Simulating the Interactions Between Economy and Pollution: An Exploratory Model

by
Tommy O. Habibe

Submitted to the Department of
Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements
for the Degree of
Bachelor of Science in Electrical Science and Engineering
at the
Massachusetts Institute of Technology
May 1987

Signature of Author
Department of Electrical Engineering and Computer Science
May 18, 1987

Certified by
David P. Kreutzer
Thesis Supervisor

Accepted by
Leonard A. Gould
Chairman, Department Committee on Undergraduate Theses

Simulating the Interactions Between Economy and Pollution: An Exploratory Model

by
Tommy O. Habibe

Submitted to the Department of
Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements
for the Degree of
Bachelor of Science in Electrical Science and Engineering
at the
Massachusetts Institute of Technology
May 1987

Thesis Abstract

A country's economic growth and progress is affected by the various regulatory policies controlling environmental pollution. Overly restrictive pollution regulation policies reduce air, land, and water availability as disposal mediums to preserve nature while being detrimental to economic progress. On the other hand, submissive policies allow greater economic development by sacrificing ecollogical order.

This project presents a computer model developed to help explore and understand some of the interactions that occur between the industrial, agricultural, and pollution sectors. The model conceptualization and development was achieved using system dynamics tools such as causal-loop diagrams, feedback-structure diagrams, stock-and-flow diagrams, and the STELLA simulation software.

The developed model follows previously predicted behavioral patterns for exponential economic and pollution growth and provides the expected results for simulations including pollution control. Various sample experimental runs are included and some suggestions for further improvements of the model are presented at the end of the report.

Table of Contents

Introduction

Model Structure and Major Loops

Description of Model Variables and Equations

The Industrial Sector

The Agricultural Sector

The Pollution Sector

Sample Experimental Runs

Conclusion and Suggestions for Further Study

Appendix

References

Introduction

Recently, there has been a growing public concern about pollution and its effect in our ecosystem. People are realizing that high levels of contamination are not only hazardous to our environment but, also, to ourselves. The public usually blames the constant growth of the economy as the main cause of pollution. Furthermore, people believe that if the economy does not stop expanding, pollution will reach levels which will permanently affect nature's balance and alter it. On the other hand, a growing economy leads to progress, innovation, and a better living standard. In order for economic development to be possible, environmental resources such as air, land, and water must be available to use as disposal mediums. So the question emerges as to which side will eventually dominate over the other, a growing economy or a clean environment.

Economic growth is affected by all of the regulatory policies limiting industrial emission of contaminants into the environment. These emissions can take the form of solid waste contaminating the land, chemicals disposed in the water, or toxic gases which are emitted into the air. Regulations have to be imposed to maintain the quality of the environment at a level adequate for human existence.

It is puzzling to think about the possible consequences that stringent regulatory policies may have in the evolution of the economic system. One may assume that regulations may slow down economic growth until it reaches an equilibrium level of economic development, or maybe that, at a certain moment in time, it will prevent any further progress and drive the economy into stagnation. All of these conclusions are derived from "mental models" which relate our knowledge of the economic sector to that of the environmental resources. We use certain logical relations between specific elements of each of the sectors and relate them to others in order to derive conclusions. A problem with this kind of "mental model" is that, if all of the detail or relations between these two sectors are taken into consideration to provide for a dynamic description of the system, the model will become too complex and vague.

The purpose of the model presented in this thesis is to provide a tool which formally describes some of the interactions between the economic and the pollution sectors. The model developed is a graphical and mathematical interpretation of my mental model of this problem. Since the complexity of the mathematics involved in dynamics systems goes beyond what can be done mentally, it is appropiate to implement this type of mathematical problem in an "analyzer" designed for this task, such as a computer. The advantage of developing and implementating the model on a computer lies on the speed and flexibility provided for exploring different scenarios and policies. At the same time, it provide the users with a common model to which they can refer to, since each individual may have a model which differs from that of others. The model provides a basic framework through which the knowledge of many people can be incorporated in a common arena.

Philosophy and Methodological Assumptions

The model is based on previous models of the world system, such as the *World* and *World3* models. Most of the relations and assumptions within the different sectors can be found as parts of the models indicated as references. Therefore, I will not rejustify the validity of these well documented studies. However, the interconnection between the different sectors and some of the philosophical assumptions have been done on my own initiative. This have been based on personal studies on economy-pollution interactions and the logical paths of action which I, as part of humanity, assumed would be taken by it. For example, one of the major rules I assummed in the model is that it is priority to allocate the necessary capital to maintain adequate agricultural and environmental pollution levels before any industrial investment, since, in my opinion, it is more important to provide the population with food and adequate levels of health than to expand the industry and have people dying of starvation or disease. Other assumptions similar in nature which have been included in the development of the model will be explained throughout its description in the following sections.

Model Structure and Major Loops

The model is structured in three sectors, even though it consists of six level variables. The three sectors are the industrial sector, the agricultural sector, and the pollution sector.

The industrial sector has one level variable, industrial capital. This sector represents the production of industrial goods and energy. The level variable represents the aggregate sum of all of the available goods and energy capital utilized for industrial production. For example, factory buildings, manufacturing equipment, and material inventories all contribute in part to the total industrial capital.

The use of industrial capital lead to the production of more goods. These new goods can be invested into either one of three categories: industry, agriculture, or pollution. Goods invested in industry replace depreciated capital stock or increase the total industrial capital available for expanding the economy. The investment in agriculture helps develop more land in order to supply food to the what we perceive as an ever expanding population and economy. Investments in pollution control are used to reduce existing pollution and develop new ways to diminish it in order to be able to keep regulatory policies limiting environmental resources to a minimum.

The agricultural sector is composed of two level variables. The first of these, agricultural land, represents the total land available for cultivating food. Agricultural investment increases the ability to develop untreated or "wild" land into potentially arable fields while, at the same time, industrialization decreases agricultural land. The second level variable in the agricultural sector is land fertility. This variable, as well as the agricultural land, is important in agriculture because agricultural output is partially dependent on it. The level of land fertility describes the conditions of agricultural land at a particular moment in time. If land conditions erode, fertility diminishes; However, if land conditions improve, the level of fertility increases until they become normal again. The fertility level portrays the fact that land yield may decrease if its "health" conditions are not kept at acceptable levels. As an example imagine an area highly contaminated with chemicals and waste. Any attempt to cultivate anything in this area would lead to disaster. This is the picture which the level of land fertility tries to communicate to the model user.

In the pollution sector, the interactions leading to pollution generation and reduction take place. The amount of pollution generated by the industrial and agricultural sectors are depicted as linear functions of their outputs. Also, pollution reduction is portrayed as a function of the amount of goods produced by the industrial sector. For example, if the industrial sector produced 100 capital units/year, the amount of pollution generation was 1 pollution unit/capital unit produced, and investment for pollution reduction was .25 of the total industrial production, the total pollution emitted would be 100 pollution units/year and the total investment in pollution reduction would be 25 capital units. This sector also presents some of the natural interactions occurring between air, land, and water by allowing flows of pollution from one environmental resource to the other. For example, air pollution can be reduced by precipitating into the ocean or onto the land; however, this reduction in the level of air pollution increases proportionally the level of land pollution.

Next, I will present each of the major loops controlling the behavior of each of the three sectors of the model. These loops not only describe the intricacies within the different sectors, but also the interactions occurring between them.

Industrial Sector

Under the industrial sector there are three major loops. These are the *Industrial Capital* loop, the *Industrial Capital Controlled by Agriculture* loop, and the *Industrial Capital Controlled by Pollution* loop.

Industrial Capital Loop

This loop represents the flow of capital stock in the industrial sector. It is composed of two internal loops: one controlling investment and another controlling

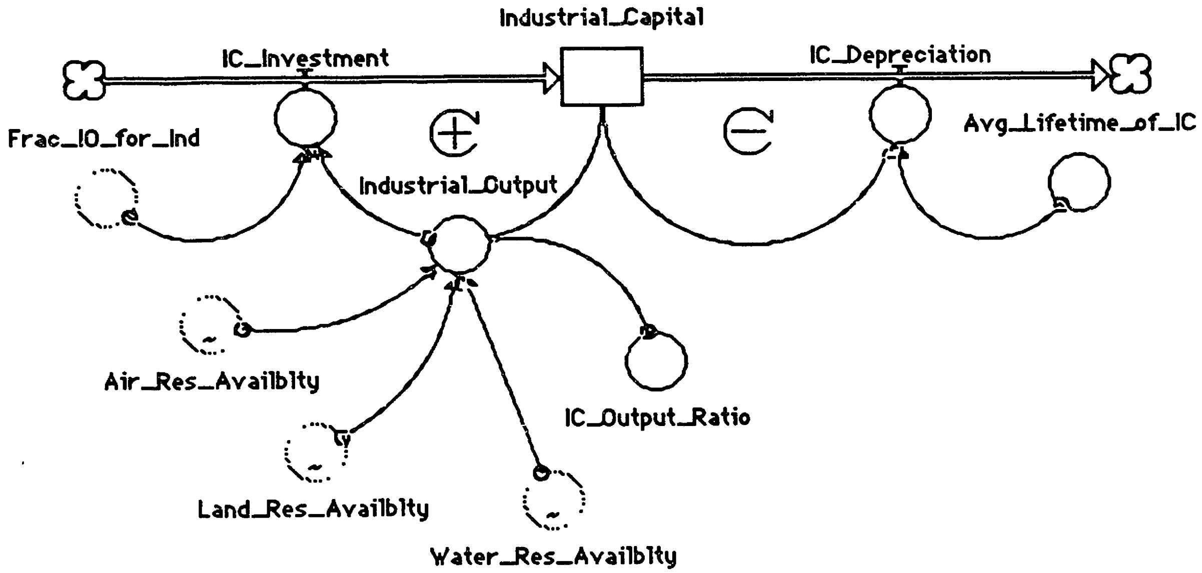


figure 2-1

depreciation. As we can see from figure 2-1, there are some external factors controlling the level of investment in capital stock. For the purpose of explanation, assume for the moment that the values for these factors are fixed. Their definitions will be provided in the next chapter.

The loop on the right side of figure 2-1 is the capital investment loop. As the industrial capital increases, the level of industrial output increases proportionally and, consequently, the amount of industrial output invested in the industry increases for a fixed value of the variable representing the fraction of industrial output re-invested in industry (*Frac_IO_for_Ind*). This means that an increase in industrial capital increases the available output for re-investment and, consequently, leads to growth in the level of industrial capital, giving the loop a "positive" or self-generating characteristic, represented by the "+" sign in its center.

The left hand of the diagram shows the effect of yearly depreciation on capital stock. Capital goods depreciate throughout the years as they are used. They end their service when they wear out or become obsolete. Industrial capital, representing the aggregation of all kinds of manufacturing goods, also depreciates. The average lifetime of industrial capital (*Avg_Lifetime_of_IC*), which is the weighted average of the lifetimes of all the goods included as part of industrial capital, dictates the fraction of capital stock which becomes obsolete yearly. This fraction is subtracted from the total industrial capital, thus characterizing the loop as negative or goal-seeking. This last observation is represented in the diagram by the "-" sign in the middle of the loop.

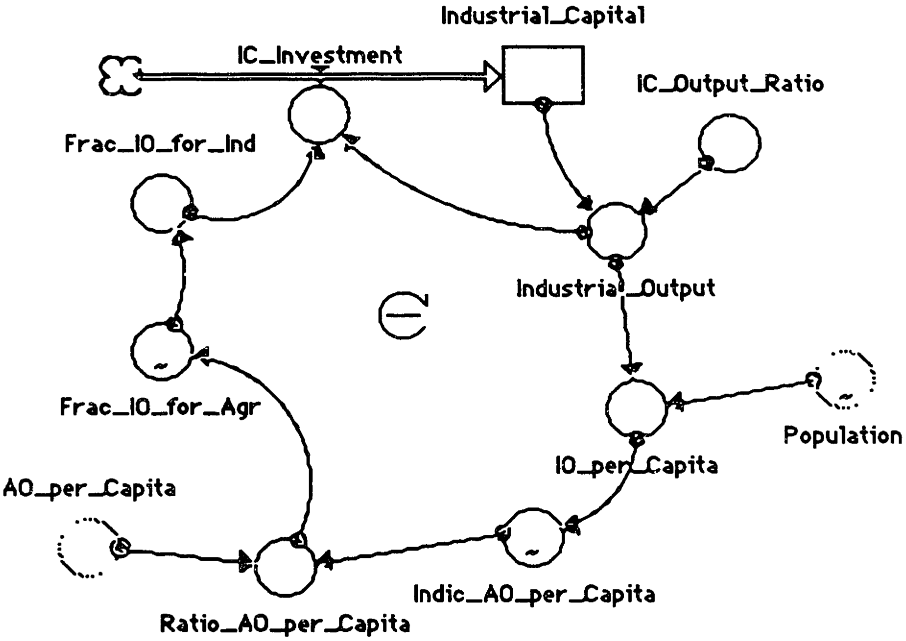


figure 2-2

Industrial Capital Controlled by Agriculture Loop

The explanation for the agricultural land loop assumes that capital will be allocated for agricultural use but does not explain its effect on the capital sector. The *Industrial Capital Controlled by Agriculture* loop (shown in figure 2-2) explains the effects of utilizing industrial output for agricultural development versus utilizing this output for capital re-investment and its further consequences on the fraction of industrial output allocated for agriculture.

A difference between agricultural output supply and demand gives rise to an increase in agricultural investment by augmenting the fraction of industrial output allocated for agricultural development. This reduces the capital re-invested in the industry and, in turn, decreases the total capital stock. A decrease in capital stock reduces the total industrial output which decreases the agricultural output demand, represented by the variable *Indic_AO_per_Capita* . This reduction in demand reduces the gap between food demand and supply and drives the system to equilibrium, which is why the loop is denominated as a negative feedback loop.

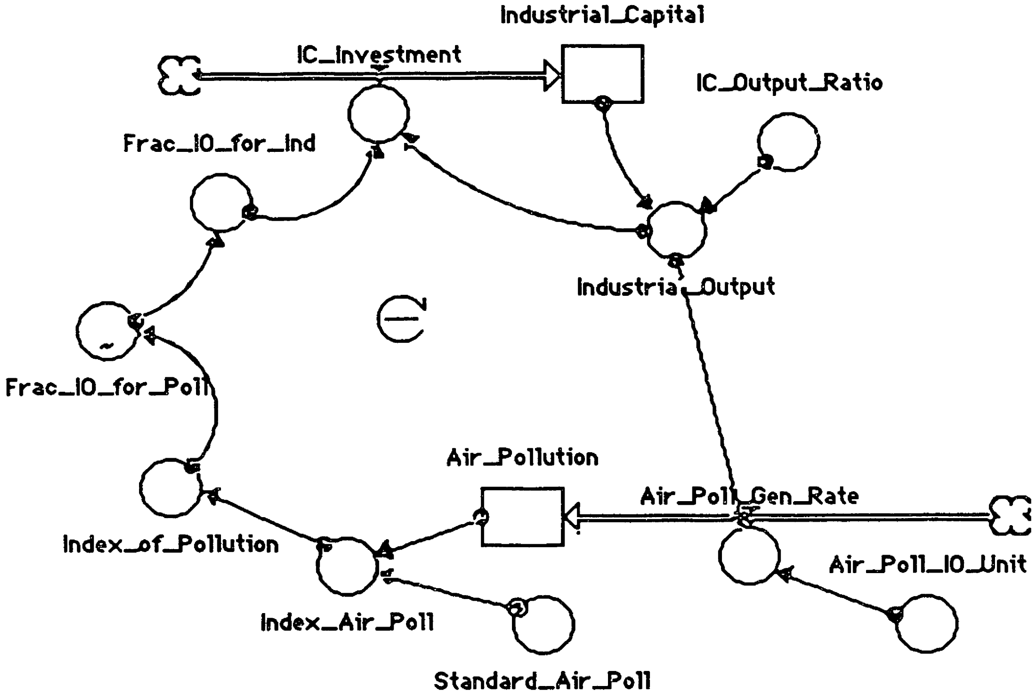


figure 2-3

Industrial Capital Controlled by Pollution Loop

Similar to the previous loop, the *Industrial Capital Controlled by Pollution* loop describes the intricacies of pollution control investments and its effect on the industrial sector. In figure 2-3, a diagram representing the interactions between the industrial sector and one of the pollution variables is presented. Similar loops exist for the land and water pollution variables.

As we know, an increase in the amount invested in pollution control reduces the capital re-invested in replacing or expanding industrial capital. This reduces any growth in industrial capital accumulation and, consequently, the output produced by industry. The reduction in the growth of industrial output reduces the total generation of pollution and, at the same time, the perceived index of pollution. This decrease in the index of pollution triggers a decrease in the fraction of capital invested in pollution and drives the loop into a seeking the goal of minimizing the fraction invested in pollution control.

The Agricultural Sector

There is only one loop which appreciably influences the behavior of the model in the agricultural sector. This is the *Agricultural Land* loop, which describes the intricacies of land development and industrialization.

Agricultural Land Loop

The *agricultural land* loop, shown in figure 2-4, consists of two negative loops. The first one presents the idea of investing in agricultural development in order to be able to satisfy demand. The second loop, parallel to the capital depreciation loop, is an aggregated description of the effects of industrialization in the agricultural environment.

As mentioned above, the agricultural development loop strives to maintain equilibrium between food supply and demand. A difference between the agricultural output allocated per capita and the indicated agricultural output allocated per capita gives rise to an increase in the fraction of industrial output allocated to agricultural development. This increases the investment in agricultural development and, consequently, the total amount of agricultural land. This increase in land produces more agricultural output which, in turn, reduces the gap between demand and supply.

The effect of industrialization is summarized in the right-hand loop in figure 2-4. Every year the amount of agricultural land is decreased by a fraction determined by the average time for industrialization of agricultural land (*Ind_Develop_Time*). The fraction of land which is converted into industrial land is then subtracted from the total land for agriculture. This decrease in land consequently reduces the amount converted to industrial use even though the conversion factor is constant throughout the time horizon of the model.

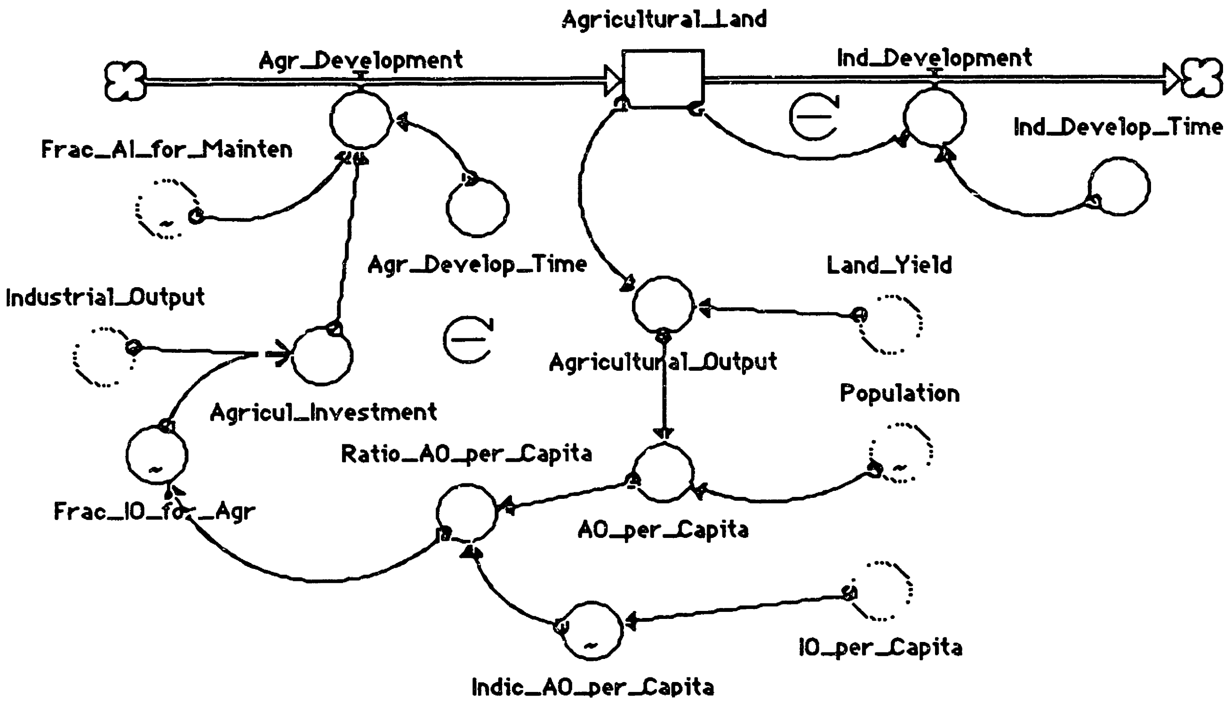


figure 2-4

The Pollution Sector

The most important loop in the pollution sector is the *Pollution Generation/ Reduction from Industry* loop. In this loop we can see the interactions occurring between the industrial and environmental sectors

Pollution Generation/Reduction from Industry

This loop is the last of the influential loops of the model. In this loop there are three internal loops representing the different interactions between environmental resource regulations, investment in pollution reduction, and the levels of pollution. Once again, the diagram in figure 2-5 presents the interactions occurring for only one of the pollution variables. The other two pollution variables have similar loops with their respective index and regulation variables.

