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I am submitting herewith a dissertation written by Ying Feng entitled "Transport of Aquatic Contaminant and Assessment of Radioecological Exposure with Spatial and Temporal Effects." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

L F Miller

L. F. Miller, Major Professor

We have read this dissertation
and recommend its acceptance:

SM Bartel

Pete J. Gioi

Joseph L. Stummel

Accepted for the Council:

C W Minkel

Associate Vice Chancellor and
Dean of The Graduate School

**TRANSPORT OF AQUATIC CONTAMINANT
AND ASSESSMENT OF RADIOECOLOGICAL EXPOSURE
WITH SPATIAL AND TEMPORAL EFFECTS**

A Dissertation

Presented for the

Doctor of Philosophy Degree

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by

Ying Feng

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Dedicated to my mother.

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Ying Feng

The University of Tennessee, Knoxville

ABSTRACT

A comprehensive study of the radioecological exposure assessment for a contaminated aquatic ecosystem has been performed in this dissertation. The primary objectives of this research were to advance the understanding of radiation exposure in nature and to increase current capabilities for estimating aquatic radiation exposure with the consideration of spatial and temporal effects in nature. This was accomplished through the development of a two-dimensional aquatic exposure assessment framework and by applying the framework to the contaminated Chernobyl cooling lake (pond).

This framework integrated spatial and temporal heterogeneity effects of contaminant concentration, abundance and distribution of ecosystem populations, spatial- and temporal-dependent (or density-dependent) radionuclide ingestion, and alternative food web structures. The exposure model was built on the population level to allow for the integration of density dependent population regulation into the exposure assessment. Plankton population dynamics have been integrated into the hydrodynamic-transport model to determine plankton biomass density changes and distributions. The distribution of contaminant in water was also calculated using a hydrodynamic-transport model.

The significance of adding spatial and temporal effects, spatial and temporal related ecological functions, and hydrodynamics in the exposure assessment was

illustrated through a series of case studies. The results suggested that the spatial and temporal heterogeneity effects of radioactive environments were substantial. The conventional bioaccumulation factors with the assumption of homogeneous and steady-state conditions significantly over estimated the radionuclide accumulation in predator-fish by a factor of four to six, while they under estimated the exposure in planktons at some locations.

Among the ecological functions considered, the food web structure was the most important contributor to the variations of fish exposure. The results obtained using a multiple prey food web structure differed by a factor of 10 from the equilibrium concentration, and by a factor of 2.5 from the concentration obtained using a single-prey food web.

Impacts of changes in abundance and distribution of biomass on contaminant bioaccumulation varied among different populations, spatially and temporally. It is necessary to consider the biomass effects for fish during periods of accelerated growth, or when the radionuclides or ecological species have low radiobiological turn-over rates.

Influences of adding spatial- and temporal-dependent ingestion rates into the exposure model structure were not significant for this study when there were excess prey relative to the predators.

The influence of hydrodynamics on radioactive material transport and distribution was significant in the study of the contaminated Chernobyl cooling lake.

The framework is cast in a generalized form such that extension to other aquatic exposure assessment problems is direct.

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CHAPTER 1

INTRODUCTION

The last few years have witnessed a rise in concern for environmental contamination from past nuclear weapon development and from accidents in the nuclear power industry. This concern leads to increased requirements on our basic scientific capability to forecast the probable effects on ecosystems and on an human health (Warner, 1993).

The study of contamination in aquatic environments is of considerable importance since a major fraction of the earth's surface is occupied by rivers, lakes, and seas. Radioactive materials can enter aquatic systems from atmospheric fallout, land runoff, and routine or accidental point discharges. Once in the water, radioactive materials are redistributed and taken up by ecosystem components. The radioactive hazard to the ecosystem components is based on the accumulated activities.

The study of radioactive contamination in aquatic ecosystems consists of two important aspects: *exposure assessment* and *radioecological effect assessment* (Schultz, 1992). An exposure assessment characterizes the contaminant transport and fate in the water and the associated exposure on all resident biota or the radionuclide bioaccumulation within specific ecosystem components. A radioecological effect assessment characterizes the subsequent biological effects of ionizing radiation of various radionuclides on the vital processes and development of organisms (Platt, 1965; Blaylock, 1993). The two assessments constitute the *radioecological risk analysis*. The exposure assessment, as a part of the overall risk analysis, will be studied in this research.

1.1 Background: Radioecological Exposure and Ecosystem

A radioecological exposure study incorporates environmental engineering, ecology, health physics, and radiation biology. Because it involves different scientific disciplines, it is ordinarily considered to be interdisciplinary (Odum, 1965). As the word "radioecological" implies, radioecological exposure study is intimately related to ecology.

Ecology is defined as the study of the relation of organisms or groups of organisms to their environment (Odum, 1971). In regard to subdivisions, ecology is sometimes divided into autecology and synecology. Autecology deals with the study of the individual organism or an individual species. Synecology deals with the study of groups of organisms, which are associated together, such as populations and communities (Odum, 1971). Population is defined as a collective group of organisms of the same species (or other groups within which individuals may exchange genetic information occupying a particular space) (Odum, 1971). Communities consist of all of populations.

In nature, an ecosystem is not just a collection of independent plants, animals, and microorganisms which happen to live in a given region and tolerate the climate and stress conditions (Buchsbaum, 1958). The components of an ecosystem are dependent upon one another at least through a prey-predator relationship (food web). For the purpose of studying exposure occurring in nature, it would appear adequate to study the exposure in a population level.

With respect to exposure and radiation, knowledge of the sources and distribution of radionuclides is a prerequisite for evaluating possible exposure in natural ecosystems. In any given contaminated environment, populations are subject to the same over-all potential exposure since they are interrelated and coexist in the same area. If radioactivity is introduced into the physical environment, characterization of exposure will depend not

only upon the concentration in the water and physical properties of the radioactive materials but also upon the ecosystem capabilities of taking up, transferring, and retaining radionuclides among the populations.

In aquatic systems, there are two principal pathways of radionuclide accumulation by organisms: (1) uptake of radioactive materials directly from water, and (2) accumulation of radioactive materials through feeding on contaminated food. Thus, the following are general components of an aquatic exposure assessment: (1) calculation of radioactive material concentration in water; (2) estimation of radioactive material concentration in primary food producers; and (3) calculation of concentration accumulation in predators, analogous to the ecological food web.

1.2 Research Problems and Motivations

Most of the work in radioecological exposure assessments has been performed with the trade-off between the increased sophistication of water circulation, contaminant transport, and ecological interactions versus the assumption of well-mixed and steady-state systems that characterize current models for estimating ecological risk (Bartell, 1994; Breck, 1980).

Among the simplified approaches, bioaccumulation factor (BF), the ratio of concentration of radionuclides in an organism to the contaminated environment, is the most widely used approach to characterize the accumulation of radionuclides (Williams, 1960; Friend, 1963; Harvey, 1964; Fujita, 1966; Garder, 1966; Fleishman, 1973). Most of the time, the BF is acceptable for screening level analysis (NCRP 1992, Evans, 1988; IAEA, 1993; Feng, 1994 and 1995). However, significant heterogeneity of environments and extreme variability of ecological processes complicate the exposure occurring in nature, and their effects are not included in the BF.

An exposure assessment for an aquatic ecosystem in nature has the following characteristics:

- First, radionuclide transport and distribution in water are controlled by water circulation in lakes or rivers under the influences of wind, temperature change, inlet and outlet flow, and bathymetry of the water systems (Bartell, 1981; Bedford, 1987; Connolly, 1985; Thibodeaux, 1979; Csanady, 1970; Schwab, 1987). Therefore, a realistic assessment model should assess the contaminant concentration in water with the consideration of hydrodynamic effects.
- Second, the biota are not exposed to a lake-wide averaged contaminated condition. The contaminant concentration distribution in water is heterogeneous. The ecological components are also heterogeneously distributed in water due to their migration or forage (DeAngelis, 1978; Harden Jones, 1972; Lampert, 1989; Steele, 1974). These heterogeneity in the physical environment and in ecological systems can result in significant variations of exposure occurring in nature (Smith, 1992).
- Third, all ecological activities, such as the biota growth, and contaminant transport, are dynamic in nature (Odum, 1971; Carpenter, 1988). Correspondingly, the radionuclide uptake and accumulation processes in ecosystem components are also time-dependent. Thus, the exposure assessment models should be capable of describing dynamic effects.

The assessment of aquatic radioecological exposure in nature should consider: (1) the nature of water movement in lakes or rivers, and (2) the impacts of spatial and temporal heterogeneity of environments and of ecological activities on the exposure modeling.

1.3 Objectives and Contributions

The principal objectives of this research are to advance understanding of radiation exposure in nature and to increase current capabilities for estimating aquatic radiation exposure with considerations of spatial and temporal effects.

Specifically, this study answers the following questions:

1. What is the influence of hydrodynamics on radioactive material transport and distribution in the contaminated Chernobyl cooling lake (pond) ?
2. How is the bioaccumulation affected by the spatial and temporal heterogeneity of radioactive environments ?
3. What are the effects of the changes in abundance and distribution of population biomass upon the bioaccumulation ?
4. How do the spatial- and temporal-dependent (density-dependent) radionuclide ingestion rates influence the exposure ?
5. How is the plankton biomass distribution determined in a physical world, and what factor, population growth or physical environment, dominates the variation of plankton biomass distribution ? and
6. How do different food web structures magnify or reduce the exposure to predators in a heterogeneous radioactive environment ?

The contributions of this dissertation are summarized as follows:

First, a two-dimensional hydrodynamic-transport model is used to calculate the contaminant concentration distribution in the Chernobyl cooling lake (pond) for the first time. The concentration distribution provides an essential component for the exposure assessment, which permits an investigation of the impacts of spatial and temporal

heterogeneity of radioactivity on bioaccumulation. The method and the model have a general applicability to other contaminated free surface water systems.

Second, a two-dimensional dynamic exposure assessment framework is developed for exploring the implication of a realistic physical description of water systems and aquatic ecosystems in exposure assessment. The model describes the uptake and accumulation processes at the population level. Four populations are linked into a single-prey food web structure. The exposure model is coupled with the contaminant concentrations defined on a finite element mesh.

Third, changes in abundance and distribution of population biomass are integrated into the exposure model to investigate their effects on the bioaccumulation.

Fourth, a hydrodynamic-transport model is combined with a population dynamic model to compute the phytoplankton and zooplankton biomass distributions. In this manner, the biomass changes due to growth, respiration, and grazing are incorporated into the transport model.

Fifth, as is true of other ecological attributes in nature, radionuclide ingestion rates from prey vary spatially and temporally due to the variation of the food abundance. To investigate this effect on the radionuclide accumulation through food consumption, a spatial- and temporal-dependent (or density-dependent) ingestion rate is integrated into the model.

1.4 *Organization of the Dissertation*

This dissertation is composed of five additional chapters.

Chapter 2 presents the theory of contaminant transport in free surface water systems, such as the Chernobyl cooling pond. The boundary conditions for a free-surface water system are categorized, and the equations are presented.

Chapter 3 describes the exposure framework and model. This chapter first reviews the concept of concentration factor and discusses its limitations relative to spatial and temporal heterogeneity. This is followed by a detailed development of the bioaccumulation modeling for four populations in a heterogeneous environment. The four populations are phytoplankton, zooplankton, prey-fish, and pred-fish. It is also shown how this framework incorporates changes of population biomass, temporal- and spatial-dependent ingestion rate, and different food web structures. Finally, coupling the radioecological exposure model with the results from transport modeling are illustrated in the context of a two-dimensional space.

Chapter 4 describes the application of the hydrodynamic-transport model for calculating the flow field and the Cs-137 distribution in the Chernobyl cooling lake. A finite element code is used to perform numerical calculations in a two-dimensional space. The description of this computer program and input files is given in Appendix A.

In Chapter 5, a series of cases with spatial and temporal details and with different ecological functions are studied using the proposed exposure assessment framework for the Chernobyl cooling pond ecosystem. The numerical simulations are performed using Mathematica package. The code input files are listed in Appendix B. The modeling results are analyzed and examined. This analysis leads to the conclusions analogous to the objectives of this study.

Concluding remarks and recommendations for further researches are given in Chapter 6.

CHAPTER 2

CONTAMINANT TRANSPORT IN SURFACE WATER

Transport of aquatic contaminants includes two stages: hydrodynamic modeling and transport modeling. Hydrodynamic modeling provides the advective and turbulent mass transfer coefficients for the subsequent contaminant transport process. Together these two models determine the flow circulation and predict contaminant concentration in an aquatic system. This chapter presents the hydrodynamic and pollutant transport governing equations for free surface water systems, explains major terms of the governing equations, and describes their physical meanings. The primary focus will be on basic features of free surface flow and on the physical processes of contaminant transport in aquatic environments.

2.1 *Contaminant Transport*

The mathematical modeling of contaminant transport in an aquatic system employs the principle of conservation of contaminant mass. In this section, the basic conservation equation is first stated for an infinitesimal control volume to represent the net change of contaminant mass within that volume. Then, the general dimensional governing equation with dimensionalities is presented, and the processes affecting the contaminant mass change are discussed.

2.1.1 Contaminant Mass Balance Equation

The contaminant mass balance equation corresponds to a total mass balance over a stationary volume element $\Delta x \Delta y \Delta z$ through which a fluid is flowing within the time Δt (see Figure 2.1), and is

$$\frac{\Delta C}{\Delta t} = (C_{in} - C_{out}) + R_c + S_c \quad (2.1)$$

where $\Delta C/\Delta t$ = the change in contaminant mass within the volume per unit time;

C_{in} = the inflow of contaminant to the volume from adjacent regions;

C_{out} = the outflow of contaminant from the volume to adjacent regions. Both C_{in} and C_{out} depend upon the hydrodynamic properties of the flow;

R_c = the rate of production/reduction of contaminant within the volume. It represents the effects from processes such as radioactive decay and sedimentation inside the volume; and

S_c = a supply of contaminant to the volume from sources external to the system. It includes contaminant discharge and fallout at the boundary of the volume.

2.1.2 Transport Governing Equation

Equation (2.1) generally expresses the concentration change assuming no spatial variation. For a heterogeneously contaminated water system, a partial differential equation is necessary to express the contaminant transport processes in the space and concentration distributions. At a fixed point, this equation is stated as (Hayter, 1989; Sheng, 1982; Thomann, 1987; Richardson, 1976):

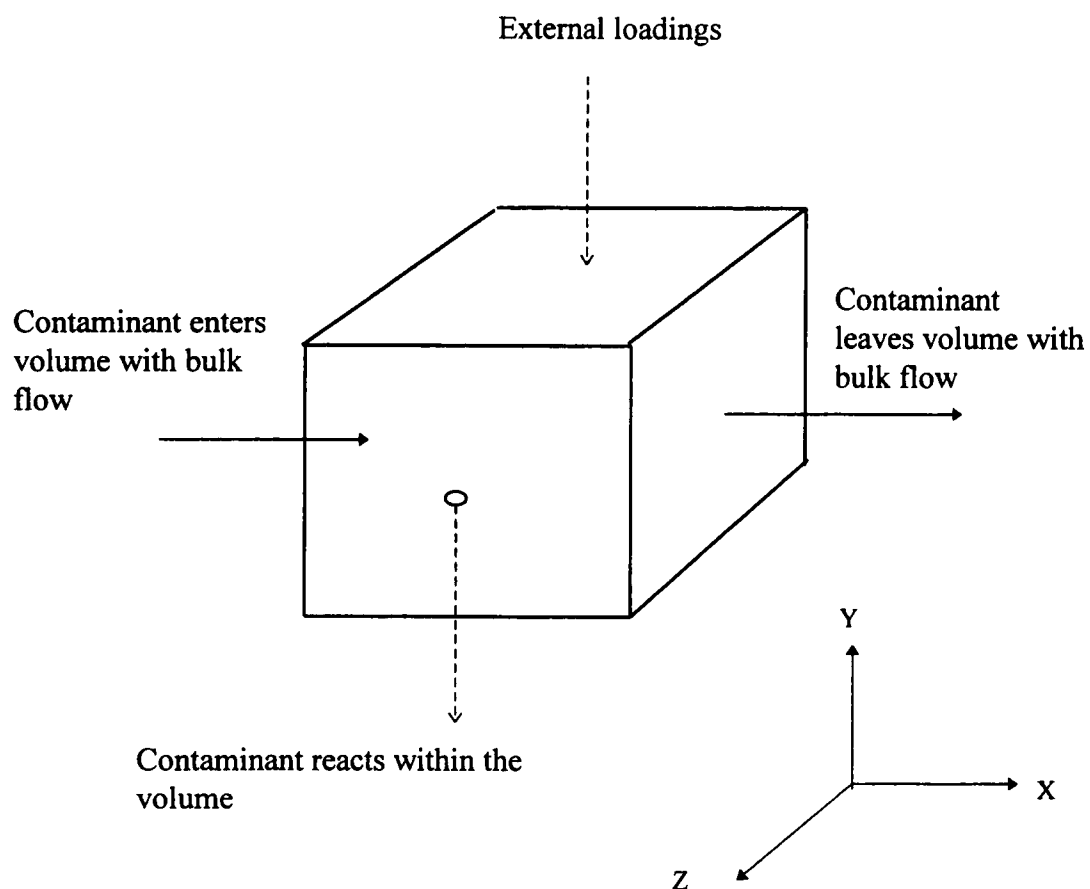


Figure 2.1 Contaminant Mass Balance for an Element of Volume ($\Delta x \Delta y \Delta z$) Fixed in Space through Which a Fluid is Flowing

$$\begin{aligned} \frac{\partial C}{\partial t} = & -v_x \frac{\partial C}{\partial x} - v_y \frac{\partial C}{\partial y} - v_z \frac{\partial C}{\partial z} + \\ & \frac{\partial}{\partial x} \left(D_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial C}{\partial z} \right) + \theta_s, \end{aligned} \quad (2.2)$$

where x , y , and z are Cartesian coordinates. v_x , v_y , and v_z are the Euler flow velocity components in the selected initial reference system. The flow velocity components, v_x , v_y , and v_z , determine the multi-dimensional advection of the contaminant. $C(x,y,z,t)$ denotes the contaminant concentration at a specified time and location. D_x , D_y , and D_z indicate the diffusion coefficients of the contaminant. And θ_s is the source/sink term of the contaminant concentration which includes the external loading, internal physical and chemical reactions, and radioactive decay.

The term “advection” describes the transport of contaminant in terms of the movement of the fluid. The advection rate of the contaminant is the same as the fluid flow velocity, which is obtained by solving the hydrodynamics continuity and momentum equations discussed later in Section 2.2.

The diffusion term $\text{div}[D \text{ grad } C]$ describes the transport of the contaminant within the water system boundaries caused by molecular and eddy diffusion. Molecular diffusion is induced by spatial concentration gradients, and contaminants migrate from areas of high concentration to areas of low concentration. The molecular contaminant transport is determined from concentration gradient and the diffusion coefficients.

Eddy diffusion accounts for the contaminant transport caused by the mixing and blending of the flow eddies in a turbulent environment. The mathematical expression for the eddy diffusion process is similar to the molecular diffusion relationship where the eddy diffusive coefficients replace molecular diffusion coefficients. In turbulent flows, such as those in lakes and rivers, the eddy diffusion contaminant transport is far more effective than molecular diffusion.

2.2 Hydrodynamics in Free Surface Water

Hydrodynamics is one of the most important aspects of aquatic transport of contaminants (Pond, 1983; Raudkiv, 1975; Hutter, 1984; Iannelli, 1994). The topic of contaminant transport modeling cannot begin without introducing the ideas of hydrodynamics in general. The flow patterns predicted by the hydrodynamic model determine the advection of the contaminant transport. In this section, the free-surface hydrodynamics equations are presented and turbulent-flow terms and boundary conditions are discussed.

2.2.1 Hydrodynamics Governing Equations

The conservation of mass and linear momentum equations governs the fluid flow. The continuity equation is given by

$$\frac{\partial \rho}{\partial t} = - \left[\frac{\partial}{\partial x} (\rho v_x) + \frac{\partial}{\partial y} (\rho v_y) + \frac{\partial}{\partial z} (\rho v_z) \right] \quad (2.3)$$

where ρ denotes the fluid density and v_x, v_y, v_z are the flow velocity components in the x, y , and z directions. Equation (2.3) is a statement of the conservation of mass, and it describes the rate of change of density at a fixed point resulting from the changes in the mass fluxes at that point.

The momentum equations are given by

$$\begin{aligned} \frac{\partial}{\partial t} (\rho v_x) = & - \left[\frac{\partial}{\partial x} (\rho v_x v_x) + \frac{\partial}{\partial y} (\rho v_y v_x) + \frac{\partial}{\partial z} (\rho v_z v_x) \right] \\ & - \left(\frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial y} \tau_{yx} + \frac{\partial}{\partial z} \tau_{zx} \right) - \frac{\partial P}{\partial x} + \Gamma_x \end{aligned} \quad (2.4a)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\rho v_y) = & - \left[\frac{\partial}{\partial x} (\rho v_x v_y) + \frac{\partial}{\partial y} (\rho v_y v_y) + \frac{\partial}{\partial z} (\rho v_z v_y) \right] \\ & - \left(\frac{\partial}{\partial x} \tau_{xy} + \frac{\partial}{\partial y} \tau_{yy} + \frac{\partial}{\partial z} \tau_{zy} \right) - \frac{\partial P}{\partial y} + \Gamma_y \end{aligned} \quad (2.4b)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho v_z) = & -\left[\frac{\partial}{\partial x}(\rho v_x v_z) + \frac{\partial}{\partial y}(\rho v_y v_z) + \frac{\partial}{\partial z}(\rho v_z v_z)\right] \\ & -\left(\frac{\partial}{\partial x}\tau_{xz} + \frac{\partial}{\partial y}\tau_{yz} + \frac{\partial}{\partial z}\tau_{zz}\right) - \frac{\partial P}{\partial z} + \Gamma_z \end{aligned} \quad (2.4c)$$

where P is the fluid static pressure, and $\Gamma_x, \Gamma_y, \Gamma_z$ denote the external volume forces that operate on the boundaries or on the interior in the x, y, z directions, such as surface wind force, bottom fractions, and body forces. The six terms $\tau_{xx}, \tau_{xy}, \tau_{xz}, \tau_{yy}, \tau_{yz}, \tau_{zz}$ are the components of the symmetric stress tensor acting on the volume fluid. For example, τ_{xx} corresponds to the normal stress on the x surface along x direction, τ_{xy} denotes the shear stress on the x surface along y direction, and τ_{xz} is the shear stress on the x surface along the z direction, shown in Figure 2.2. For a Newtonian fluid, the constitutive expression that relates the stress tensor (τ_{ij}) to the velocity gradients is,

$$\tau_{ij} = -\mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad (2.5)$$

where μ is called dynamic coefficient of viscosity. The viscosity is a physical property of a fluid, which characterizes momentum exchange at the molecular level. The divergence of the stress tensor determines the viscous force per unit volume.

Equation (2.4) is a statement of Newton's second law of dynamics and results from a linear momentum balance for the fluid. Linear momentum and forces acting on the volume element are balanced along each direction. Term by term, Equation 2.4 states:

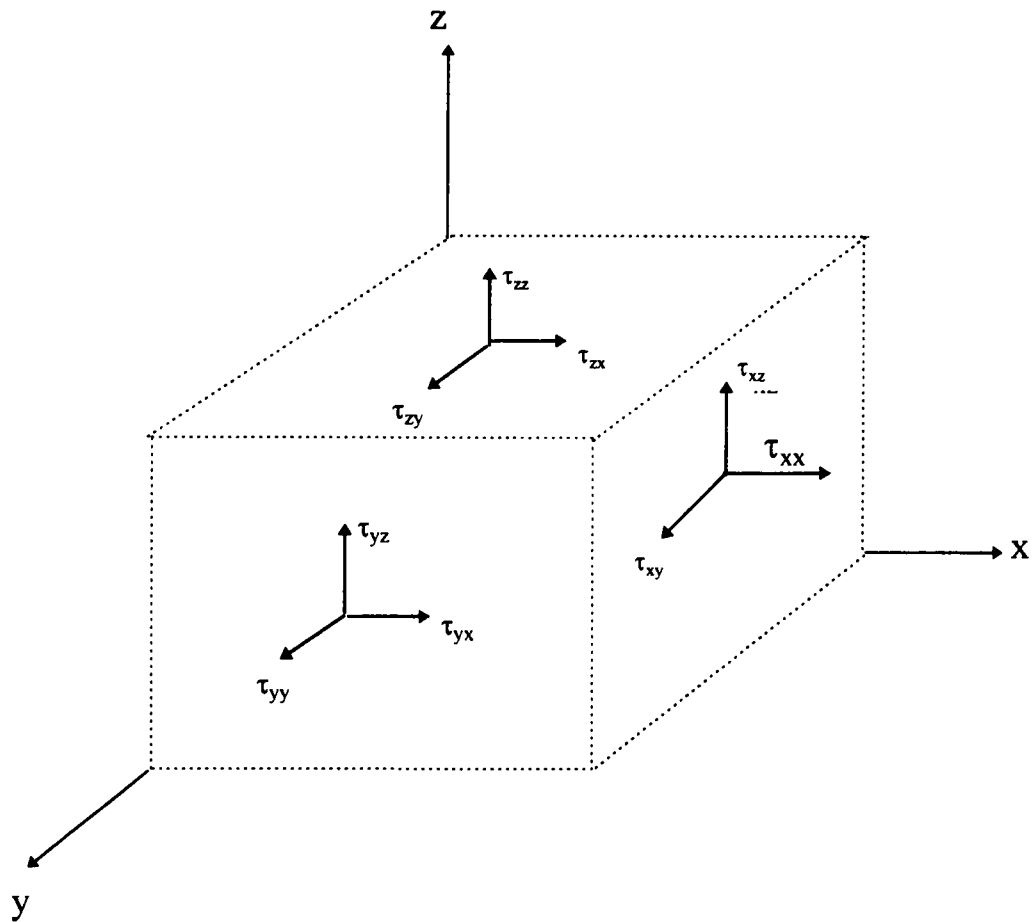


Figure 2.2 Illustration of Shear Stresses Acting on the Volume ($\Delta x \Delta y \Delta z$)

$$\begin{array}{c}
\boxed{\text{Rate of increase of}} \\
\boxed{\text{linear momentum}} \\
\boxed{\text{per unit volume}}
\end{array}
= - \begin{array}{c}
\boxed{\text{Rate of momentum}} \\
\boxed{\text{change by convection}} \\
\boxed{\text{per unit volume}}
\end{array} - \begin{array}{c}
\boxed{\text{Rate of linear momentum}} \\
\boxed{\text{change by viscous forces}} \\
\boxed{\text{per unit volume}}
\end{array} \\
- \begin{array}{c}
\boxed{\text{Pressure force on}} \\
\boxed{\text{element per unit}} \\
\boxed{\text{volume}}
\end{array} + \begin{array}{c}
\boxed{\text{External force on}} \\
\boxed{\text{element per unit}} \\
\boxed{\text{volume}}
\end{array}$$

Equations (2.3) , (2.4), and (2.5) are the general continuity, momentum, and constitutive equations for Newtonian flow. If density ρ and viscosity μ are constant, the continuity and momentum equations become

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \quad (2.6)$$

$$\rho \left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) + \frac{\partial p}{\partial x} - \mu \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) - \Gamma_x = 0 \quad (2.7a)$$

$$\rho \left(\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) + \frac{\partial p}{\partial y} - \mu \left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right) - \Gamma_y = 0 \quad (2.7b)$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) + \frac{\partial p}{\partial z} - \mu \left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2} \right) - \Gamma_z = 0 \quad (2.7c)$$

Equations (2.6) and (2.7) are collectively known as the Navier-Stokes equations (Raudkivi, 1975), which are widely used to describe unsteady multi-dimensional flow in free surface water.

2.2.2 Turbulent Flow

While Equations (2.6) and (2.7) constitute a theoretically consistent model for all Newtonian flows, it is numerically very difficult to extract instantaneous information on velocity and pressure at each point in space from this model. Turbulence is the nature possessed by almost all flows in lakes and rivers, and is commonly pictured as consisting of a number of closed flow structures of diverse shapes and sizes, called “eddies”

(Csanady, 1982). Turbulence will significantly increase flow mixing (ASCE, 1988; Hinze, 1959).

Since it is virtually impossible to obtain instantaneous velocity and pressure, one then seeks mean quantities to describe turbulent flows. A more feasible velocity component and pressure are therefore typically written as the sum of mean variables and fluctuations due to the statistical nature of turbulent flow (Hinze, 1959)

$$v_x = \overline{v_x} + v \quad (2.8a)$$

$$v_y = \overline{v_y} + v \quad (2.8b)$$

$$v_z = \overline{v_z} + v \quad (2.8c)$$

$$p = \overline{p} + p' \quad (2.8d)$$

where overbar denotes a mean quantity and prime signifies fluctuation.

Since by definition the average of a fluctuation vanishes, the insertion of all components (2.8) into the Navier-Stokes equation (2.6) and (2.7) results in the following Reynolds equations in terms of the mean velocity and fluctuating velocity components

$$\begin{aligned} \rho \left[\frac{\partial \overline{v_x}}{\partial t} + \overline{v_x} \frac{\partial \overline{v_x}}{\partial x} + \overline{v_y} \frac{\partial \overline{v_x}}{\partial y} + \overline{v_z} \frac{\partial \overline{v_x}}{\partial z} \right] + \frac{\partial}{\partial x} (\rho \overline{v_x v_x}) + \frac{\partial}{\partial y} (\rho \overline{v_y v_x}) + \frac{\partial}{\partial z} (\rho \overline{v_z v_x}) \\ + \frac{\partial \overline{p}}{\partial x} - \mu \left[\frac{\partial^2 \overline{v_x}}{\partial x^2} + \frac{\partial^2 \overline{v_x}}{\partial y^2} + \frac{\partial^2 \overline{v_x}}{\partial z^2} \right] - \Gamma_x = 0 \end{aligned} \quad (2.9a)$$

$$\begin{aligned} \rho \left[\frac{\partial \overline{v_y}}{\partial t} + \overline{v_x} \frac{\partial \overline{v_y}}{\partial x} + \overline{v_y} \frac{\partial \overline{v_y}}{\partial y} + \overline{v_z} \frac{\partial \overline{v_y}}{\partial z} \right] + \frac{\partial}{\partial x} (\rho \overline{v_x v_y}) + \frac{\partial}{\partial y} (\rho \overline{v_y v_y}) + \frac{\partial}{\partial z} (\rho \overline{v_z v_y}) \\ + \frac{\partial \overline{p}}{\partial y} - \mu \left[\frac{\partial^2 \overline{v_y}}{\partial x^2} + \frac{\partial^2 \overline{v_y}}{\partial y^2} + \frac{\partial^2 \overline{v_y}}{\partial z^2} \right] - \Gamma_y = 0 \end{aligned} \quad (2.9b)$$

$$\begin{aligned} \rho \left[\frac{\partial \overline{v_z}}{\partial t} + \overline{v_x} \frac{\partial \overline{v_z}}{\partial x} + \overline{v_y} \frac{\partial \overline{v_z}}{\partial y} + \overline{v_z} \frac{\partial \overline{v_z}}{\partial z} \right] + \frac{\partial}{\partial x} (\rho \overline{v_x v_z}) + \frac{\partial}{\partial y} (\rho \overline{v_y v_z}) + \frac{\partial}{\partial z} (\rho \overline{v_z v_z}) \\ + \frac{\partial \overline{p}}{\partial z} - \mu \left[\frac{\partial^2 \overline{v_z}}{\partial x^2} + \frac{\partial^2 \overline{v_z}}{\partial y^2} + \frac{\partial^2 \overline{v_z}}{\partial z^2} \right] - \Gamma_z = 0 \end{aligned} \quad (2.9c)$$

Comparing Equations (2.9) with the Navier-stokes equation (2.7) shows that new terms arise in the governing Equations (2.9) for the turbulent mean velocity and pressure. These new terms are associated with the turbulent velocity fluctuations. Furthermore, comparing Equations (2.4) with Equations (2.9) indicates that the mathematical form of these new terms is similar to the stress tensor terms in Equation (2.4). For this reason, these new terms appear as stresses and are called Reynolds stresses. The *Reynolds stresses* is further expressed as

$$\overline{\tau_{ij}} = -\rho \overline{v_i' v_j'} \quad (2.10)$$

The process of relating these turbulence Reynolds stresses to the mean velocity components constitutes the problem of turbulence modeling. A correct representation for these turbulent effects is central to further progress in lake or river flow modeling. The unresolved turbulent motions can result in significant momentum.

The study, understanding, and development of meaningful turbulence models have been ongoing for decades. A considerable body of literature on turbulence models exists which encompasses theoretical ideas and experimental results in the laboratory and field. The texts of Phillips, 1969, Tennekes and Lumley, 1972, Monin and Yaglom, 1971, Turner, 1973, and Hinze, 1969, provide much of this information. Two methods are generally used for modeling the Reynolds shear stresses: Prandtl's mixing length method and k-ε theory.

Prandtl's theory (Prandtl, 1952) is used for representing turbulence by means of an empirically determined reference length. This is the oldest and still the most popular semi-empirical expression for the Reynolds stresses. The Reynolds stresses are assumed to be related to the gradient of the mean velocity multiplied by eddy viscosity. The eddy viscosity is proportional to the product of the velocity fluctuation and the mixing length. The mixing length represents the average size of the eddy spectrum.

Other more sophisticated mathematical models of turbulence have been used (Rodi 1984). In these models the eddy viscosity is related to characteristic quantities of the turbulence flow such as kinetic energy k and dissipation ϵ . The unknowns k and ϵ are determined by additional transport equations (Launder and Spalding, 1972).

2.2.3 Boundary Conditions in Free Surface Water

The hydrodynamic equations require boundary conditions which specify the interaction of the flow elements with their external environment. The principal mechanical influences on free surface water circulation are illustrated in Figure 2.3. The inflows and outflows supply fluid from tributaries. The wind drag and atmospheric pressure lead to additional forces at the boundary (Liggett 1975, Sanady, 1968 and 1972; Schwab, 1981 and 1984).

Note that each of the boundary conditions involves vector quantities, such as velocity and friction. Since the shape of the natural boundary is irregular, it is customary to discuss boundary conditions in terms of normal and tangential directions.

The boundary conditions for a body of water at three locations are: (1) the free surface; (2) the bottom; and (3) the solid side boundaries.

The Free Water Surface

Wind over the surface of a water system will exert stresses on the system. The actual stress transmitted to the interior is influenced by a number of factors, including the wind strength and its variability.

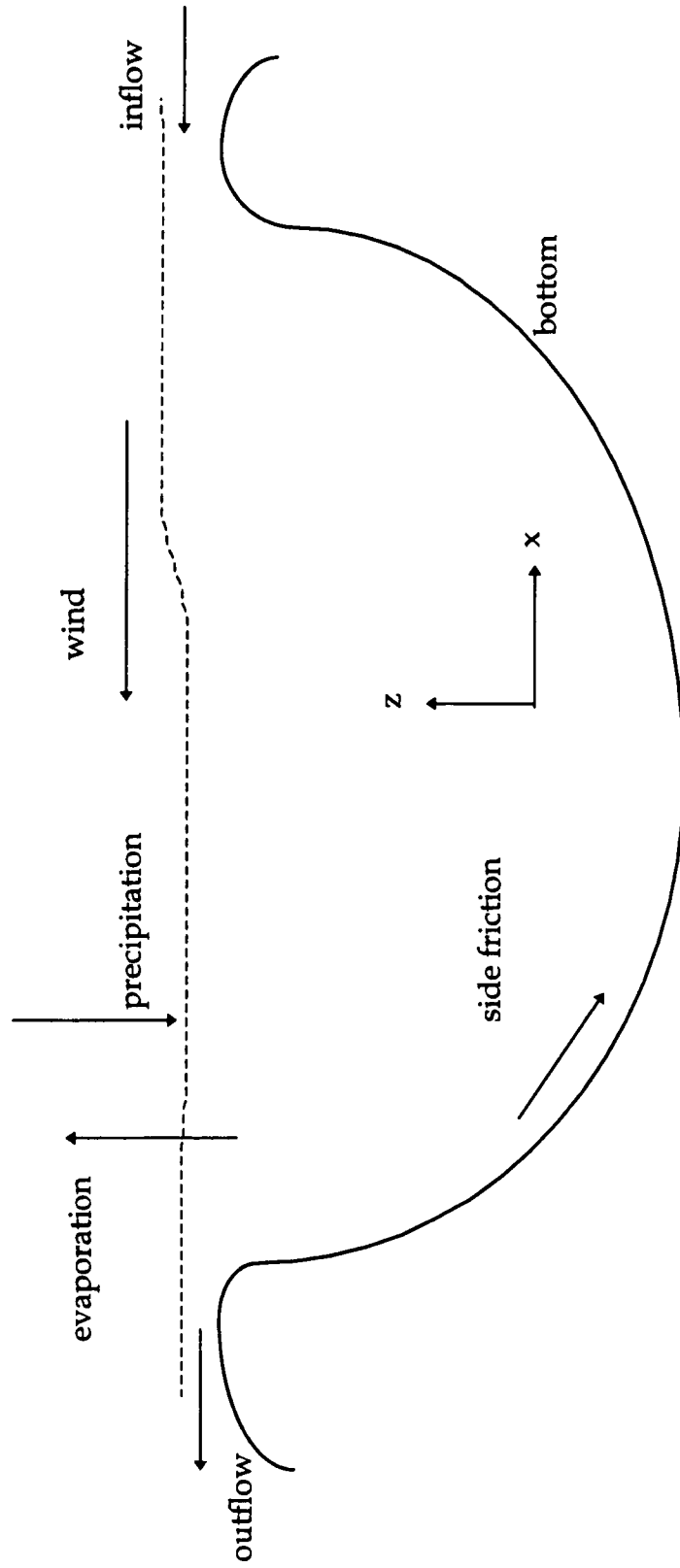


Figure 2.3 Mechanical Forcing on Lake Boundaries
(redrawn from Liggett, 1975)

Due to the changing shape of the free surface, the water depth varies. In general the water surface elevation and bottom profile will be irregularly distributed. It is thus desirable to make reference to the elevation of the free surface above a horizontal datum plane, as shown in Figure 2.4 (King, 1984). One of the dependent variables is then taken to the water depth with respect to the basin bottom. In this manner, the water surface elevation ($a+h$) can be directly computed during the solution. The free surface motion modeling has been studied by Cheng, 1967, Simons, 1976, and King, 1994. The following equation describes the boundary condition specified for the water surface (King, 1994):

$$\frac{dh}{dt} + v_x \frac{d(h+a)}{dx} + v_y \frac{d(h+a)}{dy} - v_z = 0 \quad (2.11)$$

Correspondingly, the governing equations should be modified to reflect the new dependent variable h .

The wind stress is applied to the water surface in a horizontal direction as an external force. The wind shear stresses are independent of water velocity and are treated as constants at each time step for modeling purposes. The relationship between the time-dependent wind over the water surface and the shear stress at the air-water interface is expressed using the following empirical formulas (Sheng, 1978 and 1977; King, 1994):

$$\Gamma_x = \psi W^2 \cos(\phi) \quad (2.12a)$$

$$\Gamma_y = \psi W^2 \sin(\phi) \quad (2.12b)$$

where $\psi =$ a constant, 13.6×10^{-6} (1/m),

$\phi =$ wind direction angle (positive anti-clockwise), and

$W =$ wind speed (m/s).

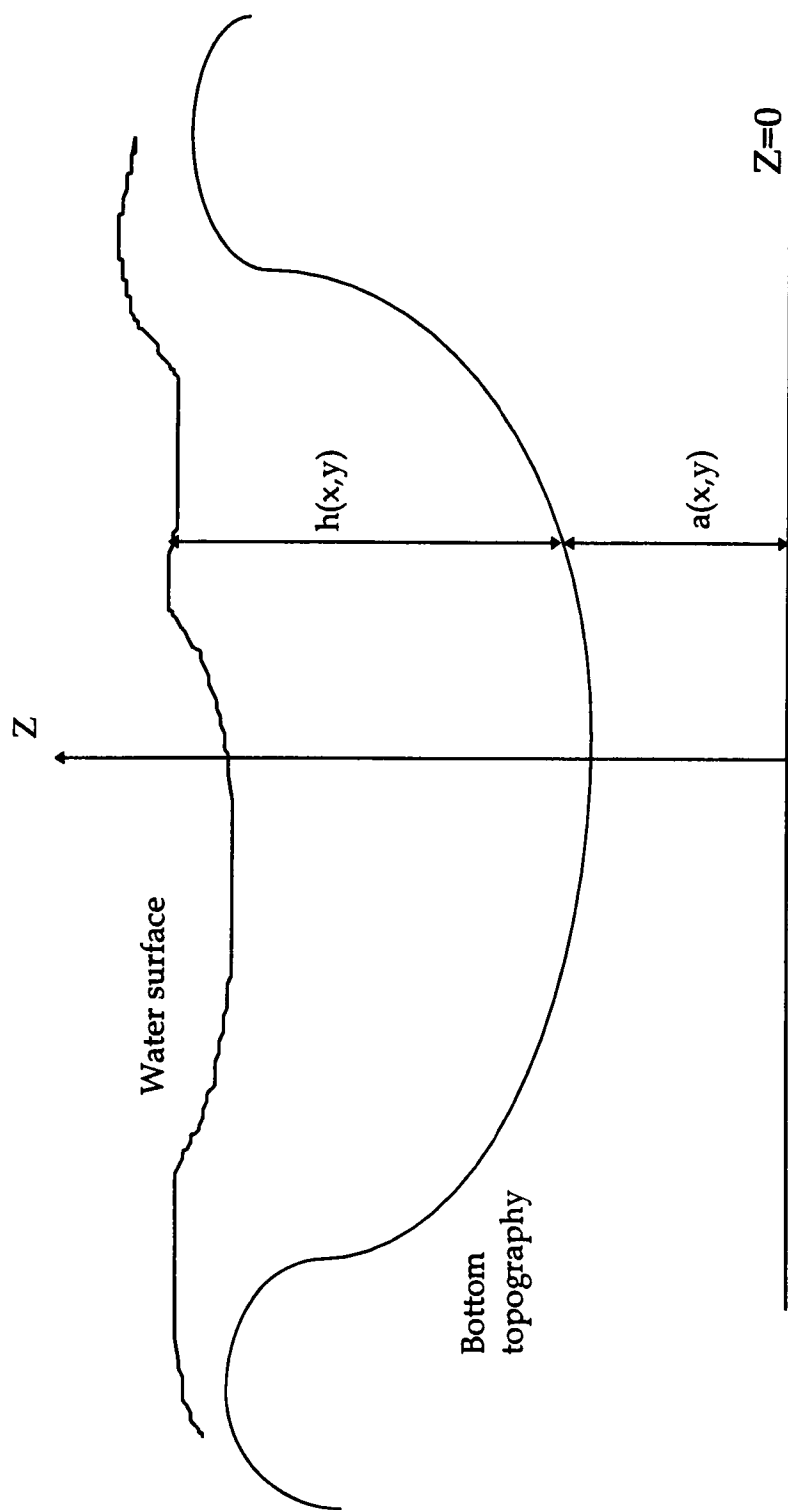


Figure 2.4 Sketch of Transformed Coordinate System.

The Bottom

Two types of bed boundary conditions are possible for the flow close to the bottom depending on the assumptions. Conceptually, a boundary layer exists between fluid and solid boundary. If sufficient detail is added to the model to resolve boundary layer effects, then the no-slip boundary condition, $V = 0$, could be used. If it is assumed that boundary layer effects are not being modeled because the thickness of the boundary layer is less than the resolution permitted by the available computational tools, then the velocity no-slip boundary condition is reflected by a lake bottom friction force source term. The boundary condition then will be defined by the following equation (King, 1994):

$$v_x \frac{\partial a}{\partial x} + v_y \frac{\partial a}{\partial y} - v_z = 0 \quad (2.13)$$

The bottom friction force is empirically related to the flow velocity at the bottom (Hutter, 1984). The components of this force in a direction counter to the flow are described by Chezy's formulas (Sheng, 1978):

$$\Gamma_x = -\frac{\rho g v_x V}{C^2} \quad (2.14a)$$

$$\Gamma_y = -\frac{\rho g v_y V}{C^2} \quad (2.14b)$$

where $V = \text{magnitude of water velocity at the bed } (v_x^2 + v_y^2)^{0.5} \text{ (m/s)}$,

$C = \text{Chezy coefficient (m}^{2/3}\text{/s)}$, and

$\rho = \text{fluid density (kg/m}^3\text{)}$.

The Side boundaries

Side boundaries occur at two locations, (1) at lake banks and (2) at system cuts, such as the mouth of the river where the water enters another system. Naturally, the flow

boundary condition at banks must be zero normal velocity. Cuts isolating the system, require more involved boundary conditions depending on the data and modeling specifications. The choices include specified velocities at the x, y, z locations of a cut, specified volume flow rate or specified water surface elevation at the cuts. A shear force is applied to the surface area of side banks and is computed in an analogous fashion to the bottom friction forces using Chezy's formulas.

2.3 *Spatial Considerations*

The number of spatial dimensions needed in a realistic model involving the previous equations is dictated by the degree of heterogeneity of the system. The number of required spatial dimensions determines model complexity. Homogeneity in hydrodynamics and contaminant distribution may allow dimensional reduction. Four models may be defined based on the number of dimensions.

- If the water system is characterized by a complete heterogeneity, meaning that contaminant concentrations are different in all directions, hydrodynamic and contaminant transport calculations are carried out in three dimensions.
- If uniformity can be assumed in one direction, a two-dimensional model can be applied. The 3-D governing equations are then integrated over that direction, which reduces the problem dimensionality. Two-dimensional models are generally used for shallow water systems in which vertical homogeneity may be assumed, which will be discussed in Section 2.4.
- A quasi one-dimensional model is practical when the hydrodynamic system is uniform in two directions as may be the case of a shallow river.

- Zero-dimensional models (“box” models) consider a completely homogeneous system in which contaminant concentrations do not vary in space. Calculations of contaminant concentration are then carried out over the entire volume.

2.4 Two-dimensional Depth-Averaged Model

A two-dimensional depth averaged model constitutes the most widely used approach to simulate the flow patterns and contaminant transport in shallow water systems. If the depth of the water is sufficiently small compared to the length of the body of water, the vertical momentum becomes negligible in comparison to the horizontal momentum components. The momentum equation in the vertical direction (z) is then reduced to:

$$\frac{\partial P}{\partial z} + \rho g = 0 \quad (2.15)$$

which is representative of a hydrostatic approximation and is widely used in two-dimensional depth averaged flow analyses (Celia, 1988; Rao, 1970; Rastogi, 1978; King, 1994).

Mathematically, the pollutant transport, continuity, and momentum equations are integrated over the vertical direction (z). The horizontal components of velocity v_x and v_y , are replaced by corresponding depth-averaged components. Under these conditions all derivatives with respect to z no longer appear, and vertical velocity component v_z is then expressed through the water depth h and through its change in space. The continuity, momentum, and pollutant transport equations for a two dimensional shallow lake (Norton, 1973; Thomas, 1990) will then become,

Continuity Equation

$$\frac{\partial h}{\partial t} + h \frac{\partial u}{\partial x} + h \frac{\partial v}{\partial y} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \quad (2.16)$$

Momentum Equations

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \left(\frac{\partial h}{\partial x} + \frac{\partial a}{\partial x} \right) - \frac{\epsilon_{xx}}{\rho} \frac{\partial^2 u}{\partial x^2} - \frac{\epsilon_{xy}}{\rho} \frac{\partial^2 u}{\partial y^2} + \Gamma_x = 0 \quad (2.17a)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \left(\frac{\partial h}{\partial y} + \frac{\partial a}{\partial y} \right) - \frac{\epsilon_{yx}}{\rho} \frac{\partial^2 v}{\partial x^2} - \frac{\epsilon_{yy}}{\rho} \frac{\partial^2 v}{\partial y^2} + \Gamma_y = 0 \quad (2.17b)$$

Transport Equation

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} - D_x \frac{\partial^2 C}{\partial x^2} - D_y \frac{\partial^2 C}{\partial y^2} - \theta_s = 0 \quad (2.18)$$

where: u = horizontal flow velocity in the x-direction [LT^{-1}],

v = horizontal flow velocity in the y-direction [LT^{-1}],

g = acceleration of gravity [LT^{-2}],

h = water depth [L],

a = bottom elevation with respect to a given datum [L],

ρ = fluid density [ML^{-3}],

ϵ_{xy} = normal eddy viscosity coefficient in the x-direction [$MT^{-1}L^{-1}$],

ϵ_{xx} = tangential eddy viscosity coefficient in the x-direction [$MT^{-1}L^{-1}$],

ϵ_{yx} = tangential eddy viscosity coefficient in the y-direction [$MT^{-1}L^{-1}$],

ϵ_{yy} = normal eddy viscosity coefficient in the y-direction [$MT^{-1}L^{-1}$],

C = contaminant concentration [ML^{-3}],

θ_s = local concentration source or sink [$ML^{-3}L^{-1}$],

D_x = eddy diffusion coefficient in the x-direction [L^2T^{-1}],

D_y = eddy diffusion coefficient in the y-direction [L^2T^{-1}],

Γ_x = external force in x-direction [LT^{-2}], and

Γ_y = external force in y-direction [LT^{-2}].

