SYSTEM DYNAMICS MODELLING IN RESOURCE MANAGEMENT: A SUSTAINABLE DEVELOPMENT APPROACH TO RESOURCE EXTRACTION IN SIERRA LEONE.

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ABSTRACT: This paper is a contribution to the urgent need for effective sustainable development strategies within the framework of Agenda 21 put forward at the 1992 World Conference on Environment and Development. It describes the development of a natural resource management model, which is able to capture the economic, social and ecological variables that influence resource management. The model is validated and used to analyse policies available to government to regulate national development. Three policy approaches are analysed: the conservative policy approach, which allows mining activity to continue in its current state, and which is shown to lead to near catastrophic environmental results; the radical policy approach, which would terminate all mining activities immediately, and which is shown not to be economically viable for an economy dependant on natural resources; and the harmonious policy approach, which is based upon the first two analyses and advocates a gradual reduction of mining activities whilst at the same time investing in intensive agricultural development. This third policy is then used as an approach to control environmental degradation through the gradual reduction of mining activities and the improvement of agriculture, with the objective of achieving sustainable development. The implementation strategies of this policy are also discussed.

INTRODUCTION

This paper applies Simulation Modeling techniques to the problems of the sustainable management of natural resources. It specifically describes the development and use of a System Dynamics Model of the mining systems of Sierra Leone for policy analysis in order to achieve the goals of sustainable development.

The main goal of development in general is to satisfy human needs and wishes, a goal which, does not seem to be achieved by a large proportion of people in developing countries. There are many possible contributing factors to this underdevelopment, which are still under discussion. What is however evident is that achieving an acceptable form of development in developing countries is often associated with irreversible ecological and social problems, which are effectively contributing to the present global environmental problems. Consequently, discussions around this problem, were a major element of the World Conference on Environment and Development at Rio de Janeiro in 1992, where the inter-relationship between environment and development was strongly emphasised. On the basis of this discussion, Agenda 21 for Sustainable Development was recommended, in which recommendations were made for the development of methodologies and strategies to achieve this goal (United Nations Conference on Environment and Development (UNICED), 1992).

This paper presents a contribution to this aspect of development through applying System Dynamics Modeling technique to recommend sustainable resource extraction policies. It first describes of the study area - the mining regions of Sierra Leone, followed by model development and validation processes. The validated model is then used to simulate the existing environmental problems of resource extraction. The empirical results and recommendations for policy implementation are also discussed.

THE STUDY AREA

Sierra Leone is a small West African state located along the Atlantic Ocean with a population of about 4 million, and a land area of about 72,000 square km (Sierra Leone Government, 1974). The country was initially established as two separate entities - the crown colony (1808) and the Protectorate (1896), which merged after independence (27.04.1961) to form the present Sierra Leone (William, 1975).

Before the outbreak of the present war, the economy of Sierra Leone was characterised by two major components: (i) the modern high productivity sectors like mining, foreign trade and related financial services, concerned primarily with the export of minerals and the import and distribution of manufactured goods. And (ii) agriculture, on which more than 75% of the population depended, which was characterised mainly by subsistence farming but with some production both for domestic and export markets.

Almost 28,000 square kilometres (approximately 40%) of Sierra Leone is covered by mining leases or prospecting licenses (Clarke, 1975), and the mining industry is one of the most important in terms of employment, exports and contribution to the national economy. According to the Government of Sierra Leone (1974), export of minerals contributed around

80% of the total value of domestic export during the last decade. It contributes to revenues of the government through taxes on the mining companies, export duties on diamonds, royalties and license fees and profits of the joint enterprise of National Diamond Mining Company (NDMC).

Diamond mining, which started in 1930, forms the oldest of the mining systems. The two methods of mining used in diamond mining are as follows: (i) Industrial mining; and (ii) alluvial mining. The industrial mining by the National Diamond Mining Company (NDMC) is done by removing gravel from river valleys and streambeds with the use of draglines and dredges. The gravel is then loaded into trucks and taken to the washing plants. Eight such plants were in operation in Yengema and two at Tongo Field in Eastern Sierra Leone. Each area has a separation house for the final treatment of the gravel concentrates. The alluvial diamond-mining scheme was set up by government in 1956 to allow the native operators to take out mining licenses in certain declared chiefdoms. These licensees' claims are worked on the “tributor” system, that is, the licensee employs several labourers who work for a proportion of the diamonds won. The miners use hand digging and hand panning along the marginal river swamps. This type of mining is mainly done on a seasonal basis, and due to the primitive methods used, the recovery rate is low. It also encourages smuggling and has many social and environmental problems at the local level.

Until 1975, iron ore was mined at Marampa in northern Sierra Leone. This mining activity started in 1933, and was at that time the country’s second largest foreign exchange earner. But due to technical problems it was forced to close down in 1975. Open cast methods were employed in the mining operations.

Bauxite was mined at Mokanji in southern Sierra Leone. Opencast methods were used in the mining operation. This was done, by cutting ‘benches’ along the hillside in order to reduce erosion of the ore during the rainy season. Prior to the excavation, prospecting and surveying of the mining area was done in order to classify the ore bodies, which exist in different quantities and qualities. The resulting map was then used during the excavation to blend the different ores together in order to obtain a homogenous quality. Bulldozers were used to clear the vegetation, stockpile the topsoil and remove the overburden until the ore was exposed. The mine face was then opened up at different levels and excavators were used to scoop out the ore and load it directly into trucks for transportation to the washing plants. This mine was forced to close down in 1996 due the civil war in Sierra Leone.

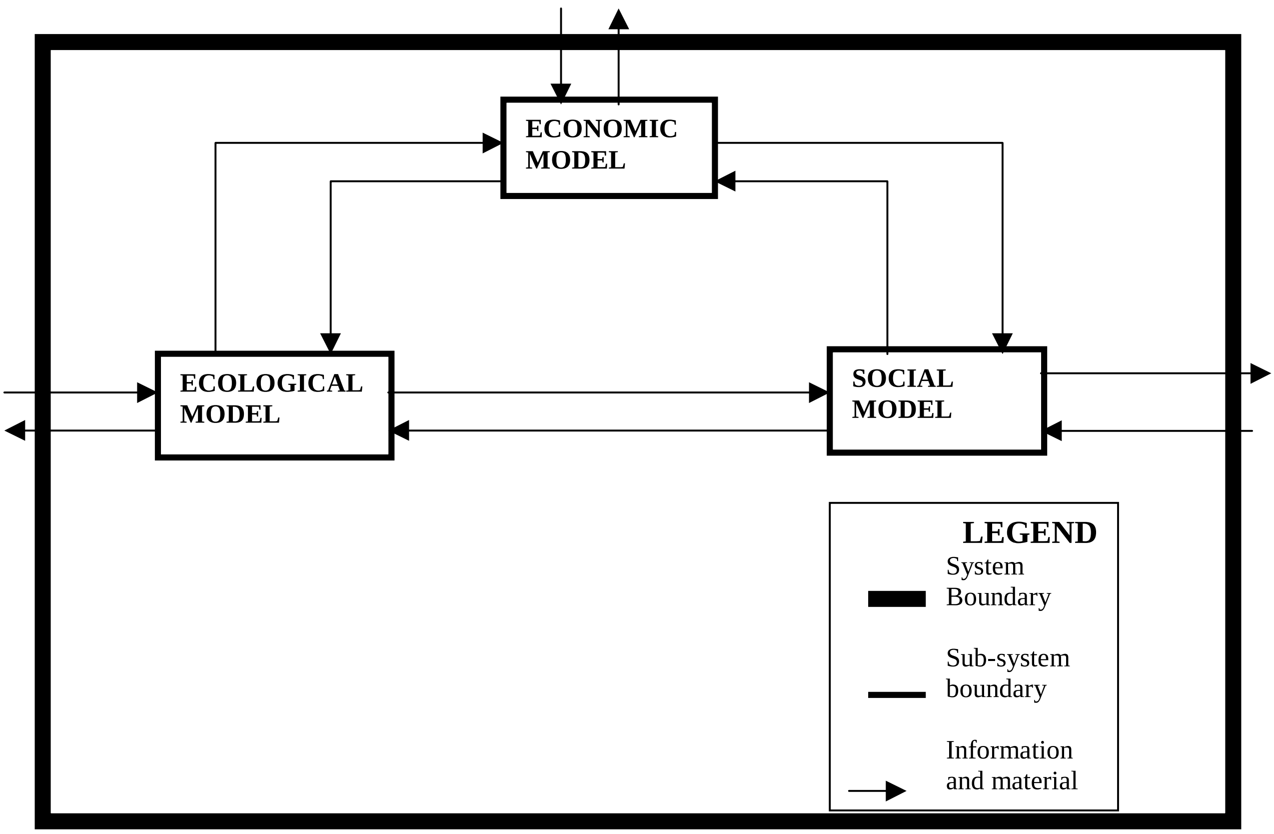
Rutile was mined in Southern Sierra Leone using two methods: (i) Bucket and Ladder dredging, and (ii) open cast method. The dredging operation is done after the ore deposit has been flooded (mostly through damming of nearby watercourses). The floating dredge which needs a minimum of about 6 meters depth of water, is capable of digging up to 15 meters below the water level. The extracted ore is scrubbed and screened by the primary processing plant integrated in the dredge, and the waste is discarded behind the dredge. The screened ore is then pumped through floating pipes to the wet plant located behind the dredge that further processes the ore to the grade of 50% recoverable rutile. The concentrate is then stockpiled and transported to the table plant where it is upgraded to about 70% recoverable rutile and 95% total heavy mineral sand content.

