A GENERIC EXAMPLE OF PROBABILISTIC RADIOLOGICAL PERFORMANCE ASSESSMENT MODELING

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ABSTRACT

Presented is an example of environmental modeling using the GoldSim systems simulation software platform. The model concerns contaminant transport and dose estimation in support of a generic radiological Performance Assessment (PA). Both the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) require a PA to assess the potential future risk to human receptors of disposal of low-level radioactive waste (LLW). Commercially operated LLW disposal facilities are licensed by the NRC (or agreement states), and the DOE operates such facilities for disposal of DOE-generated LLW.

The type of PA model presented is probabilistic in nature, and hence reflects the current state of knowledge about the site by using probability distributions to capture what is expected (central tendency or average) and the uncertainty (e.g., standard deviation) associated with input parameters, and propagating through the model to arrive at output distributions that reflect expected performance and the overall uncertainty in the system. Estimates of contaminant release rates, concentrations in environmental media, and resulting doses to human receptors well into the future are made by running the model in Monte Carlo fashion, with each realization representing a possible combination of input parameter values. Statistical summaries of the results can be compared to regulatory performance objectives, and decision makers are better informed of the inherently uncertain aspects of the model which supports their decision making. While this information may make some regulators uncomfortable, they must realize that uncertainties which were hidden in a deterministic analysis are revealed in a probabilistic analysis, and the chance of making a correct decision is now known rather than assumed.

The model includes many features and processes typical of a PA, but is entirely fictitious. This does not represent any particular site and is meant to be a generic example. A practitioner could, however, start with this model as a template and, by adding site specific features and parameter values (distributions), use this model as a starting point for a real model to be used in real decision making.

INTRODUCTION

Regulators and other decision makers are faced with the problem of making decisions in light of uncertainty, and often do not have an adequate appreciation for the uncertainty inherent in the environmental analysis informing the decision. The standard development of radiological performance assessments (PAs) concerning the fate and transport of radionuclides originating in disposed low-level radioactive waste (LLW) suffers from inadequate communication of uncertainty. Typical LLW PAs have used a deterministic approach, producing a single set of values (concentrations, receptor risks) to represent the performance of a contaminated site. The decision maker need only compare these values to those presented in relevant regulations in order to be satisfied that a site is in compliance. These single values, however, are inherently uncertain, and this uncertainty is not generally communicated to the decision maker or to the public.

Through probabilistic modeling, a more thorough and honest estimate of risks can inform the decision maker and the public. A probabilistic analysis should be designed to represent the state of knowledge about the site and its behavior. Given uncertain estimates of performance objectives, the decision maker's job may seem more difficult (certainly more difficult than comparing two values) but in fact she or he is empowered by a greater appreciation for the uncertainties present in the conceptualization of the site and in its analysis. The decision maker is also provided with information related to the chance of making the right or wrong decision.

When probabilistic modeling is coupled with subsequent multivariate sensitivity analysis an even more powerful tool emerges. A sensitivity analysis can identify which parts of the model are most significant to the results in question. This information can help to guide further investigation aimed at reducing uncertainties should they be uncomfortably large.

This work introduces a generic probabilistic PA model developed using the GoldSim systems analysis programming platform (http://www.goldsim.com), using the example of shallow land burial of LLW. The model considers typical stochastically-defined PA input parameters and processes, and produces probabilistic results suitable for sensitivity analysis. Similar models are in use at some existing LLW sites, and not only assess regulatory compliance, but are used to inform operational decisions such as the acceptance of candidate waste streams, and to develop long-term site monitoring strategies. Unlike models being developed for actual LLW sites, the generic PA model is freely available to practitioners and to the public, to serve as an example for performing probabilistic risk assessment, and as a template for constructing similar analyses.

A popular approach to performance assessment has been to run a deterministic analysis using "conservative" bounding assumptions, producing unquestionably conservative results, i.e. results showing doses that would be much higher than would reasonably be expected. This approach has its purpose in demonstrating compliance for a closed site, and if compliance can be assured with a demonstrably conservative assessment, indeed much effort can be saved by precluding more sophisticated modeling. This approach, however, does have its pitfalls, and should not be used when attempting to assess the full capabilities of an operating or planned site. When maximizing the potential use of a site, or evaluating a site that is accepting or planning to accept waste, the conservative approach is inappropriate. It is not an accurate reflection of the risk posed by the site, and, in many cases, the judgment of what constitutes a conservative value for a given parameter or process is not always clear. For example, what inhibits transport along one environmental pathway may promote it along another.

