AN ABSTRACT OF THE THESIS OF

Nathan Kent Potter for the degree of Master of Science in Radiation Health Physics completed on August 6, 1997. Title: Development of a Functional Prototype of an Environmental Risk Assessment Parameter Database on the World-Wide Web.

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Kathryn A. Higley

The goal of the project was to develop a functional prototype of an environmental risk assessment parameter database on the World-Wide Web. The ability to develop a consolidated environmental database has become possible due to the phenomenal growth of the *Internet* and the *World-Wide Web* over the past few years. A large number of environmental resources do currently exist; however, with the large volume of information available, access, management, reliability, and retrievability have become increasingly difficult.

To illustrate the prototype database, a practical environmental concern and the tools necessary to evaluate and characterize that concern were needed. Uranium (^{238}U) daughters leaching from abandoned mill tailing piles at three abandoned uranium mines in southwestern Colorado were chosen to demonstrate the database concept. The RESRAD environmental pathway modeling code served as the evaluation and characterization tool. Due to the size and complexity of RESRAD, a single radionuclide release rate equation was isolated as a controllable component of the code. The equation was a small part of the water pathway factor and examined the rate at which radionuclides absorbed in soil were leached by infiltrating water. This serves as the

source term for groundwater contamination and directly applies to the ^{238}U progeny leaching from mill tailing piles scenario. Parameters selected from the equation dealt with the background data that directly influenced the mobility of contaminates in the environment. Environmental data for the three Colorado sites were gathered and interpreted. Probability Density Functions (PDFs) were developed for input parameters and the results were then incorporated into the web site.

Development of a Functional Prototype of an Environmental Risk Assessment Parameter Database on the World-Wide Web.

by

Nathan Kent Potter

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Nathan Kent Potter, Author

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1. INTRODUCTION

1.1. Project Focus

The focus of this project was to develop a functional prototype of an environmental risk assessment parameter database on the world-wide web. The primary motivator for this project was to organize environmental data so that it can be applied to a probabilistic risk assessment. Initially, the scope of the work concerned data specifically involved with the movement of radioactive materials through a subsurface environment and the environmental modeling codes used to predict a potential exposure scenario. Eventually, the scope of the database will be expanded to include other types of contamination and transport methodologies.

The project was conducted in three phases. The first phase involved outlining the project goals and a general literature review of current world-wide web environmental database technologies. Additionally, a need was identified for a current environmental contamination scenario and an initial group of environmental parameters to focus the data gathering efforts. The second phase involved the gathering and evaluation of environmental data from a contamination scenario and formulation of distribution functions that could be used in probabilistic risk assessment methodologies. The final phase consisted of the development of the website as well as a functional user interface.

The need for a comprehensive, quality controlled environmental database has become more apparent due to public demand for a cleaner environment and the corresponding shift in industry and the scientific community towards providing that environment. Environmental research being conducted requires accurate and comprehensive data as well as literature references explaining how and where the data was obtained. The values that have been used thus far are not incorrect; however, parameters such as climatological data, soil data, ingestion rates, and inhalation rates have usually been chosen to represent worst case conditions (Till and Myer, 1983; Yu, et al., 1993; USDA, 1987, 1988, 1995; USDC 1992). When these values are applied to a *"worst case"* scenario or a *"maximally exposed individual"* as a method for predicting population dose or determining a remediation goal, an overly conservative estimate is determined. And, when this result is compared to the actual risk to a population the determined solution could prove expensive (Till and Myer, 1983; Cole, 1993; Horgan, 1994)

An example of this is in the proposed Environmental Protection Agency (EPA) remediation of a Grand Junction, Colorado community where uranium mill tailings from the local mine were used in the construction of homes, schools, and other buildings. The proposed remediation plan was to excavate a neighborhood and replace the foundation materials. The significance of the project, and how it applies to a need for an environmental risk assessment database, is that the remediation project itself presents a larger risk to the community than the presence of uranium progeny (Cole, 1993; Makofske, 1988).

There has been a debate among regulatory agencies recently over the use of deterministic versus probabilistic data sets in calculating remediation goals (USNRC, 1995). Additionally, there has been a governmental shift to performance based remediation strategies because the vast pools of government funding have virtually disappeared (Stewart, 1996). Terms such as *"cost estimates"* and *"risk assessments"* have now moved more to the forefront in any environmental remediation project.

The deterministic approach to modeling examines a set of data, selects a specific value for each parameter in the model, and calculates a single result. This approach can be useful in communicating with the public by showing a specific individual's dose or a worst case scenario. Unfortunately, the development of a remediation strategy from a deterministic methodology produces an estimate of the potential risk based solely on the level of conservatism present in the selection parameters used to calculate that estimate.

A probabilistic approach treats data as a distribution and randomly selects variables from that distribution. This, therefore, calculates the solution in terms of a probability (or frequency) distribution function or probability density function (PDFs). These PDFs can then be used as a tool to integrate a cost versus risk analysis into the final solution and possible future remediation strategies. A probabilistic approach does not provide a *"more correct"* or *"better"* solution to a remediation problem as compared to a deterministic approach; however, it does allow for uncertainty in model parameters to be incorporated into the decision making process.

The major problem is the gathering of pertinent data for each parameter and determining these distributions for any given situation. A great deal of environmental information presently exists; however, it is located in many different places and is maintained by many different organizations (Alston, 1991, 1993, 1994, 1996). The need for a consolidated environmental database, which can be used to obtain reliable input parameters, exists because of the vast amount of available information.

Currently, there is a large amount of information from a variety of different sources, variations in particular values can cause a large difference in solutions developed from a given set of input parameters. When dealing with the *"how clean is clean"* philosophy, risk assessment facilitates a cost versus risk analysis in determining a remediation goal. This is not a popular solution but it does present a practical solution.

1.2. A Consolidated Environmental Database

The development of a consolidated environmental database has become possible due to the growth and ease of use of information gathering technologies. The *Internet* and the *world-wide web* over the past few years have grown exponentially. More recently, newer computer languages such as HTML, Java, and Perl have allowed the *Web* to become visually appealing by incorporated interactive graphics and animation into websites. One of the goals of prototype environmental database was to make data recovery simple and easy by incorporating a *search engine* along with menus that could guide the user to the desired material.

Currently, there are a large number of *environmental* information resources available. However, with the larger volume of information available, access, management, and retrievability has become increasingly more difficult. Combine this with the varied and incongruent nature of environmental data, a problem exists where obtaining accurate and valuable solutions has become more difficult.

Developing a consolidated environmental database has its own problems. During the development of the environmental database prototype, certain problems arose. Due to the complexity of an environmental system, management and quality control of the data in the database could not be effectively controlled by one organization.

A decision was made to archive the information at several different sites, such as universities and national laboratories, where quality control of smaller pieces of information could be more manageable. These pieces could then be administered from a central site location, which could concentrate on the organization and administration of the database. Those who created it could still manage the physical information. The ultimate goal of the project was to achieve a site that anyone with Internet access could access and search from any computer in the world and see a virtually seamless, comprehensive environmental database.

2. THE WORLD-WIDE WEB

The world-wide web, commonly referred to as the *Web*, is officially described as a "wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents" (Hughes, 1994). It was created in March 1989, when Tim Berners-Lee of the European Particle Physics Laboratory (known as CERN, a collective of European high-energy physics researchers) proposed a method for scientists to collaborate using a global information system for communicating and transferring information effectively throughout their organizations. The initial project proposal outlined a simple system of using networked hypertext to transmit documents and communicate among members in the high-energy physics community. In the original concept, there was no intention of adding sound or video, or the capability to transmit images (Hughes, 1994).

Since its beginning, thousands of people throughout the world have contributed their time writing web software and documents educating others about the capabilities of the world-wide web. It has become a simple method for accessing a variety of multimedia easily. Using freely available software and inexpensive readily available technology, such as personal computers, anyone can access virtually any information stored on any accessible networked computer in the world.

There are many specific words used when describing the Internet and the world-wide web and their definitions are as intertwined as the networks they represent. Terms such as the world-wide web and the Internet are not interchangeable. The world-wide web refers to hypermedia in which information is organized and stored, while the Internet refers to the physical pieces of technology that make up the global network. In ways never envisioned by the original project group at CERN, the world-wide web has truly reached global proportions and still continues to grow.

Trying to apply this fabulous resource to practical work is where complications arise. When dealing with the environmental data and resources there are several useful information links currently available on the world-wide web. However, many sites provide just novelty information about their organization or a list of other sites that can be possibly provide some information to a potential researcher. Another problem exists with many of the existing on-line databases in that they can be accessed before the database has been completed (Notess, 1994).

There are advances occurring. Currently there is a project that is putting the complete code of federal regulation on-line for easy access. Other than resources such as this or access to organizations, these links do not provide a significant resource for research material. With the tremendous amount of information available it has become increasingly difficult to locate environmental information and actually utilize the world-wide web as a starting point for productive work.

2.1. Hypertext and Hypermedia

The world-wide web relies mainly on the transfer of hypertext as the method of interacting with its users. Hypertext is basically the same as regular text in that it can be stored, read, searched, or edited. The major exception separating it from regular text is that it contains connections within the text to other documents.

In a hypertext system, you could have one or more related documents appear before you as you search for data. These "other documents" could themselves have links and connections to other documents, and so on. In this way, hypertext links, commonly called hyperlinks, can take a user on a free-associative tour of information in a complex virtual web of connections.

Hypermedia is just the logical expansion of hypertext. Hypermedia documents contain not only links to other pieces of text, but the user can also access other forms of digital media such as images, sounds, and video. Images themselves can be linked to sounds or other documents. Hypermedia simply combines hypertext with multimedia to create an interactive management of information. The world-wide web facilitates the easy exchange of hypermedia through networked computer environments (Hughes, 1994).

2.2. The Internet

The Internet, in its simplest definition, is a term used to describe the massive world-wide network of cables, satellites, and computers. The word *"Internet"* literally means, "network of networks". In itself, the Internet is comprised of thousands of smaller regional networks scattered throughout the globe (Hughes, 1994). The basis for what is now the Internet began in 1969. It was called ARPANET (Advanced Research Projects Agency Network) and its objective was to provide the government with a secure communications tool. ARPANET grew with the invention of electronic mail, or e-mail, in the early 1970's and many colleges and government organizations connected and went on-line. In 1973, the first international links began to develop in Europe. From the 1970's to the 1980's, the Internet matured with more and more tools such as Telnet, which allows someone to remotely login to another computer over the Internet (Huang, 1995).

In the United States, the Internet has been developed around the NSFNET (National Science Foundation Network), five super-computing centers located at the John von Neumann Super Computer Center (JVNC) in Princeton, New Jersey, the Pittsburgh Supercomputing Center (PSC) in Pittsburgh, Pennsylvania, the San Diego Supercomputer Center (SDSC) in San Diego, California, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, and Theory Center at Cornell University in Ithaca, New York. In 1986, the NSFNET was founded with a backbone speed of 56 kbps *(kilobits per second)*. In 1988, it was upgraded to a T1 digital connection running at 1.544 Mbps *(mega or million bits per second),* and then again in 1991, it was upgraded to a T3 digital connection running at 44.736 Mbps (Huang, 1995).

2.3. What the Future Holds

The invention of the world-wide web can be said to be the one thing most responsible for the rapid expansion and development of the Internet. It has brought together a huge mass of technology and information and made it available to any user. But now there are many new inventions such as GopherSpace, which is a gopher-based tool (a text oriented database), used under a graphical interface. WebSpace is also a new graphical interfaced web browser based on VRML (Virtual Reality Mark-up Language), rather than HTML (Hypertext Mark-up Language), which is used in World-Wide Web pages. There is also HotJava from Sun Micro Systems, which allow a user to see 3-D modeling and view spreadsheets. With inventions such as WebSpace, virtual reality is the future. With the development of more advanced computers and faster connections, what we know and understand as the World-Wide Web today may one day become obsolete.

3. A DATABASE FOR ENVIRONMENTAL PARAMETER VALUES

3.1. Database Focus

The intent of this work is to develop a comprehensive database of environmental input parameters for the environmental scientist, researcher, and engineer. Initially the focus has been towards parameters describing radiological contamination moving through the ground. The ultimate goal is to establish a comprehensive environmental database for input parameter values that deal with all aspects of the environment and all types of contamination. Ideally, users would be able to access the database from anywhere, download any pertinent environmental parameter values, view relevant data distributions, find pertinent references to qualify their research, and develop an environmental remediation strategy.

The database eventually would be able to provide information on the physical and chemical nature of compounds as well as specific nuclide data. Additionally, information would be available concerning pathway analysis, how materials move through a system, ingestion and inhalation rate for animals and humans, and general environmental data.

Other significant features would incorporate relevant data into distribution functions to allow a researcher to perform a probabilistic risk assessment analysis on a given environmental situation and provide access to the gray literature of federally sponsored laboratory research.

3.2. Accessibility

The prototype database was constructed with accessibility and usability as key attributes. The goal of the database was to balance a depth in the information while still remaining usable by all levels of users. Nearly everyone has, or can gain, access to the world-wide web and the Internet. This, in conjunction with heavy influence of computers in environmental modeling, provides a nearly ideal method for quickly searching for information.

3.3. Organization

The original database prototype existed originally on one computer. Early in the project, this was deemed inadequate for two key reasons. First, was the vast volume of information available that would need to be stored and, second, was the quality control of the information being stored. It was determined that maintaining the data at the location where it was developed and allowing user access over the world-wide web could solve both problems. This would ensure the data would be maintained and explained by the same people that performed the research and studies. Additionally, this would distribute the storage requirements over many different systems, alleviating the strain on individual systems.