2.5 Computational Method

To solve the above transport and hydrodynamic equations, a finite element method is used. Finite element analyses have been used for decades for simulating multi-dimensional fluid dynamic problems (Akin, 1986; Ziversley, 1983; Reid, 1975; Zienkiewicz, 1977). In the finite element method, an approximate solution to a boundary and initial-value problem is determined by subdividing the domain into well-defined subdomains called finite elements and by approximating the unknown functions within each element by a way of linear combination of unknown coefficient and specified trial functions. These individually defined trial functions match one another at the connection points (element nodes). In this fashion the unknown functions are then approximated over the entire domain. Figure 2.5 sketches how the domain is discretized through a set of triangular elements. The unknown function is then approximated in terms of its values at nodes (Figure 2.6), and the solution is computed at every node and each time step. It is, therefore, inevitable that the determination of u , v , and C will require solution of simultaneous equations. A computer code, TABS (FastTABS, 1994), has been used to perform these computations in this study.

The TABS computer program was developed by the U.S. Army Corps of Engineers at Waterways Experiment Station (WES) over a period of twenty years. TABS is a specifically designed finite element code for modeling two-dimensional depth averaged flow patterns and contaminant transport. The TABS consists of three sub-programs, GFGEN, RMA-2, and RMA-4.

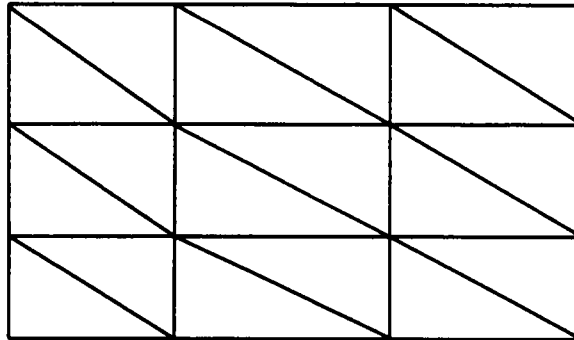


Figure 2.5 Quadrilateral Domain Subdivided into a Mesh of Triangular Elements

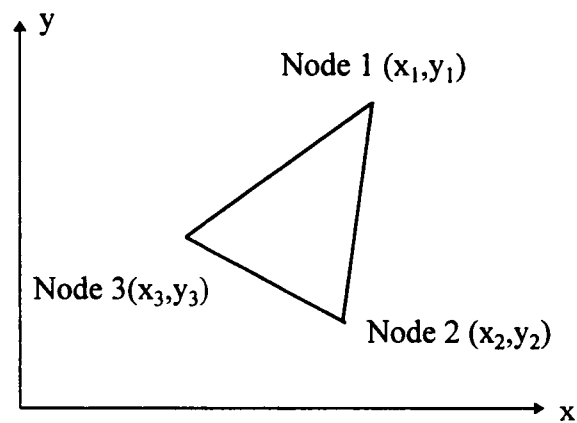


Figure 2.6 Generic Two-dimensional Triangular Element

The purpose of GFGEN is to create a geometry and finite element mesh file for input to the RMA-2 and RMA-4 programs. The heart of the TABS system is the program RMA-2, which can be used to compute water surface elevations and flow velocities at nodal points in a finite element mesh representative of a body of water. RMA-2 can generate both steady-state and time-dependent solutions. In other words, the boundary conditions (wind force) can vary with time and a solution can be found at a number of time steps. RMA-4 is the contaminant transport modeling portion of the TABS system. It uses the hydrodynamic solution from RMA-2 to provide a flow velocity field for a given mesh, and it computes the concentration distribution for a given number of time steps. TABS has been successfully used in a variety of projects, such as Saugus River Estuary study. The purpose of the study is to determine the impacts of a tidal flood gate on tidal circulation and sedimentation in an interior estuary wetland. The mesh contains 6300 elements and 18500 nodes (FastTABS, 1994).

CHAPTER 3

RADIOECOLOGICAL EXPOSURE MODEL WITH HETEROGENEITY AND DYNAMIC EFFECTS

This chapter consists of the following sections: current methods for describing radionuclide accumulation, development of the modeling framework, discussion of parameters and model integration.

3.1 Current Methods for Describing Radionuclide Accumulation

Three terms, bioconcentration, bioaccumulation, and biomagnification (Jorgensen, 1990), are generally used for describing uptake and retention of contaminants by biota. Most of the time, these terms are determined from controlled experiments or from collections of literature data (Vanderploeg, 1975; Brungs, 1965).

Bioaccumulation factor (BAF) signifies the uptake and retention of radionuclides by biota through any mechanism or pathway. It includes direct uptake from water and indirect uptake from food. The general expression for BAF is *Concentration in biota/Concentration in water*.

Bioconcentration (BCF) stands for the uptake and retention of radionuclides by biota directly from water, where $BCF = \text{Concentration in biota} / \text{Concentration in water}$. The BCF has to be found only from direct uptake from water.

Biomagnification (BM) describes the process in which radionuclides are concentrated from one trophic level prey to another predator, where $BM = \text{Concentration}$

in biota /Concentration in food. The BM gives the ecological magnification from one level to the next.

The use of these factors simplifies radioecological exposure calculations. Generally, if the information regarding the radionuclide concentration in water is available, the concentration in biota could be immediately estimated using these factors. A range of BF values for different radionuclides has been published (Vanderploeg, 1975; NCRP, 1992), and most exposure studies calculate the concentration in biota by using the concentration factors discussed above.

One of the most important assumptions associated with using constant concentration factors is that the biota should be in equilibrium with the contaminant concentration in the environment (Davis, 1958; Fleisnman, 1973). Concentration factors are constant in many cases when steady-state and spatial homogeneous conditions are achieved. Steady-state here indicates that the aquatic radioactive environment and ecological activities are characterized by constant conditions. However, radionuclide transport, and various physical and biological processes are dynamic. Therefore, the steady-state and homogeneous assumptions prevent the concentration factors from being used in a dynamic or heterogeneous environment. Furthermore, since the bioconcentration factor is calculated as the ratio of the concentration in biota divided by the concentration in environment, the detailed information on radionuclide uptake, transformation among ecosystem components, is lost.

3.2 Development of the Modeling Framework

3.2.1 Spatial and Temporal Effects

Spatial and temporal heterogeneity in an environment is an integral part of natural systems (Mackay, 1984) and such heterogeneity complicates exposure modeling. The

effects of spatial and temporal variations of contaminant concentrations on the bioaccumulation have been recognized, and have been recently given more attention. For example, Bartell (1991) made a simulation on a grid model of nitrogen dynamics in a deciduous forest watershed. The results demonstrated the potential errors in describing nitrogen dynamics that can result from ignoring spatial heterogeneity. Breck (1988) studied the effects on individual fish survival of spatial heterogeneity in toxicant concentrations. The results highlighted that the potential importance of a chemically heterogeneous natural environment in allowing a population to survive.

Biological populations are often unevenly distributed in space, i.e., a "clumped" distribution (Patalas, 1969; Lewis, 1979; Nihoul, 1975). The varying degree of heterogeneity in population distributions may be influenced by water circulation, biota behavior, and their migration (Arnold, 1978; Cherry, 1982; DeAngeli, 1978).

3.2.2 Ecological Process Effects

Ecological exposure assessments should be integrated with ecosystem science. Understanding of ecosystem structure, functions, and interactions among ecosystem components is necessary. The following ecological processes or factors are closely related to the exposure assessment: predator-prey relationship in the context of a multi-dimensional environment, population dynamics (physiological process), changes in abundance and distribution of population biomass, the density-dependent ingestion rates, and metabolic processes. For example, physiological processes control growth. Food web structure determines the radionuclide flow among the ecosystem components. The metabolic processes influence the radionuclide retention in biota.

3.2.3 Model Structure

The formulation of model structure begins with the principle of conservation of mass for populations in a dynamic three-dimensional space. Then, with specific assumptions, the three-dimensional model is transformed to a two-dimensional model. Four populations, phytoplankton, zooplankton, prey-fish, and predator-fish are studied in this model.

The conservation equation of radionuclide mass is derived for the same infinitesimal volume as the one used to derive the transport equation in Chapter 2. In this manner, the concentrations of contaminants in water obtained from the contaminant transport modeling can be integrated into the exposure model.

Three types of concentrations are involved in modeling the accumulation processes occurring in the infinitesimal volume:

- Radionuclide concentration in water $C_w(x,y,z,t)$ with the unit of Bq/m^3 which is converted from mass unit by multiplying specific activity;
- Specific radionuclide concentration in populations $C_i(x,y,z,t)$ with the unit of Bq/kg , where i is the index of the population; and
- Radionuclide concentration possessed by a population residents in the infinitesimal volume. Mathematically, it is expressed as the product of population biomass density ($m_i(x,y,z,t)$, kg/m^3) and specific radionuclide concentration ($C_i(x,y,z,t)$, Bq/kg) in the same volume. The unit of $(m_i(x,y,z,t) \cdot C_i(x,y,z,t))$ is Bq/m^3 .

In fact, the third expression of concentration ($m_i(x,y,z,t) \cdot C_i(x,y,z,t)$, Bq/m^3) transfers the specific concentration ($C_i(x,y,z,t)$, Bq/kg) in a population into a *volume concentration* with the unit of Bq/m^3 . The transformation makes it possible to study

population exposure in the water volume in which $C_w(x,y,z,t)$ is calculated using a hydrodynamic-transport model. Thus, the *volume concentration* $C_i(x,y,z,t)m_i(x,y,z,t)$ is used as the quantity for formulating the model.

The *volume concentration* conservation equation which describes the net flux of radionuclides into the biota as the sum of all of the uptake and loss flux is presented as,

$$\frac{D[m_i(\vec{r},t)C_i(\vec{r},t)]}{Dt} = k_{ui}m_i(\vec{r},t)C_w(\vec{r},t) + k_{fi}m_i(\vec{r},t)C_{i-1}(\vec{r},t) - k_{bi}m_i(\vec{r},t)C_i(\vec{r},t) - \lambda m_i(\vec{r},t)C_i(\vec{r},t) \quad i=1,4 \quad (3.1)$$

where $\mathbf{r}$ = location (x,y,z) in a coordinate space,

i = population index (1 for phytoplankton, 2 for zooplankton, 3 for prey-fish, and 4 for predator-fish),

$C_w(\mathbf{r}, t)$ = radionuclide concentration (Bq/m³) in water, which is calculated using a hydrodynamic and transport model discussed in Chapter 2,

$C_i(\mathbf{r}, t)$ = radionuclide concentration (Bq/kg) in a population at i th-position of food web,

$C_{i-1}(\mathbf{r}, t)$ = radionuclide concentration (Bq/kg) in a population at $i-1$ th-position of food web, when $i=1$, $C_0 = 0$.

$m_i(\mathbf{r}, t)$ = biomass density (kg/m³) of the population at i th-position of food web, which will be detailed discussed in Section 3.2.5.

k_{ui} = radionuclide uptake rate (m³/kg day) from the water for the population at i th-position of food web,

k_{bi} = radionuclide biological elimination rate (1/day) for the population at i th-position of food web,

k_{fi} = radionuclide ingestion rate (kg food/kg biota/day) from prey for the population at i th-position of food web, and

λ = radioactive decay constant (1/day).

The term on the left side of Equation (3.1) denotes the concentration rate of change at a given location. The first term on the right side of Equation (3.1) describes the radionuclide uptake from water. The second term accounts for the bioaccumulation of radionuclides from food. The third and fourth terms express radionuclide loss from the biota due to biological elimination and radioactive decay. Equation (3.1) is further expanded to

$$\frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial \vec{r}} \frac{\partial \vec{r}}{\partial t} + \frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial t} \frac{\partial t}{\partial t} \quad (3.2)$$

$$= k_{wi} m_i(\vec{r}, t) C_w(\vec{r}, t) + k_{fi} m_i(\vec{r}, t) C_{i-1}(\vec{r}, t) - k_{bi} m_i(\vec{r}, t) C_i(\vec{r}, t) - \lambda m_i(\vec{r}, t) C_i(\vec{r}, t)$$

then

$$\frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial t} = k_{wi} m_i(\vec{r}, t) C_w(\vec{r}, t) + k_{fi} m_i(\vec{r}, t) C_{i-1}(\vec{r}, t) - k_{bi} m_i(\vec{r}, t) C_i(\vec{r}, t) \quad (3.3)$$

$$- \lambda m_i(\vec{r}, t) C_i(\vec{r}, t) - \frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial \vec{r}} \cdot \vec{V}$$

where the advection term $\frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial \vec{r}} \cdot \vec{V}$ stands for the concentration change in populations in the volume due to the movement of populations.

Two assumptions are applied to the advection term: (1) that the fish stay within their home range (or volume) which is assumed to be about 200(m) x 200 (m) x h (m). The rational for this assumption is that fish movement is not expected to be totally random. It is likely that the fish moves but generally stays within a fixed home range (Breck, 1988); and (2) that both phytoplankton and zooplankton accumulate radionuclides within the volume and eliminate them within the volume before they leave the volume. The rational for this assumption is that the concentrations taken up in both

plankton are quickly eliminated since they both have a very fast radiobiological turn-over rates (Henry, 1978). Therefore, the advection term in Equation (3.3) is assumed to be negligible. The concentration change in the volume is expressed as

$$\frac{\partial [m_i(\vec{r}, t) C_i(\vec{r}, t)]}{\partial t} = k_{wi} m_i(\vec{r}, t) C_w(\vec{r}, t) + k_{fi} m_i(\vec{r}, t) C_{i-1}(\vec{r}, t) - k_{bi} m_i(\vec{r}, t) C_i(\vec{r}, t) - \lambda m_i(\vec{r}, t) C_i(\vec{r}, t) \quad (3.4)$$

To directly express the concentration in the population at the i th-position of the food web as a function of concentrations in water and food, and also of population biomass, Equation (3.4) is further expanded as

$$C_i(\vec{r}, t) \frac{\partial m_i(\vec{r}, t)}{\partial t} + m(\vec{r}, t) \frac{\partial C_i(\vec{r}, t)}{\partial t} = k_{wi} m_i(\vec{r}, t) C_w(\vec{r}, t) + k_{fi} m_i(\vec{r}, t) C_{i-1}(\vec{r}, t) - k_{bi} m_i(\vec{r}, t) C_i(\vec{r}, t) - \lambda m_i(\vec{r}, t) C_i(\vec{r}, t) \quad (3.5)$$

Rearranging Equation (3.5), one obtains

$$m(\vec{r}, t) \frac{\partial C_i(\vec{r}, t)}{\partial t} = k_{wi} m_i(\vec{r}, t) C_w(\vec{r}, t) + k_{fi} m_i(\vec{r}, t) C_{i-1}(\vec{r}, t) - k_{bi} m_i(\vec{r}, t) C_i(\vec{r}, t) - \lambda m_i(\vec{r}, t) C_i(\vec{r}, t) - C_i(\vec{r}, t) \frac{\partial m_i(\vec{r}, t)}{\partial t} \quad (3.6)$$

Divide both sides by $m_i(\vec{r}, t)$ to obtain,

$$\frac{\partial C_i(\vec{r}, t)}{\partial t} = k_{wi} C_w(\vec{r}, t) + k_{fi} C_{i-1}(\vec{r}, t) - C_i(\vec{r}, t) \left(\frac{\partial m_i(\vec{r}, t)}{\partial t} \frac{1}{m_i(\vec{r}, t)} + k_{bi} + \lambda \right) \quad (3.7)$$

Equation (3.7) expresses the specific concentration in populations as a function of population biomass change $\frac{\partial m_i(\vec{r}, t)}{\partial t} \frac{1}{m_i(\vec{r}, t)}$. This term allows for the influence of population dynamics with the spatial heterogeneity of population distributions to be included into the modeling of radionuclide uptake and accumulation processes.

Equation (3.7) presents the modeling framework in a continuous three-dimensional space. In this study, the continuous space has been replaced by a series of discrete elements defined on the finite element mesh used in the contaminant transport

calculation, illustrated by Figure 3.1. On the figure, each element location is represented by a location index j . In this manner, the exposure model (Equation (3.7)) represented in a continuous space can be replaced by a series of succeeding exposure models for every element in the mesh with the location index j

$$\frac{dC_{ij}(t)}{dt} = k_{wi}C_{wj}(t) + k_{fi}C_{(i-1)j}(t) - C_{ij}(t)\left\{\frac{dm_{ij}(t)}{dt}\frac{1}{m_{ij}(t)} + k_{bi} + \lambda\right\} \quad (3.8)$$

where $C_{ij}(t)$ denotes the concentrations in population i at location j . $C_{wj}(t)$ denotes concentration in water at the same location, which is calculated using the hydrodynamic-transport model. The $C_{(i-1)j}(t)$ stands for the concentrations in prey at location j . $m_{ij}(t)$ represents the biomass densities of four populations at location j , which will be discussed in Section 3.5.

Three cases are discussed to demonstrate how Equation (3.8) links to a homogeneous exposure condition or to a homogeneous and steady state exposure condition,

- If spatial effects are ignored, Equation (3.8) becomes

$$\frac{dC_i(t)}{dt} = k_{wi}C_w(t) + k_{fi}C_{i-1}(t) - k_{bi}C_i(t) - \frac{dm_i(t)}{dt}\frac{1}{m_i(t)}C_i(t) - \lambda C_i(t) \quad (3.9)$$

Equation (3.9) is a kinetic model that describes bioaccumulation under a homogeneous environment. Therefore, the location index j is eliminated.

- If population biomass changes are insignificant ($dm_{ij}(t)/dt/m_{ij}(t)=0$), one obtains,

$$\frac{dC_i(t)}{dt} = k_{wi}C_w(t) + k_{fi}C_{i-1}(t) - k_{bi}C_i(t) - \lambda C_i(t) \quad (3.10)$$

- Further, if a steady state condition ($dC_i/dt=0$) is assumed, the steady state solution of Equation (3.10) is

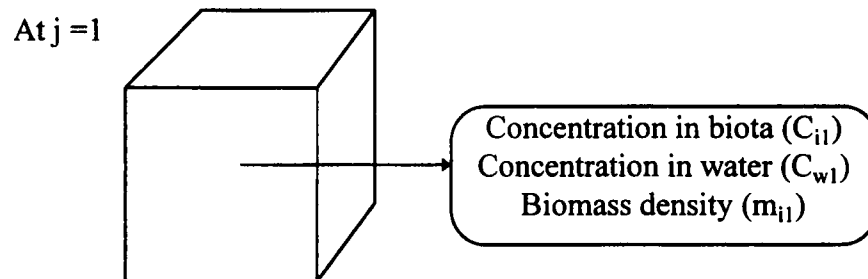
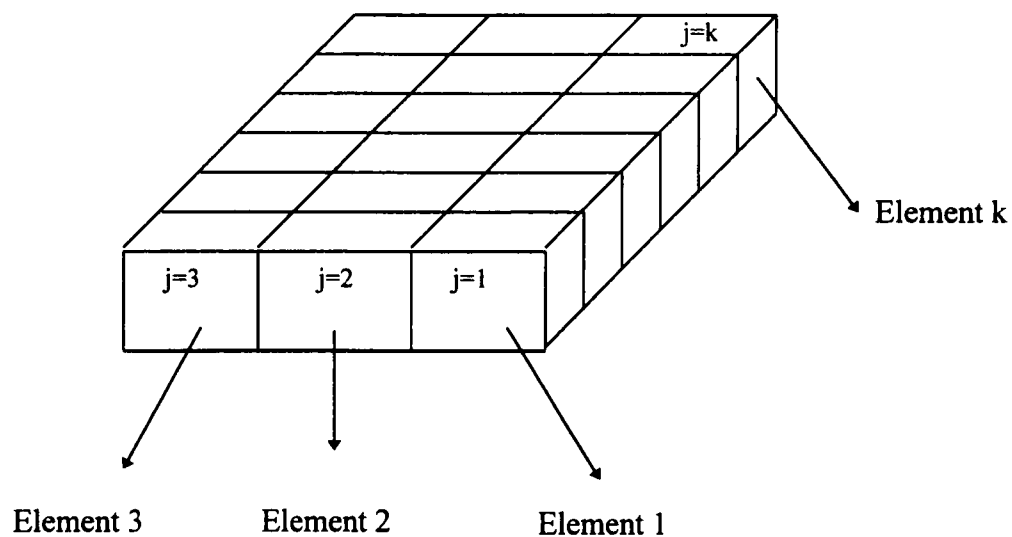


Figure 3.1 A Conceptual Picture Illustrating that a Continuous Space is Represented by a Discretized Element Mesh with Location Index j .

$$\begin{aligned}
C_i &= \frac{k_{ui}C_w + k_{fi}C_{i-1}}{k_{hi} + \lambda} \\
&= \frac{k_{ui}}{k_{hi} + \lambda}C_w + \frac{k_{fi}}{k_{hi} + \lambda}C_{i-1}
\end{aligned}
\tag{3.11}$$

Equation (3.11) defines the bioaccumulation factor discussed in Section 3.1. Correspondingly, $k_{ui} / (k_{hi} + \lambda)$ denotes the bioconcentration factor, and $k_{fi} / (k_{hi} + \lambda)$ is the biomagnification factor.

3.2.4 Food Web Structure

Aquatic organisms can take up radionuclides released in water either from ingestion of contaminated food or from direct intake of water, or from both. As a result of the feeding relationships, the radionuclide concentration in the predator is related to that in its prey.

Figure 3.2 illustrates a conceptual diagram of a simple food web structure. The flow of radioactive substance is from phytoplankton, through zooplankton and prey-fish to pred- fish. The phytoplankton is the basic food for the ecosystem. Predatory fish are on the top of the food web. Phytoplankton is a general name for minute floating plants, usually algae. They are distributed throughout the water as deep as light penetrates and give water a greenish color (Odum, 1971). Zooplankton (animal plankton) is the name for the primary macroconsumers which feed directly on living phytoplankton or their remains. All zooplankton, prey-fish, and predator-fish are called consumers; in contrast, the phytoplankton is called producer. The food web structure can be complex and vary with time and space.

Equation (3.8) gives a general accumulation relationship for any population. In terms of radionuclide transfer processes for each particular population through the food web, Equation (3.8) may be rewritten as

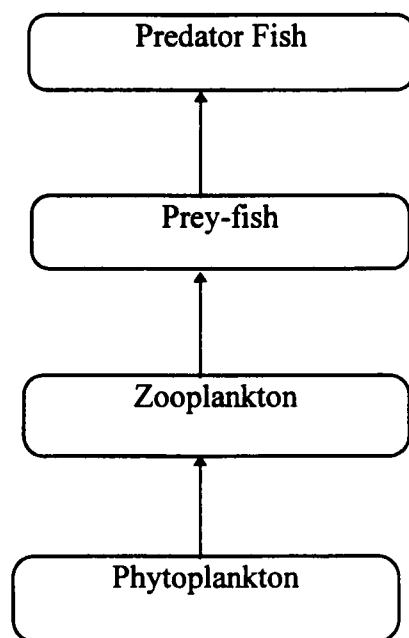


Figure 3.2 **Single-prey Food Web Structure for Transferring Radionuclides among Four Populations (Phytoplankton, Zooplankton, Prey-fish and Pred-fish). The Arrows Show the Prey-predation Relationship.**

Phytoplankton

$$\frac{dC_{1j}(t)}{dt} = k_{u1}C_{wj}(t) - C_{1j}(t)\left\{\frac{dm_{1j}(t)}{dt}\frac{1}{m_{1j}(t)} + k_{b1} + \lambda\right\} \quad (3.12)$$

Zooplankton

$$\frac{dC_{2j}(t)}{dt} = k_{u2}C_{wj}(t) + k_{f2}C_{1j}(t) - C_{2j}(t)\left\{\frac{dm_{2j}(t)}{dt}\frac{1}{m_{2j}(t)} + k_{b2} + \lambda\right\} \quad (3.13)$$

Prey-fish

$$\frac{dC_{3j}(t)}{dt} = k_{u3}C_{wj}(t) + k_{f3}C_{2j}(t) - C_{3j}(t)\left\{\frac{dm_{3j}(t)}{dt}\frac{1}{m_{3j}(t)} + k_{b3} + \lambda\right\} \quad (3.14)$$

Pred-fish

$$\frac{dC_{4j}(t)}{dt} = k_{u4}C_{wj}(t) + k_{f4}C_{3j}(t) - C_{4j}(t)\left\{\frac{dm_{4j}(t)}{dt}\frac{1}{m_{4j}(t)} + k_{b4} + \lambda\right\} \quad (3.15)$$

where $C_{1j}(t)$, $C_{2j}(t)$, $C_{3j}(t)$ and $C_{4j}(t)$ are radionuclide concentrations in phytoplankton, zooplankton, pre-fish, and pred-fish in the j th-element. The $m_{1j}(t)$, $m_{2j}(t)$, $m_{3j}(t)$ and $m_{4j}(t)$ denote biomass densities for four populations in the same element.

So far it has been discussed that the radionuclide accumulation in the predator fish only relates to prey-fish. It is natural that the predator may feed on several prey (Odum, 1971). To include effects of feeding interactions on the bioaccumulation in pred-fish, food preference factors (f_i) are added into Equation (3.15) to give

$$\frac{dC_{4j}(t)}{dt} = k_{u4}C_{wj}(t) + \sum f_i k_{f4i} C_{ij}(t) - C_{4j}(t)\left\{\frac{dm_{4j}(t)}{dt}\frac{1}{m_{4j}(t)} + k_{b4} + \lambda\right\} \quad (3.16)$$

where $\sum f_i k_{f4i} C_{ij}(t)$ = uptake from the composition of the predator's prey ($i=1,2,3$),

i = predators' prey which include phytoplankton ($i=1$), zooplankton ($i=2$), and prey-fish ($i=3$),

f_i = fraction of predator's prey that consists of populations with radionuclide concentration of $C_{ij}(t)$.

Figure 3.3 shows a specific case for predator's food preferences: 50% phytoplankton (f_1), 30% zooplankton (f_2), and 20% prey-fish (f_3), adding up to total prey for pred-fish (omnivorous fish).

3.2.5 Population Dynamics and Biomass Distributions

As shown in Equation (3.7), the biomass density change $\frac{\partial m_i(\vec{r}, t)}{\partial t} \frac{1}{m_i(\vec{r}, t)}$ is an integral part of the radionuclide accumulation process. The effect of biomass density variation on the accumulation of radionuclides in a two-dimensional space can be treated by varying m_{ij} in Equation (3.8). The mechanisms influencing biomass variation are discussed for each of the four trophic level populations.

Phytoplankton

Phytoplankton biomass change is related to daily variations in incident light, water temperature, excretion, mortality, and grazing by higher trophic level biota (Mitsch, 1981). The mathematical form for such change is expressed as (Bartell, 1988),

$$\frac{dm_1}{dt} = m_1(P_1 - M_1 - G_1) \quad (3.17)$$

where m_1 = biomass density of phytoplankton (kg/m^3),

P_1 = photosynthetic rate (1/d) which determines the phytoplankton growth,

M_1 = mortality rate (1/d) accounting for sinking, respiration, and non-predatory loss, and

G_1 = zooplankton grazing rate on phytoplankton (1/d).

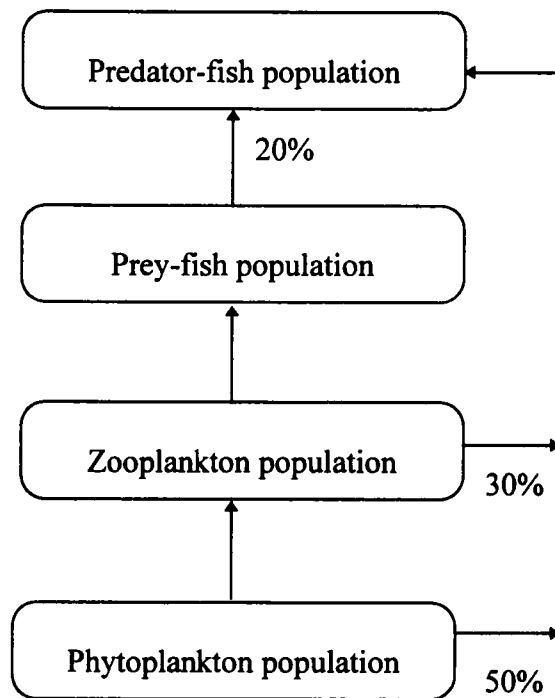


Figure 3.3 A Multi-prey Food Web Structure (Predators Feeding on More Than One Prey). The Predation Preferences are 50% Phytoplankton, 30% Zooplankton, and 20% Prey-fish.

In nature, all of these rates are not constant but vary with environmental conditions and population physiological processes. If one considers these rates, the net biomass change rate (θ_1) due to phytoplankton population dynamics is

$$\theta_1 = P_1 - M_1 - G_1 \quad (3.18)$$

The physical factors in environments, such as wind-driven water circulation, may force phytoplankton to follow the flow field. Phytoplankton are floating organisms whose movement is partly dependent on flow circulation patterns (Riley 1976, Rasmussen, 1988; Pinel-Alloul et al. 1988; George 1973; Smith 1976; Taylor, 1984 and 1977). Thus, the phytoplankton biomass modeling will be driven by a physical model to determine phytoplankton distributions in a two-dimensional space.

Phytoplankton population dynamics is integrated into a two-dimensional transport model by,

$$\frac{\partial m_1}{\partial t} + v_x \frac{\partial m_1}{\partial x} + v_y \frac{\partial m_1}{\partial y} - D_x \frac{\partial^2 m_1}{\partial x^2} - D_y \frac{\partial^2 m_1}{\partial y^2} + m_1 \theta_1 = 0 \quad (3.19)$$

where m_1 = biomass density of phytoplankton,

v_x and v_y = flow velocity components in x and y directions,

D_x and D_y = turbulent diffusion coefficients in x and y directions, and

θ_1 = net change rate of phytoplankton biomass due to physiological process,

which is described by Equation (3.18).

By solving Equation (3.19), one obtains phytoplankton temporal- and spatial-dependent biomass distributions. In each element, a time history data regarding phytoplankton biomass density is generated. Then, the function of biomass $m_{ij}(t)$ in j th-element can be interpolated from those data. In turn, the phytoplankton biomass density change term ($dm_{ij}(t)/dt/m_{ij}(t)$) in Equation (3.12) can be calculated.

Zooplankton

Population dynamics formulation of the zooplankton growth is

$$\frac{dm_2}{dt} = m_2(C_2 - M_2 - F_2) \quad (3.20)$$

where m_2 = biomass density of zooplankton,

C_2 = zooplankton growth rate,

M_2 = combined non-predatory mortality rate, such as natural death, and

F_2 = loss rate due to the predation by prey-fish.

Therefore, the net change rate of zooplankton biomass (θ_2) due to population dynamics will be

$$\theta_2 = C_2 - M_2 - F_2 \quad (3.21)$$

Like phytoplankton, zooplankton are generally unable to move against appreciable flow circulation even though some zooplankton may exhibit active swimming movements in the vertical direction (Malone and McQueen, 1983; Steven, 1977). Therefore, the same physical model (Equation (3.19)) is used for zooplankton transport and growth except using net change rate θ_2 which is solely determined by zooplankton population dynamics, in stead of using net change rate θ_1 .

Prey- and pred-fish

Similar to the expression of zooplankton, the mathematical forms of population dynamics for prey- and pred-fish are expressed separately as

prey-fish

$$\frac{dm_3}{dt} = m_3(C_3 - M_3 - F_3) \quad (3.22)$$

pred-fish

$$\frac{dm_4}{dt} = m_4(C_4 - M_4) \quad (3.23)$$

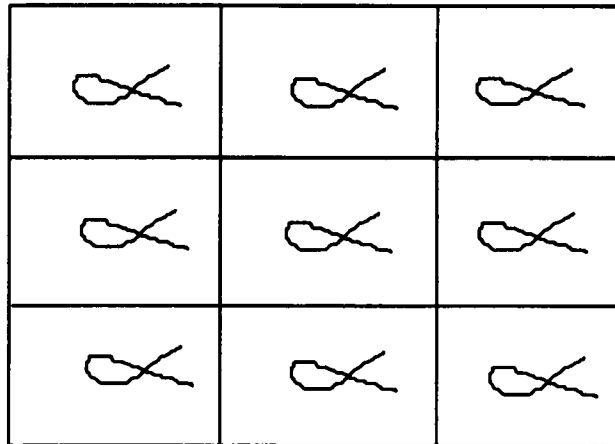
where parameters C_i , M_i , and F_i have the same meanings as those defined in Equation (3.20).

Compared with plankton distributions, the impact of environmental physical factors on fish distributions is complicated by fish migration, random movement, and home range movements (Harden Jones, 1988). Fish may move through the entire lake mainly depending on fish species, migration habits, and environmental conditions, or they may forage within a limited home range (Arnold, 1984; Salis, 1969). The complex field of fish migration and behavior goes beyond the present investigation. For the purpose of studying the influence of fish distribution on their exposure, the following simulations of fish distributions in a two-dimensional environment are examined:

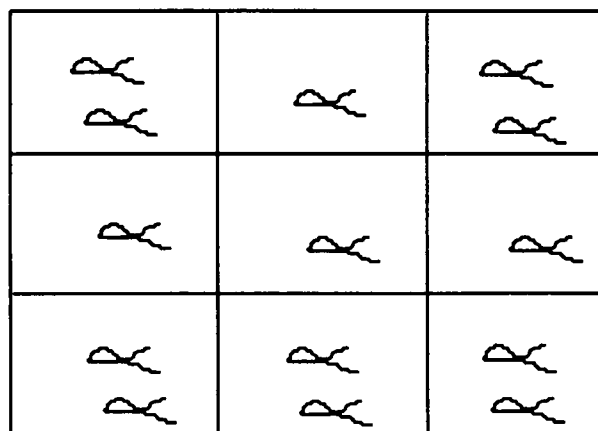
- Pattern 1: fish are homogeneously distributed in water (shown in Figure 3.4 (a)); and
- Pattern 2: fish are heterogeneously distributed in water (shown in Figure 3.4 (b)).

3.2.6 Spatial and Temporal-dependent Radionuclide Ingestion Rate

As stated previously, one of the important pathways through which biota accumulate radionuclides is the consumption of prey. The specific rate at which prey are captured by a unit of predator is proportional to the concentration (biomass densities) of prey. This density-dependent effect indicates that the radionuclide ingestion capability of predator is dependent on the abundance of prey. The rationale behind density-dependent ingestion rate is the competition for the food sources in a limited space. Lotka (1924) proposed the feeding rate with the predator-prey relationship which was extensively studied by O'Brien, 1972, Canale, 1976, Dugdale, 1975, Holling, 1965, Ivlev, 1961, Rosenzweig, 1971, Steel, 1974, and Takahashi, 1959. Mathematically, Park et al. (1974) and Bartell (1992) formulated feeding rate as:



(a) Homogeneous



(b) Heterogeneous

Figure 3.4 A Conceptual Sketch for Fish Distributions under Homogeneous and Heterogeneous Conditions

$$F_{fi} = aC_{mi}h(T) \frac{f_{i-1}m_{i-1}}{\sum f_{i-1}m_{i-1} + m_i} \quad (3.24)$$

where F_{fi} = feeding rate of predator,

m_{i-1} = biomass density of prey,

m_i = biomass density of predator,

f_{i-1} = preference of the predator for the prey,

$h(T)$ = correction factor of temperature dependence,

C_{mi} = maximum rate of consumption for predator i , and

a = assimilation efficiency of the prey by the predator.

In radioecological studies, the radionuclide ingestion rate (k_{fi}) is directly linked to the feeding rate (Harvey 1964), then

$$k_{fi} = E_{fi}F_{fi} = E_{fi}aC_{mi}h(T) \frac{f_{i-1}m_{i-1}}{\sum f_{i-1}m_{i-1} + m_i} \quad (3.25)$$

where E_{fi} is the assimilation efficiency of the specified radionuclide from prey. When food is abundant, the ingestion rate is inversely related to the biomass of the predator. When prey biomass value is low or predators are abundant, prey biomass determines the ingestion rate (DeAngelis et al. 1975, Bartell 1992).

The density-dependent ingestion rates are integrated into the exposure model to investigate their influence on the radionuclide transfer and accumulation within four populations. The radionuclide ingestion rate varies in space and time since the prey biomass density varies spatially and temporally. Therefore, the ingestion rate (k_{fi}) of zooplankton, prey-fish, and pred-fish can be represented as the function of location and time,

$$k_{fi}(x, y, t) = E_{fi}aC_{mi}h(T) \frac{f_{i-1}m_{i-1}(x, y, t)}{\sum f_{i-1}m_{i-1}(x, y, t) + m_i(x, y, t)} \quad i=2,3,4 \quad (3.26)$$

where prey biomass density $m_{i-1}(x, y, t)$ is calculated using the integrated transport-growth model (Equation (3.19)). Figure 3.5 illustrate a conceptual mesh for calculating the

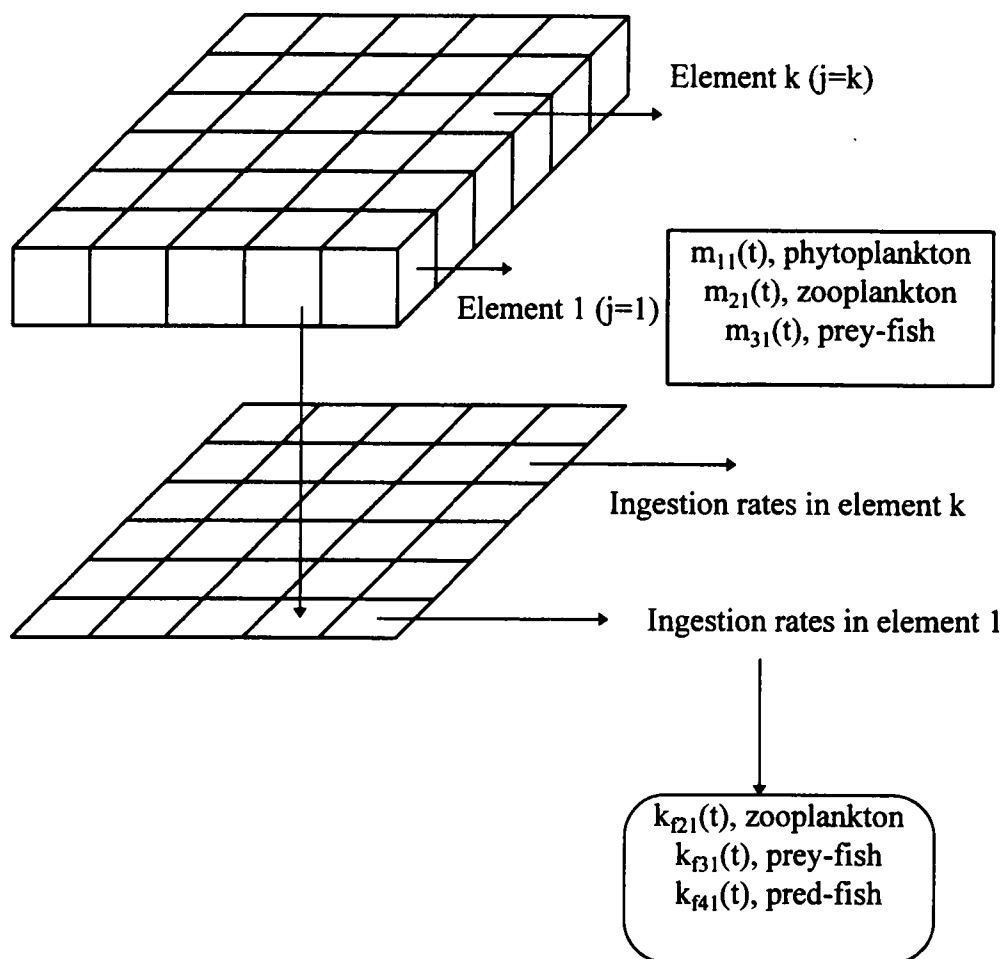


Figure 3.5 A Conceptual Illustration of Mesh Calculating Spatial and Temporal-dependent Ingestion Rates in a Two-dimensional Grid System from the Prey and Predator Biomass Density Distributions

spatial- and temporal- dependent ingestion rates based on the population biomass distributions.

3.3 Parameters

Exposure Equations (3.12), (3.13), (3.14), (3.15), and (3.16) involve parameters, such as uptake rates, elimination rates, assimilation efficiency, and so on. The quantitative value of those parameters are associated with environmental conditions, physical-chemical forms of radionuclides, populational and radiobiological processes. In this section, the underlying mechanisms influencing those parameters are addressed.

Mode of uptake

There are essentially two principal modes of uptake of radionuclides by biota: (1) absorption, which includes metabolic uptake or assimilation, and (2) adsorption, which includes physical exchange process taking place on the exterior surface of the biota (King, 1964; Kolehmainen, 1972).

Metabolic uptake by phytoplankton is related to photosynthesis and mineral assimilation. Adsorptive uptake by phytoplankton is directly related to their large surface to volume ratio. Adsorption may be the first step followed by metabolic uptake through the cell walls (Chipman, 1956; Foster, 1955).

For fish, the specific radionuclide plays an important role. For instance, the principal mode for accumulation of Cs-137 by pred-fish may be through food consumption. While for Sr-90, it is the direct uptake from water (Vanderploeg, 1975).

- **Uptake from contaminated water**

Uptake rates from contaminated water are generally expressed by the uptake coefficients u_w , and radionuclide assimilation efficiency E_w ,

$$k_{ui} = u_{wi} E_w \quad (3.27)$$

The uptake coefficients and assimilation efficiency directly depend on the mode of uptake, chemical-physical form of radionuclides, species, stable element concentrations.

- **Ingestion through food consumption**

Radionuclide ingestion rates from food consumption are commonly linked to the rate of feeding, F_f (kg food/kg biota per day), and to assimilation efficiency of radionuclide. The rate of feeding is a function of many factors, such as temperature, food source availability, and the position of populations in a food web. The assimilation efficiency of a particular radionuclide depends on properties of radionuclides and on species. For example, the assimilation efficiency of Cs-137 among different populations could vary from 10% to 80% (Kevern, 1966; Kolehmainen, 1969; Pendleton, 1965).

Retention-elimination

A knowledge of the retention of a particular radionuclide inside biota is fundamental to the long term exposure. Radionuclide elimination from biota occurs in two ways: biological turnover and physical decay. The radiobiological half-life is defined as the time needed to eliminate half of concentration from biota due to the biological process. Factors, such as temperature, biota growth, species, type of radionuclides may affect the retention of radionuclides in biota (Vanderploeg et al, 1974, Henry, 1975; Harvey, 1964; Hasanen, 1966; Pendleton, 1965; Nelson, 1966; Suzuki et al., 1972; Templeton and Brown, 1964; Agnedal, 1966).

Environmental conditions

Influences of environmental factors on parameters are many. Significant factors include temperature, the abundance of stable elements, non-isotopic carrier elements

analogues, and physical properties of lakes. For example, a turbid environment reduces biota bioaccumulation capabilities (Vanderploeg, 1974; Kolehmainen, 1963; Gardet, 1964 and 1966; Pendleton, 1959).

Carrier elements and some radionuclides are metabolized somewhat similarly by organisms because of their chemical similarities. Many chemically similar carrier elements are essential for organisms to grow, and therefore are actively accumulated from the environment. When organisms take essential elements from contaminated water, they also accumulate radionuclides. Essential elements usually are maintained at a constant concentration in a given organism (Henry, 1975; Nelson, 1969). Therefore, the amount of radionuclide taken up is inversely proportional to the concentration of their chemically similar carrier elements in water.

3.4 Model Integration and Procedure for Exposure Calculation

After the contaminant concentration distributions in water are computed using a hydrodynamic-transport model, and population distributions are determined using either a transport-growth model or a population dynamic model, the exposure model is applied to estimate the accumulated concentrations in four populations. Figure 3.6 illustrates the integration process and the procedures to perform the exposure assessment using the proposed model framework.

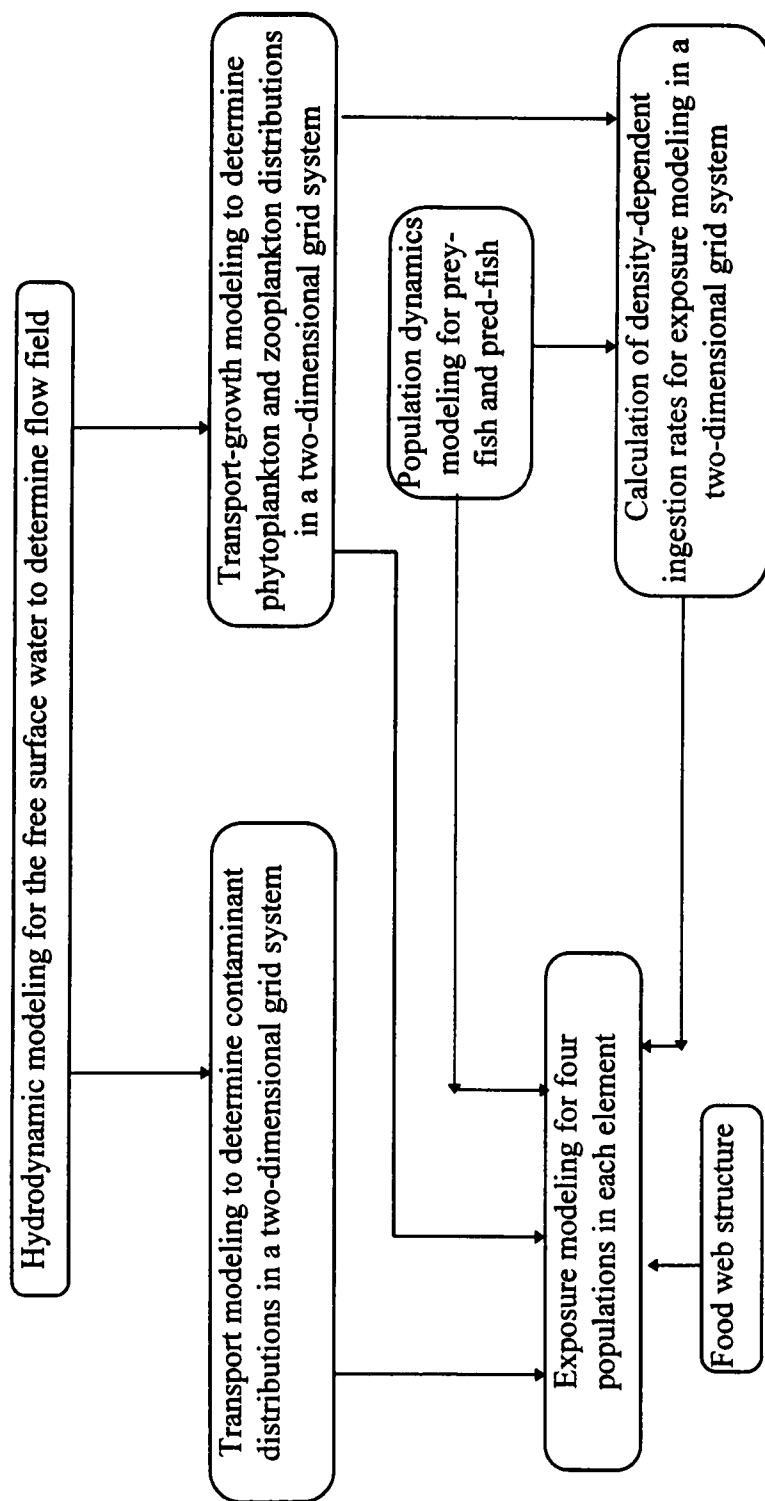


Figure 3.6 Model Integration and Procedures for Exposure Calculations Using the Proposed Framework

CHAPTER 4

TRANSPORT AND DISTRIBUTION OF RADIONUCLIDES IN THE CHERNOBYL COOLING LAKE

This chapter presents the modeling process of contaminant transport in the Chernobyl cooling lake. The mechanisms of contaminant transport in free surface water were discussed in Chapter 2. A finite element program (FastTABS, 1994) is used to predict the flow field and Cs-137 concentration distribution in the cooling lake.

