emissions control at this source, which in turn leads to the total costs reduced by some 20 percent for the grand coalition in the Phase 2 analysis. Similarly, the total costs are found to be reduced for any other coalitions including going independently. In consequence, all sources enjoy decreased costs to share. Especially, Source 3 shares costs reduced by 35 to 50 percent, since its bargainability is improved as a result of increased efficiency in

emissions control, thus justifying amounts of emissions reduction concentrated exclusively on this source. This fact holds for whatever mode of target ratio assignment is applied or whichever method of cost allocation is used. Otherwise, the same tendencies may be obtained as those for Case A.

(3) Case D is a variant of Case A and in a way symmetrical to Case C. Those transfer coefficients related to Source 3 are reduced by 20 percent. As a result, precisely the reverse facts are claimed as compared to Case C. Less efficiency is achieved at Source 3, with a result in a less intensive treatment of emissions at this source and more distributed treatments at other sources than in Case A, which in turn leads to an increased share of costs imposed on the source. This is true irrespective of the mode of target ratio assignment selected or the method of cost allocation applied. In other respects, the tendencies are found to be basically the same as obtained from Case A.

(4) Case E assumed to adopt the federal-level policy of reducing the current deposites in receptors by 70 percent, other than 50 percent which is assumed for Case A. The result is that the total costs as well as those allocated to each source increase by 50 to 100 percent. This is the case for whatever mode of target ratio assignment is selected or whichever method of cost allocation is applied. Otherwise, we get the tendencies that parallel those derived for Case A.

5. Conclusion

As has well been illustrated in the above analyses, the proposed model has been proved to derive scientifically some reasonable allocations of both the emission loads for reduction and resultant costs to their sources. The decision-making mechanism assumed in this paper was a three-phased process, and thus the conflcit has been formulated as a hierarchical game. With a hypothetical example of analysis abstracted from a real-world conflict taking place in North America and Canada, systematic analyses have been conducted and the implications of the results discussed in detail. We may conclude from this that the proposed model will become a useful scientific tool in developing efffective, and equitable, alternatives of acid rain abatement.

However, there remains much to be done in this line of research. For instance, the plausibility of the major assumtions that underly the proposed model should be carefully reexamined against actualities. This is even more important if the model is to be applied to a real-world conflict, with a view to developing a viable means of acid rain abatement. Uncertainties involved in estimating values of parameters should be more explicitly accounted for. From a veiwpoint of game theory, the hierarchical structure of the conflict may need a more theoretical development.

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