An Ecological and Socio-Economic System for Lake Superior

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I. Introduction

This paper presents a prototype version of the Superior Environmental Assessment Model (SEAM) that is currently being developed for the North Shore area of Lake Superior.

SEAM and the prototype version contain three components- the economic component, the contaminant component, and the ecological component. The prototype version being presented here represents three northern Minnesota counties that border the north shore of Lake Superior. These counties are St. Louis, Lake, and Cook. The regional and inter-regional delineation for SEAM has not yet been determined.

Many believe that Lake Superior is one of the world's few remaining "unspoiled" great fresh water lakes. Moreover, many regard Lake Superior as a very "delicate" lake because of its relatively cold waters. Its average annual water temperature is approximately 43 degrees Fahrenheit, which is nearly constant throughout the year. This means that the biotic life of the lake is relatively slow. Contaminants that are discharged in the lake become only slowly disposed of through its biotic processes. The only major disposition of lake contaminants is through sedimentation, but sedimentation does not permanently remove the contaminants since disturbances in the sedimentation occur. Therefore, Lake Superior has a very limited capacity to dispose of waste materials, which can enter the lake system in two ways--point source entry and atmospheric deposition.

Lake Superior, with its limited capacity, is under considerable stress to serve the great variety of current and future market and non-market human needs and pleasures, and at the same time maintain its delicate ecological system.

One of the most difficult socio-economic issues facing decision makers in the public arena is the allocation and regulation of a complex natural resource system, such as Lake Superior, that has limited capacity to serve the present and future human market and non-market environments and, also, to serve the natural needs of the nonhuman life forms that depend on the its ecological system. Decision makers who are responsible to the Lake Superior region face an almost impossible task in the formulation of environmental policy for the region. It is believed that the kind of information that can be generated from the type of model being presented here can be useful in this process.

II. The Model Components

SEAM and the prototype version contain three components or groups. The two major components of the model are the economic and the ecological components, which are linked through a contaminant component. Contaminants occur in two ways. Contaminants enter the lake system through point sources, such as the historical deposition of mercury into the St. Louis River by paper plants. The second way is through the atmosphere, such as the emission of PCB's by power plants, which can be carried a considerable distance by the atmosphere before settling into the lake system.

The prototype version contains only a single region to represent the economic component of SEAM, and also, it contains only a single food chain to represent the ecological component. As noted earlier, the economic region for the prototype model is a three county area in northern Minnesota. The ecological component in the prototype version is represented by the predator fishes (walleye) food chain for the St. Louis River and the St. Louis Bay area of Lake Superior.

The basic framework for SEAM and the prototype version is an input-output system of accounts, since an input-output system depicts both the general characteristics of inter-industry relationships and the relationships of an ecological system. Thus, SEAM and the prototype version are simply expanded forms of the traditional Leontief input-output model.

II.A. The Economic Component

The economic component for the prototype version is a regional input-output model for the Minnesota counties of St. Louis, Lake, and Cook.

The inter-industry relationships for the economic component of the prototype version were constructed from non-survey information. National coefficients for the 1977 national Use and Make tables were used to determine the inter-industry relationships. The calculations involved six steps. First, the 1977 national Use table was price updated to reflect 1985 relative prices. The national Make table was not price updated, since and industry-by-industry based technology assumption was followed in the derivation of the regional (industry-by-industry) input-output model. Next, the price updated national Use table was normalized on the basis of industry totals (i.e., the column sums of the Use table). The third step involved the removal of competitive imports from the national Use table. The fourth step adjusted the national industry mix to reflect the industry mix of the three-county region. Employment information for the three-county region was used to adjust for industry mix. Step five consisted of combining information from the Make and Use tables to form an industry-by-industry input-output model for the prototype region. The final step involved the regionalization of the input-output model developed from step five to reflect regional trade patterns. Using employment data, the simple location quotient technique was employed to complete the regionalization process. The final regional input-output component for the prototype version contains eleven endogenous sectors, which are defined below in Figure One.