The first loop (left side of figure 2-5) depicts the feedback paths existing between the levels of pollutions, regulation policies, and industrial production. For a fixed level of pollution there is a level of regulation associated with it. For a higher index of pollution there will be more regulations prohibiting the use of environmental resources as disposal mediums. The existence of these regulations forces the industrial sector to invest in developing alternatives for waste disposal or to limit their production. This increases the cost involved in goods manufacturing and, therefore, reduces the total industrial output. The reduction of industrial output decreases the pollution generation rate which, in turn, decreases the growth of the level of pollution and regulation policies.

The positive feedback loop in the middle of figure 2-5 describes the effect of an increase in industrial output in relation with the amount of investment in pollution control. As industrial output increases, the level of investment in pollution reduction increases, reducing the level of pollution. This reduction in the level of pollution decrease the number of regulations limiting the use of environmental resources (air, land, and water) as mediums for waste disposal. The cost of manufacturing goods decreases as less regulations are imposed upon the industrial sector. Therefore, an increase in resources availabilities increases the total industrial output which, consequently, increases the investment in pollution control.

The last section of the *Pollution Generation/Reduction from Industry* loop (right side of figure 2-5) presents the goal-seeking aspect of pollution reduction. As pollution decreases and reaches acceptable levels, the fraction of industrial output allocated for pollution control decreases. This, in turn, decreases the rate at which existing pollution is reduced and, consequently, slows the decrease in the fraction of industrial output allocated for pollution control.

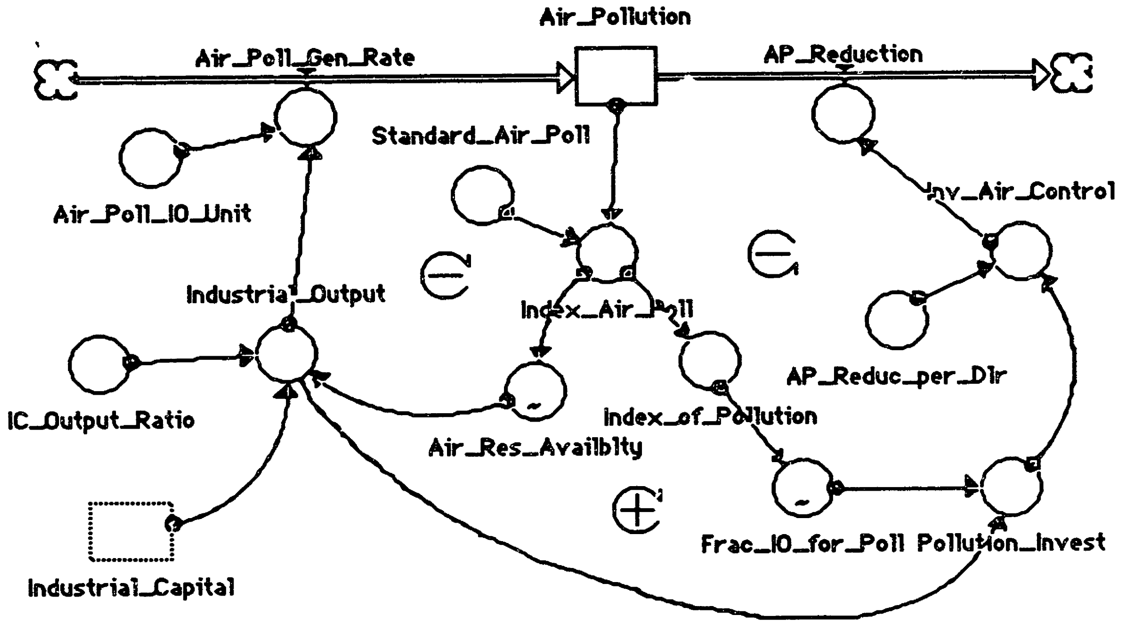

Air_Pollution
Air_Poll_Gen_Rate
AP_Reduction
Standard_Air_Poll
Air_Poll_IO_Unit
Inv_Air_Control
Industrial_Output
Index_Air_Poll
AP_Reduc_per_Dlr
IC_Output_Ratio
Index_of_Pollution
Air_Res_Availblty
Frac_IO_for_Poll
Pollution_Invest
Industrial_Capital
−
−
+

figure 2-5

Description of Model Variables and Equations

The Industrial Sector

Population

Population is defined as a policy variable in the model. By this I mean that it is included in the model in order to allow us to study the effects of the level of population in economic demand. The population level is implemented as a table function of year in order to provide for changes in its level throughout time. Currently, population is set to a constant level of .1 population units throughout the entire time horizon of the model.

Industrial Capital

Industrial capital (measured in capital units) represents the accumulation of all past investments in industrial expansion decreased by the fraction of capital depreciated. It is an aggregation of all the goods employed in the production of industrial output (defined later). Industrial plants and buildings, manufacturing equipment, and material inventories are all part of the industrial capital. In addition, all of the investments incurred in the production of energy are implicitly taken into consideration.

In the model, industrial capital is implemented as a level variable. By "level" we mean that all of the additions and subtractions to industrial capital throughout the simulation are integrated or compounded rather than being added discretely. This gives the variable the characteristic of continuity throughout time. In reality, any flow of capital occurs continuously throughout the year, not only at its beginning or end. This observation makes it appropriate to implement this kind of integrating accumulation in the system.

Level variables have to be initialized in order to provide the model a starting point from which it can proceed simulating. In the case of *Industrial Capital*, since the model focuses on providing the framework for further research on the area of pollution-economy interaction, a value of 100 capital units was chosen for rounding purposes.

```
Industrial_Capital = Industrial_Capital + dt * (-IC_Depreciation
       + IC_Investment )
INIT(Industrial_Capital) = 100
```

Industrial Capital Investment

By definition, industrial capital investment is the amount of yearly industrial output allocated for replacement of depreciated capital stock or for investment in industrial expansion. It is defined in the model as the industrial output multiplied by the fraction allocated for industrial re-investment. It has been assumed that industrial capital and industrial output are have the same dimension, since both represent industrial goods. This statement implies that goods manufactured by the industrial sector can be used to produce more goods. For example, a manufacturing firm can produce equipment which, in turn, produces other goods.

The fraction allocated for industrial capital investment is the industrial output remaining once the investments in agriculture and pollution control have been substracted. In other words, it is implicitly assumed in the model that it is more important to provide people with food and a clean environment than to increase the industrial capital stock.

```
IC_Investment = Industrial_Output * Frac_IO_for_Ind
```

Industrial Capital Depreciation

As for everything that is material, capital stock wears out throughout the years. Industrial capital depreciation represents the fraction of capital stock that ends service or becomes obsolete throughout the year. This figure is calculated by dividing the total captital stock by its average lifetime. The resulting number yields the amount of capital stock which has completely depreciated throughout the year.

The average lifetime of industrial capital is the weighted average life of every kind of good taken to be part of the industrial capital. In the model, a value of 7 years was taken as a rough approximation for the average lifetime of capital.

```
IC_Depreciation = Industrial_Capital / Avg_Lifetime_of_IC
Avg_Lifetime_of_IC = 7
```

Industrial Output

Industrial output is defined as the amount of goods manufactured by the existing capital stock. The figure is calculated by multiplying the industrial capital times a conversion ratio which indicates the yearly amount of capital units produced per existing unit of capital. Also multipliers representing air, land, and water availability are included in determining the industrial output. These factors take into consideration regulations imposed by the government on the use of these mediums as waste disposals. Restrictions on the use of air, land, and water as industrial waste disposals impose limitations on industrial production and, consequently, drives the industry into spending money in finding new ways to dispose of their waste. These expenses increase the cost of producing goods and, consequently, reduce the possible output for a fixed level of capital. Summarizing, these multipliers implicitly take into consideration industrial investment in waste disposal technology and its cost on industrial output. In addition, we have included a policy variable (*Switch_Res_Avlblty*) which enables the modeler to include or exclude the effects of regulating the use of environmental resources during the simulation by placing a 1 or 0 respectively.

```
Industrial_Output = (Industrial_Capital*IC_Output_Ratio)*
      (Switch_Res_Avlblty*MIN(Air_Res_Availblty,Land_Res_Availblty,
      Water_Res_Availblty)+(1- Switch_Res_Avlblty))
IC_Output_Ratio = 1/4
Switch_Res_Avlblty = 1
```

Industrial Output per Capita

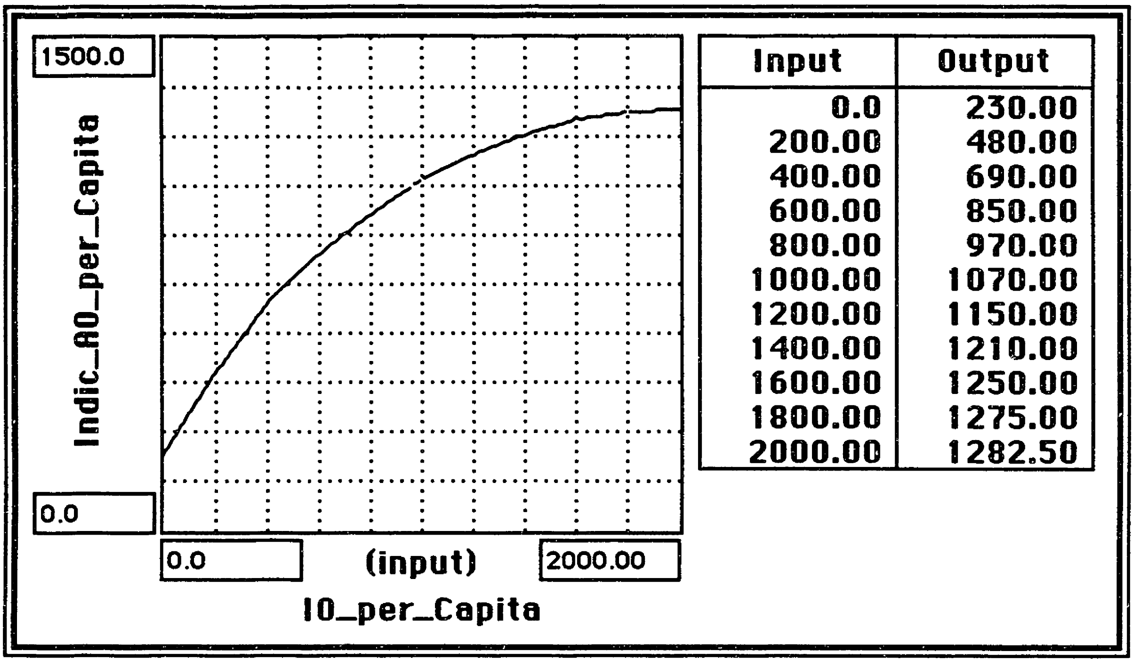
Industrial output per capita is the amount of industrial capital that, if it was evenly divided between the entire population, each individual unit would receive. It is defined as the industrial capital divided by the population and is measured in terms of capital units per population unit.

```
IO_per_Capita = Industrial_Output / Population
```

Fraction of Industrial Output for Agriculture

The fraction of industrial output allocated for agriculture is based on a comparison between the actual agricultural output per population unit, which indicates the food supply, and the indicated agricultural output per population unit, which represents the demand. The demand for food is a function of the industrial output per capita, as shown in figure 3-1. As can be observed, the demand for food increases exponentially as the industrial output per capita increases. This is due to the increasing demand of food consumption as an individual's income increases. The ratio between demand and supply is indicated by the variable *Ratio_AO_per_Capita.* A ratio of 1 indicates that demand and supply are in equilibrium. If demand is greater than supply, the fraction of industrial output allocated for agricultural investment increases exponentially (see figure 3-2) since the model assumes that food availability is essential. As supply increases and surpasses demand, the fraction allocated for agriculture reaches a constant level. This level of agricultural investment is preserved in order to mantain the existing land and to provide for its maintenance.

```
Frac_IO_for_Agr = graph(Ratio_AO_per_Capita)
Ratio_AO_per_Capita = AO_per_Capita / Indic_AO_per_Capita
AO_per_Capita = Agricultural_Output / Population
Indic_AO_per_Capita = graph(IO_per_Capita)
```

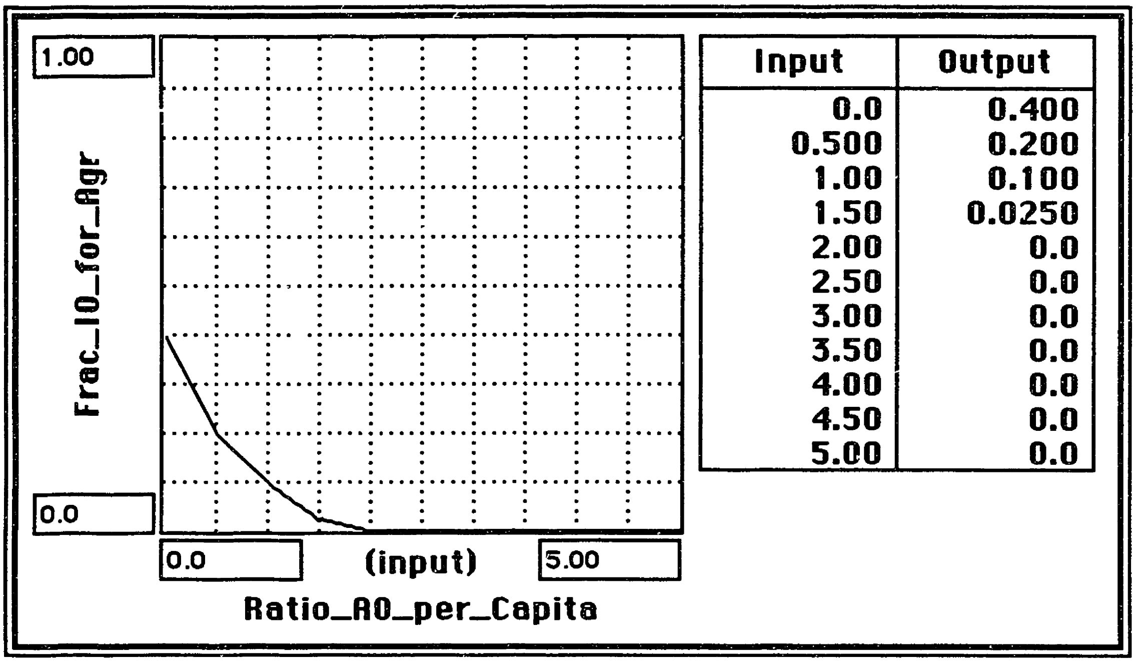


Input	Output
0.0	230.00
200.00	480.00
400.00	690.00
600.00	850.00
800.00	970.00
1000.00	1070.00
1200.00	1150.00
1400.00	1210.00
1600.00	1250.00
1800.00	1275.00
2000.00	1282.50

figure 3-1

Fraction of Insutrial Output for Pollution

The fraction of industrial output allocated for pollution control is a function of the index of pollution, which is explained in detail in the section describing pollution variables. This variable is implemented as an "S" shaped function (figure 3-3). The reason for defining the variable as an "S" function rather than a linear one is the following: it is assumed that, when pollution levels are on a minimum, very little is done to control it, but when it increases to unacceptable levels (over 6) people start concerning about its control and start investing in order to reduce it. The final turn in the "S" function represents the point in which extra capital units spent in pollution reduction do not have any effect because there already is a maximum effort being put into it. The values chosen were rough approximations and should not be taken as accurate by any means.



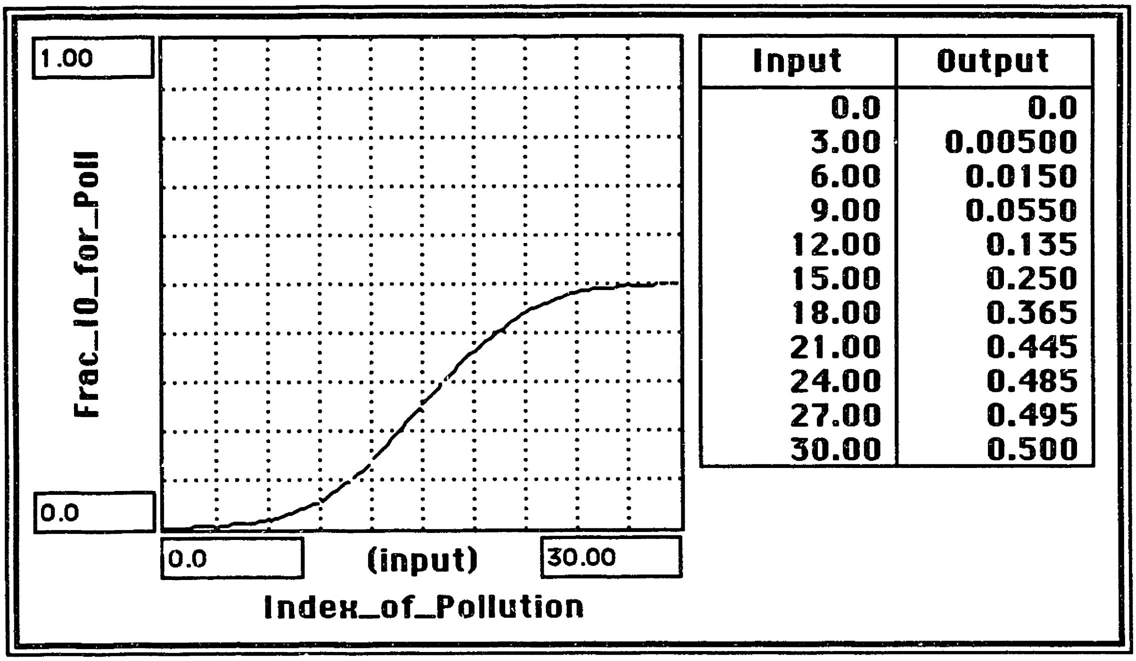
Input	Output
0.0	0.400
0.500	0.200
1.00	0.100
1.50	0.0250
2.00	0.0
2.50	0.0
3.00	0.0
3.50	0.0
4.00	0.0
4.50	0.0
5.00	0.0

figure 3-2

Fraction of Industrial Output for Industry

As mentioned earlier, the fraction of industrial output allocated for industrial investment is the industrial output remaining after allocating capital for investment in agriculture and pollution control. A policy variable (*Switch_Poll_Control*) is included in the equations in order to provide the modeler with the ability to either exclude or include investment in pollution control by making the variable a 0 or 1 respectively.

```
Frac_IO_for_Ind = 1 - (Frac_IO_for_Agr + (Switch_Poll_Control *
      Frac_IO_for_Poll))
Switch_Poll_Control = 1
```



Input	Output
0.0	0.0
3.00	0.00500
6.00	0.0150
9.00	0.0550
12.00	0.135
15.00	0.250
18.00	0.365
21.00	0.445
24.00	0.485
27.00	0.495
30.00	0.500

figure 3-3

Agricultural Investment

The fraction of industrial output allocated for agricultural investment times the total agricultural investement yields the total agricultural investment. This is the capital which is used for agricultural land development and maintenance. It is employed in the agricultural sector to determine the yearly amount of land developed and added to the available agricultural land.

```
Agricul_Investment = Industrial_Output * Frac_IO_for_Agr
```

Pollution Investment

This is the yearly amount of capital reserved for investment in pollution reduction. It is defined as the total industrial output multiplied by the fraction of industrial output allocated for pollution control.

```
Pollution_Invest = Industrial_Output * Frac_IO_for_Poll
```

The Agricultural Sector

Agricultural Land

The variable *Agricultural Land* represents the total available land used for the production and cultivation of food. The level of agricultural land embodies the average characteristics of the land used for cultivation throughout a particular region. The specific figures characterizing the land are represented as other variables which will be presented in this section, such as land fertility and yield factor. Again, an initial value of 100 was selected for purposes of consistency and experimentation. In the model, land is represented by the dimensions of land units.

```
Agricultural_Land=Agricultural_Land+dt*(Agr_Development-Ind_Development
       -Erosion_and_Damage )
INIT(Agricultural_Land) = 35
```

Agricultural Development

This is one of the variables which represents the rate at which industrial investment in agriculture is converted into agriculural use. In specific, this variable demonstrates how the fraction of agricultural investment which is not put into land maintenance is converted into agricultural land development. The amount invested into developing land is divided by the cost of developing one land unit. The value of developing one unit of land is implicitly included in the equations defining agricultural development (the dividing 1 term). This calculation yields the amount of land which may be developed with the invested capital. This figure is divided by the time it takes to develop one unit of agricultural land to determine the yearly rate of agricultural development.

```
Agr_Development = (Agricul_Investment*(1-Frac_AI_for_Mainten)/1)
        /Agr_Develop_Time
Agr_Develop_Time = 1
```

Industrial Development

The variable *Industrial Development* indicates the rate at which land previously allocated for agricultural purposes is converted into industrial use. In the model, it is assumed that the fraction of land converted for industrial use is a fixed portion of the total available agricultural land. It is also assumed that there are no restrictions opposing this development and that the funding for developing the land is always available.