Optimizing the use of a site (and of public funds) requires realistic estimates of site performance. In order to honestly reflect the state of knowledge behind a risk assessment analysis, uncertainty must be accounted for and communicated to the decision maker. Probabilistic analysis offers such a communication aid. The challenge, then, is to perform a transparent and defensible assessment, accounting for uncertainties and variabilities, that can be understood by decision makers and the general public.

The generic PA model uses probability distributions to capture what is expected (central tendency or average) and the uncertainty (e.g., standard deviation) associated with input parameters. The uncertainties are propagated through the model to arrive at output distributions that reflect expected performance and the overall uncertainty in the system. Estimates of contaminant release rates, concentrations in environmental media, and resulting doses to human receptors well into the future are made by running the model in Monte Carlo fashion, with each realization representing a possible combination of input parameter values. While there are many Monte Carlo sampling approaches, Latin Hypercube (LHC) sampling of the parameter distributions offers the quality that each realization is equally likely. Such a sampling paradigm allows for the calculation of minimum variance unbiased estimates of distribution parameters. Statistical summaries of the results can be compared to regulatory performance objectives, and decision makers are better informed of the inherently uncertain aspects of the model which supports their decision making. While this information may make some regulators uncomfortable, proper explanation of the model allows them to realize that uncertainties which were hidden in a deterministic analysis are revealed in a probabilistic analysis. Thus, the chance of making a correct decision is now quantified rather than simply assumed.

The Computational Modeling Environment

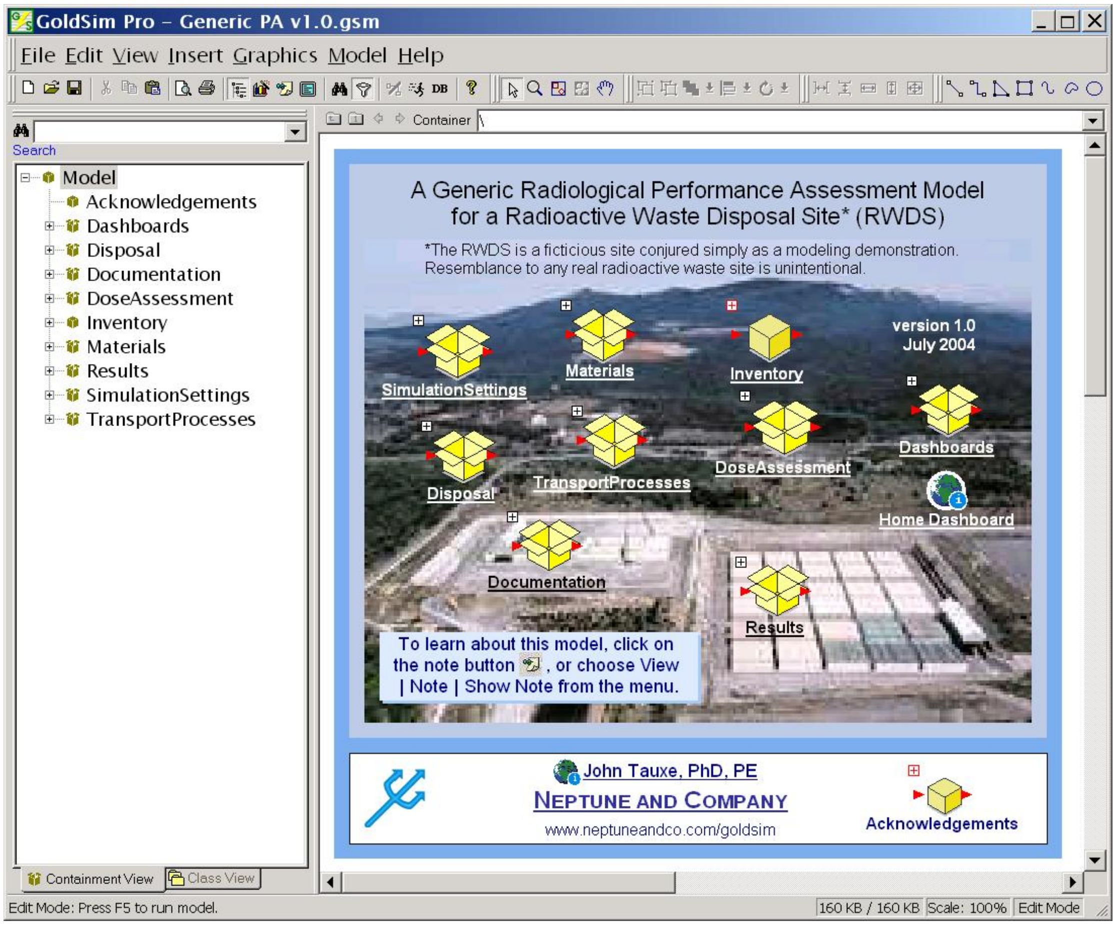
Using the GoldSim modeling platform, the modeling environment is expressed in a graphical fashion, and is organized by hierarchical “containers.” The modeler works with a collection of “whiteboard pages” that are used for adding input data, mathematical expressions, and specialized contaminant transport modeling elements. These are all interconnected with transport process definitions, and GoldSim solves the system of differential equations set up by the modeler. The model is executed as a time-dependent process, using time steps defined by the modeler.

