QUANTITATIVE RISK ANALYSIS METHODOLOGY FOR THE TRANSPORTATION OF NUCLEAR WASTE

AD McGoey-Smith[1] and E. Haack[2]
[1] Advisian, WorleyParsons Canada, Calgary, Alberta, Canada
[2] Advisian, WorleyParsons Canada, Mississauga, Ontario, Canada
andrew.mcgoeysmith@.advisian.com and Elizabeth.Haack@advisian.com

Abstract

Transportation of nuclear waste poses risks to human health and safety, and the environment. In quantitative applications, risk is defined as a measure of the likelihood and consequences of an adverse event: it is a combination of event, probability and consequences, given the presence of a hazard. Cause-consequence analysis is used to define a set of risk scenarios involving the hazards associated with an accidental spill of nuclear waste from a truck during transportation along public roads. This involves the chain of events linking the primary hazard event, which is a truck collision, to the various risk endpoints which involve hazards to people and the environment and is represented in cause-consequence analysis by an event tree. By combining data on truck collision frequencies and conditional probabilities associated with release and dispersion, the frequencies associated with the risk endpoints are estimated. For the consequence estimation, fate and transport modelling is utilized based on chemical thermodynamics, specifically fugacity modelling. This enables the quantification of the effects of spills of nuclear waste into multiple media such as soils, streams, lakes and groundwater, as well as uptake by flora and fauna in a food web. A novel methodology is utilized in this work which integrates discrete tree structures, reliability analysis, Monte Carlo simulation, fate and transport modelling, and food webs. In this representation the explicit quantification of uncertainties is also undertaken. The GoldSim environmental risk and decision tool is used for the computation, which combines the aforementioned elements in an integrated way, and addition also provides strong graphical capabilities for communication of system complexity and risk to scientists, engineers, planners and other stakeholders.

1. Introduction

Transportation of nuclear fuel from commercial nuclear reactors to a central deep geological repository will be required in the future [1], and assessing the risk is a mandate of the NWMO. Here we present a methodology and modelling approach for quantifying the health, safety and environmental risks of transporting nuclear waste by truck on public roads.

Risk is a measure of both the likelihood and consequence of an adverse event such as the accidental release of nuclear waste from its containment during transportation. In quantitative risk assessment we are concerned with answering the following questions [2]:

- What can go wrong?
- What are the causes?
- What are the consequences?

- How likely is it?

We also draw upon the definition of risk developed by Kaplan and Garrick [2], which has been adopted by the nuclear power and chemical process industries worldwide. This defines risk as a triplet: risk is a triple combination of **event, probability** and **consequences**.

A risk scenario thus defined comprises an incident, which in this case is is a loss of nuclear waste containment. It also includes several incident outcomes stemming from that loss of containment incident, such as: damage to human health and safety, damage to the environment and ultimately, loss of reputation of the NWMO and the nuclear power industry. The initial causes and subsequent events leading up to the loss of containment are included in the risk scenario.

The practice of risk management, including risk assessment, has been encapsulated in the ISO31000 international standard [3]. It comprises the following steps as shown in Figure 1:

Establish the context: this frames the risk assessment in a broad context and defines the objectives and outcome measures which can be used by decision-makers. The internal and external context is that effectively managing the transportation of nuclear waste reduces the risk to the NWMO and nuclear power industry.

Risk Assessment: this comprises three stages: risk identification, risk analysis and risk evaluation which is the focus of this paper.

Risk Identification: this involves identifying the sources of risk, the events which cause these sources of risk to occur and the impacts these risks have on individuals and the environment. The outcome of this step is to produce a set of hazard scenarios which involve risks which can halt the transportation of nuclear waste. As per standard practice in the nuclear and chemical process industries, which handle hazardous materials, Cause-Consequence Analysis (CCA) is used here to identify the risks and define the hazard scenarios [4,5]. Cause-consequence analysis is generally used for analyzing failures in safety critical systems, which is the case in transportation.

