

**AERB SAFETY GUIDE NO. AERB/SG/S-2**

**HYDROLOGICAL DISPERSION  
OF RADIOACTIVE MATERIALS  
IN RELATION TO  
NUCLEAR POWER PLANT SITING**

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**Atomic Energy Regulatory Board  
Mumbai 400 094**



## FOREWORD

Since the inception of nuclear power development in the country, maintenance of high safety standards has been assigned prime importance. Recognising this aspect of nuclear power development, Government of India constituted Atomic Energy Regulatory Board (AERB) in November 1983 vide standing order No. 4772 notified in Gazette of India dated 31.12.1983. AERB has been entrusted with the responsibility of laying down safety standards and frame rules and regulations in respect of regulatory and safety functions envisaged under the Atomic Energy Act 1962. Under its programme of developing Codes and Safety Guides, AERB has issued four Codes of practice covering the following topics:

Safety in Nuclear Power Plant Siting

Safety in Nuclear Power Plant Design

Safety in Nuclear Power Plant Operation

Quality Assurance for Safety in Nuclear Power Plants

These Codes are intended to establish the objectives and to set the minimum requirements that shall be fulfilled to provide assurance that nuclear power plants will be sited, designed, constructed and operated without undue risk to personnel, public and environment.

The Codes and Safety Guides will be subject to revision as and when necessary in light of experience as well as the current state of the art in science and technology. The first revision of this Guide will be considered after a period of about five years.

In preparation of the Codes and Guides emphasis is on protection of site personnel and public from undue radiological hazard. This Safety Guide on Hydrological Dispersion of Radioactive Material in Relation to NPP Siting outlines the methodology and procedures for carrying out analysis as applicable for implementing the relevant parts of the Code of Practice on Safety in Nuclear Power Plant Siting published by AERB No. AERB/SC/S.

Consistent with accepted practice for Codes and Guides, "shall" and "should" are used to distinguish for the potential user between a firm requirement and a desirable option. An appendix when included is a part of the document, whereas annexures, foot notes, and bibliographies where included are only to provide information that might be helpful to the user.

This Safety Guide has been prepared by the staff of AERB and other professionals. The criteria followed by DAE for selection of site and the relevant

International Atomic Energy Agency (IAEA) documents under the NUSS programme specially the Hydrological Dispersion of Radioactive Material in Relation to Nuclear Power Plant Siting (50-SG-S6 of IAEA) and similar documents from various leading countries, suitably adapted to Indian conditions have been utilised extensively in the preparation of this Guide. It has been reviewed by experts both in the Government and outside and amended by an Advisory Committee before issue. AERB wishes to thank all individuals and organisations who have contributed in the preparation, review and amendment of this Guide. List of persons who have participated in the Committee meetings and their organisations is included for information.

(Prof. P.Rama Rao)  
Chairman, AERB

## DEFINITIONS

### Accident Conditions

Substantial deviations<sup>1</sup> from Operational States which are expected to be infrequent, and which could lead to release of unacceptable quantities of radioactive materials if the relevant engineered safety features did not function as per design intent.

### Atomic Energy Regulatory Board (AERB)

National authority designated by Government of India having the legal authority for issuing the regulatory consents for various activities related to a facility and to perform safety and regulatory functions including enforcement for the protection of the public and operating personnel against radiation and Factories Act for Department of Atomic Energy.

### Construction

The process of manufacturing and assembling the components of a facility, the erection of civil works and structures and installation of components and equipment.

### Critical Group

A group of members of the public which is reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) by the given exposure pathway from the given source. When exposure occurs by more than one pathway, the term may also be used to mean the group which receives the highest total doses by all the pathways of exposure from a given source or practice.

### Critical Pathway

The dominant environmental pathway through which members of the critical group are exposed to radiation.

### Critical Nuclides

Nuclide(s) that contribute(s) to major fraction of effective (equivalent) dose to the critical group of population.

### Discharge Limits

The limits prescribed by the Regulatory Body for effluent discharges into atmosphere/aquatic environment from facilities.