The model can be run in deterministic mode as well as probabilistic mode, a feature enabling easy comparison of the two approaches. For deterministic runs, each stochastic input parameter can be assigned a value to use, or it can default to the expected value of its distribution. Given this functionality, constructing a probabilistic model is no more difficult than constructing a deterministic one, and no additional modeling elements are required.

For probabilistic runs, the user can select the number of realizations to perform, and can choose to use LHC sampling of the stochastic parameters. Sets of realizations can be made entirely reproducible, and individual realizations can be rerun for further investigation.

Contaminant Fate and Transport

The generic model includes many features and processes typical of a PA, but does not represent any particular site. A screen shot of the top-level “page” is shown in **Fig. 1**.



A Generic Radiological Performance Assessment Model for a Radioactive Waste Disposal Site* (RWDS)

*The RWDS is a ficticious site conjured simply as a modeling demonstration. Resemblance to any real radioactive waste site is unintentional.

To learn about this model, click on the note button, or choose View | Note | Show Note from the menu.

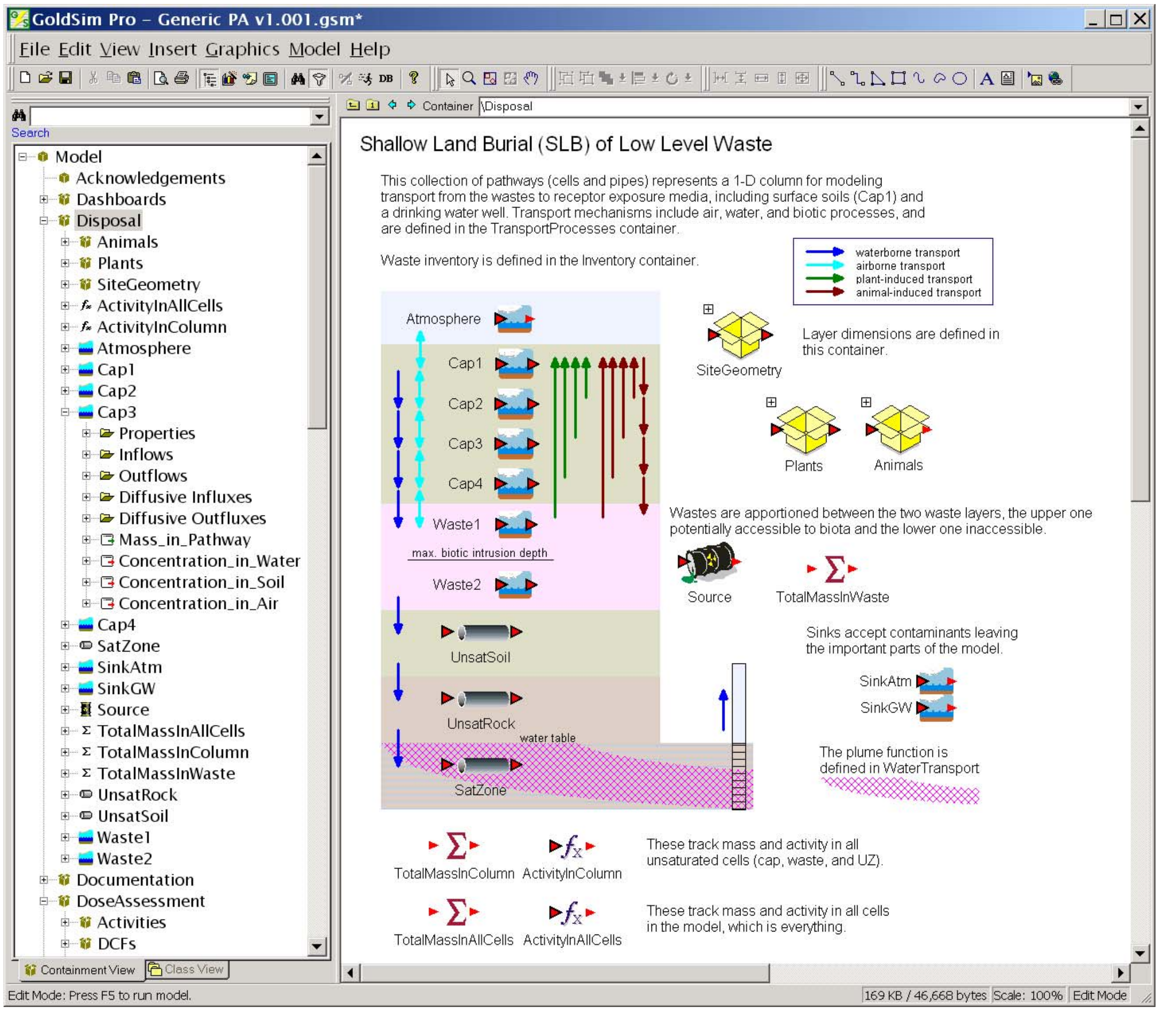
Fig. 1. Screen shot of the top level of the generic PA model. The yellow boxes are GoldSim modeling containers, used to organize the calculations.

