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A COMPUTER MODEL TO DETERMINE PATHOGEN TRANSPORT THROUGH ENVIRONMENTAL PATHWAYS

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A computer program was developed to model the transport of pathogens through environmental pathways as a result of the application of treated sewage sludge. Specific sludge application cases included the use of treated sludge as a cropland fertilizer, as a soil conditioner by the general public, and as a feed supplement for ruminant animals.

A comprehensive review of relevant literature sources led to the definition of environmental pathways from the point of sludge production to points of potential human contact. Along these pathways, discrete points were designated where it was desired to compute pathogen populations. In this model, each point in these pathways is treated as a mathematical state. The transfer of pathogens between these states is described by a set of ordinary differential equations derived using conservation principles, environmental parameters, and relationships developed from data obtained in the literature review. These equations are then integrated to determine the pathogen populations at each state.

This computerized model has been used in several applications and has helped to assess the risks associated with certain sludge utilization and treatment practices.

1. INTRODUCTION

During the 1970's clean air and water legislation imposed constraints on sewage treatment and disposal. These constraints led to increased amounts of sewage sludge which municipalities had to dispose of, but reduced the number of disposal alternatives available to municipal officials. Legislation also encouraged waste management procedures which emphasized the recycling and beneficial use of waste materials.

The use of municipal sewage sludge as a fertilizer and soil conditioner has been practiced in the United States for many years. For example, the city of Albuquerque has spread dried, anaerobically digested sludge from its secondary treatment plant on city parks for over forty years. The new emphasis encouraging such use, however, brought questions concerning the consequences and risks imposed by the beneficial use of sewage sludge which were not easy to answer. While no record of disease attributable to the use of sewage sludge from secondary treatment plants could be found in the literature, sewage sludge was known to contain viable pathogenic organisms. Further, municipal sewage sludge was known to contain varying levels of toxic chemicals including heavy metals.

It was the responsibility of the Environmental Protection Agency (EPA) to evaluate the risks imposed by the use of sewage sludge and to develop regulations governing sludge treatment and use. Environmental modeling techniques had proved to be effective in bringing order to the study of water pollution problems. Similar modeling techniques seemed to be applicable to the problem of evaluating sludge use risks. The agency decided to develop a set of companion models, one addressing the pathogen population of sludge and the other, the heavy metal content.

At the same time that the EPA was considering the best way to evaluate the possible risks imposed by sludge use, the Department of Energy through contracts with Sandia National Laboratories (SNL) was developing an innovative sludge treatment scheme. One mission of the Applied Biology and Isotope Utilization Division of SNL was the development of cost-beneficial uses for existing and future supplies of radioactive isotopes. Beginning in 1974, the Waste Resources Utilization Program developed methods, using cesium-137, to reduce the pathogen content of municipal sludge and began experimenting with the use of irradiated sludge as an animal feed supplement. As a result of this effort, a prototype sewage sludge irradiator (the Sandia Irradiator for Dried Sewage Solids) was designed and built. SNL was then tasked with transferring sludge irradiation technology to the public sector. Discussions with municipal officials revealed their concerns with both the placement of a gamma radiation source within their cities and with the risks in using

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sludge. Like the EPA, SNL recognized the ability of an environmental model to address the latter concern but the aims of the two agencies were slightly different.

Well aware of the broad scope of a modeling effort designed to evaluate the risks imposed by using sludge and the lack of data available in many relevant areas, the EPA wanted a flexible model that would identify research needs and accommodate new information as it was developed. The ability to document any conclusions reached by the modeling effort and trace conclusions back to hard data points or estimates was of paramount importance. In 1978, the EPA was in the process of promulgating regulations specifying acceptable sludge treatment processes as a function of sludge use and decided a modeling effort would support decisions being made using less quantitative methods. SNL was looking for a marketing tool which would be flexible enough to accommodate many sludge treatment and use scenarios but would also be useable by municipal officials who had little knowledge of biology, civil engineering, or computer science. Emphasis was to be placed on demonstrating the ability of irradiation to reduce risks and on a user-friendly format. Both agencies recognized that no well defined information base existed from which to develop a model. What data was available would be found scattered throughout civil engineering, biological, medical, veterinary, soils science, hydrological, and risk assessment literature.

In the fall of 1978, SNL subcontracted to The BDM Corporation (BDM) the task of developing a Sewage Sludge Pathogen Transport Model which would meet the objectives of both agencies. The model was to be flexible, changeable, easy to use, and accurate within the constraints of available data. The effort was jointly funded by the Department of Energy and the EPA. The differing objectives of these funding agencies led occasionally to conflicting demands upon the BDM modeling team*.

