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A PROBABILISTIC TOTAL SYSTEM APPROACH TO THE SIMULATION OF COMPLEX ENVIRONMENTAL SYSTEMS

Rick Kossik
Ian Miller

GoldSim Technology Group LLC
22516 SE 64th Place, Suite 110
Issaquah, WA 98027 U.S.A.

ABSTRACT

GoldSim is a powerful and flexible Windows-based computer program for carrying out probabilistic simulations of complex systems to support management and decision-making in engineering, science and business. The program is highly graphical, highly extensible, able to directly represent uncertainty, and allows you to create compelling presentations of your model. Although GoldSim can be used to solve a wide variety of complex problems, it is particularly well-suited (and was originally developed) to support evaluation of complex environmental systems. Powerful contaminant transport features allow nearly any kind of natural or man-made environmental system to be simulated. This paper provides a brief overview of GoldSim, with special emphasis on environmental applications.

1 INTRODUCTION

1.1 The Environmental Modeling Problem

Three problems are common to most complex environmental modeling efforts:

- **Uncertainty:** For most real-world applications, a large degree of uncertainty usually exists with regard to the controlling parameters and processes. When carrying out predictive simulations, these uncertainties cannot be properly represented using deterministic techniques alone.
- **Multi-disciplinary:** Most modeling efforts are multi-disciplinary in nature. Unfortunately, in such efforts it is easy for individuals building submodels to get caught up in the details of their model, and lose sight of the "big picture" (i.e., the ultimate problem which the model is trying to address). The end result is typically separate submodels which are unjustifiably complex. More importantly, the complex interactions and interdependencies between subsystems are often ignored or poorly represented.
- **Communications:** Many complex environmental models are built such that they can only be understood and explained by the people who developed them. A model which cannot be easily understood (by decision-makers or the public) is a model that will not be used.

1.2 The Solution: A "Total System" Probabilistic Approach

Although these problems occur in nearly any kind of complex environmental modeling effort, they are particularly relevant to modeling the performance of proposed and existing radioactive waste management facilities (due to the very long time frames involved, the large uncertainties, and the public's reaction to radioactive waste issues). Therefore, at the request of the US Department of Energy, starting in 1990, we began to develop a new simulation tool to specifically address these problems.

The result of this development effort is a Windows-based graphical simulation tool called GoldSim. GoldSim is a flexible and powerful program for simulating the release, fate and transport of contaminants within complex engineered or man-made environmental systems. It was specifically designed to:

- Explicitly represent uncertainty in processes, parameters, and events;
- Facilitate a "top-down" total system modeling approach aimed at integrating all aspects of the system and keeping a modeling effort focused on the "big picture"; and
- Facilitate the documentation and presentation of complex models to multiple audiences at an appropriate level.

2 OVERVIEW OF THE GOLDSIM SIMULATION FRAMEWORK

GoldSim is a powerful and flexible platform for visualizing and numerically simulating nearly any kind of physical, financial or organizational system. In a sense, GoldSim is like a "visual spreadsheet" that allows you to visually create and manipulate data and equations (see Figure 1). Unlike spreadsheets, however, GoldSim allows you to readily evaluate how systems evolve over time, and predict their future behavior.

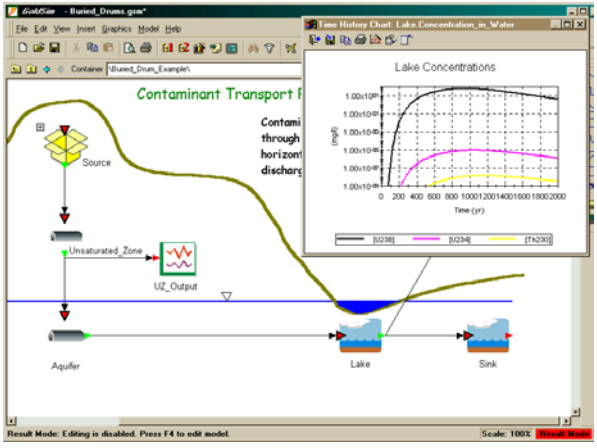

Figure 1: GoldSim Offers a Highly Visual Interface

Because simulation can be such a powerful tool for understanding and managing complex systems, a variety of simulation tools currently exist. The following combination of features, however, makes the GoldSim approach unique:

