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MODELLING AND SIMULATION OF ENVIRONMENTAL IMPACTS OF A COALFIELD: SYSTEM DYNAMICS APPROACH

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ABSTRACT

This article presents a system dynamics analysis of environmental impacts of a coalfield. In this article, a system dynamics model is developed for environmental impact analysis of a coalfield. The model is simulated for a period of 20 years assuming that existing conditions will prevail in the future. This is the Basic Scenario. Alternative pollution control measures are tested for their viability by generating alternative scenarios and comparing them with the Basic Scenario.

INTRODUCTION

In this article, a system dynamics model is built to capture the interactions among the activities and impacts of coal mining and to test the viability of alternative pollution control policies. This study has been conducted in an area which includes a semi-urban town and its surroundings, with a total population of more than 50,000. In this area, there are nine collieries, four opencast mines, and twenty underground pits. The total coal production from this area is about 2,000 tons per annum. There are no coke ovens or washeries within this area. The area under study covers all the collieries lying within this area. The area under study covers all the collieries lying within 10 km radius of the semi-urban town. Environmental impacts of a coalfield were identified earlier using an eclectic approach employing expert opinion, content analysis,

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the "Strategic Impact Assumptions-Identification Method" (SIAM), and opinion surveys [1, 2]. An "interpretive structural model" of the identified impacts was also developed, as shown in Figure 1 [3]. The causal structure shown in Figure 1 is used as the basis to develop the model. The model is later used to generate the dynamic behavior and to test the effect of policy alternatives.

CAUSAL STRUCTURE OF THE MODEL

Extraction and transportation of coal are the two main activities of coal mining. Both these activities generate dust in high quantities and discharge it to the atmosphere, thus deteriorating the quality of surrounding air. Water quality is also adversely affected by mine drainage. The pollution thus created poses hazards to human health, reduces crop yields, and deteriorates cattle health.

Another source of air pollution is the combustion of coal as a domestic fuel. The combustion of coal releases pollutants in the form of particulate matter, sulphur dioxide, nitrogen oxides, carbon monoxide, and hydrocarbons. Carbon monoxide is generated during the incomplete combustion of both coal and fuel oil. Butler reports that the concentration of carbon monoxide in the troposphere is not considerable and remains sensibly constant though emission rates are very high even from natural sources [4]. Bose [5], Ghosh [6], and Sinha [7], in extensive and experimental studies on pollution in coalfields, have reported the presence of suspended particulate matter, sulphur dioxide, and nitrogen oxides only. Therefore, the model presented in this article considers only these three emissions.

The weather conditions also greatly affect the pollution levels in the atmosphere. Ghosh found correlations between the weather conditions and the pollutant levels [6]. These correlations have been used in the model.

Production of coal produces high quantities of drain water. The drain water is pumped out to the surface and most of it is led to a nearby stream. The inhabitants of the area use the stream and the underground wells as the main sources of drinking water. Both these sources are polluted by the mine drainage. Some people even use the drained out water directly before it reaches a stream. This is very hazardous to human health as this untreated water contains suspended solids and dissolved solids, and is of high pH value. The water quality is modelled here as an index that is a function of pH bi-chemical oxygen demand (BOD), chemical oxygen demand (COD), and levels of dissolved oxygen and dissolved solids.

The air and water pollution cause health hazards, reducing the quality of life. Quality of life is, of course, improved by the beneficial effects of coal mining, prominent among them being the generation of employment, development of education and other infrastructural facilities, and increase in local business.

The opportunity for employment attracts people from neighboring areas and increases the population of the area.

Coalfields are known in India for notoriety and crime. Unfortunately, no systematic study has been made of this social impact of coal mining. In the absence

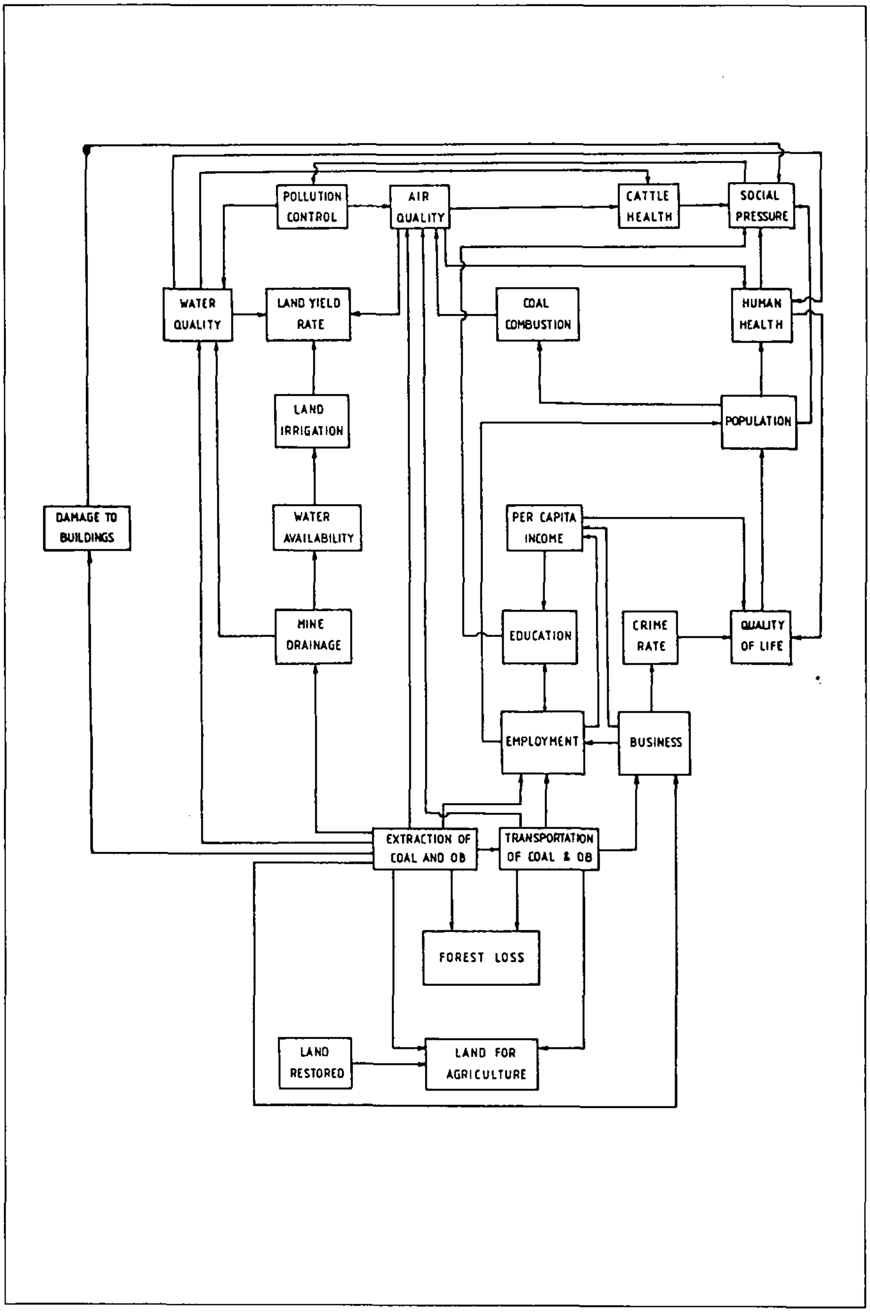

Figure 1. Interpretive structural model of a coalfield.

of sufficient information, it was decided not to consider this aspect in the present study.

