United States
Environmental Protection
Agency
Research and Development

Robert S. Kerr Environmental
Research Laboratory
Ada, OK 74820
EPA/600/S2-91/062 Mar. 1992

EPA

Project Summary

A Model of Virus Transport in Unsaturated Soil

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As a result of the recently-proposed mandatory ground-water disinfection requirements to inactivate viruses in potable water supplies, there has been increasing interest in virus fate and transport in the subsurface. Several models have been developed to predict the fate of viruses in groundwater, but few include transport in the unsaturated zone, and all require a constant virus inactivation rate. These are serious limitations in the models, as it has been well documented that considerable virus removal occurs in the unsaturated zone, and that the inactivation rate of viruses is dependent on environmental conditions. The purpose of this research was to develop a predictive model of virus fate and transport in unsaturated soils that allows the virus inactivation rate to vary based on changes in soil temperature. The model was developed based on the law of mass conservation of a contaminant in porous media and couples the flow of water, viruses, and heat through the soil. Model predictions were compared to measured data of virus transport in laboratory column studies, and were within the 95% confidence limits of the measured concentrations. The model should be a useful tool for anyone wishing to estimate the number of viruses entering ground water after traveling through the soil from a contamination source. In addition, model simulations were performed to identify variables that have a large effect on the results. This information can be used to help design experiments so that important variables are measured accurately.

This Project Summary was developed by EPA's Robert S. Kerr Environmental Research Laboratory, Ada, OK, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The significance of viruses as agents of ground-waterborne disease in the United States has been well documented. The increasing interest in preventing ground-water contamination by viruses and other disease-causing microorganisms has led to new U.S. Environmental Protection Agency proposed regulations regarding ground-water disinfection, the development of wellhead protection zones, and stricter standards for the microbiological quality of municipal sludge and treated effluent that is applied to land. For many of the new regulations, a predictive model of virus (or bacterial) transport would be helpful in the implementation process. For example, such a model could be used to determine where septic tanks could be placed or where land application of sludge or effluent could be practiced relative to drinking water wells to minimize negative impacts on the ground-water quality. Another application of microbial transport models is related to the ground-water disinfection rule. Water utilities wishing to avoid ground-water disinfection may use a pathogen transport model to demonstrate that adequate removal of viruses in the source water occurs during transport to the wellhead.

Several models of microbial transport have been developed during the past 15 to 20 years . The models range from the very simple, requiring few input parameters, to the very complex, requiring numerous input parameters. For many of the more complex models, the data required for input are not available except for very limited environmental conditions. They may be useful for research purposes, but would be impractical for widespread use. The potential applications of these models also range considerably, from being useful only for screening purposes on a regional scale, to predicting virus behavior at one specific location.

One limitation of almost all of these models is that they have been developed to describe virus transport in saturated soils (i.e., ground water). However, it has been demonstrated many times that the potential for virus removal is greater in the unsaturated zone than in the ground water. Neglecting the unsaturated zone in any model of virus transport could lead to inaccurately high predictions of virus concentrations at the site of interest. This omission would be especially significant in areas with thick unsaturated zones, such as those in many western states. The one transport model that has reportedly been developed for predicting virus transport in variably saturated media is not specific for viruses, but can be used for any contaminant. In addition, it has not been tested using data of virus transport in unsaturated soil.

Another, and more important, limitation of published models of virus transport is that none of them has been validated using actual data of virus transport in unsaturated soils. Most models are developed based on theory, and are fitted to data obtained from one or two experiments. Rarely are they tested by applying the model to data collected under a variety of conditions and then determining how well the model predicts what has been observed in the laboratory or field without any fitting or calibration of the model.

Transport Processes

The transport of viruses through a porous medium such as soil is affected primarily by the following mechanisms and processes: Advection; Hydrodynamic dispersion; Adsorption (and desorption); Filtration; and Inactivation.

Factors Affecting Transport Processes

The transport of viruses through soil is controlled by climatic conditions such as the rate of rainfall (or water application) and evaporation and by soil properties such as soil water content, soil temperature, adsorption and desorption, filtration, soil pH, and salt concentration. The properties of the specific virus of interest are also important in determining its behavior in the subsurface. Some of the most important factors that affect the transport of viruses through soil include soil water content, soil temperature, the rate of water application and evaporation , and soil heterogeneity.

Objectives

The purpose of this research was to develop a model that can be used to predict virus movement from a contamination source through unsaturated soil to the ground water. Several model simulations were performed to determine the effects of different input variables on model predictions. The model was tested by comparing model prediction to results of laboratory studies.

The specific objectives of this project were:

1. To develop a mathematical model to describe the transport of viruses in unsaturated soil that includes factors specific to viruses, and
2. To test model predictions with experimental data of virus transport in soil.

