ENVIRONMENTAL MODELS FOR RADIATION SAFETY

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Contents

Summary

This chapter aims at outlining the most commonly used techniques for modeling the behavior of radionuclides in the environment. The phenomenological aspects of the overall migration processes are delineated and the main techniques implemented in the models to reproduce the complex behavior of radionuclides in the biosphere are described. In particular the properties and some examples of the applications of compartment and diffusion-advection models are presented and discussed.

1. Introduction

1.1. What is a Model?

This chapter describes some of the basic methodologies for developing models aimed at predicting the behavior of radioactive substances in the environment. First, it is important to explain what we mean by "model", a word that, in common language, is used in different senses. This word can indicate an object, for instance a copy on a reduced scale, of another object or something that serves as a subject to be reproduced. The term "model" frequently designates a variety of representations, such as the material or symbolic reproductions of objects (e.g. a globe or a planetarium representing the earth and the solar system, respectively).

In science, the concept of “model”, or more precisely “formal model”, denotes any “system” of sentences that concerns empirical phenomena and processes and that obeys the rules of “symbolic logic”. This means that the sentences can be treated and combined by logic operations such as conjunction, negation and implication. In other words, the naïve assumption is that the events in our world occur according to a “rational plan” of natural laws.

A simple definition of “formal model” was suggested by René Thom (*Thom, 1975*):

A formal model is a system P of sentences satisfying the following conditions:

- Each state A of the phenomenological processes under consideration can be parameterized by a set of sentences S_A of the formal system P;
- If, in the course of time, state A is transformed into state B, then B can be parameterized by a set of sentences S_B that can be deduced from S_A in P.

The notion of “formal model” is epitomized by two well known examples: Euclidean geometry interpreted as a model of real space, and Newtonian mechanics that models the motion of macroscopic objects in space.

For instance, let A be a triangular material object. Let us assume, moreover, that we have measured one of its corners and that it is 100°. We can deduce that the sum of the other two corners is 80° from the following logical implications:

"A is a triangle" $\Rightarrow$ "the sum of the corners of A is 180°"
“one of the corners of A is 100°” *and* “ A is a triangle” $\Rightarrow$ ”the sum of the other two corners of A is 80°”
.
In the previous sentences we have introduced the logical operators “$\Rightarrow$” (implication) and “*and*” (conjunction).

We can continue in order to “predict” several other properties of the above mentioned material triangle.

Similarly, from the sentences “a given object C occupies position X at time 0” and “the object moves with constant velocity v”, we can deduce that “the object at instant t will be in a certain position Y such that the distance between Y and X is equal to v multiplied by t”.

It is worthwhile to note that it must be always possible to design and perform suitable experiments in order to validate the sentences of the formal system P. For instance, we can verify the above mentioned properties of our material triangle A by measuring its angles by a goniometer. Validation is a particularly important facet of the whole modeling process. However, it is a complex subject whose discussion is beyond the scope of the present chapter. The models that we present here are assemblages of mathematical equations aiming at describing the processes occurring in environmental systems. This is not surprising in view of the profound links between mathematics and logic.

1.2. Why Models Are Useful For Radiation Safety

Although traditional applications of mathematical modeling pertain to physics, models today are currently developed to solve different kinds of problems arising in many other sciences, such as biology, ecology and economy.

In particular, environmental models are important tools for assessments of radiation safety. The main aim of this kind of models is to evaluate the potential risks associated with the exposure of man, other organisms and ecosystems to radiation from the natural background and from the use of radioactive substances in the human activities.

In a nutshell, radiation safety assessments are essentially based on the concepts of "absorbed dose" and "equivalent dose". The former is the energy released by ionizing radiation into living tissues per unit mass (J kg^{-1} or, equivalently, Gy), the latter is the released energy (per unit mass) multiplied by suitable weighting factors that account for the different levels of damage induced in living tissues and organs by each specific kind of radiation (X and γ rays, electrons, α particles, etc.) (ICRP, 2007). The equivalent dose is measured in Sievert (Sv). The radiation dose is a risk factor related to the harmful consequences of the exposure of an organism to ionizing radiation.