The model is organized into several "containers", based on conceptual distinctions. For example, definitions of material properties are in the "Materials" container, the radiological inventory is defined in "Inventory", the disposal system is constructed in "Disposal", and so on. In addition to modeling elements, a container is provided for model documentation, with links to references, illustrations of model processes, and a change log. "Dashboards" contains examples of dialog boxes which can provide a simpler interface to the model.

The various contaminant fate and transport processes modeled in GoldSim include the following:

- radioactive decay and ingrowth, with branching decay chains,
- partitioning between the various solid and fluid phases, using soil/water partition coefficients (Kd) and Henry's Law coefficients for air/water partitioning,
- solubility constraints on aqueous concentrations of contaminants,
- advection and limited dispersion in fluid phases in the porous media,
- diffusion in the air phase,
- contaminant uptake and redistribution by plants, and
- movement of bulk materials by animals.

Specialized contaminant transport elements are used to perform the fate and transport analysis. These include GoldSim "cell pathway" and "pipe pathway" elements. Cells behave mathematically like continuously-stirred tank reactors, i.e. all contaminants within a cell are mixed and partitioned among the various materials present within the cell. These cells can be arranged into simple finite difference modeling configurations, such as the stack of cells representing the disposal facility cap in **Fig. 2**.



This collection of pathways (cells and pipes) represents a 1-D column for modeling transport from the wastes to receptor exposure media, including surface soils (Cap1) and a drinking water well. Transport mechanisms include air, water, and biotic processes, and are defined in the TransportProcesses container.

Waste inventory is defined in the Inventory container.

Layer dimensions are defined in this container.

Wastes are apportioned between the two waste layers, the upper one potentially accessible to biota and the lower one inaccessible.

Sinks accept contaminants leaving the important parts of the model.

The plume function is defined in WaterTransport

These track mass and activity in all unsaturated cells (cap, waste, and UZ).

These track mass and activity in all cells in the model, which is everything.

Fig. 2. Model container with principal contaminant transport elements.

Below the cells in the example are pipe elements, which are modeled mathematically as reactive columns. Pipes contain a porous medium, and contaminants entering at the upstream end are transported along with a flowing fluid, subject to dispersion, partitioning, matrix diffusion, and other processes. A time series of outflow concentrations is produced by the pipe, and this outflow stream can be connected to other pipes or to cells. In the present example, the pipe immediately below the waste models vertical transport through unsaturated soil, and is connected to another pipe representing unsaturated rock. This is in turn connected to a pipe representing the lateral transport in the saturated zone. This aquifer transport takes advantage of GoldSim's Plume function, which allows for implied lateral dispersion of contamination as well. At the outflow from the aquifer pipe is a well, which provides the dose assessment calculations with drinking water concentrations.