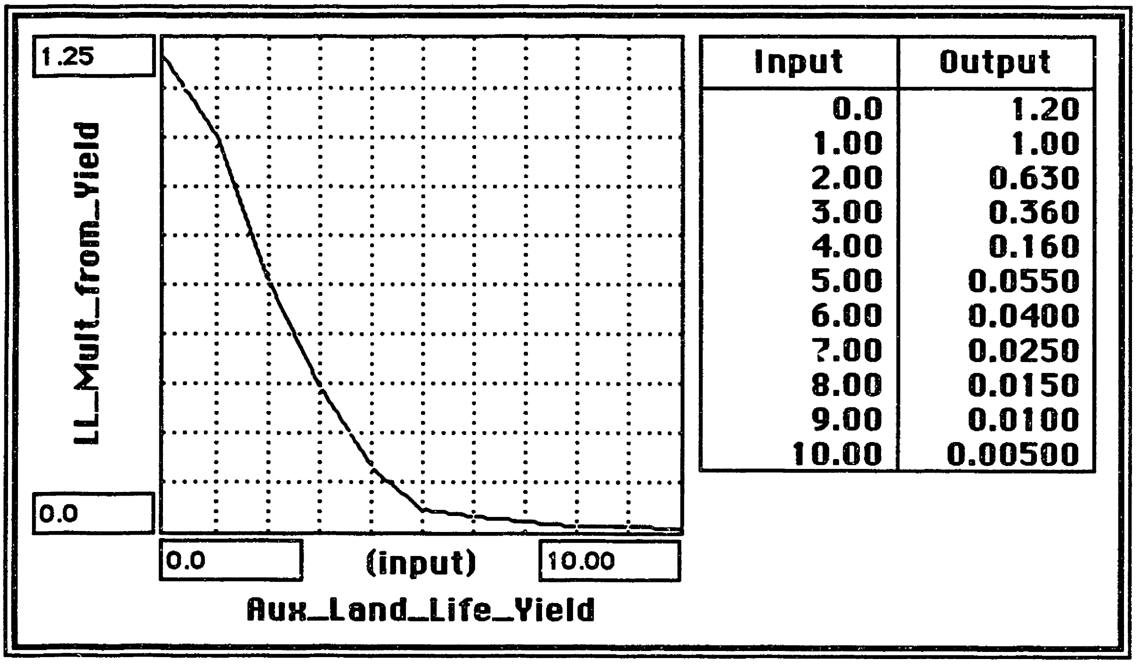
```
Ind_Development = Agricultural_Land / Ind_Develop_Time
Ind_Develop_Time = 10
```

Erosion and Damage

Erosion is the term used to define the detachment and transportation of earth contents (rock or soil), whether it is induced by nature or man. In this model, the effect of erosion and other related damage is included in the agricultural sector. This variable is included in order to allow the modeler to include other losses of agricultural land which may be influential to the sector. Also, the inclusion of this variable provides the modeler a way to study other aspects of pollution or industrialization which may affect the agricultural sector and where not originally taken into consideration in the model.

As the previous two variables were, *Erosion and Damage* is defined in terms of land units displaced per year. The equation definition of this variable includes references to two other variables: the *Normal Life of Land* and a land life multiplier from yield (*LL_Mult_from_Yield*). The first variable indicates the average time it would take for a unit of land to be displaced by nature and normal cultivation of land. As yield rises, the amount of earth transported rises and leads to an increase in the level of erosion. This increase in the erosion rate affects the amount of time a unit of land stays in its current location and effectively reduces the normal life of the land: this is the idea lying behind the variable *LL_Mult_from_Yield*. The value of this multiplier is calculated by comparing the land yield to the inherent land fertility through the variable *Aux_Land_Life_Yield.* From here, the model determines the value of the multiplier by referring to the table function presented in figure 3-4.

```
Erosion_and_Damage=Agricultural_Land/(Normal_Life_of_Land
      * LL_Mult_from_Yield)
Normal_Life_of_Land = 6000
LL_Mult_from_Yield = graph(Aux_Land_Life_Yield)
Aux_Land_Life_Yield = Land_Yield / Inherent_Land_Fert
```

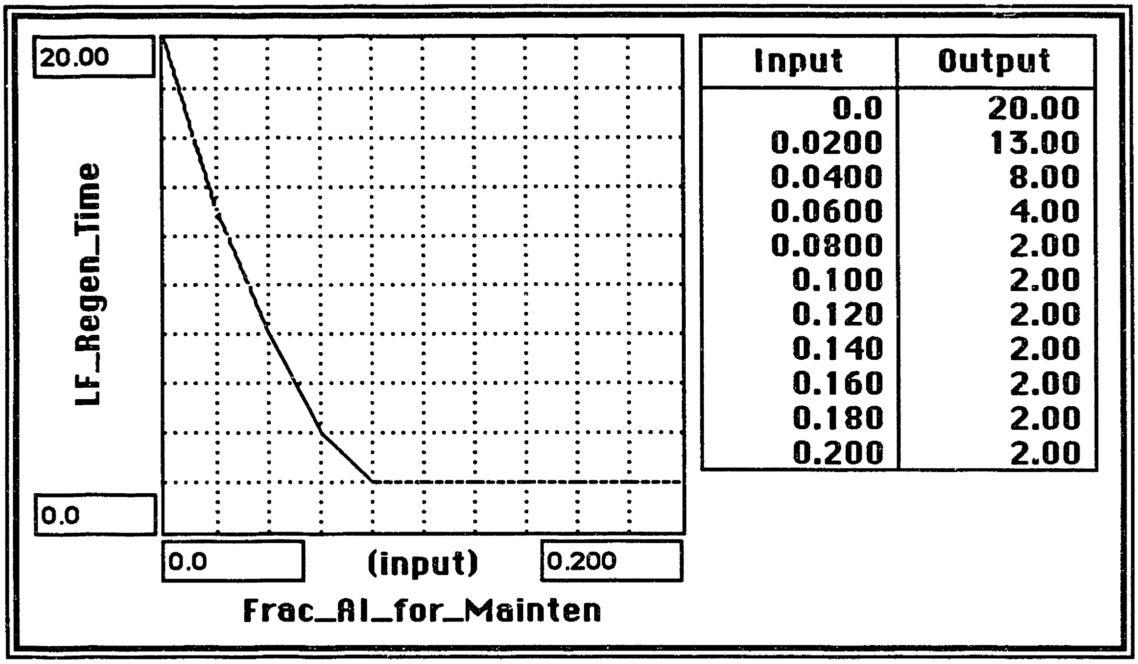


Input	Output
0.0	1.20
1.00	1.00
2.00	0.630
3.00	0.360
4.00	0.160
5.00	0.0550
6.00	0.0400
7.00	0.0250
8.00	0.0150
9.00	0.0100
10.00	0.00500

figure 3-4

Land Fertility

This is the variable in the agricultural sector which represents the aggregated characteristics of the land at a particular moment in time. Furthermore, *Land Fertility* represents the agricultural conditions of the land due to land maintenance and pollution. The level of fertility indicates how appropiate the land is for cultivation. A low fertility level indicates that the land has not been well maintained and that contamination is affecting the conditions required for plant growth, limiting agriculture. *Land Fertility* is represented in the model by



Input	Output
0.0	20.00
0.0200	13.00
0.0400	8.00
0.0600	4.00
0.0800	2.00
0.100	2.00
0.120	2.00
0.140	2.00
0.160	2.00
0.180	2.00
0.200	2.00

figure 3-5

fictional units called *Fertility Units*. This units have no physical significance and are only used for purposes of facilitating the job of dimension consistency throughout the model.

```
Land_Fertility = Land_Fertility + dt * ( -LF_Degradation +
      LF_Regeneration )
INIT(Land_Fertility) = Inherent_Land_Fert
```

Land Fertility Regeneration

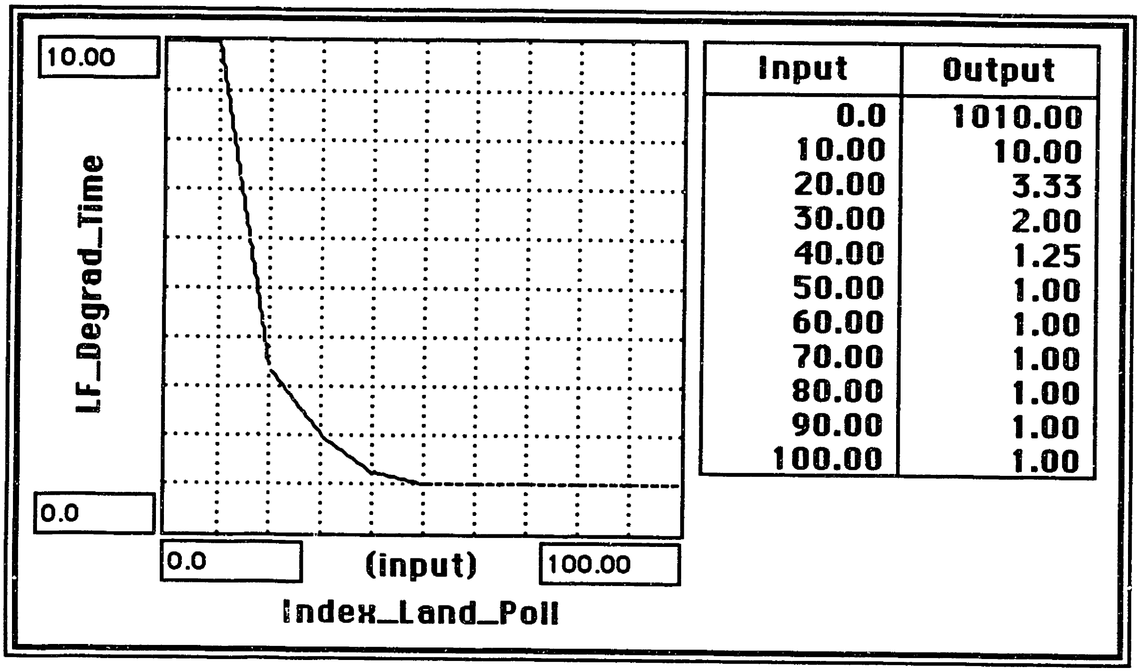
Land Fertility Regeneration describes how, once capital has been allocated for investments in land maintenance, regeneration of fertility occurs. It is assumed in the model that land maintenance aims at raising the level of fertility up to its original level. This is implicitly presented as part of the land fertility regeneration variable equation by calculating the total regeneration rate as being the difference bewteen actual fertility and its normal level. Once investment has been allocated for maintenance, it is assumed that maintenance reduces from earth pollutants which reduce agricultural yield. This actual process of increasing fertility takes effect by reducing the time the earth takes to regain its original fertility. In other words, fertility is regained by decreasing the land's "healing" time. The exact figures representing this process are presented in figure 3-5.

```
LF_Regeneration =(Inherent_Land_Fert-Land_Fertility)/LF_Regen_Time
Inherent_Land_Fert = 1
LF_Regen_Time = graph(Frac_AI_for_Mainten)
```

Land Fertility Degradation

The time it takes for natural degradation of land fertility is very long. Land contamination decreases this time drastically, as can be observed in figure 3-6. An index of pollution of only ten times the normal reduces land fertility's effective life by two orders of magnitude at least. Further increases in the level of pollution reduce fertility life to approximately nothing. This is concept represented by the variable *Land Fertility Degradation.* This variable determines the annual reduction in fertility due to increasing levels of land pollution which will be substracted from the fertility level. The land fertility degradation time is determined by the table presented in figure 3-6, which is a function of the index of land pollution.

```
LF_Degradation = Land_Fertility / LF_Degrad_Time
LF_Degrad_Time = graph(Index_Land_Poll)
```



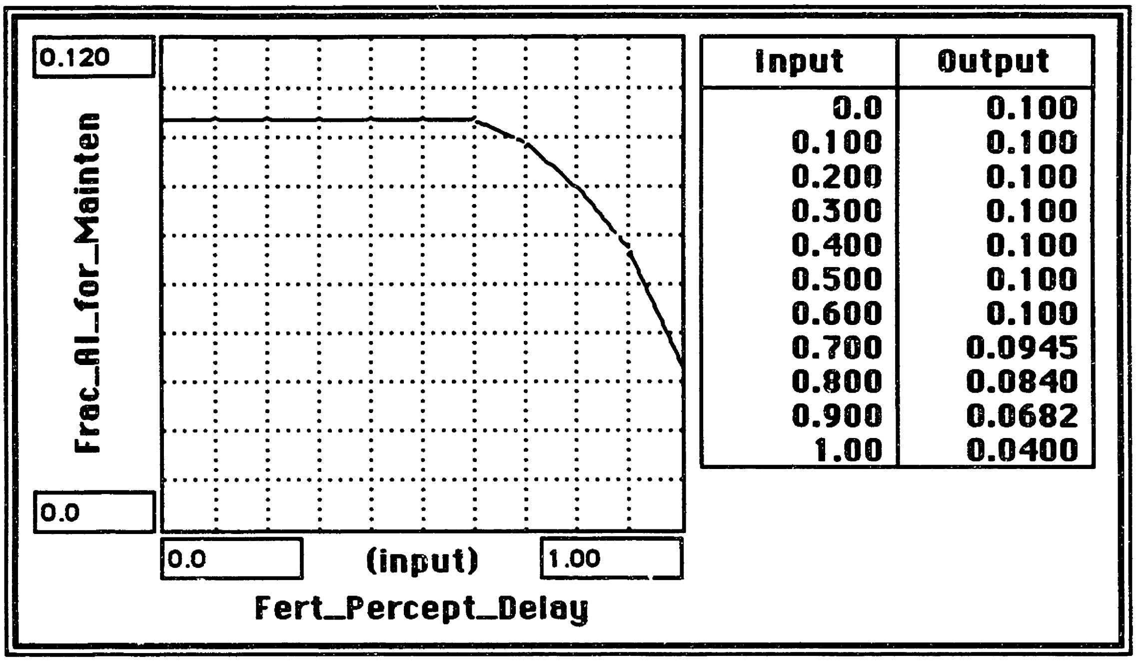
Input	Output
0.0	1010.00
10.00	10.00
20.00	3.33
30.00	2.00
40.00	1.25
50.00	1.00
60.00	1.00
70.00	1.00
80.00	1.00
90.00	1.00
100.00	1.00

figure 3-6

Fraction of Agricultural Investment for Land Maintenance

This variable describes the process of delay in the perception of changes in the levels of fertility and how capital invested in agriculture is allocated to land maintenance. The delay in the perception of the level of land fertility is represented in the model by the smooth function included in the equations defining this variable. This function provides a "smoothing" effect in which drastic changes in fertility are distributed throughout a period of time. Presently, the delay effect is set to a value of 2 years. The actual allocation of agricultural investment for land maintenance is implemented as the table function presented in figure 3-7. The graph incorporates the idea of low concern for initial reductions in fertility, as generally happens in reality, but exponentially increasing investment in land maintenance as the level of fertility nears critical levels.

```
Frac_AI_for_Mainten = graph(Fert_Percept_Delay)
Fert_Percept_Delay = SMTH3(Land_Fertility,2,Inherent_Land_Fert)
```



Input	Output
0.0	0.100
0.100	0.100
0.200	0.100
0.300	0.100
0.400	0.100
0.500	0.100
0.600	0.100
0.700	0.0945
0.800	0.0840
0.900	0.0682
1.00	0.0400

figure 3-7

Land Yield

The variable *Land Yield* represents actual output per land unit when fertility and air quality are considered. The agricultural yield is determined by multiplying the fertility of the land (which is normalized to 1), a multiplier representing the quality of air, and a scaling factor. The multiplier representing air quality (figure 3-8) determines the condition of the air agricultural material are being exposed to. Contamined air will not support vegetarian life and, therefore, will reduce the agricultural yield of the land. The land yield factor is a policy variable provided to enable the modeler to alter the land yield calculation by a chosen constant. At the moment, it is not in use and is set to a value of 1. The dimensions of agricultural yield are agricultural units per land unit per year.

```
Land_Yield = Land_Yield_Factor*Land_Fertility*LY_Mult_Air_Poll
Land_Yield_Factor = 1
LY_Mult_Air_Poll = graph(Index_Air_Poll)
```

Agricultural Output

Once all aspects affecting cultivation have been considered, the yearly production of food can be determined. The *Agricultural Output* represents the yearly supply of food available for consumption. It is calculated by multiplying the total agricultural land times the average land yield per unit of land, determining the total agricultural units produced yearly.

```
Agricultural_Output = Land_Yield*Agricultural_Land
```

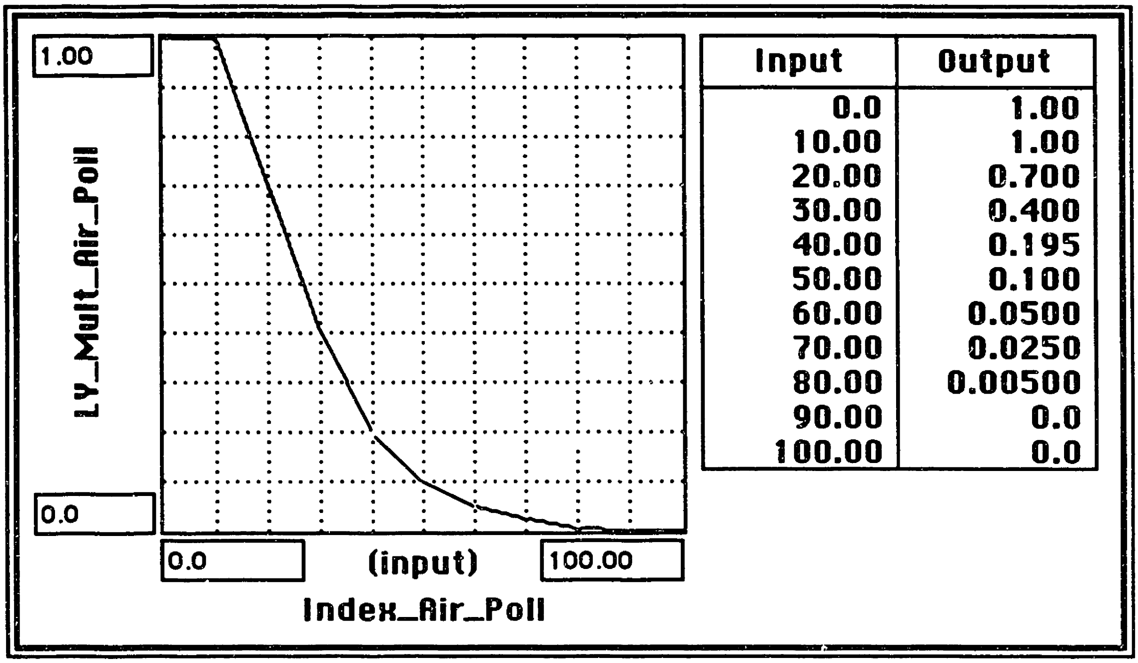
The Pollution Sector

Industrial Pollution Rate

The *Industrial Pollution Rate* is the variable which indicates the amount of pollution being emitted by the industrial sector. It is seggregated into the three different categories (air, land, and water pollution), and each of the categories has its own variables adjusting the emission ratio. This variable encompases all of the pollution emissions ocurring in the industrial sector, such as solid waste, ash and toxic gas emission, hydrothermal pollution, and others.

For each of the rate variables, *Industrial Output* and another variable determine the emission rate of industry. In the model, it is assumed that the total output produced by the industry determines the amount of pollution being emitted, which explains why the industrial output variable is present in the equations. The other variables are conversion variables which determine how many pollution units are been emitted for each unit of capital produced. The equation is prsented in three different versions, one for each of the different environmental resources.

```
Ind_Air_Poll_Rate = Industrial_Output * Air_Poll_IO_Unit
Air_Poll_IO_Unit = 2
Ind_Land_Poll_Rate = Industrial_Output * Land_Poll_IO_Unit
Land_Poll_IO_Unit = 1
Ind_Water_Poll_Rate =Industrial_Output * Water_Poll_IO_Unit
Water_Poll_IO_Unit = 1
```



Input	Output
0.0	1.00
10.00	1.00
20.00	0.700
30.00	0.400
40.00	0.195
50.00	0.100
60.00	0.0500
70.00	0.0250
80.00	0.00500
90.00	0.0
100.00	0.0

figure 3-8

Agricultural Pollution Rate

Parallel to the variable presented above, the *Agricultural Pollution Rate* determines the total pollution being emitted by the agricultural sector. It is seggregated into the two different types of emissions, air and land pollution. The main cause of agricultural pollution is pesticide spraying, but some gas, ash, and waste emission due to agricultural processing exists.