Risk Analysis: this provides inputs into the risk evaluation process, as well as inputs into the decision-making, which are part of risk treatment. The analysis of each risk involves an estimation of both the likelihood and consequences of that risk. In this paper, the methodologies and software are focused on quantitative methods. Estimates of likelihood of risk endpoints are evaluated using an event tree which is part of the CCA. Site-specific and vehicle-specific transport accident data can be used to estimate the likelihood of a traffic collision for a truck carrying nuclear waste. Quantification of consequences uses fugacity modelling for estimating concentrations of radionuclides in environmental media and food web modelling for modelling the biological uptake of radionuclides and eventually potential ingestion by humans. As will be seen later, event trees are easy to develop in GoldSim, which is graphical in nature. It also contains a contaminant transport module which implements fugacity modelling between coupled environmental media. The consequences will differ depending on the environmental medium into which nuclear waste is accidentally released, and the pathway through which the waste propagates can be elucidated using the hazard scenarios defined in the event tree.

Risk Evaluation: the purpose of risk evaluation is to assist in making decisions based on the outputs from the risk analysis. It involves comparing the levels of risk output from the risk analysis process against a set of risk criteria, which include considerations of risk tolerance [4,5] such as the As Low as Reasonably Achievable (ALARA) principle.

Risk Treatment: following risk evaluation, this involves application of several prevention and mitigation methods which are designed to reduce the likelihood and consequences of a loss of containment of nuclear waste in the event of a truck collision.

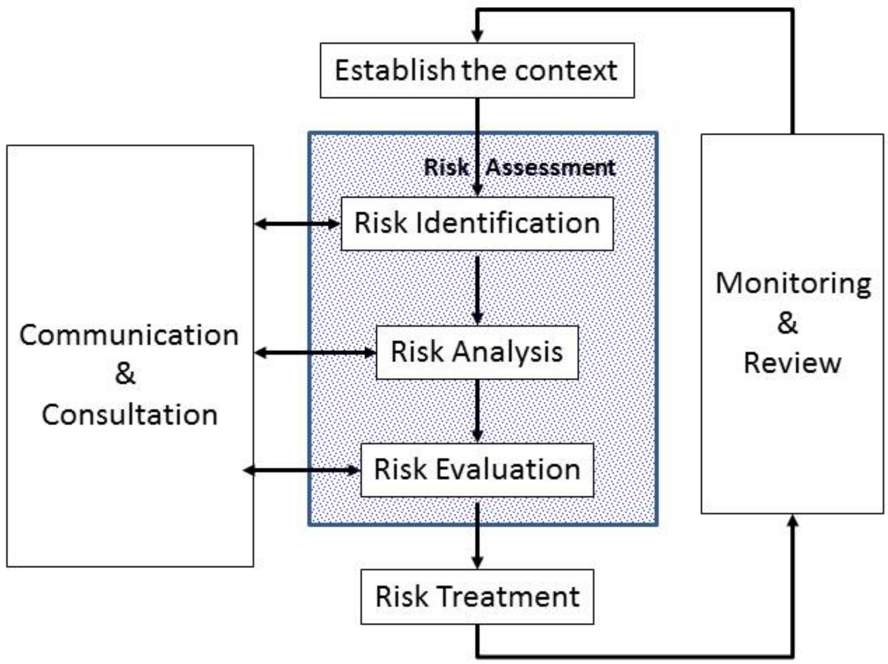

Figure 1 ISO Risk Management Process.

2. Context

For the truck transportation of nuclear waste, the context of risk management is: how can we make the transportation as safe as possible? While it is not possible to totally eliminate the risks involved in transportation, it should possible to apply risk mitigation methods to make risk as low as reasonably achievable. Also, as a result of the risk analysis, safety measures which have been already incorporated into the transportation protocol such as containment of the waste into bundles, will be taken into account.

An example of how nuclear waste might propagate through different environmental pathways is shown in Figure 2. This is in the form of an influence diagram [6] which was drawn using GoldSim. In an actual risk assessment for specific transportation route, development of the influence diagram would be a major focus of the contextualization process and would be typically developed in a facilitated team environment led by an experienced risk assessor working with the client team.