Gold mining is also in operation in Sierra Leone but on a very insignificant scale.

MODEL DEVELOPMENT

This section discusses the structure of the Natural Resource Management Model (NRMM). Its description involves a general introduction to the model structure that comprises the variables of the economic, ecological and social subsystems. Causal loops of each subsystem are formulated based on its respective function. Figure 1 below shows the basic building block of the modelling exercise. It depicts the flow of material and information in the feedback systems of the three subsystems.

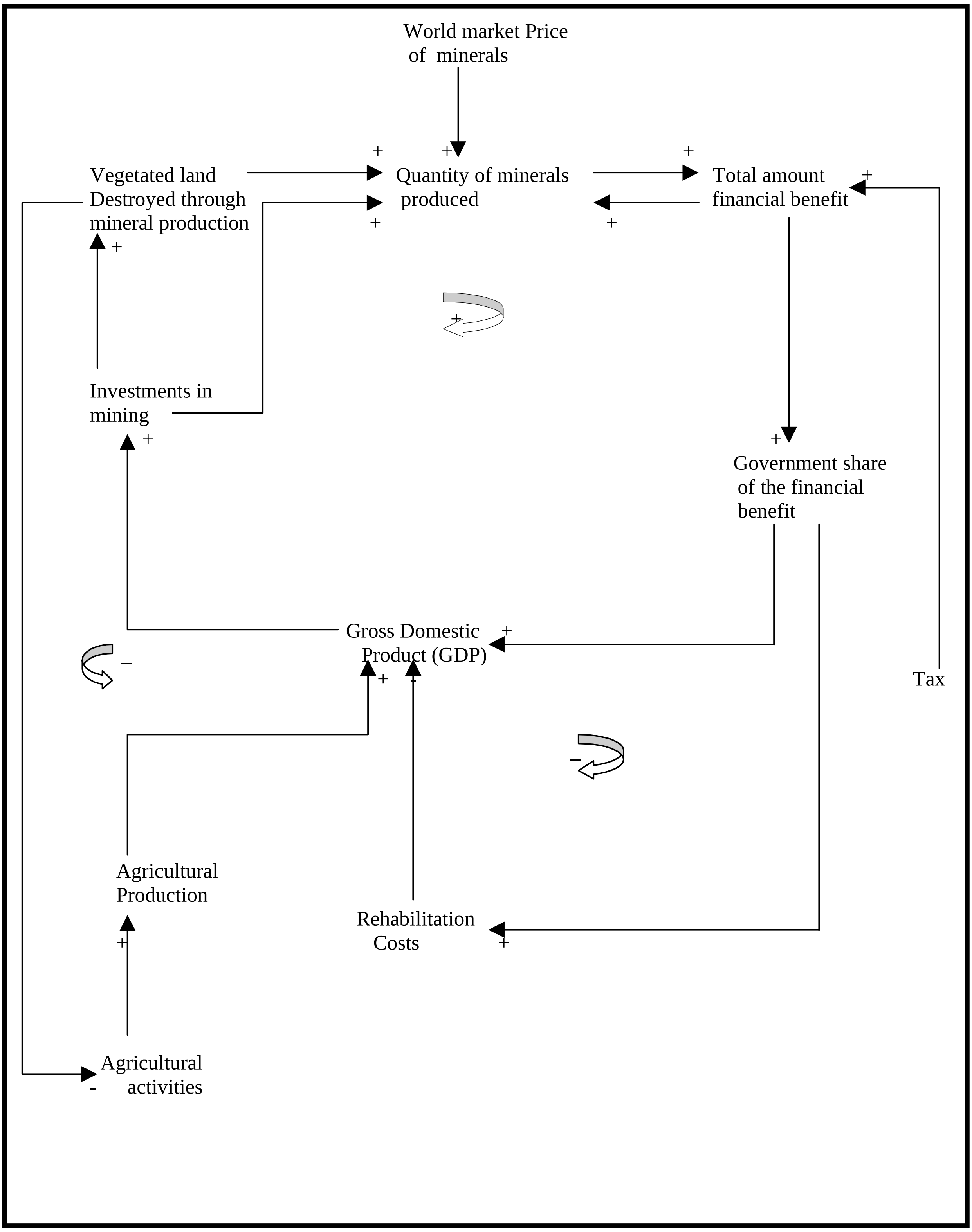
Figure1: Structural components of the Natural Resource Management Model (NRMM)



Development of the economic model

The structure of the economic subsystem is shown in the causal loops of figure 2. It shows the interaction between two negative loops and one positive loop. The positive loop depicts the interaction between mineral production and the Gross Domestic Product (GDP) of the country. It shows a systematic increase in the GDP. One negative causal loop depicts the effect of rehabilitation cost incurred through mining activities on the GDP as a systematic decline. The second negative causal loop depicts the effect of mining on agricultural production, which also causes a systematic decline in the GDP. The actual effects of this interaction are determined through the development of model equations. The model developed using the DYNAMO programming language is detailed in Tengbe (1994, 2000b).

Figure 2:The causal loop network of the economic system



Modelling the economic system

The aim of this sub-model is to determine the relationship between the mineral produced through open cast mining and the vegetated land destroyed to achieve this. It is shown in the causal loop of Figure 2 that the vegetated land destroyed through mineral production, leads to the production of a certain quantity of mineral. The government's share of the financial benefit is obtained through taxing the total financial benefit obtained from this mineral production. This accrues to the Gross Domestic Product (GDP) of the country. The level of the GDP is also a decisive factor for further investment in mining. The cost of rehabilitation measures take up part of the financial benefit of government on the assumption that the rehabilitation will not be undertaken by the mining company after it terminates its mining operation. This assumption is made because the current government policy on rehabilitation is relatively ineffective and not properly monitored (Sierra Leone Government, 1989). Agricultural production, which contributes to the GDP is also affected by the mining activities as put forward in the causal loop. The model attributes the reduction of agricultural production to the depletion of cultivated areas.

The following dynamo equations were developed:

L PRO.K=PRO.J+DT*RPRO.JK
R RPRO.KL=(DVEGM.K*ARCON)/PAT
C PAT=5
C ARCON=400
A DVEGM.K=VRTL.K+DMINE.K
Where :
PRO - Produced mineral (tons)
RPRO - Rate of mineral production (tons/yr)
PAT - Production adjustment time associated with vegetation destruction (yrs)
DVEGM - Destroyed vegetation through mining (ha)
VRTL - available artificial lakes (ha)
DMINE - dry mining areas (ha)

The rate of production therefore depends on the destroyed vegetation, which is caused by artificial lakes formed through mining and excavation. The average mineral content and the production adjustment time associated with destroyed vegetation are assumed to be a constant during the simulation process, although the rutile content of land varies from one place to another. This is shown in the Table 1.

Table 1: Showing the production records of some of the already mined out deposits of the Sierra Rutile mining activities.

Name of mined out deposit	Size of deposit (ha)	Total production (tons)	Time taken to mine out (yrs)	Rutile content (tons/ha)
Mogbwemo	303.00	196619.00	5	648.90
Bamba/Belebu	540.80	173056.00	4	320.00
Pejebu North	411.02	127526.00	0.58	310.26
Pejebu South	882.00	291100.00	1.08	330.06

Information source: Sierra Rutile Mine Planning Department.

From this table, the average rutile content of land is calculated as 400 tons/ha with a production adjustment time of 5 years, determined after a series of simulation runs.

Modelling the aspects of overheads and profits

This model is trying to determine the amount of money obtained from the sale of the mineral produced. This amount could be obtained by multiplying the world market price for mineral with those of the produced mineral. The government share is obtained through taxing the amount obtained. The net amount after taxes is considered the overheads and profits of the mining company. The cost of rehabilitation measures is also taken into account assuming that it is to be undertaken by the mining company.