4.1 Introduction

The reactor of unit No. 4 at the Chernobyl nuclear power plant, which was put into operation in December 1983, suffered an explosion on April 26, 1986. By that time it had been in service for 865 days. At the time of the accident, the reactor core had 1659 fuel assemblies, and most of the assemblies were the first loading. Each fuel assembly contained 0.1147 tones of uranium (Borovoy, 1990).

The total release of fission products from the damaged unit is estimated to be 1.85×10^{18} Bq, which is about 4% of the total activity in the reactor (IAEA, 1986). Estimates of total Cs-137 released is about 8.5×10^{16} Bq (IAEA, 1986). After the accident, extensive radiological consequence investigations were conducted. The contaminated Chernobyl cooling lake provided an unique scenario for the radioecological exposure study.

Water to the Chernobyl nuclear power plant is supplied from a cooling pond which was located south-east of the plant site and was made by cutting off part of the river flood plain with a dam, shown in Figure 4.1 (BIOMOVs II, 1993).

All units at the site were shut down from May to September of 1986. During that period, neither was there heated water discharged nor water intake. The cooling pond was approximately a closed lake system with no inflow or outflow. The major forcing function causing the water movement was wind. After September of 1986, the unit was placed in operation, and water discharge and intake activities were resumed. This research focuses on the radioactive contamination during the early period (May-September, 1986).

4.1.1 Description of the Chernobyl Cooling Pond

The cooling pond has an area of 22 km², a volume of 1.5x10⁸ m³, and is an oval shape, as shown in Figure 4.2. Table 4.1 provides more detailed geometry information. There are a number of deep water pits in the cooling pond with a depth of over 10 meters, and about 28% of the pond water is contained in these deep water pits. The bathymetry contour of cooling pond is also shown in Figure 4.2.

Table 4. 1 Geometry Information of the Chernobyl Cooling Lake

Volume (m ³)	1.5x10 ⁸
Area (km ²)	22
Length (km)	11.4
Width, average (km)	2.0
Depth, maximum (m)	20
Depth, average (m)	6.6

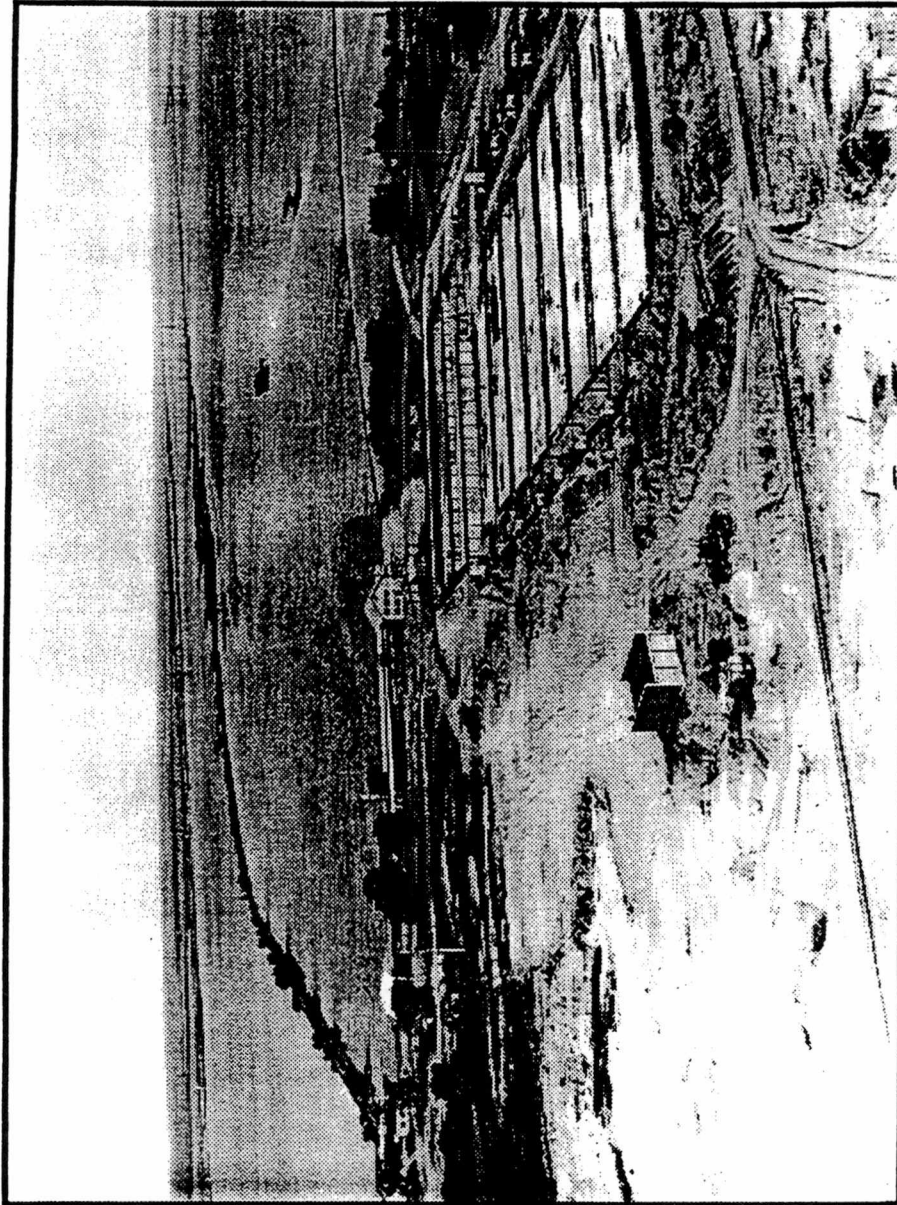


Figure 4.1 The Cooling Lake of the Chernobyl Nuclear Power Plant. View from the Reactor Side (1987) (BIOMOVs, 1993)

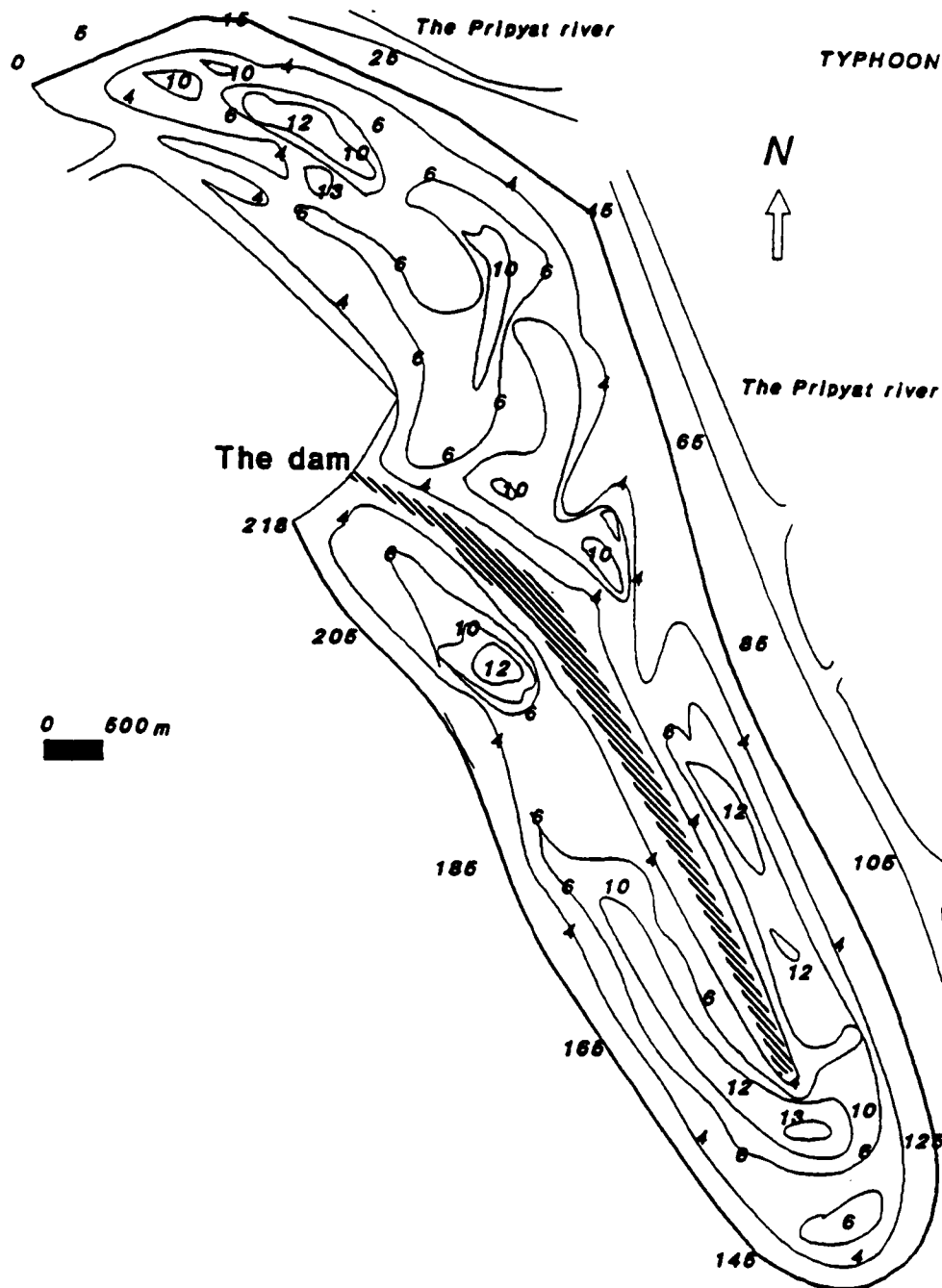


Figure 4.2 Schematic Drawing of the Chernobyl Nuclear Power Plant Cooling Pond Showing the Bathymetry Contour (BIOMOVs, 1993)

4.1.2. Meteorological Information

The information regarding the direction and magnitude of wind from June to September is listed in Tables 4.2 and 4.3. These data were gathered near the Chernobyl site based on averaged conditions from 1975 to 1985. The direction of wind is categorized into eight categories: north, northeast, east, southeast, south, southwest, west, and northwest. The wind duration time in each particular direction is represented by a probability. The wind velocity magnitude is divided into six intervals and is documented at the different hours of the day: 1 AM, 7 AM, 13 PM, and 19 PM. The wind duration time with a particular velocity magnitude in each interval is also represented by a probability.

*Table 4. 2 Probability (%) of the Direction of Wind in Eight Categories
from June to September (BIOMOVs II, 1994)*

Month	N	NE	E	SE	S	SW	W	NW
June	15.0	9.4	10.9	11.0	6.6	14.4	15.4	16.1
July	13.9	9.6	9.4	9.2	4.9	10.7	22.1	18.5
August	16.7	11.4	13.4	8.7	4.8	12.5	14.6	15.1
September	9.2	5.9	9.4	16.4	6.0	15.7	20.8	15.0

Table 4. 3. Probability (%) of Wind Velocity Magnitude in the Different Hours of the Day from June to September (BIOMOVs, 1994)

		Intervals of Wind Velocity Magnitude (m/s)					
Month	Time	0-1	2-5	6-9	10-13	14-17	18-20
June	1 AM	34.8	56.7	7.2	1.2	0.1	-
	7 AM	25.5	62.8	11.2	0.5	-	-
	13 PM	9.0	59.5	27.6	3.2	0.4	0.3
	19 PM	22.2	62.7	13.4	1.6	0.1	-
July	1 AM	40.2	53.8	5.6	0.3	0.1	-
	7 AM	27.0	63.1	9.1	0.7	0.1	-
	13 PM	9.5	60.0	27.7	2.4	0.4	-
	19 PM	27.0	60.3	12.0	0.7	-	-
August	1 AM	37.9	54.4	6.9	0.7	0.1	-
	7 AM	25.3	65.4	9.1	0.1	0.1	-
	13 PM	11.8	57.7	28.0	2.0	0.4	0.1
	19 PM	28.8	61.9	8.5	0.5	0.3	-
September	1 AM	30.1	59.5	8.5	1.2	0.6	0.1
	7 AM	23.5	65.5	10.0	0.6	0.3	0.1
	13 PM	9.9	51.4	33.3	4.5	0.9	-
	19 PM	28.2	61.7	8.6	1.2	0.3	-

4.1.3 Initial Cs-137 Contamination in the Chernobyl Cooling Pond Water

The contamination in the cooling pond water was mainly from continuous atmospheric fallout in April and May of 1986 since the release was not a single massive event and can be divided into several stages (Borovoy, 1990). The close-in zone with the 5 km radius was most contaminated. Outside the close-in zone, the fall-out was rich in iodine-131 and cesium-137 (Borovoy, 1990). Figure 4.3 shows the heterogeneous deposition pattern of radionuclides in the Chernobyl cooling pond water (Kryshev, 1992). Based on the initial deposition pattern, the cooling pond can be divided into approximately three areas (CP1, CP2, CP3) with the different levels of contamination (BIOMOVs, 1993). The concentration of Cs-137 in water was highest in the northwest part of the cooling pond water and lowest in the south part of the cooling pond. Table 4.4 lists the estimated initial concentration values in three regions.

Table 4. 4 Initial Deposition of ^{137}Cs in the Chernobyl Cooling Pond Water (Areas CP1, CP2, CP3) (Decay-corrected for May 30, 1986)

	CP1	CP2	CP3
Water volume (m^3)	13×10^6	76×10^6	62×10^6
^{137}Cs concentration (kBq/m^3)	830	600	45
or ($\mu\text{Ci}/\text{ml}$)	(2.24×10^{-5})	(1.62×10^{-5})	(1.2×10^{-6})

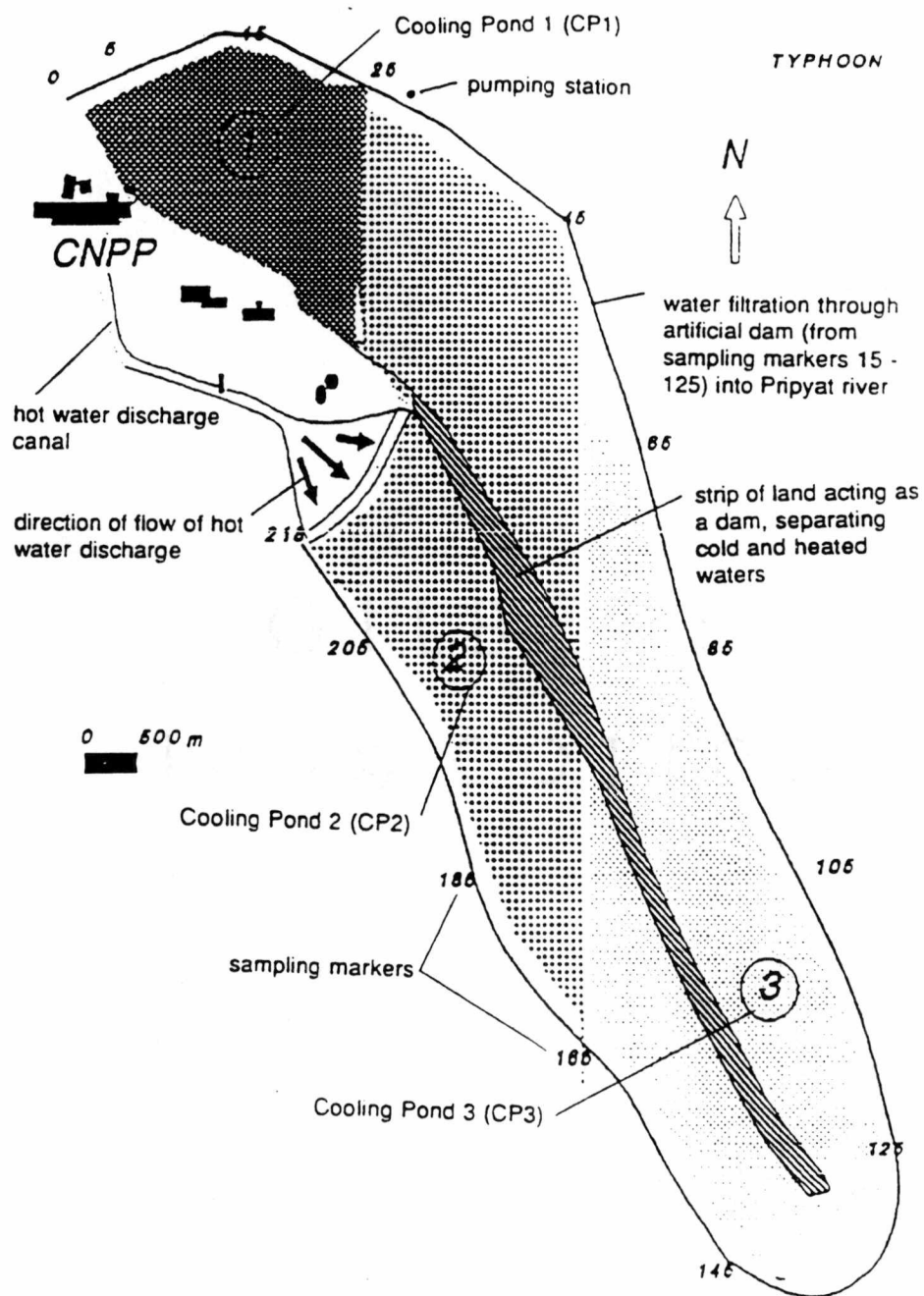


Figure 4.3 The Chernobyl Nuclear Power Plant Cooling Pond Divided into Three Areas with Different Levels of Cs-137 Contamination

4.2. Flow Field Calculations

The cooling pond is considered as a shallow lake due to the large ratio of length to average depth (11.2 km/6.6 m). A two-dimensional nodal depth-averaged free surface hydrodynamic model is used to calculate the flow field. Preparation and carrying out of the calculations can be broken down into the following steps:

- Specification of geometry
- Preparation of a preliminary two-dimensional finite element mesh
- Refinement of mesh
- Description of boundary conditions
- Specification of Chezy coefficients and eddy viscosity

4.2.1 Specification of Geometry

The geometry of the cooling pond defined by x and y coordinates and by the elevation of the pond bottom is first digitized into points in a Cartesian axis system. Each point, defined by its specific x, y, z values, defines a node which is used to construct an element mesh. The digitized bathymetry map in a Cartesian coordinate is given in Figure 4.4, and the contour of the cooling pond based on the digitized points is presented in Figure 4.5.

4.2.2 Preparation of a Preliminary Two-dimensional Finite Element Mesh

Mesh design is the most important aspect in the construction of numerical models because it physically defines the region to be modeled and it determines whether there will be significant error in the calculation. Model accuracy is sensitive to the form and

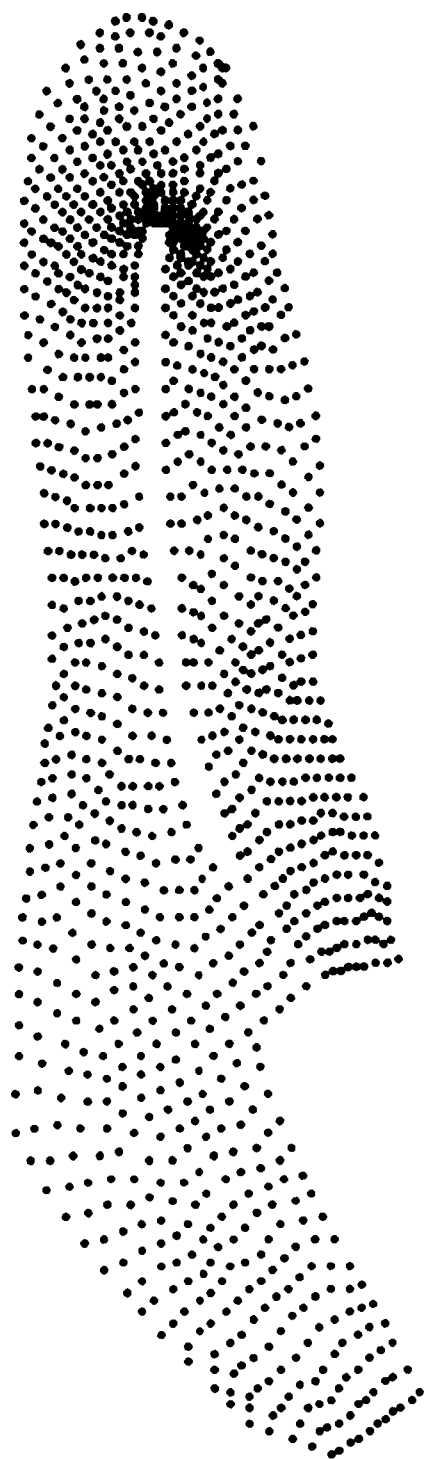


Figure 4. 4 Digitized Geometry of the Chernobyl Cooling Lake

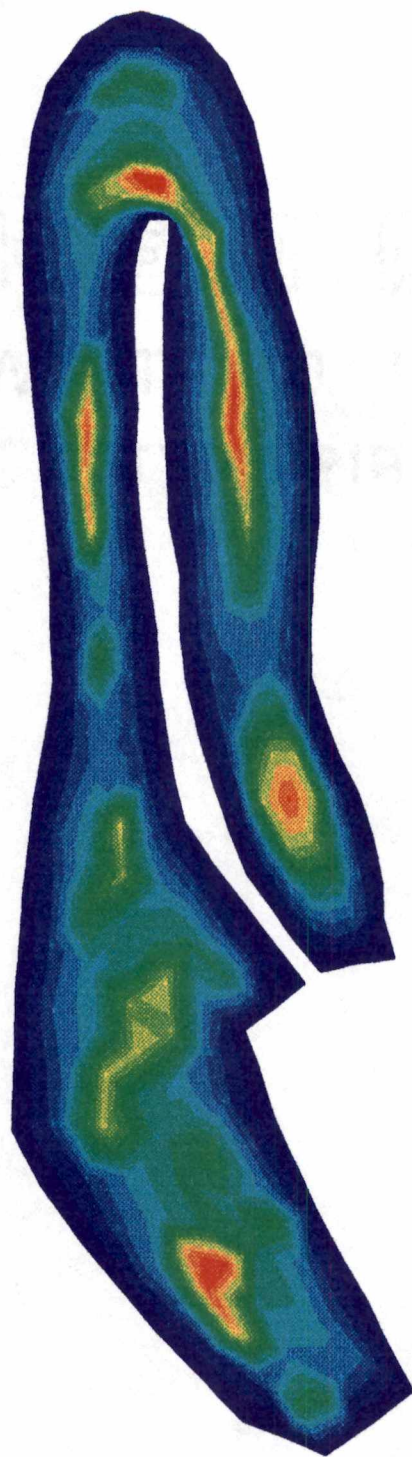


Figure 4. 5 Color Coded Depth Contour for the Chernobyl Cooling Lake (red-12-20 meters, yellow -- 10-12 meters, green-- 6-10 meters, shallow blue -- 4-6 meters, and dark blue -- 0-4 meters)

size of the mesh. A general rule is that areas where large variations are expected should have a higher level of mesh resolution. The bending area of the cooling pond requires a considerable element definition in the vicinity in order to capture the local influence on flow.

Four types of elements are normally supported by TABS: linear triangles, quadratic triangles, linear quadrilaterals, and quadratic quadrilaterals. The triangular elements are necessary in almost all mesh configuration to provide transitions between different regions of the mesh and to model complex geometry shapes. Linear triangles are generated first for the cooling pond geometry, as shown in Figure 4.6. Each node and element in the mesh has an associated ID to represent its location. A total 1321 nodes and 604 elements are used for specifying the mesh for the Chernobyl cooling pond bathymetry.

4.2.3. Mesh Refinement

When performing a hydrodynamic modeling using the finite element method, the stability problem associated with computational calculations should be tested. Element quality is one of the most important factors in obtaining a stable solution. The following issues relating to the element quality of the Chernobyl cooling pond are discussed:

Gradual element area change

When increasing the mesh density locally, such as the bending area of the cooling pond, care is taken to ensure that the elements are well-formed and their sizes do not change too abruptly from one element to the next. As a general rule, the size of the elements should not vary by more than 50% from one element to the next (TABS manual).

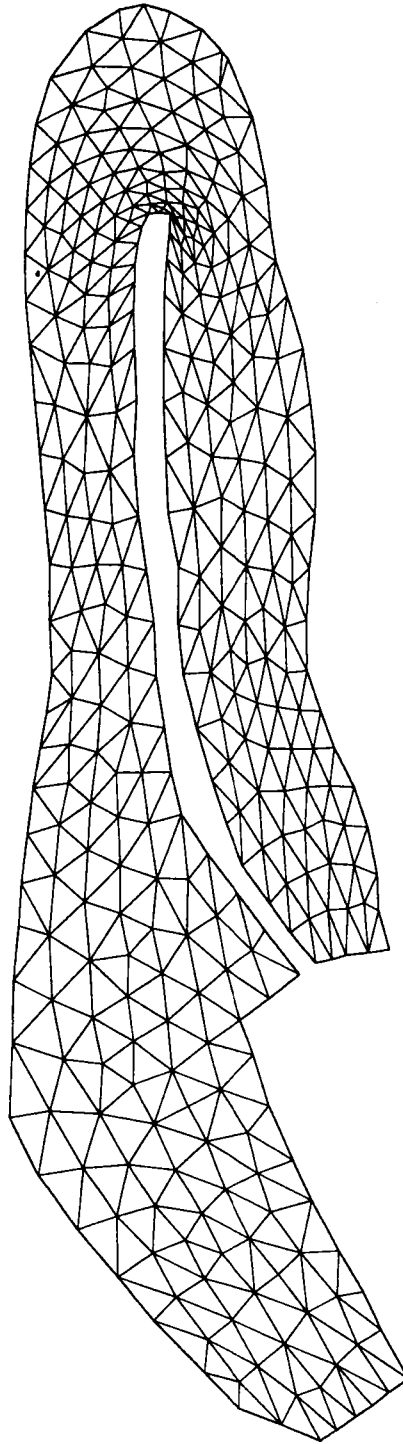


Figure 4. 6 Finite Element Characterization of the Chernobyl Cooling Lake
(Total 604 Elements)

Mild bottom slope

TABS uses a two-dimensional nodal depth-averaged equations. It assumes that the slope across an element in the direction of flow is not greater than 10%. With large slopes, there is a significant vertical component of flow and the two-dimensional assumption is violated. The topography of the cooling pond bottom is not smooth and the bottom slope is relatively steep in some spots. To avoid the results from becoming unstable, the density of the elements in the steep spots is increased.

Wet/dry edges

The Chernobyl cooling pond is a free-surface water system, and the water surface elevation at each node changes. It is expected that wetting and drying cycles may occur for nodes on the bank of the cooling pond. A node is considered to be dry if the computed water surface elevation is lower than the initial node elevation.

TABS has two built-in functions which help to refine the element mesh and insure stability: Refine Elements and Relax Elements. Refine Elements automatically quadruples the mesh density of a selected area of the mesh. The elevations of the new nodes are interpolated from the elevations of the previously existing nodes. After refining part of a mesh, the transition between the new area and the old area may violate the 50% size difference rule for adjoining elements. In such cases, the Relax Elements can improve the mesh by iteratively adjusting the element size.

4.2.4 Specification of Boundary Conditions

Boundary conditions can be applied in one of two ways in TABS: (1) to individual nodes, and (2) to a sequence or string of nodes along a mesh boundary.

The hydrodynamics modeling of the cooling pond is complicated by the meteorological conditions. The wind shear stress is exerted on the water surface when the wind blows over the surface of the Chernobyl cooling pond. The boundary input file includes the magnitude and direction of wind velocity at each simulation time step. Figure 4.7 displays distributions of the wind magnitudes recorded at the different hours of the day for four months. The mode of those distributions for each month is around 2-5 m/s. To prepare the boundary input file for the computation, the magnitudes at 1AM, 7 AM, 13 PM, and 19 PM of the day are averaged based on the above distributions in Figure 4.7. Table 4.5 lists the averaged magnitudes in the different hours of the day for each month.

Table 4. 5 Averaged Wind Magnitudes (m/s) in the Different Hours of the Day for Four Months

Time	June	July	August	September
1AM	2.85	2.554	2.707	3.12
7 AM	3.22	3.122	3.125	3.29
13 PM	5.05	4.563	4.490	5.01
19 PM	3.51	3.226	3.052	3.13

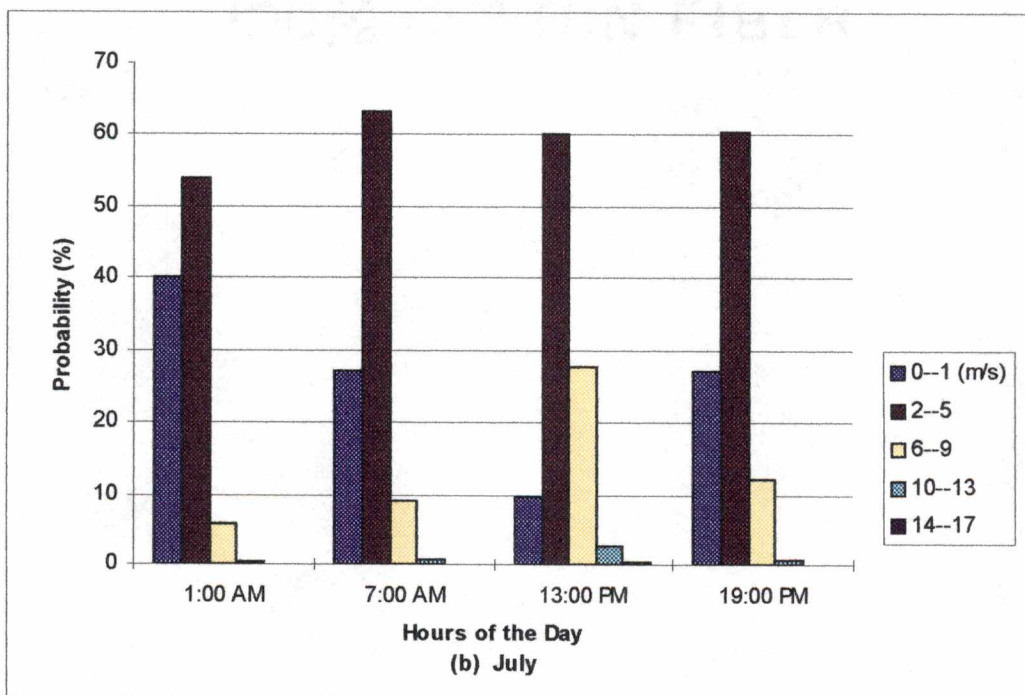
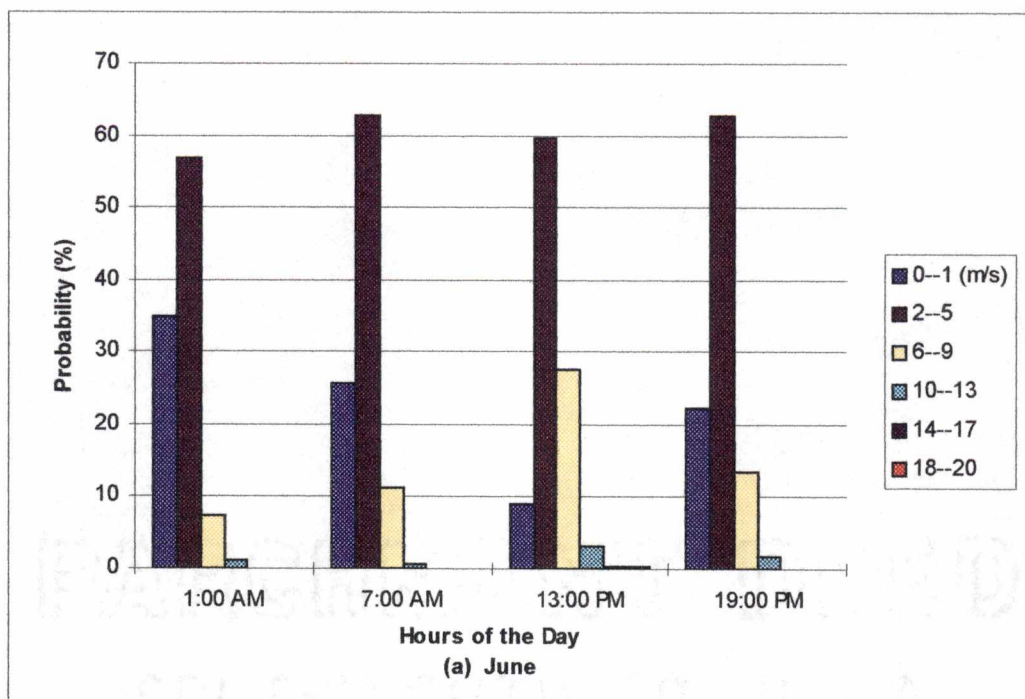


Figure 4.7 Probability of Wind Velocity Magnitude in the Chernobyl Region at 6 Categories during June, July, August, and September

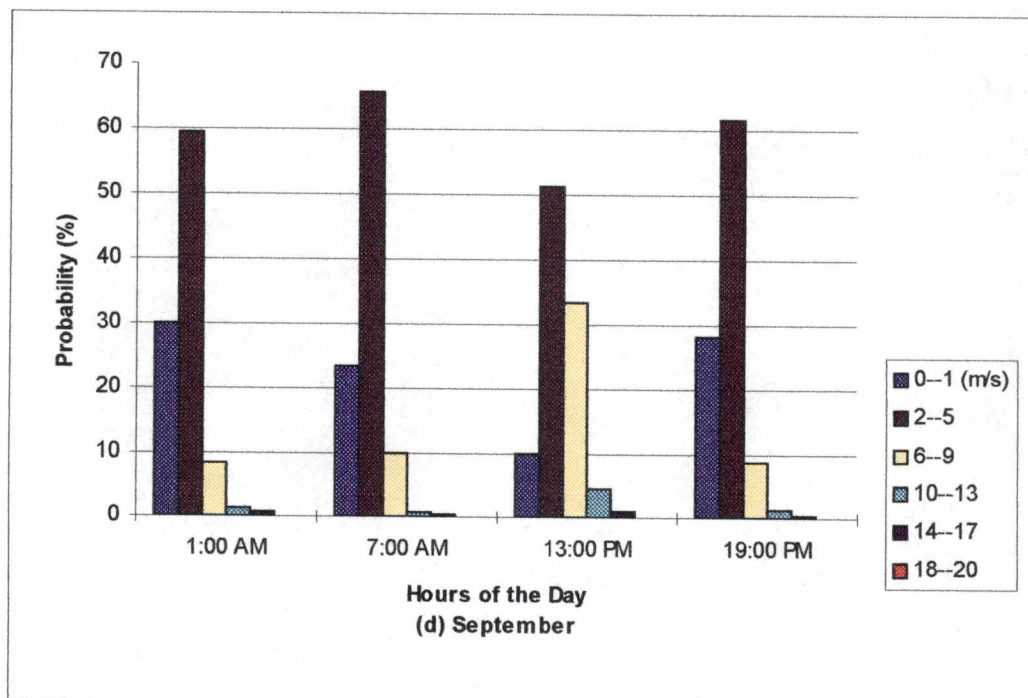
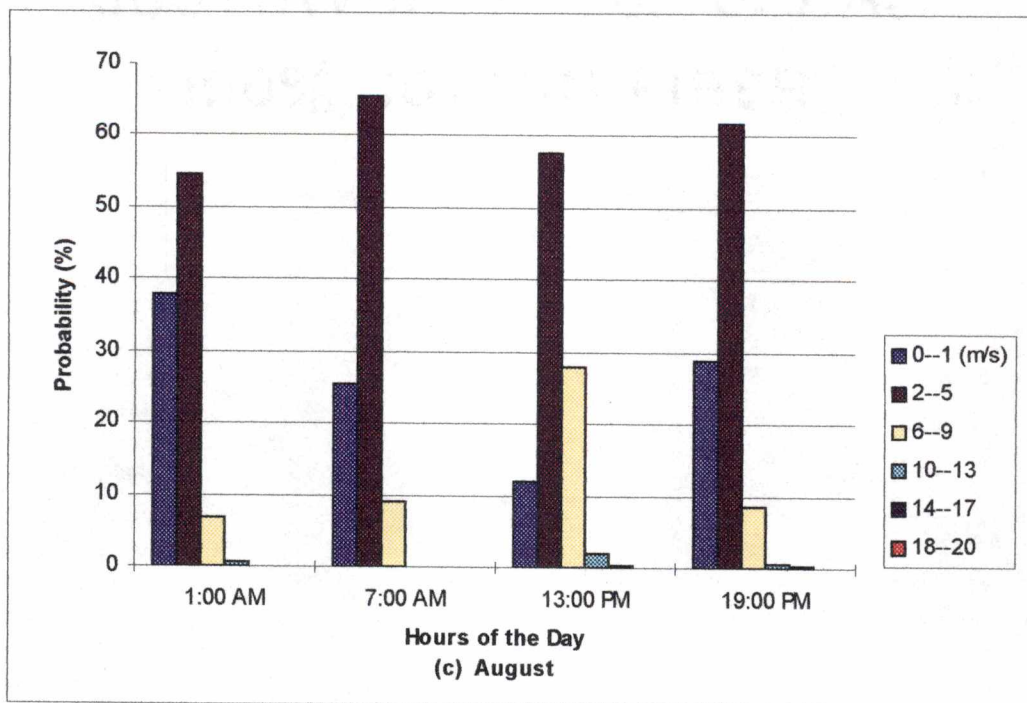


Figure 4.7 (Continued)

Figure 4.8 shows the nine categories of wind directions over the cooling pond in a Cartesian coordinate, which are input into the boundary file. Figure 4.9 illustrates the percentages of wind directions in each category from June to September. Based on the information in Figure 4.9, the actual hours during which the wind blows over the cooling pond surface with a specified direction are calculated and listed in Table 4.6. For example, the north wind blows over the cooling pond for 108 hours in June and the northeast wind dose the same for 67 hours in June.

Table 4. 6 Wind Directions over the Cooling Pond and the Corresponding Acting Hours in Each Direction during June, July, August, and September (Total 720 hours/Month)

	N (150 ⁰)	NE (105 ⁰)	E (60 ⁰)	SE (20 ⁰)	S (330 ⁰)	SW (285 ⁰)	W (240 ⁰)	NW (200 ⁰)	Calm
June	108	67.68	78.48	79.2	47.52	103.7	110.9	115.92	8.64
July	100.08	69.12	67.68	66.24	35.28	77.04	159.1	133.2	12.24
August	120.24	82.08	96.48	62.64	34.56	90.	105.1	108.72	20.16
Sept.	66.24	42.48	67.68	118.1	43.2	113.0	149.8	108	11.52

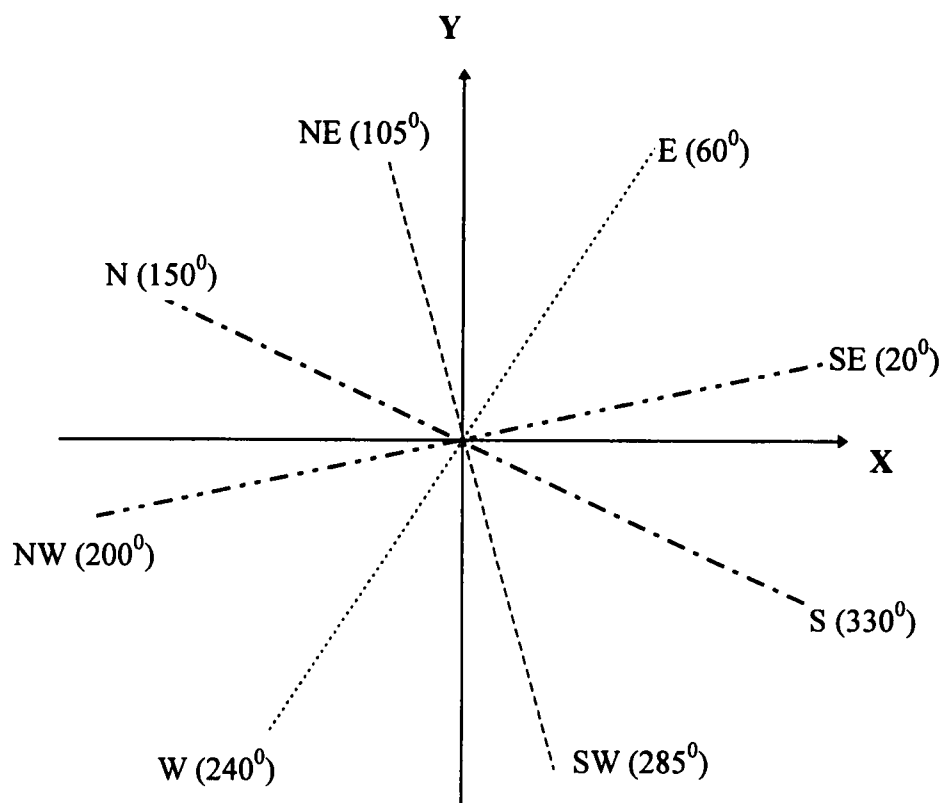


Figure 4.8 **Categorization of Wind Directions Acting on the Surface of the Cooling Pond in a Cartesian Coordinate**

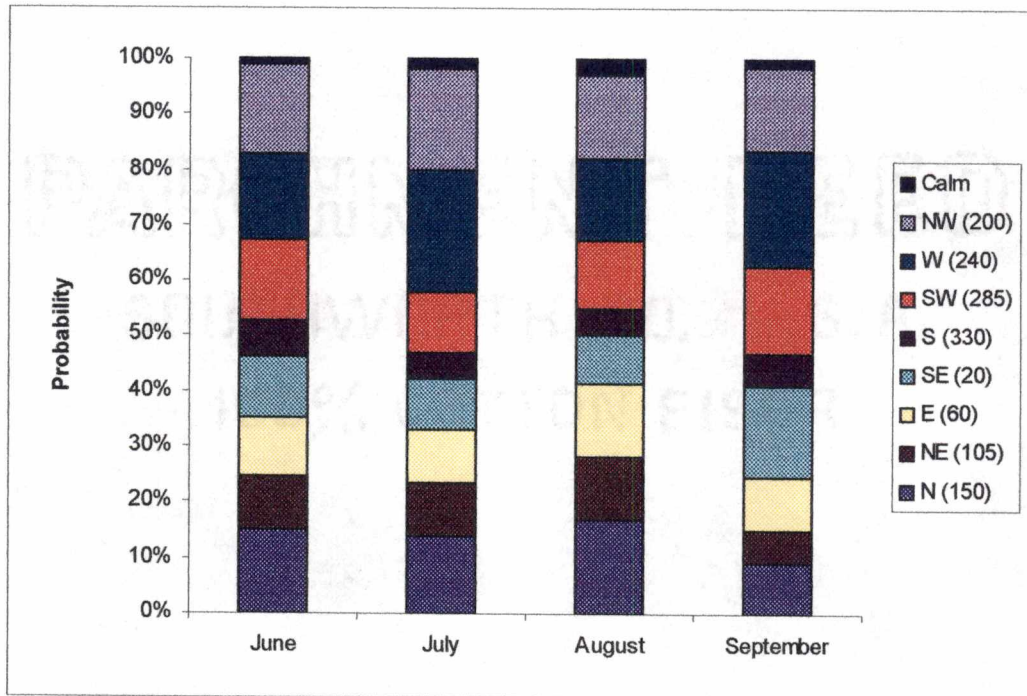


Figure 4.9 Percentage of Wind Directions over the Cooling Lake during June, July, August, and September

4.2.5 Eddy Viscosity and Manning's n Coefficients

In addition to boundary conditions, a set of material properties is necessary to define a hydrodynamic model. The material properties include four eddy viscosity and one Manning's n coefficient, which determines the Chezy coefficients. Each element in the mesh is assigned a material ID, which is associated with a list of material properties.

Eddy Viscosity

The eddy viscosity's presented in Equation (2.5) are as follows as:

ϵ_{xx} = normal eddy viscosity in the x-direction [N sec /m^2],

ϵ_{xy} = tangential eddy viscosity in the x-direction [N sec /m^2],

ϵ_{yx} = tangential eddy viscosity in the y-direction [N sec /m^2], and

ϵ_{yy} = normal eddy viscosity in the y-direction [N sec /m^2].

The eddy viscosity represent the turbulent mixing effects on the flow. Assigning appropriate eddy viscosity is an important aspect of modeling turbulent flow. Mesh spacing, expected current speed, and the dynamic nature of the problem all contribute to the initial assignment of eddy viscosity. Table 4.7 lists a range of eddy viscosity values under different conditions (FastTABS, 1994).

As a general rule, the eddy viscosity should be kept as low as possible without introducing stability problems. Eddy viscosity that are too high will produce a stable solution but will not properly model lateral current distributions, flow separation, and eddy currents. Eddy viscosity that are too low will make the simulation unstable. The Chernobyl cooling pond is a shallow water system with relative slow currents during June - September of 1986. Therefore, a smaller value is selected for the cooling pond.

Table 4. 7 Typical Values of Eddy Viscosity under Different Flow Conditions

Flow Condition	ε Value [N sec / m ²]
shallow river (slow currents)	240 - 1200
shallow river (fast currents)	1200 - 2400
deep estuary (small elements)	2400 - 4800
deep estuary (large elements)	9500 - 14400
wetland with tidal wetting and drying	4800 - 9500
flow separation around structures	50 - 240

Manning's n Coefficients

The Chezy roughness coefficient in Equation (2.14) is converted from Manning 's coefficients. Manning's n coefficient is assigned based on the physical properties of bed materials and certain geometric considerations (Stenberg, 1968). Chow (1959) and the U.S. Geological Survey (1989) provide some guidance to the assignment of these values for a variety of water systems. A set of Manning's n coefficients recommended by TABS are listed in Table 4.8 for different conditions. A value of 0.025 is selected for the application of the cooling pond.

Table 4. 8 Manning's n Coefficients under Different Conditions

Condition	n value
shallow river without snags	0.025 - 0.035
deep river	0.018 - 0.025
shallow estuary without vegetation	0.02 - 0.03
deep estuary	0.015 - 0.02
dense vegetation in a wetland	0.05 - 0.1

4.2.6 Results and Discussions

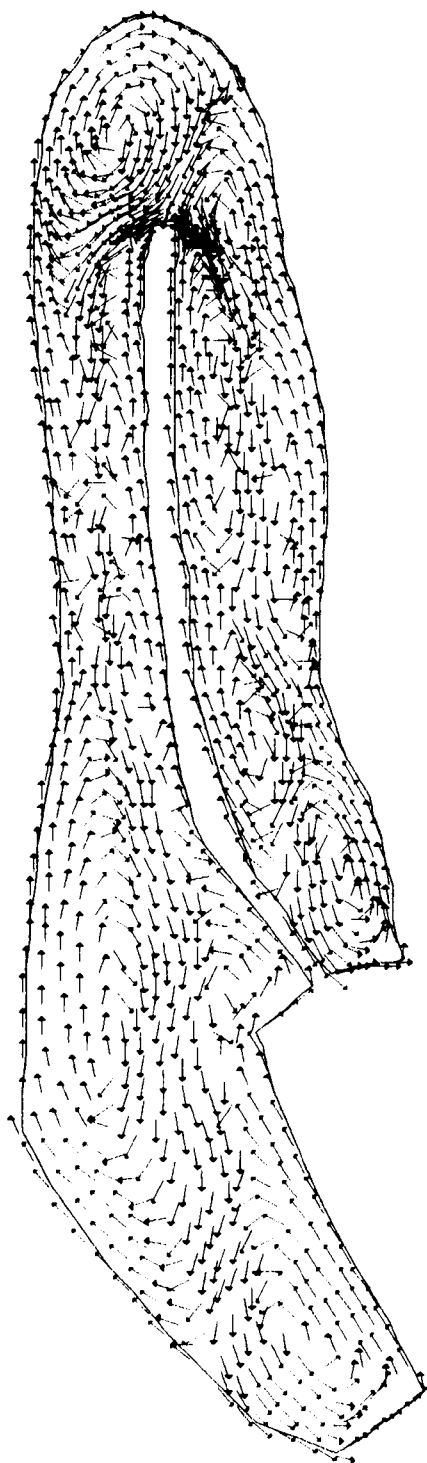
Once the finite element mesh of the cooling pond is constructed and boundary conditions and materials properties are defined, the hydrodynamic model computes the flow velocity and water surface elevation for each element in the mesh. A time step of 6 hours is used and a total 2880 hours are simulated for the cooling pond.

The transient flow field of the cooling pond under the time varying winds is illustrated by examination of Figure 4.10. Figures 4.10 (a) to (k) present current distributions for eleven time steps. The flow velocity direction is represented by a vector arrow. The arrow head size of the velocity vectors has the effect of making vectors with high velocity magnitude appear larger. These figures demonstrate that the model is capable of sustaining in a stable manner in such flow conditions.

