ERMYN: Environmental Radiation Model for the Yucca Mountain, Nevada

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Abstract

This paper briefly describes a new biosphere model, ERMYN, that was developed to characterize biosphere processes for radionuclides released from the proposed high-level radioactive waste geologic repository at Yucca Mountain (YM). Biosphere modeling for YM is conducted independently for two radionuclide release modes and resulting exposure scenarios, groundwater release and volcanic release. This paper focuses on the model for groundwater release. The groundwater release exposure scenario addresses the case in which the geosphere-biosphere interface is well extraction of contaminated groundwater.

Introduction

ERMYN is one of the process models used in the Total System Performance Assessment (TSPA). It provides the TSPA with the capability of performing radiation dose assessments. The biosphere model is used to calculate biosphere dose conversion factors (BDCFs), which are used in TSPA to calculate radiation doses from estimated radionuclide concentrations in groundwater and volcanic ash. ERMYN will be used to support the TSPA for Licensing Application (TSPA-LA). The tasks conducted in the development of the biosphere model are: (1) screening of applicable features, events, and processes (FEPs) for inclusion into the model; (2) development of a conceptual model based on the applicable FEPs; (3) construction of the mathematical model and its component submodels; (4) development of input parameters, including representation of uncertainty associated with the inputs; (5) construction of the predictive model using GoldSim stochastic simulation software; and (6) model validation and verification.

Model Development

The FEPs evaluated for applicability were from the YM Project FEP database. Thirty-three primary FEPs were determined to be partially or totally applicable. These FEPs represent the features of an arid to semi-arid environment in the YM vicinity and the possible transport processes resulting in accumulation of radionuclides in the environmental and consequent human exposure. The primary rationale for excluding FEPs was the regulatory requirements for reference biosphere and the receptor (the reasonably maximally exposed individual – RMEI) defined in the NRC final rule at 10 CFR Part 63. Other common justifications for exclusion were low probability, as defined by the regulation, and low consequence.

The biosphere conceptual model was constructed by considering the applicable FEPs. Radionuclide transport between environmental media was systematically identified by constructing a radionuclide transfer matrix. (Table 1). The environmental media (features) in Table 1 are represented by the leading diagonal elements of the matrix. The off-diagonal elements represent the radionuclide transport processes between media. The environmental media and associated transport processes in Table 1 constitute the subsystems of the biosphere system and are represented as five of the nine submodels in ERMYN. Additional submodels, not shown in the matrix, are associated with the three human exposure pathways. The relationships between the submodels are shown in Figure 1. Arrows point in the direction of radionuclide transfer among the biosphere components. A special submodel not shown in Figure 1 was developed for ^{14}C because of its unique transport requirements. Separation of ERMYN into nine submodels made the conceptual and mathematical models easier to develop and implement.

Groundwater Source

The radionuclide source for the groundwater scenario is contaminated groundwater extracted from a well. In the model, the activity concentration of a radionuclide in groundwater is set at unity (1 Bq/m^3).

Surface Soil Submodel

The surface soil submodel calculates radionuclide concentrations in surface soil resulting from irrigation with contaminated groundwater (Element [2,1] in Table 1). Based on current agricultural practices in Amargosa Valley, groundwater is the only source of irrigation water.

Table 1. Radionuclide Transfer Interaction Matrix for the Groundwater Scenario

(i, j)	1	2	3	4	5	6	7
1	**SOURCE** (well water)	*irrigation*	*evaporation, aerosol generation in swamp coolers*	*Irrigation interception*	*ingestion of water*	*bioaccumulation (water use in fisheries)*	*drinking water ingestion*
2	*leaching**	**SOIL** (surface soil)	*particle resuspension, gas release, soil erosion**	*root uptake*	*soil ingestion*	-	*soil ingestion, external exposure*
3	-	*particulate deposition, wind erosion*	**ATMOSPHERE**	*particulate deposition*	-	-	*inhalation of particulates, gases, and aerosols*
4	-	*weathering, harvest removal*	-	**PLANTS** (crops)	*ingestion of forage crops*	-	*crop ingestion*
5	-	*fertilization*	-	-	**ANIMALS** (animal products)	-	*animal product ingestion*
6	-	-	-	-	-	**FISH**	*fish ingestion*
7	-	-	-	-	-	-	**HUMAN** (receptor)

* The removal mechanisms of leaching and erosion from surface soil lead to a loss of radionuclides from biosphere system.