The collection of transport elements and the differential equations linking them are arranged in the Disposal container, as shown in **Fig. 2**. As part of the model’s self-documentation, the GoldSim elements mimic their relative positions in space. The interconnections between the various elements are shown with colored arrows. To the left is the model browser pane, which shows all the elements in the model.

Water is allowed to enter the model as infiltration from the ground surface, and percolates downward to the saturated zone. It is assumed that this advection of water dominates waterborne transport, so water-phase diffusion is ignored. Diffusion in the air phase, however, is implemented in the unsaturated cells, including one defined for the atmosphere.

Biotically-induced contaminant transport includes uptake and redistribution by plants from lower layers to the uppermost cap layer, and translocation of bulk materials (soil, and associated water, air, and contaminants) by burrowing animals from lower layers to the ground surface. The burrows are also allowed to collapse, resulting in material mass balance and a downward pathway for contaminant-laden soils.

Dose Assessment

For this example, only two receptors are modeled for the dose assessment: a transient visitor and a resident farmer. The calculation of total effective dose equivalent (TEDE) for the resident farmer includes each exposure pathway and each Species (radionuclide), summed over the Species, and over all the pathways. The exposure pathways considered include:

- inhalation of gaseous radionuclides (e.g. Ar-39),
- inhalation of airborne particulates,
- immersion in gaseous radionuclides,
- external irradiation from soil,
- ingestion of soil,
- ingestion of locally-grown plant food products,
- ingestion of locally-grown animal food products, and
- ingestion of local groundwater.

The time-series results of each expression can be examined to determine the contributions to dose from each radionuclide and each pathway.

RESULTS

As is apparent in comparing the deterministic calculation of TEDE shown in **Fig. 3** with its probabilistic counterpart in Fig. 4, the probabilistic results provide much more information than

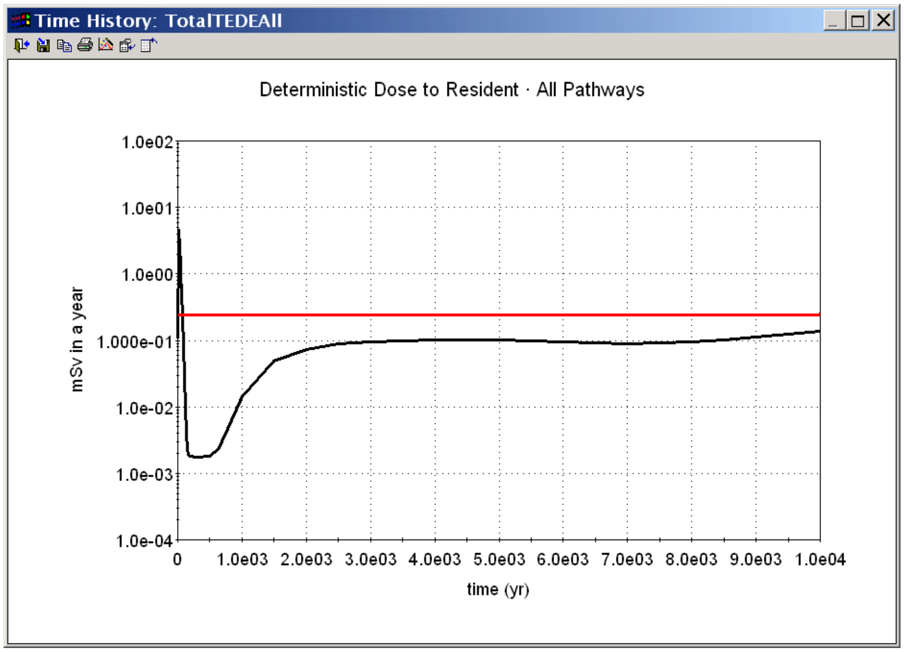


Fig. 3. Dose results from the model run in deterministic mode. The performance objective of 0.25 mSv in a year is shown in red.