These figures show the buildup of circulating eddies under the influence of time varying winds. A comparison between Figure 4.10 and Figure 4.5 shows that the flow in deeper waters is topographically controlled.

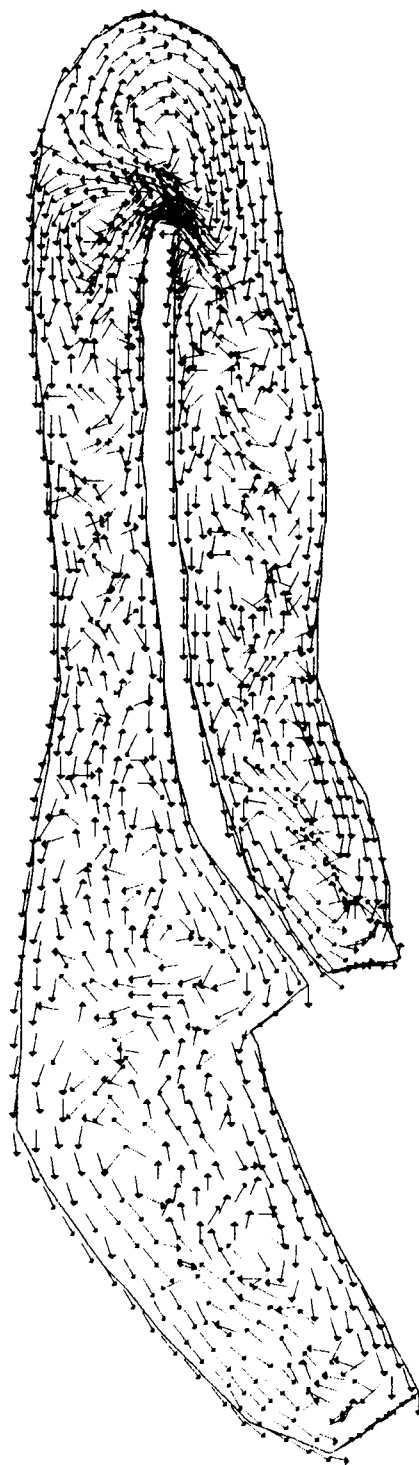
Figure 4.10 (a) presents the circulation pattern in day one under south wind with magnitude of 2.85 m/s. Eight obvious eddy currents are generated at deep spots of the cooling pond. Winds to the south move water toward the bending region of the cooling pond along the coast. There, a very strong coastal jet and a large eddy current are generated and then force water to flow back along the central line of the cooling pond.

Figure 4.10 (b) to (k) continuously describe the flow circulation patterns after 8, 16, 24, 32, 40, 56, 72, 88, 112, and 120 days. Due to the different wind loads, each figure presents its unique pattern.



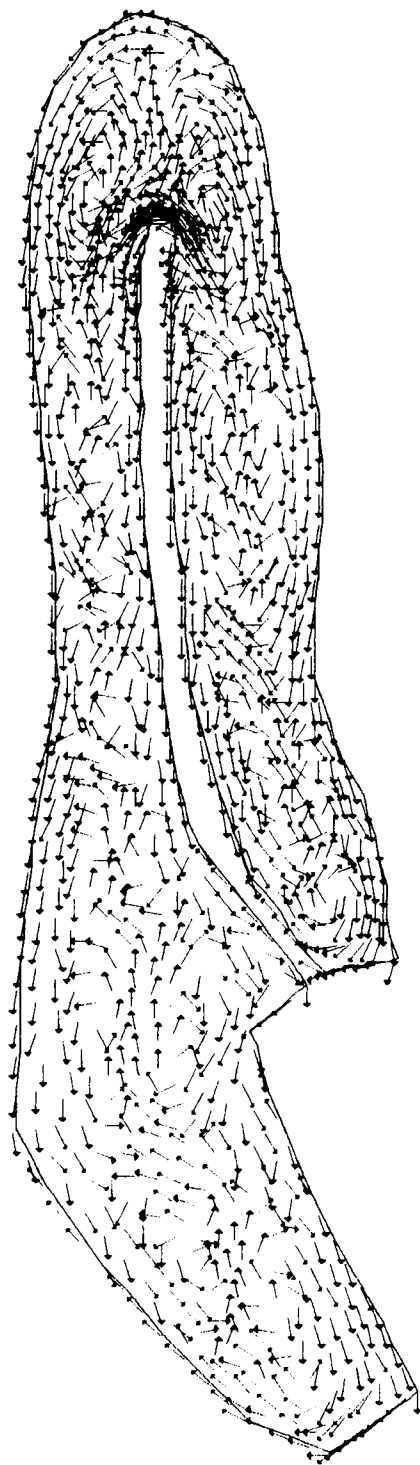
(a) Day 1, Wind Speed = 2.85 m/s, Wind Direction = 330°

Figure 4.10 Current Distributions in the Cooling Lake under Different Wind Loads after 1, 8, 16, 24, 32, 40, 56, 72, 88, 112, and 120 Days



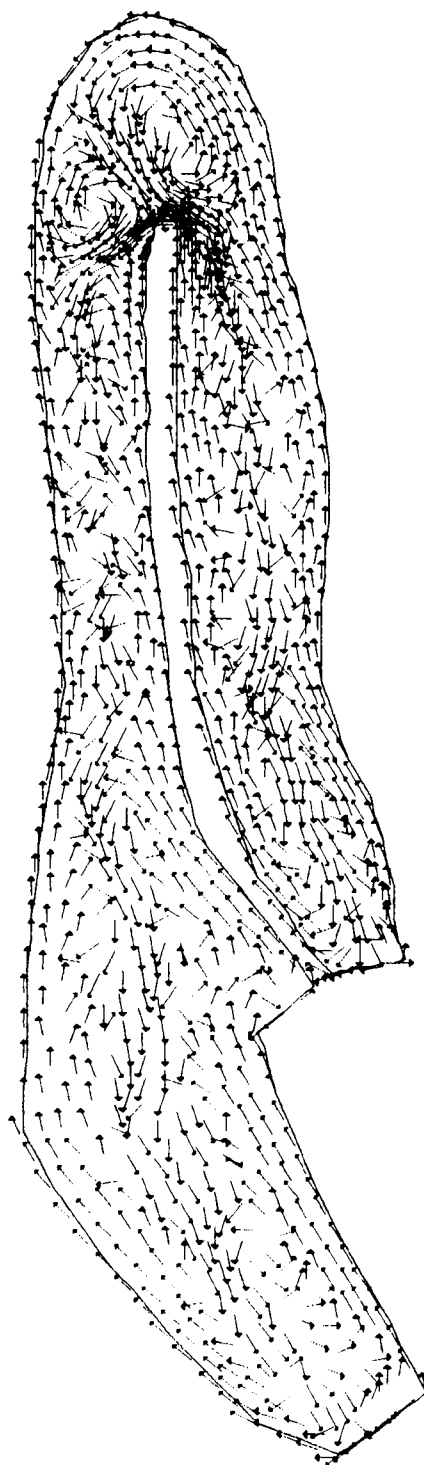
(b) Day 8, Wind Speed = 3.51 m/sec, Wind Direction = 240°

Figure 4.10 (continued)



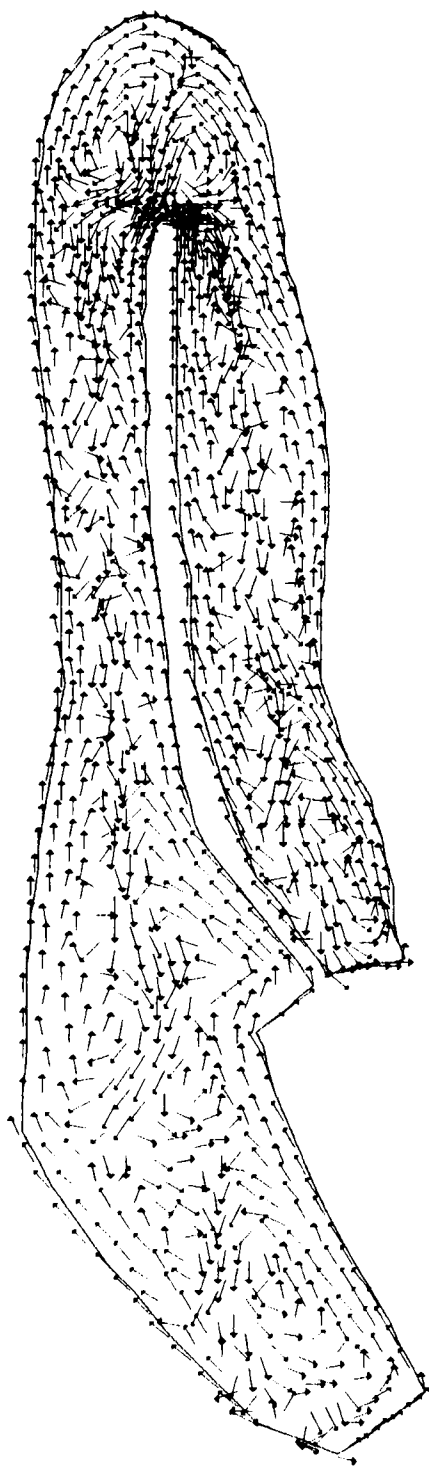
(c) Day 16, Wind Speed = 3.51 m/sec, Wind Direction = 105°

Figure 4.10 (continued)



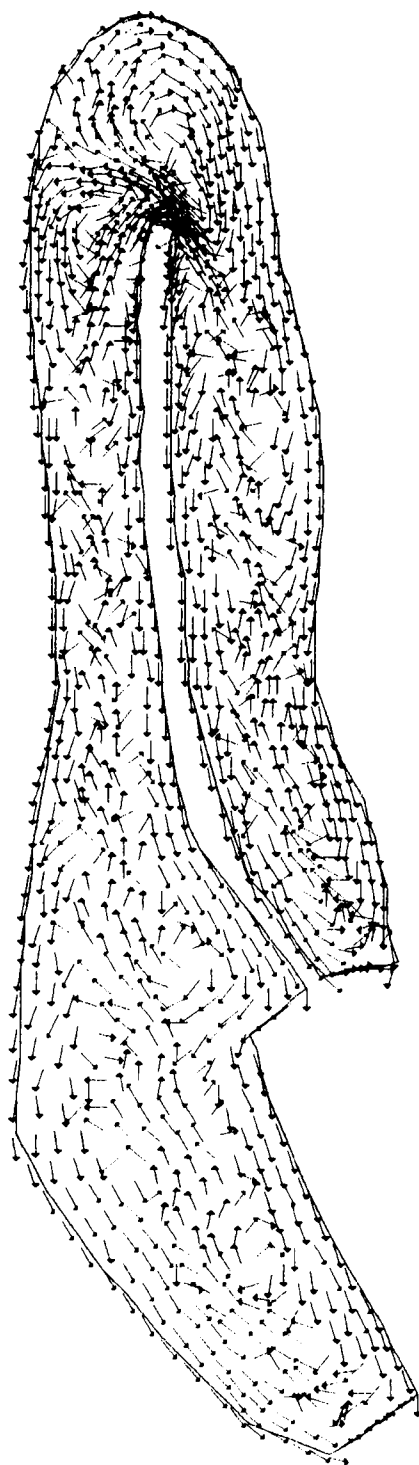
(d) Day 24, Wind Speed = 5.05 m/sec, Wind Direction = 60°

Figure 4.10 (continued)



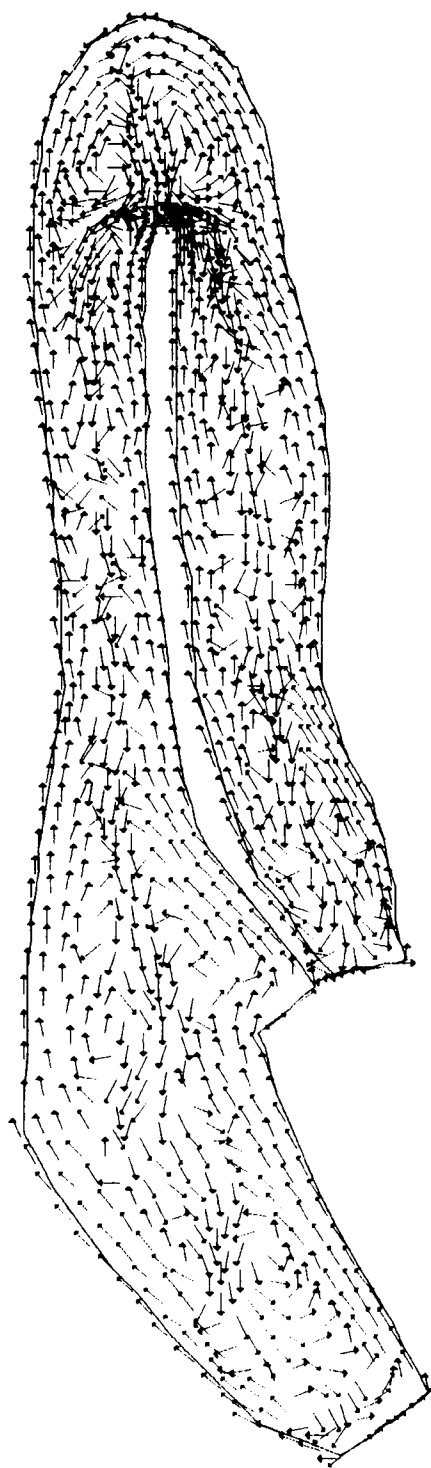
(e) Day 32, Wind Speed = 3.276 m/sec, Wind Direction = 330°

Figure 4.10 (continued)



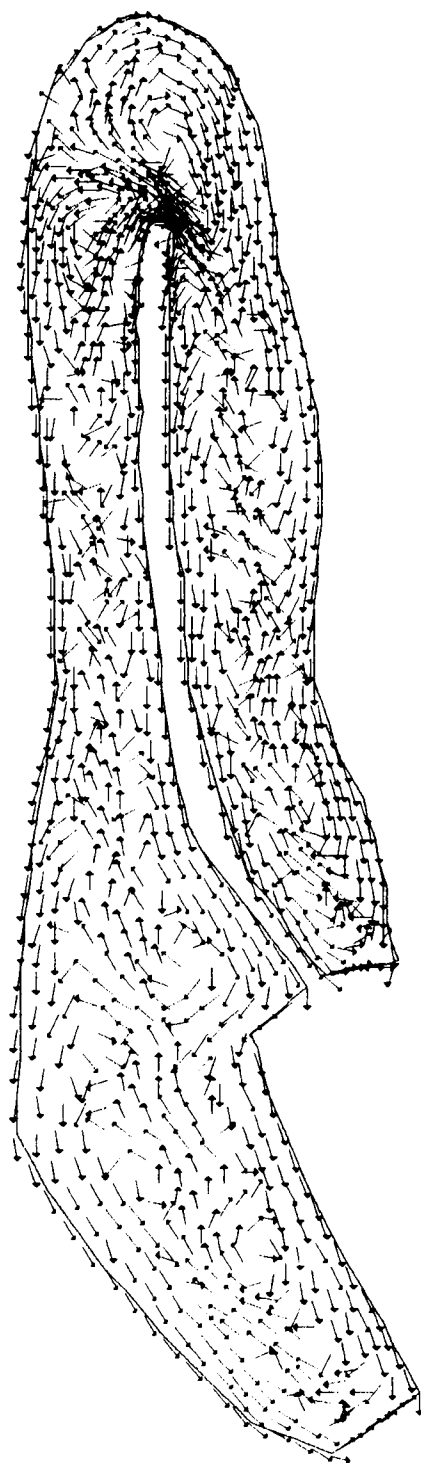
(f) Day 40, Wind Speed = 4.563 m/sec, Wind Direction = 240°

Figure 4.10 (continued)



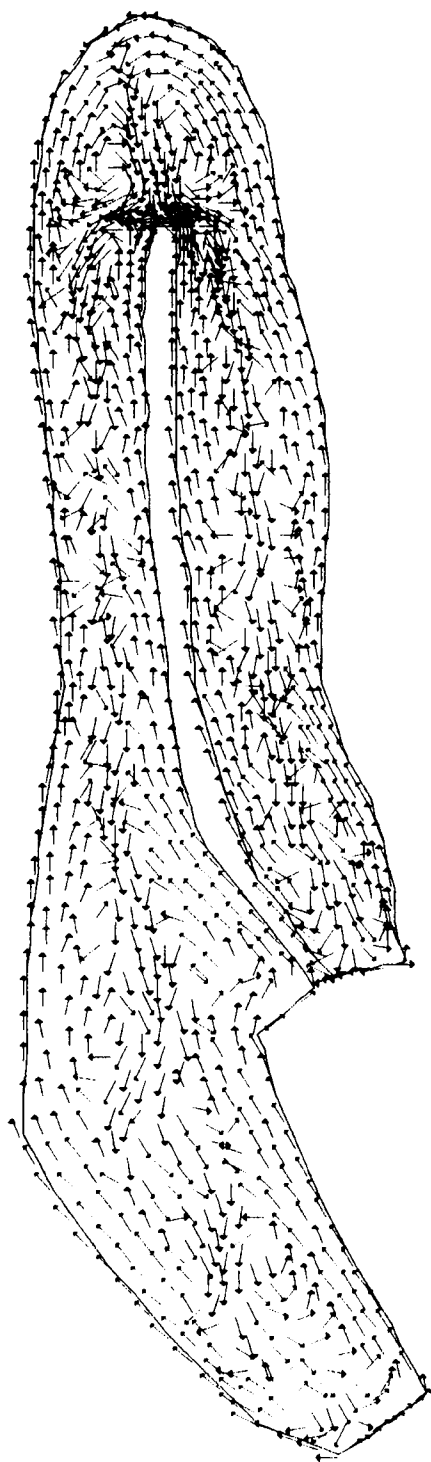
(g) Day 56, Wind Speed = 2.554 m/sec, Wind Direction = 20°

Figure 4.10 (continued)



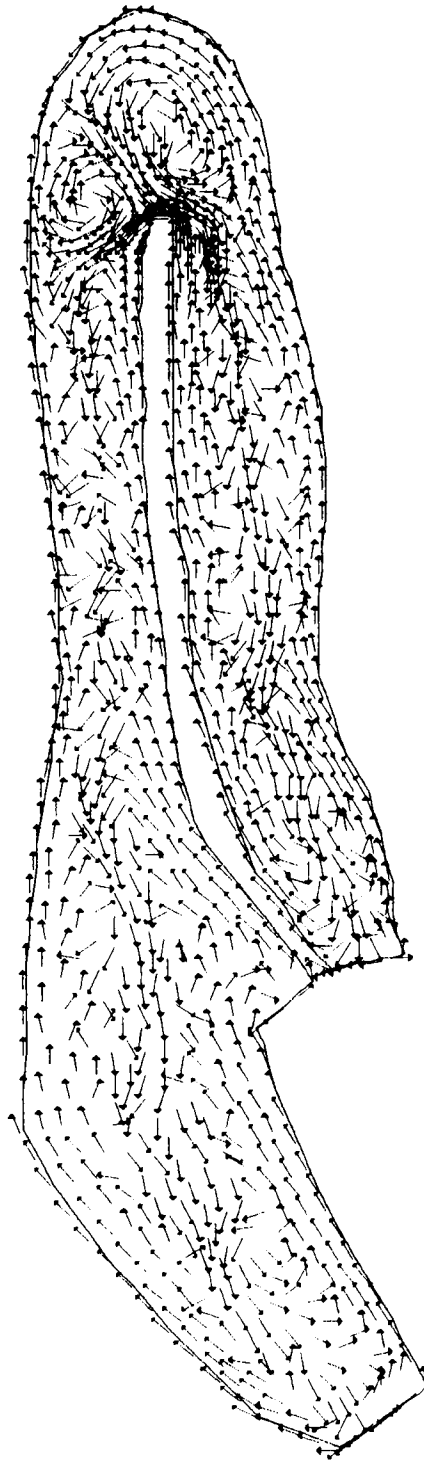
(h) Day 72, Wind Speed = 4.4895 m/sec, Wind Direction = 240°

Figure 4.10 (continued)



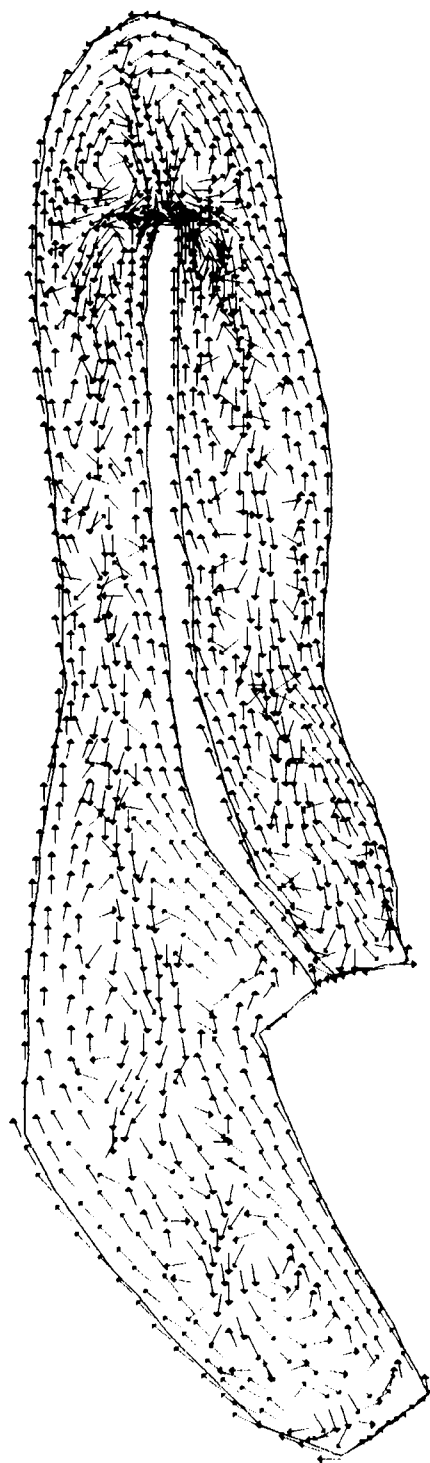
(i) Day 88, Wind Speed = 2.707 m/sec, Wind Direction = 20°

Figure 4.10 (continued)



(j) Day 112, Wind Speed = 3.2945 m/sec, Wind Direction = 60°

Figure 4.10 (continued)



(k) Day 120, Wind Speed = 2.862 m/sec, Wind Direction = 20°

Figure 4.10 (continued)

To reflect the variation of the computed velocity magnitudes at each node, time history data over a range of period are compiled in the plot forms. Total 16 nodes data from three regions are selected for the illustration. The locations of 16 nodes in the cooling pond are shown in Figure 4.11. Ten nodes are basically selected along the central line of the cooling pond, while the other 6 nodes are near the coast of the cooling pond. The same sixteen nodes will be used to study the contaminant concentrations in Section 4.3. The time history plots of the flow velocity magnitude at four locations are displayed in Figure 4.12. The range of the computed velocity magnitudes is from 0.002 to 0.025 m/s.

The calculated flow field patterns and velocities for 1321 nodes are saved for the contaminant transport modeling in Section 4.3 as the advection coefficients.

4.3 Calculation of Cs-137 Concentration Using Transport Model

Once the flow field is determined, the distribution of the contaminant concentration in a two-dimensional space is calculated using a contaminant transport model (RMA4 of TABS).

4.3.1 Preparation and Calculation

Preparation and carrying out of the calculations can be broken down into the following steps: (1) preparing initial concentration file, (2) determining diffusion coefficients, (3) determining source/sink terms, and (4) conducting calculation.

Initial concentration

As discussed in Section 4.1.3, the cooling pond can be initially divided into approximately three regions by different levels of Cs-137 contamination. The initial

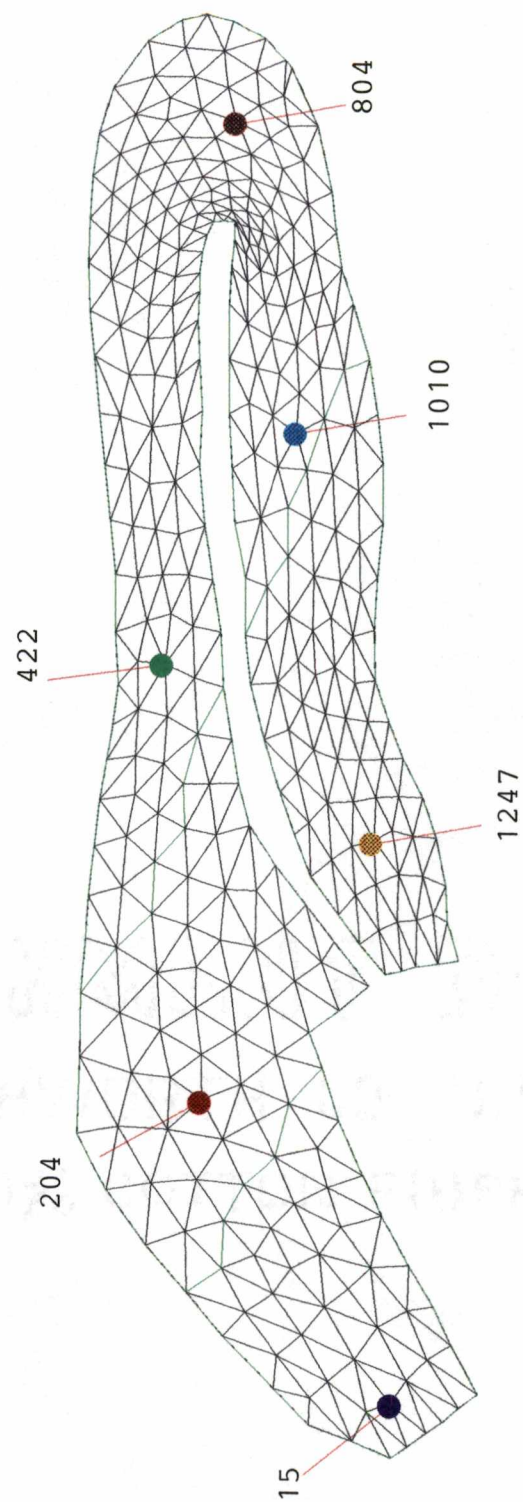
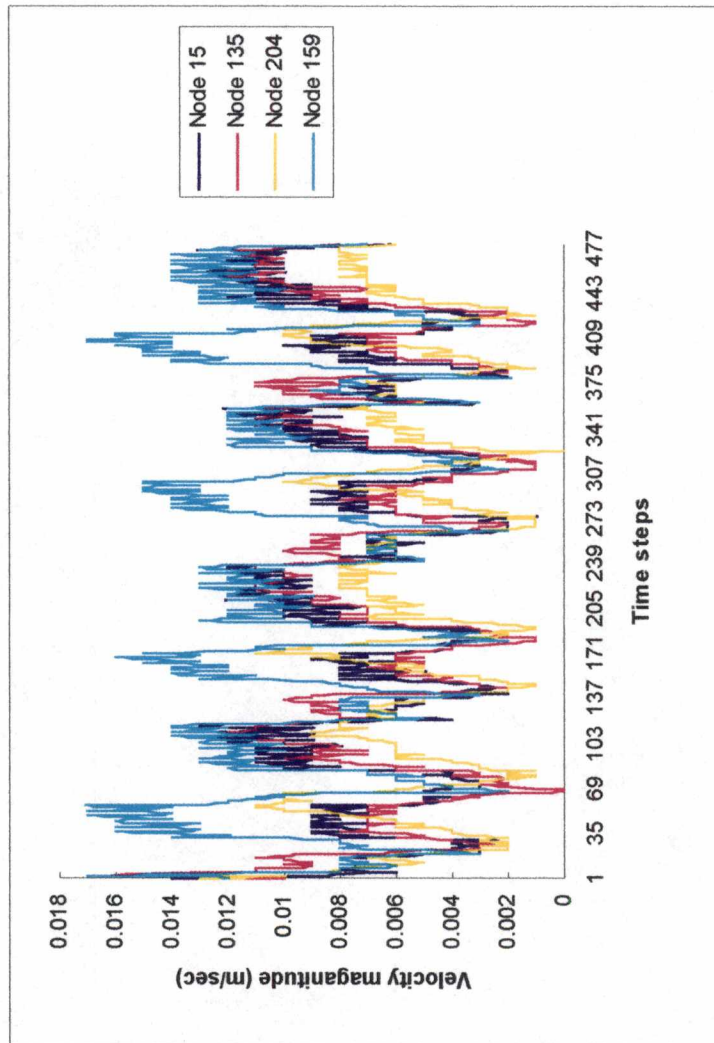


Figure 4.11 Locations of Selected Nodes for Time History Display



at Nodes 15, 135, 204, and 159

Figure 4.12 Time History Plots of Velocity Magnitudes at Selected Nodes

concentration distributions are incorporated with the generated element mesh of the cooling pond, as shown in Figure 4.13.

Eddy diffusion coefficient

As discussed in Equation (2.18), two eddy diffusion coefficients in x and y directions are required to account for the dissipation of the contaminant by the turbulent flow. Table 4.9 presents a range of diffusion coefficients under various environments. A generic value of $10^3 \text{ cm}^2/\text{sec}$ is selected for the cooling pond modeling.

Source/sink terms

The source term can be ignored for the cooling pond modeling since there is no direct discharge to the pond after the initial deposition, and meanwhile the pond is a self-contained water system with no inflow or outflow during the simulation period. However, the sink term is necessary for modeling the fate of the contaminant in the pond. Sink describes the physical processes taking place within the water system, which in turn reduce the concentration in it. Sedimentation is the major sink term for the concentration in the cooling pond.

Sedimentation is understood as the transport of particulate matter to the sediment from the water phase, and is described by the sedimentation rate (cm/year). Sedimentation rates depend on the difference in density between the suspended particle and the water, the size and shape of the particle, the water depth, and the turbulence of the field (Covenzen, 1974; Hayter, 1989; Krone, 1977). Most of the time, the range of the sedimentation rate is determined by field experiments (Bedford, 1987). The range of sedimentation rates for Cs-137 in the cooling pond is 0.4 to 2 cm/year (BIOMOVs, 1993). The loss rate due to sink is normally determined by sedimentation rate and mean

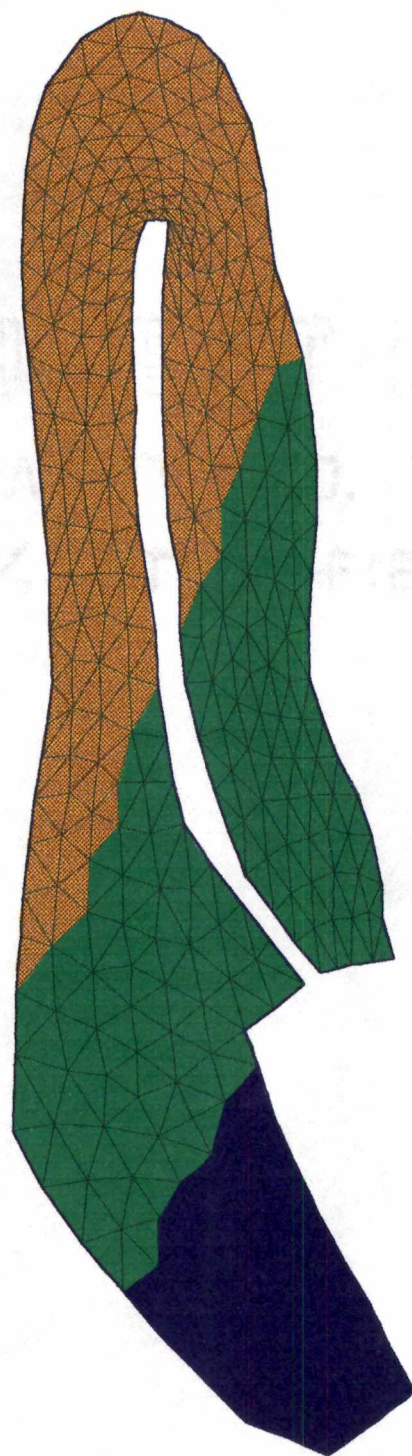


Figure 4.13 Initial Cs-137 Concentration Distributions in the Chernobyl Cooling Lake

depth of water. The estimated value of 10^{-4} d^{-1} is selected for the cooling pond computation. This rate is integrated into Equation (2.18) which is the transport governing equation.

Table 4.9 Diffusion Coefficients Characteristic of Various Environments
(Zison, et.al., 1978; Lerman, 1971)

Diffusion type	Environments	Diffusion value (cm^2/sec)
Eddy diffusion	Horizontal, surface waters	$10^2 — 10^6$
Eddy diffusion	Vertical, thermocline and deeper regions in lakes and oceans	$10^{-2} — 10$
Molecular diffusion	Salts and gases in H_2O	$5 \times 10^{-6} — 10^{-4}$
Molecular diffusion	Ionic solutes in porous media (sediments, soils)	$10^{-10} — 10^{-5}$
Thermal diffusion	Salts in H_2O	$10^{-9} — 8 \times 10^{-7}$

The computational time step for transport modeling should be the same as that for the hydrodynamic modeling, which is 6 hours. However, contaminant transport solution time step can be different from that of the hydrodynamic modeling. Since daily concentration distribution change is the interest of this study, the time step for the concentration solution file will be 24 hours.

4.3.2 Results and Discussions

Concentration distribution contours in a two-dimensional space are generated for the period of 120 days. Figures 4.14 (a) to (k) present the compiled concentration contours and illustrate the transport trend with the water movement after 1, 8, 16, 24, 32, 40, 56, 72, 88, 112, and 120 days. The corresponding water circulation patterns have been displayed in Figure 4.10 (a) to (k). Several observations can be made with respect to these figures:

(a) Day 1

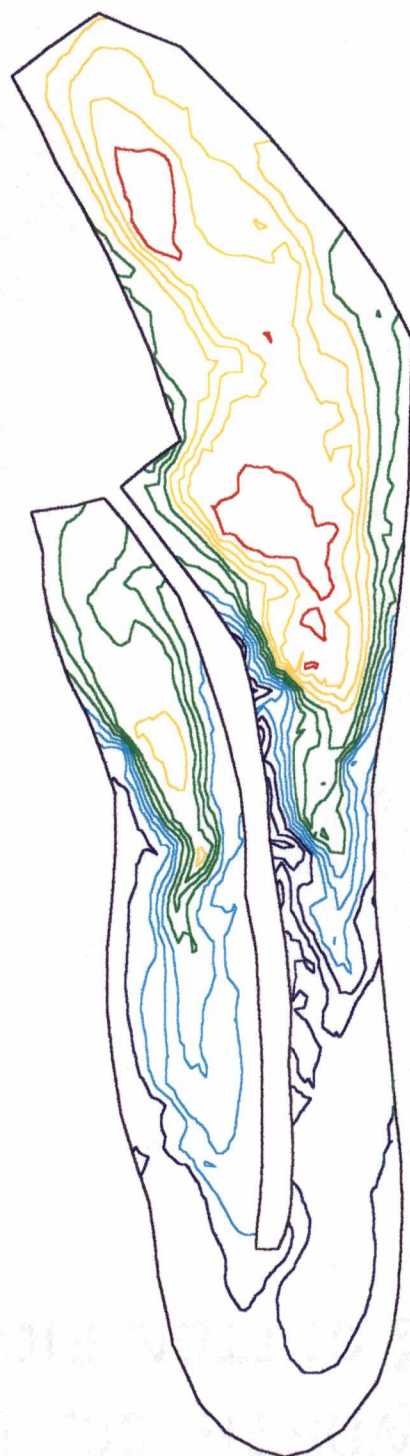


Figure 4.14 Computed Cs-137 Concentration Contour in the Chernobyl Cooling Lake after 1, 8, 16, 24, 32, 40, 56, 72, 88, 112, and 120 Days



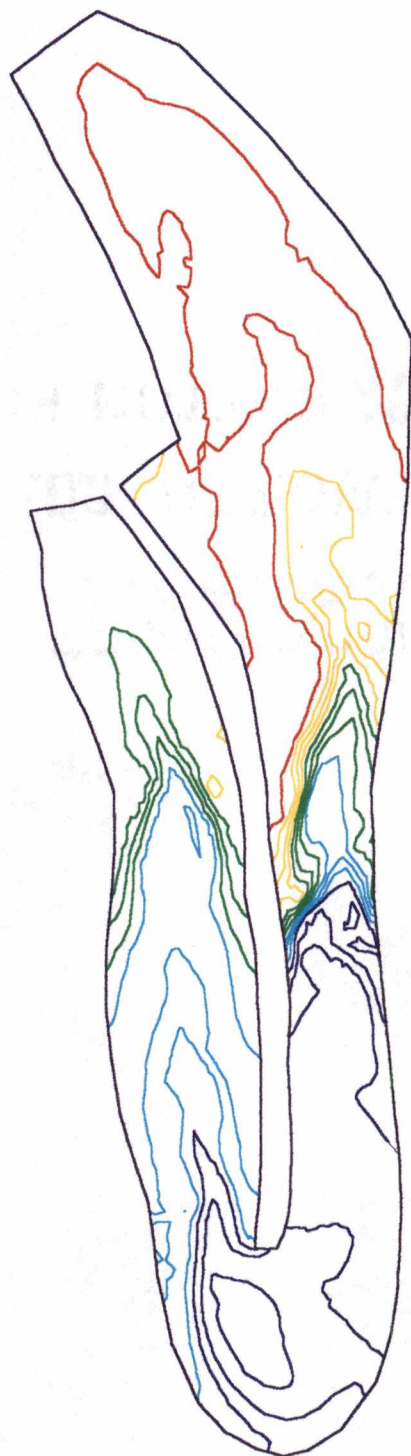
(b) Day 8

Figure 4.14 (continued)



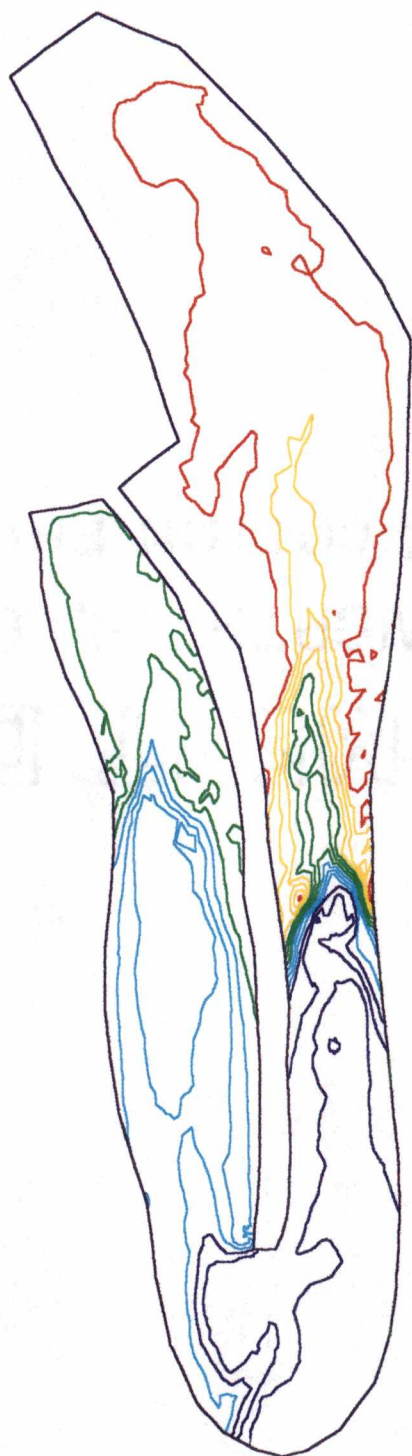
(c) Day 16

Figure 4.14 (continued)



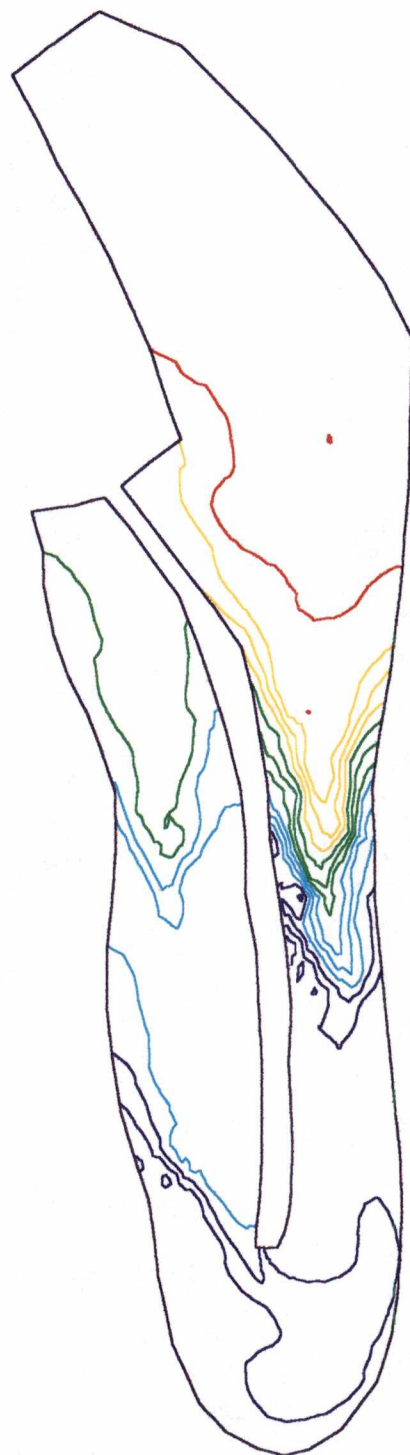
(d) Day 24

Figure 4.14 (continued)



(e) Day 32

Figure 4.14 (continued)



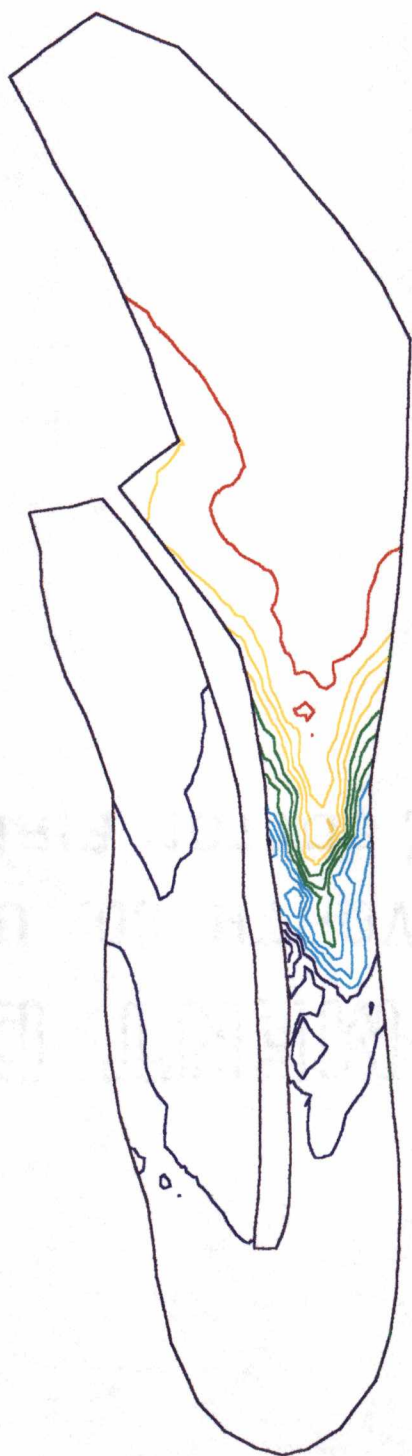
(f) Day 40

Figure 4.14 (continued)



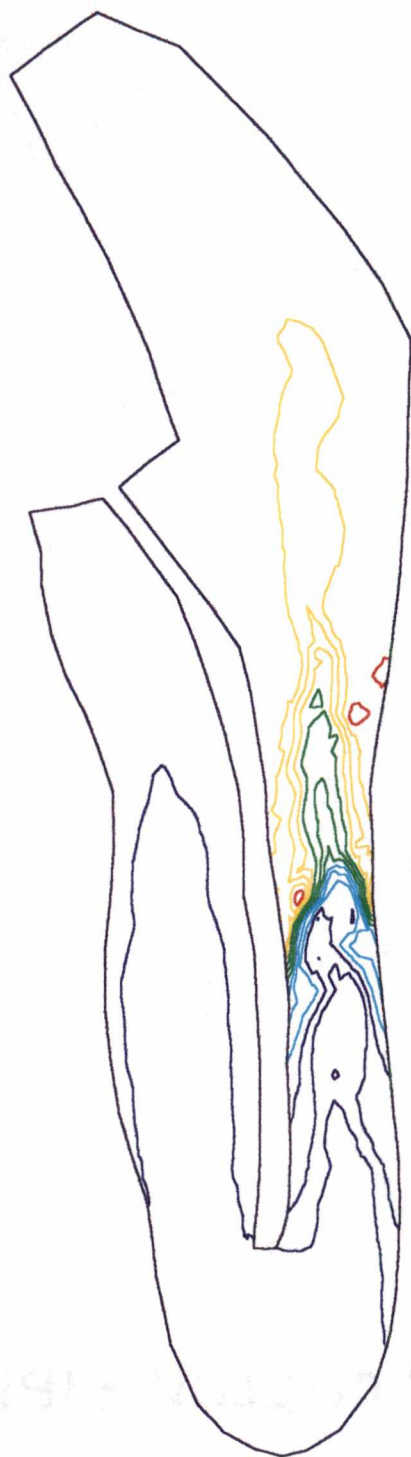
(g) Day 56

Figure 4.14 (continued)



(h) Day 72

Figure 4.14 (continued)



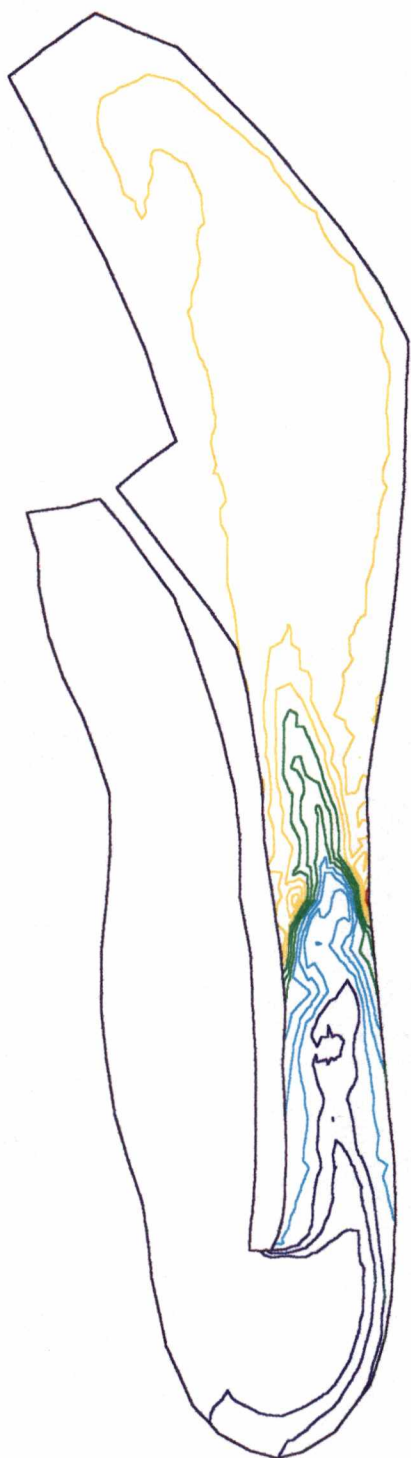
(i) Day 88

Figure 4.14 (continued)



(j) Day 112

Figure 4.14 (continued)



(k) Day 120

Figure 4.14 (continued)

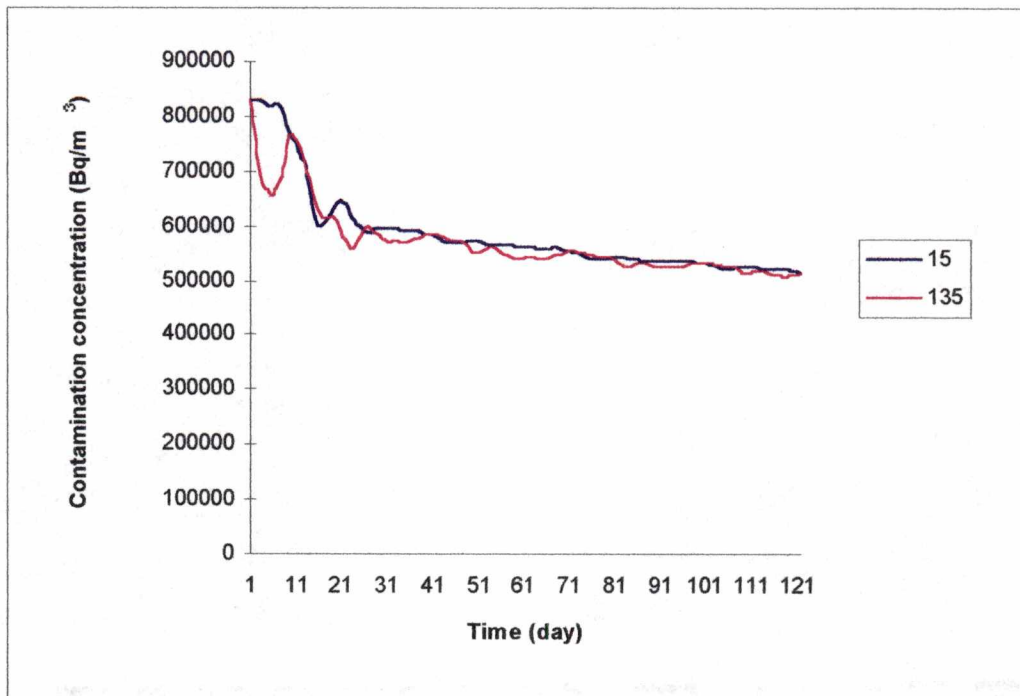
- The figures illustrate the development of the transport process following the computed velocity fields for 120 days.
- After the first day, the initial concentration is slightly dispersed. At this time, convection dominates the transport pattern. Three initial contaminated regions are still clearly visible and the maximum concentration value is still about 830 kBq/m³ in the upper north end of the cooling pond.
- Comparing concentration contours in Figure 4.14 (a) with velocity field in Figure 4.10 (a), the advection effects on the contaminant dispersion on the first day is displayed. For example, the contaminant along the central line of the cooling pond starts to move by following the flow direction which is toward to the northwest end of the cooling pond.
- Concentration distributions after 16, 24, 32, 40, 56, 72, and 88 days are shown in Figure 4.14 (c) to (i). These figures display the development of distribution patterns as a function of the time elapsed since the start of the computation. Comparing concentration contours in Figure 4.14 (c) to (i) with velocity field in Figure 4.10 (c) to (i) provides a good indication of the long-term effects of the wind-induced circulation and the turbulent diffusion on the resulted highly variable concentration distributions. The initial highest concentration in the upper north end of the cooling pond gradually decreases from 830 kBq/m³ to 600 kBq/m³.
- After 88 days, the concentration distribution obviously tends to be homogeneous (or less heterogeneous), as shown in Figure 4.14 (j) and (k). However, lake-wide total homogeneity of the contaminant distribution is still not established at the end of the computation (or the end of September). At the time, two distinctive concentration regions in the cooling pond are established with the maximum

concentration of 540 kBq/m^3 in the upper region of the cooling pond and the minimum concentration of 300 kBq/m^3 in the lower region. This observed phenomenon is due to the geometry shape of the cooling pond. The bending region of the cooling pond actually makes the total mixing difficult.