Because the objective of the postclosure dose assessment is to predict the long-term exposure consequences of the proposed repository, the model assumes that the same land is irrigated annually with contaminated groundwater, which leads to radionuclide buildup in the irrigated soil. This build-up process is mitigated in the model by removal mechanisms radioactive decay, leaching to the deep soil, surface soil wind erosion, and gaseous release (Elements [1,2] and [3,2] in Table 1). The last process applies only to modeling of ^{222}Rn and ^{14}C.

The primary removal process is leaching due to over-watering, an agricultural practice conducted to remove salts that otherwise would inhibit crop production. In the leaching process, radionuclides infiltrate below the root zone into the deep unsaturated zone where they are no longer available to crops. Radionuclides lost by leaching are not further tracked in the model.

Over the long time (i.e., >10,000 years) that agricultural land is considered to be in production, all radioactivity incorporated into crops will get recycled in the biosphere either in the form of animal manure or non-edible parts of crops (Element [2,5] in Table 1). Thus, removal of radioactivity in foodstuffs (Element [2,4]), although frequently included in some published biosphere models, is conservatively ignored in ERMYN.

Deposition of contaminated atmospheric dust on surface soil is another possible radionuclide source to the surface soil model (Element [2,3] in Table 1). However, this mechanism is considered to be balanced out by resuspension from surface soil (Element [3,2]). Thus, these two mechanisms are not included in the surface soil submodel. Furthermore, some fraction of the deposited dust may be from uncontaminated (non-irrigated) land, in which case the concentration of radionuclides in the deposited dust would be less than that in the resuspended particles. The process of inflow of uncontaminated soil and outflow of contaminated soil constitutes wind erosion considered in ERYMN. Radionuclides lost by erosion are not further tracked in the model.

Because of the continuous addition and removal of radionuclides, equilibrium conditions eventually occur and radionuclide concentration in surface soil will no longer change with time. The soil submodel in ERMYN was constructed based on the assumption that equilibrium conditions have been reached. Soil activity concentrations