BDM began by performing a literature search for the purpose of accumulating an information base. The information base was to include available relevant data regarding pathogen occurrence in sewage, pathogen survival during common sewage treatment processes, and pathogen movement through the environment as a result of sludge application. Over 1000 titles were reviewed and included in the information base. Because the information base was so extensive, a computerized library storage and retrieval system was designed to classify and store abstracts of reviewed literature. The computer interface included an interactive "fill in the blanks" library review form for entering data and an interactive query language for extracting data. The library review form was filled in by the engineering and biological researchers as literature was identified and read. This form provided the means for the classification of articles by author, title, source, and subject matter using a list of descriptive keywords. In addition, the form provided a format for entering abstracts into the computerized information base.

The list of keywords used to classify each abstract by subject matter was the basis for retrieving information for use in transport model development. The keywords provided a convenient communication link between the model researchers and the information base. A list of 82 valid key words were used to link the articles together. Other attributes used to link the articles were author name and source (e.g., Journal of the Water Pollution Control Federation). Articles could be extracted from the information base by any combination of these attribute links. Additionally, the researcher could directly access an article by using the unique title attribute.

The information base was then used to develop the transport model. The model predicts the numbers of specific pathogens that would be found in sewage sludge at various points during sludge treatment and application. Once the pathogen population has been estimated for various points in the environment, the model has the capability of assessing the risk to health resulting from human exposure to the pathogen.

The computer programs to support the information base and the model were written in FORTRAN IV for execution on the SNL CDC 6600 computer system under NOS. The user interacted with the information base using a Tektronix 4025 terminal in form display mode for entering data and any other interactive terminal (e.g., Texas Instrument Silent 700) for extracting data. The user controlled the input and output stream of the model in batch mode using the FORTRAN NAMELIST statement. This method gave the user the most flexible and easiest type of input in changing scenarios from one pathway to another or in performing sensitivity analysis on a single pathway.

The sludge treatment and application alternatives described in the transport model were specified by SNL. These alternatives included the use of cesium-137 gamma irradiation in conjunction with the following sludge uses:

(a) Dried raw sludge applied to cropland as a fertilizer.
(b) Dried, anaerobically digested sludge applied to cropland as a fertilizer.
(c) Dried raw sludge used as a feed supplement for ruminant animals.
(d) Composted sludge used as a soil conditioner by the general public.
(e) Liquid raw or anaerobically digested sludge applied to cropland as a fertilizer.

Considering modern disposal practices, any pathogenic organism can be found in municipal sewage. It would have been extremely difficult to design a model which could accurately simulate the survival and environmental movement of more than a few specific organisms. Three organisms were selected to represent the enteric pathogens most commonly found in sludge and were called indicator organisms. These organisms were chosen because each causes significant disease in the general population; there was more information available

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*(Researchers at Cornell were directly funded by EPA to develop the companion model evaluating heavy metals.)

concerning these organisms than for other members of the principal pathogen groups; and each is exceptionally hardy, surviving longer than average outside the human body. Salmonella species were used to represent the bacteria; Ascaris species were used to represent parasites, both the helminth and cestode worms and the protozoa; and polioviruses were used to represent all enteric viruses. No representative for the fungi was selected because not enough information was available on this group as a whole or on any individual member of the group to support environmental modeling.

2. MODELING METHODOLOGY

A computer program was designed to model the transport of pathogens through environmental pathways as a result of the previously mentioned applications of treated sewage sludge. The modeling approach used was the state-vector concept. This method was selected because it provided a very general and flexible base upon which to formulate a spectrum of mathematical formulas to predict pathogen populations. These formulas can be stochastic or deterministic in nature and can be developed empirically from experimental data or theoretically from dimensional and sensitivity analysis. In addition, the state-vector modeling approach permitted a rather natural and logical representation of the envionmental pathways that result from sewage sludge treatment processes and applications.

In figure 1, an example environmental pathway is presented. This pathway presents a simple description of a sewage treatment process and the subsequent application of the treated sludge by land spreading. The boxes (or compartments) in this diagram represent a discretized view of an environmental pathway that is, in reality, comprised of continuous processes in nature. Furthermore, each of these pathway boxes is a summary statement in the macro-sense of a number of subprocesses. For example, the box labeled "Primary Sedimentation" is representative of flow mixing, particulate settling, growth/death (due to nutrient supply, competition, etc.), fluid chemistry processes, etc. The essential requirement is the development of a computer model which will compute the pathogen population as a function of time in each of the pathway boxes. In order to derive the required mathematical relationships, the environmental pathway diagram is converted to a mathematical state format.