- ***GoldSim is user-friendly and highly graphical,*** such that you can literally draw (and subsequently present) a picture (an influence diagram) of your system in an intuitive way without having to learn any arcane symbols or notation.
- ***GoldSim is extremely flexible, allowing it to be applied to nearly any kind of system.*** The software allows you to build a model of your system in a hierarchical, modular manner, such that the model can readily evolve as more knowledge regarding the system is obtained. Hence, a GoldSim model can be very simple or extremely complex.
- ***Uncertainty in processes, parameters and future events can be explicitly represented.*** Uncertainty in processes and parameters can be represented by specifying model inputs as probability distributions. The impact of uncertain events (e.g., earthquakes, floods, sabotage) can also be directly represented by specifying the occurrence rates and consequences of such "disruptive events."
- ***GoldSim is highly extensible.*** You can dynamically link external programs or spreadsheets directly into your GoldSim model. In addition, GoldSim was specifically designed to support the addition of customized modules (program extensions) to address specialized applications.
- ***GoldSim allows you to create compelling presentations of your model.*** A model which cannot be easily explained is a model that will not be used or believed. GoldSim was specifically designed to allow you to effectively document, explain and present your model. You can add graphics, explanatory text, notes and hyperlinks to your model, and organize it in a hierarchical manner such that it can be presented at an appropriate level of detail to multiple target audiences.

2.1 A Powerful, Flexible Simulator

At the most fundamental level, GoldSim can be used as a powerful, flexible simulator. That is, you may only wish to apply it to a very specific problem addressing one aspect of a complex system (e.g., behavior of an engineered barrier, a site-wide water balance, or movement of contaminants through groundwater or another pathway).

In a sense, GoldSim is like a "visual spreadsheet" allowing you to *visually* create and manipulate data and equations. That is, you create, document, and present models by creating and manipulating graphical objects (referred to as *elements*) representing data and relationships between the data. As can be seen in the simple example shown in Figure 2, based on how the various objects in your model are related, GoldSim automatically indicates their influences and interdependencies by visually connecting them in an appropriate manner.

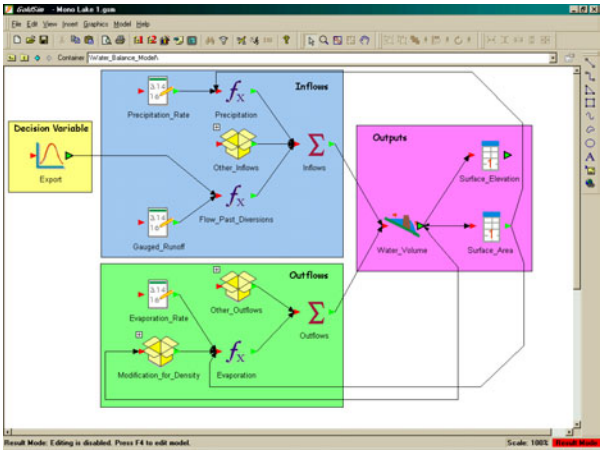

Figure 2: The GoldSim Simulation Environment is Highly Graphical and Completely *Object-Oriented*

GoldSim provides a wide variety of built-in objects from which you can construct your models, and, if desired,

you can program your own custom objects, and link them seamlessly into the GoldSim framework.

GoldSim's graphical interface and powerful computational features facilitate a wide range of simulations, ranging from a simple screening analysis put together in less than an hour, to a complex application built over a period of several months.

2.2 A System Integration Tool

Most environmental applications are multi-disciplinary in nature. That is, the system being simulated actually consists of many subsystems, and the sub-models for each subsystem must typically be built by people from a wide variety of disciplines. For example, a model intended to evaluate remediation options for a contaminated site likely would include sub-models that are developed by geologists, hydrogeologists, materials engineers, ecologists, health physicists, economists, and perhaps political scientists.