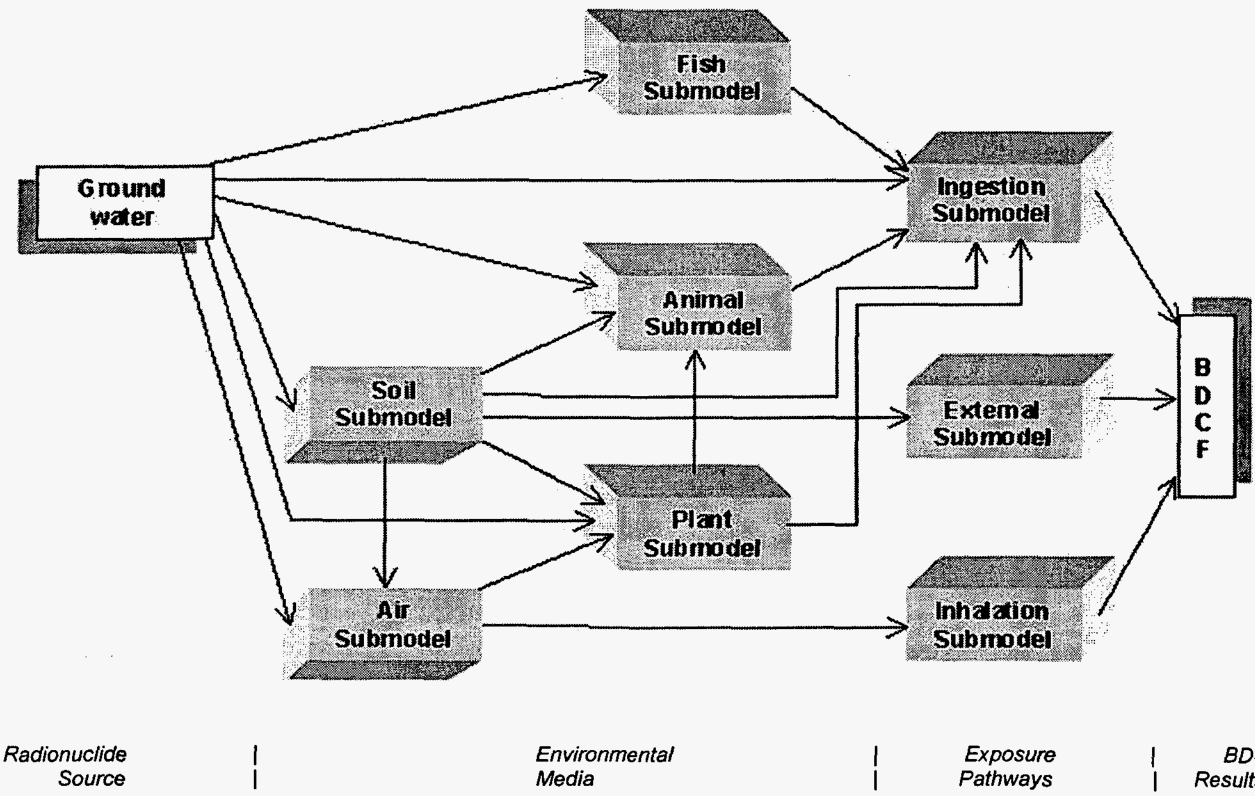

Figure 1. Relationship between the biosphere submodels for the groundwater release exposure scenario

from this submodel are used in the air, animal, and plant submodels (Figure 1).

Air Submodel

The air submodel calculates the radionuclide concentration in air. Inputs to the air submodel come from the surface soil submodel and directly as the concentration in contaminated water. Three air contamination processes are considered in this submodel: resuspension of contaminated soil particles, generation of contaminated aerosols by evaporative coolers, and gaseous release of radionuclides from contaminated soil (Elements [3,1] and [(3,2] in Table 14). The air submodel uses the equilibrium radionuclide concentration in the soil from the surface soil submodel. Resuspended particles are also considered in the indoor environment, where they are, with some attenuation, transported from outdoor source.

Resuspension of soil contaminated by irrigation occurs either by natural forces, such as wind, or by human activities. Radionuclide concentrations in air depend on atmospheric conditions and on characteristics of soil particles (e.g., size, mineralogical composition, and ability to sorb radionuclides). Resuspended particles can be deposited on crop leaves or the soil surface (Elements [4,3] and [2,3] in Table 1). Resuspended surface soil is the major source of activity for human inhalation (Element [7,3]). Airborne particles will be primarily from local, contaminated soil but some fraction also will come from uncontaminated soil. The uncontaminated fraction is difficult to predict and requires detailed knowledge of land use and meteorological conditions. The most important source of airborne particulates are human dust-generating activities, such as are common in farming and some recreational activities. Undisturbed desert pavement is a stable surface and is not a significant source of airborne particulates compared to cultivated land. Therefore, dilution of radionuclide concentration in resuspended particles is not considered in the model.

The radionuclide concentration in air is estimated using slightly different methods for direct deposition on crop leaves and for human inhalation. For crop deposition, it is assumed that mass activity concentration of radionuclides in airborne particles available for external deposition on crops is equal to the concentration in surface soil. For human inhalation, only particles with diameter is less than about 100 μm are considered and the activity concentrations in surface soil and airborne particles may be different.

Radionuclides that are gases or have gaseous chemical species may also be transported to the atmosphere via gaseous release from soil. Only two radionuclides from the YM inventory are likely to be released from soil as gases: ^{222}Rn and ^{14}C. ^{222}Rn is a decay product of ^{226}Ra and is itself radioactive, leading a chain of short-lived progeny. In ERMYN, only radon release from soil is considered because the direct release of radon from water is not a significant dose contributor. Radon concentrations in air are calculated separately for indoor and outdoor environments. ^{14}C released from soil as gas may be taken up by plants and also may contribute to inhalation exposure of the human receptor. Concentrations in air of radionuclides present as gases is affected by the atmospheric mixing and dilution.

The radionuclide concentration in air may also be affected by the operation of evaporative coolers using contaminated groundwater. During evaporation due to forced air flow through the evaporative cooler, a fraction of contaminants in the water would be released into indoor air. A key parameter in determining the radionuclide concentration in air is the fraction of the radionuclide that is transferred from water into air. The concentration also depends on the water usage and air flow rate of evaporative coolers. Air leaving buildings carries radioactive contaminants outside, where atmospheric dilution makes it an unlikely source of inhalation exposure outdoors.