The following dynamo equations could be written:

```
L    RECOV.K=RECOV.J+DT*RCOV.JK
R    AMOUNT.KL=PRO.KL*PRICE
C    PRICE= 400
A    GOVT.K=AMOUNT.K*TAX
C    TAX= 0.07
R    RCOV.KL=AMOUNT.KL-RGOVT.KL-RCOST.KL
A    RECOST.K=RELAND.K*COST
C    COST=1000
A    EREAX.K=1
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AMOUNT is the mount obtained from the sale of mineral (US$/yr); PRICE - world market price for mineral (US$/ton); TAX - taxes and royalties (fraction); RECOV - overheads and profits(US$); RECOST - rehabilitation costs (US$); COST - cost of rehabilitation per ha (us$/ha); EREAX - effects of overheads and profits on mining. The 1992 price level for rutile is given as US$400.00 per ton (according to Sierra Rutile mining company), the government tax of about 7%, and the rehabilitation cost was approximated at US$1000.00 per hectare

Modelling the aspects of government taxes and royalties

Government taxes and royalties (GOVT) are determined as the percentage of the amount of money obtained from the rutile sale (AMOUNT). This is a contribution to the Gross Domestic Product of the country (LGDP). The effect of this local contribution to the gross domestic product as a decision making factor to the mining operation is presently very insignificant as the mining operation is carried out by foreign companies whose profits are not contributing to the GDP of Sierra Leone. This effect (ELGDP) will be given a multiplier of 1 as the mining will continue at the present rate. The following dynamo equations will represent these aspects.

L GOVT.K=GOVT.J+DT*RGOVT.JK
R RGOVT.KL=TAX*AMOUNT.KL
C TAX=0.07
L LGDP.K=LGDP.J+DT*RLGDP.JK
R RLGDP.KL=RGOVT.KL+RAGPRO.KL-ERCOST.KL
A ELGDP.K=1-MULT1.K

GOVT - taxes and royalties paid to government (US$); RGOVT - rate of taxing (US$/yr); TAX - percentage tax (fraction); LGDP - local contribution to the Gross Domestic Product (US$); ELGDP - effect of GDP contribution on mining; AGPRO - agricultural production (US$); ERCOST - rehabilitation cost incurred by government (US$)

Modelling the aspects of rehabilitation costs

The rehabilitation cost (RCOST) is the expenditure incurred by the company to re-vegetate the mined out areas. The model assumes that this cost will only be undertaken during the mining operation, and the government would have to bear the rest of the ecological cost (ERCOST). The following equation depicts the situation.

L RECOST.K=RECOST.J+DT*RCOST.JK
R RCOST.KL=REHAB.KL*COST
C COST=1000
R ERCOST.KL=CLIP(RCOST.KL,0,TIME.K,2020)

RECOST - rehabilitation cost borne by the company (US$); RCOST - rate of cost incurment (US/yr); COST - unit cost of rehabilitation (US$/ha); ERCOST - rate of cost incurment by government (US$/yr); REHAB - rehabilitation rate (ha/yr)

Modelling the aspects of agricultural production

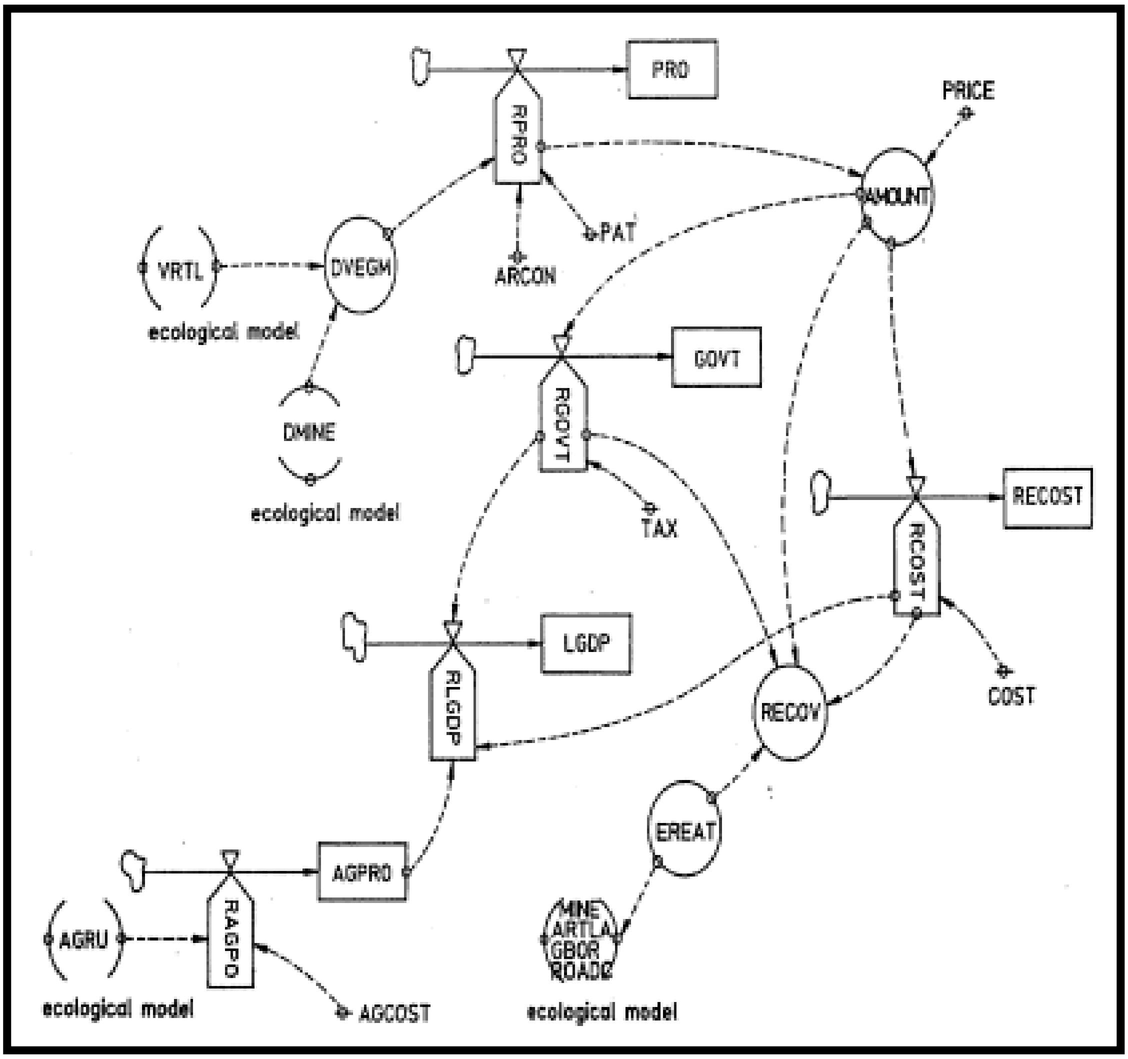
Agricultural production, which also contributed to the Gross Domestic Product (GDP) is also affected by mining activities. The model attributes the reduction of agricultural production, to the depletion of cultivated areas. The following equations will models the situation.

L AGPRO.K=AGPRO.J+DT*RAGPRO.JK

R RAGPRO.KL=AGRU.KL*AGCOST
C AGCOST=300

AGPRO - Income abtained from agricultural production (US$); RAGPRO - Rate of agricultural production (US$/yr); AGCOST - Unit cost of agricultural production (US$/ha); AGPRO - Agricultural production (US$)

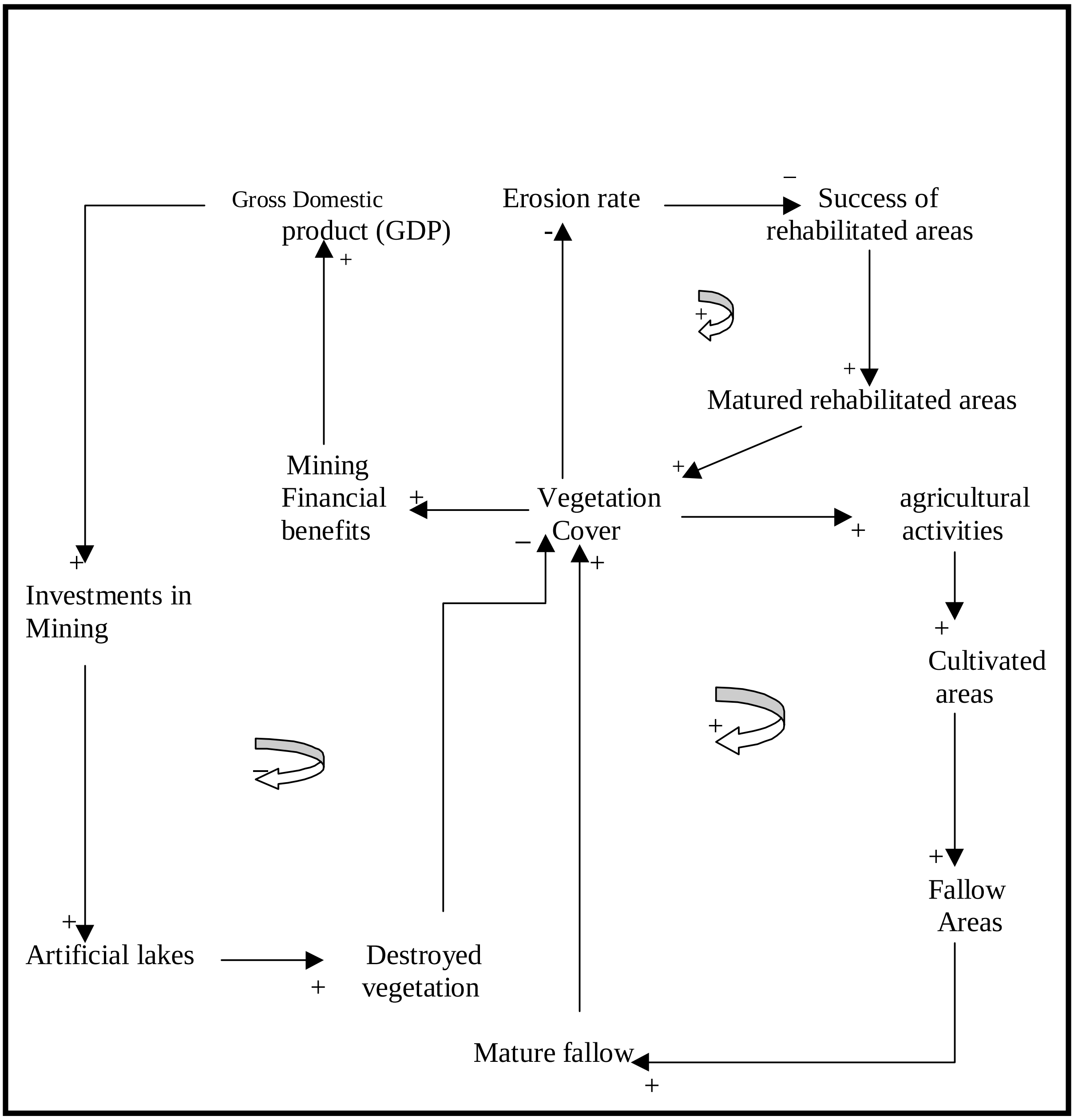
Figure 3: Flow diagram of the economic model



Development of the ecological model

The causal loop network of the ecological sub-system is shown in figure 4. Unlike the economic model where all the causal loops are connected to the GDP, the causal loops of the ecological model are all connected to the vegetation cover. The structure of this model takes two physicalfactors into consideration: (i) the reduction of agricultural land, and (ii) the reduction of vegetation cover (aggregated variable for all flora and fauna). Three main causal loops are identified in Figure 4. One of the causal loops shows how mining activities cause a systematic decline to the vegetation cover and potential agricultural land. The second loop shows how increase in erosion rate due to mining causes constraint to the re-vegetation of mined-out areas. The third loop shows the impact of shifting cultivation methods on vegetation cover.

Figure 4: The causal loop network of the ecological system



Modelling the effects of mining activities

The type of mining activities modelled is mainly the open cast or excavation method and to a lesser extent the dredging method used in the mining of rutile. As the latter creates artificial lakes in some areas due to dredging, these two mining techniques are modelled separately.

Artificial lakes, which are created through dredging soil material, reduce vegetation in river valleys of high agricultural potential. The rate and level of artificial lake formation is determined from the total lease area of the mining operation; the total area of the existing artificial lakes; and the total number of years to form these lakes. This information whose values are given in Table 1 are used to develop the ecological sub-model using the DYNAMO programming language.

Excavation is an aggregated variable that represents all activities associated with excavation in the mining area. These include road and canal construction, earth borrowing, and the excavation of the mineral. The inputs needed for formulating this model includes, the total lease area, the existing excavated area as already defined, and the total number of years to achieve the existing state of excavation.