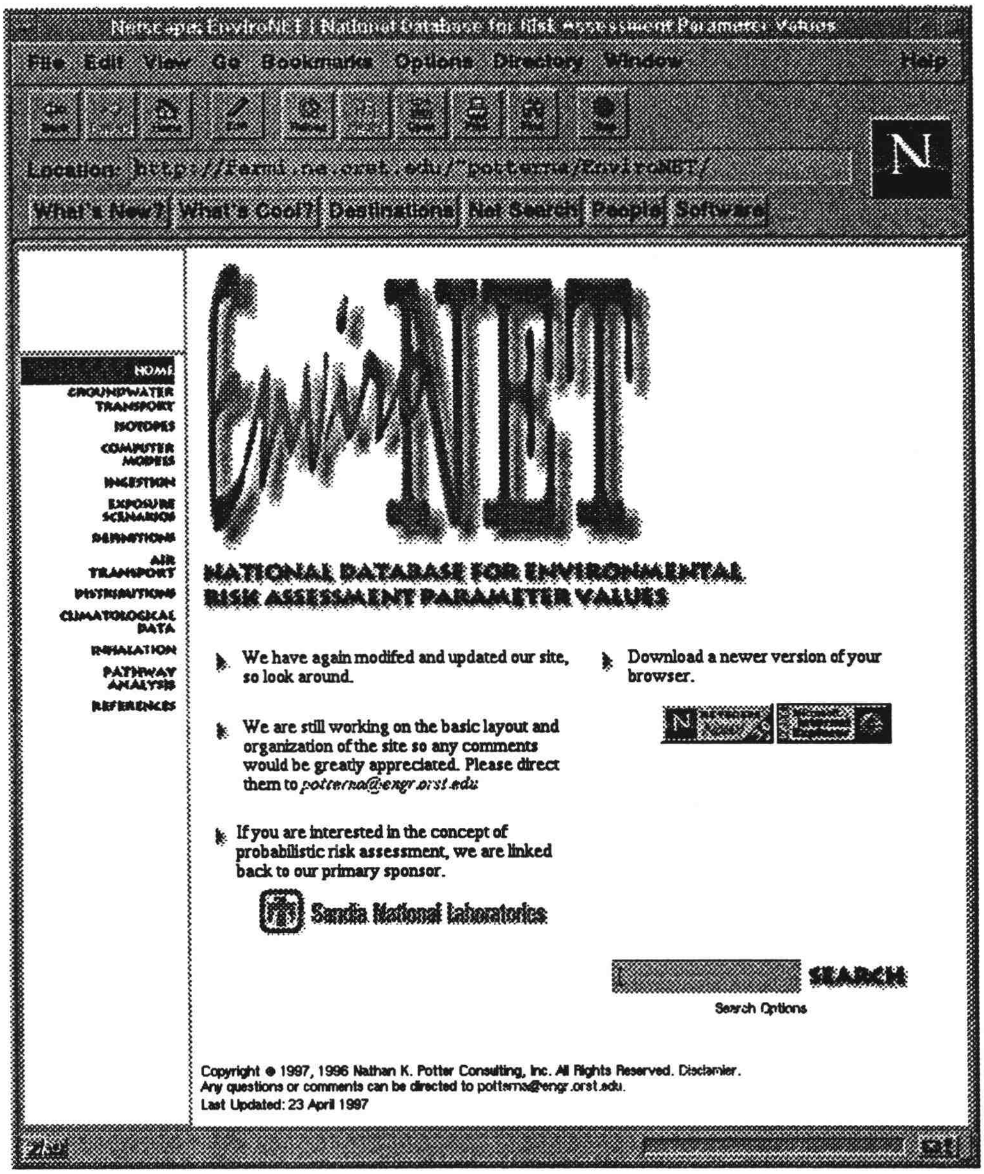
This solution does still require a central location to manage the database as well as set guidelines for the format of the data and how it is to be displayed. Through the global nature of the world-wide web the central location can be anywhere in the world. Currently, the central site is located at Oregon State University. Here, indices of the data would be maintained linking that data to search locations. Additionally, quality control of the data could be enforced as well as management of common information.

3.4. Features

Some key features the database would provide are a visually appealing graphical interface, an excellent depth of quality controlled information, and an interactive interface with the user. Figure 3.1, *Conceptual Database (EnviroNET) Front-Page,* illustrates the actual first page a database user would see when they arrived at the website. Netscape Navigator Gold 3.0® is the web browser that was used to beta test the website and illustrate specific aspects of the site in this document. Here, through the use of a Java script, the user can select the desired research area they are seeking information from the menu on the right or go directly to the database search capabilities at the bottom. Additionally, advertising and recent additions and developments can be listed for quick access. The current database was designed to be usable as well as appealing to all levels of users.

For the development of the functional database prototype, research was primarily conducted in the groundwater transport pathway, which is explained in greater depth in Chapters 5, *Using Uranium Mining Waste Remediation as a Functional Database Illustration,* and Chapter 6, *Parameter Discussion.* Figure 3.2, *Groundwater Transport Page,* illustrates the next step the researcher would follow, researching groundwater transport pathway data. From this page the researcher could then select either from the tabular data possibilities or relevant equations, represented by Figure 3.4, *Runoff*

Coefficient Table Page, and Figure 3.5, *Radionuclide Release Rate Equation Page,* respectively.



- We have again modifed and updated our site, so look around.
- We are still working on the basic layout and organization of the site so any comments would be greatly appreciated. Please direct them to *potterna@engr.orst.edu*
- If you are interested in the concept of probabilistic risk assessment, we are linked back to our primary sponsor.
- Download a newer version of your browser.

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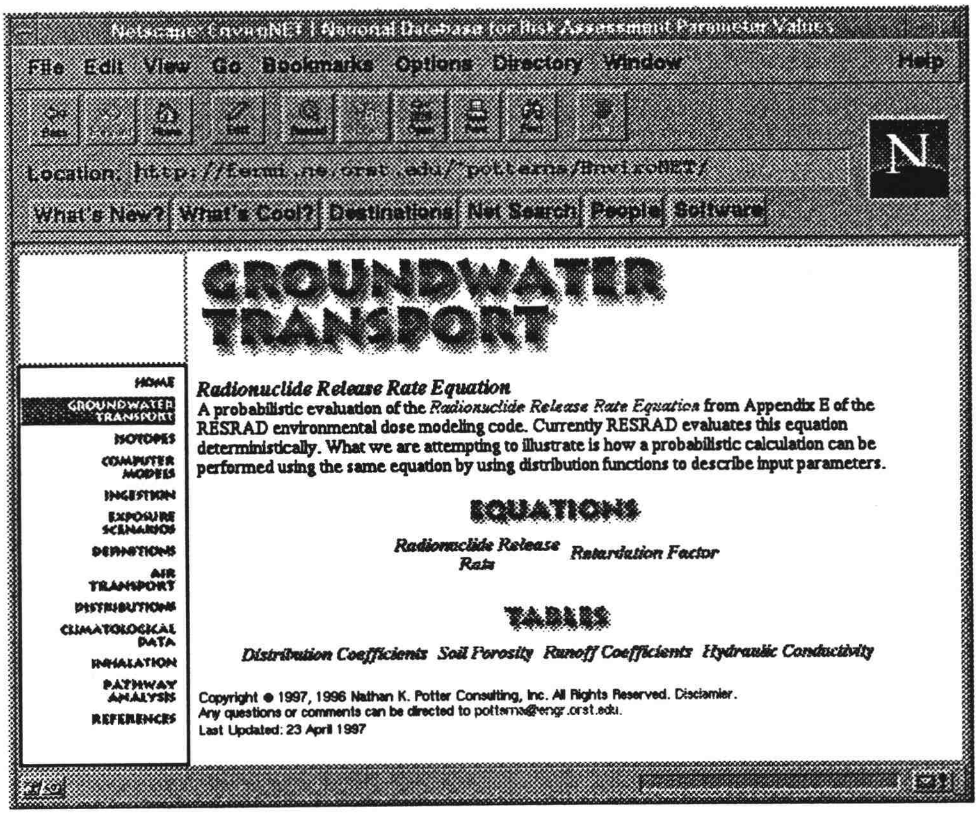
Figure 3.1: Conceptual Database (EnviroNET) Front-Page

By creating a visually appealing site that seamlessly connects and accesses information, any user can search for environmental data. A requirement for the remote sites would be that they maintain a consistent organization of their data, references, contacts, and studies, as well as, the same visual appeal.

The multimedia capabilities of the world-wide web allow the incorporation of images and video as well as the capability to download files and software. This provides a greater range of appeal as well as practical explanations and applications. The potential exists to even be able to use specific modeling codes directly on the Web. Imagine a site where a researcher can access information, search for pertinent environmental data, incorporate that same environmental data into a modeling code, and generate a solution.



GROUNDWATER TRANSPORT

Radionuclide Release Rate Equation

A probabilistic evaluation of the *Radionuclide Release Rate Equation* from Appendix E of the RESRAD environmental dose modeling code. Currently RESRAD evaluates this equation deterministically. What we are attempting to illustrate is how a probabilistic calculation can be performed using the same equation by using distribution functions to describe input parameters.

EQUATIONS

Radionuclide Release Rate *Retardation Factor*

TABLES

Distribution Coefficients *Soil Porosity* *Runoff Coefficients* *Hydraulic Conductivity*

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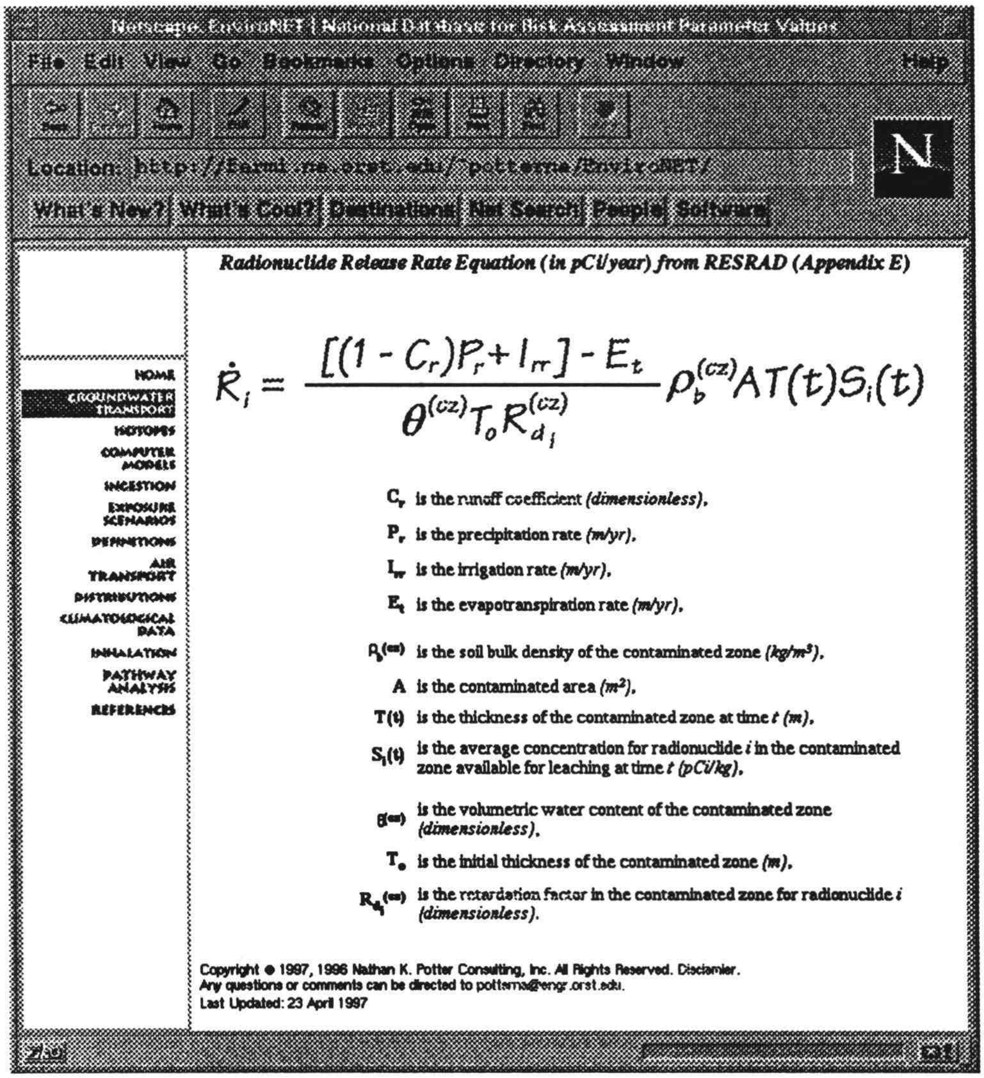
Figure 3.2: Groundwater Transport Page



Radionuclide Release Rate Equation (in pCi/year) from RESRAD (Appendix E)

$$\dot{R}_i = \frac{[(1 - C_r)P_r + I_{rr}] - E_t}{\theta^{(cz)} T_0 R_{d_i}^{(cz)}} \rho_b^{(cz)} A T(t) S_i(t)$$

C_r is the runoff coefficient *(dimensionless)*.

P_r is the precipitation rate *(m/yr)*.

I_{rr} is the irrigation rate *(m/yr)*.

E_t is the evapotranspiration rate *(m/yr)*.

$\rho_b^{(cz)}$ is the soil bulk density of the contaminated zone *(kg/m³)*.

A is the contaminated area *(m²)*.

$T(t)$ is the thickness of the contaminated zone at time *t* *(m)*.

$S_i(t)$ is the average concentration for radionuclide *i* in the contaminated zone available for leaching at time *t* *(pCi/kg)*.

$\theta^{(cz)}$ is the volumetric water content of the contaminated zone *(dimensionless)*.

T_0 is the initial thickness of the contaminated zone *(m)*.

$R_{d_i}^{(cz)}$ is the retardation factor in the contaminated zone for radionuclide *i* *(dimensionless)*.

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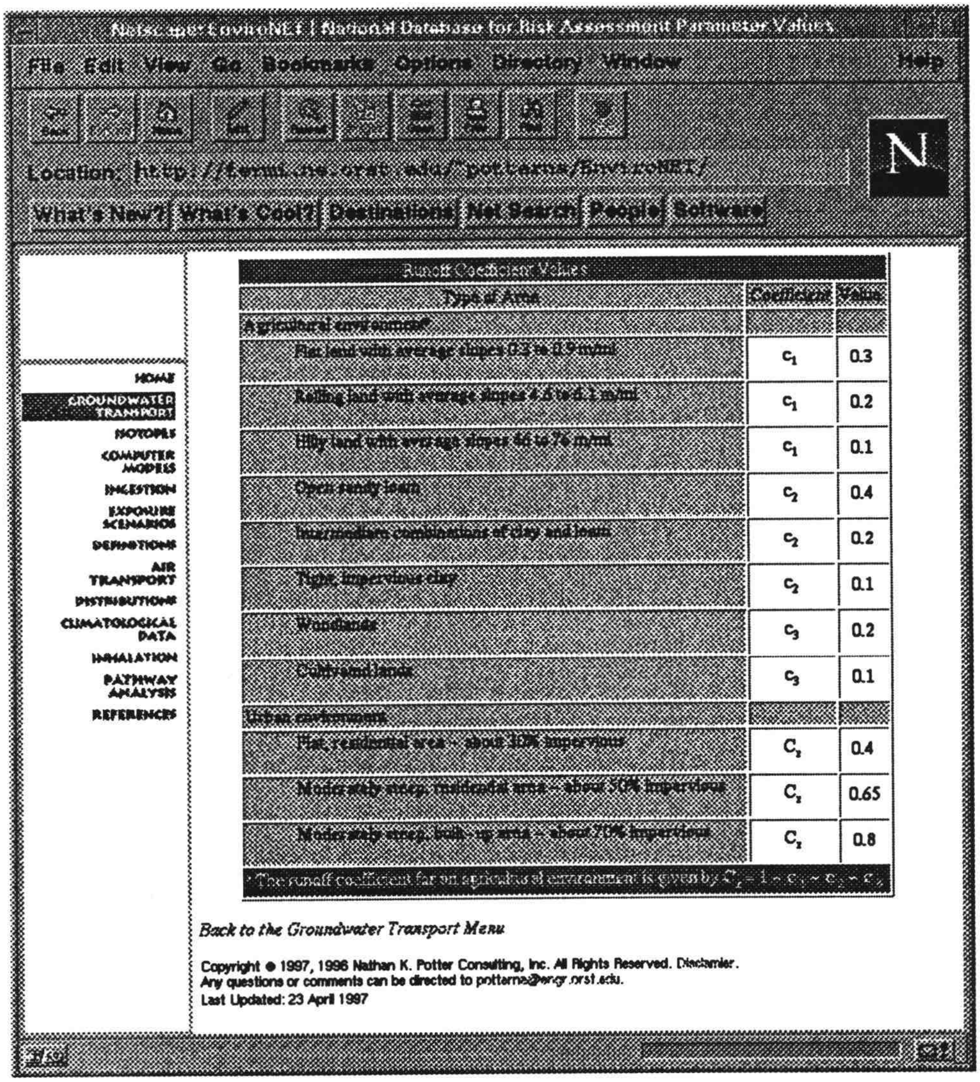
Figure 3.3: Radionuclide Release Rate Equation Page