The outputs of the air submodel (radionuclide concentrations in air from soil resuspension, gaseous release, and evaporative coolers) are used in the plant and inhalation submodels (Figure 1).

Plant Submodel

The plant submodel calculates the radionuclide concentration in crops that are consumed by humans and animals. The plant submodel uses inputs from the soil and air submodels and directly as concentrations of contaminated water. The mechanisms of radionuclide transfer to crops are root uptake, direct deposition on crop leaves from irrigation water, and deposition of resuspended soil particles (Elements [4,2], [4,1], and [4,3] in Table 1).

Root uptake is modeled on the basis of equilibrium between radionuclide concentrations in soil and crops. It is assumed that all roots are in the surface soil compartment. Direct deposition from irrigation water and resuspended particles is modeled as a continuous process occurring during crop growth, accompanied by the continuous process of radionuclide removal by weathering. The fraction of irrigation water initially intercepted by a plant depends on the irrigation practice and plant biomass. The interception fraction for deposition of resuspended particulates is a function of plant type and biomass. These two processes are modeled using empirical equations. The activity remaining on crops may be translocated in whole or in part to foodstuffs. Radionuclides removed from crop surfaces by weathering eventually are deposited on the soil. This process is not tracked separately; rather it is assumed that activity deposited onto the soil by irrigation is not reduced by interception of a fraction of this activity by plants.

Five types of crops are considered in the model: leafy vegetables, other vegetables, fruit, grain, and forage crops for beef cattle and dairy cows. Grain is considered for human consumption and as feed for poultry and laying hens. It is also assumed that fresh forage was available year around. Differences in radionuclide concentration among crops is due to differences in irrigation rates, growing times, and other agriculture-related input parameters.

The output of the plant submodel (activity concentration of a radionuclide in crops) is used in the ingestion submodel to calculate the contribution to dose from consumption of crops, and in the input to the animal submodel, as described below.

Animal Submodel

Three environmental transport pathways that contribute to radionuclide uptake by livestock are included in the animal submodel: contaminated crops, water, and soil (Elements [5,4], [5,1], and [5,2] in Table 1). Radionuclide uptake by inhalation is not included in the submodel because of its lower contribution compared to ingestion.

The equilibrium, concentration ratio, approach is also used to assess radionuclide concentrations in animal products. The equilibrium is between the rate of animal activity intake and the activity concentration in an animal product. Four types of animal products (meat, poultry, milk, and eggs) are considered in the submodel. It is assumed that meat includes beef, pork and lamb; milk could come from cow, sheep, or goat); poultry includes chicken, turkey, duck, goose, and game hen; and eggs come from laying hens and ducks. The output of the submodel, radionuclide concentrations in animal products, is used in the ingestion submodel (Figure 1) to calculate the contribution to dose from consumption of contaminated animal products.

Fish Submodel

The fish submodel calculates the radionuclide concentration in fish. Consumption of contaminated fish was considered in the biosphere model, because fish farming has occured in Amargosa Valley. Radionuclide accumulation in fish is considered to be exclusively from the use of contaminated water in fishponds. The radionuclide transfer from water to fish is through bioaccumulation (Element [6,1] in Table 1).

The transfer process is based on the equilibrium between the radionuclide concentration in water and in the edible parts of fish. This approach is most applicable to aquatic systems where all components are in equilibrium, such as rivers or lakes. Because fish farming uses uncontaminated commercial feed, the equilibrium approach likely produces upper-bound values of radionuclide concentrations in fish. Contamination of fishpond water from deposition of resuspended particles is insignificant compared to contaminated water and is not included in the submodel. The output of the fish submodel, activity concentration in fish, is used in the ingestion submodel (Figure 1) to calculate the contribution to dose from consumption of contaminated fish.