Transport equations were derived to describe the simultaneous transport of water, viruses, and heat for a soil profile.

VIRTUS: A Model of VIRUS Transport in Unsaturated Soil

The mathematical model developed is entitled VIRTUS (VIRus Transport in Unsaturated Soil), and programmed in FORTRAN for use on IBM and IBM-compatible PCs. In the Project Report there is a document describing the use of the program which is located in Appendix III. Sample input and output data that can be used to test the model are listed in Appendix IV. The mathematical model and corresponding computer program, VIRTUS, are demonstrated in a variety of situations in the Project Report. The potential applications of this model and its limitations are also discussed.

Model Applications and Limitations

Some of the features of this model include its ability to simulate:

1. unsteady flow in variably-saturated media
2. transport in layered soils
3. variable virus inactivation rate (e.g., function of temperature)
4. different virus inactivation rates for adsorbed versus freely suspended virus particles
5. the flow of heat through soil (which affects water flow, virus inactivation rate, etc.)

Discussion

The ultimate measure of a model's usefulness as a predictive tool is its ability to accurately predict field observations of virus transport under a variety of environmental conditions. However, most models that have been developed to predict microbial transport have not been tested using field or laboratory data. There are a few exceptions to this (e.g., Teutsch et al., 1991; Harvey and Garabedian, 1991). However, both of these models were developed for use by the investigators in order to simulate their own data. In the case of the colloid filtration model of Harvey and Garabedian, extensive fitting of the required input parameters was performed by calibrating different solutions of the transport equation to the observed bacterial breakthrough curves. Thus, while these models may be able to simulate the investigator's data reasonably well, they may not be able to predict the results of other investigator's transport experiments. If a model is to be used for purposes other than research, such as for community planning or for making regulatory decisions, it must be able to predict microbial transport using data obtained by anyone under a wide range of environmental conditions.

In this research a model to describe virus transport was developed based on the factors known to affect virus fate in the subsurface. A survey of the literature was conducted to locate data sets in which the investigators made measurements of not only virus properties, but also soil and hydraulic properties. Two data sets were located and used to test VIRTUS. No fitting or calibration of the model was performed; the data and measurements as reported by the respective investigators were used as model input. Model predictions compared favorably to measured experimental data as predictions were within the 95% confidence limits of the measured data. However, only one comparison to one laboratory transport study in unsaturated soil using a single soil type and a single virus type was performed.

In addition, the temperature-dependent inactivation rate capabilities of the model could not be tested by comparison to experimental data. This is due to the fact that the experiments were conducted under constant temperature conditions in the laboratory, thus the virus inactivation rate remained constant (theoretically) throughout the course of the experiment. In order to test the model's capacity to calculate new virus inactivation rates as a function of the changing soil temperature, data from a laboratory study in which the temperature, is allowed to change (and is closely monitored) or from a field study in which the temperature is monitored will be required. This will allow an assessment of the model's capability to accurately calculate heat flow through the soil, which affects water flow (and thus virus transport) as well as the rate of virus inactivation during transport. More testing of the model is required before using it for any purposes other than research.

Conclusions

This research project has resulted in the development of a mathematical model that can be used to predict virus (or bacterial) transport in unsaturated soils. The model allows the user to specify the virus inactivation rate as a function of soil temperature or any other input parameters. It will also allow the user to specify different inactivation rates for adsorbed versus freely suspended virus particles, if that information is available.

A sensitivity analysis of the model indicated that the inactivation rate of the virus has a large effect on model predictions. The adsorption coefficient and dispersivity also affect model predictions, although to a smaller extent.

Model predictions compared favorably to two data sets against which the model was tested. However, there is a lack of data available for extensive model testing. No complete data sets from field transport experiments were found that could be used to test VIRTUS. Before the model can be used for any purposes other than research, it should be extensively tested using actual field data.

In its present condition, the model requires the user to input several pieces of information related to climatic conditions. It also requires a large amount of information characterizing the physical properties of the soil, as do most models of contaminant transport. Before VIRTUS could be used for purposes other than research, a user interface, extensive help facilities, and a library of soil and virus properties would have to be added to the model.

Harvey, R.W., and S.P. Garabedian. 1991. Use of colloid filtration theory in modeling movement of bacteria through a contaminated sandy aquifer. **Environ. Sci. Technol.** 25:178-185.

Teutsch, G., K. Herbold-Paschke, D. Tougianidou, T. Hahn, and K. Botzenhart. 1991. Transport of microorganisms in the underground - processes, experiments, and simulation models. **Wat. Sci. Tech.** 24:309-314.

*U.S. Government Printing Office: 1992 — 648-080/60045

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The complete report, entitled "A Model of Virus Transport in Unsaturated Soil;" (Order No. PB92-119 957/AS; Cost: $26.00; subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

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