Models for radiation safety aim at assessing the migration of radioactive substances through the environment in order to determine the levels of contamination with radionuclides of the biotic and abiotic components of the biosphere. The model results are therefore used to assess the doses to humans and non-human biota following the ingestion of contaminated food, the inhalation of radionuclides dispersed into the atmosphere and the direct irradiation from the polluted environmental media (air, soil, water).

The theoretical concepts that we will introduce and treat in this contribution are of paramount importance to address practical problems in environmental management.

We will strive to combine mathematical rigor and precision with simplicity and clarity to allow the reader to deal with notions and methodologies that, at first sight, seem difficult to understand and master.
The comprehensive description of the migration processes and of the relevant modeling approaches would require a voluminous treatise. It is almost impossible to treat in detail the whole matter in a single chapter. However, we have provided a list of authoritative books and publications that will help the interested reader to acquire a deeper understanding of this vast subject.

2. Basic Processes of Radionuclide Migration through the Biosphere

Radionuclides can be introduced into different compartments of the biosphere following accidental discharges of radioactive substances or authorized disposal of radioactive wastes into the environment. The dispersion of radionuclides through the biotic and abiotic components of the environment is fundamentally controlled by complex mechanisms of physical, chemical, biological and ecological nature.

In this section, we will illustrate the main migration processes that models for radiation protection commonly account for.

Figure 1 shows the overall pathways of migration of radionuclides through the biosphere to man. Releases of radioactive substances may chiefly occur in the atmosphere or in aquatic systems such as lakes, rivers, seas and oceans. Contamination of lands is mainly due to the deposition onto exposed surfaces of radioactive substances previously introduced into the atmosphere. Furthermore, the terrestrial environment may be contaminated following flooding from polluted water bodies (Monte et al., 2006; Zheleznyak et al., 1997). In principle, direct releases to the terrestrial environment are also possible; however these are limited to the contamination of soils or of ground-water following discharges into the environment of waters contaminated with radionuclides. On the other hand, direct releases to land of radionuclides from solid sources may be of environmental concern when processes of re-mobilization, such as dissolution or desorption, can cause the leaching of pollutants from the contaminated source to the surrounding environment. Other possible pathways of environmental migration, such as the transport of radionuclides by animals that have ingested radioactive substances, are generally considered of little importance. However, some studies concerning non-radioactive pollutants demonstrated that in particular cases (e.g., the upstream and downstream migration of salmon from polluted reaches) the process may contribute to the dispersion of contaminants through the environment (O'Toole et al., 2006).

The arrows in Figure 1 represent the main processes of migration through the atmospheric, aquatic and terrestrial environments:

- Deposition - the vertical transport of contaminants from a gaseous or liquid medium to exposed surfaces such as soil, vegetation and the bottom sediments of a water body;
- Re-suspension and re-mobilization - the migration of radionuclides from a contaminated exposed surface to the surrounding medium (for instance, the removal and transport by wind of contaminated particles of soil, the re-suspension into the water column of particles of bottom sediment or the formation of polluted marine aerosol from contaminated seas or oceans);
- The transport of radionuclides by run-off waters from catchments to water bodies;
- The transport of radionuclides to the terrestrial environment following the flooding of lands by contaminated water bodies;
- The transport of radionuclides to seas, oceans and coastal areas by contaminated river waters;
- The ingestion by man of contaminated foods such as, vegetables, fish, water, etc.;
- The direct inhalation by man of radionuclides in the atmosphere.

Coastal waters can be categorized as marine systems. However, they represent a kind of interface between the fresh water and the sea environments and are characterized by particular processes, such as the mixing of fresh and marine waters. As coastal ecosystems have significant value from economic and ecological points of view, they are considered of particular importance in environmental assessments and studies (Håkanson, 2000).