Carbon-14 Submodel

The environmental transport pathways of ^{14}C are different from those considered for other radionuclides. While most radionuclides are in solid form, carbon readily moves in the environment as gaseous species. Moreover, carbon is a ubiquitous element with an abundance of stable isotopes in the environment. Analogous to other radionuclides, the primary source of ^{14}C in the environment is irrigation water, and the calculation of ^{14}C concentration in soil is based on the equilibrium between ^{14}C gains and losses in surface soil. However, the most important process resulting in the loss of this radionuclide from surface soil, gaseous emission, is unique to gases and is not considered for other radionuclides. Once released into the atmosphere, $^{14}CO_2$ becomes available to be incorporated into crops via photosynthesis. The predominant transport pathway to plants is foliar uptake. ^{14}C uptake may also occur via roots; however, root uptake plays a smaller role than foliar uptake. CO_2, and thus $^{14}CO_2$, is lost from plants due to respiration. Following plant uptake, ^{14}C moves through the animal food chain. Additional sources of animal carbon intake are consumption of drinking water and soil. All of these processes are incorporated into the model.

To model ^{14}C transport in the biosphere, the concentration of ^{14}C in air is calculated based on the steady state concentration in surface soil, with the rate of loss controlled primarily by the gaseous emission loss rate of $^{14}CO_2$ from soil. ^{14}C in air is subject to mixing due to atmospheric processes, which is modeled using air movement in a mixing cell of defined dimensions. Calculation of ^{14}C uptake by biota employs a specific-activity approach. This approach is based on the consideration of a steady state between the environmental media involved, such that the ratio between ^{14}C and stable carbon in environmental media is fixed. The specific-activity approach is used to calculate ^{14}C concentration in crops and animal products. Bioaccumulation of ^{14}C in fish is assessed using the same method as that used for other radionuclides, based on the concentration ratio between water and edible parts of the fish. After media concentrations of ^{14}C are calculated, the dose assessment is carried out using the same approach as that used for other radionuclides.

External Exposure Submodel

This submodel calculates the dose resulting from external radiation exposure, which occurs as a result of direct exposure to ionizing radiation emitted by radioactive materials located externally to the human receptor. For environmental dose assessments, these materials typically include three environmental media: soil, air, and water. Their corresponding exposures are known as ground exposure, air submersion, and water immersion, respectively. The conceptual model only considers exposure to emissions from radionuclides in soil (Element [7,2] in Table 1) because air submersion and water immersion contribute very little to the dose. Radionuclides of concern are those with energetic beta and gamma rays, which can deposit ionizing energy in human organs and tissues.

Although exposure from other types of media, such as building materials, furniture, and clothing is possible, predictions of this type of exposure are not common because of large uncertainties and low contributions to the dose relative to exposure from contaminated soil. This is because the contamination level in these media is lower than that in soil. It is assumed that the aerial size and depth of contaminated soil layer are infinite and that exposure time to soil is longer than that for other contaminated media. Therefore, it is reasonable to ignore external exposure from these types of media.

The submodel considers external exposure in indoor and outdoor environments. For outdoor exposures, radiation dose depends on the radionuclide concentrations in soil, duration of exposure, and the dose coefficients used to convert exposure to dose. For indoor exposures, the shielding effect of dwellings mitigates the level of outdoor exposure. Although the radionuclide concentration in soil, which is an input to the external exposure submodel, is calculated for surface soil, the dose coefficients used in the submodel apply to soil contaminated to an infinite depth. This choice of dose coefficients was considered appropriate because the radiation contributing to external exposure may originate in deep soil (i.e., contaminated due to long term leaching of radionuclides from the surface soil). The output of the external exposure submodel, annual dose from external exposure, contributes to the all-pathway dose, which is used to calculate BDCFs.

Inhalation Submodel

This submodel calculates radiation dose due to inhalation of radionuclides. The 50-year committed effective dose equivalent (CEDE) is calculated for this pathway. Three sources of contaminates, provided by the air submodel, are considered in this submodel: resuspended particles, gases emitted from soil, and aerosols generated by evaporative coolers (Element [7,3] in Table 1).

In addition to concentrations in air, inhalation doses depend on the duration of inhalation exposure, breathing rates, and intake-to-dose conversion factors. It is assumed that whenever an evaporative cooler is in operation, it provides an effective filtration of outdoor aerosols. Breathing rate and exposure times are based on typical activities by the receptor in various environments. The output of the inhalation submodel, annual committed inhalation dose, contributes to the all-pathway dose, which is used to calculate BDCFs.

Ingestion Submodel

The ingestion submodel calculates the radiation dose due to ingestion intake of radionuclides. The 50-year CEDE was calculated for this pathway. Inputs to the submodel are radionuclide concentration in well water (Element (7,1) in Table 1), and outputs from the soil, plant, animal, and fish submodels (Elements [7,2], [7,4], [7,5], and [7,6]).