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<sup>1</sup> A substantial deviation may be a major failure, a Loss of Coolant (LOCA) etc. Examples of engineered safety features are: an Emergency Core Cooling System(ECCS), and containment.

**Dose Equivalent**

Radiation dose received by a person through all pathways due to environmental releases under normal operation and due to external and inhalation and submersive doses in atmosphere under accident conditions. For long term radiation dose received by whole body or individual organs such as thyroid/bone due to ingestion of contaminated food products also will be considered.

**Effluent**

Any waste discharge into the environment from a facility either in the form of liquid or gas.

**Emergency Planning Zone**

Any waste discharged into the environment from a facility either in the form of liquid or gas.

**Exclusion Zone**

The exclusion zone extends upto a distance of 1.6 km around the plant where no public habitation is permitted. This zone is physically isolated from outside areas by plant fencing and is under the control of NPP.

**Normal Operation**

Operation of a Plant or equipment within specified operational limits and conditions. In case of nuclear power plant this includes start-up, power operation, shutting down, shutdown state, maintenance, testing and refuelling.

**Nuclear Power Plant**

A thermal neutron reactor or reactors together with all structures, systems and components necessary for safety and for the production of power, i.e. electricity.

**Operation**

All activities following commissioning and before decommissioning performed to achieve in a safe manner the purpose for which an installation was constructed, including maintenance.

**Pre-operational Stage**

The stage of study and investigation after the start of construction and before start of operation in order to complete and refine the assessment of site/plant data characteristics.

**Prescribed Limits**

Limits established or accepted by the Regulatory Body for specific activities or circumstances that must not be exceeded.

**Regulatory Body**

See “Atomic Energy Regulatory Board”.

**Safety**

Protection of all persons from undue hazard.

**Site**

The area containing the facility, defined by a boundary and under effective control of the facility management.

**Site Selection Stage**

The stage in which identification of one or more preferred candidate sites after the scrutiny of both safety and non-safety considerations is done. This involves the study and investigation of a large region. It results in the rejection of unacceptable areas, and is followed by systematic screening, selection and comparison of those sites situated in the remaining acceptable areas.

**Siting**

The process of selecting a suitable site for facility, including appropriate assessment and definition of the related design bases.





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# 1. INTRODUCTION

## 1.1 General Considerations

Environmental aspects play an important role in siting of a Nuclear Power Plant (NPP) from safety angle. The environmental considerations that govern siting and operation of an NPP are two fold:

- those that affect NPP itself; and
- those effects of NPP having direct or indirect impact on the public and immediate environs.

The site characteristics that affect the safety of NPP are natural events such as seismicity, liquefaction, subsidence<sup>2</sup>, storm, flooding etc., and man-induced events. The characteristics such as population distribution, meteorology, surface hydrology and geohydrology contribute to the impact of NPP on environment.

The hydrosphere<sup>3</sup> represents an important pathway by which radioactive materials discharged from NPPs into the environment reach man. The release of radioactive materials into the surface waters<sup>4</sup> can be either routine, planned or accidental. During normal operating conditions, the routine releases are controlled to be within the limits specified by the Regulatory Body. There can also be planned short-term releases in a controlled manner during off-normal operating conditions. Such releases are also regulated to be within the limits specified by the Regulatory Body on an annual basis. Adequate engineered safety features are provided to prevent an accident and also mitigate the consequences should one occur at all. Such provisions prevent uncontrolled releases to the environment. During accident conditions, the liquid radioactive effluents are expected to be largely contained may not find its way into the surface waters in an uncontrolled manner.

The term 'surface water' used in this Guide refers to open bodies of water on the earth surface including waters of the mixed layers of the seas. Although these form a continuum with ground water, a distinction has been made for the purpose of dispersion analysis since radionuclides are transported rapidly in surface waters.

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<sup>2</sup> The sinking or caving in of the ground to a lower level.

<sup>3</sup> The total water body including surface and sub-surface water.

<sup>4</sup> Those open bodies of water on the earth's surface.