In this variable, its is not the output but the land which determines the main values of the emission rate. Land is used since the agricultural output is dependent on the land yield and in some cases this figure can be very low and may not reflect the real amount of pesticide being used in the agricultural sector. As an example, let's assume that the level of air pollution is high and the land yield is cut in half; during the cultivation process, the same terrain has to be covered with pesticide even though the total agricultural output will be half of that under normal conditions.

In addition, conversion variables are included to provide for individual description of the emission rates for air and land pollution in terms of pollution units per unit of agricultural output.

```
Agr_Air_Poll_Rate = Agricultural_Land * Air_Poll_Agr_Unit
Air_Poll_Agr_Unit = 2
Agr_Land_Poll_Rate = Agricultural_Land * Land_Poll_Agr_Unit
Land_Poll_Agr_Unit = 1
```

Air Pollution

As one of the level variables in the pollution sector, the *Air Pollution* indicates the amount of material which has been emitted into the air and is still contamining it. Furthermore, it indicates the amount of waste in the air at every moment in time during the timespan of the model. It is the "integrated" sum of all of the contaminant emissions minus the reductions during the simulation. For example, if, during 50 years of simulation, there has been a constant emission of air pollution of 100 pollution units per year and a reduction (due to any reason, some which will be explained later) of 25 units per year; after the 50 years there will be a net total of 3750 pollution units still present in the air.

The air pollution is measured in terms of pollution units and is initialized at the beginning of the simulation to a "standard" level, to which it will be compared later to determine the index of air pollution.

```
Air_Pollution = Air_Pollution + dt * ( -Precip_into_Land -
      Precip_into_Ocean + Air_Poll_Gen_Rate - AP_Reduction )
INIT(Air_Pollution) = Standard_Air_Poll
```

Air Pollution Generation

The variable *Air Pollution Generation* is the arithmetic sum of the contamination of air from both the industrial and agricultural sectors. It is an auxiliary variable used to simplify the layout of the model and, at the same time, present and aggregate sum of all the contributions to air pollution generation.

```
Air_Poll_Gen_Rate = Ind_Air_Poll_Rate + Agr_Air_Poll_Rate
```

Air Pollution Reduction

This variable, as well as its counterparts in this sector, is included in the model to account for man intervention in pollution reduction. This reduction can take any form as long as it is artificially induced by man, such as purification processes. The source for the money incurred in these purifying processes has already been presented in the industrial sector, which is the fraction of the total industrial output that was allocated to investments in pollution control. The money invested for pollution control is then re-allocated, as will be described in the latter part of this section, to reduce pollution in the different areas of the ecosystem. The *Air Pollution Reduction* is the manifestation of investment in pollution reduction when allocated to the air resource.

The variable also includes a limiting factor (the `Air_Pollution/1` figure) in case the total reduction induced by pollution investment is bigger than the existing pollution, in which case the reduction would be the existing pollution.

```
AP_Reduction = MIN(Air_Pollution/1,Air_Poll_Red_Rate/3)
```

Precipitation into Land

As we could presume, there exist natural sources through which air pollution is reduced. One of this is the precipitation of pollutants into the land. As the air moves, the land acts as a filter through which the air is "purified." On the other hand, while air pollution is decreasing through this precipitation process, the pollutants in the air are being disposed into the land and are increasing the total pollution in the land. The total fraction of air pollution precipitated into the land is determined by the Air Pollution Time for Land Precipitation, which is the average lifetime of air pollutants before they precipitate into the land. The total reduction in air pollution due to precipitation into the land is measured in terms of pollution units per year.

```
Precip_into_Land = Air_Pollution / AP_Time_LPrecip
AP_Time_LPrecip = 5
```

Precipitation into Ocean

As precipitation into the land describes the interactions between the air pollution and other variables in the pollution sector such as land pollution, *Precipitation into Ocean* describes how air pollution is discarded from the entire system simulated by the model. The same way the pollutants in the air infiltrate into the land, they leave the region and precipitate into the ocean. The process of precipitation of pollutants into the water is more difficult than that of land precipitation, since the air cannot flow through it. These are disposed into the water when the air flows close to it and the pollutants "stick" to the water. In the model, it is assumed that the precipitation into rivers and lakes is very small and the reductions in air pollution occur by precipitation into much larger aquatic bodies such as the ocean. The model could be changed to fit situations in which precipitation into lakes and rivers is important or essential in order to describe the process of creating regulations on water resource availability. Again, the fraction of air pollution discarded from the system is determined by the average lifetime of air pollution before being precipitated into the ocean (*AP_Time_OPrecip*) and the variable is measured in terms of pollution units discarded per year.

```
Precip_into_Ocean = Air_Pollution / AP_Time_OPrecip
AP_Time_OPrecip = 9.333
```

Index of Air Pollution

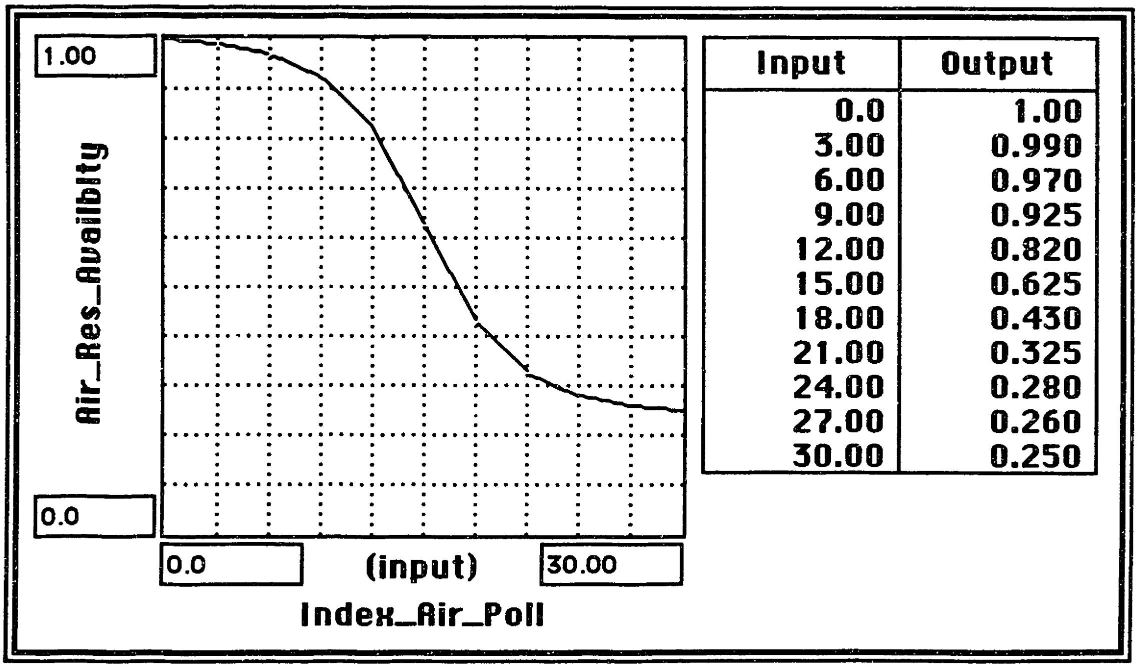
The*Index of Air Pollution* is a dimensionless ratio comparing the level of air pollution at a particular moment in time to value chosen as the "standard" or normal level of air pollution. In other words, this variable indicates the how many times greater the present level of air pollution is compared to the value chosen to be the normal level of pollution (*Standard_Air_Poll*). For example, a value of 2 in the index of air pollution means that there is twice the level of air pollution than the original or normal level.

```
Index_Air_Poll = Air_Pollution / Standard_Air_Poll
Standard_Air_Poll = 150
```

Air Resource Availability

The variable *Air Resource Availability* represents the intervention of the government in creating regulations and limiting pollution emissions versus the status of the quality of the air. The lower the number of regulations and restrictions, the more available the air is for using as a disposal medium and vice-versa. It was implemented using a table function in order to allow for discontinuities or complex functions in the process of regulation creation. In the sample experimental runs, the values used (such as the one shown in figure 3-9) reflect the way in which regulations are created in an "S" shaped fashion: there are almost no regulations created until a critical point is reached in which a linear relation is followed until the point where imposing more regulations is ineffective and the graph flattens out again.

```
Air_Res_Availblty = graph(Index_Air_Poll)
```



Input	Output
0.0	1.00
3.00	0.990
6.00	0.970
9.00	0.925
12.00	0.820
15.00	0.625
18.00	0.430
21.00	0.325
24.00	0.280
27.00	0.260
30.00	0.250

figure 3-9

Land Pollution

Land Pollution is the second level variable in the pollution sector. It represents the total amount of waste or other pollutants present in the land at any particular moment in time. It is defined similarly to the variable *Air Pollution* in the rest of its characteristics and is initialized to a normal level of pollution through the variable *Standard Land Poll.*

```
Land_Pollution = Land_Pollution + dt*( Precip_into_Land-Solution_Rate
      - Degradation_in_Land + Land_Poll_Gen_Rate - LP_Reduction )
INIT(Land_Pollution) = Standard_Land_Poll
```

Land Pollution Generation

As explained previously for the variable *Air Pollution Generation* , this variable is the arithmetic sum of the contributions of the industrial and agricultural sector to the total pollution of land. It is measured in terms of pollution units generated per year.

```
Land_Poll_Gen_Rate = Ind_Land_Poll_Rate + Agr_Land_Poll_Rate
```

Land Pollution Reduction

The *Land Pollution Reduction* has the same explanation as for its counterpart in the air pollution. The variable reflects the intervention of man in reducing land pollution through artificial processes or any other purification methods.

```
LP_Reduction = MIN(Land_Pollution/1,Land_Poll_Red_Rate/3)
```

Solution Rate

The variable *Solution Rate* describes the interaction between land pollution and other pollution variables in the sector, specifically *Water Pollution* . The name of the variable itself gives an explanation of the process through which land pollution is converted into water pollution. As time passes, rain and other causes of land erosion cause deposits of pollutants to move and infiltrate through the land until they reach rivers or lakes and contamine them. This movement of pollutants decreases the total land pollution but, at the same time, augments water pollution.

The fraction of pollution which undergoes solution is determined by the Land Pollution **Time** for **Solution**, and the variable is defined in terms of pollution units decreased per year.

```
Solution_Rate = Land_Pollution / LP_Time_Solutn
LP_Time_Solutn = 750
```

Degradation into Land

As its counterpart under air pollution, this variable describes the natural process through which land pollution is discarded from the system. Land pollution is discarded from the system through the assimilation of contaminants by the land. Again, the fraction of pollution discarded is determined by an average lifetime variable (*LP_Time_Degradtn*) and the variable is measured in terms of pollution units discarded per year.

```
Degradation_in_Land = Land_Pollution / LP_Time_Degradtn
LP_Time_Degradtn = 15
```

Index of Land Pollution

The*Index of Land Pollution* is the dimensionless ratio indicating the status of the quality of the land. As explained for the index of air pollution, this variable indicates how many times greater the present level of land pollution is compared to the value chosen to be the normal level of land pollution (*Standard_Land_Poll*).

```
Index_Land_Poll = Land_Pollution / Standard_Land_Poll
Standard_Land_Poll = 150
```

Land Resource Availability

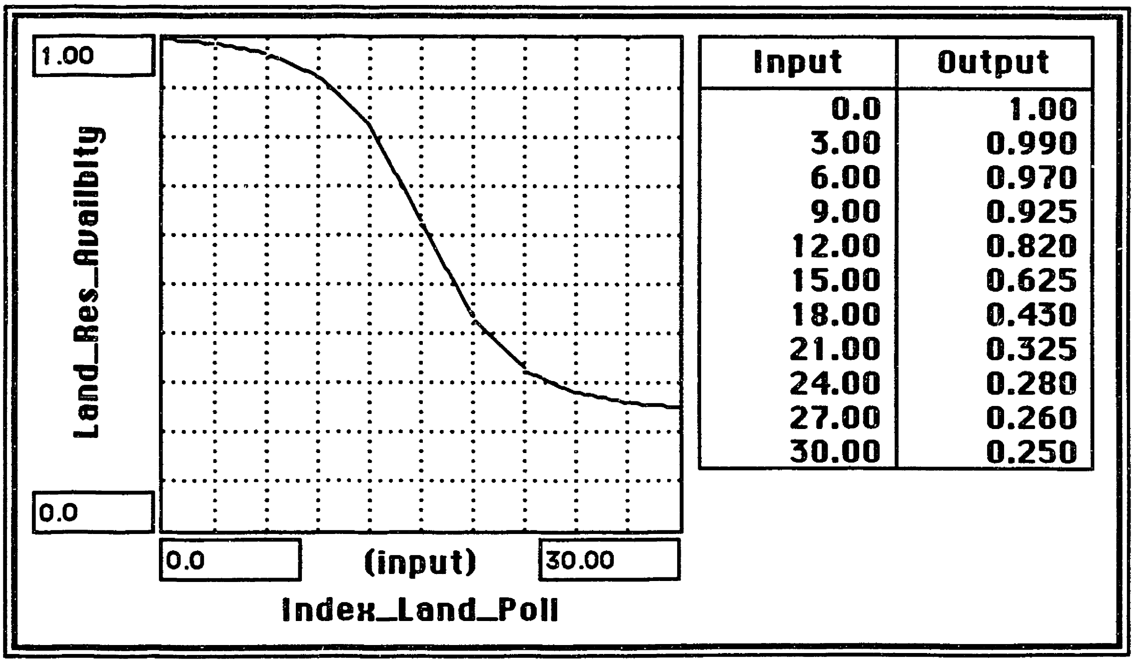
As explained for *Air Resource Availability*, this variable describes the intervention of the government in reducing pollution by creating regulations and limiting emissions versus the status of the quality of the land. The function presented in figure 3-10 presents the same ideas explained for its parallel under the air pollution section.

```
Land_Res_Availblty = graph(Index_Land_Poll)
```

Water Pollution

Water Pollution is the third and last level variable in the pollution sector. It reflects the total amount of waste and other pollutants present in rivers and lakes. It is defined similarly to the variable *Air Pollution* and *Land Pollution* in the rest of its characteristics and is initialized to a normal level of pollution through the variable *Standard Water Poll.*

```
Water_Pollution = Water_Pollution + dt * ( Solution_Rate -
      Runoff_into_Ocean + Water_Poll_Gen_Rate - WP_Reduction )
INIT(Water_Pollution) = Standard_Water_Poll
```



Input	Output
0.0	1.00
3.00	0.990
6.00	0.970
9.00	0.925
12.00	0.820
15.00	0.625
18.00	0.430
21.00	0.325
24.00	0.280
27.00	0.260
30.00	0.250

figure 3-10

Water Pollution Generation

The definition of this variable is the same as for its equivalent counterparts in the pollution sector except that it does not include any contribution from the agricultural sector. In the model, it is assumed that all of the pollution emitted by the agricultural sector takes the form of either air or land pollution.

```
Water_Poll_Gen_Rate = Ind_Water_Poll_Rate
```

Water Pollution Reduction

The *Water Pollution Reduction* has the same explanation as for the *Air Pollution Reduction* and *Land Pollution Reduction* . The variable reflects the intervention of man in reducing land pollution through artificial processes or any other purification methods.

```
WP_Reduction = MIN(Water_Pollution/1,Water_Poll_Red_Rate/3)
```

Runoff into Ocean

Differing from the other two level variables in this sector, *Water Pollution* does not interact with any other pollution variable. The only process decreasing the pollution collected in the water is the natural discardment rate through ocean runoff. The process of "running off" applies specifically to pollution in rivers. Again, the yearly fraction of water pollution discarded through ocean runoff is determined by the average lifetime of water pollution variable *WP_Time_Runoff.*

```
Runoff_into_Ocean = Water_Pollution / WP_Time_Runoff
WP_Time_Runoff = 20
```

Index of Water Pollution

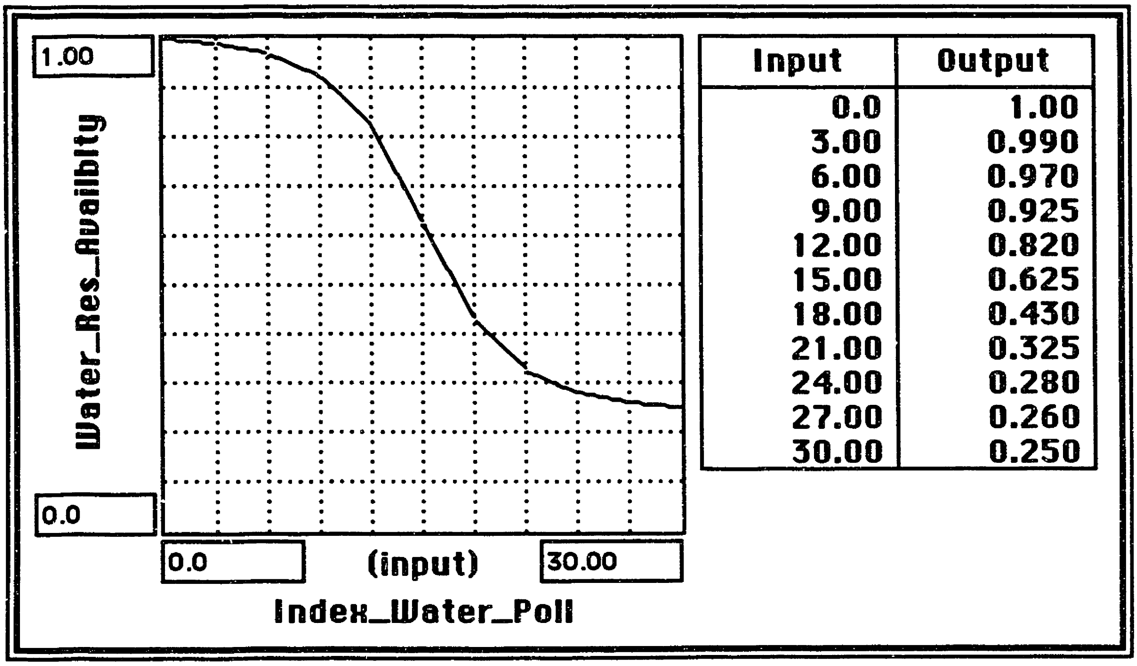
The*Index of Water Pollution* is a dimensionless ratio indicating the status of the quality of the rivers and lakes. As explained for the previous indexes, this variable indicates how many times greater the present level of water pollution is compared to the value chosen to be the normal level of pollution *(Standard_Water_Poll).*

```
Index_Water_Poll = Water_Pollution / Standard_Water_Poll
Standard_Water_Poll = 150
```

Water Resource Availability

The variable *Water Resource Availability,* parallel to the availability of air and land, represents the intervention of the government in creating regulations and limiting pollution emissions versus the status of the quality of the land. Again, the function used in the experimental runs (figure 3-11) represents the same ideas explained in the *Air Pollution* section.

```
Water_Res_Availblty = graph(Index_Water_Poll)
```



Input	Output
0.0	1.00
3.00	0.990
6.00	0.970
9.00	0.925
12.00	0.820
15.00	0.625
18.00	0.430
21.00	0.325
24.00	0.280
27.00	0.260
30.00	0.250

figure 3-11

Index of Pollution

The index of pollution represents the perception of the state of pollution (aggregated) by the government and industry in order to plan for pollution investment allocation. The exact use of the *Index of Pollution* has been explain in the industrial sector.

At present, the perception of aggregated pollution is implemented using the average from the index of air, land, and water pollution and a "smoothing" function. The smoothing function serves as a perception delay, an effect which usually occurs whenever uncertain changes are present in processes.

```
Index_of_Pollution = SMTH3((Index_Air_Poll + Index_Land_Poll +
      Index_Water_Poll)/3,2,1)
```

Total of Indexes

This is an auxiliary variable used to calculate the fraction of the total pollution caused by each of the three forms of pollution . The variable*Total of Indexes* is the arithmetic sum of the three pollution indexes. Once this variable has been calculated, each fraction is determined by dividing the appropiate index by the *Total of Indexes.* For example, if the fraction of pollution contributed by air pollution is desired, we would divide the *Index of Air Pollution* by the *Total of Indexes* in order to obtain the desired figure.

```
Total_of_Indexes = Index_Air_Poll+Index_Land_Poll+Index_Water_Poll
Frac_PI_Air_Cntl = Index_Air_Poll / Total_of_Indexes
Frac_PI_Land_Cntl = Index_Land_Poll / Total_of_Indexes
Frac_PI_Water_Cntl = Index_Water_Poll / Total_of_Indexes
```

Pollution Reduction Rate

The pollution reduction rate due to man-induced processes is subdivided into three categories, as mentioned in each of the subsections of the pollution sector. These are the air pollution reduction, land pollution reduction, and water pollution reduction. The capital allocated for pollution control is proportionally distributed among the different forms of pollution through the fractions computed in the previous variable. The capital to be invested in reduction of pollution of a particular environmental resource is calculated by multiplying the appropiate fraction times *Pollution Investment.* Once this quantity is computed, the figure is multiplied times a conversion factor, which determines the effective reduction per capital unit invested. This calculation yields the net reduction of pollution for a particular resource. For example, if air pollution was 1/3 of the total pollution, pollution investment was 300 capital units, and one pollution unit was discarded for every four capital units invested in air pollution. The total investment in air pollution control would be 100 capital units and the effective reduction in air pollution would come out to be 25 pollution units.