DESCRIPTION OF THE SYSTEM DYNAMICS MODEL

Figures 2 through 5 depict the sector-wise flow diagrams of the system dynamics model. The equations are written in Fortran 77 and the model is simulated using DYMOSIM [8]. Parameter values were selected on the basis of reports/publications by various authors. The values and the sources from which they were obtained are given in Tables 1 through 3.

Coal is produced in the area both by underground mining and opencast mining methods. As the rate of emission of dust is different for these methods, the coal production with these methods is modelled separately. The company wishes to double the production of coal by the year 2000 [9]. This is possible with an annual growth rate of about 5 percent in the coal production.

The dust emitted during coal extraction, handling, and combustion results in an increased level of suspended particulate matter. Atmospheric conditions such as temperature, wind speed, and relative humidity also affect the time of residence of suspended particulate matter and other pollutants in the air. The particulates settle down after a time lag and are deposited on the surface of land and water.

A geographic area of 20 kms. × 20 kms. was considered for this study. Taking an air height of 100 meters, the total volume (TVA) was taken as 40,000 × 10^6 m^3. The rationale for taking 100 meter height of air was that the mean level for dust measurement is often taken as 50 meters [5].

Dust emission during underground mining differs from that during opencast mining, whereas dust emission during handling, i.e., loading, unloading, and transportation, is the same for both types of mining as well as for handling overburden. In opencast mining, the upper layer of the earth, i.e., overburden, has to be removed. This causes emission of more dust.

In the area understudy, coal is a popular domestic fuel. Therefore, the emissions are of the non-point source type. Use of soft coke, instead of raw coal, as domestic fuel greatly reduces the combustion emissions in the area. Quantity of soft coke used is expressed as a function of the coal quantity used in the area.

Population in the area is taken here as an exogenous variable with a constant net growth rate that also includes immigration from other areas.

Several vehicles, such as trucks and trekkers, are used by collieries, mainly for handling coal. The rate of fuel oil used per ton of coal production is estimated from the data available in collieries.

Bose has made an empirical study of pollution and weather conditions in this area, and has obtained a regression equation which expresses the suspended particulate matter as a linear function of weather conditions, temperature, wind speed, and relative humidity [5]. Temperature, wind speed, and relative humidity vary seasonally. To represent the seasons, a variable time duration is defined.

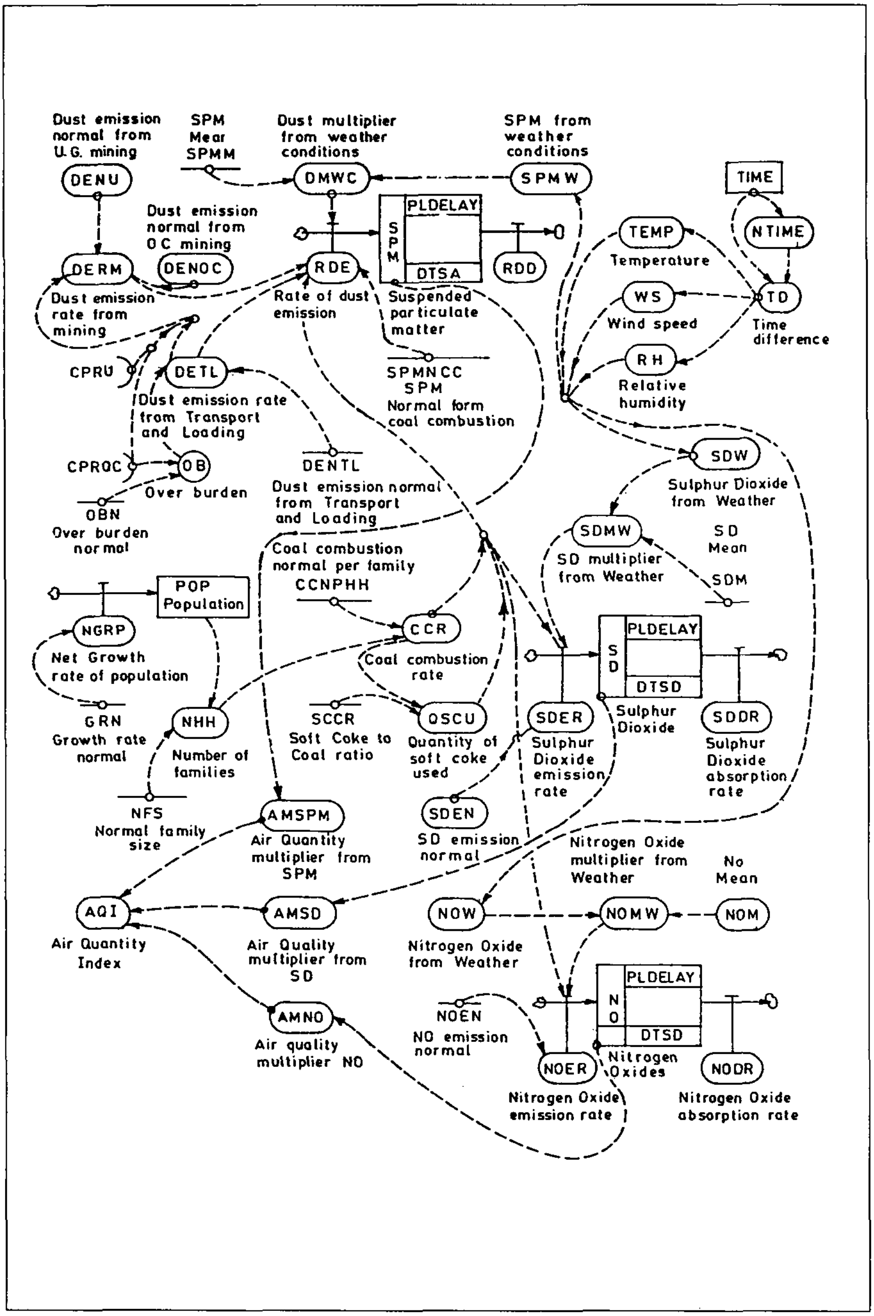

Figure 2. Air pollution in coal mining.