## 1.2 Scope

This Guide covers the dispersion of radioactive materials released from NPPs into the surface waters under normal operating and accidental conditions. The effect of washout of air-borne radionuclides during normal conditions is negligible and in case of accidents is small and they are however considered in the source term evaluation, and method of evaluation and analysis remains the same. The Guide gives:

- Information which needs to be collected during various stages of siting;
- A minimum measurement programme; and
- The selection and validation of appropriate mathematical models for predicting dispersion.

Puff releases are short term uncontrolled off-normal releases from NPPs (these can be brought under control by engineered safety features). However, the total amount of release on an annual basis will be restricted within the prescribed limits. The models presented in this Guide provide estimates of radioactivity concentrations for varied situations such as steady state (routine) releases, instantaneous or puff (accidental) releases and time-dependent long-term releases (routine or accidental). For all these situations, both simple and complex models are available. The parametric values are chosen for these models in such a way to predict conservative concentrations and thereby restrict the releases so as to minimise undue risk to the population through aquatic pathway. However, when simple models provide adequate solution, they are preferred. Guidelines are also provided for the optimal use of models for a specific site situation and for the necessary input parameters.

For the purpose of collection of data, an area within 16 km of radius from the point of discharge should be covered as regulatory requirement. However, it is desirable that monitoring is carried out in an area of 30 km radius as mentioned in this Guide.

Regulatory Body stipulates a dose limit to a member of a critical group from all exposure pathways. This total dose in turn is apportioned at a particular site between various facilities including a reserve for possible expansion. In a facility, the dose apportionment is further subdivided into different pathways, i.e., air, water, and terrestrial. The scope of this Guide, is to obtain derived limits for surface water discharges consistent with the authorized dose apportionment. This will enable regulating the discharges as, the derived limits are obtained using the models described in this Guide to predict the concentration in the water bodies which can

be translated into dose using the radiological pathway. Measures like pre-dilution, adequate waste management provision and adequate engineered safety features control the releases to be within the prescribed limits.

## 2. RADIONUCLIDE DISPERSION IN SURFACE WATERS

### 2.1 Dispersion Phenomena

Radioactive materials released into surface waters are subjected to the same physical, chemical and biological processes that affect non-radioactive isotopes in the same physical state. The additional factor influencing the distribution of a released radionuclide is the radioactive decay. From a practical standpoint, the introduction of radionuclides will result in some initial mechanical mixing. The initial mixed volume resulting from this mechanical mixing is termed as initial cloud. The local current pattern will advect the initial plume away from the point of introduction and the small scale turbulent motion will produce dispersion of the cloud causing it to grow in volume and thus decrease the concentration within it. As the cloud increases in size, the scale of motion producing an advection of the cloud as a whole increases. Eddies much larger than the cloud are considered to be responsible for the advection of the cloud as a whole, and eddies much smaller than the cloud produce dispersion by turbulent diffusion. However, eddies approximately of the same size as the cloud significantly influence the shape of the cloud and contribute to the dispersion as well. Consequently, any model intended to describe changing shape and concentration distribution for considerable length of time must take into account the changes in scales of motion contributing to the various aspects of the movement and mixing of the initial cloud.

Dispersion in the surface water is the result of diffusion and hydrological dispersion. Dispersion, being a macroscopic process, usually dominates the microscopic diffusion. Both processes are commonly lumped together and modelled using macroscopic dispersion coefficients denoted by  $K_x$ ,  $K_y$  and  $K_z$ . The importance of dispersion and the value of the corresponding coefficient may thus be quite large especially in rivers along the direction of flow of the effluent. In case of estuaries and tidal seas<sup>5</sup>, all turbulent mixing processes are also included in the values of  $K_x$ ,  $K_y$  and  $K_z$ .