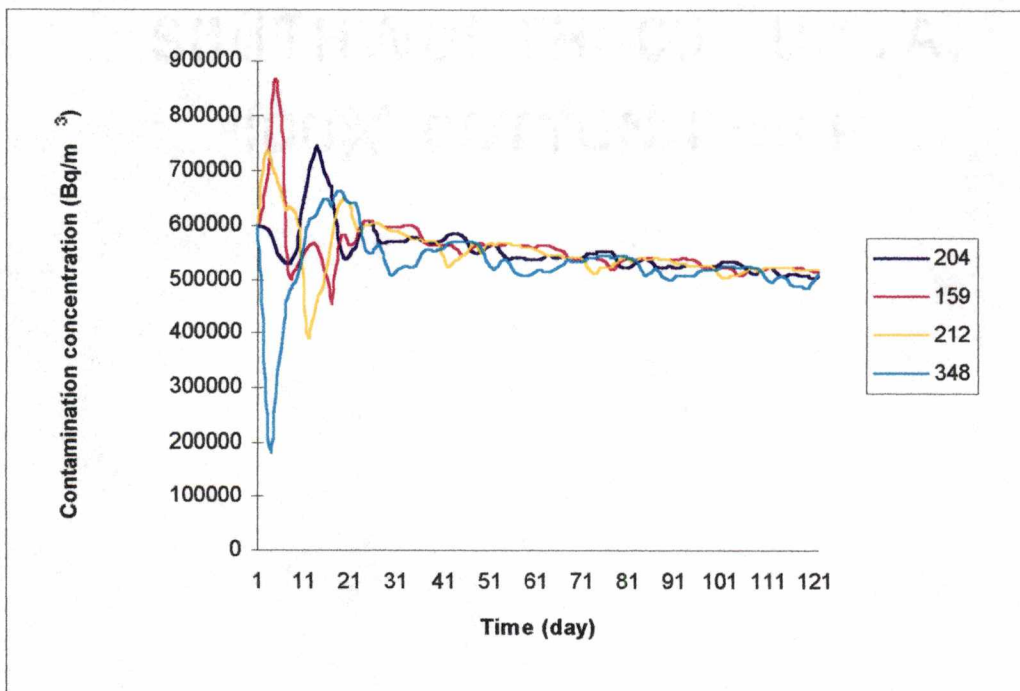
Time history plots for sixteen nodes are presented to display the concentration variation in each specified location, shown in Figure 4.15 (a) to (d). The selected sixteen nodes are in the same locations as that selected for displaying velocity magnitude in Figure 4.11.

Figure 4.15 (a) presents the concentration changes as a function of time for selected nodes located in region I. It is obvious that the initial highest concentration decreases since the start of the computation.

Figures 4.15 (b) and (c) show the concentration change patterns at the nodes located in region II, which was initially less contaminated comparing with region I. Large concentration fluctuations occur at several locations which are near the cutting edges among three regions for the early period since the start of the computation. For example, the concentration at node 1076 dramatically decreases in the early time since node 1076 is located in the region II but near the cutting edge between regions II and III. Region II initially has a concentration of 600 kBq/m^3 , while region III has the lowest initial concentration of 45 kBq/m^3 . During early several days since water flows from region III to region II through node 1076, in turn, the region III concentration flows through node 1076. Later on, water flows in a reverse direction, then the concentration at node 1076 increases. Generally, the concentrations in the upper part of region II (Figure 4.15 (b)) tend to reach the concentration level of 540 kBq/m^3 and the concentrations in the lower part of the region II approach the concentration level of 320 kBq/m^3 at the end of the computation.

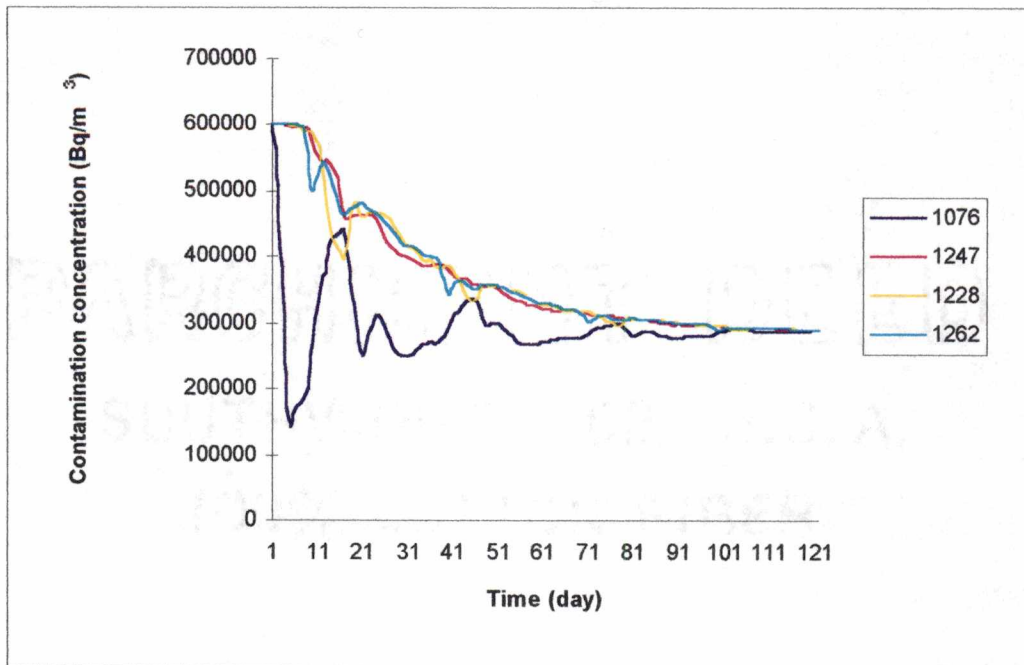


(a) Region I

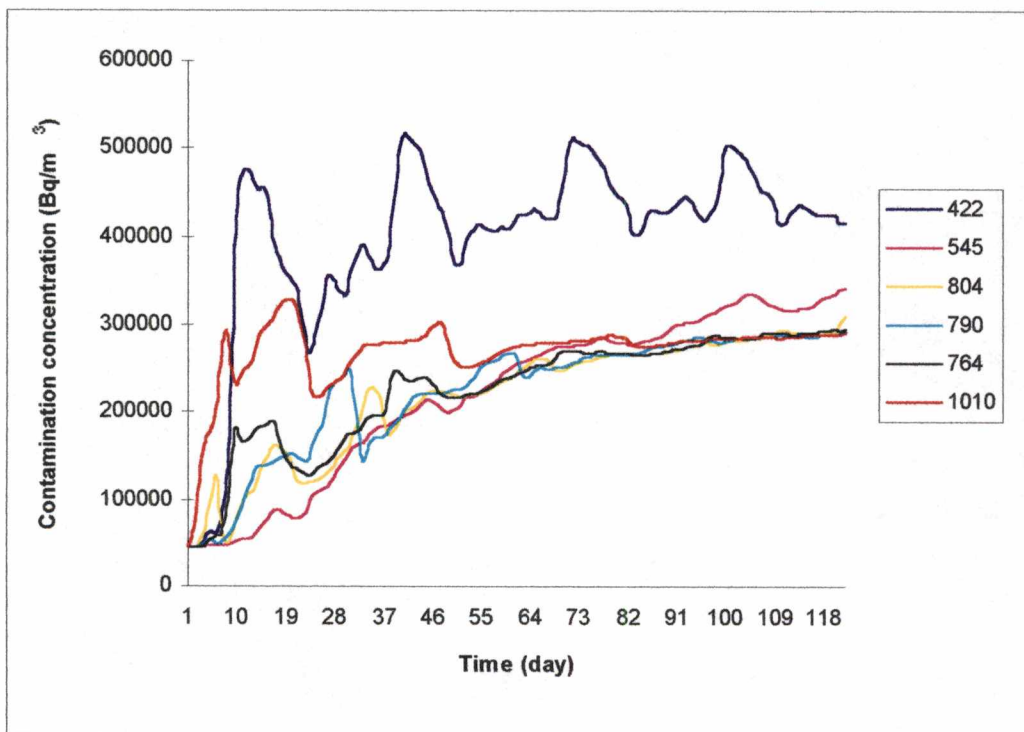


(b) Region II (Upper)

Figure 4.15 Time Histroy Plots of Cs-137 Concentration at Selected Nodes



(c) Region II (Lower)



(d) Region III

Figure 4.15 (Continued)

Figure 4.15 (d) shows the concentration changes in region III. All concentrations at selected locations increase toward to the level of 300 kBq/m^3 .

The concentration information at the selected six locations are saved for use in the exposure study in Chapter 5.

CHAPTER 5

RADIOECOLOGICAL EXPOSURE STUDY

This chapter presents the exposure modeling process for the Chernobyl cooling pond using the framework presented in Chapter 3. First, a general introduction is provided for the Chernobyl cooling pond ecosystem. Next, an outline regarding the categorization of the cases under different exposure conditions is presented. This is followed by a detailed simulation process for each case, analysis of results and discussions, and summary.

5.1 Introduction of Chernobyl Cooling Pond Ecosystem

The Chernobyl cooling pond served as a recreational lake for fishing before the accident and as a habitat for more than 700 species, which included 500 algae species and over 20 fish species. The nonpredator fish (prey-fish) include carp, silver bream, bream, silver carp, roach, and goldfish. The predator fish include pike perch, pike, and perch (BIOMOVs, 1993). Each year, there are about 2100,000 kg of total biomass production (BIOMOVs, 1993). Table 5.1 lists the annual averaged biomass and biomass densities for four populations (phytoplankton, zooplankton, prey-fish, and pred-fish) in the cooling pond. The cooling pond can be classified as slightly or moderately polluted with respect to the organic matter and is heavily polluted with respect to nitrogen.(Kryshev et al., 1992).

Table 5.1 Annual Averaged Biomass and Biomass Density in the Chernobyl Cooling Pond

Population	Biomass (kg)	Biomass Density (kg/m ³)
Phytoplankton	1000x10 ³	6.67x10 ⁻³
Zooplankton	270x10 ³	1.8x10 ⁻³
Non-predatory fish	50x10 ³	3.3x10 ⁻⁴
Predatory fish	10x10 ³	6.67x10 ⁻⁵

5.2 Categorization of Simulation Cases

As stated in Chapter 1, the principal objectives of this research include (1) to examine the effects of temporal and spatial heterogeneity on the radioecological exposure assessment; (2) to investigate the impacts of incorporating the temporal and spatial-dependent ecological processes into the radioecological exposure assessment model.

One way to examine the spatial and temporal heterogeneity effects on radionuclide accumulation is to successively add more spatial and temporal details into the model simulation. By comparing the results of simulations with and without spatial and temporal details, their effects and significance on the exposure to biota can be evaluated.

By examining the relative changes of various modeled results with and without one specific function, its impacts can be revealed. As discussed in Chapter 3, the temporal and spatial-dependent population biomass changes and radionuclide ingestion rates will be incorporated into the exposure model in this study. Also, the effects of different food web structures on predator exposures are studied.

Based on the above two approaches, a total of seven simulation cases that represent different exposure conditions are considered. The seven cases are listed in Table 5.2 and explained as follows.

Table 5.2 Categorization of Simulation Cases based on Spatial and Temporal Details and on Spatial and Temporal-dependent Ecological Functions

Cases	Temporal	Spatial	Population biomass	Radionuclide ingestion rates	Multi-prey food web structure
Case 1	x	x	x	x	x
Case 2	✓	x	x	x	x
Case 3	✓	x	✓	x	x
Case 4	✓	✓	x	x	x
Case 5	✓	✓	✓	x	x
Case 6	✓	✓	✓	✓	x
Case 7	✓	✓	✓	✓	✓

where

x: without this function or effect in the modeling; and

✓: with this function or effect in the modeling;

Case 1: homogeneous and steady-state radioactive environment;

Case 2: homogeneous and dynamic radioactive environment;

Case 3: homogeneous and dynamic radioactive environment with the consideration of constant population biomass;

Case 4: heterogeneous and dynamic radioactive environment. The radionuclide distributions in the cooling pond were calculated using a hydrodynamic and transport model in Chapter 4;

- Case 5: heterogeneous and dynamic radioactive environment with the consideration of population biomass changes;
- Case 6: heterogeneous and dynamic radioactive environment with the consideration of population biomass changes and variable radionuclide ingestion rates; and
- Case 7: same as the case 6 except a multi-prey food web structure used in this case instead of a single prey food web structure in study of bioaccumulation in pred-fish.

5.3 Case Simulations

5.3.1 Homogeneous and Steady-state (Case 1)

The homogeneous and steady-state exposure modeling for four populations is described by Equation (3.11). To solve this equation, the following data are necessary: the lake-wide averaged concentration of Cs-137 in water (C_w) which is 4×10^5 Bq/m³, uptake rates from water (k_{ui}), ingestion rates from food (k_{fi}) and biological elimination rates (k_{bi}). The previous studies of those parameters for the Chernobyl cooling pond are limited or lack details for this level of modeling; thus, parameter values were chosen based on applicable literature surveys.

Radionuclide ingestion rates are calculated using Equation (3.21), and the averaged biomass densities of prey and predators are listed in Table 5.1. Temperature is assumed at 20°C. The maximum consumption rates (C_m) are taken from Bartell (1992). Temperature dependence factor ($h(T)$) is set to one. Assimilation efficiency of the prey by the predator is set equal to 0.8 for all consumers (Bartell, 1992). Since a single-prey food web structure is used in this case, the preference coefficients (f_i) are set equal to one. The variation of the assimilation efficiency of radionuclides between different

populations could be from 10% to 80% for Cs-137 (Kolehmainen, 1972). Higher trophic level biota tend to have a higher assimilation efficiency. Therefore, assimilation efficiency for Cs-137 was set equal to 0.2 for zooplankton, 0.35 for prey-fish, and 0.6 for pred-fish. The calculated ingestion rates for three consumers are listed in Table 5.3.

Radiobiological turn-over rates of Cs-137 for four populations are estimated from their retention times in biota (Henry, 1975; King, 1964; Hasanen, 1966), which are listed in Table 5.3 (Henry, 1978). Uptake rates of Cs-137 from water for four populations are taken from Sombre (1993).

Table 5.3 Selected Parameter Values for Bioaccumulation Calculations

Populations	Uptake from water (k_{ui})	Maximum consumption (C_{mi})	Radionuclide ingestion (k_{fi})	Radiobiological elimination (k_{bi})
Phytoplankton	0.1			0.69
Zooplankton	0.008	0.6	0.07	0.14
Prey-fish	0.004	0.25	0.06	0.0069
Pred-fish	0.004	0.20	0.08	0.0069

Based on the above information, the concentrations in four populations under a homogeneous and steady-state radioactive environment are calculated and results are presented in Table 5.4. Results from Case 1 will be utilized later as reference values for comparison with the results from the six other cases in Section 5.4.

5.3.2 Homogeneous and Dynamic Radioactive Environment (Case 2)

The biota exposure modeling processes for four populations under a time-dependent and homogeneous condition are described by Equation (3.10). By assuming homogeneity, the radionuclide concentration in the water ($C_w(t)$) is a function of time

only. There are two loss mechanisms controlling the concentration change in the cooling pond water: sedimentation and radioactive decay. By solving the conservation Equation (2.1), the concentration change in water is calculated. The change is small during the simulation period of 120 days due to a small sedimentation rate (0.0001 d^{-1}) and a long decay half-life of Cs-137.

Table 5.4 Concentrations Calculated for Four Populations under a Homogeneous and Steady-state Condition (Case 1)

Populations	Concentration (Bq/kg)
Phytoplankton	57965
Zooplankton	54161
Prey-fish	689424
Pred-fish	8125000

Equation (3.11) is solved based on the calculated time-dependent radionuclide concentration in water. Results for calculated concentrations in four populations are presented in Figure 5.1. The concentrations in phytoplankton and zooplankton quickly approach the equilibrium state since the radionuclide concentration in water is stable for this case and also since radiobiological turn-over rates for both plankton are high. On the other hand, the prey- fish and pred-fish gradually accumulate the radionuclides from water and from prey with an almost linear or exponential trend because of the slow elimination rates. Fish have accumulated higher concentrations than phytoplankton and zooplankton have after 120 days.

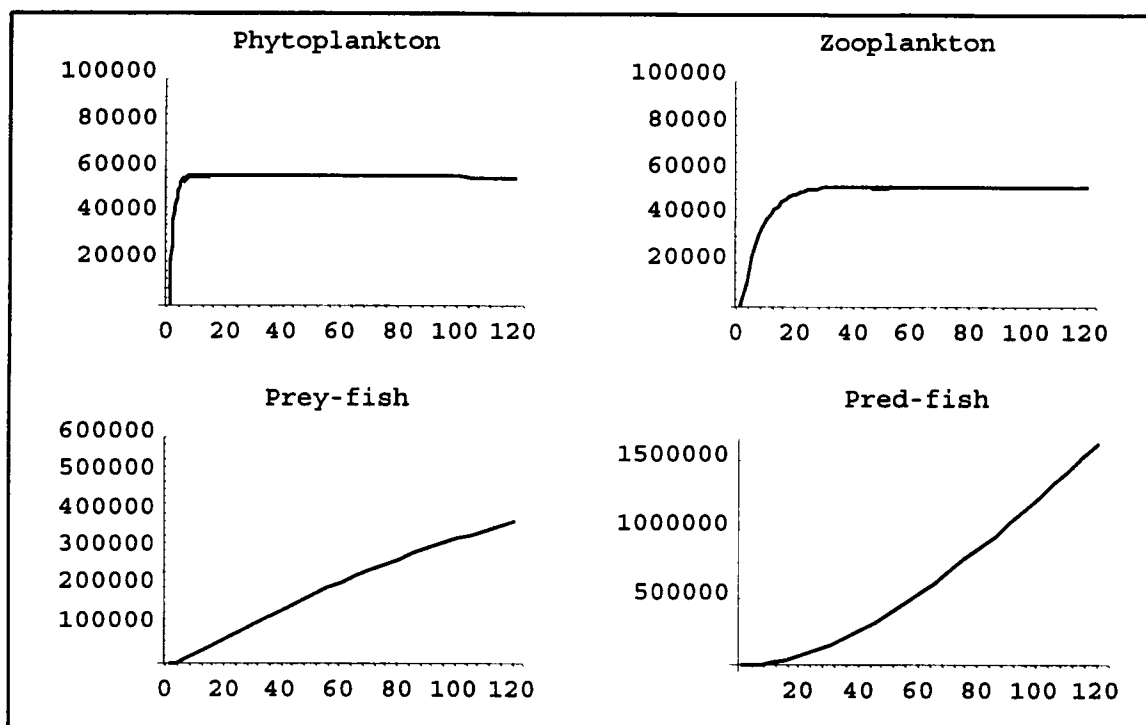


Figure 5.1 Concentrations (Bq/kg) Accumulated in Four Populations for 120 Days under a Homogeneous and Dynamic Radioactive Environment (Case 2).

5.3.3 Homogeneous and Dynamic Radioactive Environment with Population Dynamics (Case 3)

Case 3 is based on case 2 conditions, but it includes the population dynamics in the exposure model. Equation (3.9) describes the bioaccumulation process in Case 3 with interaction of populational effects through the use of the $dm_i(t)/dt m_i(t)^{-1}$ terms. Biomass density changes of the four populations due to the population dynamics are included in the model as illustrated by Equations (3.17), (3.20), (3.22), and (3.23). Net change rates (θ_i) of the four population biomass are set to 0.003, 0.002, 0.001, and 0.001 (d^{-1}) for phytoplankton, zooplankton, prey-fish, and pred-fish separately (Canale, 1976). Water circulation effects on the populational biomass distributions are eliminated by the assumption of spatial homogeneity.

Results from simulations using Equation (3.9) are shown in Figure 5.2. Comparing Figure 5.1 (Case 2) with Figure 5.2 (Case 3) shows that there is no obvious difference between the bioaccumulation patterns under these two conditions. This indicates that the changes in population biomass during 120 days are too small to result in a large change in the Cs-137 bioaccumulation under Case 3 conditions.

5.3.4 Heterogeneous and Dynamic Radioactive Environment (Case 4)

Exposure modeling for a heterogeneous radioactive environment is described by Equations (3.12), (3.13), (3.14), and (3.15). The parameters in the exposure equations have the same values as the ones used in case 1, case 2, and case 3. Since the biomass effects are not included in this case, the terms $dm_{ij}(t)/dt m_{ij}(t)^{-1}$ (i is population index and j is the location index) are set to zero. Equations are solved at selected locations, which are elements 15, 204, 422, 804, 1010, and 1247 whose locations are shown in Figure 4.8.

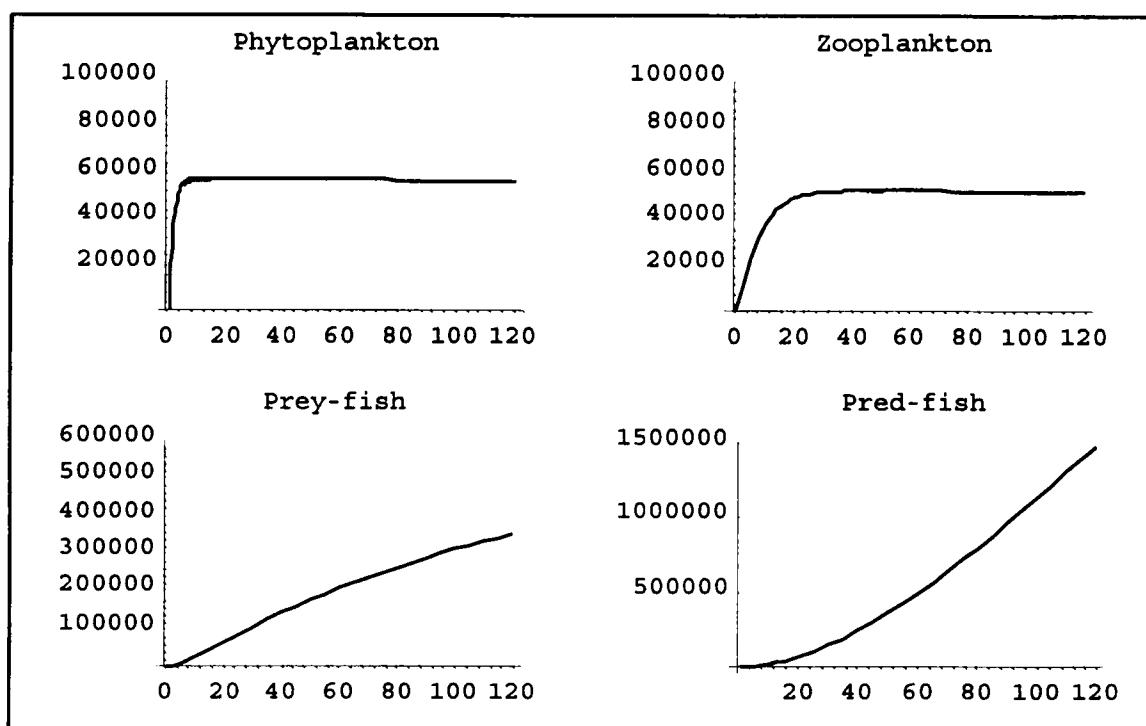


Figure 5.2 Concentrations (Bq/kg) Accumulated in Four Populations for 120 Days under a Homogeneous and Dynamic Radioactive Environment and with Biomass Effects (Case 3).

The concentrations in water for these locations are determined from a hydrodynamic and transport model described in Chapter 4. Figure 5.3 illustrates the results.

Results from the simulations using Equations (3.12), (3.13), (3.14), and (3.15) are illustrated for six locations in Figure 5.4 (a) to (f). By examining Figure 5.4 (a) to (f) and Figure 5.3, it is apparent that the bioaccumulation patterns of phytoplankton and zooplankton at six locations are largely affected by the spatial heterogeneity of concentrations in water at the same locations. For example, the temporal changes of the accumulated concentrations in element 15 are different from that in elements 422, 804, and 1010. Quantitatively, the accumulated concentration in phytoplankton and zooplankton in element 15 are 4 times higher than in element 804 during the early period of the simulation and about 2.5 times higher after 120 days of simulation. Correspondingly, the accumulated concentrations in fish in element 15 are higher resulting from the higher Cs-137 concentrations in water and in fish prey.

5.3.5 Heterogeneous and Dynamic Radioactive Environment with Biomass Terms (Case 5)

Case 5 expands on the Case 4 conditions, by retaining the spatial- and temporal-dependent biomass change terms $dm_{ij}(t)/dt/m_{ij}(t)$ in exposure Equations (3.12), (3.13), (3.14) and (3.15).

Before conducting the simulation, the biomass distributions ($m_{ij}(t)$) must be calculated. As discussed in Chapter 3, both water circulation and population dynamics may contribute to the variation of phytoplankton and zooplankton distributions. Both phytoplankton and zooplankton naturally tend to aggregate in space, but the turbulent waters mix and dissipate them (Peters, 1983; Calder 1984). In this research, it is hypothesized that both plankton are initially distributed in four regions of the cooling

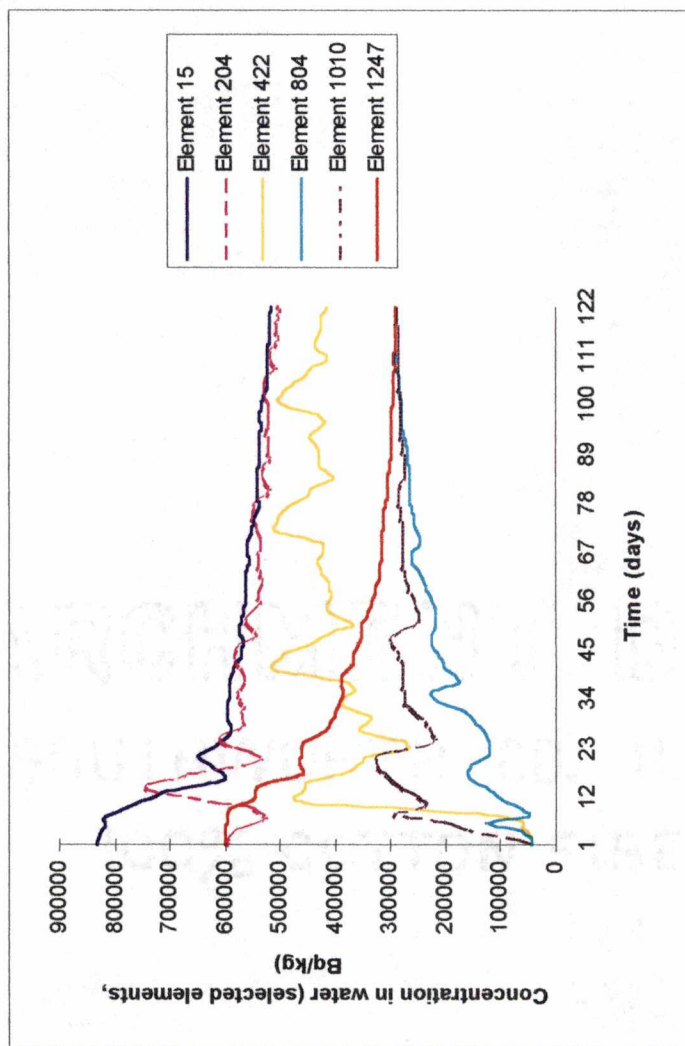
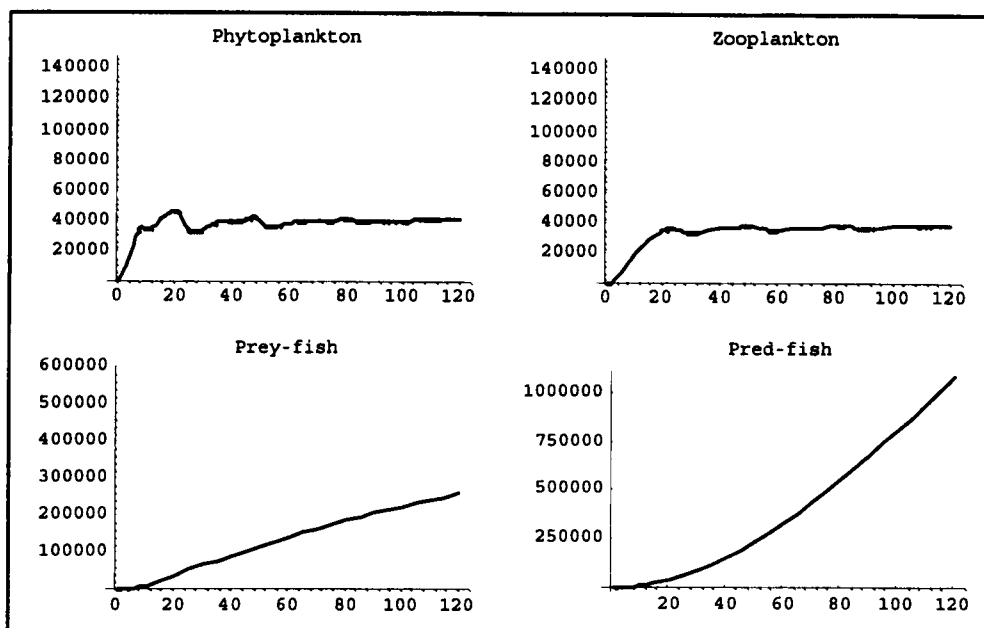
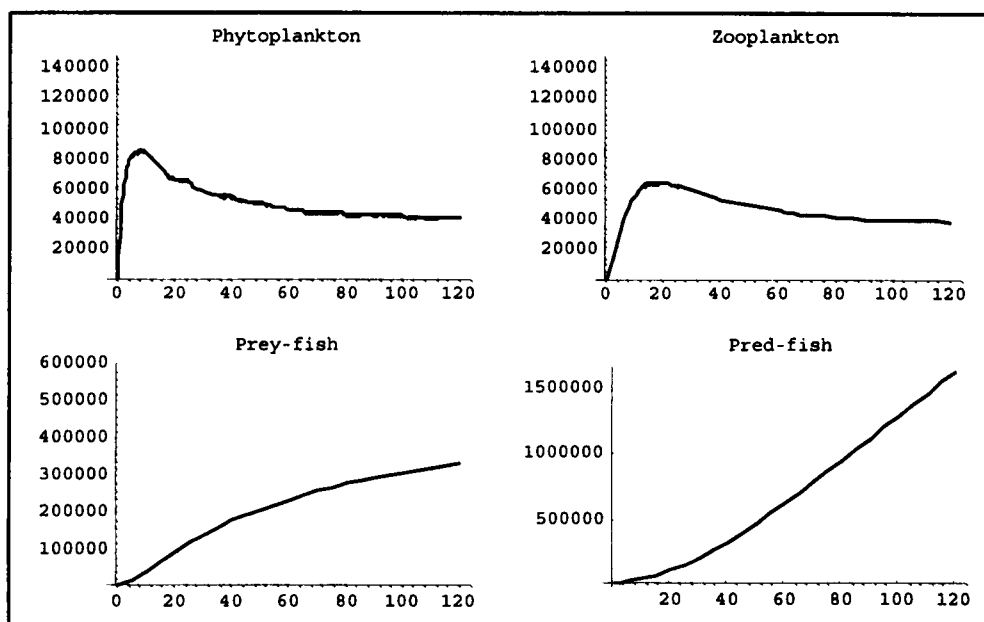


Figure 5.3 Concentrations in the Cooling Lake Water at Selected Locations

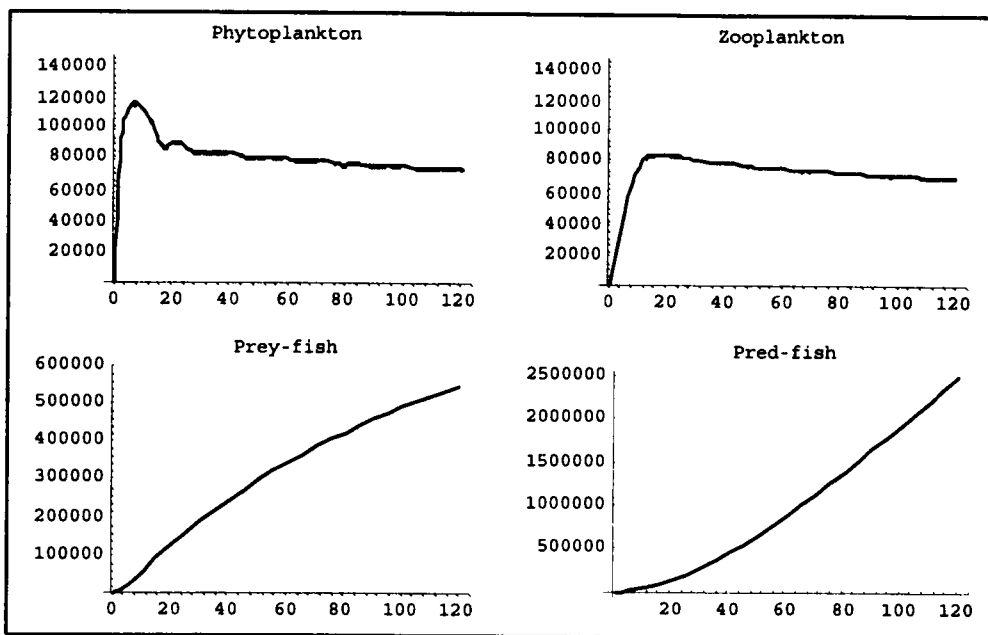


(a) Node 1010

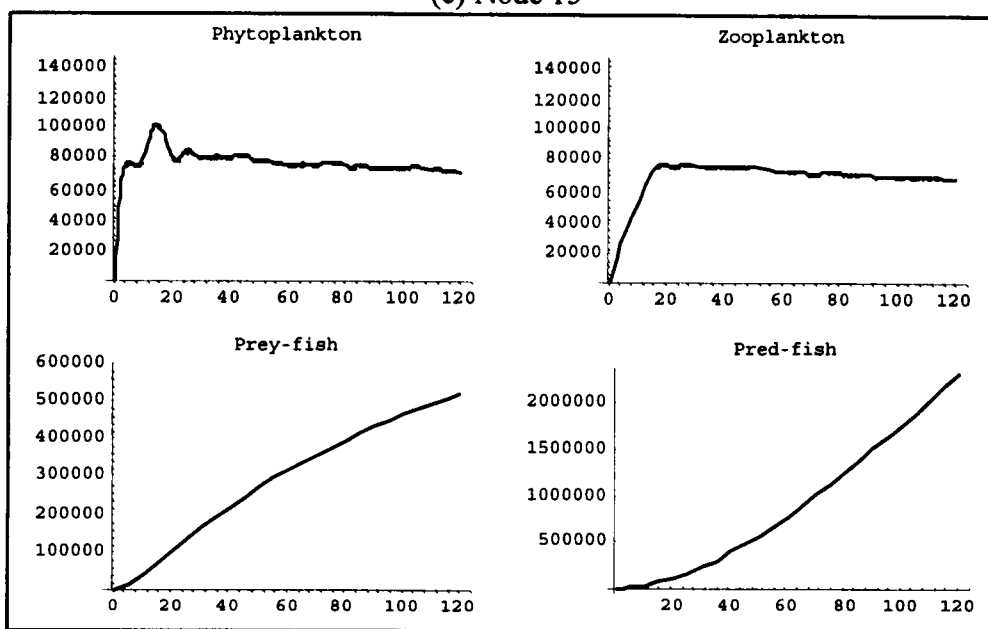


(b) Node 1247

Figure 5.4 Concentrations (Bq/kg) Accumulated in Four Populations for 120 Days under a Heterogeneous and Dynamic Radioactive Environment (Case 4)

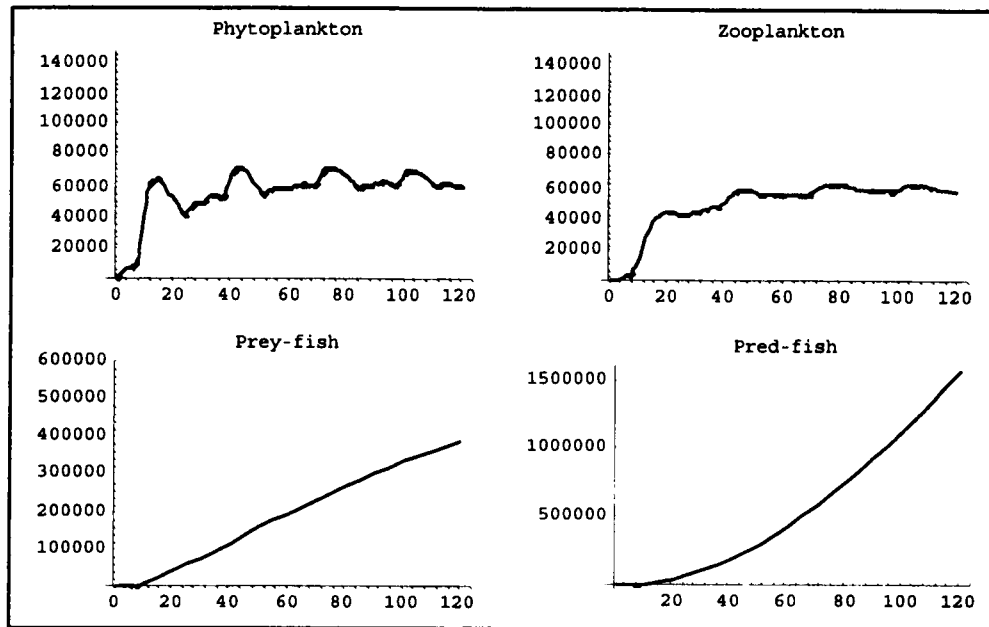


(c) Node 15

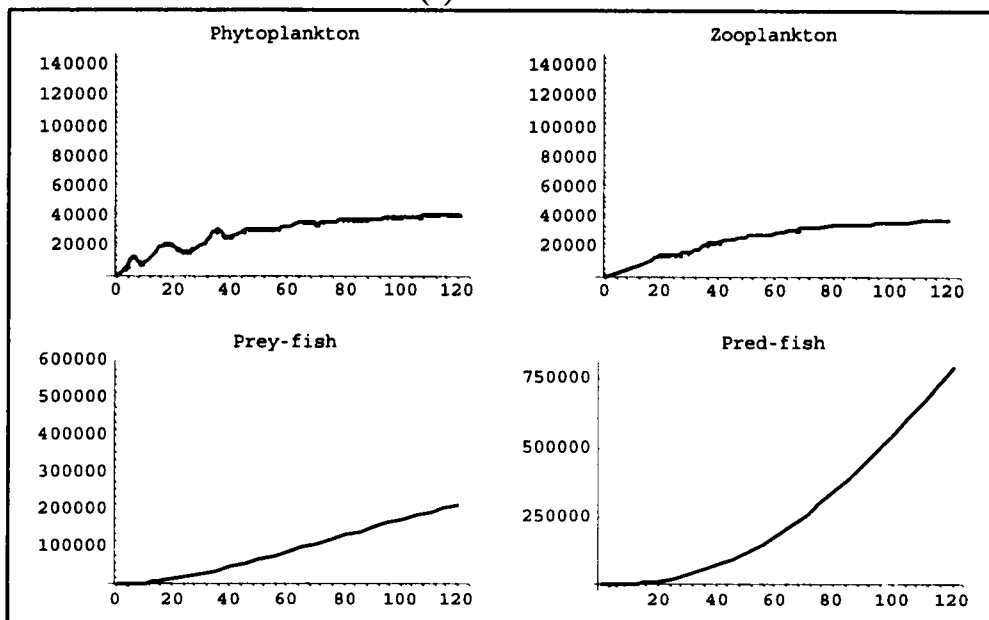


(d) Node 204

Figure 5.4 (Continued)



(e) Node 422



(f) Node 804

Figure 5.4 (Continued)

lake with different densities. Under the turbulent environment, the plankton are transported and redistributed, while they grow. The overall spatial biomass variations of phytoplankton and zooplankton are calculated by solving Equation (3.19), which is a transport model with hydrodynamics and population dynamics. The same flow field used for contaminant transport presented in Chapter 4 is used for the case 5 simulations.

Figures 5.5 and 5.6 show the calculated phytoplankton and zooplankton biomass changes at six locations. By observing the trends on these figures, the plankton biomass fluctuates in a very early period and then tend to increase with time. It suggests that the water circulation has a strong impact on the early biomass change, but as the plankton keep growing, the population dynamics dominates the plankton biomass changes in the later period in this turbulent environment. Based on the information in Figures 5.5 and 5.6, the plankton biomass change terms $dm_{ij}(t)/dt/m_{ij}(t)$ at six locations are calculated and results are illustrated in Figure 5.7. The values fluctuate between +0.4 and -0.2 in the early period, then stabilize during the later simulated period.

It is assumed that the fish are also distributed in four regions at different densities and that they stay in their locations as discussed in Chapter 3. In this case, population growth determine the fish biomass changes. Equation (3.22) and (3.23) describe the fish biomass changes. The small net growth rate (0.001 d^{-1}) for prey-fish and pred-fish results in a relatively small change in fish biomass.

Based on above information, the concentrations in four populations with biomass effects at six locations are calculated and results are shown in Figure 5.8 (a) to (f).