The economic component of SEAM will also be constructed from non-survey information. There are two reasons for this approach. First, the development of a regional or inter-regional system of inter-industry accounts from survey information is cost prohibitive. Second, the use of non-survey techniques provides flexibility 1) in the delineation of regional boundaries and 2) in the formulation of regional or inter-regional economic systems. This flexibility is necessary because the source and disposition of contaminants in the Lake Superior system are not fully known at this time. It should be noted that the forthcoming 1982 national Use and Make tables will be used to construct the economic component of SEAM.

Figure One

Sector Definitions

Sector Number	Sector Description
Sector One	Agriculture
Sector Two	Mining
Sector Three	Construction
Sector Four	Other Manufacturing
Sector Five	Logging, Sawmills, & Products
Sector Six	Paper & Paper Products
Sector Seven	Heavy Industry
Sector Eight	Transportation & Warehousing
Sector Nine	Utilities
Sector Ten	Trade
Sector Eleven	Services

The direct requirements coefficients for the eleven endogenous sectors are given below in Table 1.

Table 1

Direct Requirements Table
for Eleven Sector Region

	1	2	3	4	5	6	7	8	9	10	11
1	.13	.00	.00	.10	.11	.00	.00	.00	.00	.00	.01
2	.00	.06	.01	.00	.00	.00	.01	.00	.02	.00	.00
3	.01	.01	.00	.00	.01	.00	.01	.01	.03	.01	.02
4	.04	.00	.00	.23	.00	.00	.00	.00	.00	.00	.06
5	.00	.00	.04	.00	.15	.00	.01	.00	.00	.00	.00
6	.00	.00	.00	.04	.01	.19	.01	.01	.00	.03	.02
7	.11	.17	.29	.06	.10	.04	.29	.08	.06	.02	.05
8	.02	.03	.03	.02	.03	.04	.02	.19	.02	.02	.02
9	.02	.12	.01	.02	.03	.03	.02	.02	.05	.04	.04
10	.04	.03	.07	.06	.04	.03	.05	.02	.01	.01	.02
11	.09	.06	.09	.04	.04	.13	.05	.10	.13	.15	.15

Source: See test for discussion.

The above industry-by-industry direct requirements table (Table 1) is linked later with the contaminant and ecological components to create a prototype version of SEAM.

II.B. The Ecological Component

The ecological component for the prototype version of SEAM is the predator fishes (walleye) food chain for the St.

Louis River and St. Louis Bay area of Lake Superior.

The walleye food chain consists of four elements that can be treated like sectors in an input-output context. The input-output relationships for the walleye food chain are given below in Table 2.

Table 2

Walleye Food Chain and Input-Output Relations

	Algae/ Bacteria (1)	Benthic Invertebrates (2)	Forage Fishes (3)	Walleye (4)
Algae/ Bacteria		10.0		
Benthic Invertebrates			3.0	
Forage Fishes				5.4
Walleye				

Source: The Bioenergetics Models of St. Louis River for walleye and yellow perch

The input values presented in Table 2 represent pounds of food consumptions per one pound of output. For example, to produce one pound of walleye 5.6 pounds of forage fish (e.g., yellow perch) is required on average. To produce one pound of yellow perch for walleye consumption, three pounds of invertebrates are required. Thus, the input amounts (in pounds) presented in Table 2 have been normalized on the basis of one pound of output. Thus, in an input-output context, Table 2 is a direct requirements table for the walleye food chain.

II.C. Contaminants

Two contaminants are used in the prototype version of SEAM to represent the contaminant component. These contaminants are mercury and polychlorinated biphenyls (PCB's). Mercury is mostly a point source contaminant, but PCB's can enter a system either from a point source or through atmospheric deposition.

There are at least two sources for the deposition of mercury in the St. Louis River. Mercury may come into the River either from the weathering of natural deposits or from anthropogenic sources. Historically, the most likely anthropogenic source was a bactericide used by paper plants, located in the St. Louis River Basin, to prevent a slime build-up on rollers. The use of mercury for this purpose was banned by the U.S. Environmental Protection Agency (EPA) in 1976.