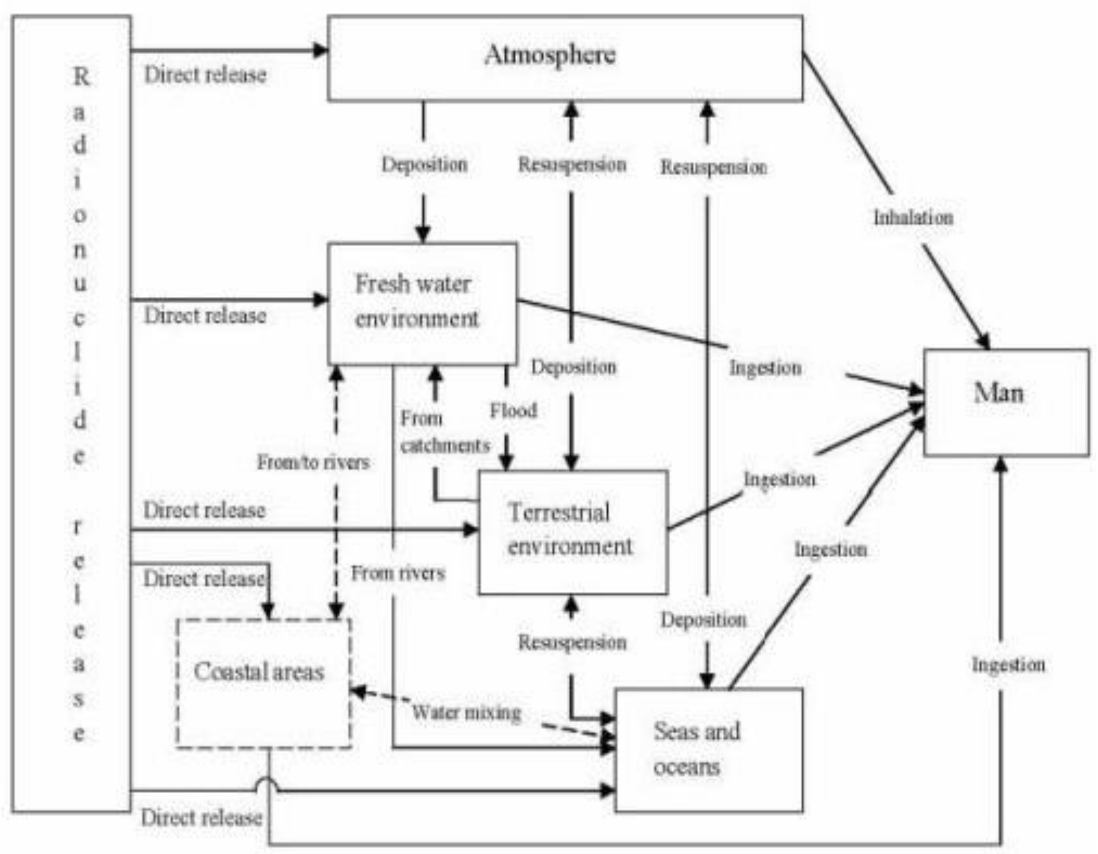

Figure 1. Main environmental compartments and pathways of radionuclide migration. The dotted box denotes coastal areas that, in principle, can be categorized as a special kind of marine system.

Comprehensive descriptions of the processes of radionuclide migration through the environment and of the relevant modeling approaches are available in several treatises (Hisamatsu et al., 2006; Scott, 2003; Warner and Harrison, 1993; Whicker and Schultz, 1982).

2.1. Radionuclide Dispersion through the Atmosphere

Radionuclides released into the atmosphere are transported by winds and undergo mixing processes caused by turbulent movements of air masses. The mechanisms of pollutant transport through the atmosphere are controlled by meteorological processes, in particular, the conditions of thermal vertical stability. Furthermore, the dispersion of contaminants in the atmosphere is significantly affected by topographic or structural elements such mountains, valleys and buildings (IAEA, 2001).