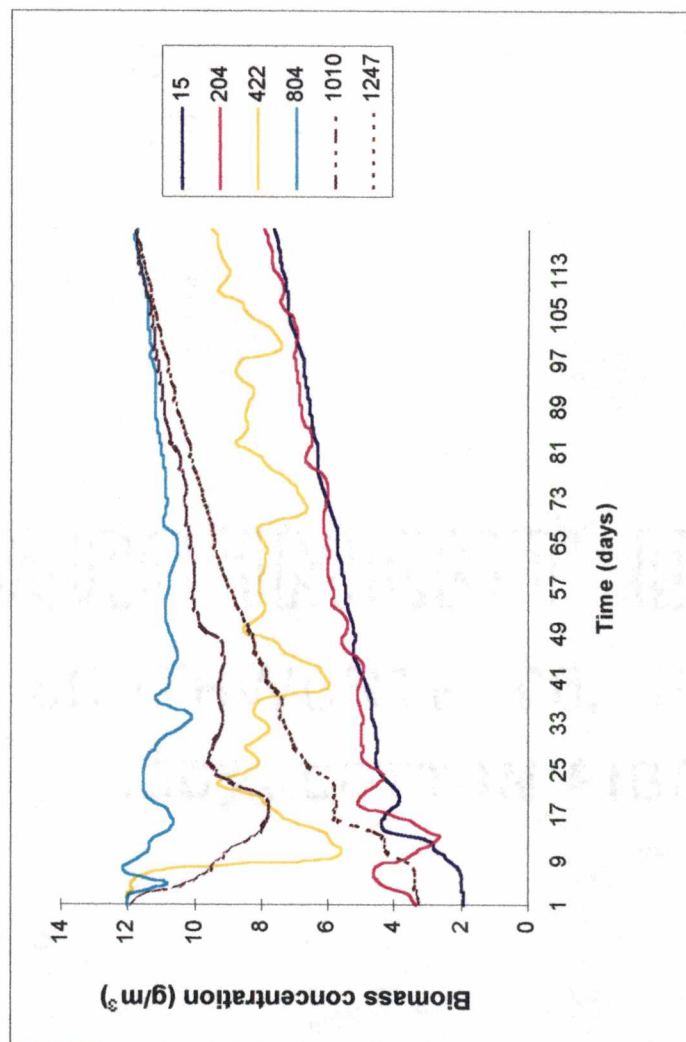


Figure 5.5 Phytoplankton Biomass Changes at Six Locations

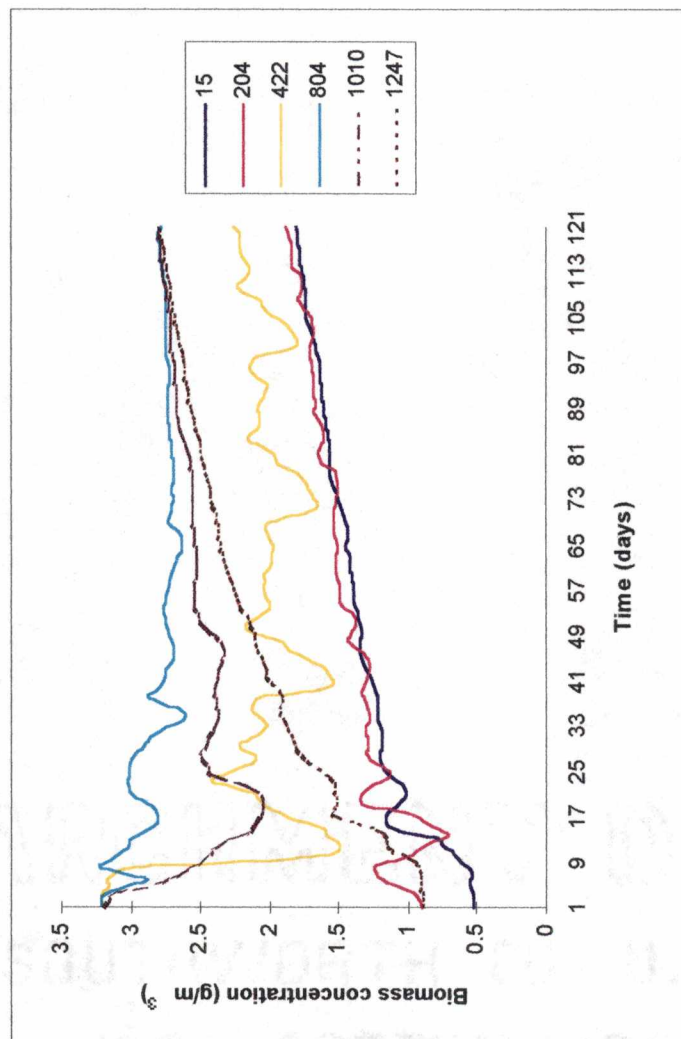
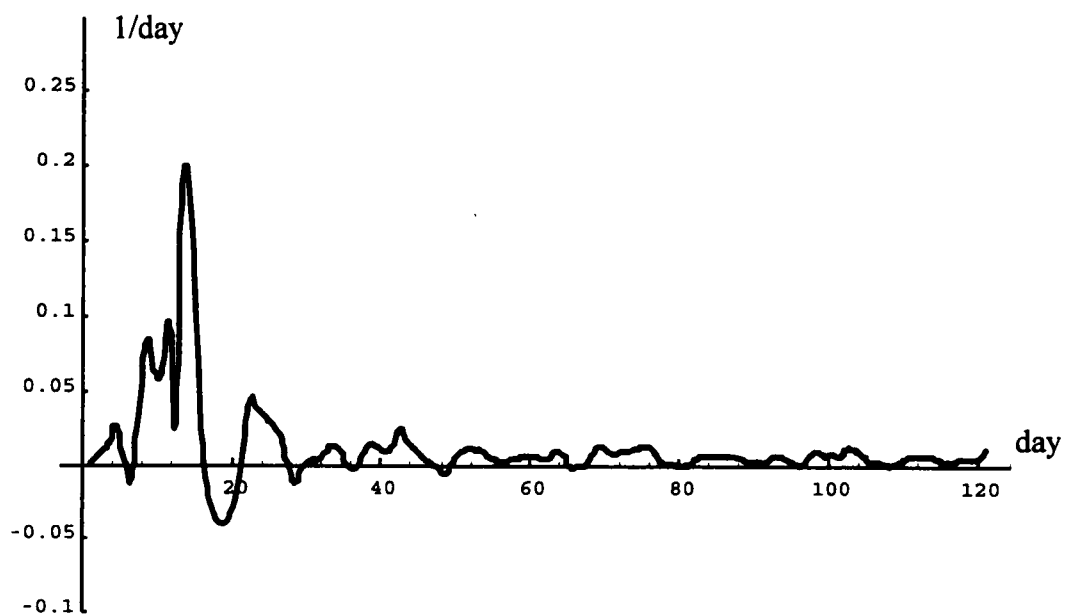
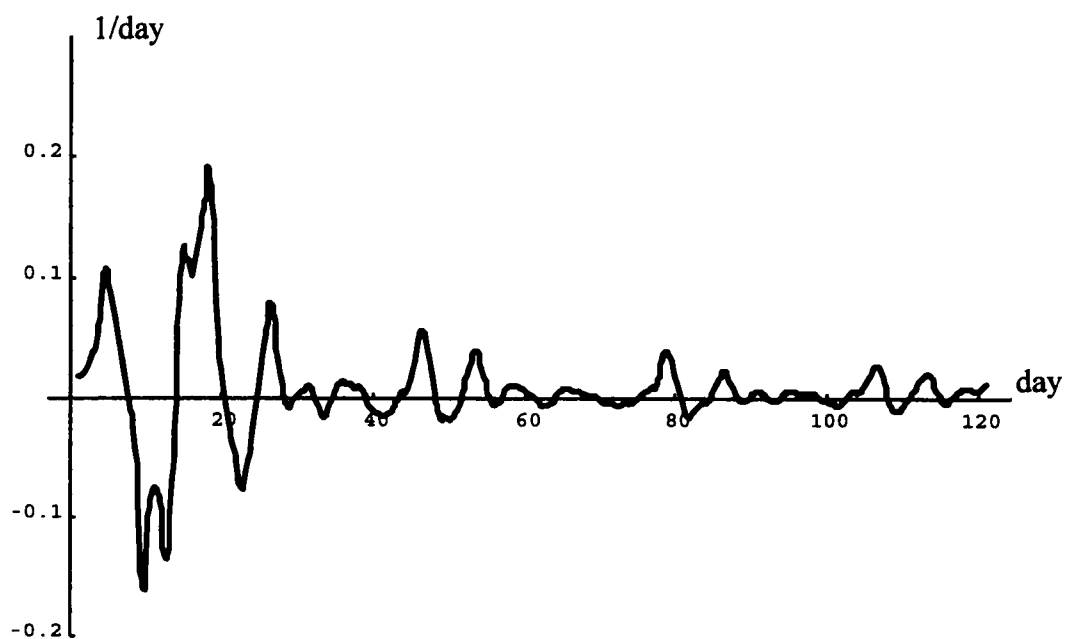


Figure 5.6 Zooplankton Biomass Changes at Six Locations

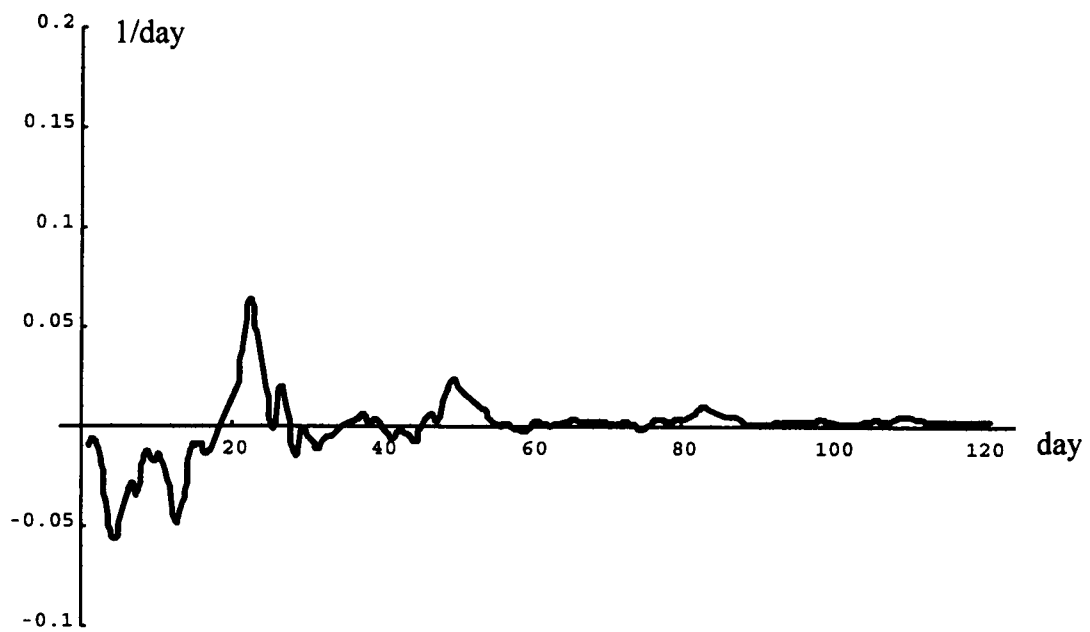


(a) in element 15

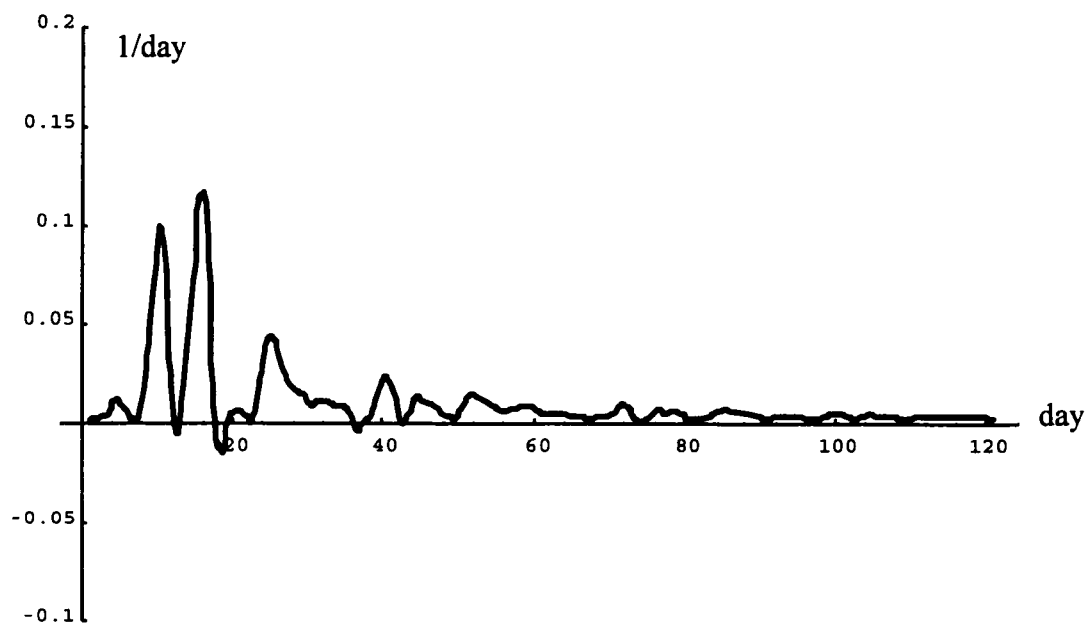


(b) in element 204

Figure 5.7 Plankton Growth Rates ($dm_j(t)/dt/m_j(t)$) at Six Locations. Biomass Values were Determined Using an Integrated Transport-growth Model.

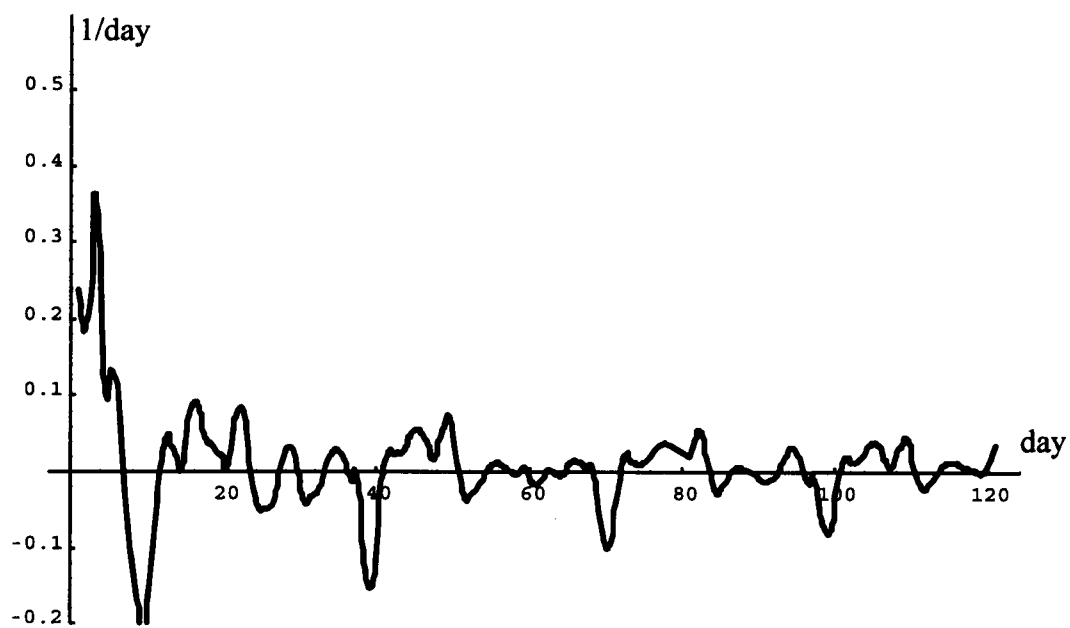


(c) in element 1010

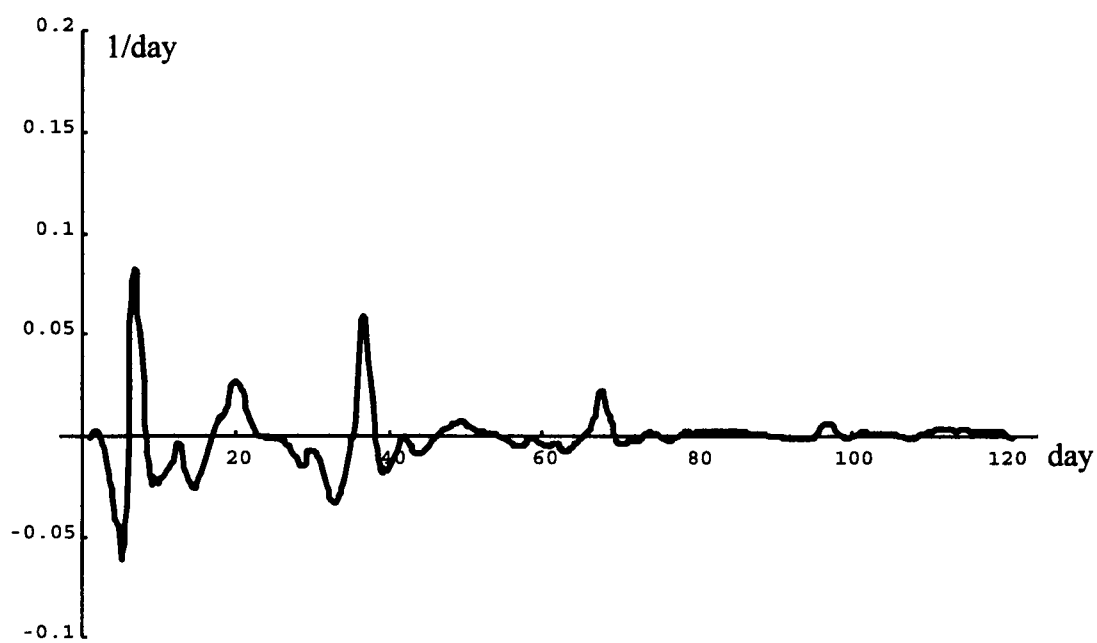


(d) in element 1247

Figure 5.7 (Continued)

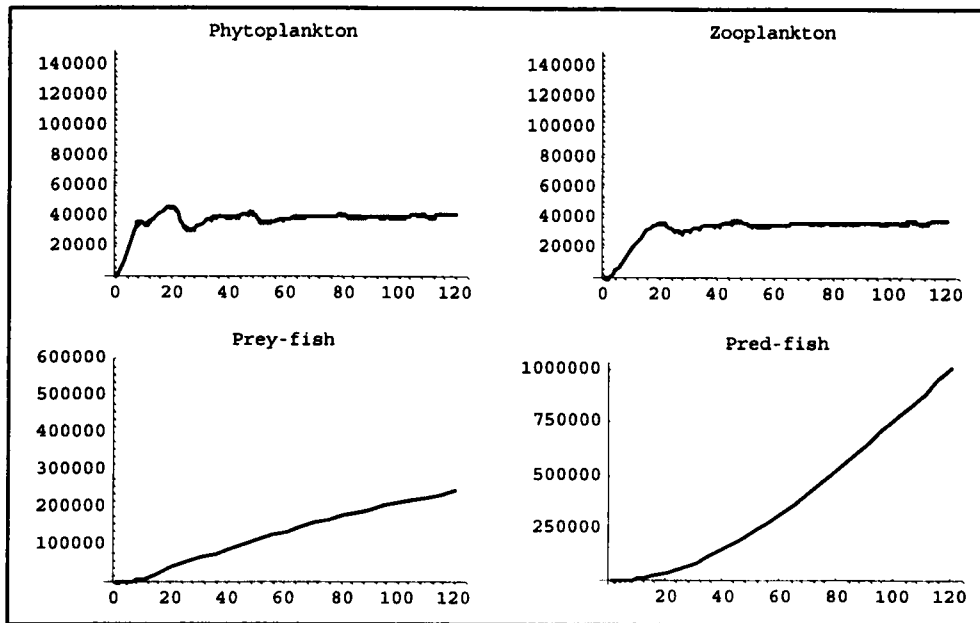


(e) in element 422

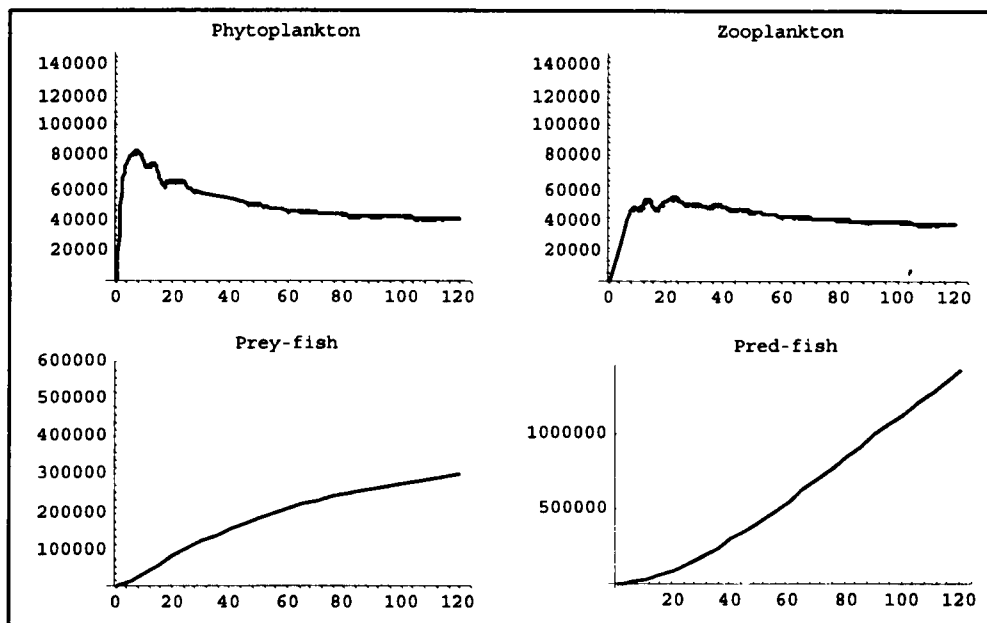


(f) in element 804

Figure 5.7 (Continued)

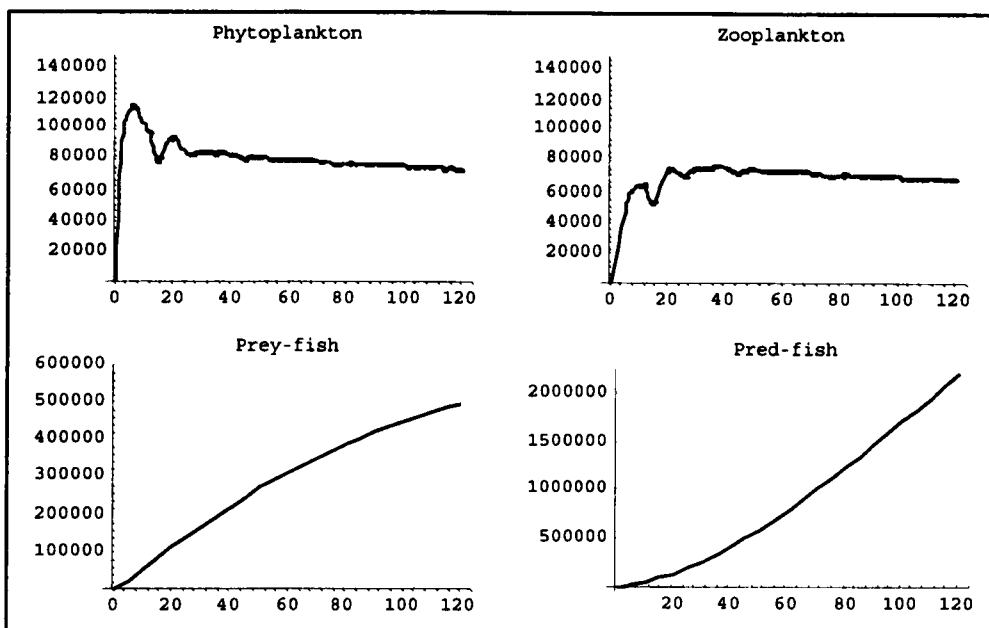


(a) in element 1010

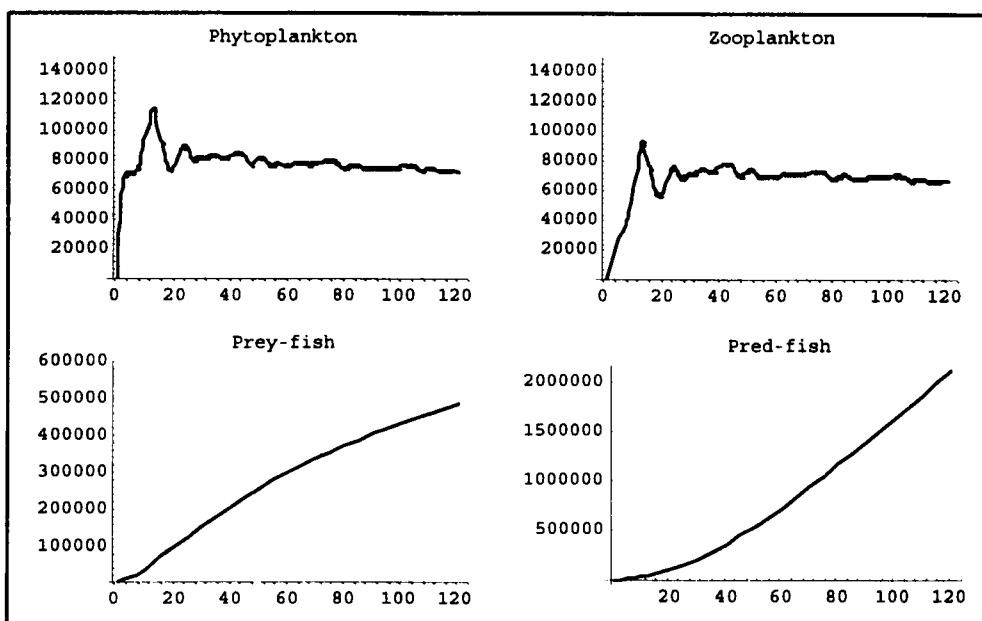


(b) in element 1247

Figure 5.8 Concentrations (Bq/kg) Accumulated in Four Populations for 120 Days under a Heterogeneous and Dynamic Radioactive Environment and with Population Biomass Effects (Case 5)

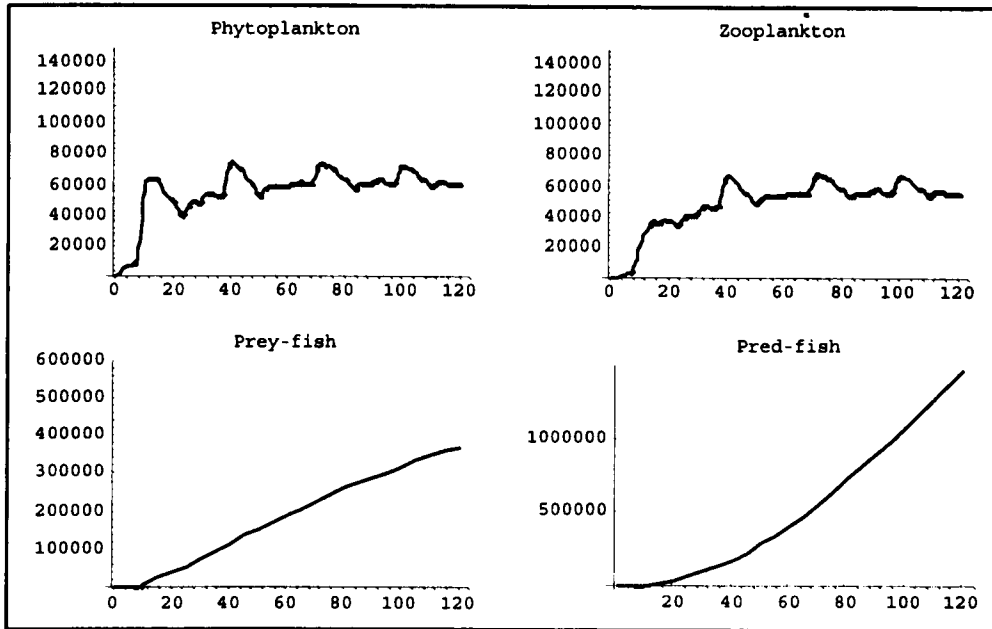


(c) in element 15

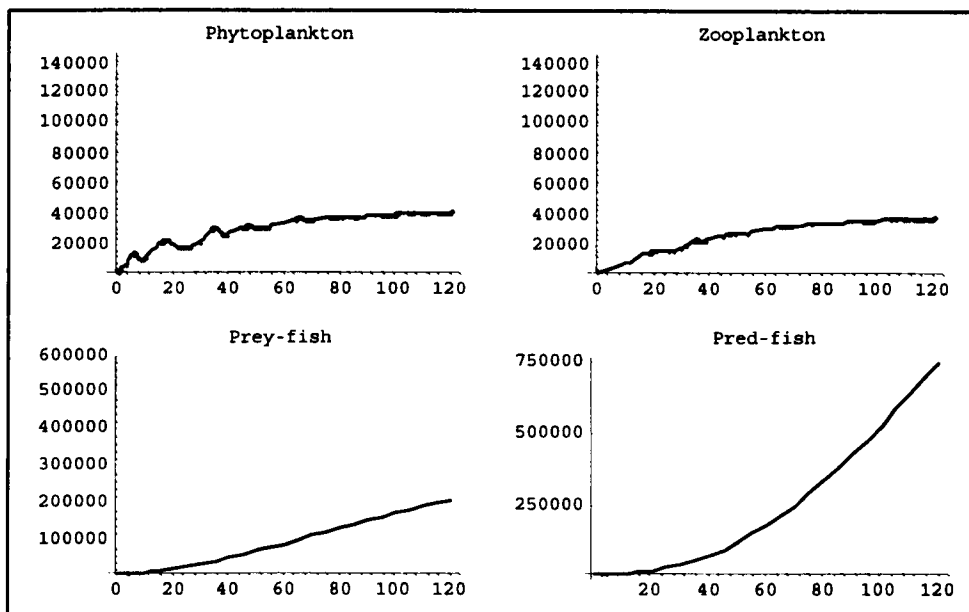


(d) in element 204

Figure 5.8 (continued)



(e) in element 422



(f) in element 804

Figure 5.8 (continued)

5.3.6 Exposure Modeling with Spatial and Temporal-dependent Radionuclide Ingestion Rates from Food (Case 6)

In the previous five cases studies, the radionuclide ingestion rates for zooplankton, prey-fish, and pred-fish are constant since it is assumed that they are independent of the abundance of preys (food sources). As discussed in Section 3.6, the ingestion rates vary spatially and temporally due to variations of food source distributions. Thus, in the Case 6 simulation, the averaged constant ingestion rate for each consumer population (zooplankton, prey-fish, and pred-fish) is replaced by a temporal and spatial-dependent ingestion rate (or density-dependent ingestion rate).

Equation (3.25) is used to calculate the new ingestion rates for consumer populations at selected locations with zooplankton feeding on phytoplankton, prey-fish feeding on zooplankton, and pred-fish feeding on prey-fish. The biomass data generated in the Case 5 simulation are used to calculate these new ingestion rates. Figure 5.9 presents the calculated spatial and temporal-dependent ingestion rates for three consumers in element 204. As Equation (3.26) states, the ingestion rate is determined by the basic relationship of $m_{i-1}(x,y,t) / (m_{i-1}(x,y,t) + m_i(x,y,t))$. Since prey (m_{i-1}) is abundant relative to predator (m_i) in the cooling pond, the impact of variation of prey biomass is not important in this case. Thus, the calculated ingestion rates are almost constant for three consumers.

Using these new determined variable ingestion rates, exposure Equations (3.13), (3.14), and (3.15) are applied to calculate the concentrations accumulated in three consumers. Results from the simulation at six locations are plotted in Figure 5.10.

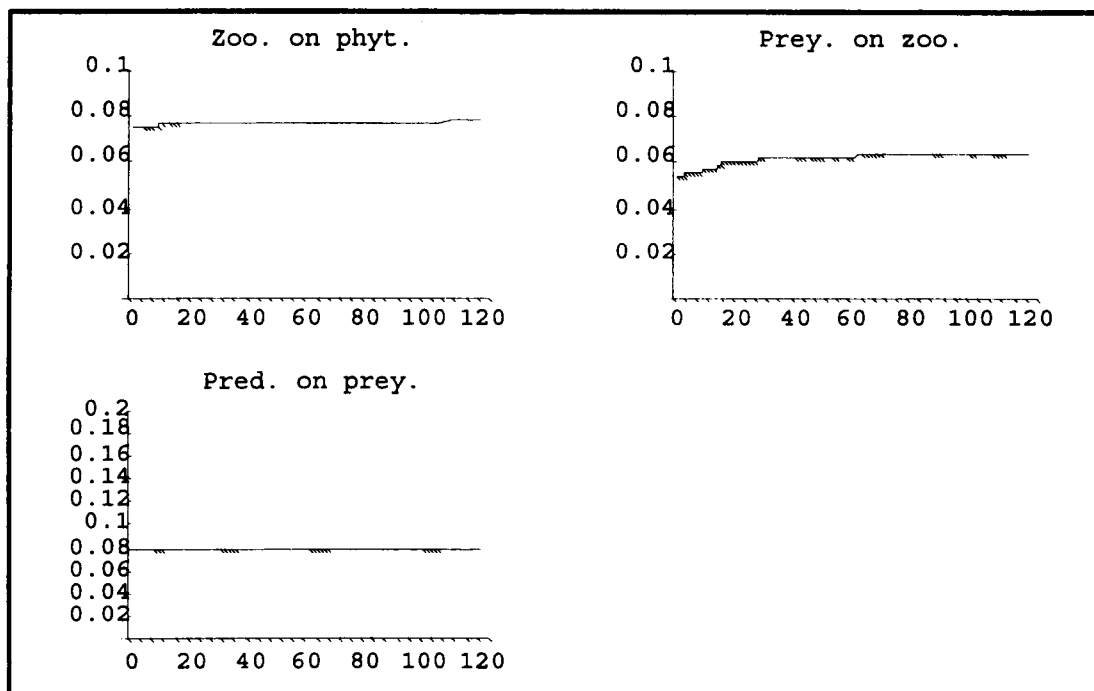
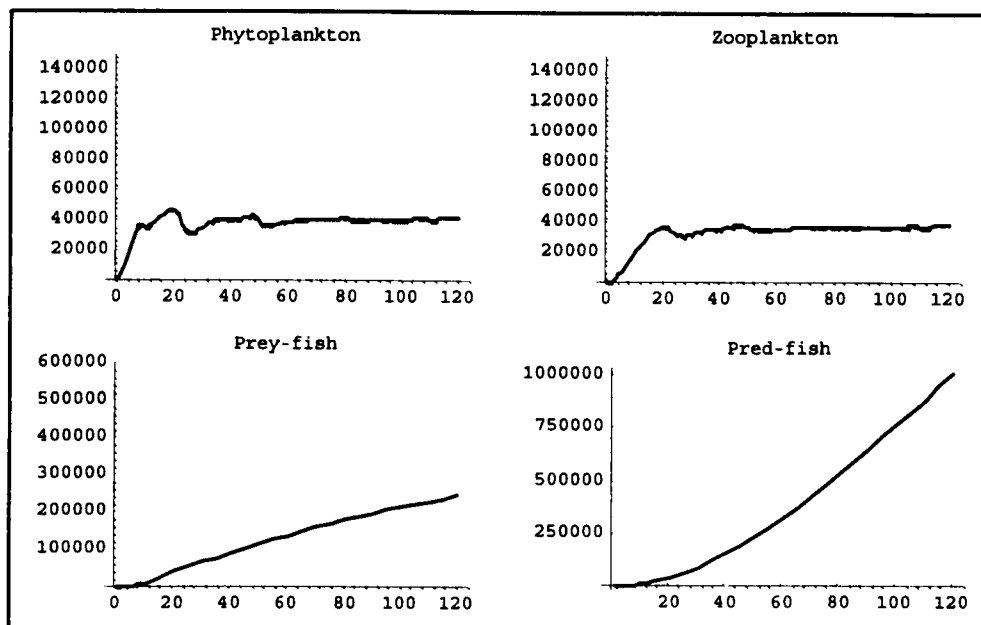
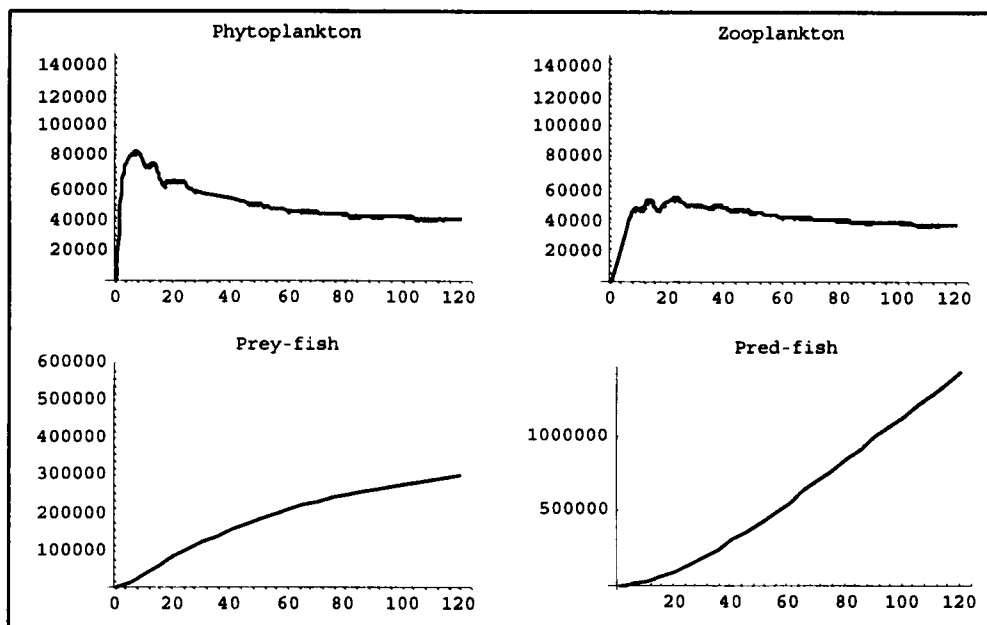


Figure 5.9 Temporal- and Spatial- dependent Ingestion Rates $k_f(x,y,t)$ (1/day) in Element 15: Zooplankton Feeding on Phytoplankton, Prey-fish Feeding on Zooplankton, and Pred-fish Feeding on Prey-fish.

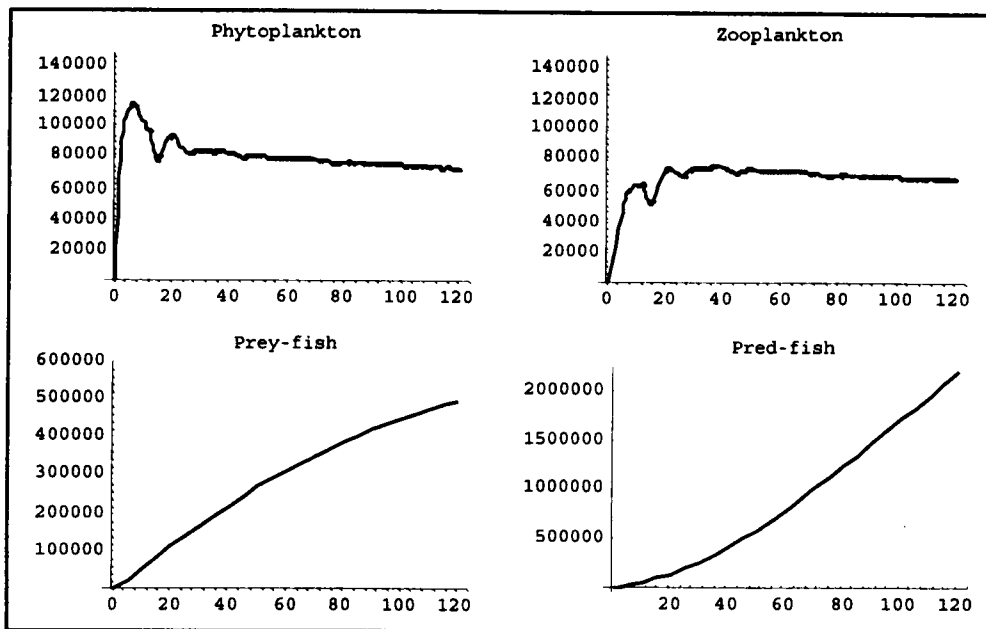


(a) in element 1010

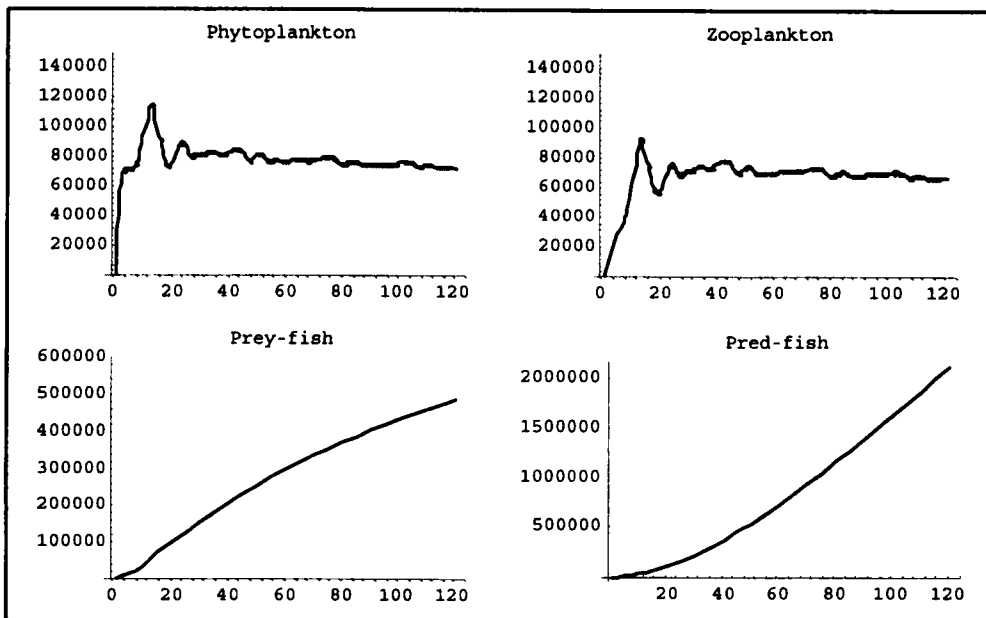


(b) in element 1247

Figure 5.10 Concentrations (Bq/kg) Accumulated in Four Populations for 120 Days under a Heterogeneous and Dynamic Radioactive Environment. The Biomass Terms and Variable Ingestion Rates are Incorporated into the Model (Case 6).

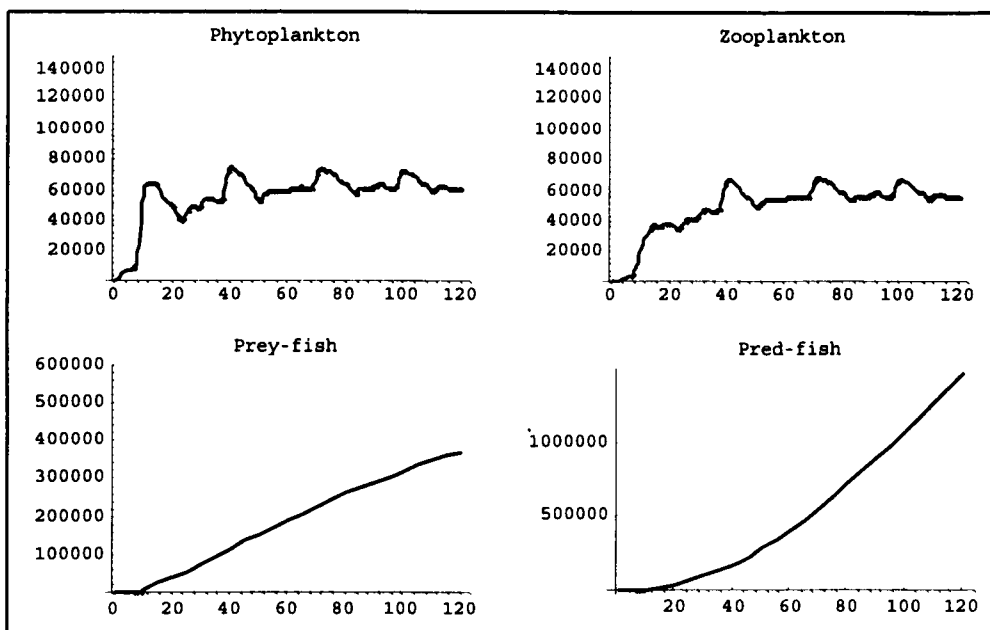


(c) in element 15

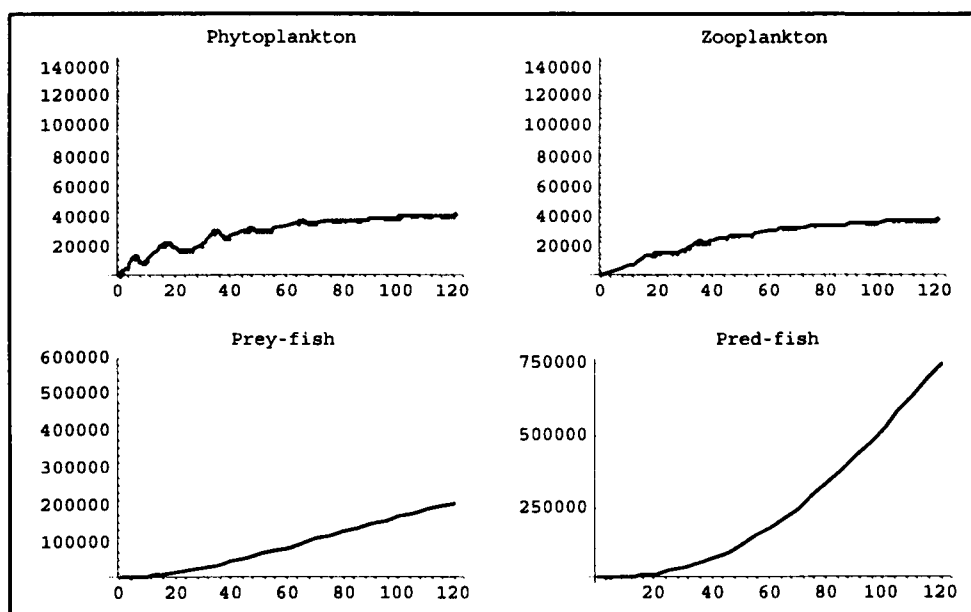


(d) in element 204

Figure 5.10 (continued)



(e) in element 422



(f) in element 804

Figure 5.10 (continued)

5.3.7 Exposure Modeling with a Multi-prey Food Web Structure (Case 7)

Case 7 is based on Case 6 conditions but with a different food web structure. All above six case studies use a single prey food web structure, which was conceptually illustrated in Figure 3.3. To examine the influence of pred-fish feeding on different prey on the bioaccumulation, a multi-prey food web structure (shown in Figure 3.4) is used in Case 7. It is assumed that the pred-fish diet consists of 50% phytoplankton, 20% zooplankton, and 30% prey-fish. Equation (3.16) is used to calculate the concentration accumulated in pred-fish with a multi-prey food web structure. Results from simulations for six elements are presented in Figure 5.11. It is apparent that spatial heterogeneity in radioactive environment and in food sources resulted in a 2.5 times difference from Case 6 among the concentrations accumulated by pred-fish at six locations.

5.4 Analysis and Discussions of Modeling Results

5.4.1 Temporal and Spatial Effects from Heterogeneous Radioactive Environment

It was the intention of this research to investigate how and up to what degree the accumulated radionuclide concentration by aquatic biota is affected by the spatial and temporal heterogeneity of radioactive environments. To examine the temporal and spatial effects associated with heterogeneous radioactive environment, three cases were developed: Case 1: homogeneous and steady-state; Case 2: homogeneous and time-dependent; and Case 4: heterogeneous and time-dependent. The Case 4 simulation is carried out at six locations. By comparing the results of simulations with and without spatial and temporal details, their effects and significance on the biota exposure are evaluated quantitatively.

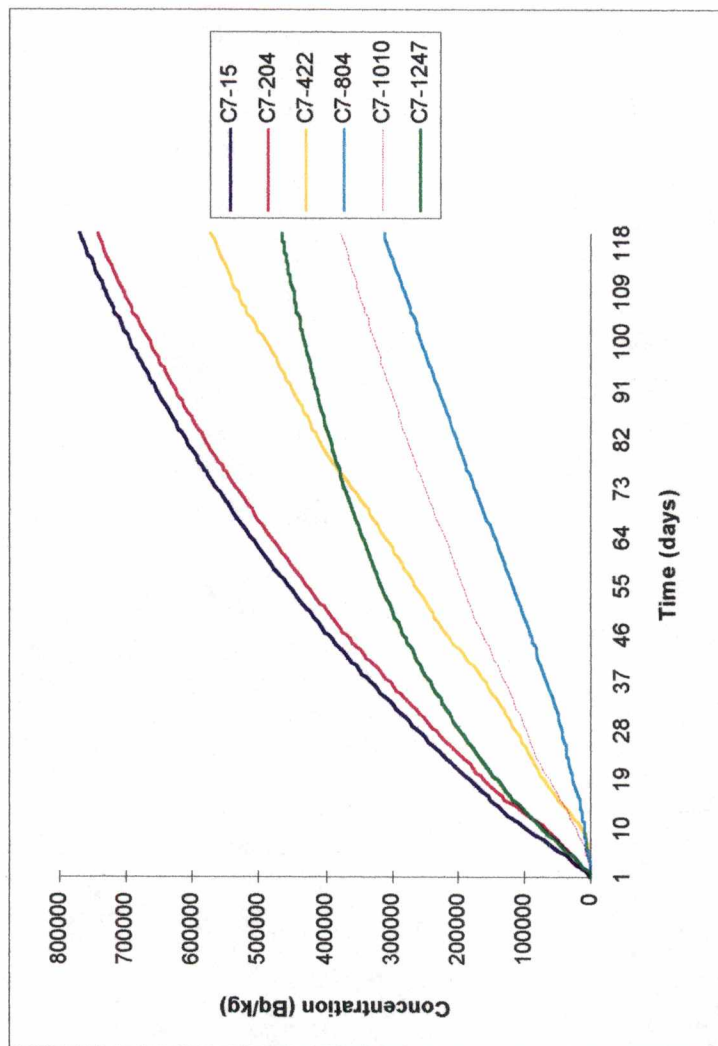
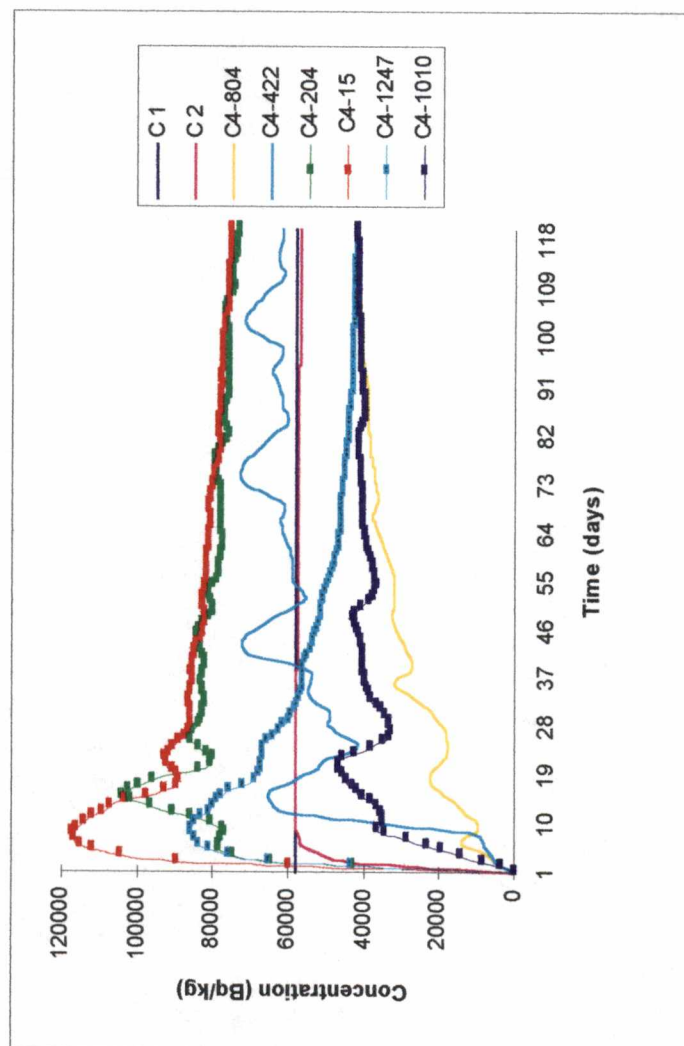


Figure 5.11 Concentration Accumulated in Pred-fish with a Multi-prey Food Wed Structure (Case 7)

Figures 5.12 (a) to (d) present the results from three cases simulations for four populations. The exposure model produced a spatial pattern of radionuclide accumulation in each population through time. The results presented in Figure 5.12 (a) demonstrate that the temporal change in phytoplankton concentration at different locations depends on the spatial and temporal change of the radionuclide concentration in water. The highest accumulated concentration by phytoplankton occurs in a highly contaminated region (element 15).