The dimensions of the reduction rates have been implicitly presented in the previous explanation as well as in the explanations in the previous subsections. The variable is measured in terms of pollution units per year, while the *Reduc_per_Dlr* variables are measured in terms of pollution units per capital unit.

```
Air_Poll_Red_Rate = Inv_Air_Control * AP_Reduc_per_Dlr
AP_Reduc_per_Dlr = 1
Inv_Air_Control = Pollution_Invest * Frac_PI_Air_Cntl

Land_Poll_Red_Rate = Inv_Land_Control * LP_Reduc_per_Dlr
LP_Reduc_per_Dlr = 1
Inv_Land_Control = Pollution_Invest * Frac_PI_Land_Cntl

Water_Poll_Red_Rate = Inv_Water_Control * WP_Reduc_per_Dlr
WP_Reduc_per_Dlr = 1
Inv_Water_Control = Pollution_Invest * Frac_PI_Water_Cntl
```

Sample Experimental Runs

In the previous chapters, the assumptions and structure of the model were explained in careful detail. The assumptions represented by the model seem plausible and realistic. Many of them are based on observations made from current environmental problems. Furthermore, some of the assumptions and explanations will be recognized by the reader as daily issues present in most newspapers and magazines.

The equations presented in the previous chapter specify the rules which the model must follow and which prescribe its behavior. These rules describe how each individual part of the system behaves to a set of pressures imposed upon it. The model's behavior is determined by the state of the level variables. These variables represent a historic account of the dynamics of the system while the rest of the variables represent momentaneous decisions. The behavior and dynamics of the model can be observed by stepping through the simulation at a small enough time unit which will preserve the intricacies of a continous flow behaviour without making the calculations cumbersome. As each sector of the model behaves according to the original assumptions, the interconnection of these previously independent suppositions presents an aggregate behaviour which, in some cases, may prove to be rather surprising.

In this section I present four experimental runs which summarize the current status of the model. The first run presents the basic behavior that must be simulated in order support the validity of the model. The behavior is that of an exponential growth in pollution with a constant growth in the economy. This situation leads to the "death of agriculture" and is one of major concern to countries such as Taiwan, in which, in order to keep a growing economy, they permit unrestricted use of environmental resources as disposal mediums. The other three graphs present the behavior of the system taking into consideration capital investment in pollution reduction, restrictions on pollution emissions, and a combination of both. The values of the axis have been purposely omitted since the objective of the model is not to predict any exact values of the system at any particular moment in time but to present what the mode of behaviour may be. Also, since the values chosen were completely experimental and do not represent any valid set of data, no false predictions or conclusions are to be inferred from these runs. Again, this is an exploratory model which simulates the interactions between forces which are assumed to be the most important in the economy-pollution relation. Obviously, the model reflects the conceptual bias of the author and may not take into consideration factors which others may consider influential to the behavior of the simulation.

Notice that at some points in the graphs the apparent growth of some variables seems negligible compared to others, as happens at the beginning of the first agricultural land plot. This is caused by the different scales on which the graphs were plotted. For example, in the first runs presented the continuing rise of agricultural output seems contradictory to what appears to be a drastic decrease in fertility and a suddle increase in agricultural land. This observation is misleading since the agricultural land plot would be growing more rapidly than tother if they would have been presented in a common reference scale.

Sample Run with no restrictions on pollution and no capital investment in pollution reduction

Presented in figures **4.1a** to **4.1c** is the outcome of simulation in which no pollution control mechanisms affected the model. As expected, the levels of pollution for this kind of system grow exponentially (figure 4.1a). The high levels of pollution are the result of contaminant emissions from a growing economy and expanding agriculture, as seen in figure 4.1b and 4.1c.

As we can see in figure 4.1b, the economy's growing rate is almost exponential. This leads to an exponential growth of agricultural land and of the levels of pollution. The rising levels of pollution damage the quality of the land and air, which directly affect land fertility and the effective agricultural yield (figure 4.1c). Until the level of fertility becomes negligible, the rising levels of agricultural land dominate over the declining fertility, accounting for an increase of the agricultural output. Once the levels of land and air pollution become critical, the rate of industrial growth slightly decreases due to the high amounts of money invested in agricultural maintenance, which leads nowhere without pollution control. This is what I call the death of agriculture, the point in which the levels of pollution are so high that no agricultural life can be supported anymore and, therefore, the agricultural sector ceases to exist and to contribute at all to the economic progress of the nation. The amount of agricultural land can keep growing, as in figure 4.1c, but the agricultural output is negligible.

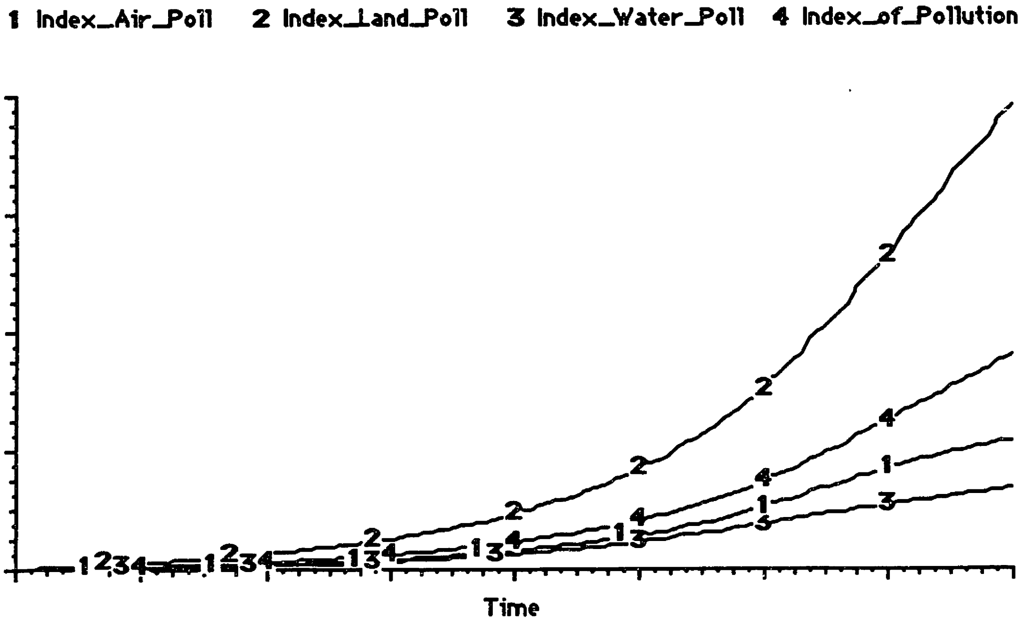


figure 4.1a

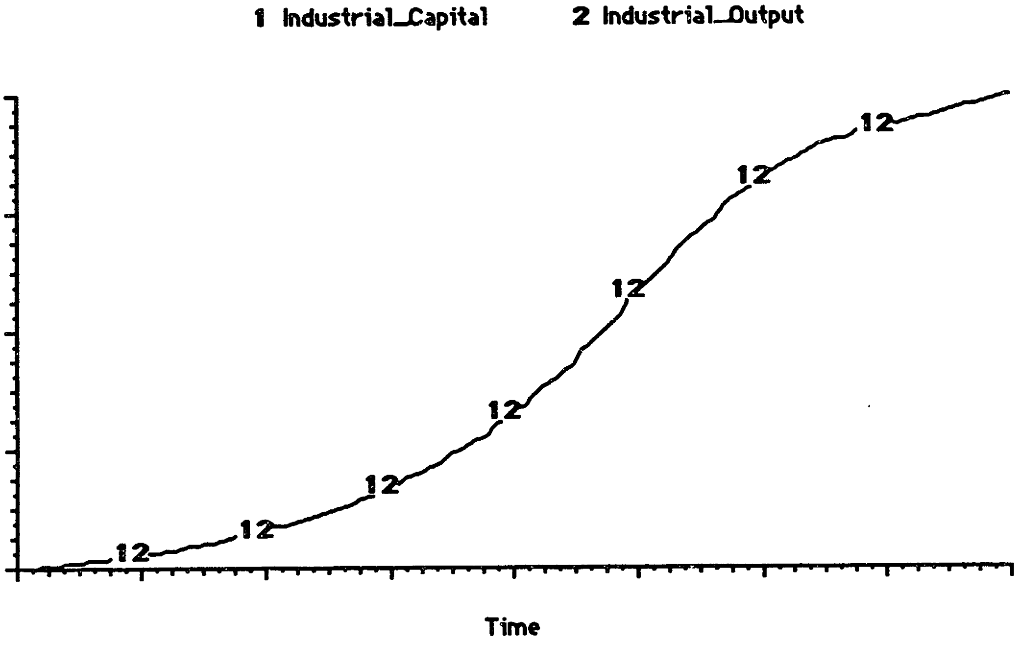


figure 4.1b

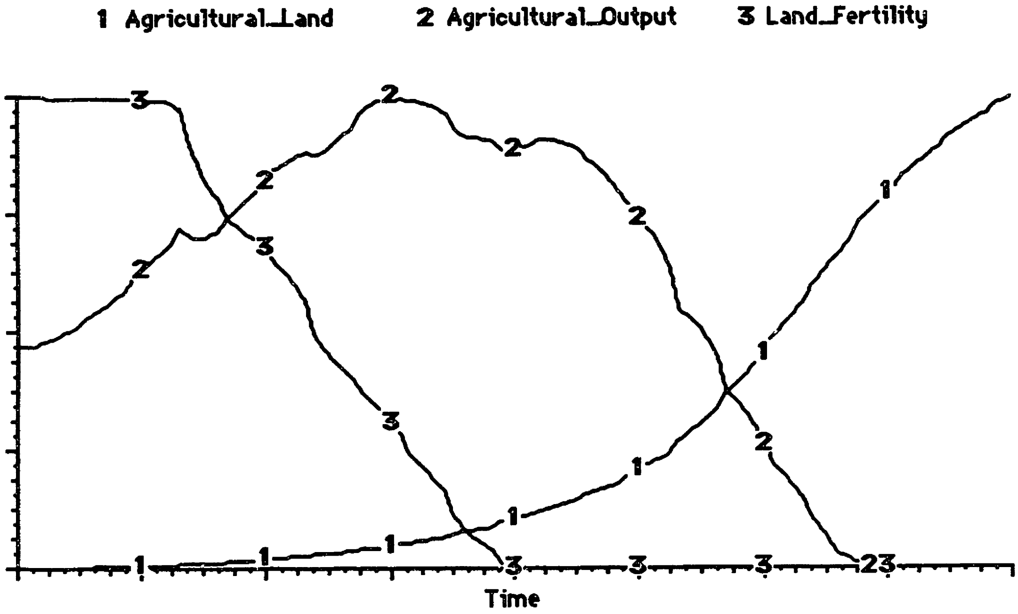


figure 4.1c

Sample run including capital investment in pollution reduction only

The outcome of this simulation is presented in figures **4.2a** to **4.2c**. Again, the plot starts with an exponentially growing economy represented by the rapid growth in the industrial and agricultural sectors. The levels of pollution are also growing accordingly. In this simulation, however, pollution reaches a level in which public concern about the high levels of pollution slows the growth of the industrial sector by allocating some of the capital previously utilized for industrial re-investment to investments in pollution reduction. There is a delay between the time money is invested and the actual decrease in pollution levels. This effect and the delay of the public in perceiving pollution leads to reductions in the industrial capital and output due to capital investment depreciation. At the time in which pollution starts to decline appreciably, economy has returned almost to the original levels.

The situation in the agricultural sector is relatively simple: agricultural output follows the trend of agricultural land, which is influenced by the industrial sector, and is scaled by the level of fertility. This can be observed in figure 4.2c, where the agricultural land overshoots and collapses to a level a little bit higher than the original while the output collapses to a level lower than the original due to decrease in land fertility.

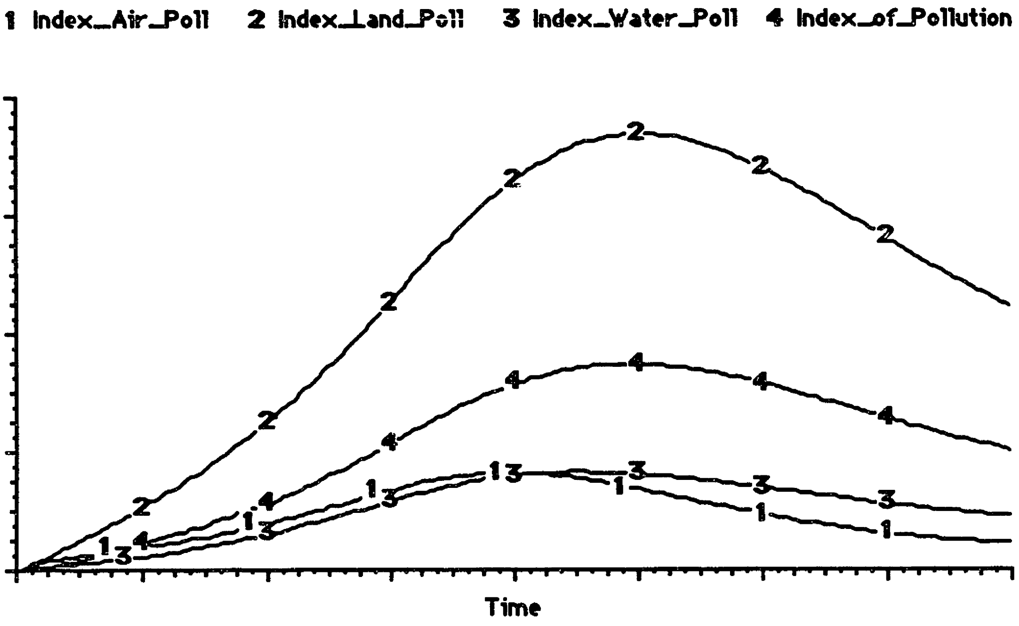


figure 4.2a

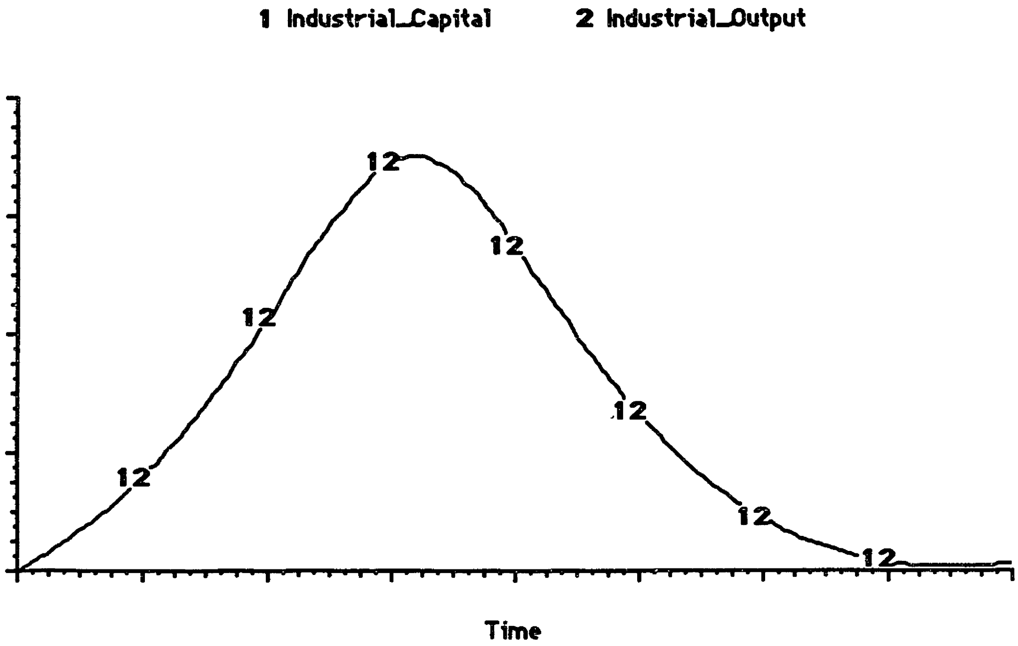


figure 4.2b

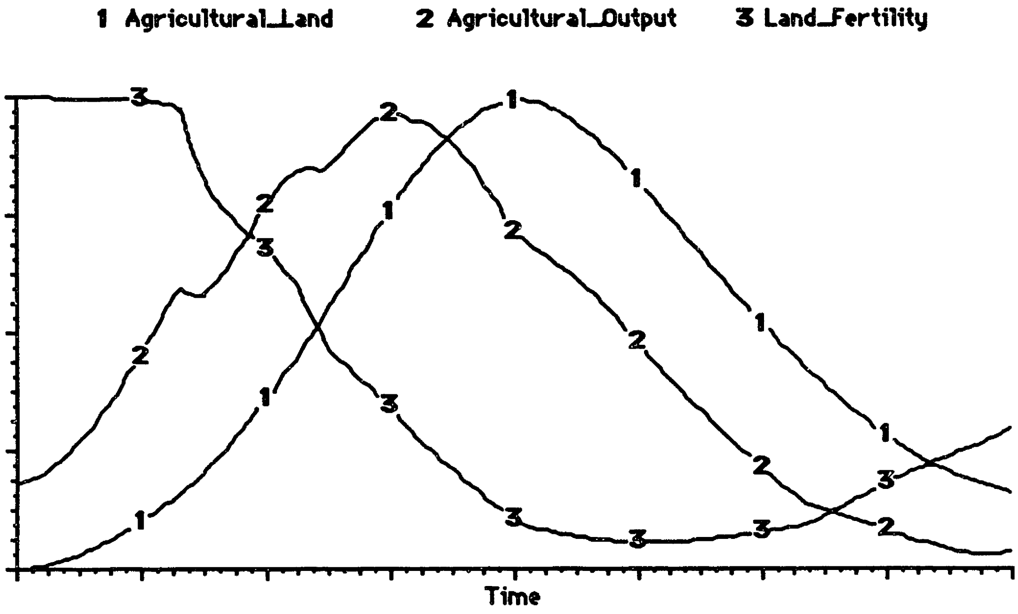


figure 4.2c

Sample run including pollution control by limiting air, land, and water resources availability only

The situation in this simulation is parallel to the previous, but instead of re-allocating capital in pollution reduction, pollution is controlled by imposing regulations on waste emissions. These regulations drive industrial production costs up and, therefore, control pollution by limiting industrial progress. The dynamics involved in this simulation are very similar to the ones presented before except that, instead of allocating output to reduce pollution, the effective industrial production is scaled down by a factor determined by the predominant level of pollution, in this case land pollution. This cut in production efficiency descreases the level of industrial output and, therefore, the capital invested in expanding the industrial and agricultural sectors. This reduces the rate of growth until it reaches a point in which depreciation dominates over replacements and the economy collapses. below its original level. This effect is caused by the long times it takes pollution to be discarded from the system compared to those of industrial depreciation.