Modelling the effects of soil erosion on rehabilitation measures

The rehabilitation of mined out areas was not an established policy of government at the time of this modelling exercise. However, since it was at that time practised by the mining companies, and it is also a foreseeable future policy of government, the model has assumed a rehabilitation rate, which was used for the initial runs. This rate of rehabilitation was based on data obtained from the experimental plots of land around the Sierra Rutile mining area. The effectiveness of the re-vegetation depends on the rate of soil erosion determined from the universal soil loss model as put forward by Wischmeier (1978). Its main use in this modelling exercise was to determine the average rate of soil erosion that is accelerated by the mining activities in the region and the constraint it puts on the re-vegetation efforts. This constraint increases as the predicted losses exceed the soil loss tolerances of the region. The soil loss equation is as follows:

Soil loss (A) = RKLSC

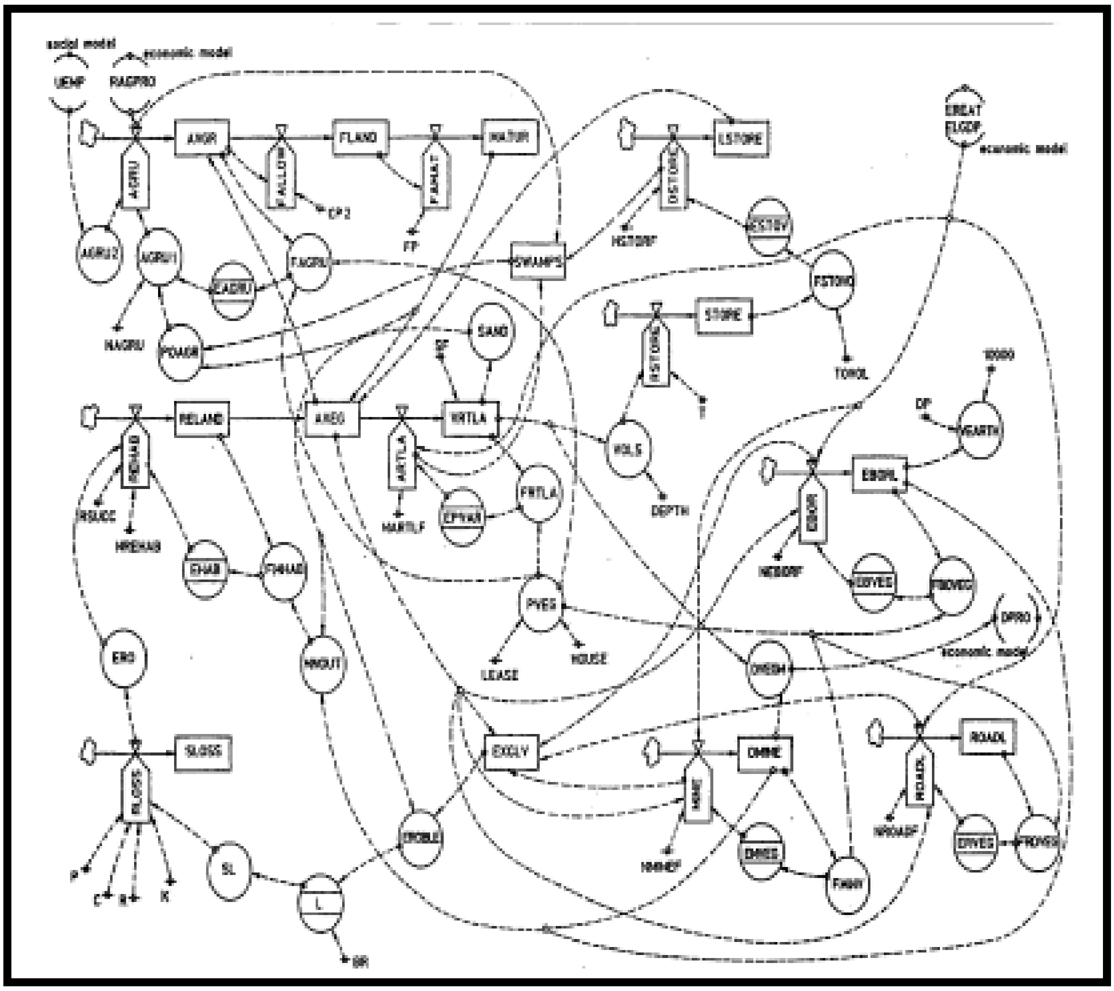
The variables are defined as: rainfall erosion index (R), Soil Erodibility factor (K), Slope Length factor (LS), Vegetation Cover factor (C). Details of this model is described in Tengbe (1994, 2000b), Lal (1979), Roose (1977), Wischmeier (1978).

Modelling the vegetation and agricultural land use systems

This model determines the impact of shifting cultivation methods on vegetation cover.
Since agriculture is the main occupation of the people in this region it is estimated in Sierra Leone (1980) that 75% of the people residing in the region receive a major portion of their income from agricultural activities. Shifting cultivation, which is practised by approximately 65% of the farming population is the preferred method of farming in the region. In this method, plots of land are cultivated for 1 to 2 years and left for a fallow period. The fallow

period is normally 15 years. During this fallow period, the cultivated land is allowed to regenerate itself, but due to pressure from other land use activities such as mining, this fallow period has been shortened to 7 years. According to Sierra Leone Government (1980), the shortened fallow period has reduced soil productivity, and farmers complain of declining crop yield. This is modelled in DYNAMO programming language as depicted in the causal loop network of the ecological system in Figure 3

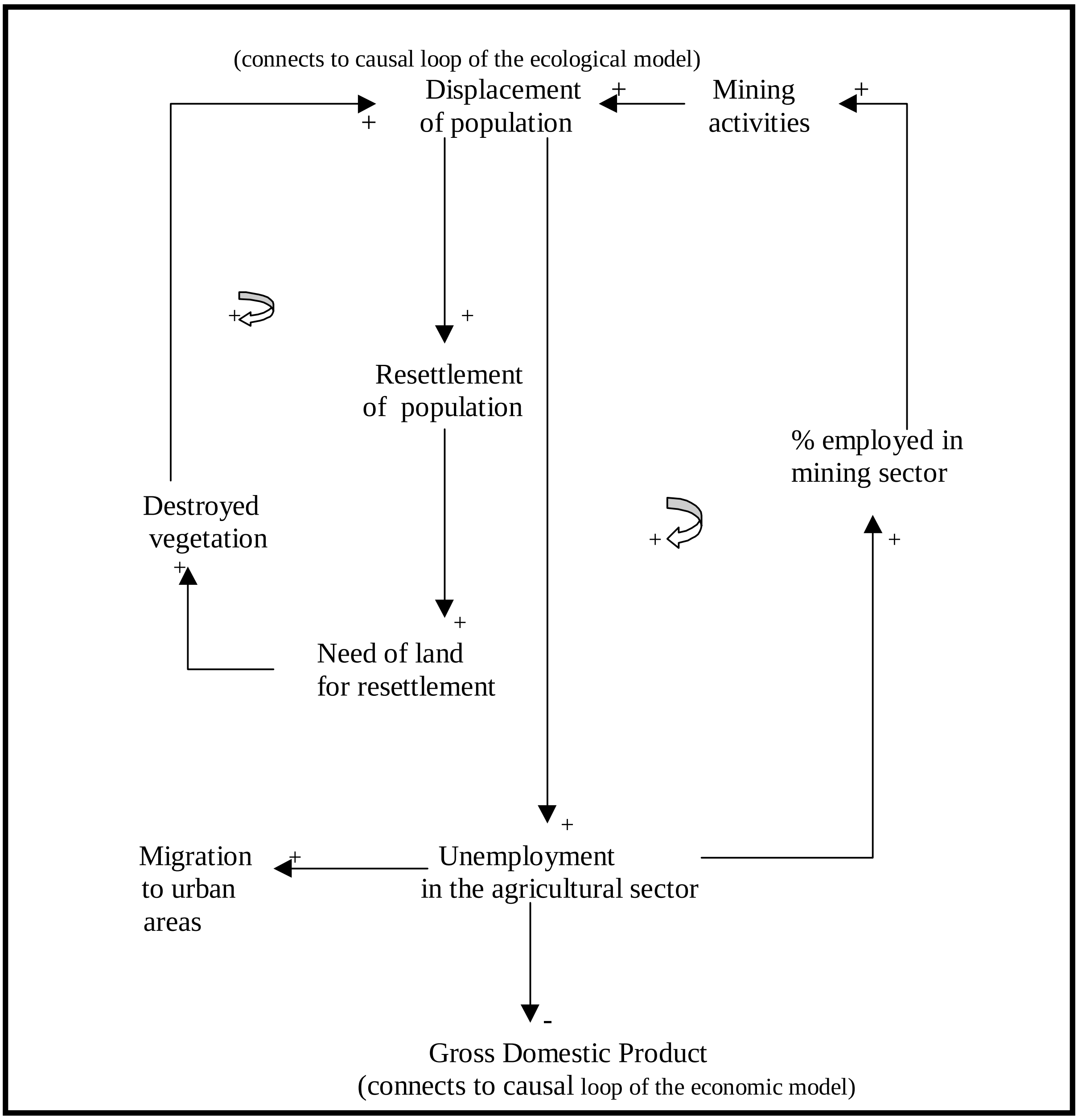
Figure 5: Flow diagram of the ecological model



Development of the social model

Figure 4 shows the causal loop network of the social model. In this model, the displacement of population is the most important variable around which causal loops are developed. Two main causal loops could be identified: (i) the positive loop of the effect of resettlement of displaced population on vegetation cover, and (ii) the positive loop of the effects of displacement of population on agricultural production and ultimately on the Gross Domestic Product. Another effect depicted is the migration of population to other areas with agricultural potential or to urban areas.

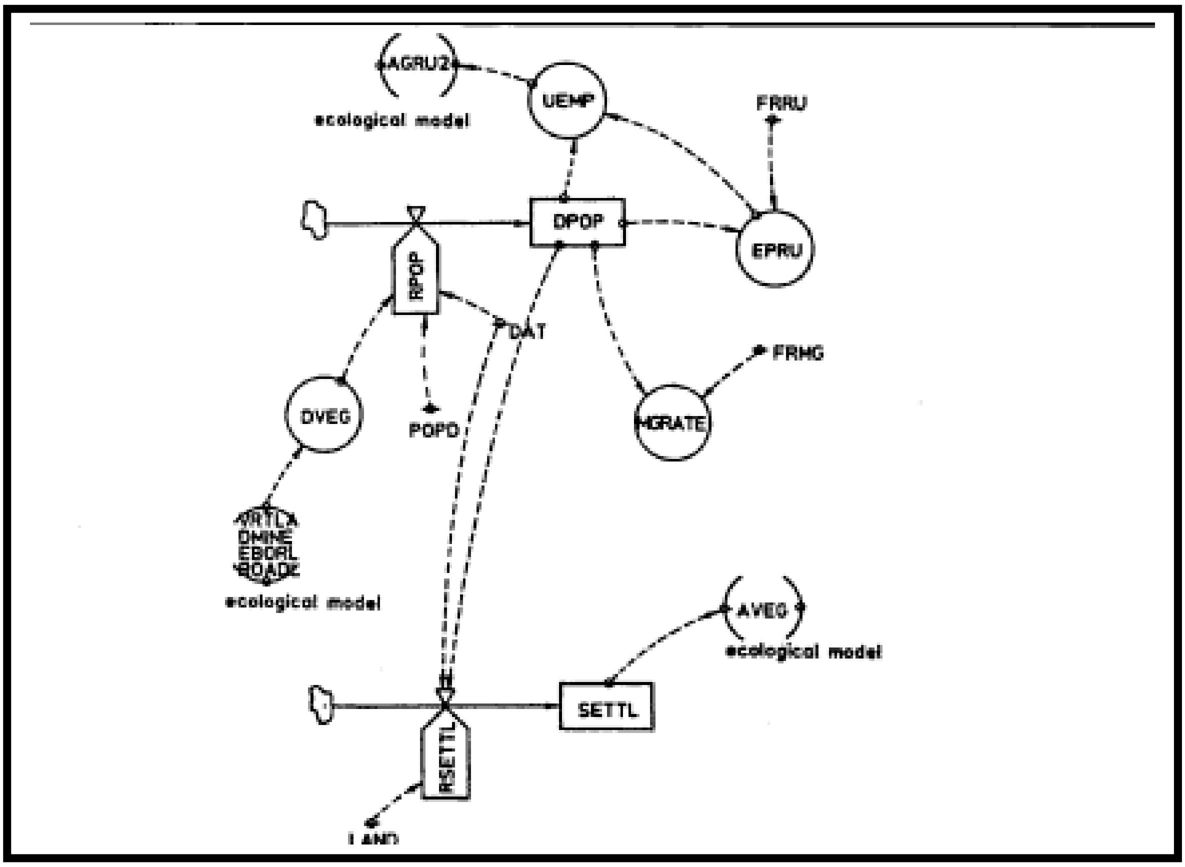
Figure 6: The causal loop network of the social system



Modelling the social system

This assumes the displacement and resettlement of population due to mining activities to be the most important sociological problem. The rate of displacement of the population depends on the destroyed vegetated area and the density of population. According to Sierra Rutile Limited, (1988), a certain percentage of the displaced population is employed by the mining industry as labourers. The rest of the population is unemployed due to the lack of agricultural land. Some of these people migrate into urban areas in search of employment. Others migrate to areas outside the mining regions, where land is available. Acquisition of land outside their home areas is often difficult due to the nature of the land tenure system. In the land tenure system, land ownership is at two levels. At the first level the village chief is the keeper of the land belonging to that village. At the lower level, each family in the village has its own share, which is passed on from one generation to the other. If a family loses land due to mining activities, it is virtually impossible to claim ownership elsewhere. However, it is sometimes possible to lease land somewhere else, but the payment involved is beyond the reach of most of them, as they are not properly compensated. This social system is modelled in DYNAMO programming language as depicted in the causal loop network of the social model in figure 4.

Figure 7: Flow diagram of the social model



DATA ACQUISITION AND MODEL VALIDATION

In building this model, hypotheses of the system were formulated and transformed into model equations using the DYNAMO programming language with data and information from the mining systems of Sierra Leone. One of the major constraints encountered during the process was the availability of data. This model is based on both primary data from the assessor and secondary existing data. The main sources of secondary data and information are the Sierra Rutile (1988), SIEROMCO (1988), Sierra Leone Government (1974a, 1974b), Sierra Leone Government (1980), Sierra Leone Government (1989), Clarke (1975). The sources of primary data are measurements, observations, interviews and through visits to all the mining areas over a certain period of time. The structure of this model was first developed for the Sierra Rutile mining system, and was later adapted to the other three mining systems. Structures that were not relevant to other mining systems were discarded and new ones developed based on the type of mining in use. However, the main difference was in the values of the model parameters and the artificial lake structure, which exists for the Rutile Mining System only. All the other mining systems used open cast methods of mining.