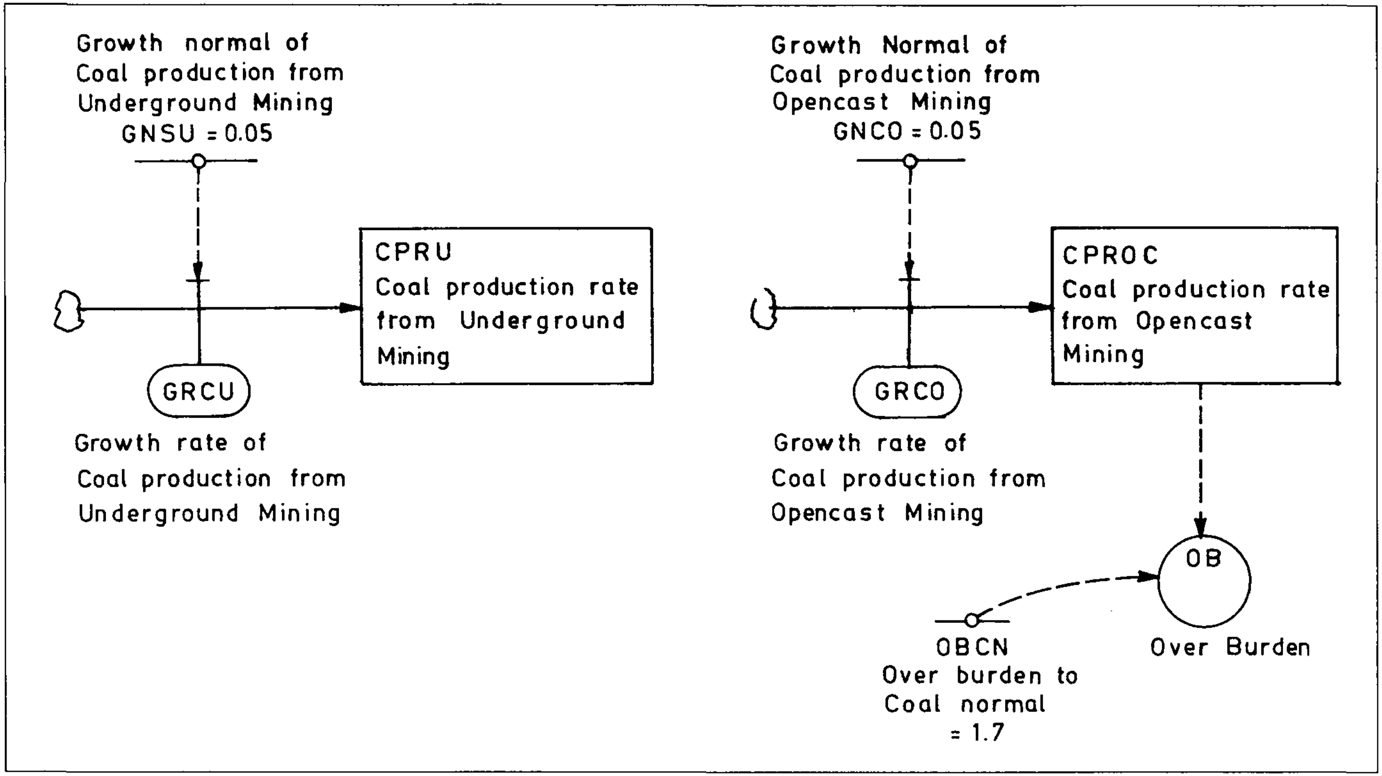

Figure 3. Coal production.

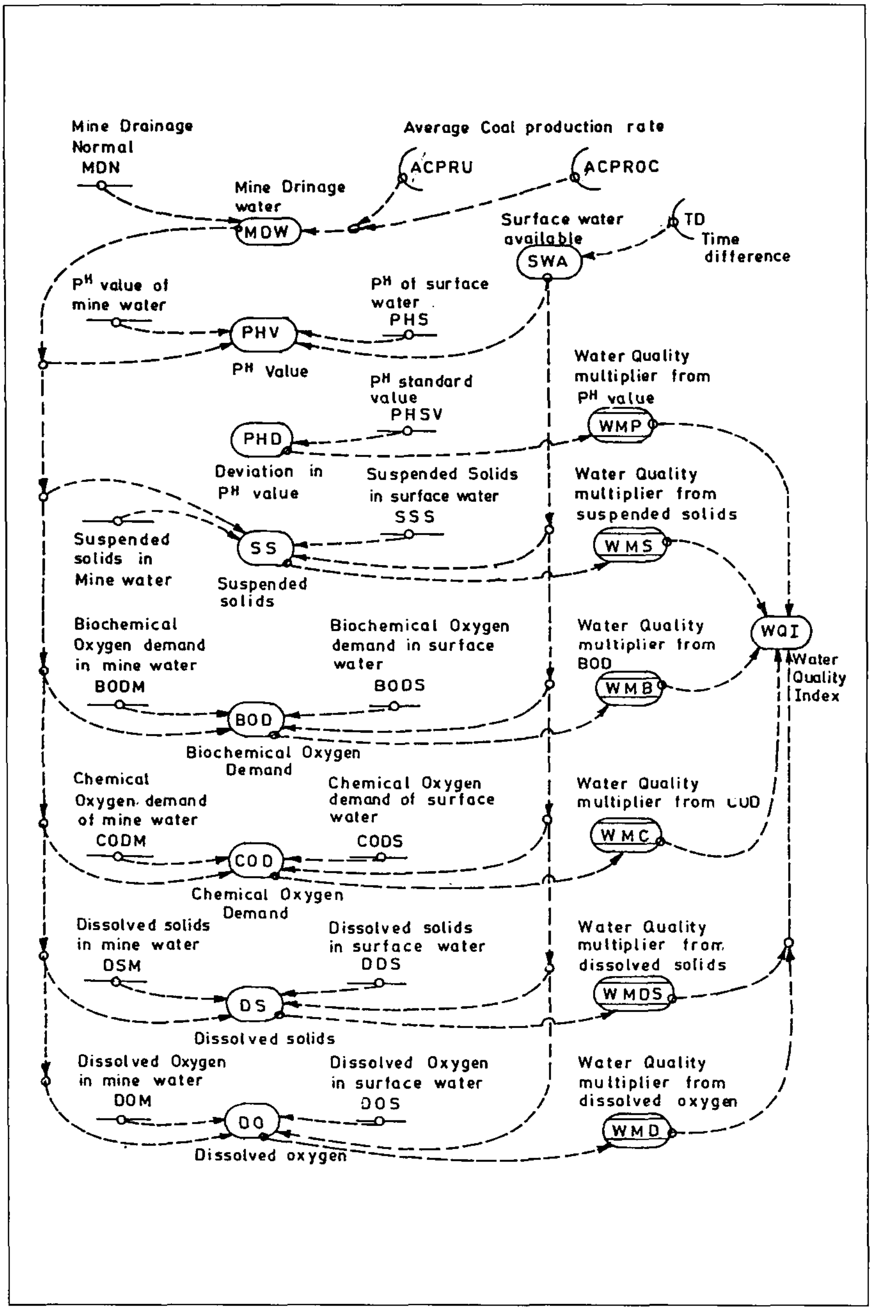

Figure 4. Water pollution in coal mine.