Eleven ingestion pathways are considered for the groundwater scenario, including drinking of contaminated. untreated groundwater, inadvertent soil ingestion, four types of plant foodstuffs, four types of animal products, and fish. Radionuclide concentration in these media are combined with corresponding consumption rates and dose conversion factors to produce ingestion doses. The output of the ingestion submodel, annual committed ingestion dose, contributes to the all-pathway dose, which is used to calculate BDCFs.

BDCFs and Model Results

The radionuclide-specific, all-pathway dose is the sum of the annual doses from external, inhalation, and ingestion exposure pathways. The BDCFs, in units of $(Sv/y)/(Bq/m^3)$, are numerically equal to the all-pathway dose from a unit activity concentration of a given radionuclide in groundwater. The calculation of each radionuclide concentration in groundwater as a function of time is carried out in the TSPA model. The total dose calculated in the TSPA model is the sum of the products of the radionuclide-specific BDCFs and the time-dependent activity concentrations of radionuclides in groundwater.

Model Implementation

The ERMYN is implemented using GoldSim software to facilitate stochastic computations. Separate models were built using GoldSim for the groundwater and volcanic release scenarios. Figure 2 shows the basic structure of the groundwater ERMYN within GoldSim.

Model Validation

The mathematical representation of radionuclide migration through the environment and human exposure in ERMYN is based on published biosphere models, including GENII-S [1,2], BIOMASS ERB2A [3], RASRAD [4], EPRI-YM [5], and NCRP 129 [6]. Model validation was conducted by comparing the mathematical models of ERMYN to these published biosphere models. For submodels with conceptual or mathematical differences, numerical comparisons were made to evaluate the representation of each submodel.

Model Enhancement

ERMYN and the TSPA models were both developed using GoldSim, which will allow the eventual integration of the biosphere model into the TSPA code with the attendant benefit of transparent sensitivity and uncertainty studies. Although based on the previous biosphere model GENII-S, ERMYN was constructed to incorporate some of the recent enhancements seen in newer models, include new FEPs not considered by GENII-S, and address some criticisms from reviewing organizations. Table 2 lists enhancements of ERMYN relative the GENII-S model used for the YM TSPA conducted for the site recommendation (TSPA-SR).

Conclusions

As an on-going effort to support the TSPA-LA, the new biosphere model for Yucca Mountain, ERMYN, was developed to enhance the dose prediction capability. The model considers more site-specific information in both model and parameter development than the previous YM biosphere model; has the flexibility to be readily modified to include new FEPs or sub-models; and, being developed in GoldSim, can easily be integrated into the TSPA code.