### 2.2 Factors Governing Dispersion

Radionuclides introduced into the surface waters in liquid or particulate form are subject, on varying time scales, to some degree of dispersion

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<sup>5</sup> Seas in which the influence of tides is predominant. These seas have spring tidal ranges greater than 50 cm for the semi-diurnal tide and greater than 20 cm for the diurnal tide.

and dilution. The degree of dispersion depends on not only the physical state in relation to the receiving medium, but also on the distance from the source (point of introduction) and mode of introduction. This, in turn, will depend to some extent on temperature and density differences between the effluent and the recipient medium, on its rate of introduction relative to factors such as river flow, movement of suspended silt and turnover time<sup>6</sup> of the nuclide, tidal current etc.. Two additional factors which must also be taken into account are fractionation which occurs between different components of receiving medium (e.g. water and sediment) and ageing (physical decay) processes which will modify the extent to which a radionuclide is available for transfer through subsequent stages of a pathway. All these factors are to be considered to determine dilution and dispersion.

### **2.3 Processes Governing Concentration Distribution**

The concentration distribution of radioactive materials released into surface water is governed by processes such as transport by movement of water, dispersion in water, adsorption and retention of radioactive materials by suspended sediments and detrital materials and their settlement, uptake by biota and radioactive decay and build-up. The transport and turbulent dispersion processes are governed by normal wind driven currents. However, extreme wind effects which are short term phenomena, cannot be modelled into the dispersion equations. Basically, all processes other than radioactive decay, which lead to depletion of concentration in the primary receiving medium, result in transfer to other compartments of the environment. Transfer of radioactivity from the recipient medium to biological and physical materials as well as its resuspension processes can be evaluated assuming quasi steady-state situation. It is adequate to use concentration factors at equilibrium for evaluation of such transfers. Simplified representations of the pathways to man from aquatic releases during normal operations of NPP and from atmospheric wash-out releases under accident conditions are represented in Figure-2.1.

### **2.4 Information needed for the study**

The general information required for the evaluation of concentration distribution of radioactive materials in the aquatic environment and dose resulting there from include:

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<sup>6</sup> The time in which any radioactive nuclide introduced into a water body gets flushed out from the water body.

- Source terms (Release rate, duration and radionuclide composition) of radioactive materials released from the NPP;
- Physico-chemical characteristics of the released radioactive materials, hydrological characteristics governing transport and dispersion of materials, and geochemical and biological characteristics of the recipient medium. (This information should be provided for different parts of the aquatic system of the region<sup>7</sup>);
- Location and amount of water used downstream of point of introduction for drinking, industrial, agricultural and recreational purposes [within Emergency Planning Zone (EPZ)]; and
- Dietary and dwelling habits, including occupational habits (handling of fish gear) and hobbies (fishing, sunbathing and swimming) of the members of critical group.

The above information is needed in order to select an appropriate dispersion model for a specific site and to establish the limiting discharge rate for radioactive effluents into the surface waters.