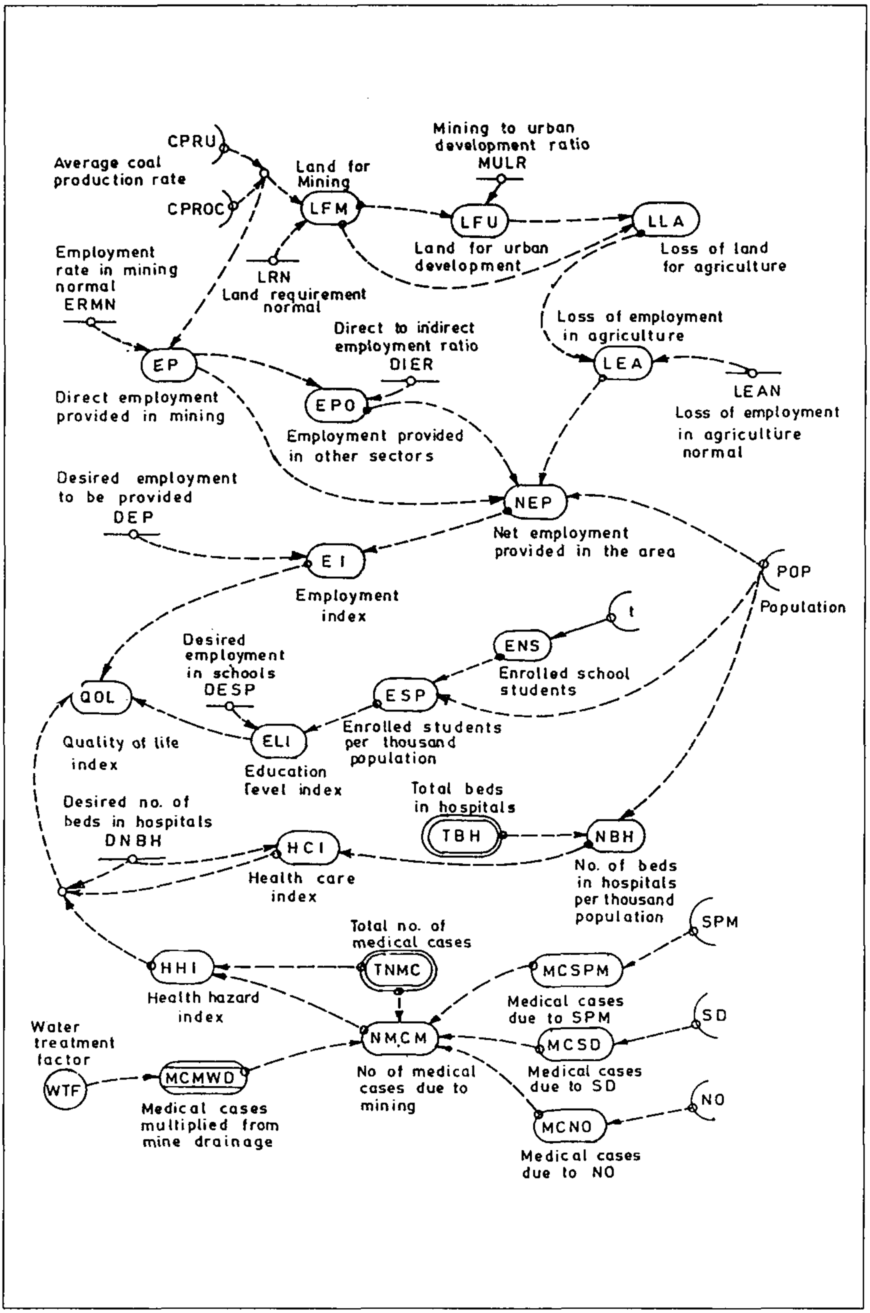

Figure 5. Quality of life in a coalfield.

Table 1. Parameter Values Based on Past Studies

Definition	Symbol	Value	Source
Growth normal of coal production from UG mines	GNC4	0.05	[9]
Growth normal of coal production from OC mines	GNCOC	0.05	[9]
Delay time for SPM	DTTA	1/60	[10]
Dust emission normal from open cast mines	DENOC	100	[11]
Dust emission normal from transport and loading	DENTL	90	[12]
Dust emission normal from underground mines	DENU	30	[11]
Overburden normal	OBN	1.7:1	[6]
Suspended particulates normal from coal combustion	SPMNCC	31905.5	[6]
Particulate emission normal from fuel oil consumption	PENFO	10.0	[6]
Mean value of SPM	SPMM	492.7	[5]
Sulphur dioxide emission normal from fuel oil combustion	SDENF	19940.9	[6]
Sulphur dioxide mean	SDM	72.5	[6]
Nitrogen oxides emission normal	NOEN	30.74	[5]
Nitrogen oxides emission normal from fuel oil	NOENF	3988.18	[6]
Nitrogen oxides mean	NOM	30.0	[5]
pH standard value	PHSV	39.13	[13]
pH mean value	PHM	8.1	[13]
Suspended soilds mean	SSM	796.1	[13]
Suspended soilds standard value	SSS	261.8	[13]
Biochemical oxygen demand mean value	BODM	6.76	[13]
Biochemical oxygen demand standard value	BODS	0.82	[13]
Chemical oxygen demand mean value	CODM	37.50	[13]
Chemical oxygen demand standard value	CODS	4.51	[13]
Dissolved soilds mean value	DSM	801.5	[13]
Dissolved solids standard value	DSS	472.1	[13]
Dissolved oxygen mean value	DOM	5.82	[13]
Dissolved oxygen standard value	DOS	5.9	[13]
Dust generation ratio from drilling & undercutting to blasting	DGRDB	0.4	[14]
Dust suppression from water spray	DSWS	0.75	[15]
Dust reduction from dust arrestor in drilling	DRDA	0.975	[15]
Dust reduction from water ampoule stemming	DRWAS	0.37	[15]
Dust reduction from water and agent mixture	DRWAM	0.86	[15]
Dust multiple from transport and loading of watering	DMTLW	0.9	[15]
Direct to indirect employment ratio	DIER	2.0	[16]