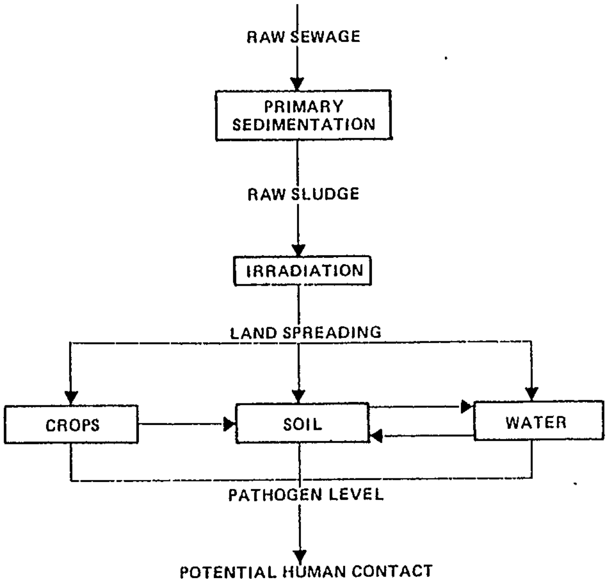


Figure 1. Example Environmental Pathway

The mathematical state representation of the environmental pathway in figure 1 is presented in figure 2. In figure 2, one mathematical state is chosen to represent each pathway box. At each state, equations are derived to compute the rate of change of pathogen population and the effect that the sub-processes in each state (or pathway box) have on the pathogen population. The process functions ρ(X) are used to predict the growth and/or death of pathogens due to the processes occurring within each state. The process functions are also referred to as state feedback functions. The variable X is a vector of parameters which quantify the change in pathogen population due to these state processes. For example, for state 1 (Primary Sedimentation) the vector X would probably consist of the following parameters: time, temperature, sunlight, pH, oxygen content, competing organisms, toxic chemicals, predation, nutrients, and so forth. The transfer functions (or state transition functions) τ_{ij} are used to define the rate of transfer of pathogens from state i to state j. Referring to figure 3, the variable N_{i_o} is used to define the number of pathogens leaving state i and the variable N_{j_I} defines the number of pathogens entering state j. The mathematical definition of τ_{ij} is expressed as:

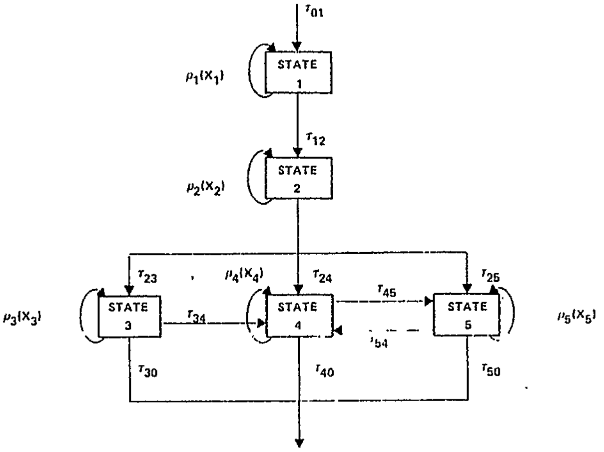


Figure 2. Mathematical State Diagram for Example Environmental Pathway

$$\tau_{ij} = \lim_{\Delta t \to 0} \left[\frac{N_{j_I} - N_{i_o}}{\Delta t} \right] = \left(\frac{dN}{dt} \right)_{ij}$$

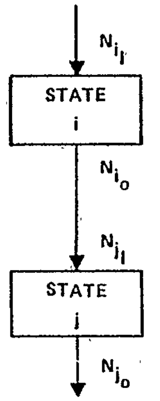


Figure 3. Definition of N_i and τ_{ij}

where Δt is the pathogen transfer time from state i to state j. Again, the state process functions and the transfer functions are necessitated by the discrete nature by which the environmental pathways are being represented and modeled. Mathematical expressions for each ρ_i and τ_{ij} are developed empirically from experimental data (if it exists) or from a dimensional analysis of the relevant vector parameters. The results of the literature search provided the base for the identification and definition of the appropriate test data and vector parameters.

At each state, the equation to compute pathogen population is derived from the principle of conservation of mass. From figure 3, the rate of change of pathogen population in state i is represented symbolically as:

$$\frac{dN_i}{dt} \text{ or } \dot{N}_i = \lim_{\Delta t \to 0} \left[\frac{N_{i_I} - N_{i_O}}{\Delta t} \right]$$

where

N_{i_I} = the number of pathogens entering state i,

N_{i_O} = the number of pathogens leaving state i,

Δt = the time interval in state i.