Runoff Coefficient Values

Type of Area	Coefficient	Value
Agricultural environment*		
Flat land with average slopes 0.3 to 0.9 m/mi	c_1	0.3
Rolling land with average slopes 4.6 to 6.1 m/mi	c_1	0.2
Hilly land with average slopes 46 to 76 m/mi	c_1	0.1
Open sandy loam	c_2	0.4
Intermediate combinations of clay and loam	c_2	0.2
Tight, impervious clay	c_2	0.1
Woodlands	c_3	0.2
Cultivated lands	c_3	0.1
Urban environment		
Flat, residential area – about 30% impervious	C_r	0.4
Moderately steep, residential area – about 50% impervious	C_r	0.65
Moderately steep, built-up area – about 70% impervious	C_r	0.8

* The runoff coefficient for an agricultural environment is given by $C_r = 1 - c_1 - c_2 - c_3$

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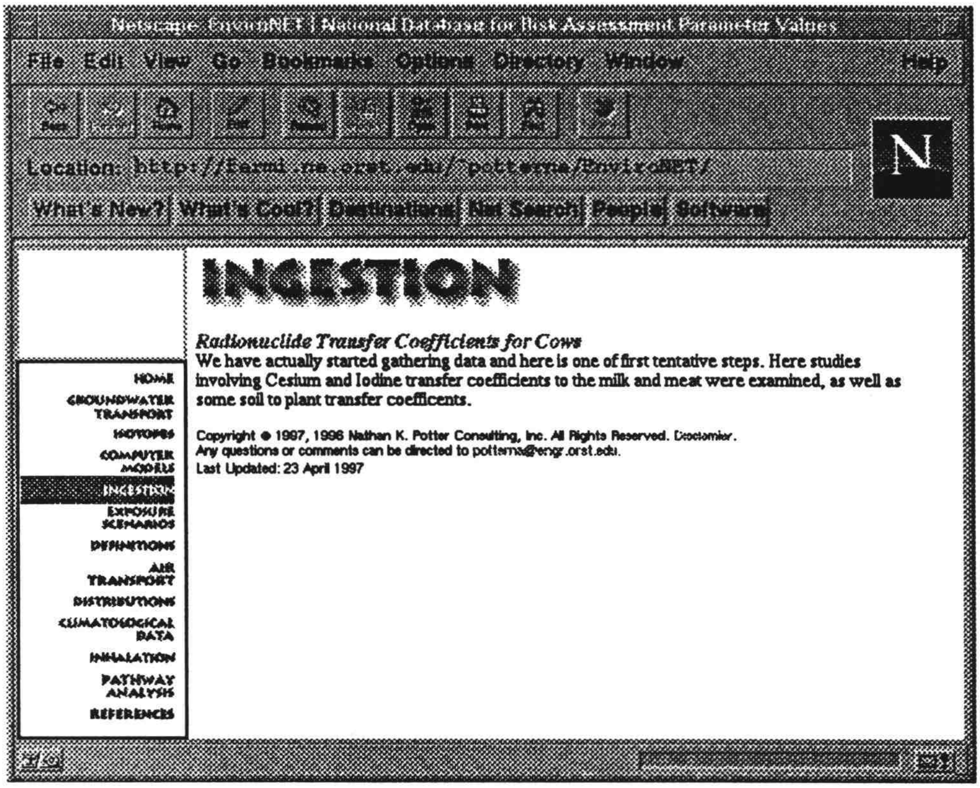
Figure 3.4: Runoff Coefficient Table Page

Currently, the only data that is maintained by a remote site is cesium uptake data in cows, which is maintained at Sandia National Laboratories. Figure 3.5 *(Ingestion Pathway Page),* illustrates how the link is maintained from Oregon State University.



INGESTION

Radionuclide Transfer Coefficients for Cows

We have actually started gathering data and here is one of first tentative steps. Here studies involving Cesium and Iodine transfer coefficients to the milk and meat were examined, as well as some soil to plant transfer coefficents.

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Figure 3.5: Ingestion Pathway Page

4. ENVIRONMENTAL MODELING

There are two methods used in constructing an environmental model: deterministic and probabilistic. Due to the inherent complexity of environmental systems, neither methodology can accurately predict what is occurring at all pathways at all times. Deterministic and probabilistic models can be used with a great deal of success to study aspects of specific pathways. Each method has its merits and drawbacks. The key is to use the appropriate model for the appropriate problem. A risk assessment attempts to interpret the results obtained from an environmental model in view of laboratory or other data concerning exposure risks to humans and other species.

4.1. Deterministic Modeling

A deterministic model assumes that a process can be defined by physical terms and without a random component (Singh, 1982a). A deterministic environmental model is essentially a mathematical calculation where single values representing environmental parameters are entered into the model representing an environmental pathway, a calculation is performed, and a solution is obtained. The environmental parameters are determined through assumptions either directly from measurements conducted on site or from compiled environmental data. For the solution to make any sense, the assumptions that are made must be focused towards specific events or populations.

Generally, the hypothetical *"maximally-exposed individual"* or *"minimally-exposed individual"* is selected to illustrate the risk of a given contamination event. Calculations are conducted to predict relevant concentrations and locations of specific contamination in the environment. *Risk factors* (laboratory compiled data relating concentration levels and location in the environment to risk to the population), are then coupled with predicted environmental concentrations used to calculate a *risk estimate.* However, the risk estimate is based solely on the initial assumptions that were made. It does not evaluate the *"potential"* or the *"possibility"* of other occurrences taking place. A remediation strategy is then determined based on those same assumptions. The financial cost of a project does not play a primary role in decision making process.

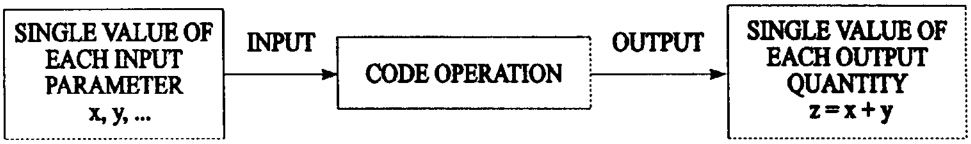


Figure 4.1: Deterministic Modeling (Till and Meyer, 1983)

4.2. Probabilistic Modeling

Probabilistic modeling examines a process using distribution data rather than specific points. A probabilistic environmental model may be based on the same, or very similar, mathematical calculations as the deterministic environmental model. The difference lies in how the environmental parameters are interpreted. Environmental parameters are interpreted as distribution functions in the probabilistic model. Here the characteristics of a target population and environment are examined as values versus frequency of those values occurring. More calculations are required due to the large volume of data that is evaluated so computers are necessary. The solution is then represented as a distribution.

The input parameter distribution functions are sampled using Monte Carlo or other techniques and a solution is determined in the form of a distribution. The necessity to make assumptions is minimized and all the available data are examined. Risk factors can also be interpreted as distributions and a risk estimate can be calculated by comparing the risk of a given situation with an acceptable risk level. This facilitates a risk-based remediation strategy and in turn a more cost effective solution to a problem.

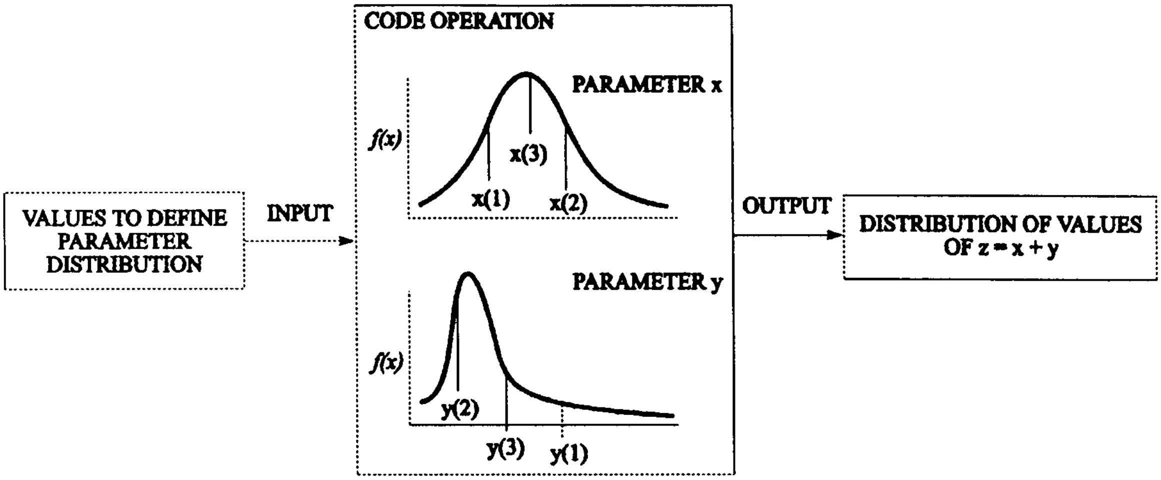


Figure 4.2: Probabilistic Modeling (Till and Meyer, 1983)

5. USING URANIUM MINING WASTE REMEDIATION AS A FUNCTIONAL DATABASE ILLUSTRATION

A practical application was needed to focus the development of the prototype database. It was decided to model uranium daughters leaching out of abandoned uranium mill tailings and uses the parameters, which described this process to form the data set for the database prototype. It is important to understand the type of data that will be included in the database. Organization of that data plays a major role. A single environmental parameter influences many different aspects of an environmental pathway. Invariably, the more important a parameter, the greater the amount of material is available describing it. This greatly influences the design of the database by attempting to facilitate the researchers needs.

Uranium mines exist all over the world in a variety of different types of environments. Since uranium is naturally present in the soil, the removal of the uranium through mining concentrates uranium decay products in the soil it is extracted from. This soil is stored and currently is considered *disposed of* in large tailings piles close to the mines it was removed from. With the fall in uranium prices throughout the 1980's and early 1990's (Chenoweth, 1984, 1985, 1986, 1988, 1989, 1990, 1991) and the current nuclear climate in the United States, many of these mines closed down. Currently there are 27 closed facilities in the western United States alone (*Journal of Environmental Engineering,* 1986).

5.1. Uranium Fuel Cycle

The uranium fuel cycle begins by the mining of natural uranium (U_3O_8) from the ground. Natural uranium is made up of approximately 99.2 percent ^{238}U and 0.711 percent ^{235}U. Due to the low nature of uranium ore concentration in the ground, it was necessary to remove a great deal of soil. This requires the uranium mine and mill to be in fairly close proximity. The soil is then milled to separate out the natural uranium oxide.

The separated natural uranium, called yellowcake, is then shipped to a conversion facility to convert it into uranium hexafluoride (UF_6). The UF_6 is then transported to an enrichment facility to concentrate and separate the fissile ^{235}U from ^{238}U. The ^{235}U is then fabricated into nuclear fuels. The remaining ^{238}U (depleted uranium) is essentially considered waste and disposed of as low level radioactive waste (LLW); although, some military uses and advanced nuclear reactor designs can use this material.

The soil, from which the uranium is separated, called mill tailings, is generally disposed of in large piles. Due to the large amount of soil displaced from the mine, the waste piles and ponds are located in fairly close proximity to the mill to reduce operating overhead. Through the natural decay of uranium in the soil and the processing of uranium ore through mining and milling, uranium decay products, called daughters or progeny, are concentrated in the mill tailings. The mill tailings are considered a form of radioactive waste and must be disposed of under its own specific regulations.

5.2. Isotopes of Concern

The major isotopes of concern for uranium mill tailings are those in the ^{238}U decay chain. Figure 5.1, *Natural Uranium (^{238}U) Decay Chain,* illustrates the decay of natural uranium as well as the half-live and percentage abundance of each decay progeny. The primary daughters of concern in the uranium decay chain are thorium (^{230}Th), radium (^{226}Ra), radon (^{222}Rn), and the daughters of ^{222}Rn.