The mercury settles out of the water column and into the sediments of St. Louis Bay. Here the mercury becomes methylated through bacterial action. Methyl mercury is extremely biologically active, meaning that more than 90 percent of ingested mercury may be retained by fish. Methyl mercury is concentrated by invertebrates which feed in/on the sediments either through consumption of bacteria or benthic algae. Yellow perch and young walleye feed on these invertebrates, which further concentrates the methyl mercury in the food chain. Larger walleye feed on the yellow perch, and again, the methyl mercury is bioconcentrated.

There are over 204 known possible PCB compounds. PCB contamination of fishes follows a similar pathway as just described for mercury. PCB enters a system either from a point source or through atmospheric deposition. (PCB use has been curtailed in most western countries). PCB's become deposited in the sediments, where they are incorporated into bacteria or algae and passed up the food chain. Approximately 65 percent of the ingested PCB is assimilated by the fish.

Table 3 below presents the transfer coefficients for mercury and PCB's into the different elements of the food chain. These transfer coefficients represent nano-pounds (which is 10^{-9} pounds) per pound of weight.

Table 3

Transfer Coefficients for Mercury and PCB's

	PCB's	Mercury
Algae/Bacteria	8	11.1
Benthic Invertebrates	2	2.75
Forage Fishes	3.3	5.05
Walleye		

Source: The PCB transfer coefficients were adapted for the St. Louis Bay area from Oliver, B.G. and A.J. Niivis 1988. "Trophodynamics analysis of polychlorinated biphenyl congeners and other chlorinated hydrocarbons in the Lake Ontario ecosystem." Environ. Sci. Technal. 22:388-397.

The mercury transfer coefficients were calculated from the Bioenergetics models of St. Louis River.

Table 3 shows that there are no transfer coefficients for walleye, since the transfer of contaminants occurs through food consumption at the predatory fishes (walleye) stage.

A major source of PCB's and mercury is industrial activity, and pollution output coefficients can be calculated from EPA records on the basis of pounds emitted per dollar of output. Such estimates have not yet been made for SEAM or the prototype versions being presented here. Therefore, hypothetical coefficients will be used, which are given below in Table 4.

Table 4

Pollution Output Coefficients

(pounds of emission per dollar of output)

Economic Sector	Mercury	PCB's
Agriculture	0.00	0.00
Mining	0.00	0.00
Construction	0.00	0.00
Logging, Wood Prod. & Furniture	0.00	0.01
Paper & Paper Products	0.02	0.00
Heavy Industry	0.00	0.02
Transportation	0.00	0.001
Utilities	0.00	0.002
Trade	0.00	0.000
Services	0.000	0.000

Source: Hypothetical

III. A Prototype Version of SEAM

The direct requirements coefficients of Tables 1 and 2 and the emission and transfer coefficients of Tables 3 and 4 have been combined in Table 5 to create a prototype version of SEAM. In the context of input-output analysis, Table 5 is an expanded direct requirements table that contains the three groups or components called the economic component, the contaminant component, and the ecological component.

The logic of SEAM, as presented here in its prototype version, can best be seen by writing the supportive system of simultaneous equations. It is important to understand that the coefficient values for these equations are the elements of the (I - A) matrix, where the A matrix consists of the direct input coefficients given in Table 5. The seventeen endogenous variables are identified below in Figure Two. The seventeen variables, Y_1 through Y_{17}, are the exogenous variables for final demand.

Figure Two

The Endogenous Variables
for the Prototype Version of SEAM

Variable Name	Description
X_1	Agriculture
X_2	Mining
X_3	Construction
X_4	Other Manufacturing
X_5	Logging, Sawmills, & Wood Products
X_6	Paper & Paper Products
X_7	Heavy Industry
X_8	Transportation & Warehousing
X_9	Utilities
X_{10}	Trade
X_{11}	Services
X_{12}	Mercury
X_{13}	PCB's
X_{14}	Algae/Bacteria
X_{15}	Benthic Invertebrates
X_{16}	Forage Fishes (yellow perch)
X_{17}	Predator Fishes (walleye)

$$\begin{aligned}+ 0.870X_1 - 0.000X_2 - 0.000X_3 - 0.100X_4 - 0.110X_5 - 0.000X_6 \\ - 0.000X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.010X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_1\end{aligned} \tag{1}$$