Unfortunately, in many such cases, the model builders get caught up in the details of their sub-models, and lose sight of the "big picture." The end result is typically separate sub-models, which are unnecessarily complex. More importantly, the complex interactions and interdependencies between subsystems are often ignored or poorly represented. Such an approach not only wastes resources, but is often too complex to be explained (and hence used) effectively, and too poorly integrated to represent the entire system in a cohesive and realistic way.

What is needed for such complex, multi-disciplinary systems is a tool that can be used to integrate all of the sub-models into a single, total-system model (see Figure 3). A total-system model focuses on creating a consistent framework in which all aspects of the system, as well as the complex interactions and interdependencies between subsystems, can be represented.

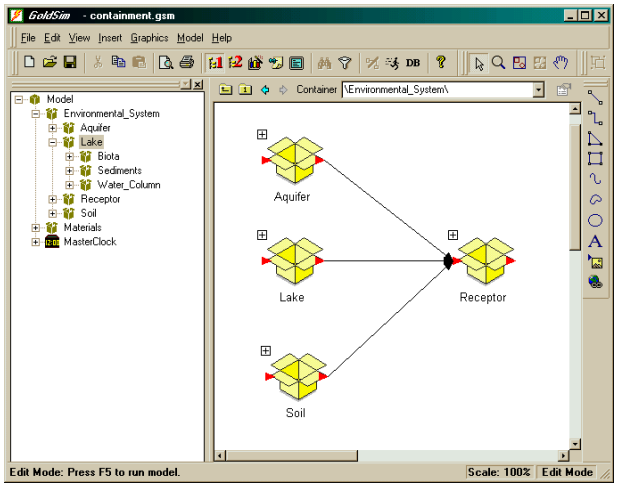

Figure 3: Total-System Model Including Submodels for the Aquifer, Lake, Soil, and Receptor Systems

Because GoldSim is flexible and powerful enough to represent practically any aspect of your system, and because GoldSim provides unique capabilities for building your model in a hierarchical, modular manner, it is ideally suited to act as a system integrator. In fact, this was the original and primary use for which GoldSim was designed.

2.3 A Visual Information Management System

Even if you can directly and visually access the input data for your model, in order for your simulation model to be useful, you must also be able to explain its assumptions (and the implications of the simulation results) in a compelling and effective manner. GoldSim provides the tools to enable you to do so.

Hence, at the highest and most powerful level, GoldSim can be used as a visual information management system, providing you with the ability to directly link to data sources, as well as describe, document and explain your model in a compelling and effective manner to any audience (see Figure 4).

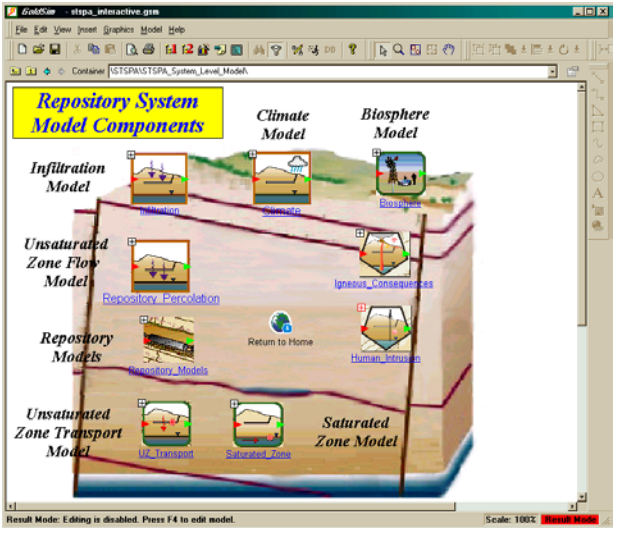

Figure 4: Yucca Mountain Radioactive Waste Repository System

3 THE GOLDSIM CONTAMINANT TRANSPORT MODULE

Although the standard elements incorporated within GoldSim can be used to build powerful and complex models, it was realized from the outset of the development of GoldSim that in some situations, specialized elements may be required in order to model some kinds of systems. As a result, GoldSim was designed to facilitate the incorporation of additional modules (program extensions) to enable the program to address specialized problems.

For environmental applications, the most important of these is the Contaminant Transport (CT) Module. The CT

Module is a program extension to the GoldSim simulation framework which allows you to dynamically model mass transport within complex engineered and/or natural environmental systems.