Table 2: Main parameters used to design the structure of the model of the mining system of Sierra Leone.

Parameter Type	**Rutile Mining system**	**Bauxite mining system**	**Native Diamond mining system**	**National Diamond Mining Company**
Average mineral content	400 (tons/ha)	3950 (tons/ha)	279 (carats/ha)	279 (carats/ha
Market price	400 (US$/ton)	25 (US$/ton)	52 (US$/carat)	52 (US$/Carat)
Government tax	7%	7%	0%	51%
Rehabilitation costs	1000 (US$/ha)	2,465 (US$/ha)	NA	NA
Agricultural production (US$/ha)	300	300	300	300 US$/ha)
Success rate of re-vegetation	65%	75%	NA	NA
Artificial lake formation	0.002 (ha/year)	NA	NA	NA
Vegetated area (lease area) (ha)	134,700	32,370	3,221,504	77,440
Settlement areas (ha)	539	126	12,652	252
Cultivated area (ha)	13,228	3,179	74,095	14,823
Population density (persons/ha)	0.3	0	NA	NA

The information in the table was obtained from sources already referenced and was used in the model in (Tengbe, 1994). NA means that model structure is not available

After developing the model, simulation runs were undertaken over the historical periods of the mining operations. The production outputs predicted by the model were compared to the actual production of the company over the same period. Although there were missing data, which is a typical problem in developing countries, a very high correlation was achieved between the simulated data and the actual data. This validation process in Tengbe (1994, 2000b) was undertaken for other variables such as "artificial lake formation, "excavated areas" and "water storage", and the results had good correlation with the actual system. The table below shows a typical result for rutile production.

Table 3: Production of Sierra Rutile from 1979 to 1991

Year	Actual Production	Simulated production
1979	11,565	11,560
1980	47,499	34,070
1981	57,668	57,070
1982	80,887	81,980
1983	Not available	103,000
1984	Not available	123,200
1985	Not available	144,100
1986	160,269	165,700
1987	Not available	187,900
1988	Not available	210,600
1989	Not available	233,900
1990	236,156	256,700
1991	215,171	282,000

Source: (Tengbe, 1994)

POLICY FORMULATION AND ANALYSIS

Policy formulation is a process through which adequate alternative policies for a system are developed based on the failures and problems of existing policies.
The developed model is to be used to simulate these alternative policies, through parameter and structural changes. The evaluation of each alternative policy will be based on the following criteria:

- Its capability to optimise the agricultural land preservation programs;
- Its capability to optimise national-park protection and wildlife conservation programs.
- Its capability to optimise rehabilitation programs.
- Its capability to optimise soil conservation programs.
- Its effects on the national economy.

Three alternative policy approaches are evaluated here using the model within the framework of the above criteria. These are the "Conservative” Policy Approach, the “Radical” Policy Approach and the “Harmonious” Policy Approach.

The “conservative” policy approach

This type of policy approach approximates to the way the Government in Sierra Leone is currently practising its environmental programs. Although environmental institutions place much emphasis on land rehabilitation, the schemes are inadequately monitored and are consequently only partly effective. Furthermore the rate of mineral extraction is not considered in planning procedures, and mining companies are allowed continuous operation.

The “conservative” policy approach assumes mining would continue as at present but allows for optimum land rehabilitation and soil conservation programs. The following changes are made to the model:

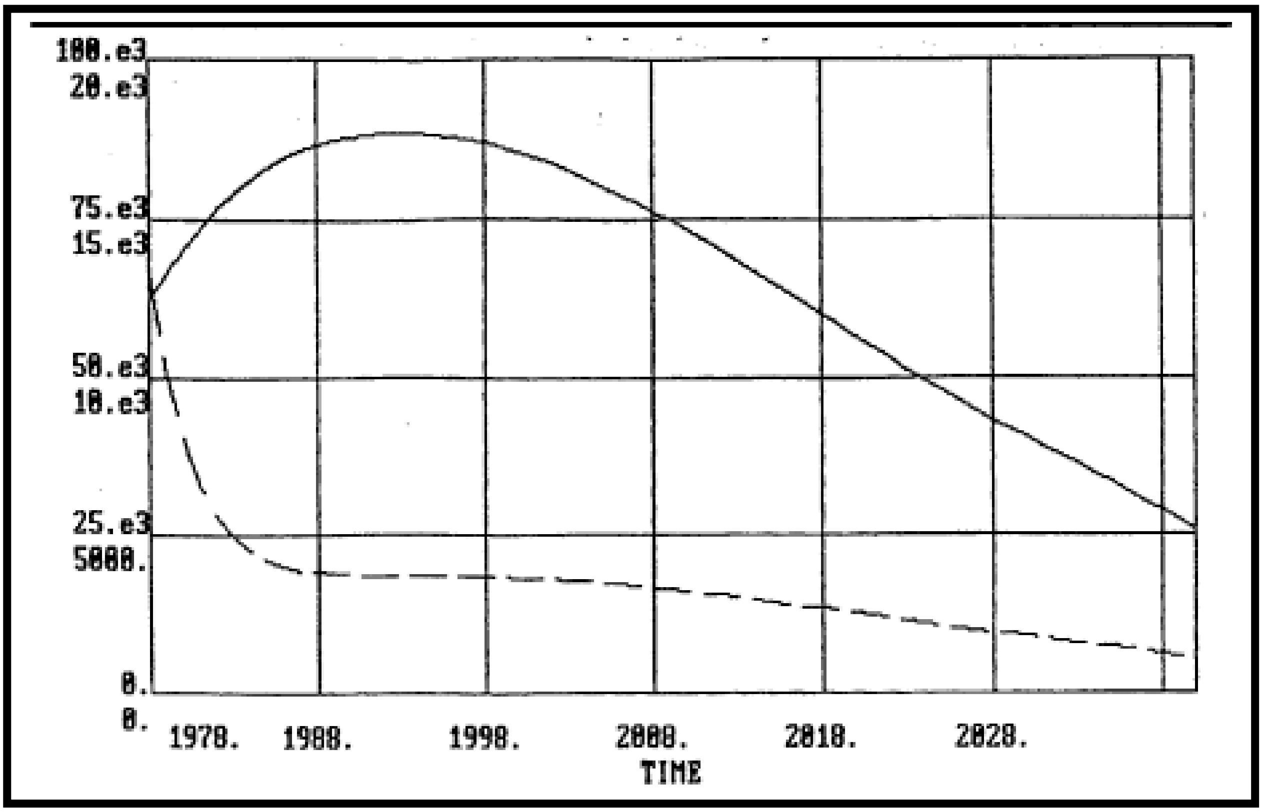
- A parameter for erosion control practice is added as a structure of the original model.
- Rehabilitation rates are increased to three times the current actual value for optimum land rehabilitation

These policies were imposed on the model through DYNAMO programming, details available in Tengbe (1994, 2000b).

The results of the simulation predict short-term economic benefits but with adverse long-term ecological, social and economic consequences. A typical result is shown in the time series for agricultural land protection programmes in the Rutile mining system. The graph in figure 6 below shows a steady decline in both the potential agricultural land and the cultivated areas after reaching an early peak.

The outcomes of this policy model indicates that immediate government policy changes are needed to avert a serious decline in the agricultural sector of the economy, especially where mining is taking place in the inland valley swamps which are the most fertile areas for cultivating the staple food crop, rice.

Figure 8: Effects of the "conservative" policy approach on agricultural land protection (Rutile mining)
(Rutile mining)
_______ Potential Agricultural land (ha) (0.,100.e3)
__ __ __ Cultivated land (ha) (.,20.e3)



The "radical" policy approach