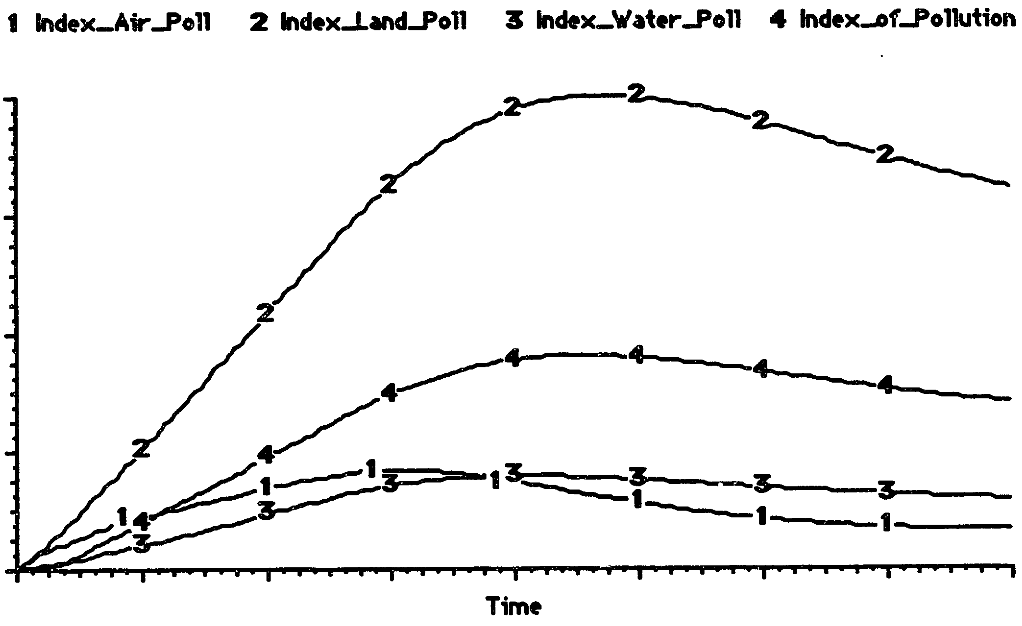


figure 4.3a

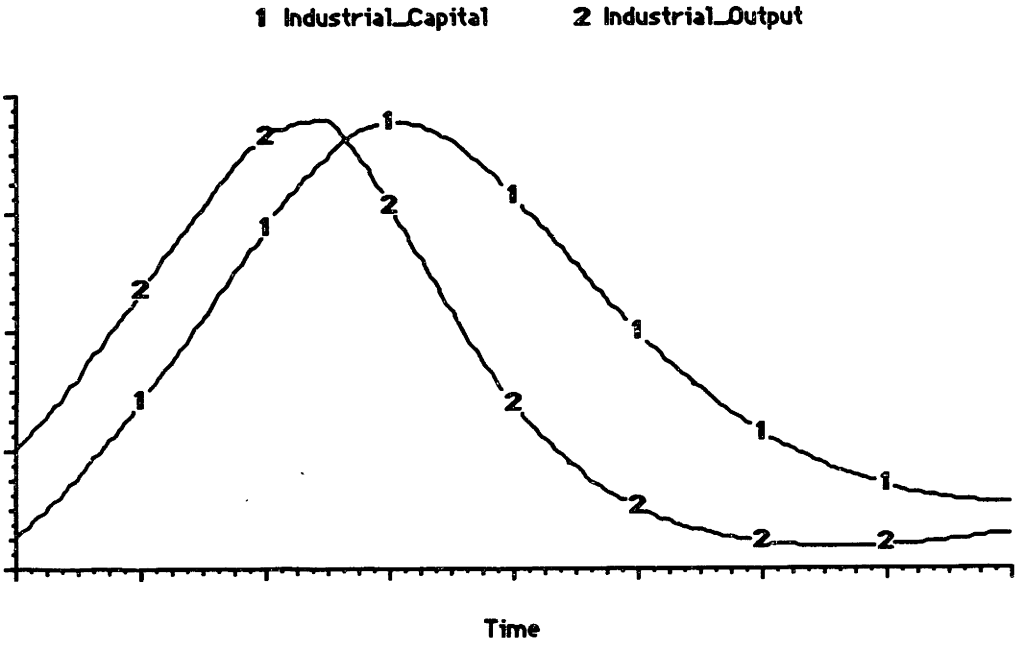


figure 4.3b

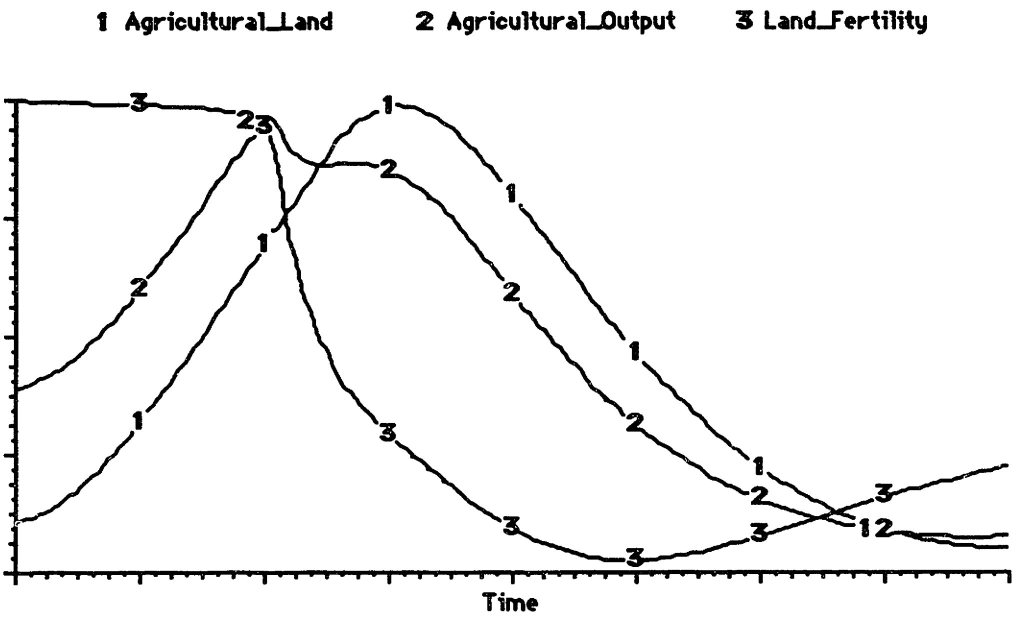


figure 4.3c

Sample run including both pollution control policies

The outcome of this simulation is very similar previous. The only difference is that the values of the plots in figure 4.4a and 4.4b were scaled up by a factor greater than one. This was surprising since one would expect that the combination of both policies (capital investment in pollution reduction and pollution control by limiting air, land, and water resources availability) would reduce pollution considerably. The fact that in this simulation pollution was not reduced considerably may be an indicator pointing at one of the flaws of using experimental data. It seems that the coefficients chosen in the model describe a particular situation in which investing in pollution control is not efficient and does not influence at all the levels of pollution. Probably, with the appropiate data, the behavior of the model could be shifted in a way that the plots would reflect an aggregate result of the previous two sets or only of the ones presented in the figures 4.2a to 4.2c. On the other hand, this could indicate that investment in pollution reduction in a situation in which regulation policies exists may not be efficient at all. In any case, no definite conclusions should be assumed until further studies are done and more realistic data is utilized.

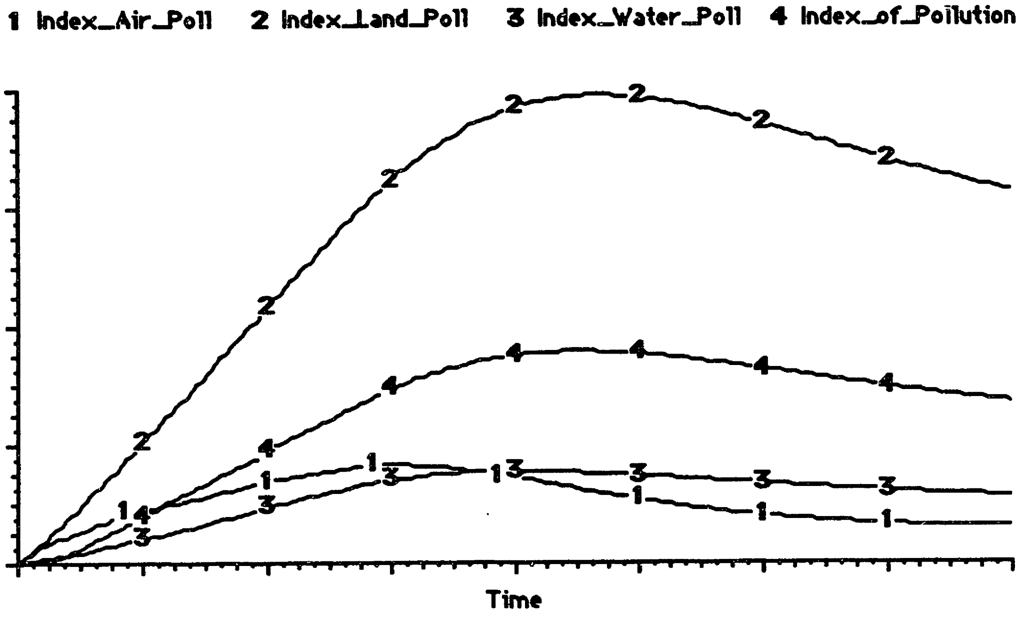


figure 4.4a

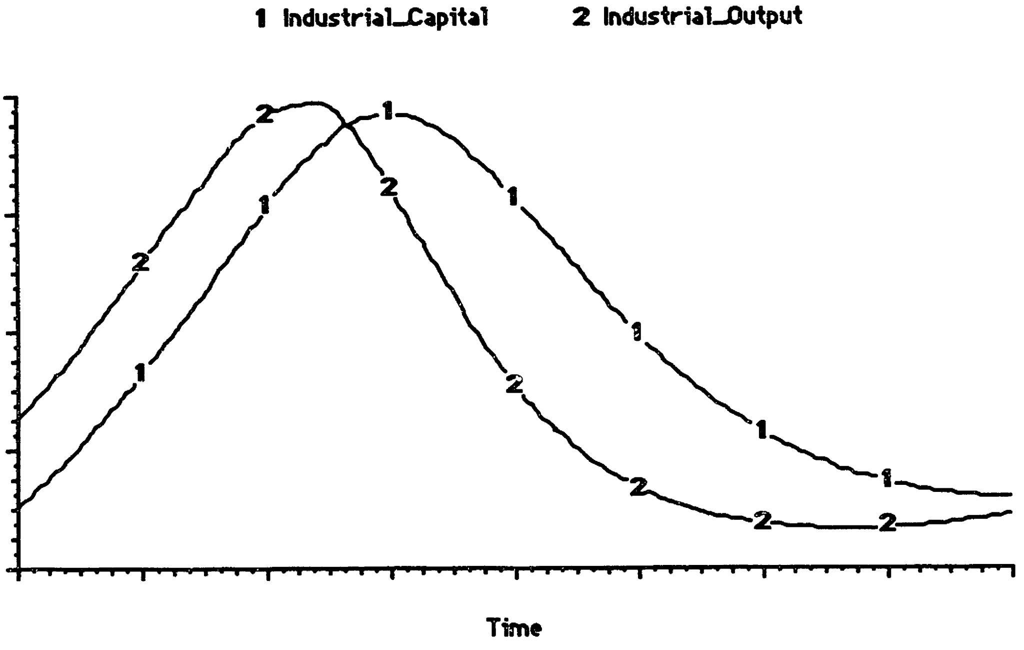


figure 4.4b

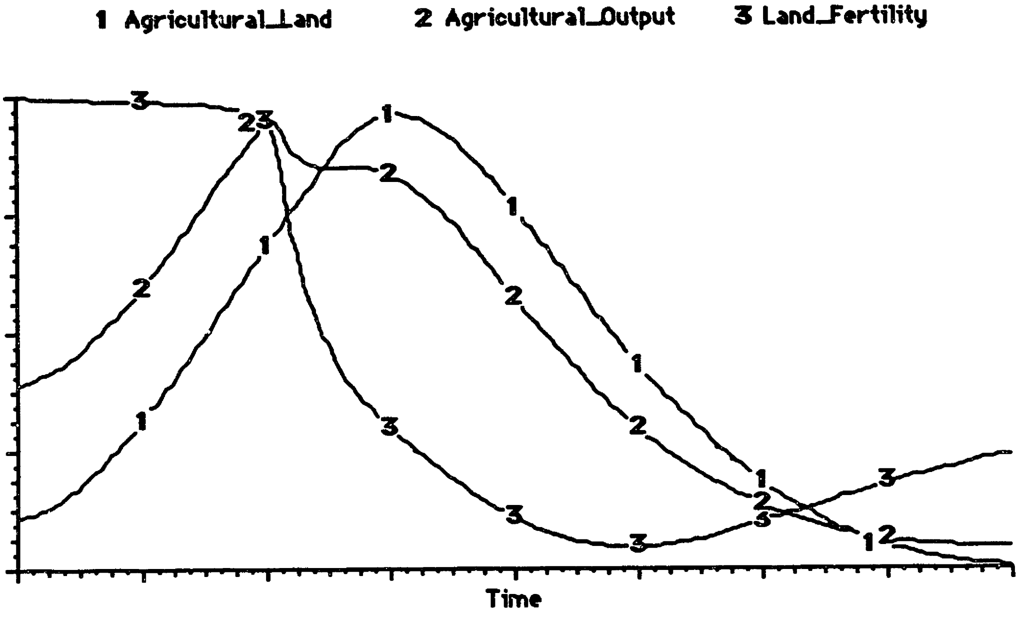

1 Agricultural_Land
2 Agricultural_Output
3 Land_Fertility
Time

figure 4.4c

Conclusion and Suggestions for Further Study

In this study, we have developed a model which simulates the interactions between the major forces of the economy and the pollution sector. We have observed through a series of simulations how this interaction can lead to a collapse of the economy and deterioration of the ecosystem. Furthermore, we have seen how we can change the behavior of the model by altering some of its calculations or "rules" to fit a particular situation.

The model provides the user with the basic framework necessary to study the dynamics governing one aspect of our economy, specifically the use of environmental resources. It also provides the user with a tool that can be easily employed to test the efficiency of various policy solutions under any specified circumstances without any time or physical constraints. This allows the user an open. This flexibility allows the user to implement any solution, even if it sounds unreasonable, and to obtain immediate results without sacrificing the ecosystem.

As expected, there were some conceptual difficulties and doubts encountered during the development of the model. The following are some of the present deficiencies of the model and points of uncertainty encountered during its development. These suggestions should be taken into careful consideration as to improve the validity and efficiency of the simulation .

The first suggestion for the improvement of the model would be to implement some realistic data in order to "fine-tune" the model. Due to the limited time for its development, it was impossible to obtain some accurate data and completely test every single aspect of the model. It would be wise to collect some historic data on a specific region in order to try to reproduce past behaviour and then proceed to predict future trends in the system.

Secondly, the assumptions taken in the model should be verified and corrected in case they are invalid. The following list indicates some of the hypotheses in which lack of data did not permit their verification or which were found to be "faulty" after the completion of the model:

a. The relation between the variables **Fraction** of **Agricultural Investment for** land **Maintenance** (*Frac_AI_for_Maint*) and **Land Fertility Regeneration Time** (*LF_Regen_Time*) was found to be "faulty" or not too clear after the model was completed. This relation should be verified and corrected to enhance the clarity of the model and to eliminate and disruption in the behaviour of the model.

b. Since the data available about the interactions between multiple-resource regulations and industrial output is not readily available, a function selecting the minimum availability between the three environmental resources was used to provide for the multiple effect. This relation should be verified to account for its validity.

c. The values chosen for the perception delays of the *Index of Pollution* and for *Land Fertility* were experimental and, by no means, should be used without any research on them. At the moment they are not affecting the behaviour of the model drastically.

d. The shape and the values of most of the table functions were selected according to my personal judgement. This should be validated before utilized for any further studies.

Presently, there exist some sections of the model which are not affecting its behaviour considerably because of its short time horizon, such as the *Erosion and Damage* and *Solution Rate*. These and other parts of the model may be important for a particular region of study, in which the rates are much higher than the existing ones. Furthermore, in some instances not only these sections may be important but others not currently taken into consideration. The insertion and deletion of variables in the model is particular to each specific region to be studied. The layout that has been provided is a general one which tries to encompass the most important aspects of the interaction between the industrial, agricultural, and pollution sectors. Therefore, if in a specific case a variable seems to be redundant or irrelevant to the model, it should be eliminated in order to enhance its clarity and efficiency.

Lastly, some other ideas, which were not taken into consideration during the development of the model, should be reviewed and implemented if necessary. During the write-up of this report, a number of new ideas which could be implemented to improve the behaviour of the simulation popped into mind. These are the following:

a. In some regions, the precipitation of air pollution into the water may be an important factor affecting the creation of regulations limiting the use of water as a disposal medium (*Water Resource Availability*).

b. The presence of human bias in the allocation capital resources between the different environmental resources for investing in pollution reduction or control. This bias could be caused by overestimation as the level of pollution increases or by underestimating the value of a specific environmental resource.

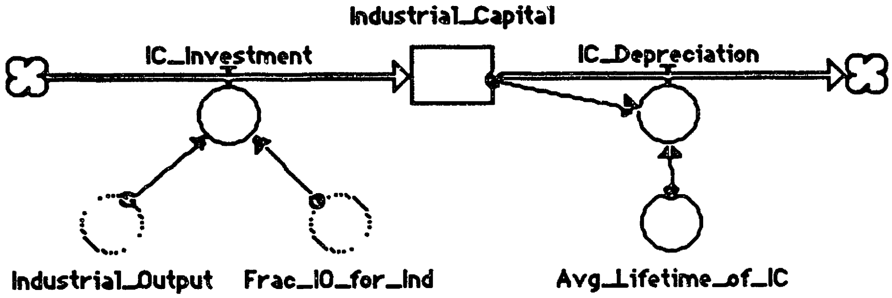
c. The change in the absorption rate of pollution in the *Degradation in Land* due to land saturation.

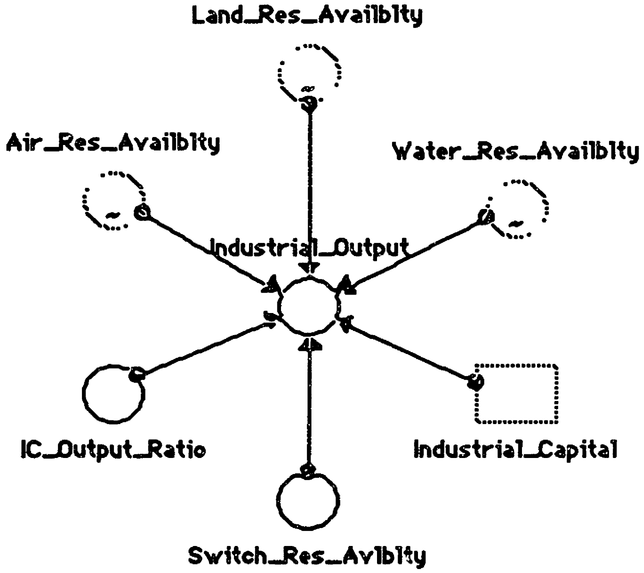
d. Reductions in the creation of regulation (resource availabilities) or increase in pollution reductions due to new emerging technologies which reduce pollution emissions.

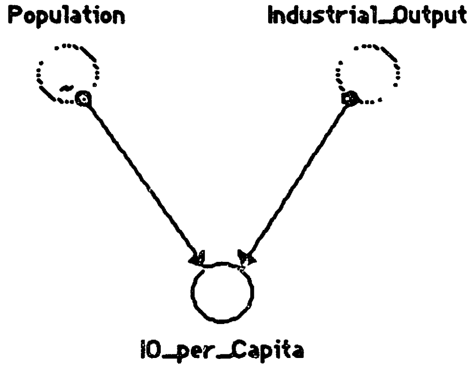
Again, I suggest careful consideration of the points mentioned above before any further use of this model. They are very important and may become critical in cases in which the region of study relies on one of the indicated deficiencies.