The fundamental output produced by the CT Module consists of predicted mass fluxes at specified locations within the system, and predicted concentrations within environmental media (e.g., groundwater, soil, air) throughout the system. If desired, concentrations in environmental media can be converted to receptor doses and/or health risks by assigning appropriate conversion factors.

3.1 Processes Simulated by the CT Module

The CT Module allows the user to explicitly represent the following processes:

- ***Release of mass*** (e.g., contaminants) from specified sources, taking into account both the failure of containers (e.g., drums) in which the contaminants are disposed; and the degradation of any materials in which the contaminants are bound (e.g., grout, metal, glass).
- ***Transport of contaminants*** through multiple transport pathways within an environmental system (e.g., aquifers, streams, atmosphere). The transport pathways can consist of multiple transport and storage media (e.g., groundwater, surface water, air, soil), and both advective and diffusive transport mechanisms can be directly simulated. Transport processes incorporate solubility constraints and partitioning of contaminants between the media present in the system, and can include the effects of complex chemical reactions and decay processes. Transport processes occurring within fractured rock (e.g., matrix diffusion) can also be simulated.
- ***Biological transfer of contaminants within or between organisms***. Like physical transport pathways, biological transport pathways can consist of any number of transport and storage media (e.g., blood, tissue), which can be linked by a variety of transport mechanisms.

As shown in Figure 5, the CT Module provides this special functionality by adding specialized elements for representing contaminant species, transport media, transport pathways, contaminant sources, and receptors to the GoldSim simulation framework:

By linking these environmental elements together (and integrating them with GoldSim's basic elements), you can build simple or complex contaminant transport simulations (see Figure 6).

4 EXAMPLE APPLICATIONS

GoldSim (and the CT Module) were originally developed to assist the United States Department of Energy (DOE) in

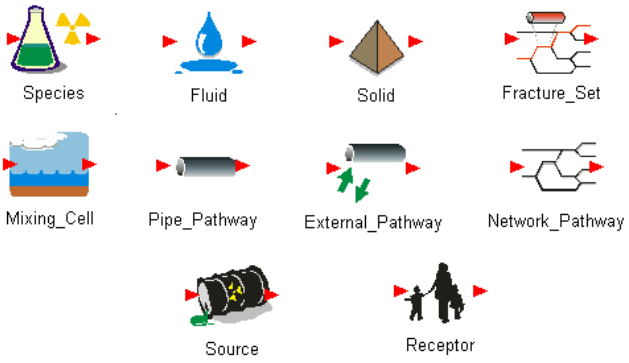

Figure 5: Specialized CT Elements

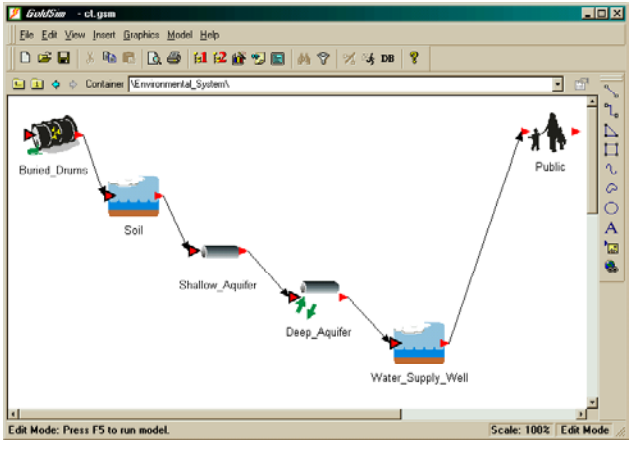

Figure 6: CT Module Incorporating Multiple Environmental Elements

the evaluation of the potential high-level radioactive waste repository at Yucca Mountain, Nevada. It is currently being used to help design remediation measures for contaminated sites and to evaluate the safety of proposed radioactive waste disposal facilities worldwide. It is also used evaluate water management, environmental compliance and mine closure plans for mines worldwide. A few environmental applications, ranging from mining applications, to radioactive waste management, to disease transmission, are listed below:

- ***Evaluation of Proposed Yucca Mountain Repository, Nevada***. The U.S. Department of Energy has been using GoldSim to evaluate the safety of the proposed repository for the nation's spent nuclear fuel at Yucca Mountain, Nevada since 1992. GoldSim is currently being used to support the License Application for the site.
- ***Remediation and Closure of Uranium Mill Tailings and Mine Workings.*** GoldSim has been used in Germany and Canada (Figure 7) to evaluate alternative remediation and closure options for abandoned mine workings and tailings facilities associated with former uranium mining operations.