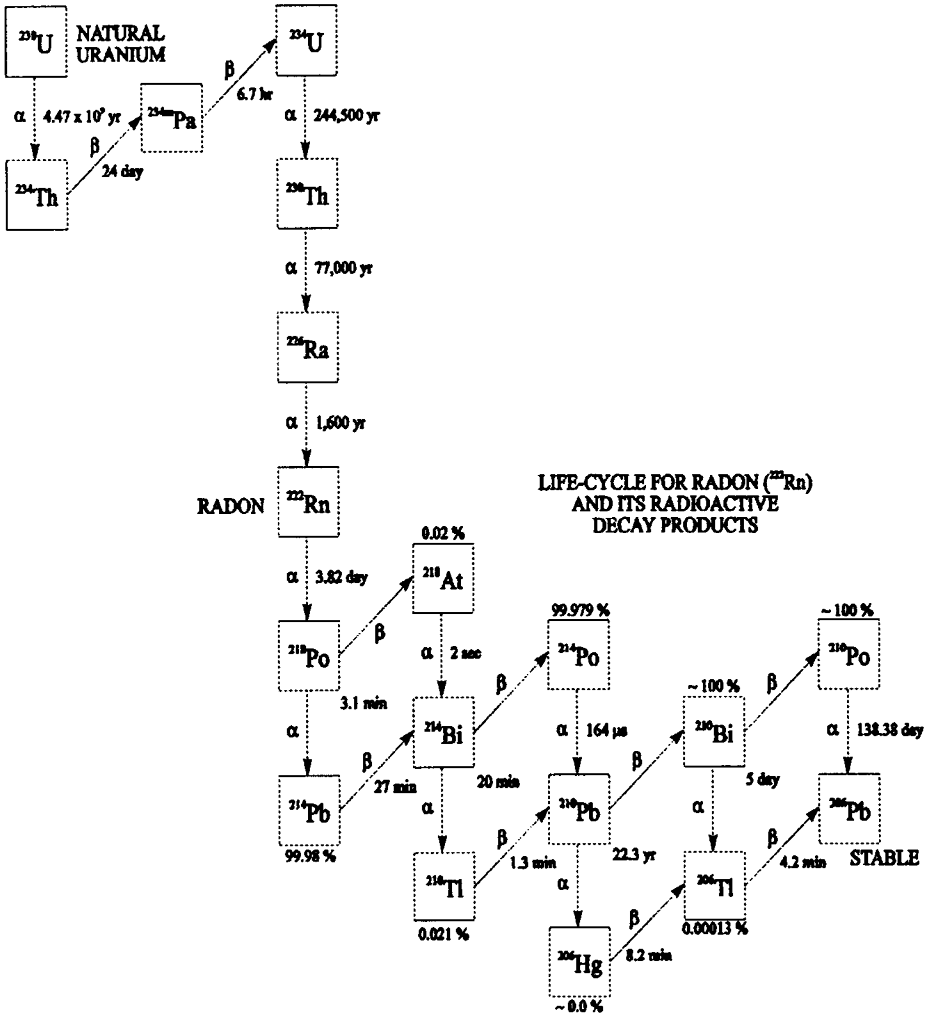


Figure 5.1: Natural Uranium (^{238}U) Decay Chain (Shleien, 1992; Walker, 1989)

5.3. Study Areas

When considering data for the construction of an environmental database, many questions arose on how the data would be stored and accessed. In answering those questions, the need for a practical example was identified. Uranium mining, the problems associated with the disposal of large amounts of soil, and the potential exposure scenarios seemed to ideally suit the database concept. Early analysis of existing and abandoned uranium mines showed that uranium is present in many completely different soil and climatological environments. With the decision already made to use uranium mining and milling waste disposal as a practical example, the logical progression was to select one of the most notorious uranium mines ever to encounter elevated exposure issues with disposal of their wastes. The Climax Uranium Mill, located south of Grand Junction, Colorado, was selected as the primary example because in 1966, it was discovered that mill tailings were used in the construction of homes, schools, and other buildings which led to increased exposure to uranium decay products (*Journal of Environmental Engineering,* 1986).

To expand the amount of available environmental data, more sites, however, were needed. To focus the scope of the project, it was determined that two additional sites would be selected while still attempting to maintain a somewhat consistent nature to the data obtained from Climax Uranium Mill in Gunnison County. The two additional sites were therefore selected from sites present in southwestern Colorado: the VCA site in La Plata County and the Kerr-McGee site in Mesa County.

5.3.1. Gunnison County (Paonia Area)

The Paonia Area has a low annual precipitation and a short growing season. Moisture is seasonally distributed. The area is also unsuited for dry-land farming and of the available farmland, 49,271 acres require irrigation (USDC, 1992). Soil types in the region consist of loam, stony loam, alluvial loam, and clay loam. All the surface water in the area flows towards the Gunnison River valley.

The 105-acre Climax Uranium (Gunnison) site has 1.9 million tons of uranium mill tailings disposed of over a 60 acre area with an average uranium content of 0.017 percent. The site is also considered a high priority for clean up. The status of the mill tailings is stabilized but needs improvement. Additionally, there is evidence of wind erosion and the site is in close proximity to surface water.

5.3.2. La Plata County

La Plata County is made up of mesas, foothills, and valleys with high mountains in the north. Its climate is semi-arid to sub-humid and receives around 18 inches of annual precipitation with heavy snows during the winter months. The area is unsuited for dry-land farming and of the available farmland, 85,394 acres require irrigation (USDC, 1992). All the surface water in the area flows towards the Animas, Florida, La Plata, and Los Pinos Rivers, which in turn flows into the San Juan River in New Mexico.

The 126-acre VCA site (Durango) has 1.5 million tons of uranium mill tailings disposed of over a 14-acre area with average uranium content of 0.04 percent. The site is considered a high priority for cleanup. The status of the mill tailings is stabilized but needs improvement. There is some evidence of wind erosion and the tailings are in close proximity to surface water.

5.3.3. Mesa County (Uncompahgre National Forest Area)

The Uncompahgre National Forest Area is a cool semi-arid high desert mesa. The region receives 15 to 35 inches of precipitation per year with at least half of that amount falling as snow. The Census of Agriculture (1992) reported 78,267 acres of the available farmland require irrigation. Soil types in the region consist of clay, and clay loam. The surface water also flows towards the Gunnison River valley.

The 61 acre Kerr-McGee (Grand Junction) site has 540,000 tons of uranium mill tailings disposed of over a 35 acre area with an average uranium content of 0.017 percent. The site is also considered a high priority for clean up. The status of the mill tailings is stabilized but needs improvement and is a probable source of groundwater contamination. Additionally, the site is in close proximity to surface water and residential housing.

5.4. RESRAD Environmental Dose Pathway Analysis Code

A mathematical model was necessary to focus the selection of parameters that would be included into the database. Examination of the available models led to the selection of a sub-model of the *RESidual RADiation* or RESRAD environmental dose pathway analysis computer modeling code (Yu, et al., 1993). The RESRAD computer code was developed by Argonne National Laboratories for the United States Department of Energy (USDOE) to guide environmental remediation activities at radioactive contaminated sites and has become an industry standard.

5.4.1. Examining RESRAD Input

In Appendix 2, *Required RESRAD Input Parameters,* the default parameters necessary for a simple exposure dose calculation are illustrated. Nine different exposure pathways are considered. Additionally, within each of the nine pathways, several environmental parameters are required. To execute a RESRAD analysis, values are entered for each possible field. The code then calculates the resulting dose for a specific individual. An unusual attribute discovered when working with RESRAD, and one of primary motivators for the database project, was how or where the default-input parameters were obtained. From the RESRAD Manual (Yu, et al., 1993), literature references pertaining to certain parameters were traced back through the literature to the original studies performed at the U.S. Geological Survey Hydrologic Laboratory (Moris and Johnson, 1967). These parameters were laboratory-derived values for the total and effective porosity and how the soil types influence those values.

5.5. Examining Radionuclide Release Rate Equation Parameters

Due to the size and complexity of the RESRAD environmental dose modeling code, a small part of the water pathway factor was selected and examined. There are two components to this pathway: (1) a water pathway segment that extends from the contaminated zone to a point where transport through the food chain begins (a well or surface water body); and (2) a food chain pathway segment that extends from the point of entry of a radionuclide from water into the food chain to a point of human exposure. The equation chosen was a component of the water pathway segment dealing with the radionuclide release rate. Radionuclides absorbed in soil are subject to leaching by infiltrating water. This serves as a source for groundwater contamination and applies directly towards the uranium daughter leaching out of mill tailings piles.

The model that RESRAD uses is a sorption-desorption, ion-exchange leaching model and is defined as the amount of radionuclide *i* leached out per unit time. It is characterized by a nuclide dependent, first order leach rate constant L_i. The radionuclide release rate given in *Appendix E* of the *Manual for Implementing Residual Radioactive Guidelines Using RESRAD, Version 5.0* (Yu, et al., 1993) is,

$$\dot{R}_i = L_i \rho_b^{(cz)} A T(t) S_i(t), \tag{5.1}$$

where

$\rho_b^{(cz)}$ is the soil bulk density of the contaminated zone (kg/m^3),

A is the contaminated area (m^2),

$T(t)$ is the thickness of the contaminated zone at time t (m),

$S_i(t)$ is the average concentration for radionuclide i in the contaminated zone available for leaching at time t (pCi/kg),

L_i is the leach rate constant for radionuclide i (yr^{-1}).

The first-order leach rate constant for a specific radionuclide is defined by the equation,

$$L_i = \frac{I}{\theta^{(cz)} T_o R_{d_i}^{(cz)}}, \tag{5.2}$$

where

I is the infiltration rate *(m/yr)*,

$\theta^{(cz)}$ is the volumetric water content of the contaminated zone *(dimensionless)*,

T_o is the initial thickness of the contaminated zone *(m)*,

$R_{di}^{(cz)}$ is the retardation factor in the contaminated zone for radionuclide *i (dimensionless)*.

The infiltration rate is determined from,

$$I = (1 - C_e)\,[(1 - C_r)\,P_r + I_{rr}], \tag{5.3}$$

where

C_e is the evapotranspiration coefficient *(dimensionless)*,

C_r is the runoff coefficient *(dimensionless)*,

P_r is the precipitation rate *(m/yr)*,

I_{rr} is the irrigation rate *(m/yr)*,

and the evapotranspiration coefficient is determined from,

$$C_e = \frac{E_t}{(1 - C_r)P_r + I_{rr}}, \tag{5.4}$$

where

E_t is the evapotranspiration rate *(m/yr)*.

Table 5.1, *Runoff Coefficient Values,* shows how RESRAD determines runoff coefficient values for agricultural and urban environments. The volumetric water content of the contaminated zone is given by,

$$\theta^{(cz)} = \theta_{sat}^{(cz)} R_s^{(cz)}, \tag{5.5}$$

where

$R_s^{(cz)}$ is the saturation ratio of the contaminated zone *(dimensionless)*, and

$\theta_{sat}^{(cz)}$ is the saturated water content of the contaminated zone *(dimensionless)*.

For saturated conditions, the saturated water content,

$$\theta_{sat} = p_t, \tag{5.6}$$

where

p_t is the total porosity of the soil *(dimensionless)*.

The saturation ratio *(dimensionless)* is given as,

$$R_s = \frac{\theta}{\theta_{sat}}, \tag{5.7}$$

by definition and by inserting Equation 5.6,

$$R_s = \frac{\theta}{p_t}. \tag{5.8}$$

Under unsaturated infiltration conditions, the saturation ratio can be estimated by,

$$R_s = \left(\frac{I}{K_{sat}}\right)^{\frac{1}{2b+3}}, \tag{5.9}$$

where

I is the infiltration rate *(m/yr)*,

K_{sat} is the saturated hydraulic conductivity *(m/yr)*, and

b is the soil-specific exponential parameter *(dimensionless)*.

Table 5.1: Runoff Coefficient Values (Yu, et al., 1993).

Type of Area	Coefficient	Value
Agricultural environment[a]		
Flat land with average slopes 0.3 to 0.9 m/mi	c_1	0.3
Rolling land with average slopes 4.6 to 6.1 m/mi	c_1	0.2
Hilly land with average slopes 46 to 76 m/mi	c_1	0.1
Open sandy loam	c_2	0.4
Intermediate combinations of clay and loam	c_2	0.2
Tight, impervious clay	c_2	0.1
Woodlands	c_3	0.2
Cultivated lands	c_3	0.1
Urban environment		
Flat, residential area - about 30% impervious	C_r	0.4
Moderately steep, residential area – about 50% impervious	C_r	0.65
Moderately steep, built-up area – about 70% impervious	C_r	0.8

[a] The runoff coefficient for an agricultural environment is given by $C_r = 1 - c_1 - c_3 - c_3$.

The retardation factor *(dimensionless)* for a radionuclide is the ratio of the average pore water velocity and the radionuclide transport velocity and was given by,

$$R_{d_i} = 1 + \frac{\rho_b K_{d_i}}{\theta}, \tag{5.10}$$

where

K_{di} is the distribution coefficient for the *ith* principle nuclide *(cm^3/g)*,

ρ_b is the soil bulk density *(g/cm^3)*, and

θ is the volumetric water content of the contaminated zone *(dimensionless)*.

Table 5.2, *Representative Values of Saturated Hydraulic Conductivity, Saturated Water Content, and the Soil-Specific Exponential Parameter*, shows some representative values for saturated hydraulic conductivity, saturated water content, and the soil-specific exponential parameter for different soil compositions given by Yu (1993). Inserting for the volumetric water content of the contaminated zone,

$$\theta = p_t R_s, \tag{5.11}$$

gives a retardation factor defined by the equation,

$$R_{d_i} = 1 + \frac{\rho_b K_{d_i}}{p_t R_s}. \tag{5.12}$$

From the definitions for the radionuclide release rate equation, leach rate equation, retardation factor, and saturation ratio, the radionuclide release rate equation can be simplified to,

$$\dot{R}_i = \frac{\left[1-\left(\frac{E_t}{(1-C_r)P_r + I_{rr}}\right)\right]\left[(1-C_r)P_r + I_{rr}\right]}{\theta^{(cz)} T_o R_{d_i}^{(cz)}} \rho_b^{(cz)} A T(t) S_i(t), \tag{5.13}$$

which can be further simplified to,

$$\dot{R}_i = \frac{\left[(1-C_r)P_r + I_{rr}\right] - E_t}{\theta^{(cz)} T_o \left(1 + \frac{\rho_b K_{d_i}}{\theta}\right)} \rho_b^{(cz)} A T(t) S_i(t), \tag{5.14}$$

giving the radionuclide release rate in picocuries per year *(pCi/yr)*.

Table 5.2: Representative Values of Saturated Hydraulic Conductivity, Saturated Water Content, and the Soil-Specific Exponential Parameter (Yu, et al., 1993).

Texture	Hydraulic Conductivity, K_{sat} (m/yr)	Saturated Water Content, θ_{sat}	Soil-Specific Exponential Parameter, b
Sand	5.55×10^3	0.395	4.05
Loamy sand	4.93×10^3	0.410	4.38
Sandy loam	1.09×10^3	0.435	4.90
Silty loam	2.27×10^2	0.485	5.30
Loam	2.19×10^2	0.451	5.39
Sandy clay loam	1.99×10^2	0.420	7.12
Silty clay loam	5.36×10^1	0.477	7.75
Clay loam	7.73×10^1	0.476	8.52
Sandy clay	6.84×10^1	0.426	10.40
Silty clay	3.26×10^1	0.492	10.40
Clay	4.05×10^1	0.482	11.40

The parameters in the radionuclide release rate equation can be divided into three general categories; (1) those measured directly on site, (2) those determined from mathematical expressions from laboratory analysis, and (3) those influenced by the environment and the contamination event. The factors influenced by the environment and the contamination event are those that lend themselves directly to the environmental database prototype, with one exception. They deal with the background data that is somewhat obscure and difficult to obtain but directly influences the mobility of contaminates in the environment. The variables examined for the database prototype were the soil bulk density of the contaminated zone *($\rho_b^{(cz)}$);* the total porosity *(p_t);* the precipitation rate *(P_r);* the irrigation rate *(I_{rr});* evapotranspiration rate *(E_t);* and the volumetric water content of the contaminated zone *($\theta^{(cz)}$)*. The *"(cz)"* qualifier is used to indicate *"contaminated zone"* parameters. Essentially there is no difference between contaminated zone parameters and non-contaminated zone parameters.

The runoff coefficient *(C_r)* and the evapotranspiration rate *(E_t)* are determined by mathematical expressions developed from laboratory analysis of specific systems. Values such as the contaminated area *(A);* the thickness of the contaminated zone at time t *($T(t)$);* the average concentration for radionuclide i in the contaminated zone available for leaching at time t *($S_i(t)$);* and the initial thickness of the contaminated zone *(T_o)* are determined when the site is characterized and are usually obtained through direct measurements.