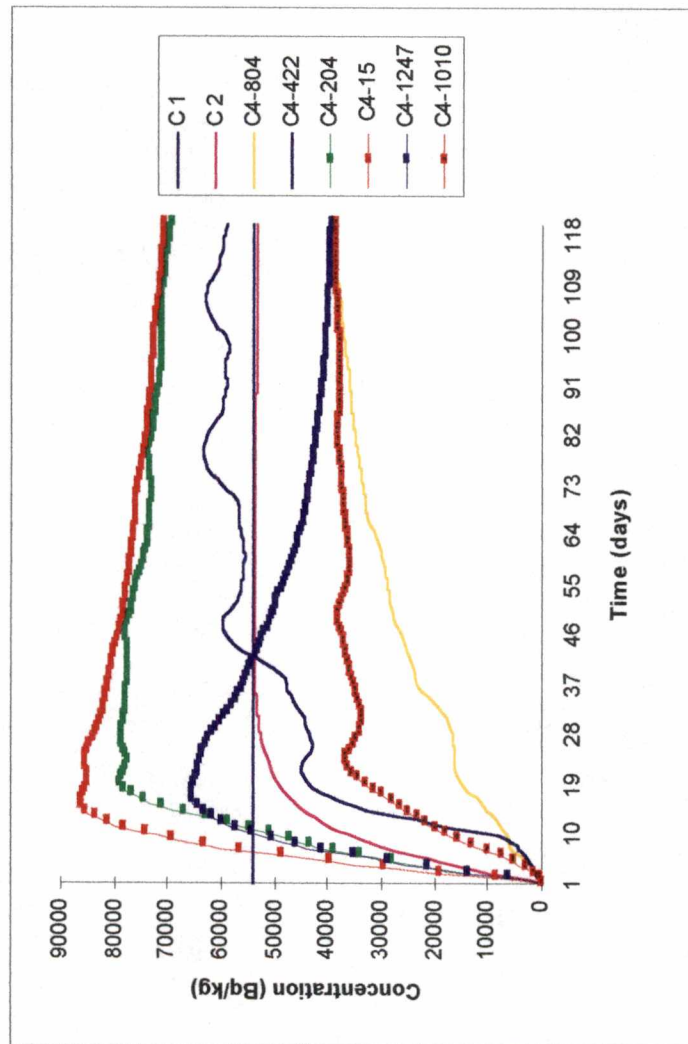
The concentrations calculated under Case 4 conditions differ from those obtained under equilibrium or homogeneous and dynamic conditions. The concentration accumulated by phytoplankton at most locations approaches a steady state in about 100 days. This is attributed to the relatively fast radiobiological turn-over rate of Cs-137 and to the stable radionuclide concentration in water during the later simulation period. Even though the concentration in phytoplankton approaches an equilibrium state at each location, these concentrations differ from the equilibrium concentration associated with homogeneous and steady-state conditions (Case 1). This is due to the spatial variation of concentrations in water. Thus, the use of bioaccumulation factors can either underestimate or overestimate the bioaccumulation in phytoplankton in a heterogeneous environment.

Figure 5.12 (b) shows the accumulation of Cs-137 by zooplankton. Zooplankton take up radionuclides directly from water and by consuming phytoplankton. Therefore, the accumulation patterns in different locations through time are influenced by both the variations of Cs-137 concentrations in water and in phytoplankton. Similar to the phytoplankton, the concentrations in zooplankton at six locations approach the equilibrium state later. However, they differ from the calculated bioaccumulation factors (Case 1) due to the spatial variation of concentrations in water and food.



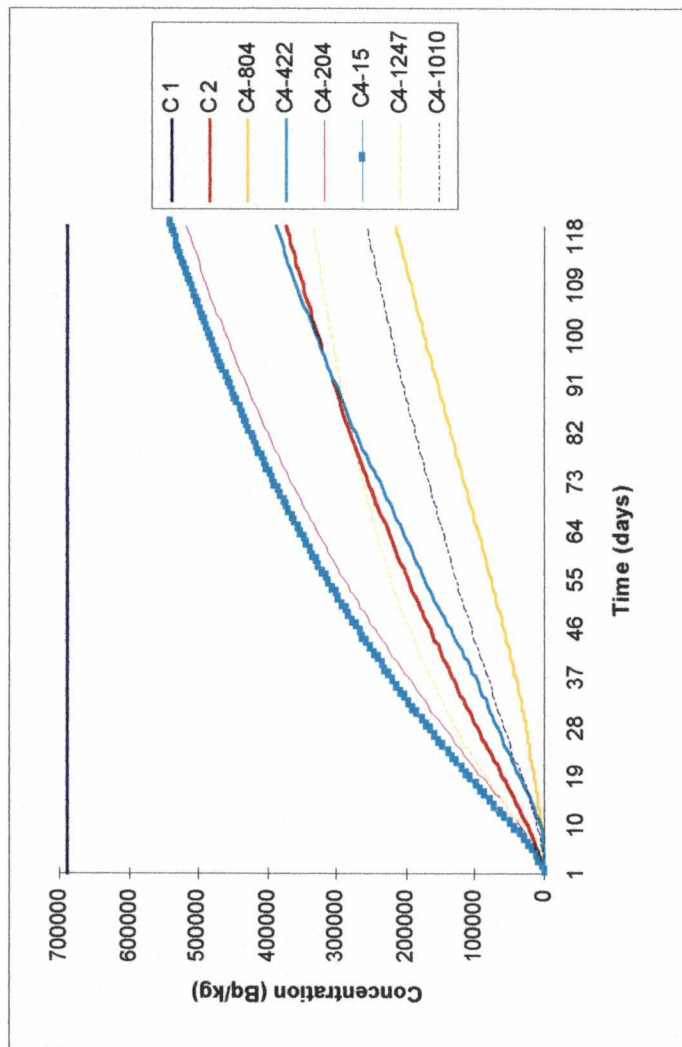
(a) Phytoplankton

Figure 5.12 Comparisons among Concentration Calculated under Conditions of Case 1, Case 2, and Case 4 to Illustrate Temporal and Spatial Effects on Biomass Exposure Assessment



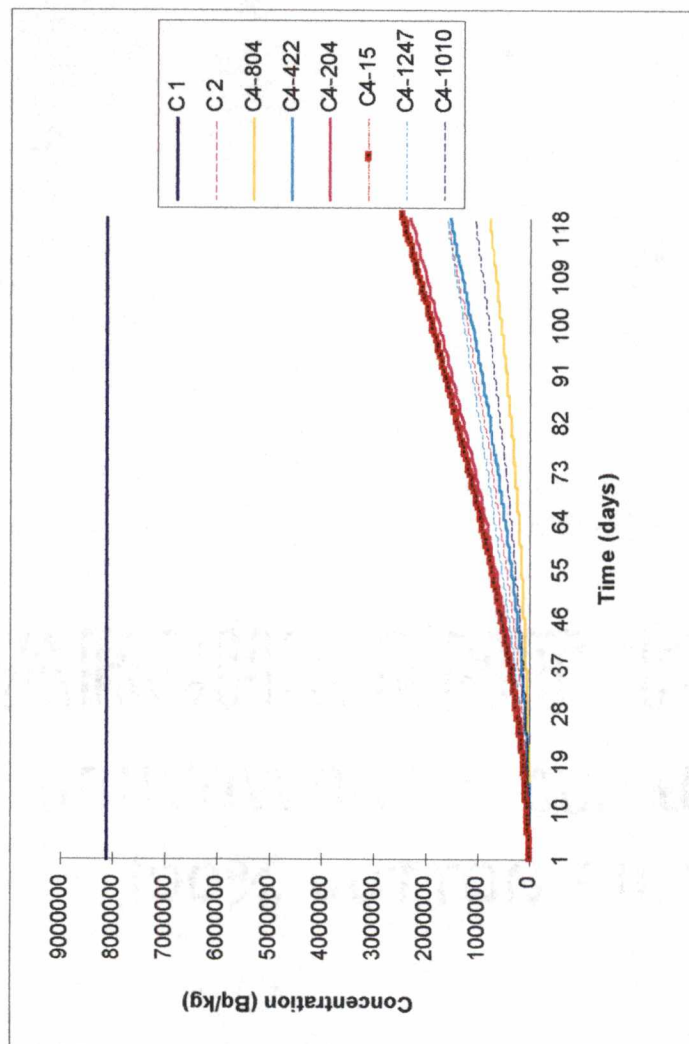
(b) Zooplankton

Figure 5.12 (Continued)



(c) Prey-fish

Figure 5.12 (Continued)



(d) Pred-fish

Figure 5.12 (Continued)

The implications of the spatial and temporal exposure model are more interesting for concentrations accumulated in fish than in the plankton. Figures 5.12 (c) and (d) illustrate the accumulation patterns for prey-fish and pred-fish. It is apparent that the concentrations in fish do not reach an equilibrium state during the simulation time period and differ significantly from the equilibrium concentration associated with homogeneous and steady-state conditions (Case 1). This pattern results from the slow radiobiological processes of fish and variation of Cs-137 concentration in water. Therefore, using bioaccumulation factors will over-estimate the accumulated concentrations in fish, especially in pred-fish during the early period. The magnitude of over estimation of the Cs-137 concentration in pred-fish caused by ignoring spatial and temporal effects can be a factor of 4 to 6 times higher at some locations.

5.4.2 Effects from Temporal and Spatial-dependent Ecological Factors

Alteration of the model structure by adding or removing some functions permits an examination of the impact and relationship of various modeled processes. Three cases (5, 6 and 7) are specifically designed by the alteration of the exposure model in Section 5.3. Case 5 includes the temporal- and spatial-dependent population biomass change terms, while Case 6 includes temporal- and spatial-dependent ingestion rates in addition to the biomass change terms. Case 7 investigates the effects of an alternative different food web.

The results from Case 5, 6, and 7 are compared with those from Case 4 to explore the significance on the exposure assessment of adding two functions separately. Case 4 describes the bioaccumulation in a heterogeneous radioactive environment without the above two functions. Figures 5.13, 5.14, 5.15, and 5.16 present the comparisons for four

populations at six locations. Results from Case 4 are considered to be as the reference values.

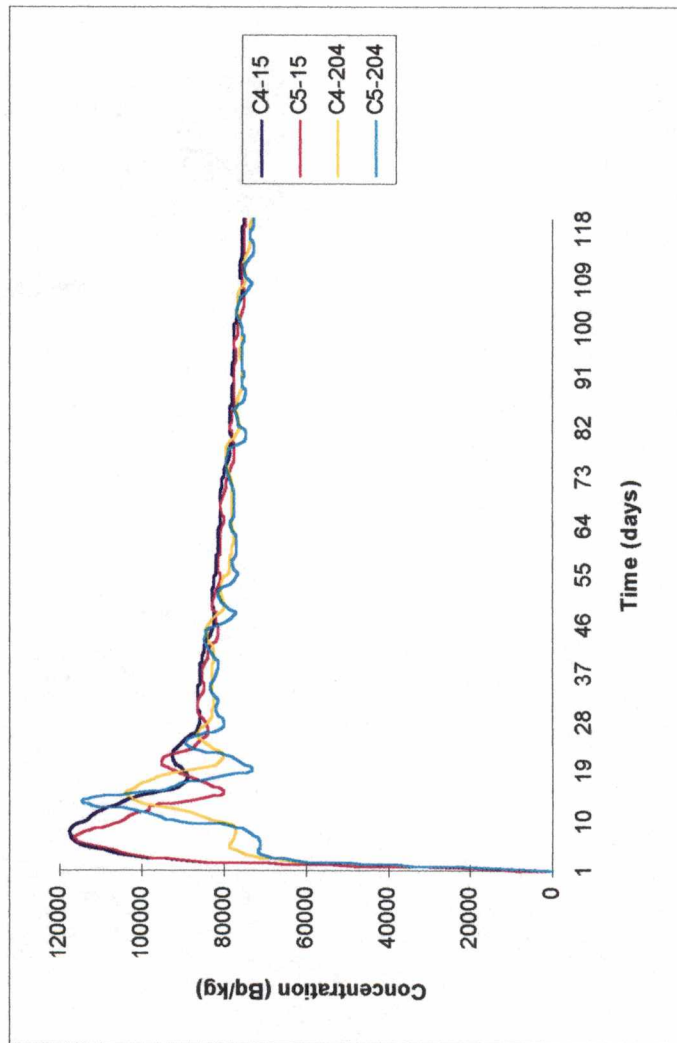
5.4.2.1 Temporal and Spatial-dependent Population Biomass

Results from Case 5 differ little from that from case 4 for phytoplankton and zooplankton at each location, as shown in Figures 5.13 and 5.14. The small difference is attributed to the calculated biomass change terms ($dm_{ij}(t)/dt/m_{ij}(t)$) being much smaller than the Cs-137 radiobiological turn-over rates (k_{bi}) in exposure Equations (3.12) and (3.13). Both biomass change terms and radiobiological elimination rates are the loss terms in the equations. The loss of Cs-137 from plankton is dominated by the radiobiological elimination rates. The plankton biomass changes due to population dynamics and physical environment (water circulation) have comparatively little influence on the Cs-137 bioaccumulations by plankton.

Small differences between the results from Case 4 and Case 5 are observed for prey-fish and pred-fish at some locations in Figures 5.15 and 5.16. This is attributed to the relative slower Cs-137 radiobiological turn-over rates of fish than that of plankton and this difference varies among different locations.

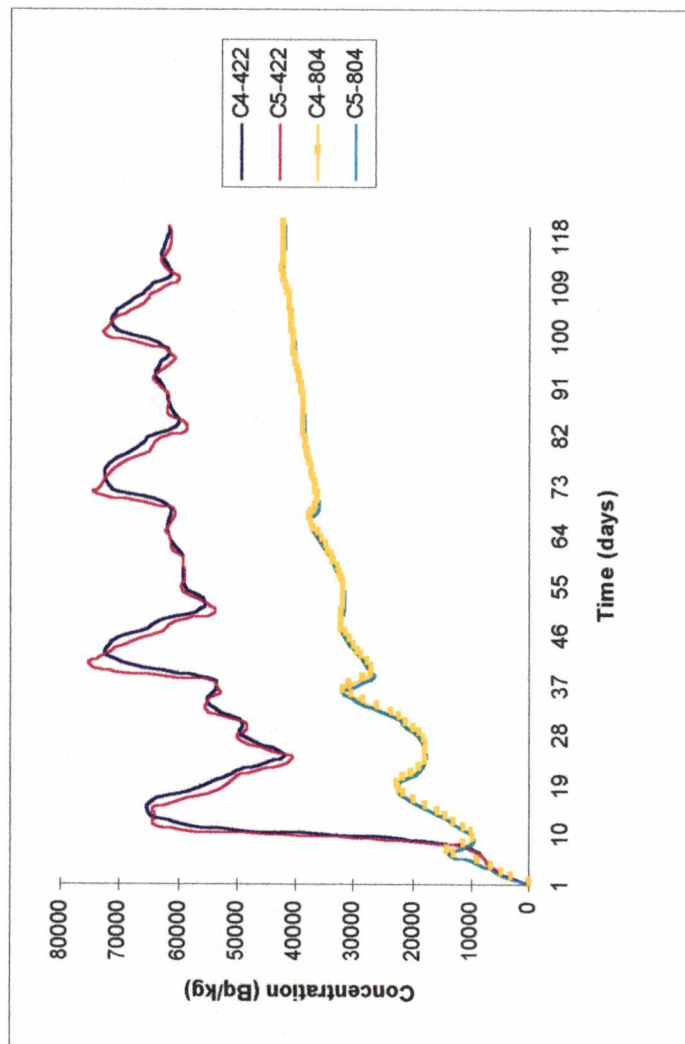
5.4.2.2 Temporal and Spatial-dependent Radionuclide Ingestion Rate

To examine the impacts of a temporal and spatial-dependent ingestion rate on the consumer exposure assessment, the results at six locations from Case 6 simulation are compared with those from Case 4 and Case 5 in Figures 5.14, 5.15, and 5.16.



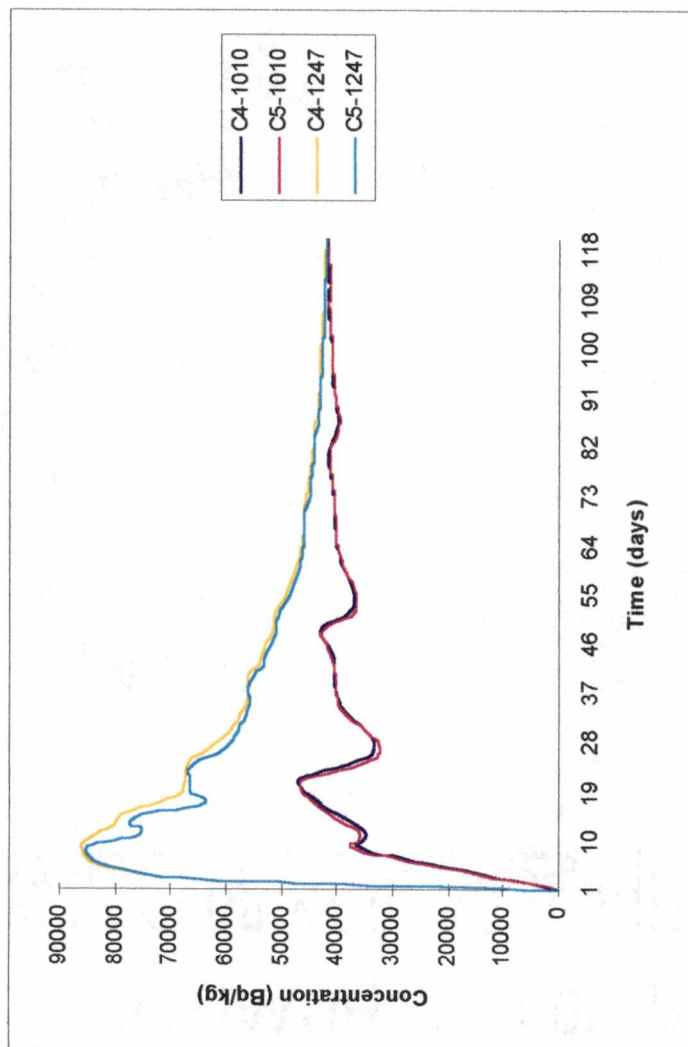
(a) at Nodes 15 and 204

Figure 5.13 Comparisons among Concentrations in Phytoplankton under Conditions of Case 4 and Case 5 to Investigate Biomass Change Impacts on Exposure Assessment in a Heterogeneous and Dynamic Radioactive Environment



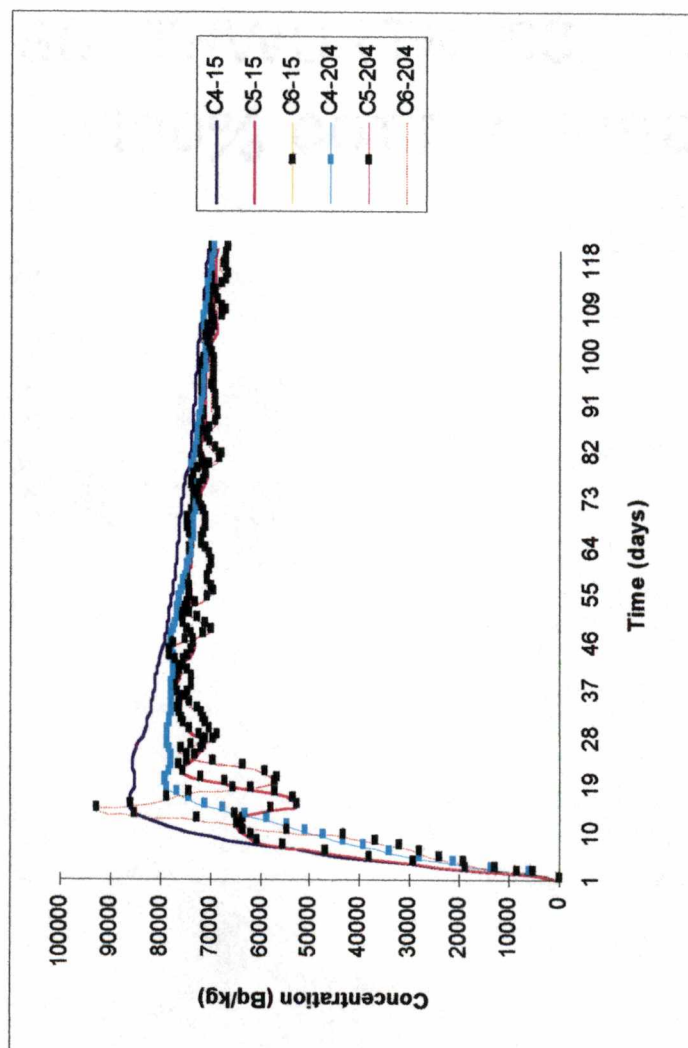
(b) at Nodes 422 and 804

Figure 5.13 (Continued)



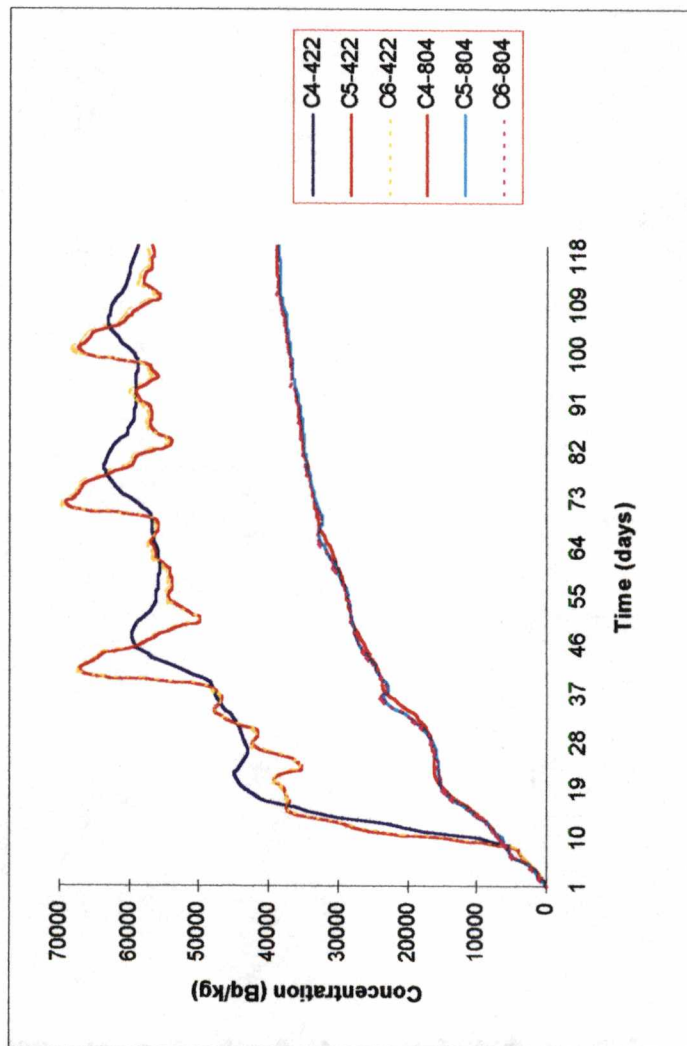
(c) at Nodes 1010 and 1247

Figure 5.13 (Continued)



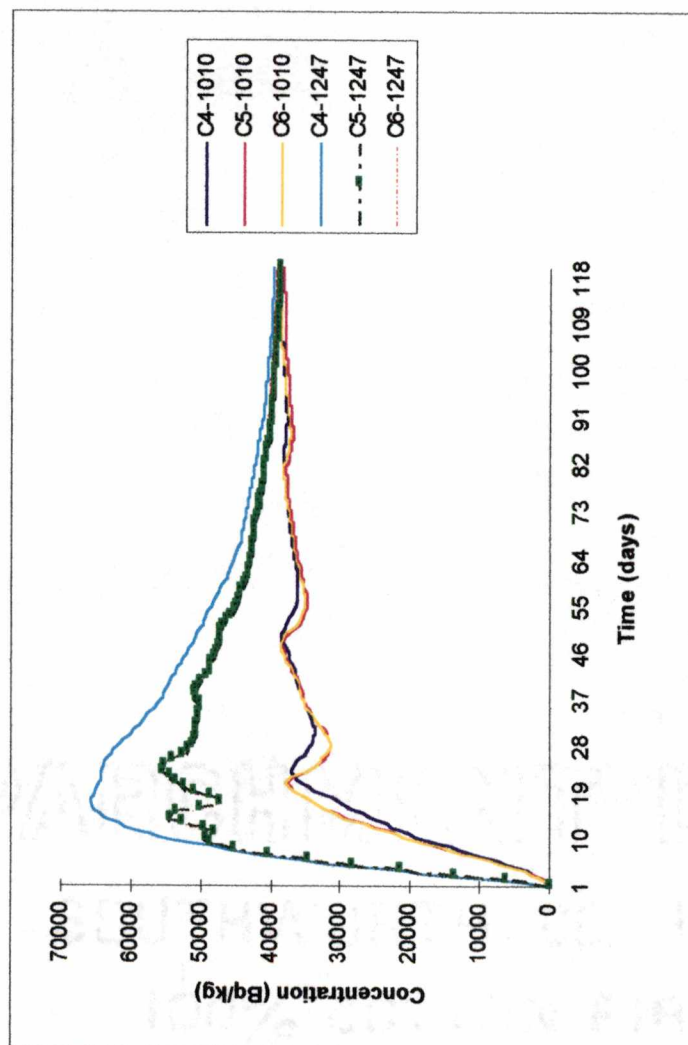
(a) at Nodes 15 and 204

Figure 5.14 Comparisons among Concentrations in Zooplankton under Conditions of Case 4, Case 5, and Case 6 for 120 Days to Investigate Impacts of Biomass Change, Variable Ingestion Rates, and Food Web on Exposure Assessment in a Heterogeneous and Dynamic Radioactive Environment



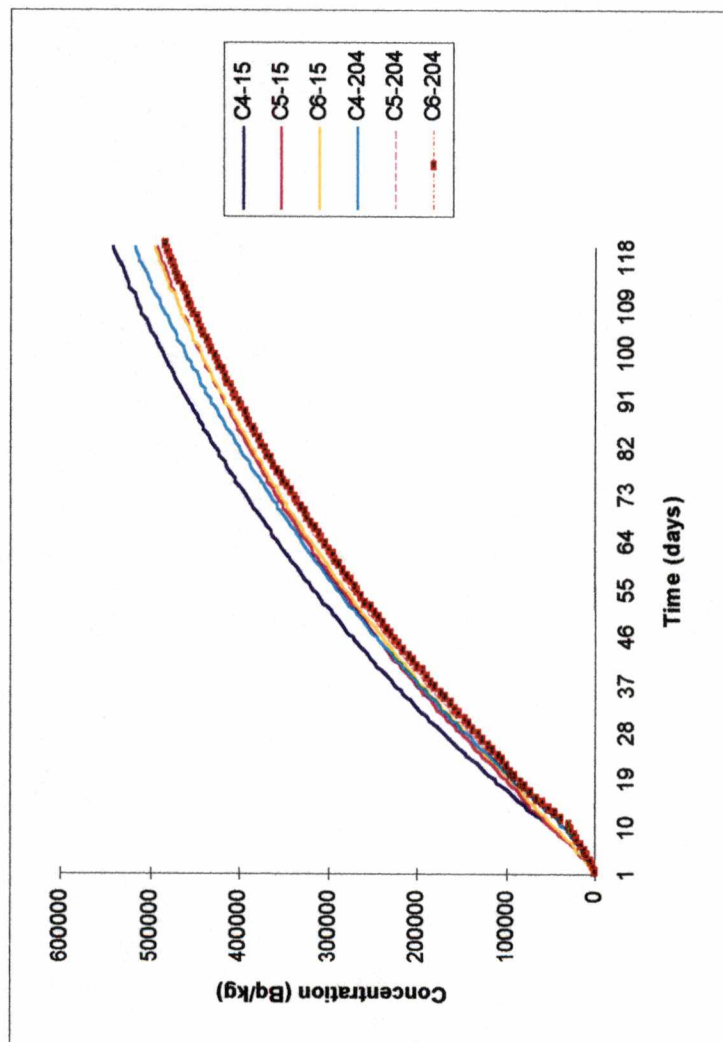
(b) at Nodes 422 and 804

Figure 5.14 (Continued)



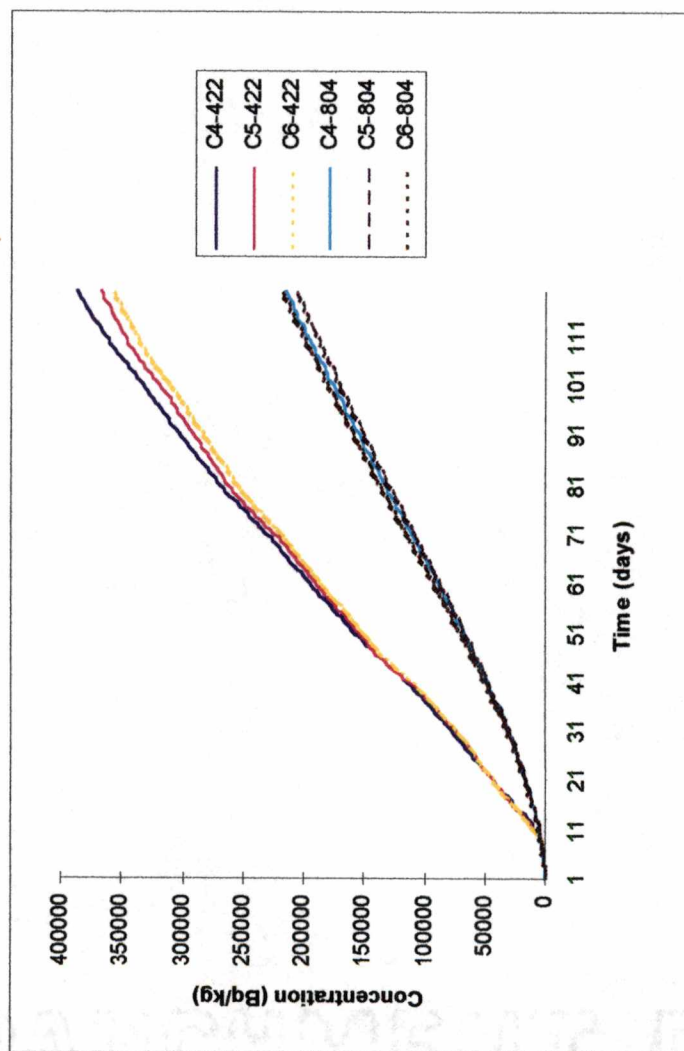
(c) at Nodes 1010 and 1247

Figure 5.14 (Continued)



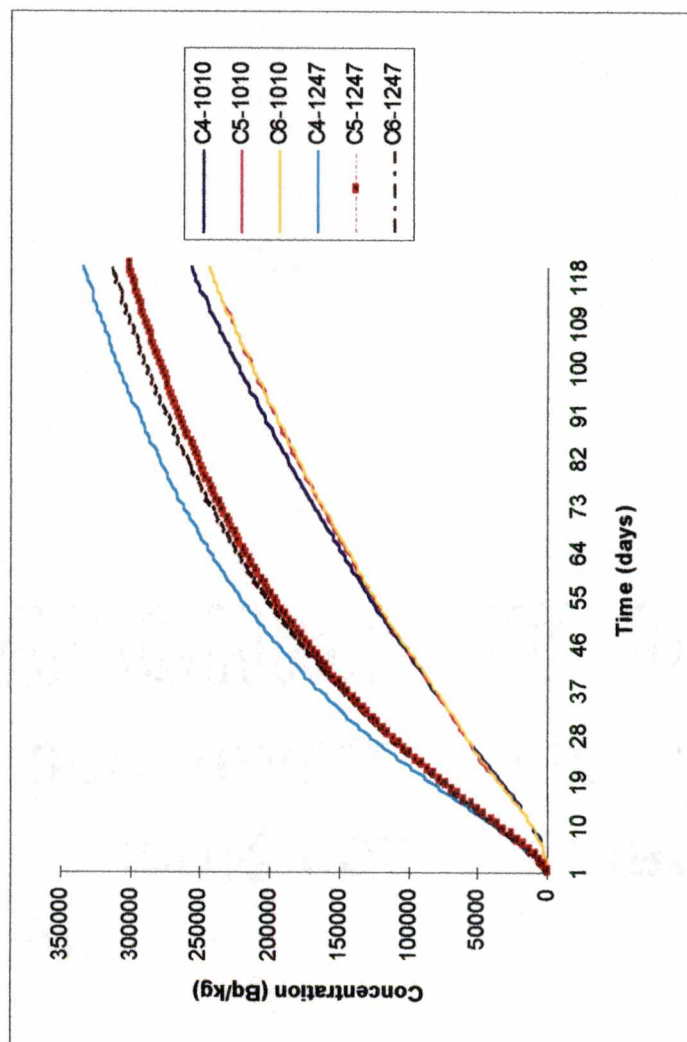
(a) at Nodes 15 and 204

Figure 5.15 Comparisons among Concentrations in Prey-fish under Conditions of Case 4, Case 5, and Case 6 for 120 Days to Investigate Impacts of Biomass Change and Variable Ingestion Rates on Exposure Assessment in a Heterogeneous and Dynamic Radioactive Environment



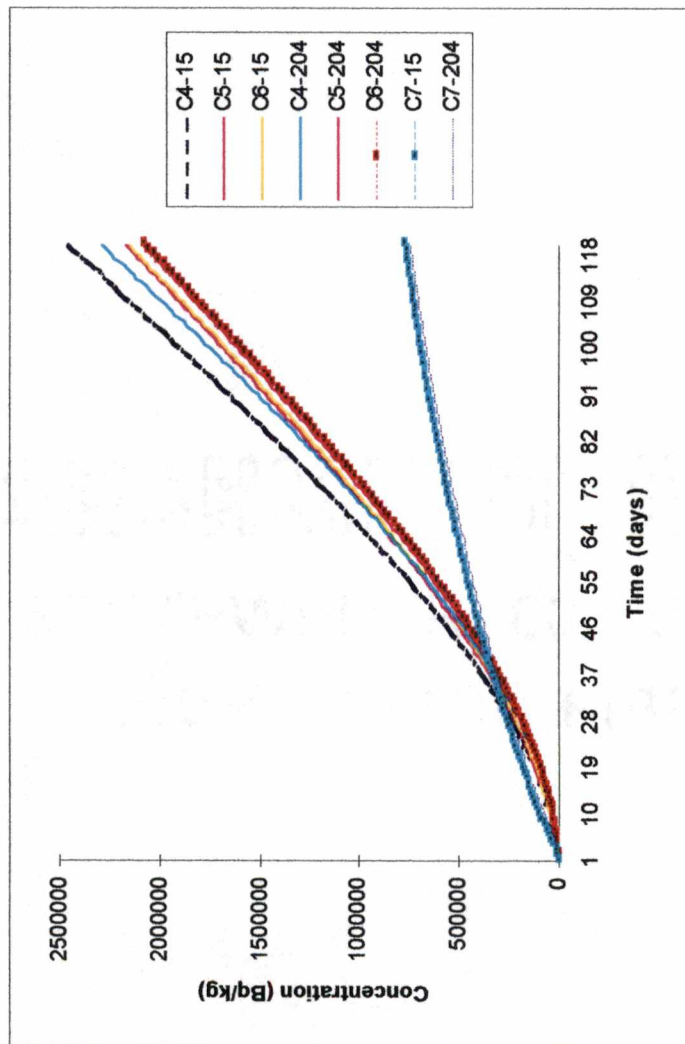
(b) at Nodes 422 and 804

Figure 5.15 (Continued)



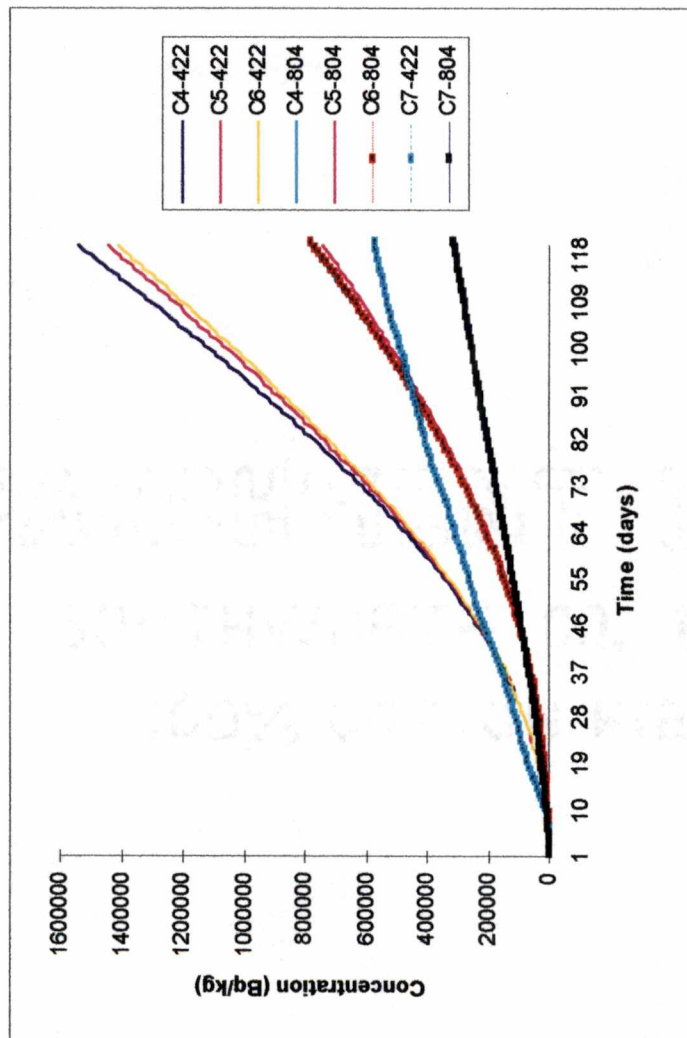
(c) at Nodes 1010 and 1247

Figure 5.15 (Continued)



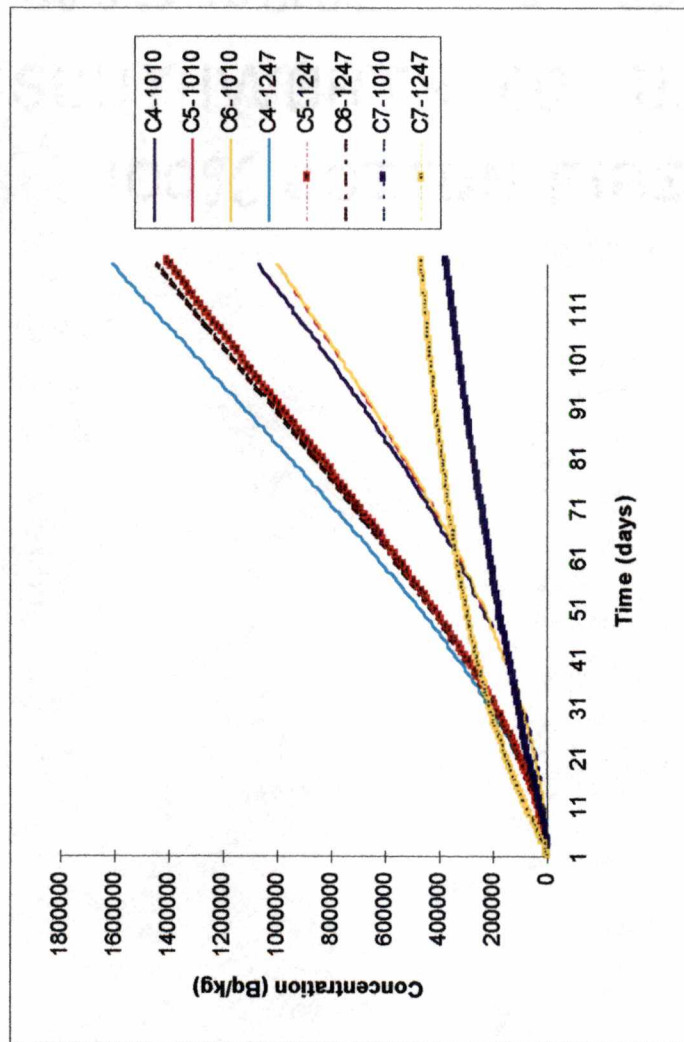
(a) at Nodes 15 and 204

Figure 5.16 Comparisons among Concentrations in Pred-fish under Conditions of Case 4, Case 5, Case 6, and Case 7 for 120 Days to Investigate Impacts of Biomass Change, Variable Ingestion Rates, and Food Web on Exposure Assessment in a Heterogeneous and Dynamic Radioactive Environment



(b) at Nodes 422 and 804

Figure 5.16 (Continued)



(c) at Nodes 1010 and 1247

Figure 5.16 (Continued)

As expected, there is very little difference between the bioaccumulation patterns with variable ingestion rates and those without because the ingestion rates at different locations are almost constant due to a large abundance of prey in this case, as discussed in Section 5.3.6.

5.4.2.3 Food Web Structure

It is expected that a different food web structure would have impacts on the radionuclide concentration accumulations in pred-fish. In the case 7 simulation, the pred-fish feed on multiple-preys: 50% phytoplankton, 20% zooplankton, and 30% prey-fish. Figure 5.16 shows the comparisons among the results of Case 7, Case 6, Case 5, and Case 4 at six locations. At all these locations, the concentrations accumulated in pred-fish are much lower than that using a single prey food web structure.

For example, by comparing the bioaccumulations in elements 15 and 204, it is evident that the concentrations accumulated in pred-fish through a multi-prey food web are almost four times lower than that obtained through a single-prey food web, and the difference varies among different locations. This is because that 50% food of pred-fish is phytoplankton which has a very much lower concentration than prey-fish. The difference occurring in this study indicates that it is important to consider the food preference and the content of diet of predators.

5.4.3 Hydrodynamics Effects

Hydrodynamics has been incorporated into this study in two ways. In order to evaluate effects of spatial variations of contaminated environmental conditions, radionuclide distributions were estimated by using a transport model which is coupled with hydrodynamics in Chapter 4. It is evident in Figure 4.6 that the hydrodynamics have a significant influence on the Cs-137 transport in the cooling pond during the simulation

period. After four months, the contaminant distributions in the whole cooling lake are still heterogeneous.

Hydrodynamics are also coupled with population dynamics in the transport model to determine phytoplankton and zooplankton distributions in the cooling pond. The results in Section 5.3.5 indicate that the hydrodynamics has impacts comparable to population growth in determining the plankton biomass changes for this ecological system in the early time. Later on, as the biota continue to grow, the relative influence of hydrodynamics gradually decreases in this particular physical environment.

5.4.4 Summary

The results presented in Figures 5.11 to 5.16 provide a spatial and temporal description of the effects of radioactive environments and of ecological functions on the biota exposure. Table 5.5 summarizes the relative effects among seven cases in element 15 after 120 days. Element 15 is located in the most contaminated region. The modeled concentrations of Cs-137 for the homogeneous and steady-state condition (Case 1) are used as the reference values. Values of the other cases are normalized to Case 1 concentrations, which are thus given values of 1.0 in Table 5.5.

The ratios in Table 5.5 indicate that the implications of these effects on Cs-137 accumulation vary among populations, and that they are significantly different in magnitude. For example, concentration under an equilibrium condition (Case 1) is almost 400% higher than under other conditions for pred-fish after 120 days, however, 30% lower for plankton. The spatial and temporal effects on bioaccumulation by all four populations, especially pred-fish, should be the primary factors which influence exposure during the early stage following the contamination.

Table 5.5 Comparison of Concentrations of Cs-137 Among Seven Cases in Element 15 after 120 Days to Give a Quantitative Estimate of the Relative Effects

Cases	Phytoplankton	Zooplankton	Prey-fish	Pred-fish
Case 1	1	1	1	1
Case 2	0.99	0.99	0.73	0.27
Case 3	0.99	0.99	0.72	0.26
Case 4	1.38	1.35	0.78	0.31
Case 5	1.38	1.34	0.69	0.26
Case 6		1.35	0.70	0.26
Case 7				0.1

Also, the summary in Table 5.5 indicates that the food web plays a significant role in the bioaccumulation in the pred-fish. For example, the concentration (Case 7) is only 10% of equilibrium concentration. Thus, the adequate determination of a diet for the population is very important for estimating radionuclide accumulation. Actually, the food diet of the biota always change during its life-span. Gardinier and Hoff (1980) indicate that 80 to 100% of the diet of young striped bass is plankton, while for age classes greater than two years, the striped bass are almost entirely piscivorous.

Based on the results in Table 5.5, the impact of adding biomass change or variable ingestion rates in the exposure model is less than that of including temporal and spatial radioactive environments or changing food web structure. However, this result should not be generalized for all physical environments, species, and radionuclides. Growth rates may have considerable impact on the exposure assessment during the accelerated growth phase of biota or for radionuclides with small radiobiological turn-over rates. Spatial- and temporal- dependent ingestion rates may cause more variations on the exposure when prey biomass values are low, or predators are abundant.

With regard to the objectives stated in Chapter 1, the modeling results suggest the following general conclusions:

1. The influence of hydrodynamics on radioactive material transport and distribution in the cooling pond is significant. The bathymetry of the cooling pond had a strong influence on formation of water circulation patterns. Consideration of hydrodynamic effects on the contaminant transport in nature may be necessary.
2. Both spatial and temporal heterogeneity of radioactive environments influence exposure, and their subsequent effects on the radionuclide bioaccumulation can be significant. The conventional bioaccumulation factors (with the assumption of homogeneous and steady-state conditions) over estimate the radionuclide bioaccumulation in pred-fish, and under estimate the bioaccumulation in plankton at some locations. Adding temporal and spatial effects into the exposure assessment may be necessary.
3. Impacts of changes in abundance and distribution of biomass on the bioaccumulation vary among different populations spatially and temporally. Although the impacts are not as significant as those associated with the other ecological factors (i.e., food web) in this study, they can be influential when biomass changes are significant, or when the radiobiological turn-over is slow.
4. The influence of spatial- and temporal-dependent radionuclide ingestion rates upon bioaccumulation is not as significant in this study if the prey is abundant. However, variable ingestion rates can be important when there are less prey or more predators as stated in Equation (3.26).
5. The plankton population growth has been integrated into the hydrodynamic-transport model to determine their biomass density change and distributions. The influences of

water circulation and plankton population growth upon the plankton biomass change and distribution are roughly equivalent in the Chernobyl cooling lake.

6. Food web structure has a significant impact upon transferring of radionuclides among populations. The impacts vary temporally and spatially. Results suggest that the determination of the diet of biota is necessary to realistically estimate exposure occurring in nature.

CHAPTER 6

CONCLUDING REMARKS AND RECOMMENDATIONS FOR FURTHER RESEARCH

A two-dimensional dynamic aquatic radioecological exposure assessment framework has been introduced in this dissertation. It integrates hydrodynamics, spatial and temporal heterogeneity effects of contaminant concentration, abundance and distribution of ecosystem populations, spatial- and temporal- dependent radionuclide ingestion, and different food web structures. The significance of integrating these effects into the exposure assessment is illustrated through a series of case studies for the contaminated Chernobyl cooling lake. Some general observations developed from this study are as follows:

1. *Hydrodynamic* effects determine the general characteristics of moving water, which in turn influences the contaminant and plankton transport in the water. As expected, the influence of hydrodynamics on radioactive material transport and distribution in the cooling pond is significant. Its impacts on changes in plankton biomass are comparable to that associated with population dynamics. This study suggests that it is necessary to include hydrodynamics in the exposure assessment, especially when there is a need for realistically estimating exposure in a two or three-dimensional space.
2. Both *spatial and temporal effects of radioactive environments* on the exposure assessment are very significant. The conventional bioaccumulation factors with the assumption of homogeneous and steady-state conditions over estimate the radionuclide accumulation in fish four to six times, and they under estimate the concentration in

plankton at some locations. This study indicates that it is very important to consider the spatial and temporal effects under the following situations: (1) when the contaminated water system is relatively isolated, such as a still lake without obvious inflow and outflow. In such water systems, the contaminant tends to be distributed heterogeneously since there may not be sufficiently intense water movement to mix and disperse the contaminants; (2) when the major fraction of bioaccumulation occurs early following the contamination, especially for fish. Due to the relatively slow radiobiological processes for most fish compared to plankton, fish require more time to reach an equilibrium condition. That is, the equilibrium concentration calculated using bioaccumulation factors will typically over estimate the concentration in fish.