Using a conservation of mass balance for each state, a first-order differential equation is derived for N. Hence, for a mathematical state diagram consisting of n states, there are n differential equations to be solved. These equations must be solved simultaneously because of variable coupling. For example, referring to figure 2, the following differential equations define the rate of change of the pathogen populations for state 1 (Primary Sedimentation) and state 2 (Irradiation)

$$\frac{dN_1}{dt} = \tau_{01} - \tau_{12} + \rho_1(X_1)$$

$$\frac{dN_2}{dt} = \tau_{12} - \tau_{23} - \tau_{24} - \tau_{25} + \rho_2(X_2)$$

Note that the transfer function τ_{12} appears in both differential equations and, therefore, these equations are coupled.

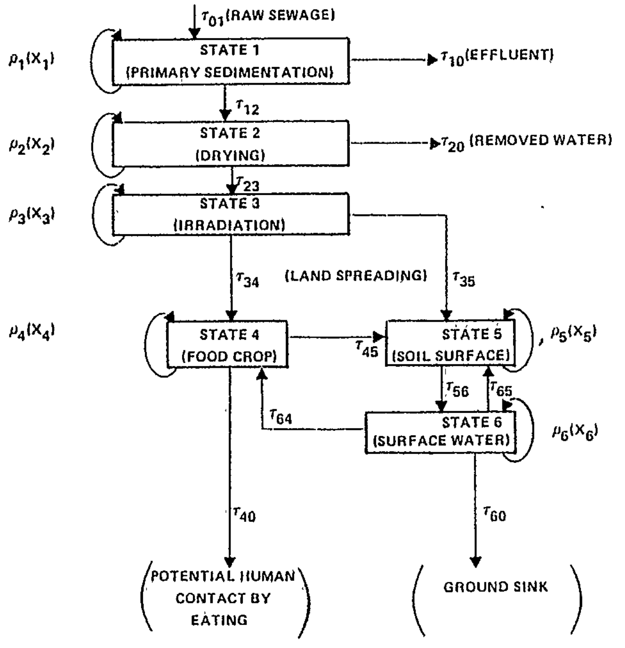
The system of differential equations must be solved separately for each of the selected indicator organisms. The functions ρ_i and τ_{ij} were developed to generally represent each pathogen class. However, for each solution of the system of differential equations, the model was programmed to select only those parameters and terms in the ρ_i and τ_{ij} relationships that were relevant to each particular indicator organism. Hence, the execution of the computer model for an environmental pathway resulted in population predictions for each indicator organism.

Because of the discrete (and macro) nature of the present modeling technique, the differential equations are not exact representations of the change of pathogen population. Solutions of these equations provide approximations to the pathogen populations at each state (or pathway box). The accuracy of these approximate solutions can be improved by utilizing either (or both) of the following strategies:

(a) Define enough mathematical states to completely describe every possible process, sub-process and micro-process that occurs along the environmental pathway.

(b) Improve the level of detail and accuracy in the state process and transfer functions used. The mathematically significant ρ_i and τ_{ij} functions can be determined by performing sensitivity analyses of the terms and solutions of the system of differential equations.

A simplified example serves to explain this modeling methodology and to demonstrate the advantages of this modeling approach. In this example, the fate of bacterial pathogens of the genus Salmonella are followed through three treatment processes (primary sedimentation, drying and irradiation) and in subsequent environmental interactions (resulting from land spreading) between soil surface, surface water and crops. Figure 4 depicts the environmental states that



were selected to represent the flow of salmonellae in these various environments. The states or (compartments) in this figure illustrate the discrete nature of this modeling approach. Also shown in this figure are the state process functions $\rho_i(X)$, which provide a description of pathogen behavior within each state, and the state transfer functions τ_{ij}, which describe the pathogen flow between states and approximate the continuous nature of the environmental pathway.

The differential equations which define the rate of change of pathogen population for this example pathway are

$$\dot{N}_1 = \tau_{01} - \tau_{10} - \tau_{12} + \rho_1(X_1)$$
$$\dot{N}_2 = \tau_{12} - \tau_{20} - \tau_{23} + \rho_2(X_2)$$
$$\dot{N}_3 = \tau_{23} - \tau_{34} - \tau_{35} + \rho_3(X_3)$$
$$\dot{N}_4 = \tau_{34} + \tau_{64} - \tau_{45} - \tau_{40} + \rho_4(X_4)$$
$$\dot{N}_5 = \tau_{35} + \tau_{45} + \tau_{65} - \tau_{56} + \rho_5(X_5)$$
$$\dot{N}_6 = \tau_{56} - \tau_{64} - \tau_{65} - \tau_{60} + \rho_6(X_6)$$

where

(a) The symbol $\dot{N}_i$ denotes the time rate of change of the variable (dN_i/dt).