This approach would terminate all mining activities immediately. The approach represents the thinking of the inhabitants of Sierra Rutile mining region, especially the farmers, as exhibited during interviews in the mining region. Environmental groups in Sierra Leone, especially NGOs, also support this approach. This is also supported to a large extent by the Department of Wildlife Conservation and the Rural Development section of the Ministry of Social Welfare (In contrast, most of the farmers of the diamond mining area welcome the continuation of mining because of the financial benefits of illicit diamond working).

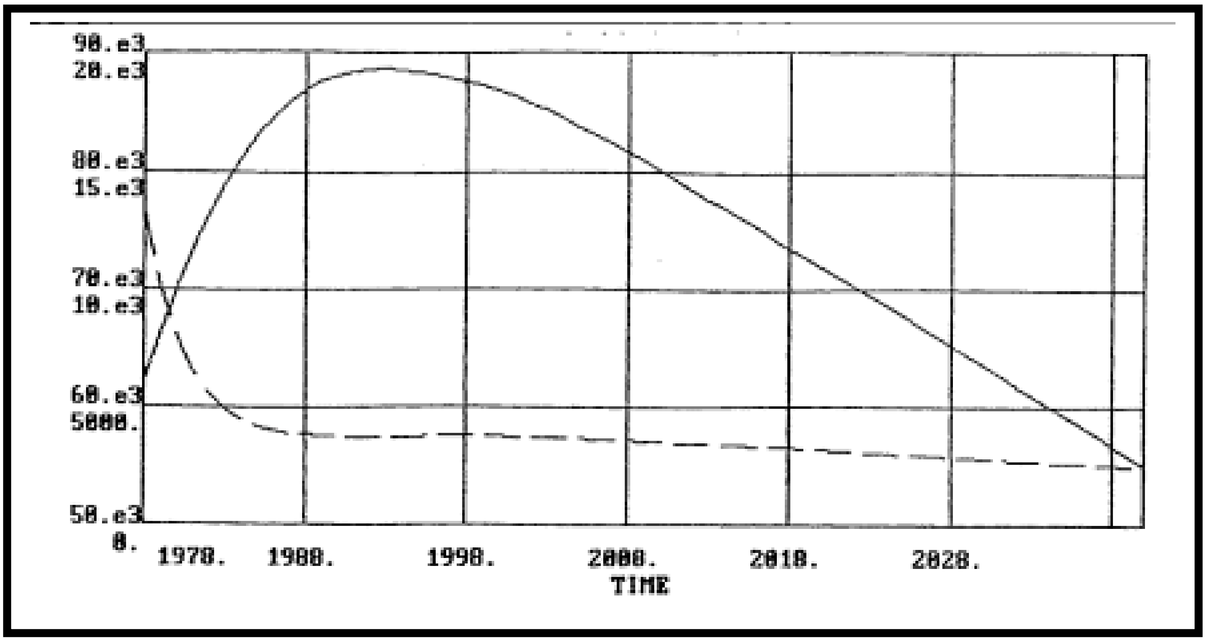
The policy approach was simulated in the model by making the following adjustments:

- All mining variables were set to zero to stop mining activities with immediate effect.
- Parameters for erosion control practices were added as a structure of the original model
- Rehabilitation rates were increased to three times the value used in the original model for

optimum land rehabilitation.

Although the option showed ecological benefits it indicated both short- and long-term adverse economic and social consequences. The model indicates, as would be expected, that there would be no contribution to the Gross Domestic Product, which would be catastrophic for a country with such a fragile economy. Further, it can be seen from figure 7 that compared to the "conservative policy approach" there is only a slight change in the projected quantity of potential agricultural land available especially during the first 20 years, even though mining activities are terminated. This unexpected result, which does not become apparent using other techniques of projection especially where there is acute lack of data, is possibly due to the continuation of shifting cultivation method. This method currently has relatively short fallow periods, which result in a high rate of conversion of potential agricultural land to land under cultivation.

Figure 9: The effects of the "radical approach" on agricultural land protection (Rutile mining) (Rutile mining)
______ Potential Agricultural land (ha)(50.e3,90.e3)
_ _ _ _ Cultivated land (ha)(0.,20.e3)



The "harmonious policy approach"

This approach strikes a balance between the "radical and the "conservative" approaches in an attempt to realise sustainable development - the main goal of environmental planning, and draws on insights arising from those approaches. The original model is adjusted as follows:

- Agricultural land use rate is decreased through intensive sustainable agricultural practices. This is to reduce the adverse consequences of shifting cultivation practices.

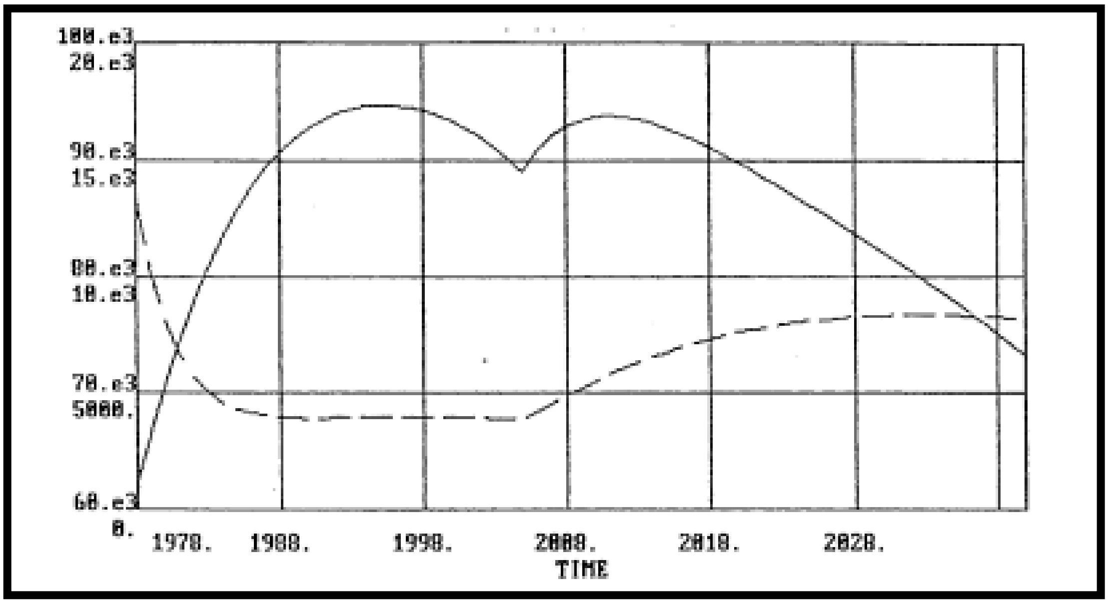
- The Fallow period is increased from the current 7 years to 12 years.
- Cultivation period is increased from the current 2 years to 10 years through intensive sustainable agricultural practices.
- Agricultural production is increased from the current US$300.00 per ha to US$600.00 per ha due to intensive sustainable agricultural practices.
- Native illicit diamond mining rate is set to zero thus terminating it with immediate effect.
- Rutile mining terminates at the year 2005
- SIEROMCO (bauxite) mining terminates at the year 2010
- National Diamond Mining Company (NDMC) stops practising open cast method of mining and changes to underground deep mining (“kymberlite” mining).

As already discussed, the "conservative" policy approach, realises short-term maximum economic benefits, which results in adverse ecological consequences, that ultimately reflect in long term economic problems due to the depletion of valuable agricultural land areas. The “radical” policy approach tries to curb this problem, without due consideration to short and medium term economic and social consequences. The "harmonious" approach aims to formulate policies that could serve as a base for sustainable development. It is hoped that the implications of the modelled outcomes of this policy approach will contribute to the preparation of programs to meet the objectives of Agenda 21. Below is a discussion of a typical result of simulating this policy on agricultural land protection programmes.

The effectiveness of the "harmonious" approach for agricultural land protection programs

In Sierra Leone Agricultural protection programs, which intends to save useful agricultural land areas from being encroached on by other land use activities have not been very effective, as shown above in discussing the “conservative” policy approach, where cultivated areas and potential agricultural land are lost to mining land use. If Figure 7 below is compared with Figures 5 and 6, it can be seen that without the introduction of the "harmonious " approach, potential agricultural land and cultivated areas are in danger. By introducing the “harmonious” policy approach, there is a complete change in the trends of the time series, which is not realised in either the "conservation" or the "radical" policy approaches. An increase is exhibited in the amount of land under cultivation, and the decline in potential agricultural land areas occurs much later. The early decline of potential agricultural land in the first two models is explained by the high land demands of shifting cultivation. The later decline of such land with application the “harmonious “policy model is due to the use of potential agricultural land for intensive cultivation, and the longer fallow cultivation periods allowed for under this policy. The model thus shows that "harmonious" policy approach is very effective in the protection of valuable agricultural land. It is also effective in the protection of flora and fauna, through the gradual reduction of mining activities and the intensification of agricultural land use.