The exception is the equilibrium distribution coefficient *(K_{di})*. It is a parameter that is unique in that it falls into two of the categories. It is determined by laboratory experiments; however, it directly affects the mobility of contamination through the environment. The distribution coefficient is somewhat controversial in how it is used and derived, but for environmental study it serves as a useful tool.

The ultimate goal in examining the parameters utilized by the radionuclide release rate equation was to determine distributions for selected environmentally specific data.

This would enable us to develop the prototype database to encompass the range of possible values and focus the structure of that database.

6. PARAMETER DISCUSSION

6.1. Distributions

There is a definite trend towards probabilistic modeling as a method for characterizing risk. However, that is not say that there are no difficulties associated with the method. For every key parameter, a reasonable and descriptive distribution must be assigned to the available data sets. Creation of reasonable and descriptive distributions proved to be somewhat involved. Existing environmental data can invariably be linked (McWhorter and Sunada, 1977) to narrow scope studies done in the past. Over the years, as research into the environmental field has broadened, these same studies have continually been referenced in newer work. Rarely has the original study been updated (Baes and Sharp, Isherwood, 1981; 1983; McWhorter and Sunada, 1977; Yu, et al., 1993). Any errors or assumptions present in the original study have propagated through the years.

With an understanding of the arguments for probabilistic modeling and therefore, the necessity of distribution data for environmental parameters, this environmental data must be re-evaluated. Examination of the radionuclide release rate equation from RESRAD yielded several parameters that lend themselves well to this application as well as identifying others where representation as a distribution were not applicable. Examining the retardation factor, distribution coefficient, soil porosity, the precipitation rate, and the volumetric water content all with respect to U.S. Department of Agriculture soil data from La Plata County, Uncompahgre National Forest Area (Mesa County), and the Paonia Area (Gunnison County), distributions of specific environmental parameters could be developed.

6.2. Retardation Factor

The retardation factor in the contaminated zone for radionuclide *i* $(R_{di}^{(cz)})$ is a dimensionless parameter represented by the equation,

$$R_{d_i} = 1 + \frac{\rho_b K_{d_i}}{\theta}, \tag{6.1}$$

which is a relationship between the equilibrium distribution coefficient, soil bulk density, and volumetric water content.

6.2.1. *Equilibrium Distribution Coefficient*

The equilibrium distribution coefficient or distribution coefficient (K_d) measured in centimeters^3 per gram, refers to the extent a radionuclide is sorbed to the soil it is passing through. In a broad sense the distribution coefficient can be explained as,

$$K_d = \frac{\text{amount of radionuclide sorbed on sediment}}{\text{amount of radionuclide in solution}}. \tag{6.2}$$

The distribution coefficient and its validity are somewhat debated (Till and Meyer, 1983); however, its prolific use, especially in contamination transport models, requires discussion. A geochemist would not consider using a K_d until all assumptions necessary to support its use could be defined. Engineers use K_d more broadly as a method of simplifying calculations. By nature, K_d is dependent on many factors; radionuclide type, concentration, soil type, pH, and oxidation-reduction conditions. For environmental modeling, K_d needs to be generalized into a bulk parameter for the entire system, which is unrealistic but is done for many models. Table 6.1 illustrates gross average distribution coefficients for uranium and radium, two leachable mill tailings isotopes. Table 6.2 shows more detailed distribution coefficients specifically for uranium and thorium under certain environmental conditions. Table values for K_d for uranium and thorium ranges from 2.9 to 62,000 cm^3/g and 8 to 400,000 cm^3/g, respectively. Table 6.3 shows some typical average distribution coefficients K_d for various mill tailing elements in sand, soil, and clay. An inherent difficulty in developing a data distribution for distribution coefficients is the strong influence of site-specific factors such as pH, soil type, volumetric water content, and the type of contaminant involved.

Table 6.1: Gross average K_d (cm^3/g) for selected radionuclides (Till and Meyer, 1983).

Elements	Range	Median
Uranium[a]	16	-
Radium	10^2-10^3	5×10^2

[a] Highly dependent on oxidation reduction conditions

Table 6.2: Distribution Coefficients for Uranium and Thorium
(Till and Meyer, 1983; Isherwood, 1981).

K_d (cm^3/g)	Conditions
	Uranium
62,000	Silt loam, U(VI), Ca-unsaturated, pH 6.5
4400	Clay soil, U(VI), 5 m*M* $Ca(NO_3)_2$, pH 6.5
300	Clay soil, 1 ppm UO^{+2}, pH 5.5
2000	Clay soil, 1 ppm UO^{+2}, pH 10
270	Clay soil, 1 ppm UO^{+2}, pH 12
4.5	Dolomite, 100-325 mesh, brine, pH 6.9
2.9	Limestone, 100-170 mesh, brine, pH 6.9
	Thorium
160,000	Silt loam, Ca-unsaturated clay, pH 6.5
400,000	Montmorillonite, Ca-unsaturated clay, pH 6.5
160,000	Clay soil, 5 m*M* $Ca(NO_3)_2$, pH 6.5
40-130	Medium sand, pH 8.15
310-470	Very fine sand, pH 8.15
270-10,000	Silt/clay, pH 8.15
8	Schist soil, 1 g/L Th, pH 3.2
60	Schist soil, 0.1 g/L Th, pH 3.2
120	Illite, 1 g/L Th, pH 3.2
1000	Illite, 0.1 g/L Th, pH 3.2
<100,000	Illite, 0.1 g/L Th, pH >6

Table 6.3: Typical Average Distribution Coefficients K_d (cm^3/g) for Various Elements in Sand, Soil, and Clay
(Yu, et al., 1993).

Element	Soils and Clays	Sand	Geometric Standard Deviation
U	50	5	3.6
Th	60,000	6,000	4.5
Ra	70	7	7

Figures 6.1 through 6.4 illustrate distribution functions for distribution coefficients for uranium, thorium, polonium, and lead developed from the table data in Table 6.1 through 6.3. Using a Microsoft® Excel add-on called Crystal Ball®, probability distribution functions could be generated from the range, mean, and standard deviation for selected uranium decay progeny presented by Baes and Sharp (1983).

Crystal Ball® is a statistical forecasting add-on for Microsoft® Excel, which incorporates Monte Carlo methodologies into simple spreadsheet calculations. It allows a user to define a distribution for a cell or specific value in the spreadsheet called an *assumption.* Then a forecasting cell is defined by an equation and from that a resulting distribution can be generated.

Assumption: Distribution Coefficient for Uranium

Log-normal distribution with parameters:

Mean	104
Standard Deviation	218

Selected range is from 10.5 to 4.40 x 10^3
Mean value in simulation was 120

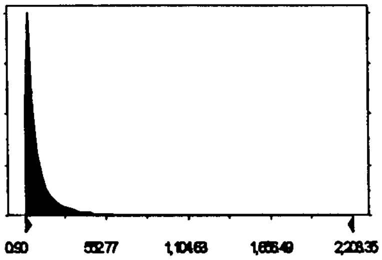


Figure 6.1: Distribution Coefficient for Uranium

Assumption: Distribution Coefficient for Thorium

Log-normal distribution with parameters:

Mean	1.84×10^5
Standard Deviation	5.37×10^5

Selected range is from 2,000 to 5.10×10^5
Mean value in simulation was 1.01×10^5

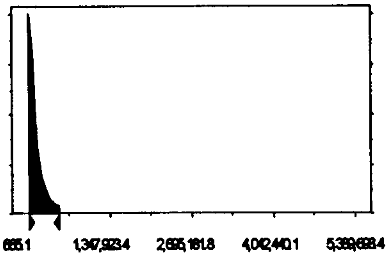


Figure 6.2: Distribution Coefficient for Thorium

Assumption: Distribution Coefficient for Polonium

Log-normal distribution with parameters:

Mean	672
Standard Deviation	487

Selected range is from 196 to 1.06×10^3
Mean value in simulation was 550

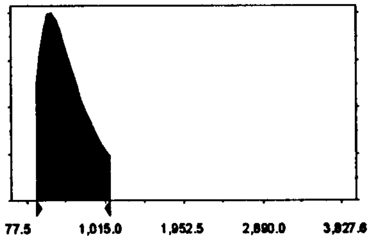


Figure 6.3: Distribution Coefficient for Polonium

Assumption: Distribution Coefficient for Lead

Log-normal distribution with parameters:

Mean	422
Standard Deviation	1.74×10^3

Selected range is from 4.50 to 7.64×10^3
Mean value in simulation was 389

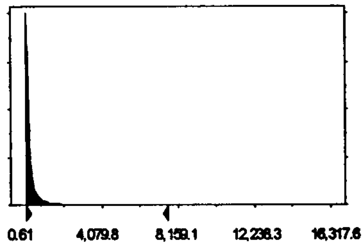


Figure 6.4: Distribution Coefficient for Lead

6.2.2. Soil Bulk Density

The soil bulk density *(ρ_b)* usually given in the range of 1.6 to 2.6 g/cm^3 or 1,600 to 2,600 kg/m^3. RESRAD requires a separate value specifically for the soil bulk density of the contaminated zone *($\rho_b^{(cz)}$)*. Dependent on the specific nature of the site and whether the presence of the contaminant modifies the specific parameter, this value can be assumed to be equal to the value as the non-contaminated zone bulk density (Yu, et al, 1993). This parameter is very closely tied to the porosity and volumetric water content, discussed in section 6.2.3, in the soil. Table 6.4 illustrates the range of soil bulk densities for five selected soil types as well as the logarithmic mean and standard deviation and the number of analyses performed. A review of the literature in this case revealed that interpretation by the original researchers (Baes and Sharp, 1983) consolidated the individual laboratory determined data points for the soil bulk density into a range of bulk densities and the number of analyses performed.

Table 6.4: Estimated Distributions of Soil Bulk Density for Five Soil types (g/cm^3) (Baes and Sharp, 1983).

Soil Type	Number Observed	Observed Arithmetic Mean of Logarithms, μ	Observed Standard Deviation of Logarithms, σ	Observed Range
Silt loams	99	0.28	0.11	0.86–1.67
Clays & clay loams	49	0.26	0.11	0.94-1.54
Sandy loams	37	0.40	0.09	1.25–1.76
Gravelly silt loams	15	0.20	0.10	1.02–1.42
Loams	22	0.35	0.08	1.16–1.58
All soils	222	0.30	0.12	0.86–1.76

Figures 6.5 through 6.9 illustrate distribution functions for soil bulk density for silt loams, clays and clay loams, sandy loams, gravelly silt loams, loams, and all five soil tested. The data in Table 6.4 was used with Crystal Ball® to generate probability distribution functions from the range, mean, and standard deviation for five soil types presented by Baes and Sharp (1983).

Assumption: Bulk Density for Silty Loam Soil

Log-normal distribution with parameters:

Mean	1.33
Standard Deviation	0.15

Selected range is from 0.86 to 1.67
Mean value in simulation was 1.32

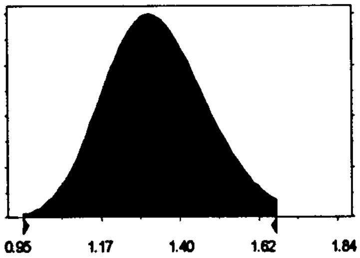


Figure 6.5: Bulk Density Distribution for Silty Loam Soil

Assumption: Bulk Density for Clay and Clay Loam Soil

Log-normal distribution with parameters:

Mean	1.30
Standard Deviation	0.14

Selected range is from 0.94 to 1.54
Mean value in simulation was 1.29

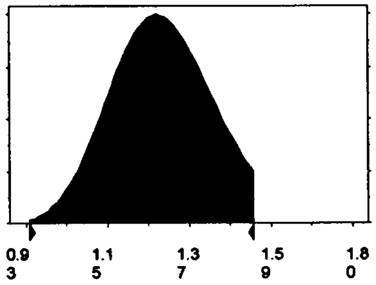


Figure 6.6: Bulk Density Distribution for Clay and Clay Loam Soil

Assumption: Bulk Density for Sandy Loam Soil

Log-normal distribution with parameters:

Mean	1.50
Standard Deviation	0.14

Selected range is from 1.02 to 1.42
Mean value in simulation was 1.34

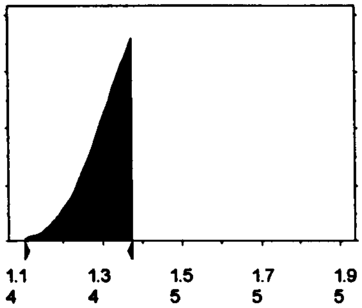


Figure 6.7: Bulk Density Distribution for Sandy Loam Soil

Assumption: Bulk Density for Gravelly Silt Soil

Log-normal distribution with parameters:

Mean	1.42
Standard Deviation	0.11

Selected range is from 1.16 to 1.58
Mean value in simulation was 1.40

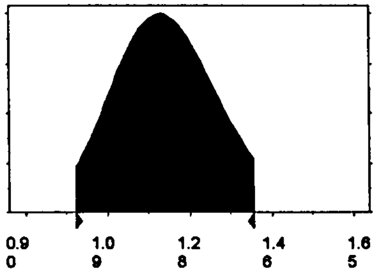


Figure 6.8: Bulk Density Distribution for Gravelly Silt Soil

Assumption: Bulk Density for Loam Soil

Log-normal distribution with parameters:

Mean	1.30
Standard Deviation	0.14

Selected range is from 0.94 to 1.54
Mean value in simulation was 1.29

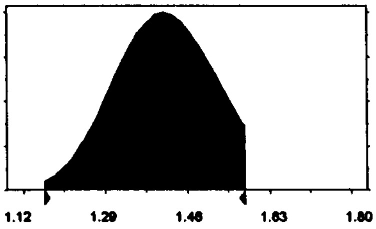


Figure 6.9: Bulk Density Distribution for Loam Soil

6.2.3. Volumetric Water Content

The volumetric water content *(θ) (dimensionless)* can be conservatively assumed to be equivalent to the field capacity. The field capacity is the maximum amount of water content where moisture can no longer be held against gravity. In turn, the field capacity is equivalent to the specific retention *(S_r)* and is defined by,

$$S_r = p_{eff} - p_t , \tag{6.3}$$

where p_{eff} is the effective porosity (or specific yield) and p_t is the total porosity (Till and Meyer, 1983). A further review of the literature supporting the Baes and Sharp (1983) article revealed that again interpretation by the original researchers consolidated the individual laboratory determined data points for the estimates of volumetric water content into a range of volumetric water contents and the number of analyses performed.

Table 6.5: Estimates of Volumetric Water Content θ, at Field Capacity for Four Soil Types (Baes and Sharp, 1983).