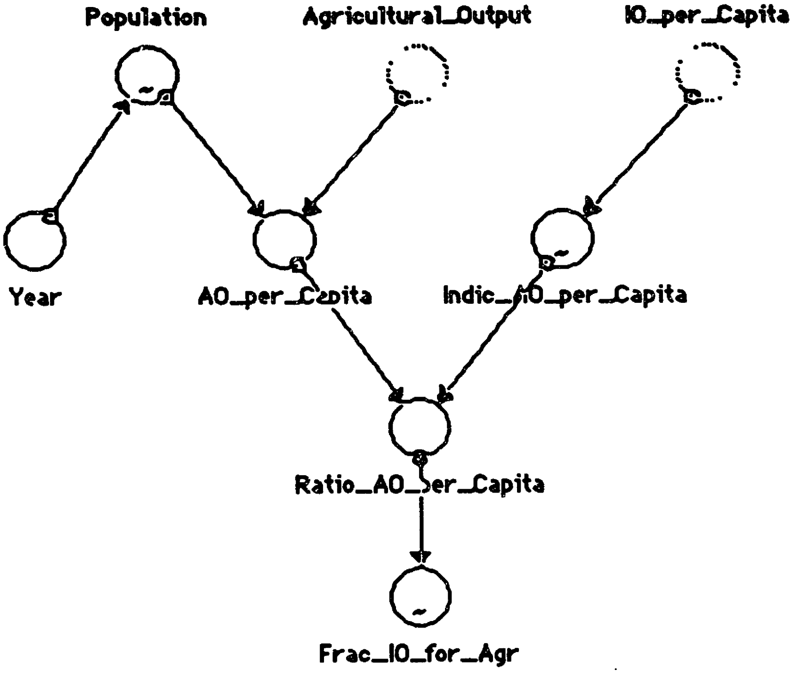
Appendix

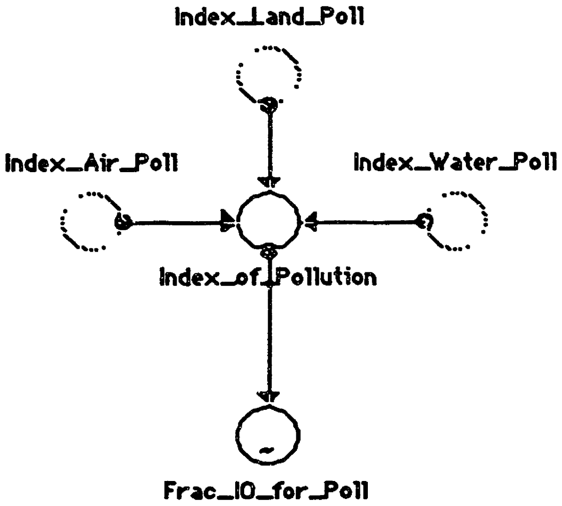
A. Model Diagram

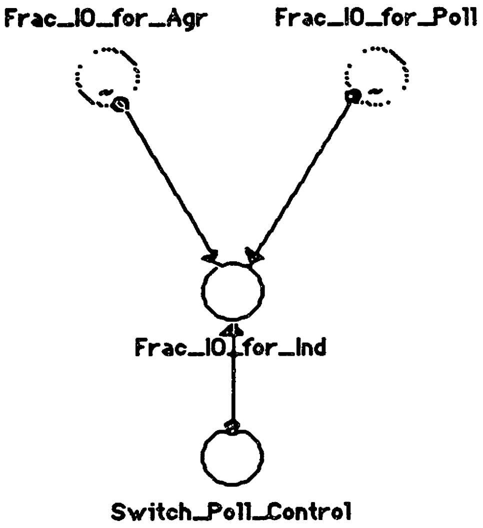

Industrial_Capital
IC_Investment
IC_Depreciation
Industrial_Output
Frac_IO_for_Ind
Avg_Lifetime_of_IC

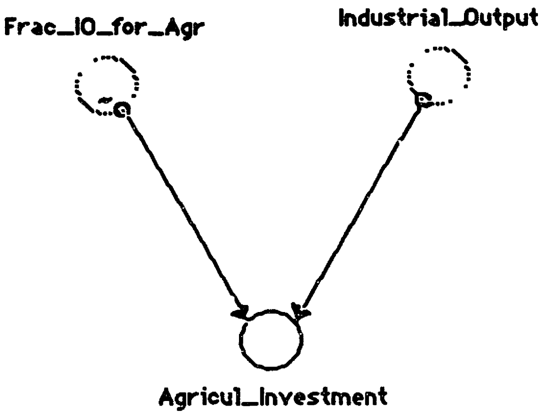

Land_Res_Availblty
Air_Res_Availblty
Water_Res_Availblty
Industrial_Output
IC_Output_Ratio
Industrial_Capital
Switch_Res_Avlblty

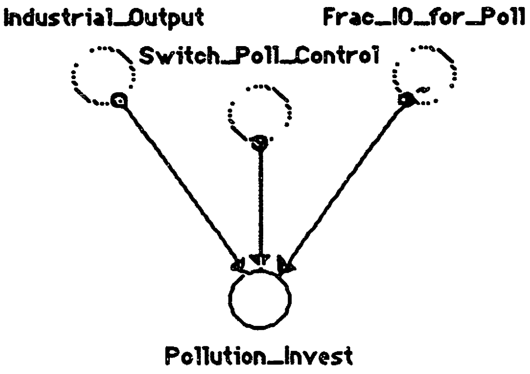

Population
Industrial_Output
IO_per_Capita

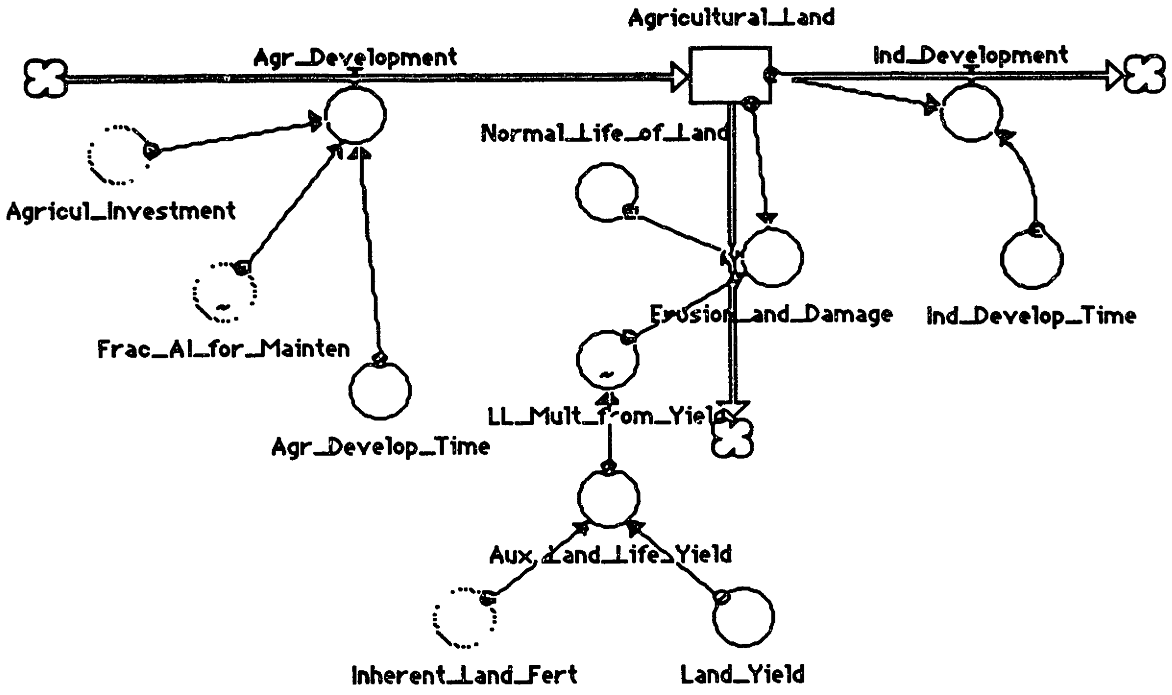

Population
Agricultural_Output
IO_per_Capita
Year
AO_per_Capita
Indic_AO_per_Capita
Ratio_AO_per_Capita
Frac_IO_for_Agr

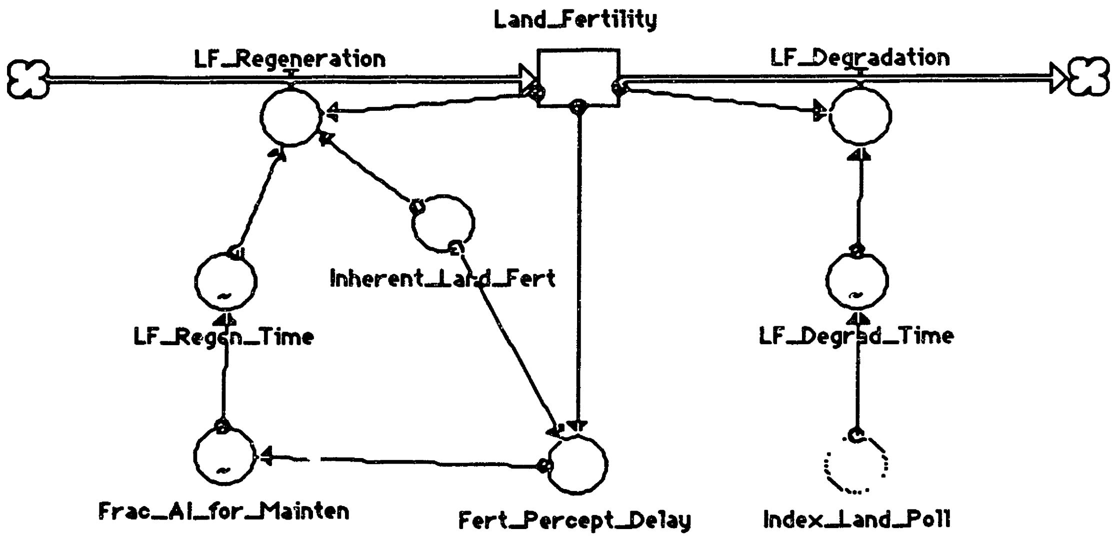

Index_Land_Poll
Index_Air_Poll
Index_Water_Poll
Index_of_Pollution
Frac_IO_for_Poll

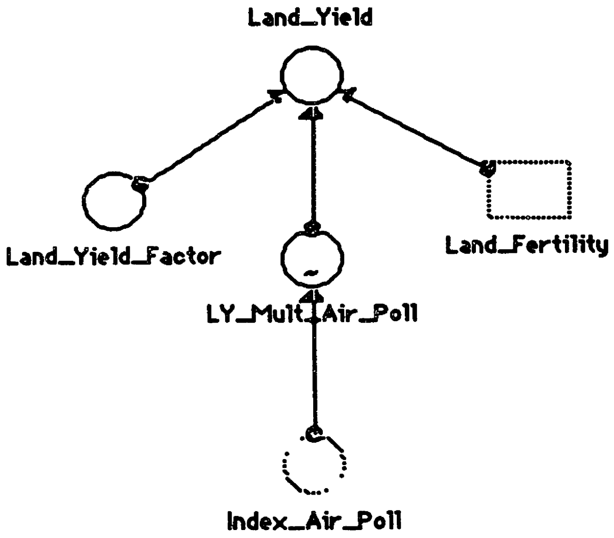

Frac_IO_for_Agr
Frac_IO_for_Poll
Frac_IO_for_Ind
Switch_Poll_Control

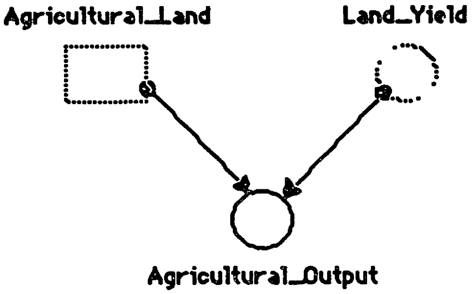

Frac_IO_for_Agr
Industrial_Output
Agricul_Investment

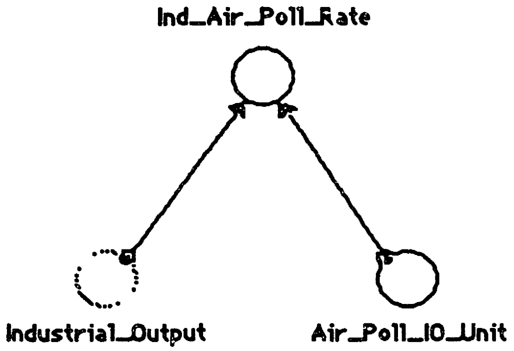

Industrial_Output
Switch_Poll_Control
Frac_IO_for_Poll
Pollution_Invest

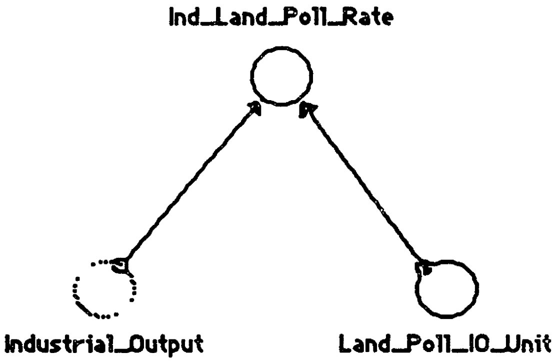

Agricultural_Land
Agr_Development
Ind_Development
Agricul_Investment
Normal_Life_of_Land
Frac_AI_for_Mainten
Erosion_and_Damage
Ind_Develop_Time
Agr_Develop_Time
LL_Mult_from_Yield
Aux_Land_Life_Yield
Inherent_Land_Fert
Land_Yield

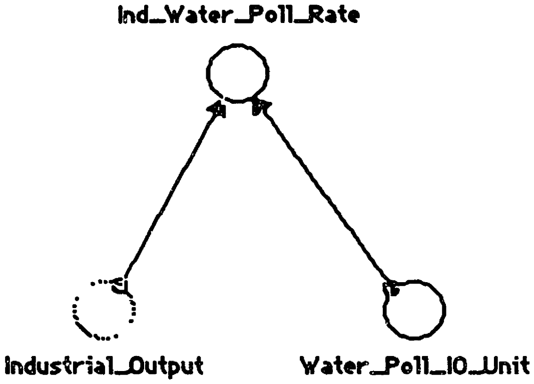

Land_Fertility
LF_Regeneration
LF_Degradation
Inherent_Land_Fert
LF_Regen_Time
LF_Degrad_Time
Frac_AI_for_Mainten
Fert_Percept_Delay
Index_Land_Poll