Table 2. Parameter Values Based on Collected Data

Definition	Symbol	Value
Total volume of the area	TVA	40000.0×10^6
Coal combustion normal per household	CCNPH	4.0
Growth ratio normal	GRN	0.02
Ratio of fuel oil to coal production	RECP	0.2
SPM emission normal from soft coke	SPMNSC	5000.0
SD emission normal from soft coke	SDENSC	100.0
NO emission normal from soft coke	NOENSC	25.0
Mine drainage normal	MDN	72.653
Employment rate from mining normal	ERMN	0.00546
Mining to urban land ratio	MULR	0.2
Land required normal	LRN	0.0005
Total beds in hospitals	TBH	50.0

Table 3. Parameter Values Based on Assumed Data

Definition	Symbol	Value
Soft coke to coal use ratio	SCCR	1.0
Normal family size	NFS	5.0
Air Quality Index Maximum	AQIM	1.0
Medical cases multiplier from water quality	MCMWD	1.5
Desired employment level	DEP	500.0
Loss of employment in agriculture normal	LEAN	2.0
Desired number of beds in hospital	DNBH	5.0
Desired enrollment of studends	DESP	500.0

The sulphur dioxide and nitrogen oxides emissions are also modelled as a function of weather conditions in a manner similar to that for particulates, adopting the regression equations in [5].

The increased presence of pollutants in the air decreases the quality of air, which is represented by the air quality index. The air quality index is taken here to vary between 0 and 1. Canter and Hill provide the relationships between pollutants and air quality [17]. These relationships are incorporated in the system dynamics model presented here.

Water quality deteriorates due to the changes in the pH value, dissolved solids, biochemical oxygen demand, chemical oxygen demand, and level of suspended

Table 4. Threshold Limits of Water Pollutants

Pollutant	Threshold Value
pH	5.5 to 9.0
Dissolved solids	< 500 mg/l
B.O.D.	< 1.0 mg/l
C.O.D.	< 5.0 mg/l
DO	> 7.0 mg/l
Suspended solids	< 15 mg/l

Source: [13].

solids. Health studies reveal that people residing in mining areas suffer from various water-borne diseases like cholera, typhoid, dysentery, jaundice, and gastroenteritis, in addition to skin diseases and diseases due to hook worms [11, 16]. In order to improve the water quality index, the amount of suspended solids can be reduced by passing the drained-out water through settling tanks. Water should also be treated by sand filtration and the addition of lime or soda, for example. The threshold limits are shown in Table 4.

The mine drainage directly joins the surface water. A weighted average of water pollutants is considered here to determine their levels. Surface water available depends on the season. The effect of suspended solids, dissolved solids, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are estimated using a weighted average.

Based on personal interviews the authors conducted with managers of coal mines and the environmental scientists, and on research reports [7, 18], the following pollution control measures are found to be feasible in the coalfield:

1. Spray water on the faces to prevent dust emission;
2. Spray water and wetting agent mixture to prevent dust emission;
3. Use dust arrestor during drilling;
4. Stem with water ampoule;
5. Provide soft coke for domestic use;
6. Pass the drained-out water through settling tanks; and
7. Treat mine drainage before discharging it to the streams.

These pollution control measures are tested in the model for their effectiveness. Dust emission can be suppressed by spraying water on to the face before blasting. Based on his South African studies, Funke [19] indicates that the quality of water used for dust suppression in underground mining equals 39 l/ton and the quantity of water used for dust suppression in opencast mines or surface mines equals 11 l/ton. However, no such data are available for India. But Ghosh *et al.* indicate that if sufficient water is sprayed, the dust emission during drilling can be reduced up to 75 percent, whereas if water wetting agent mixture is sprayed the reduction will rise to 86 percent during drilling operations [13]. Nair and Sinha experimented with a dust arrestor and found that the dust emission can be reduced during drilling operations by up to 97.5 percent [11]. Water ampoule stemming will reduce dust emission by up to 37 percent during blasting. However, this reduction depends on the volume of the ampoule.

Katiyar *et al.* estimate that the dust generated during drilling is about 40 percent of that generated during blasting [14]. Therefore, pollution control measures for these operations are dealt with separately.

Dust arrestors can be used in drilling blast holes. No dust arrestor apparatus can be used while blasting. However, using water ampoule stemming close holes filled with blasting material will reduce dust emissions. The dust suppression can be greater if water mixed with a wetting agent is sprayed instead of water only.

Coal combustion in this area is mainly due to its use as domestic fuel. Therefore, it is difficult to control the emissions unless the company supplies soft coke, instead of raw coal, to the market (particularly to the employees of the mining company). This factor is already incorporated in the model. It only depends on how far the raw coal is replaced by soft coke.

Dust emission during loading, unloading, and transportation of coal can also be reduced by spraying water and wetting agents such as foam.

The dust multiplier during transport and loading from water spraying (DMTLW) has been taken constant at 0.9.

Water can be purified by water settlement tanks and other forms of treatment. Figure 6 shows a typical purification system of mine water (taken from [13]). It is estimated that about 80 percent of the solids can be removed through settling [20]. Ghosh *et al.* suggested the following doses for treatment of mine water to bring the mine water pollutants to the tolerable limits [13]:

Lime dose	0.74 - 1.65 (gms of CaO/l)
Soda-ash	0.12 - 0.22 (gms of Na_2CO_3/l)
Chlorine demand	10.20 - 14.74 (mg/l)

No experimental data is available on the relationship between the quantity of doses and the resultant reduction in water pollution. Therefore, for the sake of this model, water treatment is modelled as a switch function which takes a value of either zero or one, zero indicating the untreated draining and one indicating that the drainage is treated (in which case the water characteristics take the threshold values).

The high level of pollutants in the atmosphere causes several diseases depending on the intensity (or level) of the pollutant. As the pollutant levels increase, the number of medical cases due to mining activities increases and thus increases the health hazard index. Ghosh has derived regression equations for illness due to pollution which were adopted in this model [6].