$$\begin{aligned}- 0.000X_1 - 0.940X_2 - 0.010X_3 - 0.000X_4 - 0.000X_5 - 0.000X_6 \\ - 0.010X_7 - 0.000X_8 - 0.020X_9 - 0.000X_{10} - 0.000X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_2\end{aligned} \tag{2}$$

$$\begin{aligned}- 0.010X_1 - 0.010X_2 - 1.000X_3 - 0.000X_4 - 0.010X_5 - 0.000X_6 \\ - 0.010X_7 - 0.010X_8 - 0.030X_9 - 0.010X_{10} - 0.020X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_3\end{aligned} \tag{3}$$

$$\begin{aligned}- 0.040X_1 - 0.000X_2 - 0.000X_3 - 0.770X4 - 0.000X_5 - 0.000X_6 \\ - 0.000X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.060X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_4\end{aligned} \tag{4}$$

$$\begin{aligned}- 0.000X_1 - 0.000X_2 - 0.040X_3 - 0.000X_4 - 0.850X_5 - 0.000X_6 \\ - 0.010X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.000X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_5\end{aligned} \tag{5}$$

$$\begin{aligned}- 0.000X_1 - 0.000X_2 - 0.000X_3 - 0.040X_4 - 0.010X_5 - 0.810X_6 \\ - 0.010X_7 - 0.010X_8 - 0.000X_9 - 0.030X_{10} - 0.020X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_6\end{aligned} \tag{6}$$

$$\begin{aligned}- 0.110X_1 - 0.170X_2 - 0.290X_3 - 0.060X_4 - 0.100X_5 - 0.040X_6 \\ + 0.710X_7 - 0.080X_8 - 0.060X_9 - 0.020X_{10} - 0.050X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_7\end{aligned} \tag{7}$$

$$\begin{aligned}- 0.020X_1 - 0.030X_2 - 0.030X_3 - 0.020X_4 - 0.030X_5 - 0.040X_6 \\ - 0.020X_7 - 0.810X_8 - 0.020X_9 - 0.020X_{10} - 0.020X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_8\end{aligned} \tag{8}$$

$$\begin{aligned}- 0.020X_1 - 0.120X_2 - 0.010X_3 - 0.020X_4 - 0.030X_5 - 0.030X_6 \\ - 0.020X_7 - 0.020X_8 + 0.950X_9 - 0.040X_{10} - 0.040X_{11} \\ - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15} \\ - 0.000X_{16} - 0.000X_{17} = Y_9\end{aligned} \tag{9}$$

$$\begin{aligned}&- 0.041X_1 - 0.030X_2 - 0.070X_3 - 0.060X_4 - 0.040X_5 - 0.030X_6\\&\quad - 0.050X_7 - 0.020X_8 - 0.010X_9 - 0.990X_{10} - 0.020X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15}\\&\quad - 0.000X_{16} - 0.000X_{17} = Y_{10}\end{aligned}\tag{10}$$

$$\begin{aligned}&- 0.090X_1 - 0.060X_2 - 0.090X_3 - 0.040X_4 - 0.040X_5 - 0.130X_6\\&\quad - 0.050X_7 - 0.010X_8 - 0.130X_9 - 0.150X_{10} - 0.850X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15}\\&\quad - 0.000X_{16} - 0.000X_{17} = Y_{11}\end{aligned}\tag{11}$$

$$\begin{aligned}&+ 0.000X_1 + 0.000X_2 + 0.000X_3 + 0.000X_4 + 0.000X_5 + 0.020X_6\\&\quad + 0.000X_7 + 0.000X_8 + 0.000X_9 + 0.000X_{10} + 0.000X_{11}\\&\quad - 1.000X_{12} - 0.000X_{13} - 11.100X_{14} - 2.750X_{15}\\&\quad - 5.050X_{16} - 0.000X_{17} = 0\end{aligned}\tag{12}$$