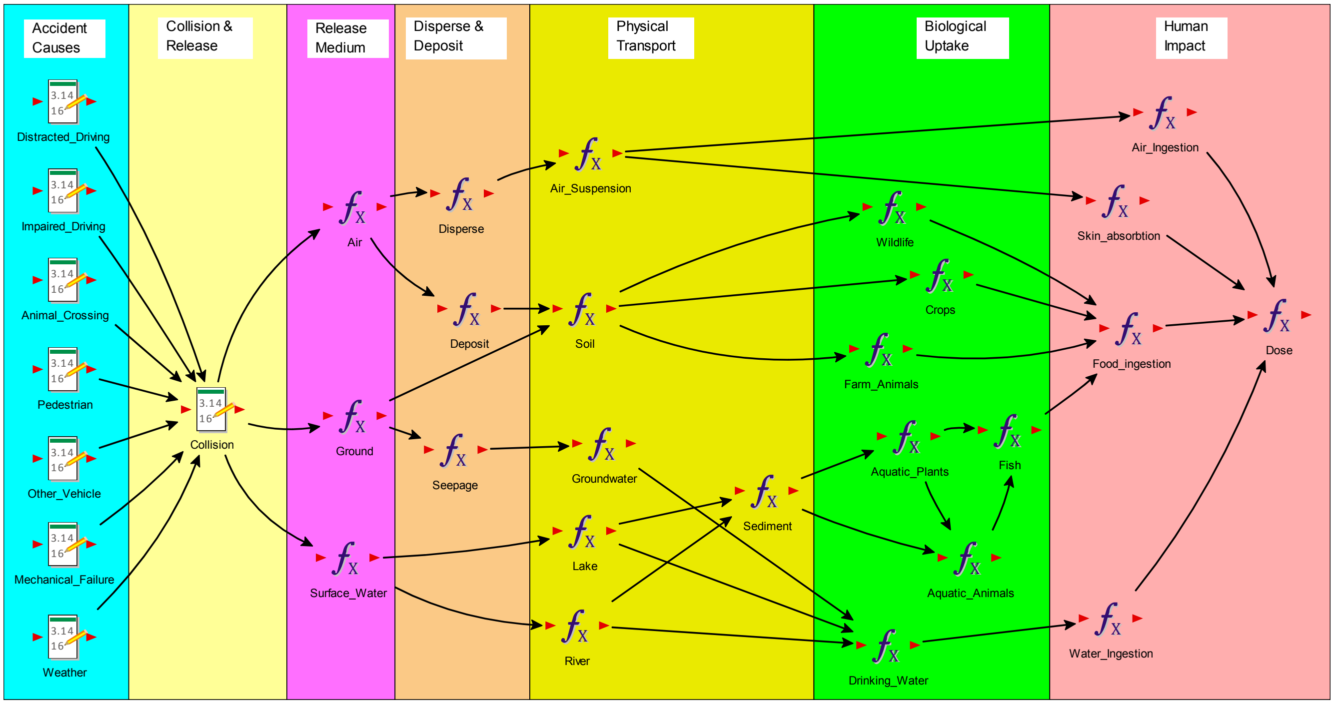

Figure 2 Influence Diagram.

3. Risk Identification and Hazard Scenarios

Cause-consequence analysis (CCA) has been utilized by the nuclear power and chemical process industries for many years and has been applied to the transportation of hazardous substances, as for example in the monograph published by the Institute for Risk Research [7]. The overall structure of the CCA process comprises a CCA diagram, see Figure 3, which relates the causes of an adverse event on the left through to the risk endpoints on the right. The adverse event is known as the primary hazard. The left part of the CCA diagram comprises a fault tree and the right part of the CCA diagram comprises an event tree. In the case of transportation of nuclear waste by truck, the primary hazard event is a collision involving the truck. An initial cause could include for example an impaired driver which is a well-known cause of traffic collisions. The risk endpoint will comprise a dose of radiation from exposure to a radionuclide in a human from for example air ingestion or contaminated water ingestion.

The fault tree comprises a series of logic gates which connect causal events to the primary hazard events. The logic gates are either an ‘AND’ or an ‘OR’. The fault tree comprises a series of causes of an accident arranged in a series of ‘OR’ gates leading to a truck collision such as driver error or impaired driver or mechanical failure or a wild animal (such as a moose), etc. For estimation of the truck collision frequency, this can be determined from historical data for each stretch of highway. The fault tree is useful for formulation of mitigation strategies and is not shown here. An example of an event tree is shown in Figure 4. This comprises a series of (usually mutually exclusive) events from the primary hazard event to the risk endpoint. This fault tree can be extended further by consideration of the various environmental media through which the nuclear waste could propagate to get to a more final endpoint which would be the exposure of humans to a radioactive dose. We now continue to the risk assessment.