Releases into atmosphere of radionuclides from nuclear plants generally occur in the troposphere (the lowest layer of the atmosphere). However, in past decades, environmental contamination with radioactive substances was also caused by nuclear weapon detonations that had sufficient energy to carry the released fission products into the stratosphere (the layer of atmosphere above the troposphere). From the stratosphere the fission products slowly returned to earth and contributed to world-wide contamination (Fowler, 1965).

Contaminants released into the atmosphere deposit on exposed surfaces by:

a) *Dry deposition* – the processes of particle settling and of direct adsorption of contaminant in the gaseous form onto exposed surfaces;
b) *Wet deposition* – the processes of scavenging by precipitation and of deposition of contaminated droplets in low clouds and mist.

2.2. Radionuclide Dispersion through the Terrestrial Environment

Figure 2 depicts the overall migration processes of radionuclides from the components of the terrestrial environment to man (Shaw, 2007).

As we would expect, radioactive substances released into the atmosphere contaminate exposed surfaces by deposition. A fraction of the deposited radionuclide is intercepted by the vegetation canopy. The process of *interception* does not depend solely on the area of the surface of the leaves exposed to radionuclide contamination. Indeed, interception involves complex physical, chemical and biological processes and depends on the nature and the characteristics of radionuclides and of the vegetation surfaces. The process of interception is strongly influenced by the environmental conditions and by the particular features of the many different mechanisms controlling this process, such as the intensity and the duration of rain causing wet deposition.

Radionuclide intercepted by the vegetation can migrate into the interior of the plant (*translocation*) or may be removed by weathering agents such as rain and wind. The removal processes and the dynamics of the metabolic /catabolic balance that causes changes in plant mass during growth are responsible for the lowering of the concentration of radionuclide per unit mass of vegetation.

Radioactive substances that are not intercepted by the vegetation canopy contaminate soils and are transported by percolating waters to soil layers containing plant roots. *Root uptake* of contaminants by plants is an important pathway of radionuclide migration to vegetation. The uptake is symbolized by a double sided arrow in Figure 2 since the complicated processes occurring in the root-soil system may imply the release of radionuclide from the roots to the soil as consequence, for instance, of root catabolism. Radionuclides are subsequently transported by percolation to groundwater which can be used for irrigation or drinking.

The ingestion of contaminated water, vegetation and fodder are the main pathways of radionuclide migration to livestock (however, it is worthwhile to note that grazing animals may also ingest particles of contaminated soil).