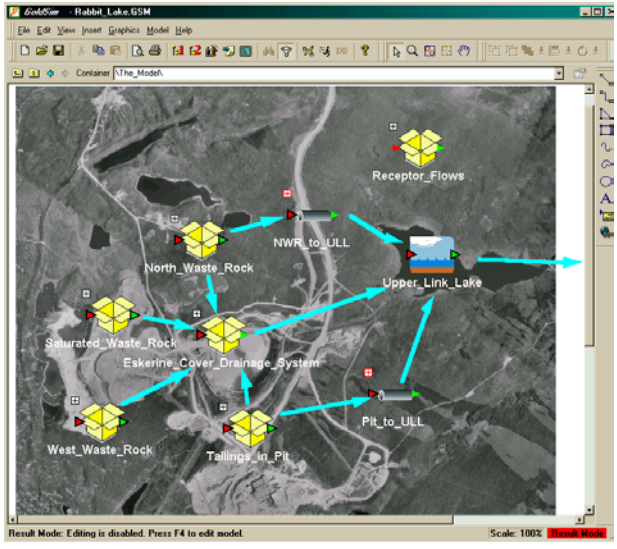

Figure 7: GoldSim Model Simulating Closure Options for a Uranium Mine in Canada

- ***Modeling Long-Term Health and Environmental Risk at the Nevada Test Site.*** GoldSim was used to create a contaminant transport and regulatory compliance model of a radioactive waste disposal site at the Nevada Test Site (NTS), northwest of Las Vegas, Nevada. The model is a management system tool that will support effective long-term management of the NTS low-level radioactive waste disposal facilities.
- ***Environmental Assessment of a Proposed Diamond Mine***. Before a new mine can be developed, it is necessary for an environmental assessment (EA) to be completed and accepted by the regulatory agencies responsible for project approvals and licensing. Recently, GoldSim was used to assess the impacts of mining and site activities on site water quality for a major new diamond mine in Canada's Northwest Territories.
- ***Modeling Transmission of Infectious Diseases***. GoldSim has been used to model the transfer of pathogens between patients and health care workers in a hospital. The model generated simulated outbreaks in hospital wards, where the onset, extent of spread, and control of the outbreak is a manifestation of natural variability and the impact of simulated control strategies.

AUTHOR BIOGRAPHIES

RICHARD KOSSIK is a Principal in the GoldSim Technology Group. For the past fourteen years, he has concentrated on developing and applying probabilistic simulation, strategic planning, and decision analysis techniques in order to understand and predict the behavior of complex systems. Mr. Kossik is the co-developer of GoldSim, a state-of-the-art probabilistic simulation software program. He has carried out numerous workshops and seminars describing methods for simulating complex systems. Mr. Kossik has been involved in modeling complex environmental systems worldwide, including numerous proposed and existing waste management facilities and mines in the U.S., Europe and Asia. Mr. Kossik has an M.S. in Civil Engineering from MIT, and a B.S. in Environmental Engineering from the University of Michigan. His email address is <rkossik@goldsim.com>.

IAN MILLER is President of GoldSim Technology Group in Issaquah, Washington. He specializes in analysis and computer-based simulations of complex systems, focusing on issues of risk and uncertainty, and has a M.S. in Civil Engineering from the University of British Columbia. Mr. Miller has directed probabilistic performance assessments of nuclear waste repositories, and risk assessments of Arctic pipelines, uranium mine tailings, hazardous waste landfills, and industrial site contamination. He led development of the GoldSim simulation model, which is used worldwide for safety assessments, risk management, and decision support. His e-mail address is <imiller@goldsim.com> and the corporate web address is <www.goldsim.com>.