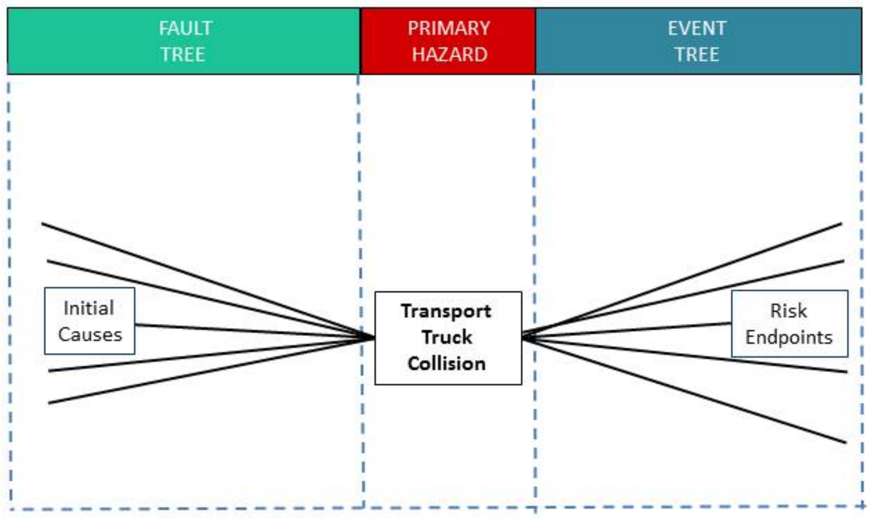

Figure 3 Cause-Consequence Analysis Diagram.

4. Likelihood Estimation

Risk assessment comprises an estimation of the likelihood and consequences of an adverse event. We begin our analysis of risk by discussing how we can estimate the frequency of release of nuclear material into the environment. First we begin with the truck collision frequency for a given section of highway which can be obtained through provincial databases. As of 2013, the general vehicle accident rate in Canada is approximately $1.4\text{x}10^{-6}$ events/km/yr. Note that the truck collision rate is lower than this number approximately by a factor of about 20 in Ontario. The track collision frequency will change depending on which stretch of highway the truck is passing through. The accidental release of hazardous radioactive waste into the environment is dependent on the truck collision frequency and a series of conditional probabilities related to the confinement of the nuclear waste in the track. These conditional probabilities are identified in the event tree as part of the CCA. In the event of a truck collision, only a fraction of trucks will roll over. In turn only a fraction of rolled over trucks will result in a breakage in the hull. Again even with a breakage in the hull, only a fraction of breakages will result in a bundle of nuclear waste being released through the hull. Finally because the bundle comprises of hard ceramic material, only a fraction of this hazardous waste material will be released into an environmental medium. Thus we can estimate the frequency of an accidental release of nuclear waste f_{rel} arising from a truck collision as

$$f_{rel} = f_{coll} \cdot P(RO \mid Coll) \cdot P(HB \mid RO) \cdot (BR \mid HB) \cdot P(BD \mid BR) \qquad (1)$$

Where f_{coll} is the truck collision frequency in events/yr, RO denotes is rollover event, HB denotes a break in the truck hull event, BR denotes a release of the nuclear waste bundle from the vehicle hull and BD denotes damage to the bundles resulting in the release of nuclear waste into an environmental medium event. In order for a nuclear waste release in to an environmental medium event to occur, a cascade of successive breakage events needs to occur. Therefore, only in the event of a high impact truck collision is it likely that nuclear waste material will be released into an environmental medium and thence propagate to a human receptors.

We can estimate the release frequency from historical data and either fit to a parametric expression, or use the mean value. Since data on the conditional probabilities is probably not readily available, these can be estimated using subjective probability and risk elicitation techniques [6]. Triangular distribution functions are often utilized for such quantities in industrial applications, which bound a probability in terms of the lower, upper and most likely values. The GoldSim model for estimating the frequency of release of radionuclides into the environment is shown in Figure 5.