(b) The subscript zero with a state transfer function indicates pathogen transfer into a state from a non-existing state (τ_{01}) or transfer out of a state to a non-existing state (τ_{40}, τ_{60}) (The term non-existing implies a state that is not considered to be part of the example pathway.)

Mathematical formulas for some of the state process and transfer functions are presented below. In the derivation of these formulas, the parameters (for example, temperature, radiation dose, pH, moisture, nutrients, predation, oxygen concentration, uv radiation, toxic chemicals) that potentially affect the number of salmonellae along this example pathway were defined. For each ρ_i and τ_{ij} formula, these parameters were compared with any available data obtained from the literature review effort. As a result of this comparative analysis, only those parameters which were deemed to have the greatest relative influence on population changes were selected for use in the development of the ρ_i and τ_{ij} relations.

Some of the state process functions for this example are defined as follows:

(a) $\rho_1(X_1) = 0$

Results obtained from the literature review effort suggested that there is no net change in salmonellae during the primary sedimentation process.

(b) $\rho_2(X_2) = \rho_2(\text{time, \% moisture})$

During the drying process of sludge in beds, the parameters time and sludge moisture content are considered to be the most significant factors affecting the salmonellae. From test data, graphs of fraction of original population versus percent solids and percent solids versus time were developed (Brandon and Neuhauser, 1978). These two graphs were cross-plotted to develop a fraction of original population versus time graph. This last graph is maintained in tabular form (where the solids range from 5% to 90%).

(c) $\rho_3(X_3) = \rho_3(\text{dose rate, time})$

$\rho_3 = -4.0\, N_3$

t = time of exposure in minutes.

No parameters were shown to have a significant impact on ρ_3 except dose rate and time. A dose rate of 100 krads per minute is assumed. The constant (-4.0) was computed from a graph derived by cross-plotting data on radiation versus time and radiation versus fraction of original population remaining (Brandon and Neuhauser, 1978).

Some of the state transfer functions for this example are defined as follows:

(a) τ_{01} = (salmonellae/10^6 gallons) (gallons/day) = salmonellae/day

$\tau_{01} = (2 \times 10^{10}/10^6 \text{ gallons})\ (30 \times 10^6 \text{ gallons/day}) = 60 \times 10^{10}$ salmonellae/day

The transfer of salmonellae into state 1 (primary Sedimentation) is based upon the input number of salmonellae for a 30 mgd (million gallons/day) sewage treatment facility (Foster and Engelbrecht, 1973).

(b) $\tau_{12} = .80\ \tau_{01}$ (number/day)

This state transfer function describes the transfer of a fraction (.80) of the salmonellae in raw sewage to sewage sludge (Mom and Schaeffer, 1940).

(c) $\tau_{34} = f_C N_3(t)\delta(t - t_a)$

where

f_C = fraction of salmonellae falling on food crop ($0 < f_C < 1$)

t_a = instantaneous application time

$$\delta(t-t_a) = \begin{cases} 0, & t \neq t_a \\ \infty, & t = t_a \end{cases}$$

(Dirac Delta Function)

$$\text{and} \quad \int_{t_1}^{t_2} \delta(t - t_a)dt = 1 \quad (t_1 \leq t_a \leq t_2).$$

For this example problem it is assumed that there was no net change in the number of salmonellae between state 3 and states 4 and 5. In addition, the sludge land spreading mechanics would be ignored. (These mechanics are dealt with in detail in the actual model pathways.) Hence, any potential environmental states or processes between state 3 and states 4 and 5 would be ignored and the land spreading process was assumed to occur instantaneously. In order to express this instantaneous transfer of salmonellae onto the food crop (state 4), the Dirac Delta Function was utilized. If the equation for N_4 is integrated, the term involving τ_{34} becomes:

$$\int_{t_1}^{t_2} \tau_{34} dt = \int_{t_1}^{t_2} f_c N_3(t)\,\delta(t - t_a)\,dt$$

$$= f_c N_3(t_a)$$

and the desired effect of the instantaneous application of a fractional portion of the total number of salmonellae to the food crop is realized (Killough and McKay, 1976).

The preceding discussion of the events associated with the flow of salmonellae through a sample environmental pathway has been greatly simplified. A number of environmental interactions have been consciously omitted in order to emphasize the general modeling approach rather than to belabor the exact definition of the parameters involved in the example. The simplified example does demonstrate the level of complexity associated with attempts to construct mathematical models that faithfully represent the multitude of environmental interactions occurring in such a process.