Soil Type	Number Observed	Observed Arithmetic Mean of Logarithms, μ	Observed Standard Deviation of Logarithms, σ	Observed Range
Silt loams	76	-1.06	0.14	0.243–0.454
Clays & clay loams	33	-1.02	0.16	0.255-0.448
Sandy loams	24	-1.53	0.27	0.124–0.329
Loams	17	-1.14	0.15	0.226–0.394
All soils	154	-1.14	0.24	0.124–0.454

Figures 6.10 through 6.13 illustrate distribution functions for volumetric water content for silt loams, clays and clay loams, sandy loams, loams, and all four soils tested. The data in Table 6.5 was again used with Crystal Ball® to generate probability distribution functions from the range, mean, and standard deviation for four soil types presented by Baes and Sharp (1983).

Assumption: Volumetric Water Content at Field Capacity for Silty Loam Soil

Log-normal distribution with parameters:

Mean	0.35
Standard Deviation	0.05

Selected range is from 0.24 to 0.45
Mean value in simulation was 0.35

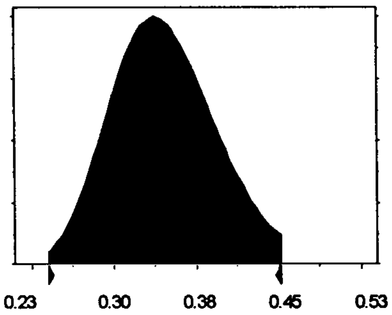


Figure 6.10: Volumetric Water Content Distribution at Field Capacity for Silty Loam Soil

Assumption: Volumetric Water Content at Field Capacity for Clay and Clay Loam Soil

Log-normal distribution with parameters:

Mean	0.37
Standard Deviation	0.06

Selected range is from 0.26 to 0.45
Mean value in simulation was 0.36

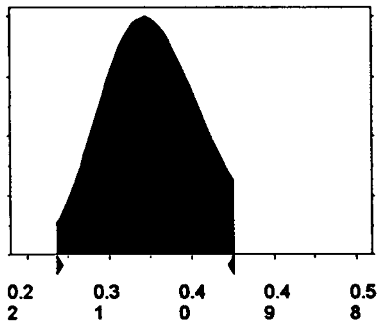
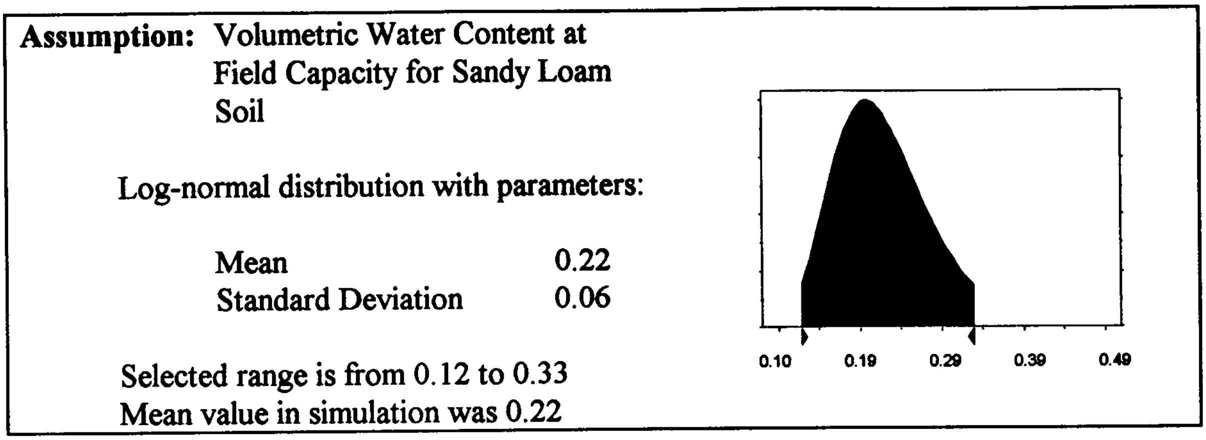


Figure 6.11: Volumetric Water Content at Field Capacity for Clay and Clay Loam Soil



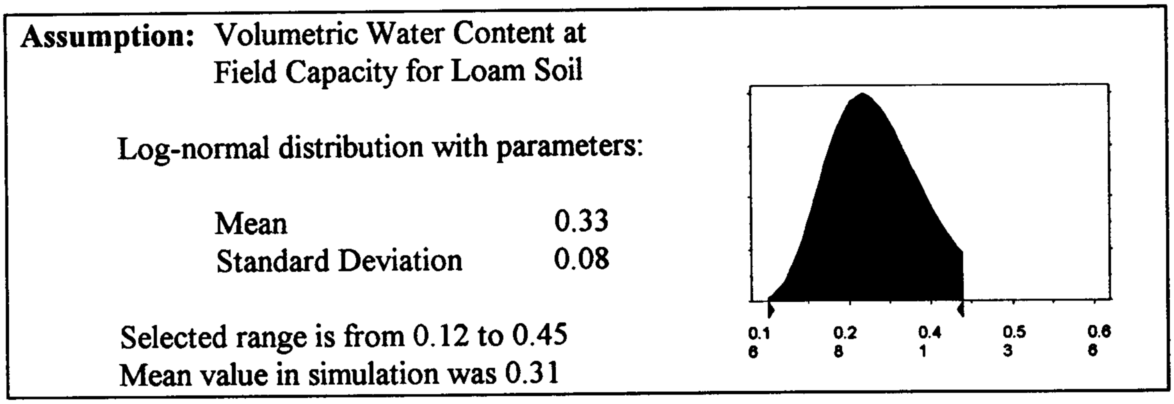
Assumption: Volumetric Water Content at Field Capacity for Sandy Loam Soil

Log-normal distribution with parameters:

Mean	0.22
Standard Deviation	0.06

Selected range is from 0.12 to 0.33
Mean value in simulation was 0.22

Figure 6.12: Volumetric Water Content Distribution at Field Capacity for Sandy Loam Soil



Assumption: Volumetric Water Content at Field Capacity for Loam Soil

Log-normal distribution with parameters:

Mean	0.33
Standard Deviation	0.08

Selected range is from 0.12 to 0.45
Mean value in simulation was 0.31

Figure 6.13: Volumetric Water Content Distribution at Field Capacity for Loam Soil

The total porosity is defined as the ratio of interstitial space to the space occupied by solid material. The effective porosity is then defined as the part of the porosity that is available for groundwater flow. Part of the water in the soil will invariably be retained in the pore space by forces associated with molecular attraction or trapped in dead-end pores. Table 6.6 illustrates some values for total porosity present in certain aquifer materials and Table 6.7 illustrates some values for effective porosity present in certain aquifer materials, as well as the number of analyses performed in each to determine their values. Again, RESRAD requires a specific value for the volumetric water content of the contaminated zone *(θ^{cz})* which is assumed to be the same as the non-contaminated zone volumetric water content.

Table 6.6: Total Porosity of Aquifer Materials
(McWhorter and Sunada, 1977).

Aquifer Material	Number of Analysis	Range	Arithmetic Mean
Igneous Rocks			
Weathered granite	8	0.34-0.57	0.45
Weathered gabbro	4	0.42-0.45	0.43
Basalt	94	0.03-0.35	0.17
Sedimentary Materials			
Sandstone	65	0.14-0.49	0.34
Siltstone	7	0.21-0.41	0.35
Sand (fine)	243	0.26-0.53	0.43
Sand (coarse)	26	0.31-0.46	0.39
Gravel (fine)	38	0.25-0.38	0.34
Gravel (coarse)	15	0.24-0.36	0.28
Silt	281	0.34-0.61	0.46
Clay	74	0.34-0.57	0.42
Limestone	74	0.07-0.56	0.3
Metamorphic Rocks			
Schist	18	0.04-0.049	0.044

Table 6.7: Typical Values of Effective Porosity (or specific yield) of Aquifer Materials (McWhorter and Sunada, 1977).

Aquifer Material	Number of Analysis	Range	Arithmetic Mean
Sedimentary Materials			
Sandstone (fine)	47	0.02-0.40	0.21
Sandstone (medium)	10	0.12-0.41	0.27
Siltstone	13	0.01-0.33	0.12
Sand (fine)	287	0.01-0.46	0.33
Sand (medium)	297	0.16-0.46	0.32
Sand (coarse)	143	0.18-0.43	0.30
Gravel (fine)	33	0.13-0.40	0.28
Gravel (medium)	13	0.17-0.44	0.24
Gravel (coarse)	9	0.13-0.25	0.21
Silt	299	0.01-0.39	0.20
Clay	27	0.01-0.18	0.06
Limestone	32	~0-0.36	0.14
Wind-Laid Materials			
Loess	5	0.14-0.22	0.18
Eolian Sand	14	0.32-0.47	0.38
Tuff	90	0.02-0.47	0.21
Metamorphic Rocks			
Schist	18	0.22-0.33	0.26

Figures 6.14 through 6.18 illustrate distribution functions for total soil porosity for silt loams, clays and clay loams, sandy loams, gravelly silt loams, loams, and total for all five of soil types tested. The data in Table 6.6 and 6.7 was used to generate probability distribution functions from the range, mean, and standard deviation for five selected soil types.

Assumption: Total Soil Porosity for Silty Loam Soil

Log-normal distribution with parameters:

Mean	0.49
Standard Deviation	0.05

Selected range is from 0.37 to 0.68
Mean value in simulation was 0.50

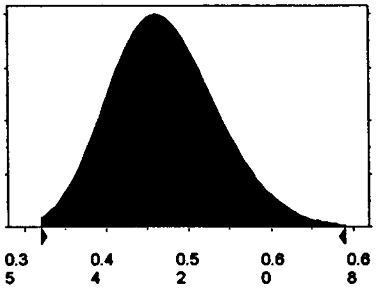


Figure 6.14: Total Soil Porosity Distribution for Silty Loam Soil

Assumption: Total Soil Porosity for Clay and Clay Loam Soil

Log-normal distribution with parameters:

Mean	0.51
Standard Deviation	0.05

Selected range is from 0.42 to 0.56
Mean value in simulation was 0.51

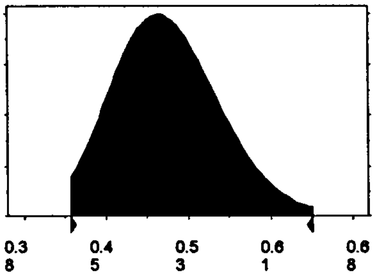


Figure 6.15: Total Soil Porosity Distribution for Clay and Clay Loam Soil

Assumption: Total Soil Porosity for Sandy Loam Soil

Log-normal distribution with parameters:

Mean	0.43
Standard Deviation	0.05

Selected range is from 0.34 to 0.53
Mean value in simulation was 0.43

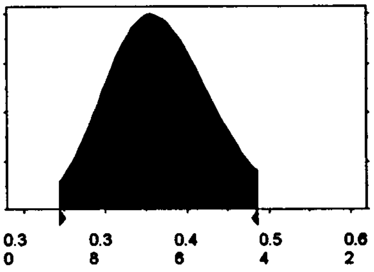


Figure 6.16: Total Soil Porosity Distribution for Sandy Loam Soil

Assumption: Total Soil Porosity for Gravelly Silt Soil

Log-normal distribution with parameters:

Mean	0.54
Standard Deviation	0.04

Selected range is from 0.46 to 0.62
Mean value in simulation was 0.54

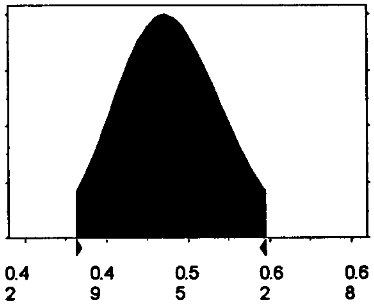


Figure 6.17: Total Soil Porosity Distribution for Gravelly Silt Soil

Assumption: Total Soil Porosity for Loam Soil

Log-normal distribution with parameters:

Mean	0.46
Standard Deviation	0.04

Selected range is from 0.41 to 0.56
Mean value in simulation was 0.47

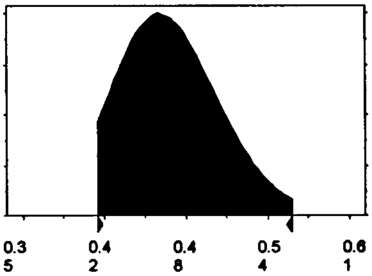


Figure 6.18: Total Soil Porosity Distribution for Loam Soil

6.3. Precipitation and Irrigation Rate

The precipitation rate *(P_r)* measured in meters per year is a parameter that, in most places in the world, is seasonally dependent. It lends itself very well to interpretation as a distribution but not necessarily a distribution function by enabling examination of the amount of rainfall as function of the time of year. Appendix 1, *Precipitation and Irrigation Data for Southwestern Colorado,* illustrates rainfall data obtained from the National Oceanic and Atmospheric Administration and the U. S. Department of Agriculture for the southwestern Colorado region (La Plata County, Uncompahgre National Forest Area (Mesa County), and the Paonia Area (Gunnison County)).

The irrigation rate *(I_{rr}),* measured in meters per year, is another parameter that can potentially be interpreted as a distribution. Irrigation rate is dependent on many factors. It is measured and reported in the amount of area that is irrigated and has a somewhat inverse relationship to the precipitation rate. The difficulty with interpreting an irrigation rate as a physical volume of water is that many other factors such as precipitation, evapotranspiration, soil porosity, soil moisture content, the length of the growing season, and the type of crop being grown, influence the amount of water being applied. Examining past irrigation histories and developing an average volume per year with a maximum and minimum yearly value could make a reasonable assumption for this parameter.

6.4. Evapotranspiration Rate

Evapotranspiration is a combined process of evaporation from the surface of the soil and transpiration by plants. It is normally the single largest component of water outflow from the soil-water subsystem. It is dependent on wind speed, humidity, temperature, solar radiation, plant cover, type of plant, and the availability of soil moisture. The evapotranspiration rate *(E_t)* measured in meters per year can be represented by the equation,

$$E_t = C_e\left[(1 - C_r)P_r + I_{rr}\right], \tag{6.4}$$

where E_t is a function of soil runoff, precipitation rate, and irrigation rate. C_e is the evapotranspiration coefficient. It has been stated that, "the reliability or adequacy of any method used to measure or calculate evapotranspiration is suspect due to the many different methods available" (Issar and Resnick, 1996). Therefore, it is necessary to stipulate that *evapotranspiration potential* and the *evapotranspiration rate* are not equivalent. The evapotranspiration potential differs by being the rate at which water will be evaporated or transpired from the soil if the source of water is unlimited. Evapotranspiration was discovered not to lend itself at all to representation as a distribution function. Both non-distribution function parameters such as the precipitation and irrigation rates as well as distribution function parameters such as the volumetric water content and the soil porosity influence it.

6.5. Discussion

Examination of the retardation factor, the precipitation rate, the irrigation rate, evapotranspiration rate, and the volumetric water content illustrate the complex interrelationships present between different parameters. The retardation factor alone involved three separate parameters. To further understand the volumetric water content of the soil, a detailed analysis of soil porosity needed to be performed as well as consideration of irrigation, precipitation, and evapotranspiration. In researching each parameter, references in the literature would be made to the importance of a certain aspect that was necessary for this condition to be valid; however, no further explanation would be provided. Other literature references would present data where the researchers had consolidated data for reporting purposes and the original numbers are not available.