$$\begin{aligned}&+ 0.010X_1 + 0.020X_2 + 0.030X_3 + 0.040X_4 + 0.010X_5 + 0.060X_6\\&\quad + 0.020X_7 + 0.001X_8 + 0.002X_9 + 0.010X_{10} + 0.000X_{11}\\&\quad - 0.000X_{12} - 1.000X_{13} - 8.000X_{14} - 2.000X_{15}\\&\quad - 3.300X_{16} - 0.000X_{17} = 0\end{aligned}\tag{13}$$

$$\begin{aligned}&- 0.000X_1 - 0.000X_2 - 0.000X_3 - 0.000X_4 - 0.000X_5 - 0.000X_6\\&\quad - 0.000X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.000X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} + 1.000X_{14} - 10.000X_{15}\\&\quad - 0.000X_{16} - 0.000X_{17} = Y_{14}\end{aligned}\tag{14}$$

$$\begin{aligned}&- 0.000X_1 - 0.000X_2 - 0.000X_3 - 0.000X_4 - 0.000X_5 - 0.000X_6\\&\quad - 0.000X_7 - 0.000X_8 + 0.000X_9 - 0.000X_{10} - 0.000X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} + 1.000X_{15}\\&\quad - 3.000X_{16} - 0.000X_{17} = Y_{15}\end{aligned}\tag{15}$$

$$\begin{aligned}&- 0.000X_1 - 0.000X_2 - 0.000X_3 - 0.000X_4 - 0.000X_5 - 0.000X_6\\&\quad - 0.000X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.000X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15}\\&\quad + 1.000X_{16} - 5.400X_{17} = Y_{16}\end{aligned}\tag{16}$$

$$\begin{aligned}&- 0.000X_1 - 0.000X_2 - 0.000X_3 - 0.000X_4 - 0.000X_5 - 0.000X_6\\&\quad - 0.000X_7 - 0.000X_8 - 0.000X_9 - 0.000X_{10} - 0.000X_{11}\\&\quad - 0.000X_{12} - 0.000X_{13} - 0.000X_{14} - 0.000X_{15}\\&\quad - 0.000X_{16} + 1.000X_{17} = Y_{17}\end{aligned}\tag{17}$$

The first eleven equations represent the sectors for the economic component of the prototype version of SEAM. The positive terms (coefficients) in this subset of equations,

Table 6
Environmental Impact Assessment Model
(prototype)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.130	0.000	0.000	0.100	0.110	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.060	0.010	0.000	0.000	0.000	0.010	0.000	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.010	0.010	0.000	0.000	0.010	0.000	0.010	0.010	0.030	0.010	0.020	0.000	0.000	0.000	0.000	0.000	0.000
4	0.040	0.000	0.000	0.230	0.000	0.000	0.000	0.000	0.000	0.000	0.060	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.040	0.000	0.150	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.040	0.010	0.190	0.010	0.010	0.000	0.030	0.020	0.000	0.000	0.000	0.000	0.000	0.000
7	0.110	0.170	0.290	0.060	0.100	0.040	0.290	0.000	0.060	0.020	0.050	0.000	0.000	0.000	0.000	0.000	0.000
8	0.020	0.030	0.030	0.020	0.030	0.040	0.020	0.190	0.020	0.020	0.020	0.000	0.000	0.000	0.000	0.000	0.000
9	0.020	0.120	0.010	0.020	0.030	0.030	0.020	0.020	0.050	0.040	0.040	0.000	0.000	0.000	0.000	0.000	0.000
10	0.040	0.030	0.070	0.060	0.040	0.030	0.050	0.020	0.010	0.010	0.020	0.000	0.000	0.000	0.000	0.000	0.000
11	0.090	0.060	0.090	0.040	0.040	0.130	0.050	0.100	0.100	0.150	0.150	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	-0.020	0.000	0.000	0.000	0.000	0.000	2.000	0.000	11.100	2.750	5.050	0.000
13	0.000	0.000	0.000	0.000	-0.010	0.000	-0.020	0.001	-0.002	0.000	0.000	0.000	2.000	8.000	2.000	3.300	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.400
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Derived from tables 1, 2, 3, and 4

which form the diagonal of the subset, indicate the amount of sector output available as input to other endogenous sectors plus final demand. For example, the coefficient value of 0.870 for X^1 in equation one indicates the amount of sector one's total output that is available as inputs to other endogenous sectors plue final demand. The reason that the coefficient value for sector one is less than one is because sector one consumes some of its own output for production purposes. In fact, it consumes thirteen cents (i.e., 0.130) of its own production for internal input requirements. The negative coefficients indicate input requirements for the respective endogenous sectors. Notice that the contaminant and food chain sectors do not directly require economic outputs.