Figure 10: Effect of "harmonious" approach on agricultural land protection programs
______ Potential Agricultural land area (ha)(60.e3,100.e3)
__ __ __ Cultivated land area (ha)(0.,20.e3)
Rutile Mining



DISCUSSION

The previous section was basically concerned with the formulation of new policies for the sustainable management of natural resources. During this process, the model developed was experimented with in the "laboratory" (in this case the computer) using different policy alternatives. Sensitive parameters were identified and manipulated, to improve the behaviour of the model. This is a major advantage of simulation modelling methodology. However, after the development of policy alternatives, strategies should be put in place to translate these parameter changes in the simulation exercise into policy actions for application in the “real world” system. This is because improving the behaviour of the model with a particular policy is not enough for positive changes to be realised in the real system. What is important, is to know why a particular policy improves model behaviour. This understanding can then be added to what is known or believed about the system so that correct decisions can be made within the limits of existing opportunities and constraints.

This discussion focuses on two important questions:

- Can those responsible for policy implementation in the “real world” system be convinced of the value of a model-based policy recommendation?
- What are the opportunities and constraints of this policy implementation?

In order to address the first question, one has to look at the current political debate concerning this issue. Since the development of this model, the National Report of Sierra Leone to United Nations Conference on Environment and Development (UNCED) in Sierra Leone (1992, 1989) discussed sector reform measures in the form of new agreements. Although, these agreements may not be entirely adequate, they are however in accord with the policies of the model-based "harmonious approach", which recommends how mining could be done in the most sustainable way so that ecological and social impacts can be minimised and at the same time realise economic benefits. The model outcome of such policies will give them greater credibility and assist in their being implemented. The second question addresses issues of opportunities and constraints. Opportunities for implementation can be defined as the different possibilities available within the present planning system that could ease the problems of implementation. The following possibilities are available:

- Leases and agreements between the government and the mining companies.
- Rehabilitation laws.
- Environmental Impact Assessment law
- Agricultural policies

The formulation of such leases, laws and policies would be helped by an understanding of the Natural Resource Management model outputs, especially the 'harmonious" policy model.
Constraints to implementation can be defined as problems existing within the system that could hinder the realisation of these alternative policies.

The basic types of problems identified are as follows: (i) availability of data and information, (ii) financial resources, (iii) technical know-how, (iv) lack of administrative and political will. The implementation of the "harmonius" policy approach will be greatly enhanced if some of the above problems are addressed.

Another aspect that needs consideration is the effect of external trade. Because the demand for these resources is mostly from industrial countries, the realisation of these proposals could not be achieved without their support. The development strategies of industrial countries should therefore take cognisance of the problems of developing countries, as was highlighted during the United Nations Conference on Environment and Development at Rio de Janeiro. The unfavourable condition of international trade, under which developing countries operate, is also one of the main reasons for the unsustainable exploitation of natural resources.

CONCLUSION

The main concern of this paper has been to contribute to the management of natural resources for sustainable development. It shows how the development and use of computer modelling using the Natural Resource Management Model (NRMM) can give insights into the mineral extraction system of Sierra Leone. During the construction phase of the model, data and information were obtained from the Sierra Rutile mining company, which stopped operations in 1996 due to civil war in Sierra Leone. The structure of the model was then adapted to data and mining techniques of the Bauxite mining, National Diamond Mining and native/illicit diamond mining enterprises in Sierra Leone. The 'Harmonious Policy' approach derived from the modelling process was shown to be the option most appropriate to the social, economic and ecological problems arising from the activities of the mineral extraction industry. Although the model has been developed for the Sierra Leone mining system it could, with appropriate changes in the values of the parameters and constants, equally well be applied to similar systems in other countries. It could also be reduced or increased in size according to the purpose of the study.

It is hoped that the results of this study will contribute to the development and implementation of Sustainable Development policies.

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APPENDIX

LIST OF VARIABLES

SYMBOL	TYPE	DEFINITION
AGPRO	L	INCOME ABTAINED FROM AGRICULTURAL PRODUCTION (US$)
AGCOST	C	UNIT COST OF AGRICULTURAL PRODUCTION (US$/ha)
AGRU	R	EFFECTIVE AGRUCULTURAL LAND USE RATE (US$/yr)