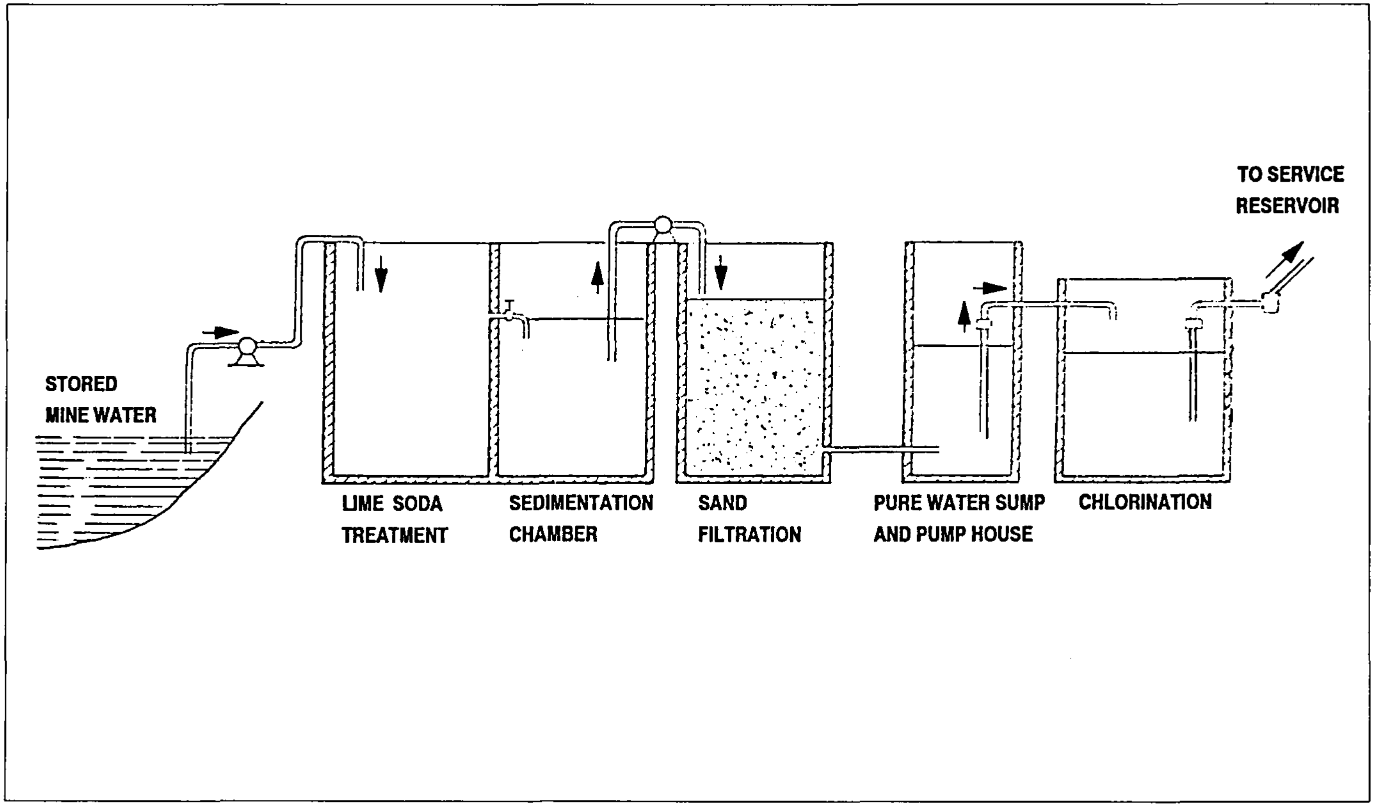

Figure 6. Schematic diagram of mine waste water treatment scheme (source: S. K. Ghosh, et al, 1977).

Hazards (in terms of the health index) and benefits (in terms of medical care, employment, and other facilities) are considered here to determine the quality of life. The health hazard index is given more weight than benefits. Quality of life index (QOL) is determined by a weighted average of benefits and hazards. Employment in mines, and employment in other industries and service sectors dependent on mines, are considered here along with loss of employment in agriculture.

Employment in mining is assumed to vary directly with production of coal. The production of coal varies every year but the recruitment may not exactly match this change. Therefore, the ratio of employed persons to ton of coal produced was determined as an average over five years. Misra estimated a ratio of 2.0 for employment in other industries and service sectors to direct employment in mines [16].

The agricultural land acquired for mining displaces the people dependent on that land. They become unemployed but some of them may be employed in mining or in other industries.

There is an enhancement of educational facilities in the area due to mining activity, though not up to the desired level. There are about six high schools, twenty-seven middle schools, and eighty primary schools in the area. There is also one degree-granting college. The education level index is determined on the basis of enrollment of students each year.

Health care is provided by the government to the general public. The mining company has also established hospitals for employees. The total number of beds in hospitals is taken into consideration in the health care index (HCI). It is assumed here that by 1995 the number of beds will increase by 50 percent.

A detailed discussion of the equations is made in Vizayakumar [1].

RESULTS AND DISCUSSION

The Base Run and Model Validation

The model is run for a period of twenty years with 1982 as the base year. This base run represents the present situation where no pollution control measures are undertaken by the mining industry. The yearly variations of the levels of suspended particulate matter (SPM), sulphur dioxide (SD), nitrogen oxides (NO), and quality of life (QOL) are shown in Figures 7, 8, 9, and 10, respectively. These figures indicate seasonal (yearly) variations of the pollution levels and of the quality of life. Each of these variables is also associated with a secular positive trend. The seasonal variations of the pollutants is due to the seasonal changes in temperature, wind speed, and relative humidity in the atmosphere, whereas the positive secular trend results from the increased coal production and the resultant pollutant emissions. Since quality of life is inversely proportional to the pollutant levels in the atmosphere, the quality of life value is low when the pollutant values

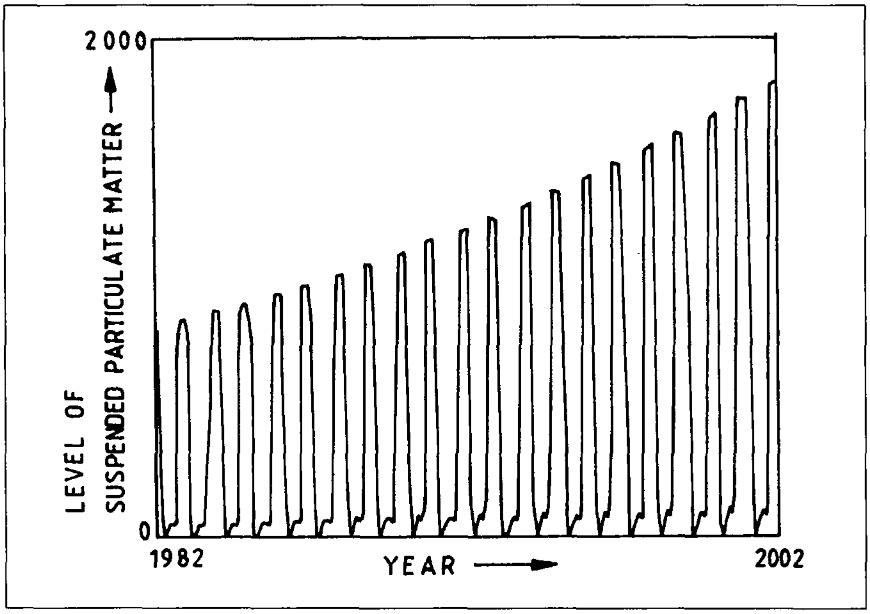

Figure 7. Seasonal variations of suspended particulate matter.