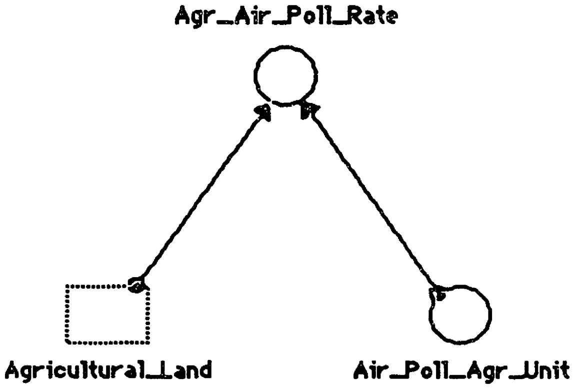

Land_Yield
Land_Yield_Factor
LY_Mult_Air_Poll
Land_Fertility
Index_Air_Poll

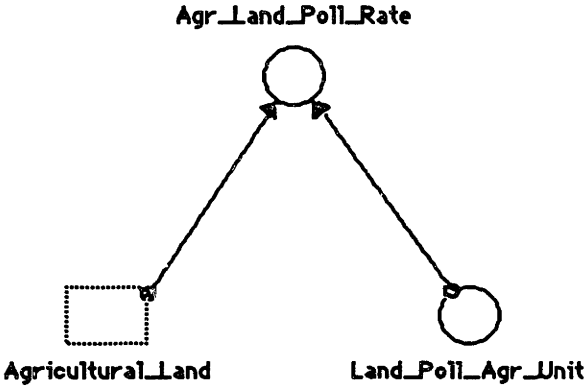

Agricultural_Land
Land_Yield
Agricultural_Output

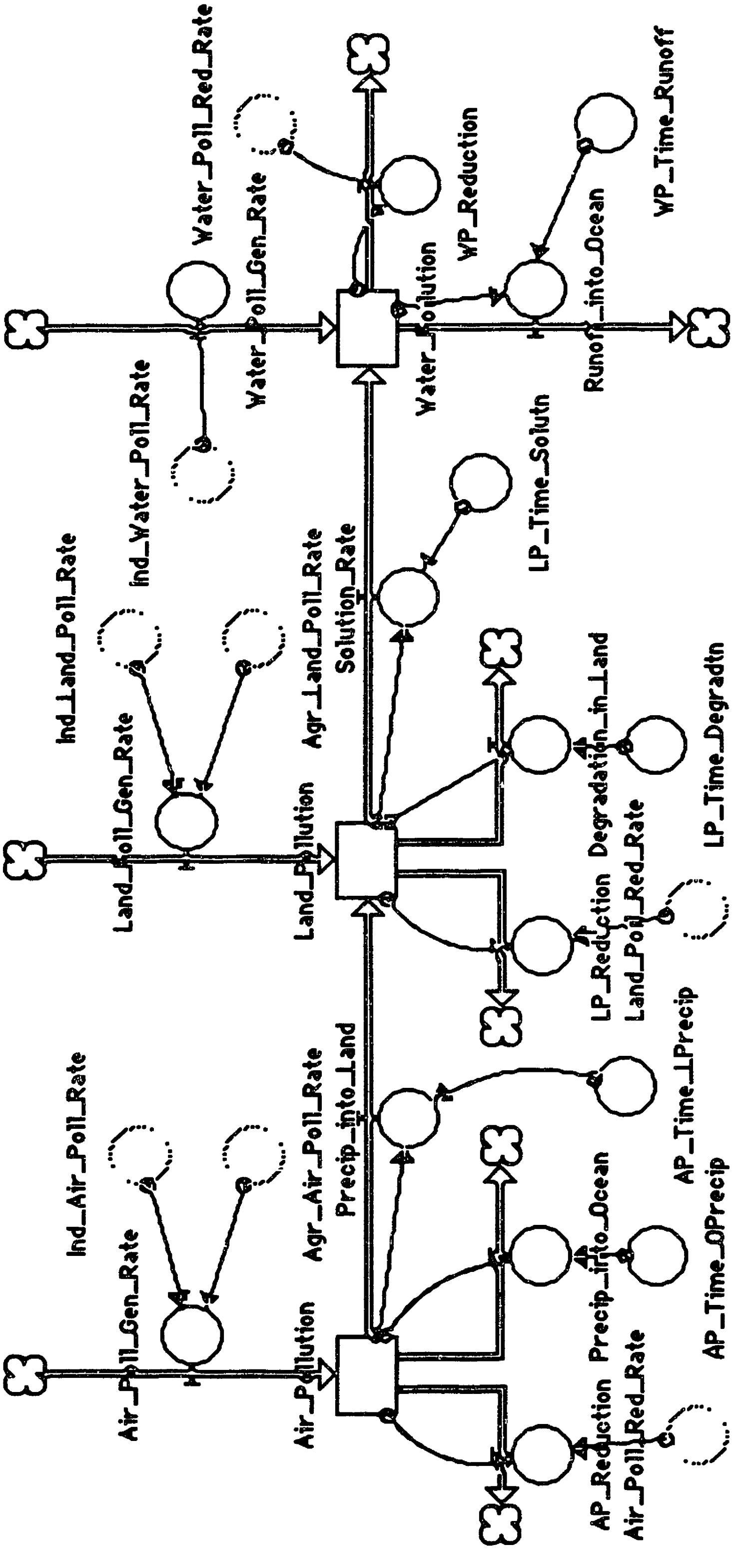

Ind_Air_Poll_Rate
Industrial_Output
Air_Poll_IO_Unit

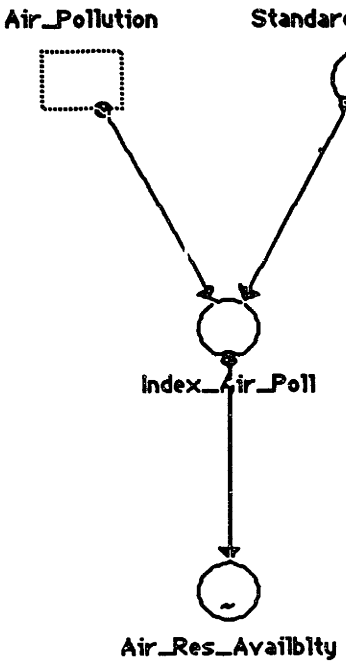

Ind_Land_Poll_Rate
Industrial_Output
Land_Poll_IO_Unit

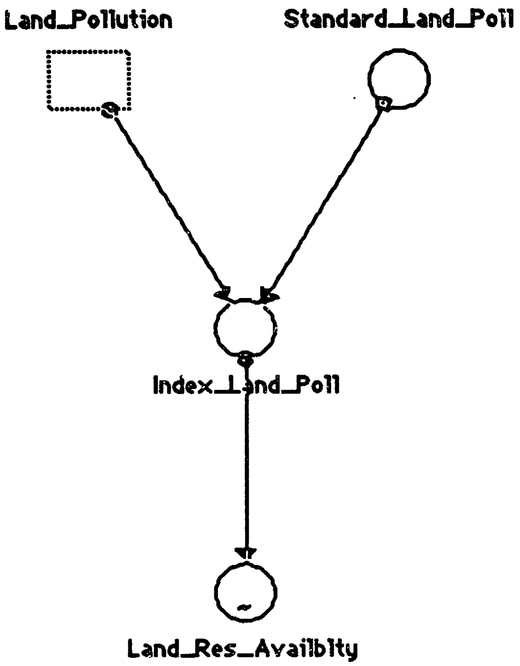

Ind_Water_Poll_Rate
Industrial_Output
Water_Poll_IO_Unit

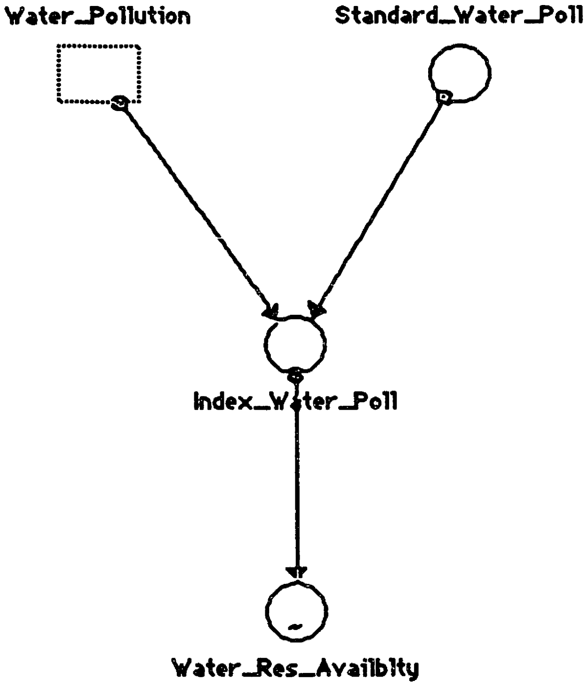

Agr_Air_Poll_Rate
Agricultural_Land
Air_Poll_Agr_Unit

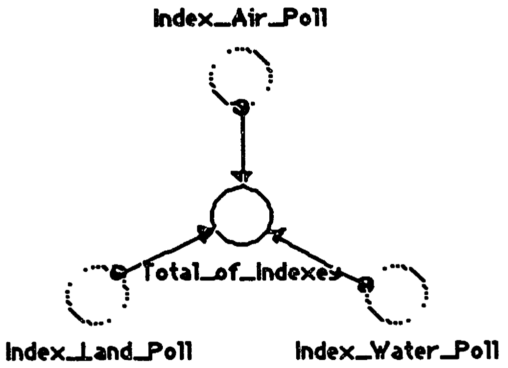

Agr_Land_Poll_Rate
Agricultural_Land
Land_Poll_Agr_Unit

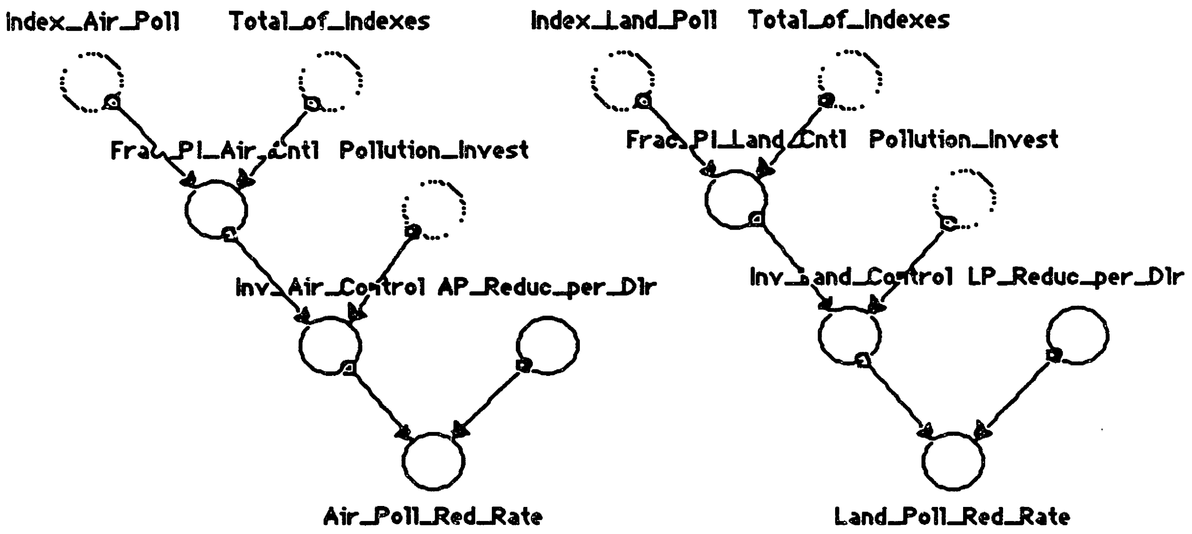

Air_Poll_Gen_Rate
Ind_Air_Poll_Rate
Air_Pollution
Agr_Air_Poll_Rate
Precip_into_Land
AP_Reduction
Air_Poll_Red_Rate
Precip_into_Ocean
AP_Time_OPrecip
AP_Time_LPrecip
Land_Poll_Gen_Rate
Ind_Land_Poll_Rate
Land_Pollution
Agr_Land_Poll_Rate
Solution_Rate
LP_Reduction
Land_Poll_Red_Rate
Degradation_in_Land
LP_Time_Degradtn
LP_Time_Solutn
Water_Poll_Gen_Rate
Ind_Water_Poll_Rate
Water_Solution
Water_Poll_Red_Rate
WP_Reduction
Runoff_into_Ocean
WP_Time_Runoff

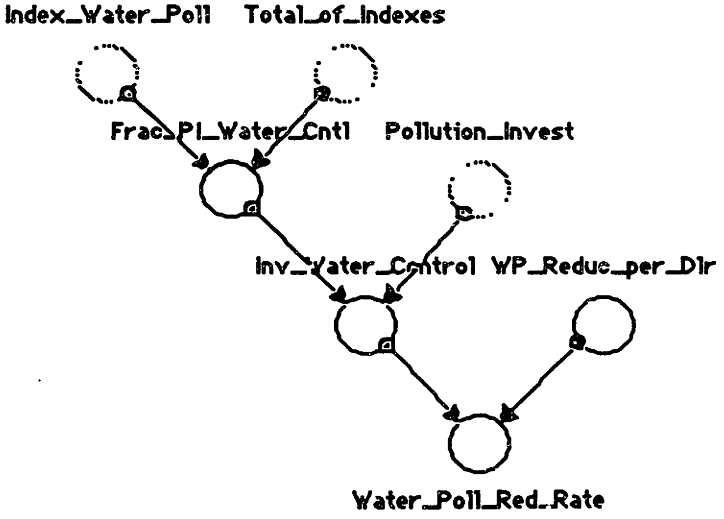

Air_Pollution
Standard_Air_Poll
Index_Air_Poll
Air_Res_Availblty


Land_Pollution
Standard_Land_Poll
Index_Land_Poll
Land_Res_Availblty


Water_Pollution
Standard_Water_Poll
Index_Water_Poll
Water_Res_Availblty


Index_Air_Poll
Total_of_Indexes
Index_Land_Poll
Index_Water_Poll


Index_Air_Poll
Total_of_Indexes
Frac_Pl_Air_Cntl
Pollution_Invest
Inv_Air_Control
AP_Reduc_per_Dlr
Air_Poll_Red_Rate
Index_Land_Poll
Total_of_Indexes
Frac_Pl_Land_Cntl
Pollution_Invest
Inv_Land_Control
LP_Reduc_per_Dlr
Land_Poll_Red_Rate


Index_Water_Poll
Total_of_Indexes
Frac_Pl_Water_Cntl
Pollution_Invest
Inv_Water_Control
WP_Reduc_per_Dlr
Water_Poll_Red_Rate

B. Model Equations

```
Agricultural_Land = Agricultural_Land + dt * ( Agr_Development -
    Ind_Development - Erosion_and_Damage )
INIT(Agricultural_Land) = 35
{ Land Units }

Air_Pollution = Air_Pollution + dt * ( -Precip_into_Land - Precip_into_Ocean +
    Air_Poll_Gen_Rate - AP_Reduction )
INIT(Air_Pollution) = Standard_Air_Poll
{ Pollution Units }

Industrial_Capital = Industrial_Capital + dt * ( -IC_Depreciation +
    IC_Investment )
INIT(Industrial_Capital) = 100
{ Capital Units }

Land_Fertility = Land_Fertility + dt * ( -LF_Degradation + LF_Regeneration )
INIT(Land_Fertility) = Inherent_Land_Fert
{ Fertility Units }

Land_Pollution = Land_Pollution + dt * ( Precip_into_Land - Solution_Rate -
    Degradation_in_Land + Land_Poll_Gen_Rate - LP_Reduction )
INIT(Land_Pollution) = Standard_Land_Poll
{ Pollution Units }

Water_Pollution = Water_Pollution + dt * ( Solution_Rate - Runoff_into_Ocean +
    Water_Poll_Gen_Rate - WP_Reduction )
INIT(Water_Pollution) = Standard_Water_Poll
{ Pollution Units }

Agricultural_Output = Land_Yield*Agricultural_Land
{ Agricultural Units / Year }

Agricul_Investment = Industrial_Output*Frac_IO_for_Agr
{ Capital Units / Year }

Agr_Air_Poll_Rate = Agricultural_Land*Air_Poll_Agr_Unit
{ Pollution Units / Year }

Agr_Development = (Agricul_Investment*(1-
    Frac_AI_for_Mainten)/1)/Agr_Develop_Time
{ Land Units / Year }

Agr_Develop_Time = 1
{ years }

Agr_Land_Poll_Rate = Agricultural_Land*Land_Poll_Agr_Unit
{ Pollution Units / Year }

Air_Poll_Agr_Unit = 2
{ Pollution Units / Agricultural Unit }

Air_Poll_Gen_Rate = Ind_Air_Poll_Rate+Agr_Air_Poll_Rate
{ Pollution Units / Year }

Air_Poll_IO_Unit = 2
{ Pollution Units / Capital Unit }

Air_Poll_Red_Rate = Inv_Air_Control*AP_Reduc_per_Dlr
{ Pollution Units / Year }
```

```
AO_per_Capita = Agricultural_Output/Population
{ (Agricultural Units / Year) / Population Unit }

AP_Reduction = MIN(Air_Pollution/1,Air_Poll_Red_Rate/3)
{ Pollution Units / Year }

AP_Reduc_per_Dlr = 1
{ Pollution Units / Capital Unit }

AP_Time_LPrecip = 5
{ Years }

Aux_Land_Life_Yield = Land_Yield/Inherent_Land_Fert
{ Dimensionless }

Avg_Lifetime_of_IC = 7
{ Years }

Degradation_in_Land = Land_Pollution/LP_Time_Degradtn
{ Pollution Units / Year }

Erosion_and_Damage = Agricultural_Land/(Normal_Life_of_Land*LL_Mult_from_Yield)
{ Land Units / Year }

Fert_Percept_Delay = SMTH3(Land_Fertility,2,Inherent_Land_Fert)
{ Fertility Units }

Frac_IO_for_Ind = 1 - (Frac_IO_for_Agr +
    (Switch_Poll_Control*Frac_IO_for_Poll))
{ Dimensionless }

Frac_PI_Air_Cntl = Index_Air_Poll/Total_of_Indexes
{ Dimensionless }

Frac_PI_Land_Cntl = Index_Land_Poll/Total_of_Indexes
{ Dimensionless }

Frac_PI_Water_Cntl = Index_Water_Poll/Total_of_Indexes
{ Dimensionless }

IC_Depreciation = Industrial_Capital/Avg_Lifetime_of_IC
{ Capital Units / Year }

IC_Investment = Industrial_Output*Frac_IO_for_Ind
{ Capital Units / Year }

IC_Output_Ratio = 1/4
{ (Capital Units / Year) / Capital Unit }

Index_Air_Poll = Air_Pollution/Standard_Air_Poll
{ Dimensionless }

Index_Land_Poll = Land_Pollution/Standard_Land_Poll
{ Dimensionless }

Index_of_Pollution =
    SMTH3((Index_Air_Poll+Index_Land_Poll+Index_Water_Poll)/3,2,1)
{ Dimensionless }

Index_Water_Poll = Water_Pollution/Standard_Water_Poll
{ Dimensionless }
```

```
Industrial_Output = (Industrial_Capital * IC_Output_Ratio)*(Switch_Res_Avlblty
    * MIN(Air_Res_Availblty,Land_Res_Availblty,Water_Res_Availblty)+(1 -
    Switch_Res_Avlblty))
{ Capital Units / Year }

Ind_Air_Poll_Rate = Industrial_Output*Air_Poll_IO_Unit
{ Pollution Units / Year }

Ind_Development = Agricultural_Land/Ind_Develop_Time
{ Land Units / Year }

Ind_Develop_Time = 10
{ Years }

Ind_Land_Poll_Rate = Industrial_Output*Land_Poll_IO_Unit
{ Pollution Units / Year }

Ind_Water_Poll_Rate = Industrial_Output*Water_Poll_IO_Unit
{ Pollution Units / Year }

Inherent_Land_Fert = 1
{ Fertility Units }

Inv_Air_Control = Pollution_Invest*Frac_PI_Air_Cntl
{ Capital Units / Year }

Inv_Land_Control = Pollution_Invest*Frac_PI_Land_Cntl
{ Capital Units / Year }

Inv_Water_Control = Pollution_Invest*Frac_PI_Water_Cntl
{ Capital Units / Year }

IO_per_Capita = Industrial_Output/Population
{ Capital Units / Population Unit }

Land_Poll_Agr_Unit = 1
{ Pollution Units / Agricultural Unit }

Land_Poll_Gen_Rate = Ind_Land_Poll_Rate+Agr_Land_Poll_Rate
{ Pollution Units / Year }

Land_Poll_IO_Unit = 1
{ Pollution Units / Capital Unit }

Land_Poll_Red_Rate = Inv_Land_Control*LP_Reduc_per_Dlr
{ Pollution Units / Year }

Land_Yield = Land_Yield_Factor*Land_Fertility*LY_Mult_Air_Poll
{ (Agricultural Units / Year) / Land Unit }

Land_Yield_Factor = 1
{ (Agricultural Units / Year) / (Land Unit * Fertility Units) }

LF_Degradation = Land_Fertility/LF_Degrad_Time
{ Fertility Units / Year }

LF_Regeneration = (Inherent_Land_Fert-Land_Fertility)/LF_Regen_Time
{ Fertility Units / Year }

LP_Reduction = MIN(Land_Pollution/1,Land_Poll_Red_Rate/3)
{ Pollution Units / Year }
```

```
LP_Reduc_per_Dlr = 1
{ Pollution Units / Capital Unit }

LP_Time_Degradtn = 15
{ Years }

LP_Time_OPrecip = 9.333
{ Years }

LP_Time_Solutn = 750
{ Years }

Normal_Life_of_Land = 6000
{ Years }

Pollution_Invest = Switch_Poll_Control*Industrial_Output*Frac_IO_for_Poll
{ Capital Units / Year }

Precip_into_Land = Air_Pollution/AP_Time_LPrecip
{ Pollution Units / Year }

Precip_into_Ocean = Air_Pollution/LP_Time_OPrecip
{ Pollution Units / Year }

Ratio_AO_per_Capita = AO_per_Capita/Indic_AO_per_Capita
{ Dimensionless }

Runoff_into_Ocean = Water_Pollution/WP_Time_Runoff
{ Pollution Units / Year }

Solution_Rate = Land_Pollution/LP_Time_Solutn
{ Pollution Units / Year }

Standard_Air_Poll = 150
{ Pollution Units }

Standard_Land_Poll = 150
{ Pollution Units }

Standard_Water_Poll = 150
{ Pollution Units }

Switch_Poll_Control = 1
{ Dimensionless }

Switch_Res_Avlblty = 1
{ Dimensionless }

Total_of_Indexes = Index_Air_Poll+Index_Land_Poll+Index_Water_Poll
{ Dimensionless }

Water_Poll_Gen_Rate = Ind_Water_Poll_Rate
{ Pollution Units / Year }

Water_Poll_IO_Unit = 1
{ Pollution Units / Capital Unit }

Water_Poll_Red_Rate = Inv_Water_Control*WP_Reduc_per_Dlr
{ Pollution Units / Year }

WP_Reduction = MIN(Water_Pollution/1,Water_Poll_Red_Rate/3)
{ Pollution Units / Year }
```

```
WP_Reduc_per_Dlr = 1
{ Pollution Units / Capital Unit }

WP_Time_Runoff = 20
{ Years }

Year = TIME

Air_Res_Availblty = graph(Index_Air_Poll)
 0.0 -> 1.00
3.00 -> 0.990
6.00 -> 0.970
9.00 -> 0.925
12.00 -> 0.820
15.00 -> 0.625
18.00 -> 0.430
21.00 -> 0.325
24.00 -> 0.280
27.00 -> 0.260
30.00 -> 0.250

Frac_AI_for_Mainten = graph(Fert_Percept_Delay)
 0.0 -> 0.100
 0.1 -> 0.100
 0.2 -> 0.100
 0.3 -> 0.100
 0.4 -> 0.100
 0.5 -> 0.100
 0.6 -> 0.100
 0.7 -> 0.0945
 0.8 -> 0.0840
 0.9 -> 0.0682
 1.0 -> 0.0400

Frac_IO_for_Agr = graph(Ratio_AO_per_Capita)
 0.0 -> 0.400
0.50 -> 0.200
1.00 -> 0.100
1.50 -> 0.0250
2.00 ->  0.0
2.50 ->  0.0
3.00 ->  0.0
3.50 ->  0.0
4.00 ->  0.0
4.50 ->  0.0
5.00 ->  0.0

Frac_IO_for_Poll = graph(Index_of_Pollution)
 0.0 ->  0.0
3.00 -> 0.00500
6.00 -> 0.0150
9.00 -> 0.0550
12.00 -> 0.135
15.00 -> 0.250
18.00 -> 0.365
21.00 -> 0.445
24.00 -> 0.485
27.00 -> 0.495
30.00 -> 0.500
```

```
Indic_AO_per_Capita = graph(IO_per_Capita)
 0.0 -> 230.00
200.00 -> 480.00
400.00 -> 690.00
600.00 -> 850.00
800.00 -> 970.00
1000.00 -> 1070.00
1200.00 -> 1150.00
1400.00 -> 1210.00
1600.00 -> 1250.00
1800.00 -> 1275.00
2000.00 -> 1282.50

Land_Res_Availblty = graph(Index_Land_Poll)
 0.0 -> 1.00
3.00 -> 0.990
6.00 -> 0.970
9.00 -> 0.925
12.00 -> 0.820
15.00 -> 0.625
18.00 -> 0.430
21.00 -> 0.325
24.00 -> 0.280
27.00 -> 0.260
30.00 -> 0.250

LF_Degrad_Time = graph(Index_Land_Poll)
 0.0 -> 1010.00
10.00 -> 10.00
20.00 -> 3.33
30.00 -> 2.00
40.00 -> 1.25
50.00 -> 1.00
60.00 -> 1.00
70.00 -> 1.00
80.00 -> 1.00
90.00 -> 1.00
100.00 -> 1.00

LF_Regen_Time = graph(Frac_AI_for_Mainten)
 0.0 -> 20.00
0.0200 -> 13.00
0.0400 -> 8.00
0.0600 -> 4.00
0.0800 -> 2.00
0.100 -> 2.00
0.120 -> 2.00
0.140 -> 2.00
0.160 -> 2.00
0.180 -> 2.00
0.200 -> 2.00

LL_Mult_from_Yield = graph(Aux_Land_Life_Yield)
 0.0 -> 1.20
1.00 -> 1.00
2.00 -> 0.630
3.00 -> 0.360
4.00 -> 0.160
5.00 -> 0.0550
6.00 -> 0.0400
```

```
7.00 -> 0.0250
8.00 -> 0.0150
9.00 -> 0.0100
10.00 -> 0.00500

LY_Mult_Air_Poll = graph(Index_Air_Poll)
 0.0 -> 1.00
10.00 -> 1.00
20.00 -> 0.700
30.00 -> 0.400
40.00 -> 0.195
50.00 -> 0.100
60.00 -> 0.0500
70.00 -> 0.0250
80.00 -> 0.00500
90.00 ->  0.0
100.00 ->  0.0

Population = graph(Year)
1970.00 -> 0.100
1980.00 -> 0.100
1990.00 -> 0.100
2000.00 -> 0.100
2010.00 -> 0.100
2020.00 -> 0.100
2030.00 -> 0.100
2040.00 -> 0.100
2050.00 -> 0.100
2060.00 -> 0.100
2070.00 -> 0.100

Water_Res_Availblty = graph(Index_Water_Poll)
 0.0 -> 1.00
3.00 -> 0.990
6.00 -> 0.970
9.00 -> 0.925
12.00 -> 0.820
15.00 -> 0.625
18.00 -> 0.430
21.00 -> 0.325
24.00 -> 0.280
27.00 -> 0.260
30.00 -> 0.250
```

References

1. **Forrester, Jay W.**; *World Dynamics* ; Wright-Allen Press; Cambridge, MA; 1973

2. **Meadows et. al.**; *Dynamics of Growth in a Finite World* ; Wright-Allen Press; Cambridge, MA; 1974

3. **Meadows, D.L. and D.H., editors**; *Toward Global Equilibrium: Collected Papers* ; Wright-Allen Press; Cambridge, MA; 1973

4. **Barkley, Paul W. and David W. Seckler**; *Economic Growth and Environmental Decay* ; Harcourt Brace Jovanovich; New York, NY; 1972

5. **Van Tasse, Alfred J., editor**; *Environmental Side Effects of Rising Industrial Output* ; Heath Lexington Book; Lexington, MA; 1970

6. **Conference Report**; *Water Pollution as a World Problem* ; Europa Publications; London, England; 1971

7. **Editorial Research Reports**; *Environmental Issues: Prospects and Problems* ; Congressional Quaterly, Inc.; Washington, D.C.; June; 1982

8. **Regulation**; *"The Emerging Market in Air Pollution Rights"* by Bruce Yandle; July/August; 1978

9. **Kreutzer, David P.**; *"Taiwan 2000 Project"* ; Research Paper; 1986

10. **de Vries, Bert**; *"Taiwan 2000: The Case of Energy"* ; Research Paper; 1986