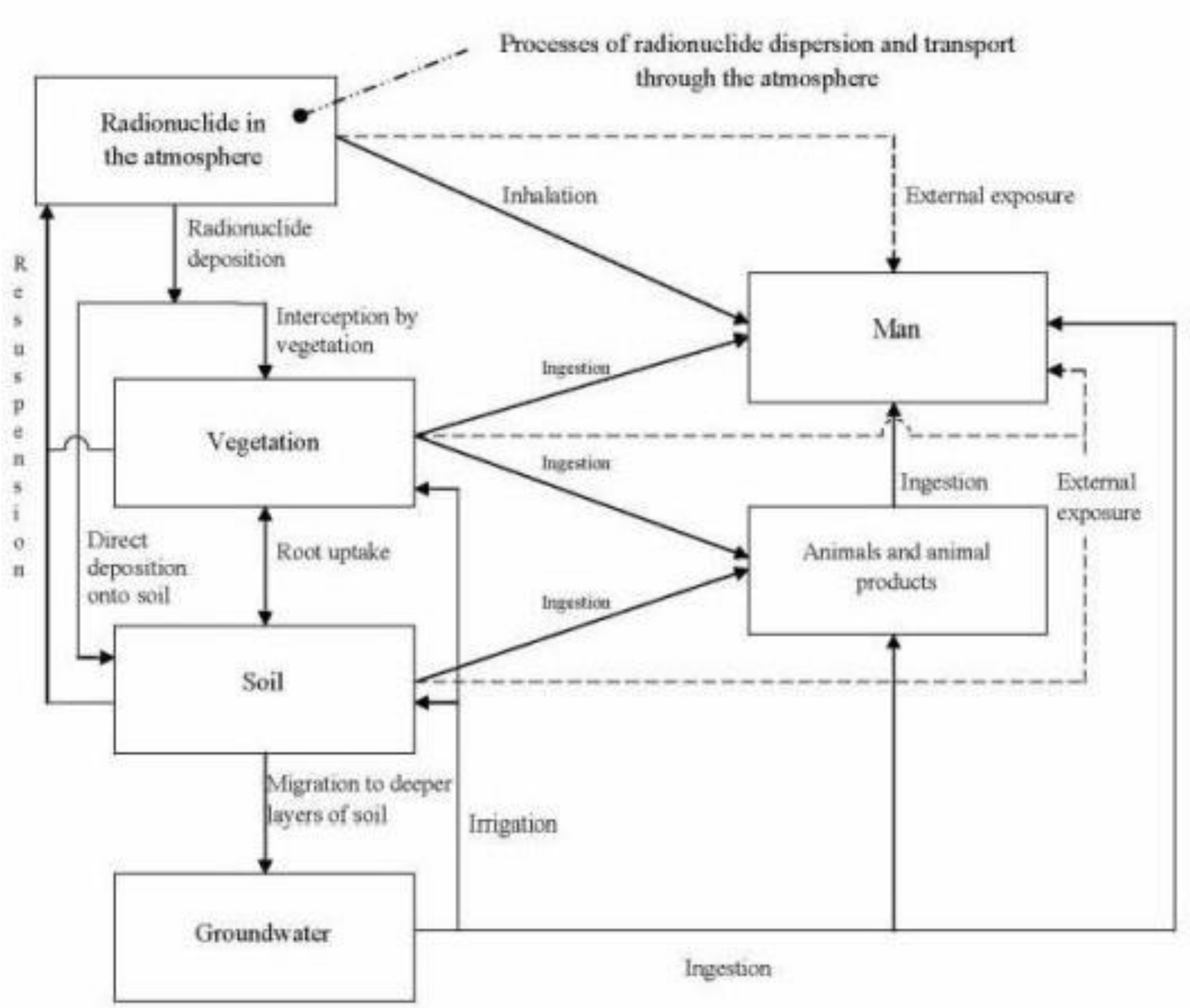

Figure 2. Main pathways of migration of radionuclides through the terrestrial environment.

Finally, radionuclides migrate to humans following the consumption of vegetables, animal products and water and the inhalation of radioactive substances in the atmosphere.

For the sake of completeness, the dotted lines in Figure 2 denote the external exposure to radiation (direct irradiation of man from radioactive substances dispersed in the environment).

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Biographical Sketches

Luigi Monte received his degree in Physics in 1976 from University “Federico II”, Naples, Italy. From 1978 to 1980 he moved to Institute “Giancarlo Vallauri” of the Italian Navy in Leghorn where he worked for the Electromagnetic Compatibility Laboratory. Since 1981 he has worked at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development). His main research activities concern the modeling of the behavior of radionuclides in the environment. In particular, he developed mathematical models and computerized decision support systems for predicting the migration of radionuclides and toxic substances in the environment and for assessing the effects of countermeasures to reduce the environmental contamination levels and the exposure of man to ionizing radiation. He has participated in a number of research projects organized by international organizations (IAEA, EURATOM). From 1996 to 1999 was the coordinator of the international project MOIRA (A MOdel Based Computerised system for management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic ecosystems and drainage areas) financed by the European Commission. From 2001 to 2004 was the coordinator of the international network EVANET-HYDRA (Evaluation and Network of EC-Decision Support Systems in the field of Hydrological Dispersion Models and of Aquatic radioecological Research) to review and assess decision support systems for the management of contaminated fresh water environments. From 2003 to 2007 was leader of the Working Group “Model validation for radionuclide transport in the aquatic systems watershed-rivers and estuaries” of EMRAS (Environmental Modelling for Radiation Safety), a project organized by the International Atomic Energy Agency.