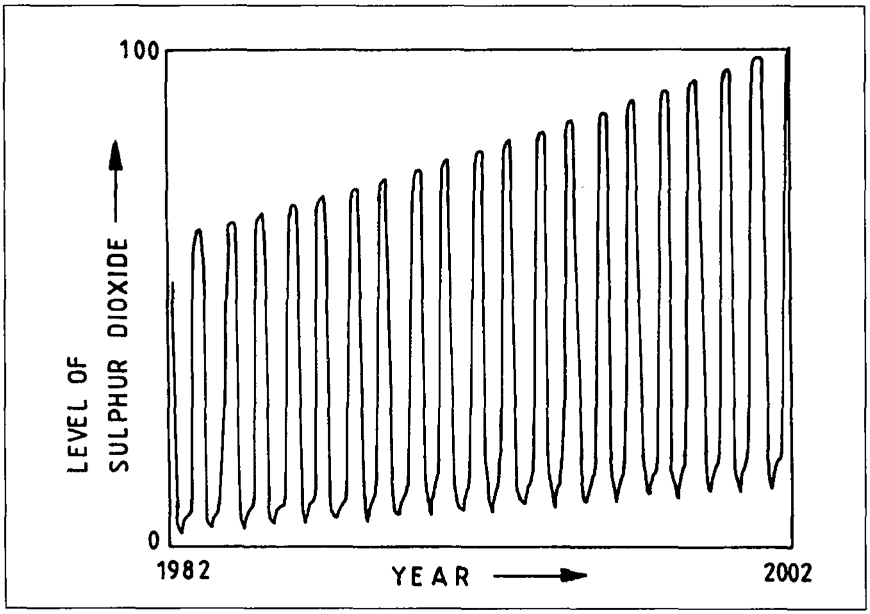

Figure 8. Seasonal variations of sulphur dioxide.

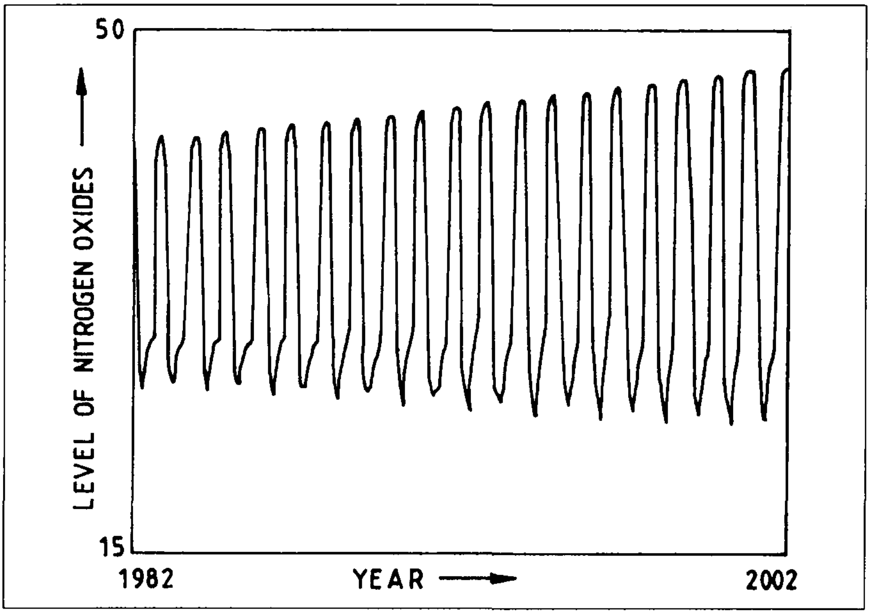

Figure 9. Seasonal variations of nitrogen oxides.

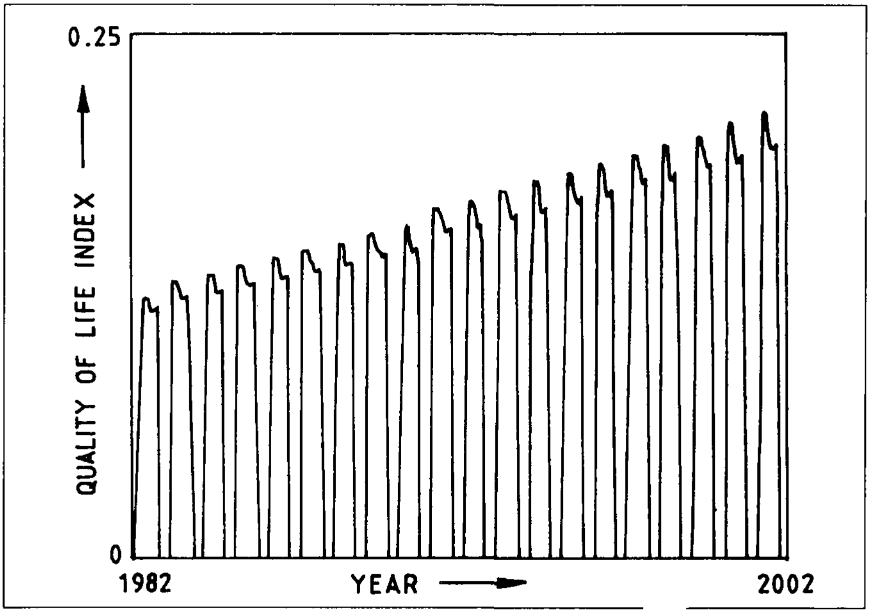

Figure 10. Seasonal variations in quality of life.

are high and vice-versa. However, instead of showing a negative secular trend, quality of life also shows a positive trend. Such a trend has resulted from the benefits of coal mining discussed earlier.

Validation has been a very complex issue in system dynamics studies. The current investigation is based on a thorough review of pertinent literature, an opinion survey among the concerned individuals and organizations to select the variables for the study, and to select their interrelationships and parameter values.

Insight was also gained from studies, reported elsewhere, which experimented on an ideal structure of a similar problem and which helped in building the structure of the present system dynamics model [1, 21]. This has highly enhanced the confidence of the authors in the model structure.

Unfortunately, data on pollution levels in the atmosphere is not available on a sufficiently long period of time to make meaningful comparisons with the model-generated data. The only way to validate the model behavior is by means of plausibility and consistency checks. While often subjective, such checks have formed the foundation of validation studies of many system dynamics models. As discussed in the beginning of this section, the generated behavior of the model seems to be highly plausible.

Based on the above arguments, it is concluded that the model under consideration is a good representation of the reality and provides useful guidance in testing various pollution control policies and in developing various alternative scenarios.

Testing Pollution Control Measures

The various feasible pollution control measures are listed under description of the model. The model is run with them individually and in combination.

To assess the policy of spraying the mine face with water before drilling, the value of the parameter, dust reduction multiplier from quality of water sprayed was expressed as a table function in lieu of its original value of one. Dust reduction multiplier from dust arrestor, dust reduction multiplier from water ampoule stemming, and dust reduction multiplier from water and wet agent mixture are also expressed as table functions.

The dust reduction multiplier from water spray during transport and loading was taken as 0.9.