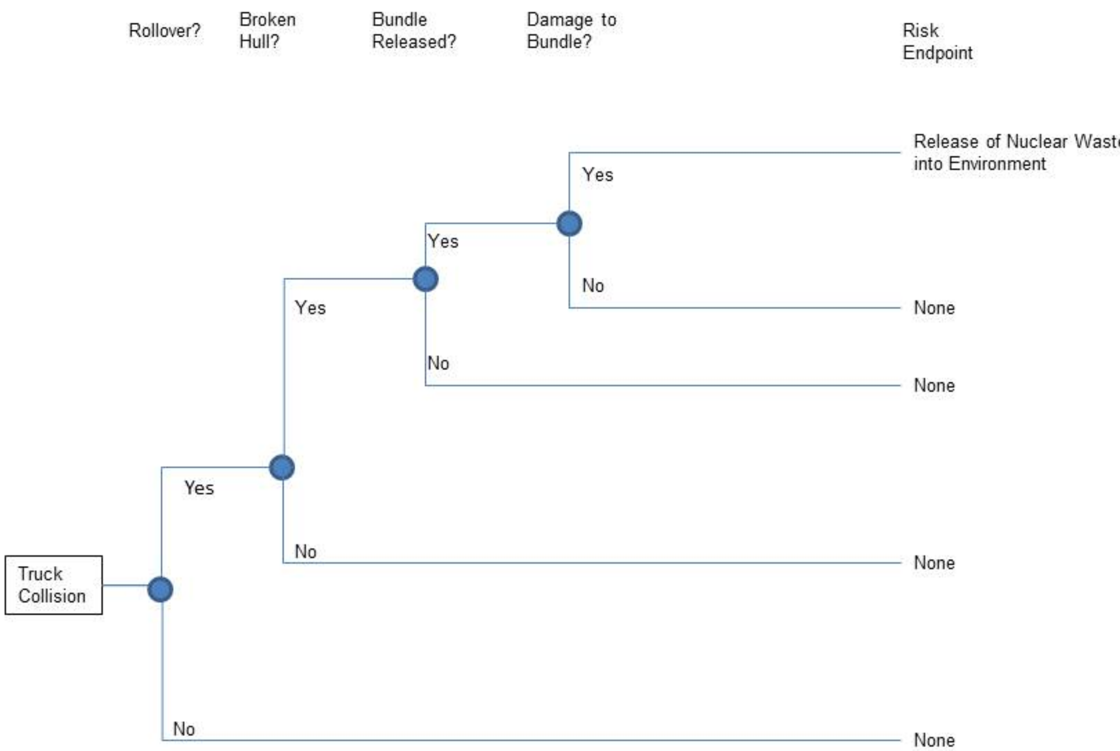

Figure 4 Event Tree.