Equations twelve and thirteen in the above system of equations represent the contaminant component of the prototype version. Notice that the coefficient values for the economic sectors (i.e., variables X_1 through X_{11}) are positive in equations twelve and thirteen, which indicate that contaminants are directly related to industrial output. These coefficients are the pollution output coefficients given in Table 4. For example, the coefficient value of 0.020 for variable X_6 in equation twelve indicates that for one dollar of X_6's output, 0.020 units of mercury are produced, indicating a positive relationship between the output of Paper and Paper Products and mercury deposition. Skipping over the contaminant sectors (i.e., sectors X_{12} and X_{13}) for the moment, the negative input coefficients for the remaining sectors (i.e., X_{14} through X_{17}) of equations twelve and thirteen represent the absorption of contaminants into the food chain. These coefficients are consistent with the information given in Table 3. Final demand for contaminants (i.e., Y_{12} and Y_{13}) is zero, which returns us to the coefficients for the contaminant variables X_{12} and X_{13}. In equation twelve, the coefficient for variable X_{12} is 1.00, which represents the amount of mercury that has not been absorbed by the food chain. Thus, X_{12} represents a residual amount of mercury that remains in the system, which is indicated by the 'bar' atop the variable term. The same notation is indicated for the second contaminant, which is PCB, in equation thirteen.

Equations fourteen through seventeen represent the four elements of the food chain. The only non-zero coefficients for this subset of equations are found in the food chain component. These coefficients reflect the food chain relations of Table 2. (The industrial processing of commercial fish would create an input coefficient for a food processing sector in the economic component of the model.

However, at present, there is no known commercial processing of fish from Lake Superior in the three county region.)

IV. Impact Assessment

IV.A. The Leontief Inverse

The total direct and indirect relations and, hence, impacts within and between the three groups or components can be determined by calculating the Leontief inverse matrix. The Leontief inverse matrix for the prototype version is given in Table 6.

IV.D. The Decomposed Inverse

The standard Leontief inverse matrix can be decomposed on the basis of the number of groups or components that are contained in the complete matrix. The purpose for decomposing the Leontief inverse is to separate the multiplicative components: the economic component, the contaminant component, and the ecology component. This allows one to measure the inter-component, intra-component, and extra-component effects. The decomposed impact matrices can be defined as:

M_1 = Intra-component effects

M_2 = Inter-component effects

M_3 = Extra-component effects

A method for decomposing the Leontief inverse on the basis of the three components is presented below. The decomposed matrices for the three components (i.e., tables for M_1, M_2, and M_3) will not be included in this paper.

The procedure for decomposing the Leontief inverse matrix into three components begins with the decomposition of the A matrix, which is Table 3.

Let,

$\tilde{A}$ = the "block" diagonal elements of the A matrix; and

$(A - \tilde{A})$ = the off-diagonal elements of the A matrix.

The algebraic formulation and derivation of the standard input-output model is given below.

$$X = AX + Y \tag{18}$$

$$X - AX = Y$$

$$(I - A)X = Y$$

$$X = (I - A)^{-1}Y \tag{19}$$

where

$(I - A)^{-1}$ is the Leontief inverse matrix.