Emission of pollutants from domestic combustion of coal can be minimized if soft coke is used instead of raw coal. Here, the extent of use of soft coke is expressed as a fraction of raw coal used. As a pollution control measure, the ratio of soft coke to raw coal used was taken to be one.

In addition, water treatment was also included as a pollution control measure as noted.

Comparing the Test Results

The model is tested with six pure policies and with six combinations of these policies as indicated below:

1. The base run;
2. Spray the face with water before drilling;
3. Use dust arrestor during drilling;
4. Use water-ampoule stemming;
5. Spray the face with water-wetting agent mixture;
6. Spray water during loading and transportation;
7. Use soft coke instead of raw coal as domestic fuel;
8. Spray the face with water before drilling and use dust arrestor during drilling;
9. Use water-ampoule stemming and dust arrestor during drilling;
10. Spray the face with water before drilling, use dust arrestor during drilling, and use water-ampoule stemming;
11. Spray the face with water-wetting agent mixture before drilling, use dust arrestor during drilling, and use water-ampoule stemming;
12. Spray the face with water before drilling, use dust arrestor during drilling, use water-ampoule stemming, spray water during loading and transportation, use soft coke instead of raw coal as domestic fuel, and treat mine drainage water; and
13. Spray the face with water-wetting agent mixture before drilling, use dust arrestor during drilling, use water-ampoule stemming, spray water during loading and transportation, use soft coke instead of raw coal as domestic fuel, and treat mine drainage water.

The model behavior for these policies also varies seasonally. For the sake of comparison, however, only the peak values of the quality of life index during the years are plotted in Figures 11 and 12. The numbers in the figures correspond to the numbers of the policies listed above.

The general trend of the quality of life index is positive for all the policies. The kink in the curves appearing during 1992 is a result of an increased number of beds in hospitals during that year.

In Figure 11, the lowest curve represents the base run result. Among the six pure policy results plotted, the policy of water spraying during loading and transportation (policy 6) shows the maximum quality of life throughout the run. The loading and transportation includes loading the tubs/tippers in the mines, transportation of coal to the surface, unloading at the surface, loading the trucks/tippers at the surface, transportation to the coal yard, unloading at coat yard, and loading the trucks/wagons to transport it to the user. Controlling dust emissions in these operations has shown better results compared to controlling dust emissions during

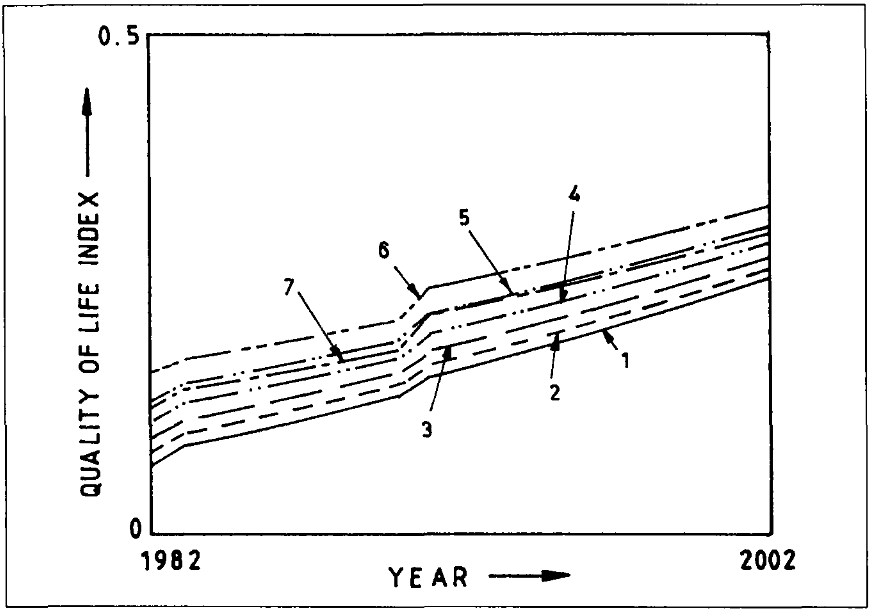

Figure 11. Behavior of base run and pure policies.

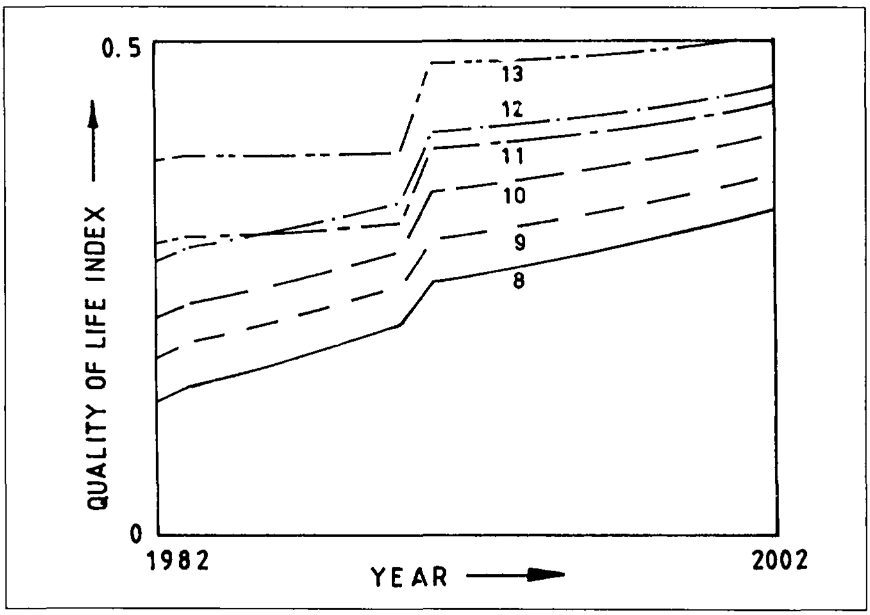

Figure 12. Behavior of policies in various combinations.

drilling or blasting. This indicates the higher rate of dust emissions during transportation and loading than during drilling or blasting.

However, combinations of these pure policies gave better results as is evident from Figure 12. Among the six combinations plotted in this figure, policy 13—combining the pollution control methods of spraying the face with water and wetting agent mixture before drilling, using dust arrestors during drilling, using water-ampoule stemming, spraying water during loading and transportation, using soft coke instead of raw coal as a domestic fuel, and treating mine drainage water —gives the highest value of the quality of life index.

This result indicates that pollution must be controlled comprehensively, at all places of coal mining activity rather than at a few key points, for the most effective control of pollution.

CONCLUSIONS

This article shows that system dynamics modelling is an effective means of synthesizing knowledge in various fields in environmental impact analysis, and of designing viable policies for effective pollution control. The results show that controls have to be applied at all phases of coal mining – drilling, blasting, undercutting, and handling – rather than at a few points.

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