The completed model contains a total of fifteen pathways. Five of these pathways describe sludge treatments. Pathway 1, General Sludge Treatment Pathway, describes the treatment of raw or digested sludge for application as cropland fertilizer. Pathway 2, Animal Feed Supplement, describes the treatment of raw sludge necessary to prepare an animal feed supplement. Pathway 3, Composting of Raw or Digested Sludge, describes a general composting cycle to render sludge an inoffensive residential soil amendment. Pathway 10, Liquid Sludge, describes the treatment of either raw or anaerobically digested, liquid sludge intended for application to cropland. Pathway 14, Albuquerque Sludge Treatment Pathway, describes the proposed process train for the city of Albuquerque's #2 waste treatment plant.

Ten pathways describe the applications of sludge that could follow the defined treatment alternatives. Pathway 4, Fertilizer for Crops Destined for Human Consumption, and Pathway 11, Liquid Sludge Used as a Fertilizer for Crops Destined for Human Consumption, describe the environmental flow of pathogens after sludge is applied to cultivated farm land producing common vegetable crops. Pathway 5, Fertilizer for Pasture Crops, and Pathway 12, Liquid Sludge Used as Fertilizer for a Grazed Pasture, describe the use of treated sludge on a grazed field, while Pathway 6, Fertilizer for Crops that are Processed Prior to Animal Consumption, and Pathway 13, Liquid Sludge Used as Fertilizer on Crops That Are Processed Prior to Animal Consumption, describe the use of treated sludge on field crops harvested for animal consumption. Pathway 7, Animal Feed Supplement, is designed to evaluate the use of herbivore feeds containing sludge such as those prepared in Pathway 2. Pathways 8 and 9, Residential Garden Soil Amendment, and Residential Lawn Soil Amendment, respectively, describe the application of composted sludge to home vegetable gardens and in the establishment of a new lawn. Pathway 15, City of Albuquerque Multiple Option Use Pathway, describes the use of treated sludge in the maintenance of city parks and recreation facilities.

The risk analysis incorporated into the computer model is a consequence analysis containing five factors which follow in logical progression (Rowe, 1977). There is the causative event, associated with the beneficial use of sludge. The outcome of that event is the introduction of pathogens into that environment. Individuals are exposed to a hazard represented by the pathogens. There is a consequence of that exposure, possibly disease and, finally, a value is assigned to that consequence. The avoidance of disease/infection is assigned the highest value.

The consideration of the risk analysis factor of exposure of individuals to pathogens in the environment as a result of sewage sludge use is somewhat complicated. Exposure results only if the individual is knowingly or unknowingly placed within a pathway of exposure to these pathogens. It is possible to estimate the probability of individuals placing themselves in an exposure pathway associated with certain events (e.g., riding in a commercial aircraft). However, because of a lack of documented experience, it is currently impossible to estimate the probability of an individual finding himself in an exposure pathway resulting from the use of sewage sludge. Therefore, for risk analysis purposes, it has been assumed that the individual at risk is within an exposure pathway. This assumption enables a more critical look at the next logical factor in the risk assessment, the consequences of exposure to pathogens. The computer model contains five exposure risk calculations that are coupled to the various environmental compartments defined in the 15 treatment and application pathways. These calculations provide estimates of the health risks resulting from exposure to sludge pathogens associated with airborne particulates, soil or residue, vegetable crops, meat, and milk. The exposure portion of these calculations defines events that would reasonably be expected to intervene between a human exposure and an environmental compartment. The calculations associated with these events modify the pathogen populations prior to a potential human exposure. For example, in describing exposure to vegetable crops, the exposure calculations modify the pathogens present on the crops based on such processes as washing, blanching, freezing, and cooking. The exposed individual consumes the final pathogen level as modified by the exposure calculations.

To summarize, the pathogen risk associated with the use of sewage sludge is a function of the probability that an individual will be placed in the exposure pathway and the probability that an individual in the exposure pathway will ingest enough pathogens to lead to the consequence of infection and/or disease. This can be stated in the following way:

$$\text{Risk} = F(P_{(e)}, P_{(i/d)}, C)$$

Where: $P_{(e)}$ = The probability that an individual is in the exposure pathway

$P_{(i/d)}$ = The probability of ingestion of sufficient numbers of pathogens

C = Consequence (infection/disease)

(a) Five exposure risk calculations describe normally expected routes of exposure for man. These calculations are coupled with the appropriate compartments in each of the 15 environmental pathways. The calculations are automatically performed when the model user elects to determine the risk associated with a particular environmental compartment. Throughout the model, it will be assumed that the individual at risk is placed within the exposure pathway, ($P_{(e)} = 1$).