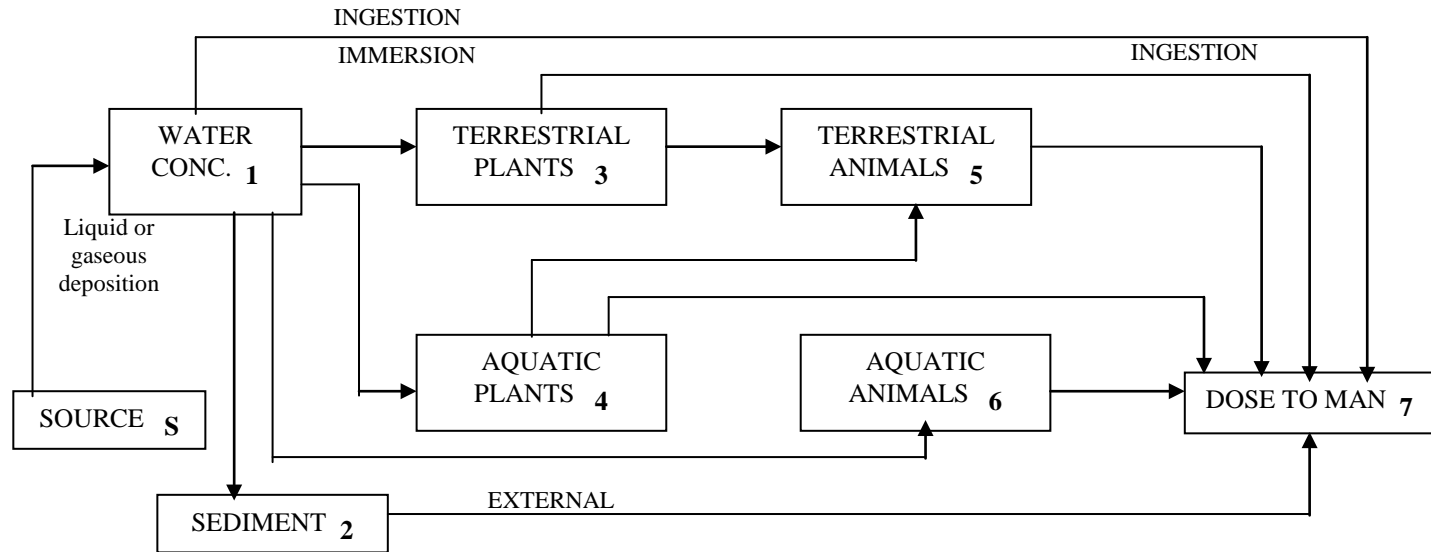
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<sup>7</sup> A geographical area, surrounding and including the site, sufficiently large to contain all the features related to a phenomenon or to the effects of a particular event.



**Fig. 2.1 : The different aquatic routes by which the radioactivity released can reach man**

Legend : ——— indicates actual contribution





### **3. INVESTIGATION PLAN AT VARIOUS STAGES OF SITING**

#### **3.1 Stages of Siting**

NPP siting procedure involves detailed investigation of varied technical information around a region (30 km radius) and these are obtained under three stages viz.: site selection stage, site evaluation stage<sup>8</sup> and pre-operational stage. The site evaluation assessment continues during Construction and Operational stages of the NPP. The models depicted in this Guide are useful to predict concentrations in the water body and in turn the derived limits using appropriate radiological models for the aquatic pathway. The releases from NPPs are controlled within the regulatory limits on the basis of sound waste management schemes with the philosophy of maximum concentration and containment of radioactivity and other engineered safety features.

#### **3.2 Information Needed at Site Selection Stage**

In site selection stage, general hydrological information is collected for a preliminary evaluation. The data required are described in the following paragraphs.

Primary information is needed on the quantity and type of radioactive material which may be released during normal operation and accident conditions of the NPP. Coarse estimate on source term under accident conditions is adequate and this should primarily include depositional flux from the atmosphere to the surface waters. At the site selection stage, this information may or may not be available. Sometimes decision may not have been made for the type of plant to be constructed. However, it should be possible to obtain some information on the quantity and type of radioactive materials for a given type of a reactor, either from past experiences or from the literature. The radionuclides discharged during normal operation into the aquatic environment as liquid effluents may include tritium, <sup>137</sup>Cs, <sup>131</sup>I, <sup>90</sup>Sr, <sup>60</sup>Co etc. within the limits specified by the Regulatory Body. However, it should be realised that the major contributor to the releases under accident situations would be

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<sup>8</sup> Site evaluation stage is a stage in which a study and an investigation of one or more preferred candidate sites to demonstrate their suitability from various aspects, and in particular from the safety point of view is carried out. At a later point of this stage, the site-related design basis are determined knowing the type and design of NPP.

atmospheric releases and the direct release of liquid effluents into the aquatic environment is not normally envisaged.

The description of important water bodies in the region (upto EPZ) is required at this stage together with an approximate evaluation of the extent of dilution of releases from NPP into the surface waters either through water route<sup>9</sup> or from the depositional flux from the atmosphere. However, the latter contribution into the water route is insignificant and in addition there is provision to isolate the containment during accident conditions and resort to only planned releases as necessary.