3. *Impacts of changes in abundance and distribution of population biomass* on contaminant bioaccumulation vary among different populations spatially and temporally. It is necessary to consider the biomass effects for fish during periods of accelerated growth, or when the radionuclides or ecological species have low radiobiological turnover rates.

4. *Influences of adding spatial- and temporal- dependent ingestion rates* upon bioaccumulation are not significant for this study. However, variable ingestion rates can be important when there are fewer prey or more predators in an ecological system.

5. Based on the comparison of quantitative effects, *food web structure* is the most influential ecological factor for determining exposure of fish in these case studies. Its impacts vary spatially and temporally. The results obtained using a multi-prey food web structure (Case 7) can differ by a factor of 10 from the equilibrium concentration and by a factor of 2.5 from the concentration obtained using a single-prey food web (Case 6). The impacts of spatial and temporal heterogeneity of the contaminant in food are either magnified or reduced based on the food web structure. This study indicates that the

knowledge of the food web structure of the system can be the most important ecological information for a site-specific exposure assessment.

During the course of this research, several additional interesting effects were observed. The following discussion summarizes the important insights and recommends additional research:

- Addition of spatial and temporal details into the exposure model must be evaluated in light of the understanding of the complex interactions of ecosystems at the same spatial and temporal levels. These include spatial patterns of fish migration and home ranges, plankton behavioral process and social aggregations in space. Currently, such understanding is limited. Improved understanding of ecosystems in the spatial and temporal framework should improve forecasts of ecological exposure that occur in complex natural systems.
- A detailed ecological model, including the species-specific information, could be integrated into this model to extend the capacity of the proposed framework.
- As each level of detail is added into the model, additional parameters, such as rates of uptake and metabolism of different radionuclides for different ecosystem components are required. Quantification of these underlying process rates will be necessary to improve model structure and to continue the development in radioecological exposure modeling.

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APPENDIXES

APPENDIX A

FASTTABS AND TAB-MD MODELING SYSTEM

A.1 INTRODUCTION OF FASTTABS AND TABS-MD

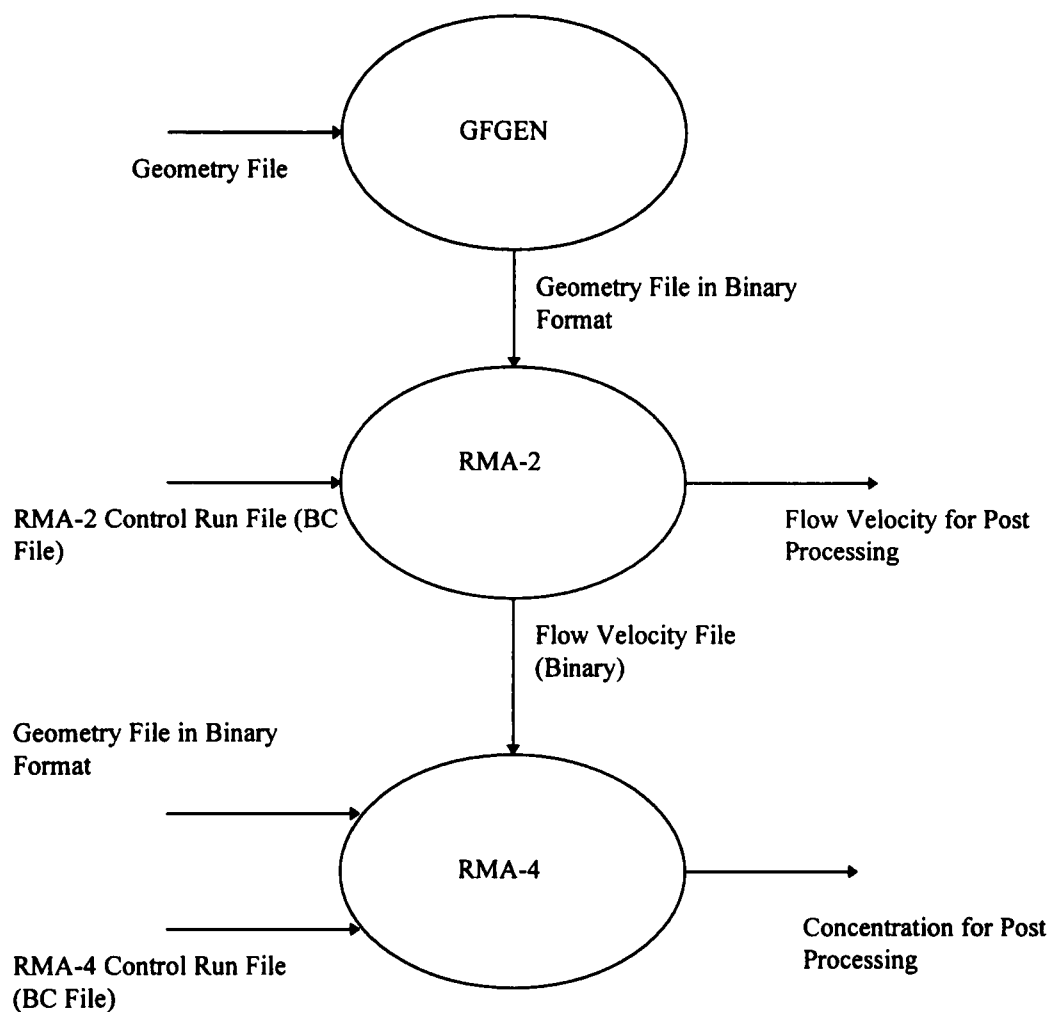
FastTABS was developed by the Engineering Computer Graphics Laboratory at Brigham Young University in cooperation with the U. S. Army Corps of Engineers Waterways Experiment Station (WES). FastTABS is a pre- and post-processor for two-dimensional finite element models and is specifically designed to be used in conjunction with TABS-MD suite of program maintained by WES.

The TABS-MD programs will calculate water surface elevations and flow velocities for shallow water flow problems. It is both a steady state and dynamic model. TABS-MD also includes codes for modeling contaminant migration.

The finite element meshes and associated boundary conditions necessary for TABS-MD modeling may be created with FastTABS and saved to geometry and boundary condition files. These files are then used by TABS-MD software to perform the hydrodynamic and contaminant transport analyses. The resulting files from the TABS-MD, which contain the water surface elevation & flow velocity at each node of the mesh and contaminant migration information, can be read into FastTABS to generate vector plots, color-shaded contour plots, time-history diagrams, and solution animation sequences.

TABS-MD consists of the following major components: GFGEN, RMA-2, and RMA-4. GFGEN generates a geometry and finite element mesh for a given research object. RMA-2 calculates water surface elevations and flow velocities for shallow water flow problems. RMA-4 models the contaminant migration for a water system.

The relationship among FastTABS, GFGEN, RMA-2, and RMA-4 is illustrated as follows:



Data Flow For the TABS-MD

A. 2 FINITE ELEMENT MESH GENERATION

A. 2. 1 Introduction of GFGEN Program

The GFGEN program is a pre-processor for other TABS-MD Modeling system. GFGEN program check the input geometry file and convert the geometry ASCII code into a Binary file for RMA-2 and RMA-4 codes.

The purpose of GFGEN program is to create a geometry and finite element mesh file for input to the TAB-MD modeling system programs and may also be used to plot the created mesh. The program GFGEN has these capabilities:

- Read node and element data and construct a finite element computational mesh for use by other programs in the TABS-MD modeling system.
- Identify errors and potential errors in the constructed mesh.
- Renumber the mesh, omitting unused nodes and element numbers.
- Fit curved element sides to land boundaries and interior element sides as specified.
- Developed an element solution order that permits the most efficient operation of models using the mesh.
- Write a file that contains the mesh information and geometry in format suitable for use by other TABS-MD programs.

GFGEN is capable of handling many different types of elements within the same computational finite element mesh. The types of elements fit into three basic categories: two dimensional elements, one dimensional elements and special elements. Elements may have either straight or curved edges.

A.2.2 Input File and Description

Input to GFGEN consists of control data. Each card image begins with a two or three character identification string followed by the data. Data may be formatted in column fields or free format separately by spaces or commas. The generation of the geometry file is much easier with FastTABS pre-and post-program. Geometry files, generated by FastTABS contain the data describing nodes, elements, and GO strings (used for node and element renumbering). Portions of the geometry data file for the Chernobyl cooling lake are listed as follows:

T1
T2 Created by FastTABS
T3
SI 1

```

$SL 3 0 6 0
GO 1 1 2 3 4 5 6 -1
GE 1 1 11 10 9 8 7 0 0 1 0.0
GE 2 1 13 2 12 10 11 0 0 1 0.0
GE 3 10 12 2 16 15 14 0 0 1 0.0
GE 4 3 17 15 16 2 18 0 0 1 0.0
GE 5 3 21 20 19 15 17 0 0 1 0.0
GE 6 3 23 4 22 20 21 0 0 1 0.0
GE 7 5 24 20 22 4 25 0 0 1 0.0
GE 8 27 26 20 24 5 28 0 0 1 0.0
GE 9 6 29 27 28 5 30 0 0 1 0.0
GE 10 6 33 32 31 27 29 0 0 1 0.0

.....
GE 601 1316 1317 1296 1302 1303 1318 0 0 2 0.0
GE 602 1308 1319 1316 1318 1303 1307 0 0 2 0.0
GE 603 1308 1310 1311 1320 1316 1319 0 0 2 0.0
GE 604 1316 1320 1311 1321 1300 1315 0 0 2 0.0
GNN 1 4.0034340e+002 1.6757463e+003 7.0000000e+001
GNN 2 5.0145075e+002 1.5240853e+003 7.0000000e+001
GNN 3 6.2783494e+002 1.3471474e+003 7.0000000e+001
GNN 4 7.2894229e+002 1.1954864e+003 7.0000000e+001
GNN 5 8.5532647e+002 1.0438254e+003 7.0000000e+001
GNN 6 9.8171066e+002 8.6688754e+002 7.0000000e+001
GNN 8 5.5285960e+002 2.0355287e+003 7.0000000e+001
GNN 10 8.2319817e+002 1.8994144e+003 6.0000390e+001

.....
GNN 1300 5.6764996e+003 1.1669896e+003 7.0000000e+001
GNN 1303 5.3581070e+003 1.4373286e+003 6.5838823e+001
GNN 1308 4.9523182e+003 1.2445805e+003 7.0000000e+001
GNN 1311 5.3402725e+003 1.1540578e+003 7.0000000e+001
GNN 1313 4.9817702e+003 1.0501446e+003 7.0000000e+001
GNN 1316 5.4109588e+003 1.2853498e+003 6.7242980e+001

```

T1-3 These three cards are used to define the title of a TABS problem. Although it is not necessary to have T1 and T2 cards, a T3 card must be included even if there is no particular title.

SI This card specifies the units to be used in the analysis. A 0 specifies English units while a 1 specifies SI units. All input parameters should be consistent; SI unit or English. The units defined by SI cards in the geometry file and the boundary condition file must match.

- \$L** This card is required by TABS-MD to identify the logical units used to open files. A 0 indicates that no file will be opened. The values are default.
- GO** GO cards are used to input the nodes for a GO string. GO strings are used as a reference line for automatic numbering of nodes and elements. The ID numbers of the nodes making up a GO string are listed in the corresponding GO card. A -1 signifies the end of a string. Several lines can be used to input a single string and several GO strings may be listed in a file.
- GE** GE cards define elements. The first integer on the line is the element ID. The next eight integers define the nodal connectivity of the element. The node ordering should be counter-clockwise beginning at a corner node and continuing sequentially around the perimeter of the element. Eight nodal ID number should be listed for each element. If an element has less than eight nodes, the indices of the unused nodes should be zero. The next term on the GE cards is the material number. A total of 604 elements is used to define the elements for the Chernobyl cooling lake.
- GNN** GNN cards are used to input nodal data. The first field on the line is an integer representing node ID. The next three fields of the line are x- and y-coordinates as well as depth of the node. Generally midside nodes for the quadratic elements are not listed. Midside nodal coordinates are automatically calculated by the program based on linear interpolation between adjacent corner nodes. There are total of 1316 nodes defined for the element generation of the Chernobyl cooling lake.

A. 3 FLOW VELOCITY CALCULATION

A. 3. 1 Introduction of RMA-2 Code

RMA-2 is a finite element hydrodynamic numerical model. It computes water-surface elevations and horizontal velocity components for subcritical, free-surface flow in 2D flow fields. RMA-2 is general purpose model designed for shallow water problems. It expects a vertically homogeneous fluid with a free surface.

RMA-2 has these capabilities:

- Read 1D and/or 2D geometry file from GFGEN, and modify as needed.
- Re-start the simulation from a previous RMA-2 run and continue.
- Identify errors in the network.
- Apply wind stress and/or frontal (storm) passages.
- Account for effects of the earth's rotation.
- Adjust for wetting and drying by element.
- March porosity wetting and drying (wetlands).

- User selectable turbulent exchange coefficients, Manning's n-values, temperature, etc. or User selectable equations for automatic dynamic assignment of Mannings n-value by depth, or User selectable Peclet number for automatic dynamic assignment of turbulent exchange coefficients.
- Model 5 different types of flow control structures.
- Accept either English or standard SI-units.
- Compute flow at continuity check points.
- Provides for user defined computational guidelines; such as: wet-dry parameters, iteration controls, revisions within a time step. Accepts a wide variety of boundary conditions.

A. 3. 2 Input File and Description

Boundary condition files to RMA-2 are associated with a particular geometry file and contain data describing boundary conditions, material properties, and other analysis parameters. The boundary condition files can be generated for steady state or dynamic analyses. In this application, the boundary conditions for the Chernobyl cooling lake are modified to include the information on wind load. A small portion of the boundary condition file is presented.

```

T1
T2 Created by FastTABS
T3
SI 1
$L 0 0 60 64 0 3 0
TR 1 -1 1 0 0
GC 6 1 3 5 7 9 11
GC 5 1292 1283 1281 1308 1313
GC 7 96 121 131 135 139 115
GC 118
GC 9 193 190 199 204 207 212
GC 216 248 289
GC 7 341 338 344 348 325 329
GC 299
GC 5 441 438 455 469 452
GC 3 506 524 521
GC 5 787 784 933 955 925
GC 6 1021 1017 1043 1071 1123 1128
GC 7 1199 1195 1192 1221 1242 1236
GC 1239
GC 4 655 676 668 661
TZ 6.0 2886.0 1924 0 0
TI 4 4 0.0001 0.0001

```

```

FT 15.0
IC 71.0 0.2 0.25
EV 1 240.0 240.0 240.0 240.0 0.025
EV 2 240.0 240.0 240.0 240.0 0.025
EV 3 240.0 240.0 240.0 240.0 0.025
EV 4 240.0 240.0 240.0 240.0 0.025
EV 5 240.0 240.0 240.0 240.0 0.025
BWC -1 1
BW 1 2.85 -30
END simulation at time = 6
BWC -1 1
BW 1 3.22 -30
END Simulation at time = 12
BWC -1 1
BW 1 5.05 -30
END Simulation at time = 18
BWC -1 1
BW 1 3.51 -30
END Simulation at time = 24 (day 1)
BWC -1 1
BW 1 2.85 -30
END Simulation at time = 30
BWC -1 1
BW 1 3.22 -30
END Simulation at time = 36
BWC -1 1
BW 1 5.05 -30
END Simulation at time = 42
BWC -1 1
BW 1 3.51 -30
END Simulation at time = 48 (day 2)
.....
BWC -1 1
BW 1 3.1205 20
END Simulation at time = 2838
BWC -1 1
BW 1 3.2945 20
END Simulation at time = 2844
BWC -1 1
BW 1 5.00525 20
END Simulation at time = 2850
BWC -1 1
BW 1 3.13 20

```

```

END Simulation at time = 2856 (day 119)
BWC -1 1
BW 1 3.1205 20
END Simulation at time = 2862
BWC -1 1
BW 1 3.2945 20
END Simulation at time = 2868
BWC -1 1
BW 1 0 20
END Simulation at time = 2874
BWC -1 1
BW 1 0.6 20
END Simulation at time = 2880 (day 120)
STOP

```

T1-3 The T cards are available for defining the title.

SI This card specifies the units used in analysis. All input parameters should be in the same units as the ones used in the geometry file. An exception occurs in the FT card (a temperature input card) where data must always be defined in degree Celsius.

\$L TABS-MD uses the \$L card to assign logical unit numbers to the files used in analysis.

TR The TR card controls the ASCII outputs generated during the analysis. A 1 in the first field specifies all input data printed except initial conditions. A -1 in the second field defines the number of iterations/time-steps between successive prints for the last iteration of every time-steps. A 1 in the third field defines that run control input is echoed. A 0 in the fourth field de-activate the print summary for each node. The last 0 in the card specifies no trace needed for subroutine calls and controllers.

GC GC cards contain data describing strings of nodes called GC string or continuity check lines. These are used to define BHL/BQL (water surface elevation card/flow rate card) lines as well as to check for mass continuity in the analysis. The data on a GC card should not extend more than 80 spaces. Therefore, if a string requires more than 80 spaces, data may be placed on additional GC cards following the first. Multiple GC strings may be input using the same guidelines. The first field defines total number of nodes to be listed for continuity like. The rest fields define the corner node number 1, ..., total number.

- TZ** The TZ card defines the number of time-steps and the time-steps length for a dynamic analysis. This card is only required for a dynamic analysis. The first field of the command defines the length of the computation time interval. A 0 is entered for a steady state analysis. The second field specifies total run times in decimal hours. The third field defines total number of time-steps (cycles). The fourth field specifies how far to skip in the BC file before the dynamic analyses. The last field is used to define initial run/restarting on the first iteration in the convergence scheme or restart at an intermediate iteration in the convergence scheme.
- TI** The TI card controls the number of iterations used in both steady state and dynamic analysis. If the default values assigned by FastTABS do not provide sufficient stability, the iteration number may be increased. The first field defines number of iterations for initial solution. The next field is used to provide number of iteration for each dynamic time-steps. The following fields are the user-defined criteria for satisfactory depth convergence during steady state or dynamic analyses.
- FT** The FT card is used to input the water temperature. The temperature must always be entered in degree Celsius regardless of the status of the SI card. RMA-2 uses a default values of 17.0.
- IC** The IC card is used to define the initial water surface elevation. If a BHL boundary condition is present, the IC value should be set equal to the BHL. If a BHL boundary condition has not been specified, this value should be set slightly higher than the maximum nodal elevation.
- EV** The EV card contains computational data associated with a specific material. Materials are assigned a material ID, eddy viscosity, and a Manning's n value. Before an analysis can be made, each element of a mesh must reference a material defined by the EV card.
- BWC** The BWC card defines the wind control formulation. The BWC card followed by a BW type card for wind speed and direction is required if a wind field is to be applied to RMA-2. The first field of the line contains the control for wind field input. A negative 1 represents that wind fields are specified at each node. The next field is a flag to identify the units of the wind speed. A 1 defines that the units of the wind speed in the analysis is meters per second. The final fields will be the necessary coefficients required for the wind formulation.
- BW** The BW card defines the wind speed and directions. The first field specifies the node or element numbers at which the wind speed applies. The second field specifies the wind velocity. The units of the wind speed is defined by a BWC

card. The third fields define the directions toward which the wind is blowing, measured in degrees, counterclockwise from the x-axis. For example, a SE wind, as reported by the conventional meteorological terms, blows toward the NW. This would be an angle of 135 degrees counterclockwise from a positive x-axis (with the + x-axis oriented to the east).

END The END card signifies the end of the boundary condition input for a particular time-step. Every time-step should be concluded with a END card. Because steady state analysis does not involve time-steps, only one end card is required.

STOP The STOP card signifies the end of an analysis.

Some commonly used cards for the boundary condition definition are also discussed.

BCN The BCN card defines various types of nodal boundary conditions including: velocity, head, or flow. The first field of the line contains the node number, the next field indicates the type of boundary condition applied, and the final field(s) is the boundary condition value(s).

BCC The parameters on this card are necessary if and only if the user wishes to revise the boundary condition update parameters between dynamic time steps. The BCC cards are used in conjunction with BCN cards to change the wind inputs on specified nodes. The first field specifies the time step length in decimal hours for changing the wind inputs. The number of nodes for which boundary conditions are specified on BCN cards. If zero, the program will self-count the number of BCN cards for this time step if and only if an END card is used.

BA Alternatives to the BC-based cards (BCN and BCC) are sets of cards (BA-BS or BQ-BH) on which the same three boundary parameters are coded as on BC-cards, but they are coded in alternate format which may be more convenient. The first set allows an azimuth to be used along with a current or discharge to establish the inflowing velocity components: BA-card = azimuth of the boundary velocity vector; BS-card = speed of the boundary velocity; and BH card = the water-surface elevations. The BQ-cards can be used in place of BS-cards. The BA-cards should proceed the others and azimuth on it will be used to calculate either velocity components or unit discharge components until another BA-card is read. Only those values which differ from previous values must be changed.

BS The magnitude of the velocity vector is coded on this card type. The input data program will convert BS data to U- and V- velocity components using the azimuth on a BA card. Sign of the component is calculated from its azimuth and the specified grid orientation. The first field define the node number. The second field specifies the current speed in fps or m/s. Sign will be determined from the

azimuth of the vector. The following fields repeat the input of nodes and current velocity. This card is optional.

- BQ** The BQ lines are used in conjunction with GC strings to define flow rate boundary conditions. The flow rate is assumed to be constant along the boundary defined by the BQ lines. A b, N, E, or L is immediately followed the BQ card. A b uses the unit discharge in Fields 2 and 3 of the BQ card for all boundary nodes equal to or greater than the number specifies in Field 1 of the BQ card. A N defines the BQ card is applied to selected node number i for inflow value. A E specifies the element number for element side inflow. A L defines the continuity line number for inflow value. The first field of the BQ card is used to define the node, element, or continuity line number as indicated by the letter N, E, or L immediately following BD card. The second field could be a unit discharge (cfs/ft) for a BQb card, the element inflow per unit area or length as appropriate to the element for a BQN card, or the total flow (cfs) crossing the continuity line for a BQL card. The last field of the BQ card is the direction of flow (radians measured counterclockwise from + x-axis). RMA-2 also adjusts the boundary directions to maintain parallel flow.
- BH** The BH lines are used in conjunction with GC strings to define head or water surface elevation boundary conditions. The head is assumed to be constant along the boundary defined by the BHL line. The BH card is immediately followed by a letter b, N, E, or L. The usage of these letter is the same as the ones in the BQ cards. The first field is the node or continuity check line number as indicated by the letter immediately behind BH card. The second field specifies the water-surface elevation (ft or m).
- BR** The BR card specifies the boundary's reflection and absorption. The special reflecting or non-reflecting rates will be calculated through RMA-2 if a BR card is presented. This card is optional.
- \$M** The \$M card may be used to identify the machines for reading data, analyzing data, and storing data.
- CA** A CA card may be used to calculate special calculation variables.
- DE** The DE card is used to identify a wet/dry element in the analysis. The variable to determine the wet/dry conditions is involved in the criterion for sufficient depth and velocity convergence to allow the code to advance to the next dynamic time-step before the variable is satisfied. If the maximum x- and y- velocity changes is less than 0.5 times of the set values, and if the maximum depth change is less than the set values for the depth, the code advances to the next dynamic time-step.

- DM The DM cards specify the wet/dry elements by Marsh Porosity. This card is optional.
- EX The EX card specifies the turbulent exchange coefficient for velocity component in x direction. This card is required if EV card or PE card is not used. Turbulent exchange coefficients should be coded by element type. The first field is used to define element type number for the set of turbulent exchange coefficients. The second defines the x-momentum turbulent exchange in x-direction (lb-sec/ft^2 or Pascal-sec for SI unit). The third field defines the x-momentum turbulent exchange in y-direction (the same units as the one in second field).
- EY The EY card specifies the turbulent exchange coefficient for velocity component in y direction. Both EX and EY cards are required if no EV cards are used.
- FC The FC card specifies the flow control structures for 1D elements. The first field is used as the control identifier. The second field defines the flow control type. A numerical number 1 to 5 can be used in this field. A 1 means a point source of flow. The conditions are that flow out equals flow in plus source, and equal total head at each node of the control element. A 2 or 3 means that flow is a reversible function of head loss across the structure, and flow out equals flow in. A 4 means that the flow is a function of water surface elevation and flow out equals to flow in. A 5 means that head loss is a function of flow and flow out equals to flow in. The third field defines the basic flow types. The fourth field specifies the relational coefficient. The fifth field specifies a reference elevation or head difference. The sixth and seventh fields specify the exponent and direction of flow respectively.
- G1 The G1 card defines grids and geometry parameters. The first field is local average latitude degrees for calculating the Coriolis force or zero to turn off the Coriolis force calculation. The following two fields are used to specify the scale factors for x- and y-coordinates. The default is 1.0. The last field specifies the number of nodes with boundary conditions specified with BCN cards.
- GE The GE card defines the element connections. The element connections will be provided by the FastTABS pre-processor and will reside on logical unit 60. If so, this card should be omitted, unless small mesh revisions are required. Otherwise, code the Nodal Point-Element Connection Table. The first field defines the element number and the followings are used for the connection nodes.
- GN The GN card defines the coordinate values for a node with the appropriate scale factors. The first field is used for the node number and the following three fields are used to define the x-, y-, and z-coordinates.

- GT The GT card defines the element by material types. The first fields specify the element number and the second field defines the material types for that element.
- GV The GV card is used to define elements by Eddy Viscosity Tensors.
- GW The GW card defines 1-dimensional node width assignment.
- HN The HN card is used to specify the Manning n-value. Three options are available for coding n-values. Option 1 specifies a constant value for the entire grid. Option 2 specifies a value by element type. And option 3 defines the Manning n-value by element number. These options are listed in the sequence which they should be coded, and their priority is that option 3 overrides 2 and option 2 overrides 1 upon execution.

A.4 CONTAMINANT TRANSPORT CALCULATION

A. 4. 1 *Introduction of RMA-4*

RMA-4 is the contamination transport modeling portion of the TABS system. It uses the hydrodynamic solution from RMA-2 to define a flow velocity field for a given mesh. It also reads a set of user-specified point loads as input. The point loads are defined by a concentration and decay rate for a particular constituent. RMA-4 then models the migration and dissipation of the constituent for a given number of time steps.

The basic steps involved in performing a transport analysis with RMA-4 are as follows:

- Computer hydrodynamic solution using RMA-2
- Prepare transport input file.
- Run RMA-4.

Once the hydrodynamic solution is available, the next step in performing a transport analysis using RMA-4 is to prepare an ASCII contaminant transport input file. The concentration, decay rate, and dispersion coefficients of each constituent are defined in the input file. The number of time steps to be solved is also specified in the input file.

A. 4. 2 *Input File and Description*

Boundary condition files to RMA-4 are associated with a particular geometry file and contain data describing boundary conditions, material properties, initial contamination concentrations, and other analysis parameters. Portions of boundary condition file for RMA-4 contamination transport analysis for the Chernobyl cooling lake are listed.

```
T1
T2
T3
$L 10 20 0 0 31 0 33 0
$M 1
GS 1 1
HS 1 1 1
TC 0.0 24 121 2880 0
TH 0.0 2880
TO 24 -1 -1
TP 1 1 0 0 0
FQ 1 0
FQC 0.0001 0.0001 0.0001
DF 1 0.1 0.1
DF 2 0.1 0.1
DF 3 0.1 0.1
```

```

FT 17.0
ICT 1 830000
ICT 2 600000
ICT 3 43548
RE -1 0 24
END End of time step 1 (day 1)
END End of time step 2 (day 2)
END End of time step 3
END End of time step 4
END End of time step 5
END End of time step 6
END End of time step 7
END End of time step 8
END End of time step 9
END End of time step 10
.....
END End of time step 111
END End of time step 112
END End of time step 113
END End of time step 114
END End of time step 115
END End of time step 116
END End of time step 117
END End of time step 118
END End of time step 119
END End of time step 120 (day 120)
STOP

```

T1-3 The T cards are available for defining the title if a TABS file.

SI This card specifies the units used in analysis.

\$L TABS-MD uses the \$L card to assign logical unit numbers to the files used in analysis.

- HS The HS card defines the hydrodynamic scale factors. The first two fields are used to define the x- and y-velocity scale factors. The third field defines the depth scale factors. The default values for these factors are 1.0 if SI unit is used in the analysis. This card can be used to convert input from English system to SI system.
- TC The TC card is for time control. The first field of this card defines the starting time for a simulation (hours). The second field is the time step for the simulation (hours). The third field defines total number of time steps. The fourth field defines the maximum simulation time (hours).
- TH The TH card is used for timing a hydrodynamic analysis. The first field of the command defines the hours to be subtracted from input velocity file generated by RMA-2. The second field defines the time of last step on input velocity files.
- TO The TO card defines timing for binary output file write. This card is optional, but if it is missing, all computed time steps are save. The first field defines the decimal hour frequency to save final results. 0.25, for instance, will save at 1/4 hours. The second field of this card specifies the decimal hour
- TP The TP card defines the trace by constituents for all nodes. The first field of the card defines the print options. The second field specifies the print interval. The next field is used to define if an echo print is required. The last two fields are used for the subroutine trace and for detail internal print trace.
- FQ The FQ card defines the fluid qualities concentration. The first field specifies the number of quality constituents in the analysis. The next field is used to identify the type of constituents. A 1 or 2 can be used to represent dissolved oxygen or biological oxygen demand respectively. A 0 is for other types of constituents.
- FQC The FQC card is used for the fluid qualities and decay control. The following fields define the decay coefficients for each constituent (1/day). A 0 in this field indicates no decay and a ∞ for decay rapidly.
- DF The DF cards are used to define full diffusion coefficient (a combination of DX and DY). The first field of this card defines an element type. A negative number in the next field invokes automatic scaling of x and y diffusion of the element type (m^2/sec). The scaling is a function of both velocity and grid size. For instance, -20 will multiply the x diffusion auto-scale by 20. A positive number in this field define the x-direction diffusion coefficient of element type (m^2/sec). The next field defines the y direction diffusion coefficient.

- IC** The IC card is used to specify the initial quality concentration. The IC card can be in the form of ICb, ICT, ICE, or ICN. A b, T, E, or N is used to specify the initial concentration assignment for all elements, for material types, for element numbers, or for node numbers. The first field of this card defines the starting node number for the initial concentration assignment, or the material types, element numbers, or the node numbers. The second field defines the initial quality concentration.
- RE** The RE card defines the re-solve solution technique. The first field is used as Resolve save switch. The next field defines the resolve restore switch. The Last field is used to define the time step for this solution step (hours).
- END** The END card is used to separate time steps.
- STOP** The STOP is used to stop the simulation.

APPENDIX B

CODE FOR EXPOSURE CALCULATIONS

/ The following documents list the codes for performing the exposure calculations using Mathematica package.*/*

*/*Case 1: Homogeneous and Steady-state*/*

Cw=4*10⁵;
a2=0.6;
a3=0.25;
a4=0.2;
m1=0.0067;
m2=0.0018;
m3=0.00033;
m4=0.000067;
ku1=0.1;
ku2=0.008;
ku3=ku4=0.004;
kb1=0.69;
kb2=0.14;
kb3=kb4=0.0069;
Ef2=0.2;
Ef3=0.35;
Ef4=0.6;

kf2=a2*0.8*Ef2*m1/(m1+m2)
kf3=a3*0.8*Ef3*m2/(m2+m3)
kf4=a4*0.8*Ef4*m3/(m3+m4)

c1=ku1/(kb1+0.000068)*Cw
wc2=ku2/(kb2+0.000068)*Cw
c2=wc2+kf2/(kb2+0.000068)*c1
wc3=ku3/(kb3+0.000068)*Cw
c3=wc3+kf3/(kb3+0.000068)*c2
wc4=ku4/(kb4+0.000068)*Cw
c4=wc4+kf4/(kb4+0.000068)*c3

*/*Case 2: Homogeneous and Dynamic Radioactive Environment*/*

cw0=4*10⁵;
s=0.0001

```

a2=0.6;
a3=0.25;
a4=0.2;
m1=0.0067;
m2=0.0018;
m3=0.00033;
m4=0.000067;
ku1=0.1;
ku2=0.008;
ku3=ku4=0.004;
kb1=0.69;
kb2=0.14;
kb3=kb4=0.0069;
Ef2=0.2;
Ef3=0.35;
Ef4=0.6;

kf2=a2*0.8*Ef2*m1/(m1+m2)
kf3=a3*0.8*Ef3*m2/(m2+m3)
kf4=a4*0.8*Ef4*m3/(m3+m4)

weq=wc'[t]==-(s+0.000068)wc[t]
solw=NDSolve[{weq,wc[1]==cw0},wc,{t,1,121,1},MaxSteps->10000]
cw[t_]=First[wc[t]/.solw]
g1=Plot[cw[t],{t,1,121},Frame->True,GridLines->Automatic,
        PlotLabel->"Concentration (kBq/m^3) in water",
        PlotRange->{300000,450000}]

eq1=c1'[t]==ku1*cw[t]-(kb1+0.000068)*c1[t]
sol1=NDSolve[{eq1,c1[1]==0},c1,{t,1,121,1},MaxSteps->10000]
c1solved[t_]=First[c1[t]/.sol1]
g2=Plot[c1solved[t],{t,1,121},Axes->True,
        PlotLabel->"Phytoplankton",PlotRange->{0,100000}]

eq2=c2'[t]==ku2*cw[t]+kf2*c1solved[t]-(kb2+0.000068)*c2[t]
sol2=NDSolve[{eq2,c2[1]==0},c2,{t,1,121,1},MaxSteps->10000]
c2solved[t_]=First[c2[t]/.sol2]
g3=Plot[c2solved[t],{t,1,121},Axes->True,
        PlotLabel->"Zooplankton",PlotRange->{0,100000}]

eq3=c3'[t]==ku3*cw[t]+kf3*c2solved[t]-(kb3+0.000068)*c3[t]
sol3=NDSolve[{eq3,c3[1]==0},c3,{t,1,121,1},MaxSteps->10000]
c3solved[t_]=First[c3[t]/.sol3]

```

```

g4=Plot[c3solved[t],{t,1,121},Axes->True,
      PlotLabel->"Prey-fish",PlotRange->{0,600000}]

eq4=c4'[t]==ku4*cw[t]+kf4*c3solved[t]-(kb4+0.000068)*c4[t]
sol4=NDSolve[{eq4,c4[1]==0},c4,{t,1,121,1},MaxSteps->10000]
c4solved[t_]=First[c4[t]/.sol4]
g5=Plot[c4solved[t],{t,1,121},Axes->True,
      PlotLabel->"Pred-fish",
      Ticks->{Automatic,{0,500000,1000000,1500000,
2000000,2500000}}}]

Show[GraphicsArray[{{g2,g3},{g4,g5}}],Frame->True,FrameTicks->None]

/*Case 3: Homogeneous and Dynamic Radioactive Environment with Population
Dynamics*/

cw0=4*10^5;
s=0.0001;
a2=0.6;
a3=0.25;
a4=0.2;
m1=0.0067;
m2=0.0018;
m3=0.00033;
m4=0.000067;
ku1=0.1;
ku2=0.008;
ku3=ku4=0.004;
kb1=0.69;
kb2=0.14;
kb3=kb4=0.0069;
Ef2=0.2;
Ef3=0.35;
Ef4=0.6;

kf2=a2*0.8*Ef2*m1/(m1+m2);
kf3=a3*0.8*Ef3*m2/(m2+m3);
kf4=a4*0.8*Ef4*m3/(m3+m4);

zeta1=0.003;
zeta2=0.002;
zeta3=0.001;
zeta4=0.001;

```

```
weq=wc'[t]==-(s+0.000068)wc[t]
solw=NDSolve[{weq,wc[1]==cw0},wc,{t,1,121,1},MaxSteps->10000]
cw[t_]=First[wc[t]/.solw]
```

```
eq1=c1'[t]==ku1*cw[t]-(zeta1+kb1+0.000068)*c1[t]
sol1=NDSolve[{eq1,c1[1]==0},c1,{t,1,121,1},MaxSteps->10000]
c1solved[t_]=First[c1[t]/.sol1]
g1=Plot[c1solved[t],{t,1,121},
  PlotLabel->"Phytoplankton",PlotRange->{0,100000}]
```

```
eq2=c2'[t]==ku2*cw[t]+kf2*c1solved[t]-(zeta2+kb2+0.000068)*c2[t]
sol2=NDSolve[{eq2,c2[1]==0},c2,{t,1,120,1},MaxSteps->10000]
c2solved[t_]=First[c2[t]/.sol2]
g2=Plot[c2solved[t],{t,1,120},
  PlotLabel->"Zooplankton",PlotRange->{0,100000}];
```

```
eq3=c3'[t]==ku3*cw[t]+kf3*c2solved[t]-(zeta3+kb3+0.000068)*c3[t]
sol3=NDSolve[{eq3,c3[1]==0},c3,{t,1,120,1},MaxSteps->10000]
c3solved[t_]=First[c3[t]/.sol3]
g3=Plot[c3solved[t],{t,1,120},
  PlotLabel->"Prey-fish",PlotRange->{0,600000}]
```

```
eq4=c4'[t]==ku4*cw[t]+kf4*c3solved[t]-(zeta4+kb4+0.000068)*c4[t]
sol4=NDSolve[{eq4,c4[1]==0},c4,{t,1,120,1},MaxSteps->10000]
c4solved[t_]=First[c4[t]/.sol4]
g4=Plot[c4solved[t],{t,1,120},
  PlotLabel->"Pred-fish",Ticks->{Automatic,{0,500000,
  1000000,1500000,2000000,2500000}}]
```

```
Show[GraphicsArray[{{g1,g2},{g3,g4}}],Frame->True,FrameTicks->None]
Do[Print[c1solved[t]," ",
  c2solved[t]," ",
  c3solved[t]," ",
  c4solved[t]],{t,1,120}]
```

*/*Case 4: Heterogeneous and Dynamic Radioactive Environment;*

Case 5: Heterogeneous and Dynamic Radioactive Environment with Biomass Terms/*

```
a2=0.6;
a3=0.25;
```

```

a4=0.2;
m1=0.0067;
m2=0.0018;
m3=0.00033;
m4=0.000067;
ku1=0.1;
ku2=0.008;
ku3=ku4=0.004;
kb1=0.69;
kb2=0.14;
kb3=kb4=0.0069;
Ef2=0.2;
Ef3=0.35;
Ef4=0.6;

kf2=a2*0.8*Ef2*m1/(m1+m2);
kf3=a3*0.8*Ef3*m2/(m2+m3);
kf4=a4*0.8*Ef4*m3/(m3+m4);

zeta1=0.003;
zeta2=0.002;
zeta3=0.001;
zeta4=0.001;

dm1[t_]=D[mm1[t],t]
dm2[t_]=D[mm2[t],t]

eq1=c1'[t]==ku1*cw[t]-(kb1+0.000068)*c1[t]
sol1=NDSolve[{eq1,c1[1]==0},c1,{t,1,121,1},MaxSteps->10000]
c1solved[t_]=First[c1[t]/.sol1]

eq2=c2'[t]==ku2*cw[t]+kf2*c1solved[t]-(kb2+0.000068)*c2[t]
sol2=NDSolve[{eq2,c2[1]==0},c2,{t,1,121,1},MaxSteps->1000]
c2solved[t_]=First[c2[t]/.sol2]

eq3=c3'[t]==ku3*cw[t]+kf3*c2solved[t]-(kb3+0.000068)*c3[t]
sol3=NDSolve[{eq3,c3[1]==0},c3,{t,1,121,1},MaxSteps->1000]
c3solved[t_]=First[c3[t]/.sol3]

eq4=c4'[t]==ku4*cw[t]+kf4*c3solved[t]-(kb4+0.000068)*c4[t]
sol4=NDSolve[{eq4,c4[1]==0},c4,{t,1,121,1},MaxSteps->1000]
c4solved[t_]=First[c4[t]/.sol4]

```

```

bbeq1=bbc1'[t]==ku1*cw[t]-(dm1[t]/mm1[t]+kb1+0.000068)*bbc1[t]
bbsol1=NDSolve[{bbeq1,bbc1[1]==0},bbc1,{t,1,121,1},MaxSteps->10000]
bbc1solved[t_]=First[bbc1[t]/.bbsol1]

bbeq2=bbc2'[t]==ku2*cw[t]+kf2*bbc1solved[t]-(dm2[t]/mm2[t]+kb2+0.000068)*bbc2[t]
bbsol2=NDSolve[{bbeq2,bbc2[1]==0},bbc2,{t,1,121,1},MaxSteps->10000]
bbc2solved[t_]=First[bbc2[t]/.bbsol2]

bbeq3=bbc3'[t]==ku3*cw[t]+kf3*bbc2solved[t]-(zeta3+kb3+0.000068)*bbc3[t]
bbsol3=NDSolve[{bbeq3,bbc3[1]==0},bbc3,{t,1,121,1},MaxSteps->10000]
bbc3solved[t_]=First[bbc3[t]/.bbsol3]

bbeq4=bbc4'[t]==ku4*cw[t]+kf4*bbc3solved[t]-(zeta4+kb4+0.000068)*bbc4[t]
bbsol4=NDSolve[{bbeq4,bbc4[1]==0},bbc4,{t,1,121,1},MaxSteps->10000]
bbc4solved[t_]=First[bbc4[t]/.bbsol4]

Do[Print[bbc1solved[t]," ",
        bbc2solved[t]," ",
        bbc3solved[t]," ",
        bbc4solved[t]],{t,1,120}]

Do[Print[c1solved[t]," ",
        c2solved[t]," ",
        c3solved[t]," ",
        c4solved[t]],{t,1,120}]

/*Case 6: Exposure Modeling with Spatial- and Temporal- dependent Radionuclid
Ingestion Rates from Food; Case 7: Exposure Modeling with a Multi-prey Food Web
Structure*/

cw=Interpolation[ReadList["c:\\result\\pol1247.txt",Number]]
mm1=Interpolation[ReadList["c:\\result\\pht1247.txt",Number]]
mm2=Interpolation[ReadList["c:\\result\\zoo1247.txt",Number]]

a2=0.6;
a3=0.25;
a4=0.2;
ku1=0.1;
ku2=0.008;
ku3=ku4=0.004;
kb1=0.69;
kb2=0.14;
kb3=kb4=0.0069;

```

```

Ef2=0.2;
Ef3=0.35;
Ef4=0.6;

```

```

zeta1=0.003;
zeta2=0.002;
zeta3=0.001;
zeta4=0.001;

```

```

im3=0.000247;
im4=0.0000493;

```

```

qm3=m3'[t]==m3[t]*zeta3
calm3=NDSolve[{qm3,m3[0]==im3},m3,{t,1,121},MaxSteps->1000]
mm3[t_]=First[m3[t]/.calm3]

```

```

qm4=m4'[t]==m4[t]*zeta4
calm4=NDSolve[{qm4,m4[0]==im4},m4,{t,1,121},MaxSteps->1000]
mm4[t_]=First[m4[t]/.calm4]

```

```

sm[t_]=0.5*mm1[t]/1000+0.3*mm2[t]/1000+0.2*mm3[t]+mm4[t]
kf2[t_]=a2*0.8*Ef2*mm1[t]/(mm1[t]+mm2[t])
kf3[t_]=a3*0.8*Ef3*mm2[t]/1000/(mm2[t]/1000+mm3[t])
kf4[t_]=a4*0.8*Ef4*mm3[t]/(mm3[t]+mm4[t])
km1[t_]=a4*0.8*Ef4*mm1[t]/1000/sm[t]
km2[t_]=a4*0.8*Ef4*mm2[t]/1000/sm[t]
km3[t_]=a4*0.8*Ef4*mm3[t]/sm[t]

```

```

dm1[t_]=D[mm1[t],t]
dm2[t_]=D[mm2[t],t]

```

```

eq1=c1'[t]==ku1*cw[t]-(dm1[t]/mm1[t]+kb1+0.000068)*c1[t]
sol1=NDSolve[{eq1,c1[1]==0},c1,{t,1,121,1},MaxSteps->10000]
c1solved[t_]=First[c1[t]/.sol1]

```

```

eq2=c2'[t]==ku2*cw[t]+kf2[t]*c1solved[t]-(dm2[t]/mm2[t]+kb2+0.000068)*c2[t]
sol2=NDSolve[{eq2,c2[1]==0},c2,{t,1,121,1},MaxSteps->10000]
c2solved[t_]=First[c2[t]/.sol2]

```

```

eq3=c3'[t]==ku3*cw[t]+kf3[t]*c2solved[t]-(zeta3+kb3+0.000068)*c3[t]
sol3=NDSolve[{eq3,c3[1]==0},c3,{t,1,121,1},MaxSteps->10000]
c3solved[t_]=First[c3[t]/.sol3]

```

```
eq4=c4'[t]==ku4*cw[t]+kf4[t]*c3solved[t]-(zeta4+kb4+0.000068)*c4[t]
sol4=NDSolve[{eq4,c4[1]==0},c4,{t,1,121,1},MaxSteps->10000]
c4solved[t]=First[c4[t]/.sol4]
```

```
mmeq4=mmc4'[t]==ku4*cw[t]+(0.5*km1[t]*c1solved[t]+0.2*km2[t]*c2solved[t]+0.3*k
m3[t]*c3solved[t])-(zeta4+kb4+0.000068)*mmc4[t]
mmsol4=NDSolve[{mmeq4,mmc4[1]==0},mmc4,{t,1,121,1},MaxSteps->10000]
mmc4solved[t]=First[mmc4[t]/.mmsol4]
```

```
g2=Plot[kf2[t],{t,1,121},Axes->True,
PlotLabel->"Zoo. on phyt.",PlotRange->{0,0.1},Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1}}]
```

```
g3=Plot[kf3[t],{t,1,121},Axes->True,
PlotLabel->"Prey. on zoo.",PlotRange->{0,0.1},Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1}}]
```

```
g4=Plot[kf4[t],{t,1,121},Axes->True,PlotRange->{0,0.2},
PlotLabel->"Pred. on prey.",Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1,0.12,0.14,0.16,0.18,0.2}}]
```

```
g41=Plot[km1[t],{t,1,121},Axes->True,PlotRange->{0,0.2},
PlotLabel->"Pred. on phyt.",Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1,0.12,0.14,0.16,0.18,0.2}}]
```

```
g42=Plot[km2[t],{t,1,121},Axes->True,PlotRange->{0,0.1},
PlotLabel->"Pred. on zoo.",Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1}}]
```

```
g43=Plot[km3[t],{t,1,121},Axes->True,PlotRange->{0,0.1},
PlotLabel->"Pred. on prey.",Ticks->{Automatic,
{0.02,0.04,0.06,0.08,0.1}}]
```

```
g5=Plot[c1solved[t],{t,1,121},
PlotLabel->"Phytoplankton",PlotRange->{0,150000}]
```

```
g6=Plot[c2solved[t],{t,1,121},
PlotLabel->"Zooplankton",PlotRange->{0,150000}]
```

```
g7=Plot[c3solved[t],{t,1,121},
PlotLabel->"Prey-fish",PlotRange->{0,600000}]
```

```

g8=Plot[c4solved[t],{t,1,121},
      PlotLabel->"Pred-fish",Ticks->{Automatic,{0,250000,
      500000,750000,1000000,1250000,1500000,1750000,2000000}}]

g9=Plot[mmc4solved[t],{t,1,121},
      PlotLabel->"Pred-fish with multi-prey",PlotRange->{0,800000}]

Show[GraphicsArray[{{g2,g3},{g4}}],Frame->True,FrameTicks->None]
Show[GraphicsArray[{{g5,g6},{g7,g8}}],Frame->True,FrameTicks->None]
Show[GraphicsArray[{{g41,g42},{g43}}],Frame->True,FrameTicks->None]

Do[Print[c1solved[t]," ",
      c2solved[t]," ",
      c3solved[t]," ",
      mmc4solved[t]],{t,1,121}]
Do[Print[c4solved[t]],{t,1,121}]

```

VITA

I was born in Beijing, China. I graduated from Beijing University of Science and Technology, in August, 1984 with a Bachelor of Science Degree in Mechanical Engineering. I had been a research engineer/nuclear equipment in Beijing Institute of Nuclear Engineering for more than five years before I came to the U. S. A. to study for an advanced degree. I received my Master of Science Degree with a major in Nuclear Engineering (Health Physics Program) and a minor in Statistics in December of 1991. I expect to be awarded the Doctor of Philosophy Degree with a major in Nuclear Engineering in August of 1995.