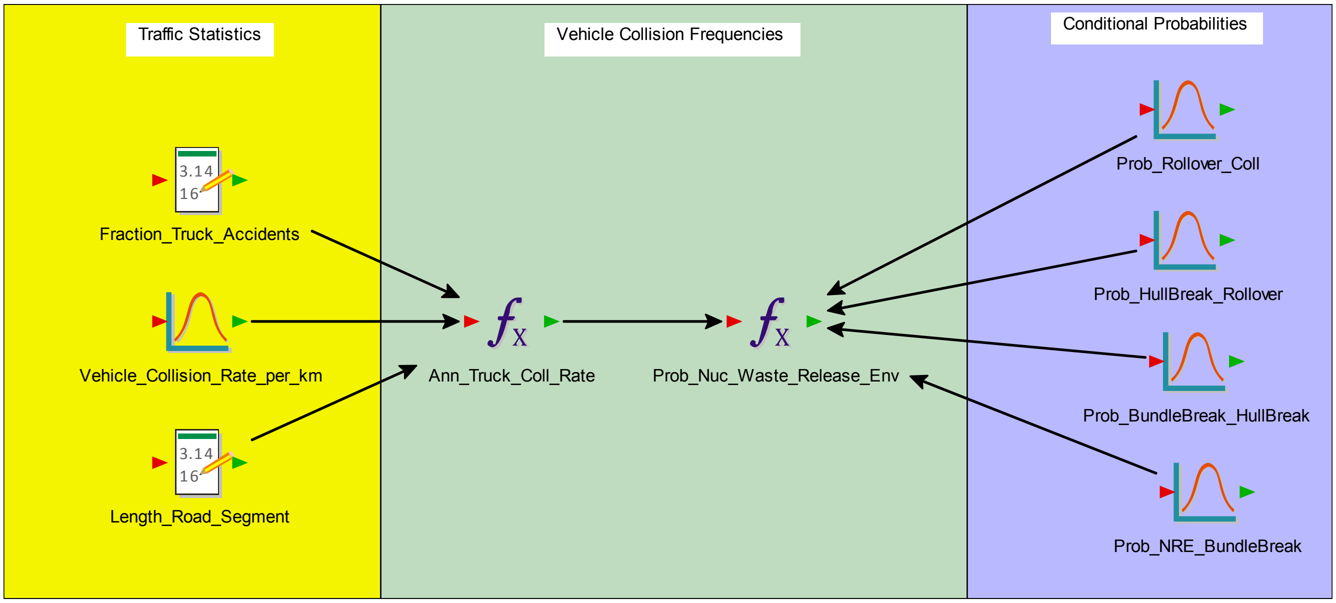

Figure 5   Frequency Estimation Model implemented in GoldSim.

5. Consequence Estimation

Consequence estimation of the impact of radionuclides on humans and the environment uses scientific models based on chemistry, ecology and radiation physics. Because there are many environmental pathways which could expose humans to a radioactive dose arising from an accidental release of nuclear waste into the environment, the "fugacity" approach of Mackay [7] for modelling fate and transport of contaminants in multiple environmental media was implemented by the developers of GoldSim. This approach is simple to apply and is based on chemical thermodynamics and mass transport theory, namely: advection and diffusion. The propagation of radioactive material through the biosphere is modelled using the AECL CALDOS [8] model, which uses a radiological physics approach.

GoldSim applies a mass balance between release point and receptor through various environmental media. The change of concentration from, for example soil to water, is governed by partition coefficients using Henry's Law. Similarly, a change in concentration of contaminants in moving from water to sediment is also governed by Henry's Law. For an overview of the environmental modelling approach used by GoldSim, consult [9] or the GoldSim contaminant transport manual [10]. Advective and diffusive fluxes in media such as water and air are taken into account by solving the advection-diffusion equations. Environmental pathways are divided into whether they are cell pathways, such as lakes and soil, and pipe pathways such as rivers and streams. Aquifer pathways are also included, which are similar to pipes because they include advection in a given direction with longitudinal dispersion.

For assessing the impact from radionuclides on humans, the AECL CALDOS model [8] is used. This model was implemented in GoldSim previously [11]. The model estimates the dose *D* to humans in Sievert from the radioactivity using the following formula:

$$D = C \cdot T_f \cdot U \cdot DF \qquad (2)$$

Where C is the concentration in Bq/m^3 in the environmental medium, T_f is the transfer factor from release to human exposure, U is the human usage and DF is the conversion factor from exposure in humans to dose in humans in Sv/Bq. Since the total dose for a human D_{tot} can come from many environmental pathways, it can be calculated by summing over these as denoted by the index p

$$D_{tot} = \sum_p D_p \qquad (3)$$

where D_p is the partial dose over pathway p denotes the particular pathway. Figure 6 shows how contaminant transport and the CALDOS model can be implemented in a single modelling framework. Because of the graphical nature of GoldSim, the different contaminant transport and environmental exposure pathways are explicitly shown. Also, GoldSim is a probabilistic tool, which enables uncertainties to be taken into account using a built-in library of probability distributions. For example, many of the parameters which go into the explicit calculation of the dose pathways are probabilistic in nature and are quantified using normal and log-normal probability density functions. Therefore, the final dose in humans is also a probability distribution function and is calculated in GoldSim using the Monte Carlo method.