In addition, information is also needed on the location and purposes of water intakes in the region. This includes mainly use of water for drinking and irrigational purposes in addition to any important use of water near the plant for swimming, salt production and fishing (molluscan fishery). Normally the dose to the critical group through aquatic pathways is small compared to that from atmospheric pathways owing to the lesser magnitude of releases and this would reduce further due to the pre-dilution practised prior to the discharge of liquid effluents. Even then, the exposures resulting from aquatic route needs to be established considering the relevant critical pathways; for e.g., drinking and irrigation can become critical pathways for inland sites while mollusc consumption can become an important pathway for coastal sites owing to their high accumulation capacity for many nuclides. In such cases, simple steady state models coupled with specific pathway can be employed for dose evaluation using default transfer factors.

### **3.3 Information Needed at Site Evaluation Stage**

The data needed for the evaluation of hydrological dispersion in surface waters are collected at the site evaluation stage. The data collected during this stage reflects the situation existing at that stage. However, all anticipated modifications of the data due to plant construction and other foreseen changes in the region should be identified along with their impact on the calculation of concentration distribution. The salient information required for hydrological dispersion study are discussed in the following sections.

#### **3.3.1 Source Parameters**

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<sup>9</sup> The entry or path through which radiation gets into different compartments of the earth.

The design of the proposed NPP, including relevant characteristics such as the expected radioactivity inventory in the core and auxiliary systems, and the specifications of the systems for controlling the release of radioactive materials into the environment, would be identified at this stage. More information on the amount of radioactive materials which would be released in routine discharges or the source terms for accidental conditions will become available at this stage. Hence detailed information on radioactive effluent discharge rate, composition, quantity and chemical or physical state is required in order to predict the behaviour of the effluent and its individual radionuclides as they are introduced into the water bodies. Further, data on liquid and solid components, density, particle size, temperature, mode of discharge and pH are useful as additional information. The information on other non-radioactive matter in the effluent (say organic matter and inorganic constituents) which may determine or modify the behaviour of radioactive constituents after their introduction into the surface waters is also needed. In many situations only estimates will be available and refinements have to be carried out during pre-operational stage.

In order to evaluate potential<sup>10</sup> contamination of a water body under accidental conditions by air-borne radioactive material, it is also necessary to know the amount, type, physico-chemical form and distribution of deposited radioactive material. This could be used as the source term in hydrological model described specific to the water body for the evaluation of time-space profile of radionuclides in water.

### 3.3.2 Dispersion Modelling Parameters

The data required for dispersion modelling can be summarised under four categories viz. hydrological data for the concerned water bodies, data on eddy diffusion coefficients, sediment distribution coefficient<sup>11</sup> and the utilization of water.

#### 3.3.2.1 Hydrological Data

The requirement of hydrological data is dependent on the type of the water body receiving the effluent. The data requirements that are presented here refer to simple models.

##### A. Sites on Rivers:

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<sup>10</sup> A possibility worthy of further consideration for safety.

<sup>11</sup> The relative ratio of radioactive and/or stable nuclide concentration in sediment to that of concentration in the medium of interest at steady state condition.

NPPs at inland sites require continuous and constant supply of water from rivers. The hydrological information required for dispersion modelling for sites on rivers, are channel geometry defined by mean values of width, cross section and slope over the river reaches of interest, average river flow rate, and suspended sediment concentration.

The conservative approach in deriving radionuclide concentration in river water is to assume no dilution of effluent with river water (however, the general approach is to pre-dilute the discharge to acceptable level of concentration at the discharge point). This is useful as a first approximation in case of NPP using river water as recipient of treated effluents. However the use of a quantity called mixing ratio which is an index of the actual dilution available in the water body is useful. This quantity has to be evaluated for realistic computation. The mixing ratio,  $M_p$ , is the dimensionless reciprocal of dilution factor [ $M_p = F/(F+R)$ ] where F is the effluent flow and R is the river flow. This has a value of unity for undiluted effluent. For actual computation, the inverse of river flow rate is used since the fully mixed concentration is proportional to the reciprocal of river flow rate if sediment adsorption effects are not considered. Thus, it is necessary to collect information at least for a period of one year on monthly quantum of flows. This can be arrived at by representative daily flows. Since average rate of flow of water as cu.m/ day is required for computation of dilution factors, it is enough to have monthly quantum of the flows. In cases when complete mixing of the effluent with the river water is not achieved at the point of discharge, dilution factor values for such locations have to be derived experimentally at the site with the aid of tracers during pre-operational stage. The parameters required for this simple model are effluent flow, river flow and the distance at which the water body is used by the members of the critical group.