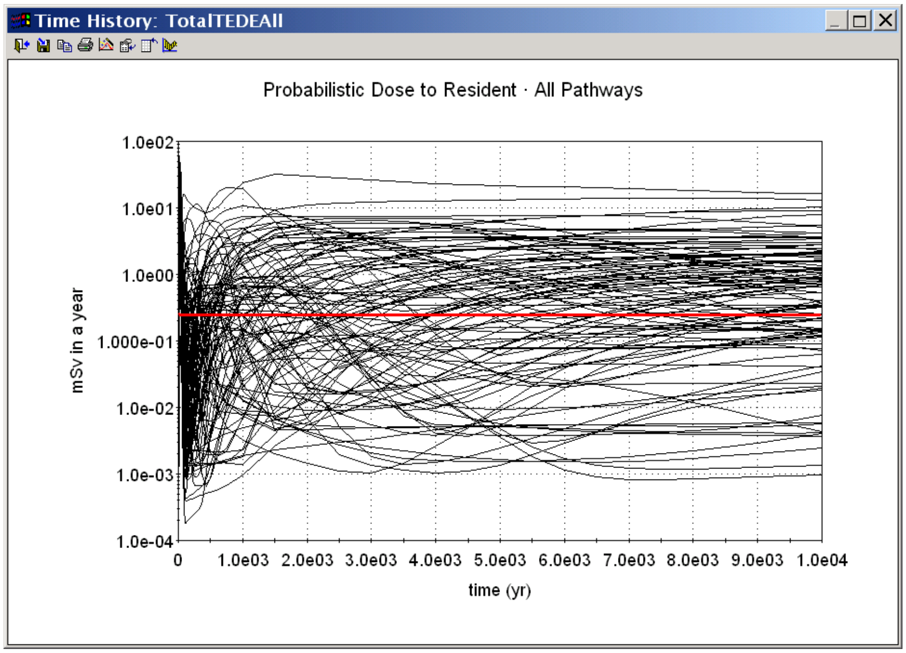


Fig. 4. One hundred realizations of the probabilistic dose results. The performance objective of 0.25 mSv in a year is shown in red.

the deterministic. The deterministic result is based on expected values for all stochastic inputs, and the probabilistic result shows 100 separate (but equally probable) realizations, sampling from the stochastic inputs. A decision maker might base his or her judgment on the deterministic model alone (seeing as the long term dose is under the performance objective of 0.25 mSv in a year, shown as a magenta line), without the significant information provided by the probabilistic result: Namely, that the actual chance (based on our state of knowledge as reflected in the model) of exceeding the performance objective is rather high; in fact it is over a 50% chance of making the wrong decision. This could lead to potentially serious decision errors, resulting in increased risk to human health and the environment.

The probabilistic result has hidden within it the solution to this very problem. Stochastic (probabilistic) results can be subjected to sensitivity analysis, providing analysts and decision makers insight into what parts of the model are most significant. Such insight can help direct model development and ensure that limited resources are not squandered in gathering irrelevant data or information. As we have found in a real application of this approach, the directing of resources into learning more about sensitive parameters can significantly reduce both the average dose as well as the uncertainty in that result. The cloud of answers analogous to those shown in Figure 4 can become narrower and even lower, so that a mere few percent of realizations exceed the performance objective. This reduction in both dose and its uncertainty came from a thorough analysis of the model alone, not from changes in management or treatment of the site.

Experience has shown that while some decision makers are comfortable with and even appreciative of the probabilistic approach, others clearly are not. There is still a feeling among some in the decision maker community that the deterministic approach serves them just fine. In many cases, they may be correct, though this would be hard to verify. In other cases, like the proverbial ostrich burying its head in the sand, they would simply rather not know the extent of uncertainty inherent in the bases for their decisions. Unless such cases are analyzed, we may never know the effects of such misguided decisions.

A model adapted from this template could be used to examine the effects of various waste management scenarios, such as the design of trenches, the development of institutional control procedures, and the acceptance of candidate waste streams. The intent of this generic example is to present a starting point for further development of models. Any application to a real site, of course, would require extensive modification to make the analysis site-specific in terms of contaminant transport and receptor scenarios, but the overall structure of the generic model may well survive such customization.

The analysis of potential costs and benefits of management controls can also be integrated into such a model. This is of particular interest in radioactive waste applications, where doses are mandated to be kept As Low As Reasonably Achievable (ALARA). That is, simply passing the performance objective is not good enough if the site can be made more protective at a reasonable cost.

The generic PA model is freely available to the public, and can be obtained via the Internet at http://www.neptuneandco.com/goldsim/generic