Figures 6.19 through 6.22 illustrate bulk distribution functions for the total range of bulk density, soil porosity, and volumetric water content (both at wilting point and at field capacity (Baes and Sharp, 1983).

Assumption: Total Range for Bulk Density for
Five Soil Types

Log-normal distribution with parameters:

Mean	1.36
Standard Deviation	0.16

Selected range is from 0.86 to 1.76
Mean value in simulation was 1.35

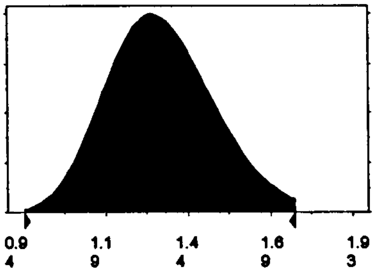


Figure 6.19: Total Range for Bulk Density Distributions for Five Soil Types

Assumption: Total Range for Total Soil Porosity for Five Soil Types

Log-normal distribution with parameters:

Mean	0.49
Standard Deviation	0.06

Selected range is from 0.34 to 0.68
Mean value in simulation was 0.48

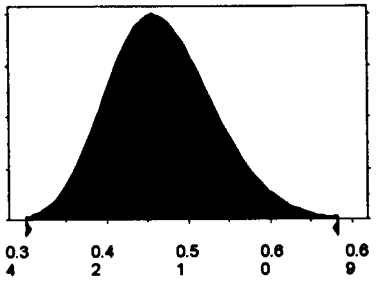


Figure 6.20: Total Range for Total Soil Porosity Distributions for Five Soil Types

Assumption: Total Range for Volumetric Water Content at Field Capacity for Four Soil Types

Log-normal distribution with parameters:

Mean	0.33
Standard Deviation	0.08

Selected range is from 0.12 to 0.45
Mean value in simulation was 0.32

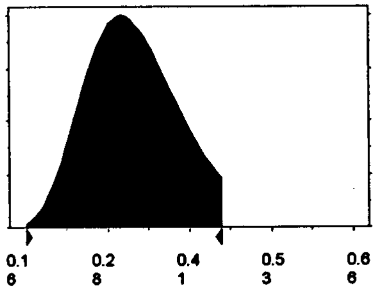


Figure 6.21: Total Range for Volumetric Water Content Distributions at Field Capacity for Four Soil Types

Assumption: Total Range for Volumetric Water Content at Wilting Point for Four Soil Types

Log-normal distribution with parameters:

Mean	0.15
Standard Deviation	0.07

Selected range is from 0.03 to 0.33
Mean value in simulation was 0.14

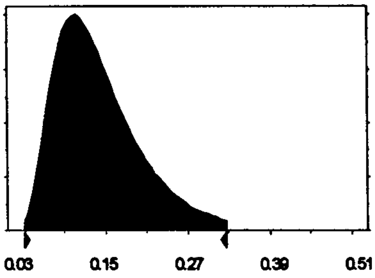


Figure 6.22: Total Range for Volumetric Water Content Distributions at Wilting Point for Four Soil Types

The process that was undertaken to generate these distributions is representative of some of the problems encountered with the development of any distribution function. Interpretation by the original researchers has a tendency to focus later research in a similar direction.

To illustrate some of the possibilities and differences between the use of deterministic methodologies versus probabilistic methodologies, a simple calculation was performed using Microsoft® Excel with the Crystal Ball® Monte Carlo add-on. The radionuclide release rate was calculated for a single time step probabilistically and deterministically using uranium specific data in a silty loam type soil. The distributions illustrated above were incorporated into the Microsoft® Excel spreadsheet and ran for the literature recommended 10,000 iterations. Here the distribution coefficient was selected from the distribution illustrated in Figure 6.1, the soil bulk density was selected from the distribution illustrated in Figure 6.5, and the volumetric water content (at field capacity) was selected from the distribution illustrated in Figure 6.10. These three values were used in Equation 5.10 to calculate a distribution for the retardation factor which is illustrated in Figure 6.23, *Retardation Factor for Uranium Forecast*. Again, Crystal Ball® refers to this distribution as a forecast in its methodologies and the cell designator indicated on the plot is just the cell that contained the equation the forecast was determined from. From this distribution, site specific data such as the contaminated area, the contaminated area thickness, the source concentration, precipitation rate, irrigation rate, evapotranspiration rate, and runoff coefficient were used in Equation 5.14 to calculate the distribution illustrated in Figure 6.24, *Radionuclide Release Rate Forecast*.

A deterministic calculation was performed using both *conservative* and non-conservative values, which, in themselves, are open to their own interpretation. Selecting specific data points from the available data for each parameter, values were chosen to facilitate maximum or minimize contaminate movement. The site-specific data was left unchanged from the probabilistic calculation. The results showed basically what has been described in previous chapters, the deterministic calculation presenting a single value for the radionuclide release rate and the probabilistic (Monte Carlo) calculation generating a distribution of the probability and frequency of any given radionuclide release rate for the given parameters. The deterministic calculations yielded a maximum retardation factor of 8.41×10^4 and minimum value of 70.6. These in turn yielded a maximum radionuclide release rate of 2.79×10^5 pCi/yr and a minimum value of 644 pCi/yr.

From here both models must now be interpreted for the validity of the results they returned. Comparison of the data illustrated in Figure 6.23 and Figure 6.24 with the results obtained from the deterministic calculation shows the variation between the deterministic calculation and probabilistic calculation. Both the conservative (maximum) and non-conservative (minimum) values are located at the right and left ends of the distribution, respectively. In either case, the deterministic results present statistically the lower probable outcome.

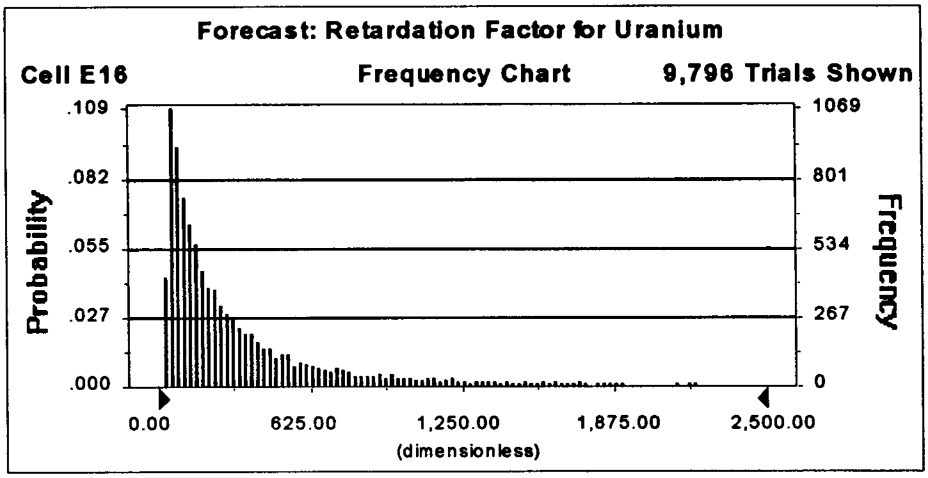


Figure 6.23: Retardation Factor for Uranium Forecast

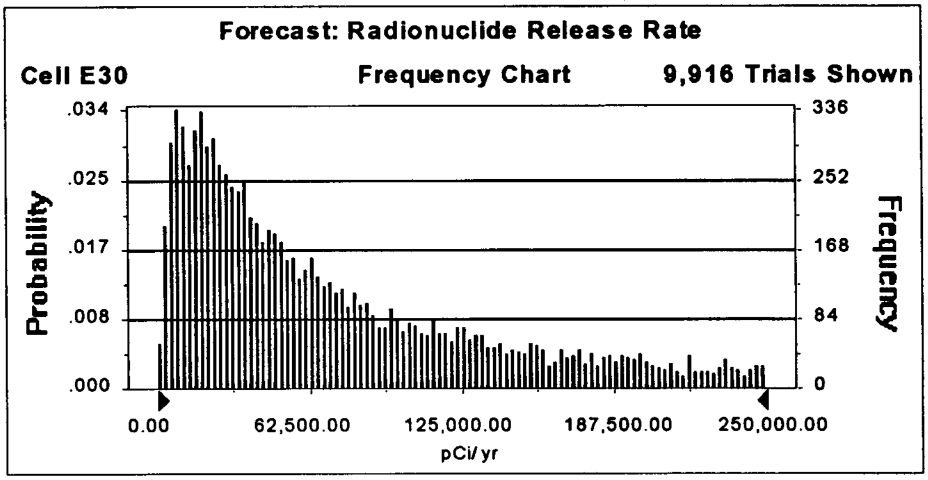


Figure 6.24: Radionuclide Release Rate Forecast

Probabilistic modeling and the development of these data distributions for environmental parameters are sound ideas and a necessary progression of the science of characterizing risk. The development, however, is still in its infancy and much of the existing data does not exist in a form that easily facilitates distribution development. Theoretically, any environmental parameter that is not a constant could potentially be represented as a distribution function. A great deal of work is still required in the examination of all aspects of environmental data.

6.6. Future Research

Examination of where research in this field needs to proceed is in two primary directions: continued research into the understanding of the environment and the methods of sharing and displaying the data that is developed from that understanding. There will always be a requirement for continued compilation and analysis of environmental data into the prototype database. More detailed studies can always be performed on environmental parameters.

An additional area that needs to be examined is related to the examples illustrated above. It concerns the use of Crystal Ball® and the correlating feature used in the data analysis. Crystal Ball® allows assumptions to be correlated or influenced by other parameters. In the examples illustrated above, the data was not correlated so that the maximum compounding of error that could occur from a simple environmental calculation could be illustrated. This is commonly referred to by the EPA and the environmental community as *creeping conservatism.* The advantage of using correlated variables is a more realist picture of risk and variability in the output. For example, if values such as the volumetric water content, soil bulk density, and soil porosity were correlated to represent how they are influenced by each other, the variations in the final results from the probabilistic calculation could be reduced. However, a problem with using the correlation that is generated by Crystal Ball® is that it only accounts for a positive or negative correlation. It is represented as a linear function and does not allow the user to deviate from this function other than by increasing the degree of random scatter in the data.

A constant area the needs to be examined is the development and incorporation of a more advanced search engine. The *FreeWAIS-sf (structured fields) Version 0.3* database searching and indexing package is currently being examined as a possible candidate. It is capable of performing many advanced text functions. It is capable of "stemming" which reduces a search word to a common form and is capable of searching for any variations on a single word. It is also capable of "streaming" which searches for words that sound like a defined search string. A limitation to the search engine is that it still requires a script to interface with an HTML page and it requires an index to be developed for it to search. This increases the amount of maintenance the database requires to be updated.

7. CONCLUSION

The consolidated environmental risk assessment parameter database concept is a significant step in the advancement of the science of characterizing risk. In our community where "in the absence of understanding, perceptions [become] realities," (Fabian, 1994) we must have access to all available information. The world-wide web, with its ever expanding capabilities, has the potential to provide that access to everyone.

The problem now lies in the interpretation of environmental data and development of data distributions for probabilistic analysis. In examining just some of the environmental parameters required in a small part of the water transport pathway of RESRAD, the complexity of an environmental problem can be illustrated. Also, a large amount of confusion exists surrounding the interrelationships present in interpreting just small part of the available data.

A standard theme of environmental parameters is a lack of precision. This makes it is easy to question the validity of data that can be considered *"accurate"* or *"representative"* while being defined by ranges covering a multiple of orders of magnitude. In turn, it becomes easy to debate those models that require that same data to achieve a result.

Sam Snead once commented to Ted Williams, *"in golf, you have to play your foul balls,"* (Feinstein, 1994). This serves as an ideal illustration of our responsibility as scientists and engineers to maintain our environment. Stewardship of nuclear waste has become the vital aspect concerning the survival of the nuclear industry. Until nuclear waste can be managed in an environmentally sound manner, the public will not allow any more abuse of their trust.

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APPENDICES

APPENDIX 1

PRECIPITATION DATA FOR SOUTHWESTERN COLORADO

1.1 Precipitation Data

Representative precipitation data was obtained from the United States Department of Agriculture Soil Conservation Service, and the National Oceanic and Atmospheric Administration. An interesting point to note was the dates of the original precipitation studies as well as the range of locations. The USDA data was conducted by counties and the NOAA data was conducted by state at five fixed sites.

Gunnison County (Panonia Area)
Data recorded in the period 1951 to 1973 at Cedaredge, Colorado (USDA, 1987)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	0.81	0.24	1.26	3	9.3
February	0.77	0.26	1.18	3	7.8
March	0.86	0.31	1.29	3	7.4
April	0.9	0.46	1.26	3	2.6
May	0.96	0.35	1.44	3	0.4
June	0.81	0.2	1.3	2	0.0
July	0.89	0.31	1.35	3	0.0
August	1.36	0.72	1.88	4	0.0
September	1.2	0.28	1.91	3	0.0
October	1.4	0.45	2.21	3	0.9
November	0.94	0.57	1.26	3	4.9
December	1.02	0.56	1.38	4	10.2
Total	11.92	9.80	13.92	37	43.5

Gunnison County (Panonia Area)
Data recorded in the period 1951 to 1972 at Delta, Colorado (USDA, 1987)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	0.33	0.08	0.51	1	3.7
February	0.36	0.08	0.58	1	2.8
March	0.39	0.08	0.62	2	1.4
April	0.55	0.19	0.83	2	0.2
May	0.56	0.17	0.86	2	0.0
June	0.51	0.12	0.81	1	0.0
July	0.61	0.24	0.9	2	0.0
August	1.04	0.44	1.51	3	0.0
September	0.92	0.17	1.49	3	0.0
October	1.13	0.25	1.84	3	0.3
November	0.56	0.31	0.76	2	2.5
December	0.49	0.2	0.71	2	4.6
Total	7.45	5.55	9.18	24	15.5

Gunnison County (Panonia Area)
Data recorded in the period 1957 to 1974 at Panoia, Colorado (USDA, 1987)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	1.15	0.39	1.75	4	12.5
February	1.1	0.4	1.66	4	7.3
March	1.27	0.55	1.85	4	7.7
April	1.47	0.84	1.98	4	3.7
May	1.24	0.46	1.85	4	0.2
June	0.89	0.26	1.39	3	0.0
July	1.06	0.39	1.6	3	0.0
August	1.46	0.64	2.12	4	0.0
September	1.53	0.62	2.25	5	0.0
October	1.54	0.57	2.32	4	0.7
November	1.22	0.7	1.64	4	3.0
December	1.56	0.87	2.12	5	15.6
Total	15.49	13.09	17.81	48	50.7