As a conservative approximation, the simple models ignore the effect of sediment in removing the activity. This assumption will maximise the predicted water concentration. Suspended sediment may affect significantly dissolved radionuclide concentration in slow-moving sections of river with high sediment load. Therefore, information on suspended sediment concentrations are needed at the downstream sections of the river where the river is slowed or depleted. This information should be generated using discrete samples collected every month for atleast an entire year. These samples are to be used for evaluating distribution coefficient factors,  $K_d$ , for various radionuclides. It is also required to have information on the sediment characteristics such as particle size, mineral composition and sedimentation rate for

different flow situations. The data on channel geometry, suspended load, its  $K_d$  and settling rates are necessary for the evaluation of fractional removal rate ( $\lambda_s$ ) of the nuclides by the sediments.

For realistic situations, the concentration of a radionuclide in the river water due to continuous effluent release can be evaluated using steady-state flow model considering predominantly one-dimensional flow and lateral dispersion. The river may be stratified or fully mixed. In case of stratification in the river, the depth down to thermocline is the depth over which dispersion takes place. This model requires data on vertically averaged velocity, depth of river as a function of width and lateral dispersion coefficient. For stratified river, the depth of the river may be identified to the depth of the thermocline. The time-dependent models used for the evaluation of temporal and spatial concentration profile from planned puff releases require data on longitudinal dispersion coefficient also.

B. Sites on Lakes<sup>12</sup>:

The basic characteristics of a lake considered in this section is that of a body of water with tank like configuration with and without stratification having river input and output. The characteristics to be identified for modelling dispersion in such lakes include the effective residence time of soluble radionuclides in the partially or totally enclosed basin, the sedimentation rate of insoluble materials, the input of and dilution by fresh water and the transport out of the basin by water currents.

The fractional removal rate coefficient of radionuclide ( $\lambda_s$ ) by sedimentation is computed using the parameters such as depth of water column, suspended sediment load, its sedimentation rate and the distribution coefficient of the radionuclide on sediments.

For routine continuous discharges a steady state condition may be rapidly attained in small lakes<sup>13</sup> and the simple complete mixing model can be used for the calculation of radionuclide concentration in water. This requires data on the rate of output of fresh water and the volume of the lake.

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<sup>12</sup> A lake is a body of standing fresh water which is of considerable expanse and is deep enough to stratify thermally; formed by processes like glacial action, land slides, limestone sinks, crustal movements of the earth, craters of extinct volcanoes and river activities.

<sup>13</sup> A small body of water lying on the surface of a continent and unconnected with the ocean with a tank like structure without stratification.

For stratified lakes, the parameters required for computation of concentration of radionuclides are thermal stratification of water layers and its variation with time including the position of the thermocline and its seasonal change. If, however, the lake has a stratified structure connected to an outlet such as river, the actual volumes, if any, of the stratified layers and exchange rates between them, if any, are important in addition to fresh water input rate.

Some of the parameters like residence times of water in each of the stratified layers, turnover times of nuclides in the basin and distribution coefficients for different radionuclides are to be generated through experimental studies at the specific site of interest during pre-operational phase. The basic information on residence time/or turnover time of the nuclides are essential for the evaluation of exchange rates between the compartments.

#### C. Sites on Sea Coasts:

Coastal seas are classified into tidal and non-tidal seas<sup>14</sup> according to the degree of influence of tides<sup>15</sup> on mixing process. The rhythmic diurnal and semi-diurnal rise and fall of sea is called tide. The tidal height can vary by two orders of magnitude (20cm-20m). The magnitude of the tidal height is generally used to classify tidal and non-tidal seas.