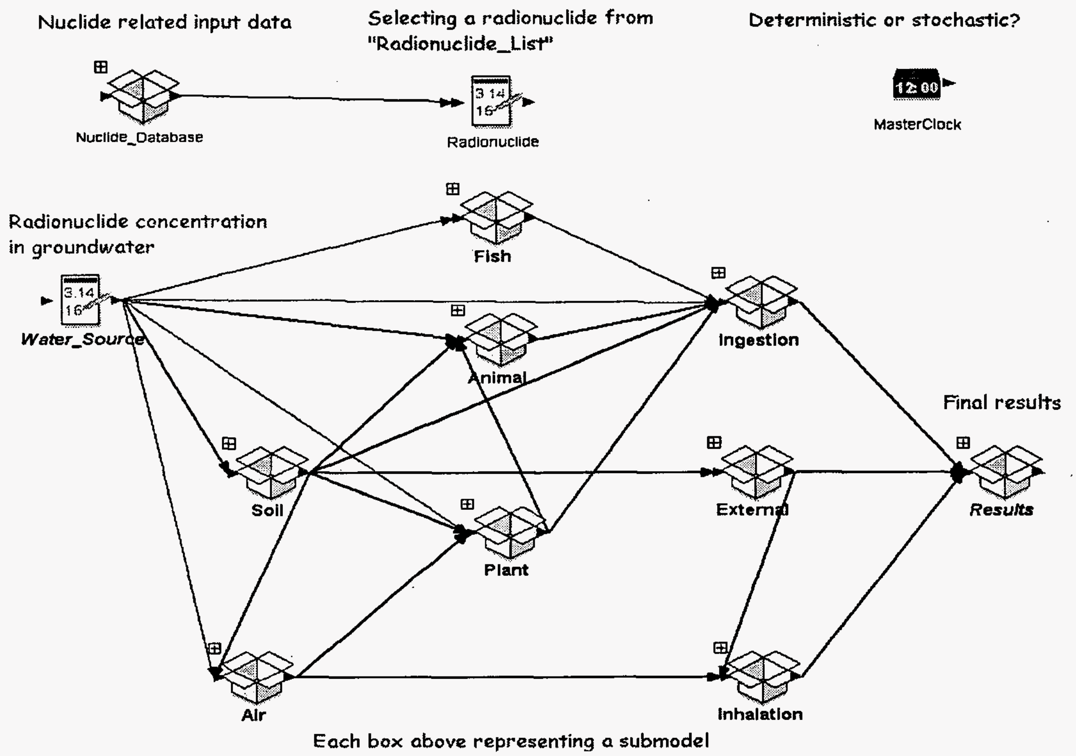

Figure 2. ERYMN in GoldSim for the Groundwater Scenario

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Table 2. Comparison of Biosphere Models for theTSPA-LA and TSPA-SR

Comparison	ERMYN (TSPA-LA)	GENII-S (TSPA-SR)
Parameter uncertainty	All parameters can be represented by probability distribution function	Limited number of parameters
Number of realizations per simulation	No limit on number of realizations	Limited number of realizations
Cumulative probability results	Calculated correctly	Some cumulative probability results calculated incorrectly (reported deficiency)
Long-term irrigation rate for agricultural land	Average irrigation rate developed to consider crop rotation and agricultural land use	Not considered, the same type of crop is indefinitely grown on a plot of land
Average radionuclide concentration in soil	Calculated using long-term irrigation rate; used for crop root uptake, external exposure, inhalation, and soil ingestion	Home lawn irrigation rate used for evaluation of external exposure, inhalation, and soil ingestion
Surface soil erosion	Included	Not included
Radionuclide accumulation in soil	Equilibrium activity concentration of radionuclides in surface soil	Calculated based on multiple irrigation periods
Harvest removal and use of cow manure as fertilizer	The two mechanisms were considered to balance out and were not included in the model	Harvest removal was in theory included, but the code did not execute this part of the model (reported deficiency)
Enhancement factor	Correction for enhancement of airborne activity concentration relative to surface soil	Not considered
Mass loading	Different values for deposition on crops and inhalation. Inhalation mass loading depends on human activity	Not used for crops; single value for inhalation
Soil-to-plant transfer factor for fresh forage	New parameter	Same value used for leafy vegetables and forage crops
Fraction of overhead irrigation	Included to better represent site-specific agricultural practice	Not considered
Crop daily irrigation rate	Included to eliminate correlation of irrigation duration with annual irrigation rate	Calculated from annual irrigation rate and duration
Irrigation interception fraction	Based on site-specific irrigation practices, including consideration of irrigation methods, irrigation frequency, and crop type. It is crop type dependent	A single value for all crop types
Animal soil ingestion	Considered	Not considered
Carbon-14 release from soil as gaseous species	Added carbon-14 submodel to include release of gaseous species of carbon from soil and subsequent uptake by plant and inhalation by humans	Not considered
C-14 leaching removal constant	User defined	Hardwired into the code, user input not used (reported deficiency)
C-14 pathways for external exposure, inhalation, and soil ingestion	Considered	Not considered
Crop C-14 uptake	Model differentiates between C-14 fractions derived from air and from soil	Root uptake only
Dose coefficients (DC) for exposure to contaminated soil	DCs for infinite depth are used to account for radionuclides removed from surface soil by leaching	DCs for 15-cm contaminated soil were used
Indoor external exposure	Considers building shielding factor	Not considered, requires modification of input data
External and inhalation exposure time	Environment specific, based on site-specific information	Used a single value for all environments
Human activity budget	Used to determine external and inhalation exposure times for receptor	Not considered
Dose conversion factors for inhalation and ingestion	Taken from FGR 11	Not consistent with FGR 11
Breathing rate	Environment-related, based on human activity	Fixed average value
Inhalation dose from evaporative coolers	Considered	Not considered
Inhalation dose from radon decay products	Considered	Not considered