The decomposed inverse for three components can be formulated in the following way.

$$X = (A - \tilde{A})X + \tilde{A}X + Y \tag{20}$$

Recall that

$$(A - \tilde{A}) + \tilde{A} = A$$

$$X - \tilde{A}X = (A - \tilde{A})X + Y$$

$$(I - \tilde{A})X = (A - \tilde{A})X + Y$$

$$X = (I - \tilde{A})^{-1}(A - \tilde{A})X + (I - \tilde{A})^{-1}Y \tag{21}$$

Let

$$A^{*} = (I - \tilde{A})^{-1}(A - \tilde{A})$$

Substituting A^{*}into equation (21) gives

$$X = A^{*}X + (I - \tilde{A})^{-1}Y \tag{22}$$

Next, multiply both sides of equation (22) by A^{*}

$$A^{*}X = A^{*2}X + A^{*}(I - \tilde{A})^{-1}Y \tag{23}$$

Then, substitute equation (23) into equation (22) to give

$$X = A^{*2}X + A^{*}(I - \tilde{A})^{-1}Y + (I - \tilde{A})^{-1}Y$$

or,

$$X = A^{*2}X + (I + A^{*})(I - \tilde{A})^{-1}Y \tag{24}$$

To continue, multiply both sides of equation (22) by A^{*2} to give

$$A^{*2}X = A^{*3}X + A^{*2}(I - \tilde{A})^{-1}Y \tag{25}$$

Substitute equation (25) into equation (24) to give

$$X = A^{*3}X + A^{*2}(I - \tilde{A})^{-1}Y + (I + A^{*})(I - \tilde{A})^{-1}Y$$

or,

$$X = A^{*3}X + (I + A + A^{*2})(I - \tilde{A})^{-1}Y \tag{26}$$

So that,

$$X - A^{*3}X = (I + A + A^{*2})(I - \tilde{A})^{-1}Y$$

$$(I - A^{*3})X = (I + A + A^{*2})(I - \tilde{A})^{-1}Y$$

$$X = (I - A^{*3})^{-1}(I + A + A^{*2})(I - \tilde{A})^{-1}Y \tag{27}$$

Let

$$M_1 = (I - \tilde{A})^{-1};$$

$$M_2 = (I - A^{*3})^{-1}; \text{ and}$$

$$M_3 = (I + A^{*} + A^{*2})$$

so that equation (27) can be expressed as

$$X = M_2M_3M_1Y \qquad (28)$$

M_1, M_2, and M_3 comprise the multiplicative components of the standard Leontief inverse matrix, $(I - A)^{-1}$. M_1 measures the multiplier effects that arise from the repercussions of an initial change within the component that the change originally occurred. Therefore, M_1 measures the intra-component effects. M_2 measures the multiplier effects that arise from the repercussions of an initial change within a component when it has completed a "tour" through all components and has returned to the one that it has originally entered. Therefore, M_2 measures the inter-component effects. Finally, M_3 measures the multiplier effects that arise from the repercussions of an initial change within a component when it has completed a "tour" outside its original component, without returning to it. Therefore, M_3 measures the extra-component effects.

V. Methodological Issues

Several methodological issues need to be resolved before SEAM is operational for policy and/or planning purposes. These issues will only be briefly mentioned here. No doubt, other issues not noted here will occur as SEAM nears completion.

The major issue is the space/time characteristics of the deposition of contaminants by industry and the absorption of these contaminants by food chains. The deposition of mercury by paper plants occurred early in this century. Yet, the absorption of mercury into food chains is a current problem, and this problem will continue long into the future. One notion is to disregard past time lags and simply focus on the current and future relationships between contaminants and ecological systems. The current deposition of contaminants has a future time stream of impacts on ecological systems, and it is believed that an input-output framework can be used to identify and measure these future time streams.

The spatial characteristics of contaminants are difficult to model, because contaminants can enter a system either from a point source or through atmospheric deposition. The atmospheric deposition of contaminants across a landscape depends upon a variety of technical, climatic, and geographic factors, such as wind direction and speed, and local topography. The development of inter-regional models can reflect the inter-regional transference of contaminants, and the use of simulation analysis may be a useful way to study the variation in the spatial deposition of contaminants.

Other, less difficult, issues include the treatment of final demand within a food chain. One question or issue is, do flows to final demand occur for the lower forms of a food chain? For example, are there flows between algae/bacteria and final demand, as indicated in the prototype version of SEAM? It can be argued that such flows simply represent a transfer of algae/bacteria to food chains exogenous to the model.

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