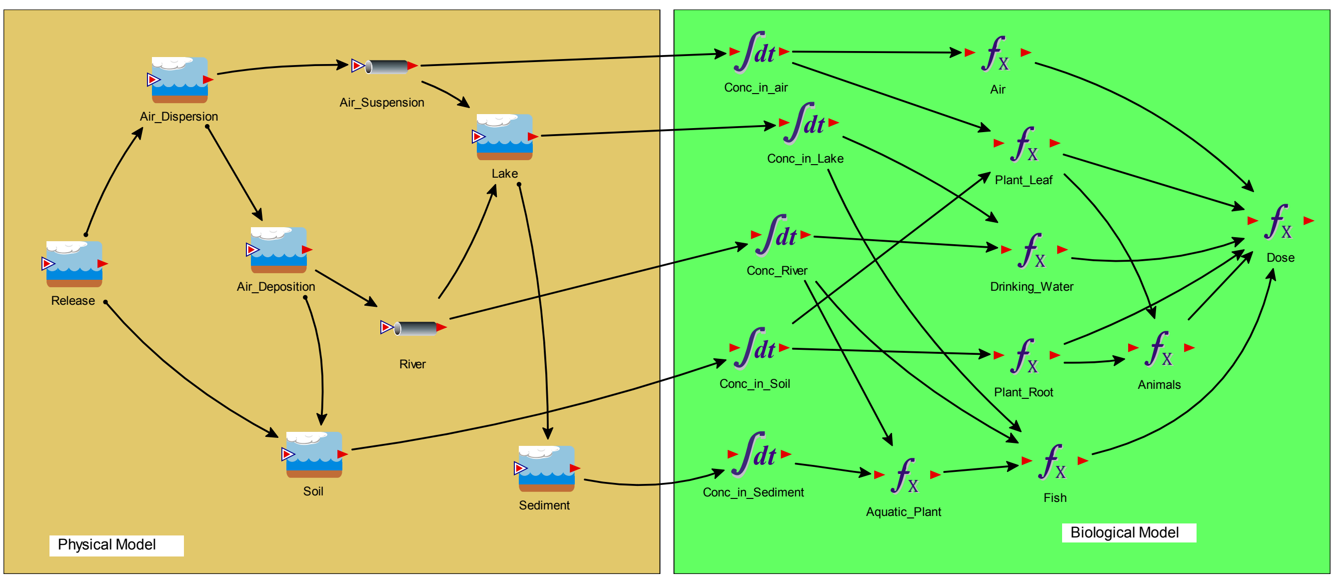

Figure 6 Consequence Model implemented in GoldSim.

6. Conclusion

We have described a methodology for quantifying the risk of transportation of nuclear waste by truck. In addition, we have shown how this quantitative risk assessment can be implemented into a single unified model using the GoldSim risk and environmental modelling environment. An implementation of the GoldSim model will be presented at the conference.

7. References

[1] *Safe and Secure Transportation of Canada's Used Nuclear Fuel*, Nuclear Waste Management Organization, May 2015, https://www.nwmo.ca

[2] T Bedford and R Cooke, *Probabilistic Risk Analysis: Foundations and Methods*, Cambridge, UK, 2000.

[3] *International Standard IEC/ISO 31000*, *Risk Management*, International Stands Organisation, 2009, International Electrotechnical Commission, Geneva, Switzerland, November, 2011.

[4] *Risk Assessment – Recommended Practices for Municipalities and Industry*, Process Safety Management Division, Canadian Society for Chemical Engineering, 2004 (formerly referred to as the Major Industrial Accidents Council of Canada or MIACC guideline, 1999).

[5] *International Standard IEC/ISO 31010, Risk Management – Risk Assessment Techniques*, 1st Edition, International Electrotechnical Commission, Geneva, Switzerland, November, 2011.

[6] MG Morgan and M Henrion, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, Cambridge University Press, Cambridge, UK, 1990.

[7] G Purdy, *The Measurement of Risk from Transporting Dangerous Goods by Road and Rail*, Chapter 1, Transportation of Dangerous Goods: Assessing the Risks, Edited by FF Saccomanno and K Cassidy, Proceedings of the First International Conference on the Risks of Transporting Dangerous Goods, held in Toronto, April 6-8, 1992.

[8] R Zach and SC Sheppard, *The Food-Chain and Dose Submodel, CALDOS, for the Assessment of Canada's Nuclear Fuel Waste Management Concept*, AECL Report AECL-10165, December, 1992.

[9] D Mackay, *Multimedia Environmental Models: The Fugacity Approach*, 2nd Edition, Lewis Publishers, Boca Raton, Florida, USA, 2001.

[10] GoldSim, Monte Carlo Simulation Software for Decision and Risk Analysis, www.goldsim.com

[11] AD McGoey-Smith, BJ Griffin, SM Swanson,, A Buoro and RC Moraes, *Risk and Uncertainty of Contamination of the Food Supply due to Sudden Release of Radionuclides in the Atmosphere*, Proceedings of the IAEA International Conference on Nuclear Safety, RioConf2005, Rio de Janeiro, Brazil, 2005.