AGRU1	A	NORMAL AGRUCULTURAL LAND USE RATE (US$/yr)
AGRU2	A	AGRUCULTURAL LAND USE DUE TO DISPLACED POPULATION (US$/yr)
AMOUNT	R	AMOUNT OBTAINED FROM THE SALE OF MINERAL (US$/yr)
ALUP	C	AVERAGE AGRICULTURAL LAND USE PER PERSON PER YEAR (ha/person/ yr)
ARCON	C	AVERAGE MINERAL CONTENT OF LAND (tons/yr)
ARTLA	R	ARTIFICIAL LAKE FORMATION (ha/yr)
AVEG	L	AVAILABLE VEGETATION (ha)
AVGR	L	CULTIVATED LAND AREA (ha)
AVGRN	C	INITIAL CULTIVATED LAND (ha)
BR	C	BREATH OF SLOPE (m)
C	C	VEGETATION COVER FACTOR
COST	C	UNIT COST OF REHABILITATION (US$/ha)
CP	C	AVERAGE CULTIVATION PERIOD (yrs)
DAT	C	POPULATION ADJUSTMENT TIME (yrs)
DP	C	AVERAGE DEPTH OF BORROWED PITS (m)
DEPTH	C	AVERAGE DEPTH OF DAM (m)
DPOP	L	DISPLACED POPULATION (persons)
DSTORE	R	RATE OF DESTRUCTION OF LAND THROUGH WATER STORAGE (ha/yr)
DVEG	A	DESTROYED VEGETATION (ha)
DMINE	L	EXCAVATED AREAS THROUGH DRY MINING (ha)
ERCOST	R	RATE OF REHABILITATION COST INCURRED BY GOVERNMENT (US$/yr)
ERVEG	A	EFFECT OF ROAD CONSTRUCTION ON VEGETATION
EHAB	A	EFFECT OF MINED OUT AREAS ON REHABILITATION
EPVAR	A	Effect Of Potential Vegetated Land On Artificial Lakes.
EREAX	A	EFFECTS OF OVERHEADS AND PROFITS ON MINING
ERAEX	A	EFFECT OF OVERHEADS AND PROFITS ON ROAD CONSTRUCTION RATE
EREAT	A	EFFECT OF OVERHEADS AND PROFITS ON THE ARTIFICIAL LAKE FORMATION.
EBOR	L	BORROWED AREAS (HA)
EAGRV	A	EFFECT OF POTENTIAL VEGETATED AREA ON AGRIC.
EHAB	A	EFFECT OF MINED OUT AREAS ON REHABILITATION
EPRU	A	NUMBER OF DISPLACED PEOPLE EMPLOYED IN MINING
EPVAR	A	EFFECT OF POTENTIAL VEGETATED AREAS ON ARTIFICIAL LAKE FORMATION
EBVEG	A	EFFECT OF EARTH BORROWING ON VEGETATION
ERO	A	EFFECT OF SOIL EROSION ON REHABILITATION

ESTOV	A	EFFECT OF WATER STORAGE ON VEGETATION
ELGDP	A	EFFECT OF LOCAL GDP ON MINING
EXCV	R	EXCAVATION RATE (ha/yr).
EXCVL	L	EXCAVATED LAND (ha)
EXVEG	A	EFFECT OF POTENTIAL VEGETATION ON EXCAVATION
EMVEG	A	EFFECT OF DRY MINING ON VEGETATION
FAGRV	A	FRACTION OF POTENTIAL AGRIC. LAND THAT IS CULTIVATED
FALLOW	R	RATE AT WHICH CULTIVATED LAND IS PLACED UNDER FALLOW (ha/yr)
FAMAT	R	RATE AT WHICH FALLOW LAND MATURES (ha/yr)
FEXCV	A	FRACTION OF POTENTIAL VEGETATED LAND EXCAVATED
FLAND	L	LAND UNDER FALLOW (ha)
FLANDN	C	INITIAL FALLOW LAND (ha)
FROVEG	A	FRACTION OF VEGETATED LAND THAT IS USED FOR ROADS CONSTRUCTION
FARTLA	A	FRACTION OF LAND OCCUPIED BY ARTIFICIAL LAKES
FMHAB	A	FRACTION OF MINED OUT AREA REHABILITATED
FBOVEG	A	FRACTION OF VEGETATED LAND BORROWED
FMINV	A	FRACTION OF VEGETATED AREAS THAT ARE MINED OUT
FP	C	FALLOW PERIOD (yr)
FRRU	C	NORMAL PERCENTAGE OF DISPLACED PEOPLE EMPLOYED IN MINING
FRTLA	A	FRACTION OF POTENTIAL VEGETATED LAND OCCUPIED BY ARTIFICIAL LAKES
FSTOVO	A	FRACTION OF TOTAL PRECIPITATION THAT IS STORED
GOVT	L	TAXES AND ROYALTIES TO GOVERNMENT (US$)
K	C	SOIL ERODIBILITY FACTOR
LOSSR	A	EFFECTIVE SOIL LOSS RATE (tons/ha/yr)
L	C	LENGTH OF THE SLOPE (m)
LSTORE	L	LAND DESTROYED DUE TO WATER STORAGE IN DAMS (ha)
MATUR	L	MATURED FALLOW LAND – SECONDARY FOREST (ha)
MATURN	C	INITIAL MATURED FALLOW LAND (ha)
MNOUT	A	MINED OUT AREA NOT FLOODED (ha)
MINE	R	RATE OF DRY MINING (ha/yr)
NMINEF	C	NORMAL DRY MINING FRACTION (frac./yr)
NAGRF	C	NORMAL AGRIC. LAND USE FRACTION
NREHAB	C	REHABILITATION RATE IMPOSED BY GOVERNMENT (fraction/yr)
NARTLF	C	NORMAL ARTIFICIAL LAKE FORMATION FRACTION. (fraction/yr)
NEXCVF	C	NORMAN EXCAVATION FRACTION (fraction/yr)
NSTORF	C	NORMAL FRACTION OF LAND DESTROYED THROUGH WATER STORAGE (fraction/yr)
NROADF	C	NORMAL FRACTION OF ROADS CONSTRUCTED PER YEAR (fraction/yr)
NBORF	C	NORMAL EARTH BORROWING RATE (frac./yr)
PAT	C	PRODUCTION ADJUSTMENT TIME (hrs)
PVEG	C	POTENTIAL VEGETATED AREA (ha)
PRICE	C	World Market Price For Mineral (US$/unit)
POAGR	A	POTENTIAL AGRIC. LAND (ha)

POPD	C	POPULATION DENSITY (persons/ha)
PRO	L	PRODUCED MINERAL (unit)
RECOV	A	OVERHEADS AND PROFITS (US$)
RECOST	A	REHABILITATION COSTS (US$)
R	C	RAINFALL EROSION INDEX
RCOST	R	RATE OF REHABILITATION COST INCURMENT (US/yr)
REHAB	R	REHABILITATION RATE (ha/yr)
RAGPRO	R	RATE OF AGRICULTURAL PRODUCTION (US$/yr)
RELAND	R	REHABILITATED LAND (ha)
RECOV	A	MINING COMPANY'S OVERHEADS AND PROFITS (US$)
REMAT	R	RATE OF MATURITY OF THE REHABILITATED AREA (ha/yr)
ROADL	L	SURFACE AREA OF ROADS CONSTRUCTED (ha)
RSUCC	C	SUCCESS RATE (FRACTION)
RSLOSS	R	TOTAL RATE OF SOIL LOSS (tons/yr)
RPOP	R	RATE OF POPULATION DISPLACEMENT (persons/yr)
RPRO	R	RATE OF MINERAL PRODUCTION ((tons/yr)
RSTORE	R	RATE OF WATER STORAGE m3/yr)
SL	A	SLOPE-LENGTH FACTOR
SAND	A	AREA OF SAND TAILINGS (ha)
SF	A	FRACTION OF ARTIFICIAL LAKE THAT IS SAND TAILINGS
SLOSS	L	TOTAL SOIL LOSS (TONS)
ST	C	STORAGE ADJUSTMENT TIME (yrs)
STORE	L	STORAGE VOLUME (m3)
TSS	C	TIME TAKEN FOR THE REHABILITATED AREAS TO MATURE
TO	A	FULLY VEGETATED AREA (yrs)
TAX	C	TAX AND ROYALTIES (fraction)
TEAGRV	T	TABLE FOR THE EFFECT OF POTENTIAL VEGETATED AREA ON AGRICULTURE
TEPVAR	T	TABLE FOR THE EFFECT OF VEGETATED LAND ON ARTIFICIAL LAKES
TERVEG	T	TABLE FOR THE EFFECT OF ROAD CONSTRUCTION ON VEGETATION
TEHAB	T	TABLE FOR THE EFFECT OF MINE OUT AREA ON REHABILITATION
TERO	T	TABLE FOR THE EFFECT OF EROSION ON REHABILITATION
TESTOV	T	TABLE FOR THE EFFECT OF WATER STORAGE ON VEGETATION
TEXVEG	T	TABLE FOR THE EFFECT OF POTENTIAL VEGETATION ON EXCAVATION
TLOSSR	R	TOLERABLE SOIL LOSS RATE (tons/yr)
TIME	N	BEGINNING OF SIMULATION
TOVOL	C	TOTAL MAXIMUM VOLUME OF WATER IN THE MINING AREA (m3/yr)
TSL	T	TABLE VARIABLE FOR SLOPE-LENGTH FACTOR
UEMP	A	UNEMPLOYED POPULATION (persons)
VEGET	L	RE-VEGETATED AREAS THAT ACTUALLY MATURES (ha)
VEARTH	A	VOLUME OF EARTH BORROWED (cubic meter)
VOLS	A	VOLUME TO STORED (m3)
VRTL	L	AVAILABLE ARTIFICIAL LAKES (ha)

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