(b) A separate portion of the exposure risk calculations uses the pathogen population estimates from the selected compartments and data from the literature review relating pathogen numbers to infection or disease to calculate the exposure conditions required for the ingestion or inhalation of an infection/disease-causing dose of pathogens. For example, in the particulate-exposure-risk calculation, the model will determine what volume of air will contain an infection/disease-causing dose of a given pathogen. The model will then calculate the length of time an individual would have to breathe the contaminated air to receive the infection/disease-causing dose of pathogens.

(c) Given the model calculation of the amount of crop, air, soil, meat, or milk, that is required to bring about the consequence (C) of infection/disease, the model user will be able to make an inference about the probability of exposure to sufficient pathogens ($P_{(i/d)}$) and consequently, the pathogen risk associated with a sludge treatment and use alternative. For example, a model run using the vegetable exposure-risk calculation may estimate that 100 below-ground crop units (carrots) contain an infectious dose of salmonella. Based upon the model user's experience, it would probably be concluded that the probability of an individual ingesting 100 carrots at a single sitting is low. Consequently, the risk associated with the particular sludge use scenario that yielded a 100-carrot result would also be low.

A summary of the benefits realized from the modeling approach discussed above are listed below:

(a) The state-vector approach presented here provides a structure with the capability of supporting both stochastic and deterministic mathematical relationships. The flexibility of this model structure permits the addition or deletion of mathematical states (pathway boxes) with minor attendant changes in the computer code.

(b) The discrete nature of the mathematical state representation of the environmental pathways readily accommodates variable time steps (increments).

(c) The development of the state process functions and state transfer functions is primarily based on a consolidation of modeling related data obtained from the literature search portion of this study. Areas where data are nonexistent or incomplete or where further research is needed, were identified during the development of these state functions.

(d) The state-vector structure outlined here provides for the straightforward incorporation of new experimental data or analytical techniques as new or improved state process or transfer functions.

(e) The solutions of the model's differential equations are approximations for the pathogen population at each pathway state. However, these approximations can be used as the basis for trend analyses of the effectiveness of various treatment options and of the relative risk potential associated with sludge application options.

(f) From a review of the preceding points of this summary, it can be concluded that this model design provides a flexible framework for the straightforward incorporation of new or additional information and mathematical relationships as they become available. These changes serve to enhance the predictive accuracy of this model, not to invalidate it. The model will not have to be scrapped or undergo major revisions as a result of these changes.

3. MODEL USAGE, SUMMARY AND CONCLUSIONS

The modeling effort began in the fall of 1978 and was completed in late 1980. The final product was submitted to the EPA. Shortly thereafter, the model was made available to the public through NTIS. Since 1981, BDM has received many requests for aid from researchers using the model and BDM personnel have used the model to evaluate sludge treatment-and-use scenarios as requested by the EPA and SNL. These evaluations have included simulation of the treatment and use of liquid sludge as a field crop fertilizer as currently practiced in several north German towns. Runs for the EPA looked at particulate risks to treatment plant operators and persons involved in distribution programs. The City of Albuquerque pathways were run several times to demonstrate the desirability of both the solar drying facility and irradiation unit. The following section is an attempt to outline the major problems encountered during the validation and initial use of the model.

From the first attempts to demonstrate the model to researchers not involved in its construction it became obvious that the user's manual was not being read. The effort to write a manual that would be easy to read, that would provide a quick introduction to the use of the model, and in which each section could stand alone was intensified. The result was a rather long document that users still did not read or use. The documentation was arranged, however, to make it very easy for BDM modelers to direct users to the information they need. The user-specifiable parameter lists allow the user to see at a glance all quantifiable input to the model and the default values for each parameter. As will be discussed later, the default values are a point of contention among the biologists and engineers who have used the model. The pathway diagrams allow for very easy tracing of the pathogen/sludge flows. Users have been encouraged to make photo copies of pathway diagrams that they are interested in and then mark parameter changes and questions on these copies as they read the descriptions of each compartment. The documentation gives a brief description and/or explanation of each compartment followed by the process and transfer functions. Once users read the manual, most found it very easy to adjust the model to simulate their particular sludge scenarios and to follow the logic involved. Working slowly from compartment to compartment, users could identify any changes they wanted to make and the effects of those changes to overall pathogen flows.