La Plata County
Data recorded in the period 1951 to 1978 at Durango, Colorado (USDA, 1988)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	1.69	0.49	2.65	5	17.2
February	1.14	0.29	1.83	4	10.8
March	1.44	0.33	2.31	5	11.4
April	1.24	0.45	1.89	3	4.0
May	1.02	0.2	1.65	3	0.5
June	0.63	0.08	1.05	2	0.0
July	1.79	0.87	2.58	5	0.0
August	2.43	1.13	3.55	7	0.0
September	1.56	0.51	2.42	4	0.0
October	2.15	0.3	3.57	4	0.3
November	1.36	0.44	2.11	4	4.5
December	2.02	0.57	3.18	5	17.8
Total	18.47	14.54	22.19	51	66.5

La Plata County
Data recorded in the period 1951 to 1978 at Ignacio, Colorado (USDA, 1988)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	1.32	0.34	2.1	4	12.6
February	0.8	0.22	1.27	3	8.3
March	1.03	0.2	1.66	4	6.4
April	1	0.4	1.49	3	1.3
May	0.91	0.23	1.45	3	0.1
June	0.56	0.04	0.93	2	0.0
July	1.56	0.57	2.38	4	0.0
August	1.73	0.74	2.56	5	0.0
September	1.29	0.36	2.05	4	0.0
October	1.71	0.2	2.84	4	0.2
November	0.94	0.34	1.43	3	2.6
December	1.22	0.33	1.93	4	6.6
Total	14.07	11.08	16.89	43	38.1

La Plata County
Data recorded in the period 1951 to 1978 at Vellecito Dam, Colorado (USDA, 1988)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	2.25	0.72	3.5	6	28.4
February	1.65	0.52	2.56	5	21.0
March	2.12	0.68	3.29	6	23.6
April	1.77	0.95	2.48	5	10.5
May	1.43	0.55	2.16	4	2.1
June	0.98	0.23	1.57	3	0.0
July	2.66	1.25	3.86	7	0.0
August	2.92	1.52	4.14	9	0.0
September	2.19	0.64	3.43	5	0.0
October	2.69	0.37	4.43	5	3.2
November	1.96	0.81	2.92	5	14.0
December	2.69	0.82	4.21	5	28.0
Total	25.31	20.50	29.85	65	130.8

Mesa County (Uncompahgre National Forest Area)
Data recorded in the period 1951 to 1980 at Norwood, Colorado (USDA, 1995)
(measurements in inches)

Month	Average	2 Years in 10 will have less than	2 Years in 10 will have more than	Average number of days with 0.10 inch or more	Average Snowfall
January	1.03	0.42	1.53	4	14.0
February	0.79	0.31	1.18	4	10.4
March	1.01	0.3	1.57	4	11.0
April	1.04	0.53	1.47	4	6.3
May	1.02	0.32	1.59	4	0.6
June	0.72	0.22	1.13	3	0.0
July	1.68	0.83	2.4	6	0.0
August	1.7	0.87	2.44	6	0.0
September	1.44	0.25	2.37	4	0.0
October	1.54	0.42	2.45	3	2.7
November	1.03	0.53	1.46	3	8.1
December	0.94	0.44	1.36	4	12.8
Total	13.94	11.18	16.65	49	65.9

National Oceanic and Atmospheric Administration Climatological Data
Data recorded in 1979 (NOAA, 1979)
(measurements in millimeters)

Month	Almosa	Colorado Springs	Denver	Grand Junction	Pueblo
January	19	13	9	35	15
February	2	1	11	16	2
March	7	60	32	51	59
April	11	46	36	11	14
May	24	80	90	37	66
June	18	40	61	20	89
July	5	69	21	2	37
August	41	64	149	5	52
September	6	23	9	Trace	16
October	5	14	33	6	9
November	13	46	42	26	24
December	14	26	27	7	25

National Oceanic and Atmospheric Administration Climatological Data
Data recorded in 1980 (NOAA, 1980)
(measurements in millimeters)

Month	Almosa	Colorado Springs	Denver	Grand Junction	Pueblo
January	8	6	16	14	10
February	8	14	11	28	4
March	17	33	29	45	31
April	38	92	65	13	76
May	31	127	69	30	56
June	Trace	42	2	Trace	11
July	14	43	74	24	19
August	5	117	42	35	60
September	12	17	16	15	12
October	13	Trace	3	33	Trace
November	Trace	9	17	13	16
December	Trace	1	3	6	Trace

1.2 Irrigation Data

Representative irrigation data was obtained from the United States Department of Agriculture Soil Conservation Service and U.S. Geological Service Water Supply Paper.

ESTIMATED SEASONAL AND MONTHLY CONSUMPTIVE USE OF CROPS

Table CO683.50(k)
Grand Junction, Colorado

TR-21 Blaney Criddle Method

CROPS	Growing Season Average Dates	Average Consumptive Use (inches of water)													
		Days	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	TOTAL
Perennials															
Alfalfa zone 1	3/12 – 11/4	237	0	0	0.74	2.58	5.15	7.69	9.35	7.59	4.65	2.43	0.10	0	40.28
Alfalfa zone 2	3/2 – 9/25	207	0	0	1.36	2.32	4.34	6.20	8.68	7.28	3.81	0	0	0	33.99
Grass, Pasture	3/2 – 11/3	246	0	0	1.17	2.01	3.59	5.05	7.20	6.23	4.02	2.02	0.06	0	31.35
Annuals															
Beans, Dry	6/1 – 9/15	106	0	0	0	0	0	4.29	8.70	7.07	1.64	0	0	0	21.70
Corn, Grain Corn, Silage	5/1 – 9/15	137	0	0	0	0	1.97	4.32	8.28	6.95	2.07	0	0	0	23.59
Grain, Spring	4/5 – 8/1	118	0	0	0	0.97	4.13	6.62	3.47	0	0	0	0	0	15.19
Orchard zone 1 (w/ cover)	4/1 – 10/10	192	0	0	0	2.50	5.14	7.68	9.36	7.59	4.64	0.78	0	0	37.69
Orchard zone 2 (w/o cover)	5/9 – 9/29	143	0	0	0	0	3.07	6.19	8.69	7.28	4.41	0	0	0	29.64
Small Vegetables	4/15 – 10/15	183	0	0	0	0.43	2.40	4.91	6.81	5.73	3.13	0.59	0	0	24.00
Sugar beets	4/15 – 10/15	183	0	0	0	0.60	2.72	5.75	9.25	8.85	5.59	1.41	0	0	34.18
Wheat, Winter	4/4 – 8/1	118	0	0	0	2.66	5.33	6.16	2.86	0	0	0	0	0	17.01
Average Precipitation			0.64	0.61	0.75	0.79	0.63	0.55	0.46	1.05	0.84	0.93	0.61	0.55	8.41
Effective Precipitation			0	0	0.29	0.54	0.49	0.49	0.45	0.97	0.65	0.64	0.04	0	4.59

Net irrigation requirement is the difference between crop consumptive use and effective precipitation.

ESTIMATED SEASONAL AND MONTHLY CONSUMPTIVE USE OF CROPS

Table CO683.50(h)
Durango, Colorado

TR-21 Blaney Criddle Method

CROPS	Growing Season Average Dates	Average Consumptive Use (inches of water)													
		Days	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	TOTAL
Perennials															
Alfalfa	3/27 – 11/7	225	0	0	0.10	1.83	3.40	4.90	6.44	5.47	3.39	1.81	0.15	0	27.49
Pasture Grasses	3/27 – 11/7	225	0	0	0.09	1.58	2.81	3.99	5.34	4.67	2.98	1.59	0.12	0	23.17
Annuals															
Corn, Silage	5/1 – 9/15	126	0	0	0	0	0.26	2.27	4.79	5.49	3.25	0	0	0	16.06
Spring Grain	4/5 – 8/1	133	0	0	0	0	1.63	4.51	7.22	3.26	0.11	0	0	0	16.73
Wheat, Winter	4/15 – 8/15 9/5 – 10/25	172	0	0	0	1.26	4.20	5.15	4.15	0.34	1.53	1.84	0	0	18.83
Average Precipitation			1.70	1.14	1.47	1.36	1.12	0.88	1.85	2.43	1.59	1.94	1.11	2.00	18.59
Effective Precipitation			0	0	0.09	0.89	0.80	0.69	1.54	1.86	1.12	1.20	0.10	0	8.34

Net irrigation requirement is the difference between crop consumptive use and effective precipitation.

ESTIMATED SEASONAL AND MONTHLY CONSUMPTIVE USE OF CROPS

Table CO683.50(m)
Gunnison, Colorado

TR-21 Blaney Criddle Method

CROPS	Growing Season Average Dates	Average Consumptive Use (inches of water)													
		Days	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	TOTAL
<u>Perennials</u>															
Alfalfa	4/16 – 9/7	144	0	0	0	0.60	2.71	4.24	5.35	4.47	0.62	0	0	0	17.99
Pasture Grasses	4/16 – 10/8	175	0	0	0	0.52	2.24	3.46	4.44	3.82	2.35	0.29	0	0	17.12
Average Precipitation			0.97	0.98	0.81	0.80	0.76	0.78	1.47	1.46	0.89	0.72	0.60	0.76	11.00
Effective Precipitation			0	0	0	0.24	0.52	0.59	1.18	1.11	1.14	0	0	0	3.80

Net irrigation requirement is the difference between crop consumptive use and effective precipitation.

APPENDIX 2

REQUIRED RESRAD INPUT PARAMETERS

I. COVER & CONTAMINATED ZONE HYDROLOGICAL DATA

A. contaminated zone total porosity
B. density of cover material
C. contaminated zone effective porosity
D. cover erosion rate
E. contaminated zone hydraulic conductivity
F. density of contaminated zone
G. humidity
H. contaminated zone erosion rate
I. evapotranspirition coefficient
J. precipitation
K. runoff coefficient
L. irrigation & mode
M. watershed area

II. SATURATED ZONE PARAMETERS

A. density
B. hydraulic gradient
C. total porosity
D. well pump intake depth
E. effective porosity
F. water table drop rate
G. hydraulic conductivity
H. well pumping rate

III. CONTAMINATED ZONE PARAMETERS

A. area
B. length parallel to aquifer flow
C. thickness

IV. UNCONTAMINATED UNSATURATED ZONE PARAMETERS

A. total porosity

B. thickness
C. effective porosity
D. density
E. hydraulic conductivity

V. OCCUPANCY, INHALATION, & EXTERNAL GAMMA

A. inhalation rate
B. shielding factor
C. mass loading
D. external gamma shielding factor
E. dilution length
F. indoor & outdoor time fraction
G. exposure duration

VI. INGESTION (dietary) PARAMETERS

A. meat
B. fish
C. milk
D. fruit, vegetable, grain
E. water
F. leafy vegetable
G. soil
H. contamination fractions for above

VII. INGESTION (non-dietary) PARAMETERS

A. livestock fodder intake for meat & milk
B. soil mixing layer
C. livestock water intake for meat & milk
D. depth of roots
E. livestock soil intake
F. groundwater fraction usage (drinking, household, livestock, irrigation)

VIII. STORAGE TIME PARAMETERS

A. meat
B. crustacea & mollusks
C. milk
D. fruit, vegetable, grain
E. surface & well water
F. leafy vegetable
G. soil
H. livestock fodder

I. fish

IX. RADIONUCLIDE CONCENTRATION IN SOIL

APPENDIX 3

COMPUTER HARDWARE AND SOFTWARE REQUIREMENTS

3.1 Hardware Requirements

3.1.1 Server requirements

Any PC or workstation type system with networking capabilities and access to the Internet would be adequate in this role. The system must be robust enough to handle continual use and access from remote sites. A great deal of data storage capabilities would additionally be required to handle the amount of data expected. Ideally, the system should be completely dedicated to the database and not serve as a duel role system, such as a general user system. Eventually, as the database grows and is accessed by more people, a digital connection would be ideal to support the increased data transfer requirements.

3.1.2 Storage capabilities

Ideally, environmental data should be maintained on some form of CD-ROM (Compact Disk- Read Only Memory) technology. This will facilitate the storage and access of a large amount of information while limiting potential or possible damage to the storage media. Additionally, CD-ROM have a data storage term of well over 100 years.

Currently, a standard CD-ROM can contain 650 MB of information. For a software download, the data can be compressed which enables a faster download of information to the user as well as increasing the amount of information that can be stored. Newer technologies, such as the Panasonic five disk CD changer, which is currently available, and the DVD (Digital Video Disk), expected early in 1997, will be able to increase the amount of information capable of being stored on a single CD to just over 3 GB and 5 GB, respectively. Layering of the data stored on a DVD can even achieve 17 GB of storage on a single CD.

3.1.3 Network support

A critical aspect of a multi-site database would be the ability of the machines involved to communicate easily. The world-wide "network" already exists; however, standardization of software and critical pieces of hardware would be essential. As with any network, untrained personnel have the ability to "crash" parts of the system. This requires that security firewalls and data management be maintained by professionals.

3.2 Software Requirements

3.2.1 HTML editing capabilities

To create hypertext pages, some form of text editor will be necessary. Currently, there are several commercial and shareware packages available that can be used to develop web pages. HTML is a fairly simple programming language, which uses simple commands that web browsers interpret and display to a computer screen.

For this project, available freeware and shareware HTML developing tools were downloaded from the World-Wide Web and used to create the necessary HTML files for the website. *HTML Writer 0.9 beta 4a* was obtained from an applications database and installed on personal computer. It served as the primary development tool. Later in the project *Netscape Navigator Gold 3.02* was used to create tables and develop pages. Files were created and then transferred, via File Transfer Protocol (FTP), to a UNIX based Hewlett-Packard 7000 Series Workstation. Here files could be simply edited by simple text editors.

3.2.2 Scripting (PERL) capabilities

The initial search capabilities and communication forms were developed using simple PERL scripts downloaded from shareware and freeware sites on the world-wide web. PERL stands for the Practical Extraction and Report Language and was designed to assist the UNIX user by performing common tasks too large or complex for shell programming. It was selected because it is highly portable and fairly simple to create or modify existing scripts. The scripts developed handle the database search and mail form. The search.pl and string.pl scripts takes a user defined search string and searches files with a specific extension, in a defined directory and for the desired search string. The mail.pl takes the user input and "posts" it to the database administrator. The search scripts can perform a Boolean search using, "and" or "or", and will return a link to the file were the search string appeared. A limitation to the search script is that it will only search for the string entered. It cannot "stem" the word to search for variations in tense or plural words. Additionally there are no "streaming" capabilities; therefore, no correction for spelling.

3.2.3 Graphic development capabilities

Graphic development involved many separate programs, usually dependent on the capabilities and graphic manipulation tools. Graphics are very important for the visual appeal and usability of a website. The text was created and manipulated using *CorelDRAW 3.0* and later *CorelDRAW 7.0.* The final composition and assembly of images were performed using *Paint Shop Pro 32-bit* and *16-bit (shareware versions)* and *PhotoPAINT 7.0.*