It was surprising that very few users had any problems with the exposure risk calculations. This section of the model was the most debated during model construction. Most users either did not use the calculations, being more interested in comparing population numbers, or exhibited a tendency to simply accept the calculations. This unquestioning use of the model has been the greatest problem to its validity. The documentation begins with an accurate description of the model's limitations which essentially originate from a lack of basic data from which to derive process and transfer functions. Users accepted final population figures as fact even when growth rates were unsubstantiated. The model was designed to be used for comparing sludge treatment and use options. It has been misused to determine final pathogen populations and risks based on unverified and assumed data.

As mentioned above, researchers who were using the model for comparisons often disagreed strongly with some of the user-specifiable parameter default values. When the BDM modelers pointed out that any value could be changed and explained the procedure for effecting such changes, the arguments persisted. It seemed that some researchers did not quite understand the purpose of default values. Since the model was originally designed to allow SNL to show the effects of adding irradiation to common sludge treatment process trains, default values were supplied for all parameters. At a demonstration, values specifying treatment plant size and climatic features were quickly changed to simulate the hometown plant while values specifying the effects of processes on pathogens were already in the program ready for use. Normally, municipal officials are not particularly concerned with the biology involved and find discussions of death rates, drying times, and dust inhalation efficiency confusing. Researchers on the other hand demand references and reasons for each default value. When these are supplied, they often proceed to contest a colleague's results. BDM has stated many times that the values used in the model were the best available 5 years ago and anyone who disagrees could change the value in contention.

Several of the data points which generated the most discussion dealt with the dose of a pathogen which will lead to infection of an individual. Experiments of this type needed to answer these questions cannot easily be done in the United States. Healthy Americans who are educated well enough to give informed consent usually do not volunteer for dose response experimentation. Data obtained in third world nations is not readily extrapolated to the U.S. because the general health, nutrition, and previous exposure histories of the two populations tend to be very different. The model is acknowledged to be no more accurate than the available data and the holes in the data are acknowledged.

Beyond problems with the information used in modeling, many potential users have rejected the model because it requires a larger computer than they have access to. The model was written to be run on large computers available at SNL and the EPA. Many potential users would like a program which would run on a mini or micro computer.

The computer environment for the model development and usage was the SNL CDC 6600 computer system operating under NOS. This computer system provided a useful math package (specifically an ordinary differential equation solution package - ODE) as well as a large computer support facility that included disk drives, magnetic tape drives, and consulting services. As with any large, multi-user computer facility, the turnaround time (i.e., the time between input and output) was occasionally one day or less. However, this was due to the large number of users requesting computer access rather than the size of the model. The size of the model should not prohibit anyone from placing it onto a different computer system. In fact, some of the microcomputers now on the market could handle the memory and disk space requirements. For instance, a 16-bit micro system with two single-sided, double density disk drives and 128k of internal memory could adequately handle the low complexity pathways. Higher complexity pathways may require memory to be expanded to 512k (e.g., the IBM PC could easily handle this requirement). Larger machines such as the VAX-11/780 or 11/750 mini-computers provide the capability to transfer the entire model without special requirements.

The user who does transfer the model to another computer system should be aware of the following model requirements. First, the input/output process of the model is implemented via the FORTRAN NAMELIST statement. This statement permits the input and output of groups of variables and arrays with an identifying name. This statement also provides the flexibility needed to change scenarios from one pathway to another and the means to perform a sensitivity analysis on a single pathway. Hence, this statement is necessary to the implementation of the model and must be supported by the computer system that the model is to be implemented on.

The interactive user input interface for selecting pathways and default parameters is tied to the NOS procedure file system as configured by SNL. The transfer to another computer system will require the model/user interaction to be redesigned for the particular computer system. The interface redesign should not require a large amount of resources to perform; however, anyone attempting to do this should try to make the interface as independent as possible of the computer system characteristics.

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5. REFERENCES

Brandon JR, Neuhauser KS (1978), Moisture effects on inactivation and growth of bacteria and fungi in sludges, Technical Report SAND78-1304, Sandia National Laboratories, Albuquerque, New Mexico, 23 pp.

Foster DH, Engelbrecht RS (1973), Microbial hazards in disposing of wastewater on soil. In: Recycling Treated Municipal Wastewater Through Forest and Cropland, WE Sapper and LT Kardos (eds.), Pennsylvania State University Press, University Park, PA, pp 247-266.

Killough GG, McKay, LR (1976), A methodology for calculating radiation doses from radioactivity released to the environment, Publication No. 660, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 47 pp.

Mom CP, Schaeffer CO (1940), Typhoid bacteria in sewage and in sludge--an investigation into the hygienic significance of sewage purification in the tropics with regard to typhoid fever. Sewage Works Journal, Vol. 12, pp 715-731.

Rowe, WD (1977), An Anatomy of Risk, John Wiley & Sons, Wiley-Interscience, New York.

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