Among two types of models, box model assumes full mixing within the effective volume, whereas, transient models take into account both transport and dispersion as a function of space and time. Box model assumes full mixing and is conservative. It is therefore used for fixing the regulatory limits. However, transient models are also used for finding the effect of releases from NPPs at long distances and is used as a tool to estimate population dose.

In the case of tidal seas, mixing processes are strongly influenced by tides. In the case of box model, complete mixing is assumed to take place within a volume from which radioactivity is lost by a combination of water exchange, radioactive decay and sediment interaction. The volume of interaction is generally governed by the tidal excursion<sup>16</sup> volume (V). The water exchange rate (r) is related to give net water movement rate

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<sup>14</sup> Seas where the presence of tides are minimal. In these seas the spring tidal ranges for both semi-diurnal tide and diurnal tide are very less compared to the corresponding ranges for tidal seas.

<sup>15</sup> Variations of sea level due to gravitational action of sun and moon are referred to as tides.

<sup>16</sup> The average distance travelled by a particle of water on the flood tide.



coefficient ( $r/V$ ) called as residual tidal drift. The tidal excursion is the distance travelled by a particle of water on the flood tide. The residual drift determines the net flow of water during this period. These two parameters viz.:  $V$  and  $r/V$  are essential in determining the turnover time of the radionuclides released into the mixed volume which in turn is used for the evaluation of steady-state concentration of nuclide in coastal waters.

The use of fully mixed model (box model) may overestimate the concentration due to built-in conservatism as aforesaid. The convection equations for near shore dispersion of radionuclides allow for inclusion of the advective effects of tides and wind driven current. The models require data on direction and magnitude of the current along the shore, depth of the coast, coastal water, dispersion coefficients and the intended location of discharge. To include tidal effects<sup>17</sup> for transient situations, data on tidal current components in X and Y directions, period and amplitude of the tide, depth at the discharge point and its gradient towards open sea are required. The data on the amount and characteristics of shallow water sediment and its  $K_d$  have to be obtained by sampling and analysis. The tidal parameters may usually be found from hydrographic charts. Speeds and direction of near-shore currents need to be obtained at appropriate depths and distances depending on the bottom profile and the intended location of discharge. In these systems, generalised value, for coastal seas may be applicable and refinement of values could be taken at pre-operational stage.

When considering tidal and non-tidal seas, the parameters have to be generated on site-specific information. The mixing volume and the nature of water movement tend to be more site-specific for non-tidal than for tidal situation. If the location of discharge is near the shore, data on Bathymetry upto about 16 kilometers from the shore and data on the amount and character of sediment and its  $K_d$  value for different nuclides are also necessary.

#### D. Sites on Estuaries:

The estuaries have a number of peculiar characteristics since they fall in between rivers and seas. They are characterised by the substantial gradient in the salinity and this change in salinity has a profound influence on the concentration of radionuclides both in sediments and biota. When there is a tidal influence on the estuaries, good mixing of

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<sup>17</sup> Effects induced by tides.

both water and sediment occurs and often results in high suspended sediment load, leading to depletion of some radionuclides from the water phase. The parameters required for evaluating steady-state concentration of a radionuclide in the tidal plug volume include the channel characteristics such as volume of the tidal plug (V) and the water exchange rate computed from the rate of fresh water input (r) into the head of the estuary<sup>18</sup> (flushing time = V/r). The suspended sediment load and its  $K_d$  value for different radionuclides have to be obtained by sampling and analysis.

Measurements on salinity distribution should be made at appropriate depths, distances and times depending on the river flow and the water body configuration during different seasons. In addition, measurements on salinity made at various cross sections of estuary throughout the tidal cycle would facilitate knowing the internal circulation pattern caused by vertical and longitudinal salinity gradients. This data is needed to compute the flow pattern towards the estuary mouth in the upper layers and towards the inner reaches in the lower layers of estuary.

The application of tidally averaged one-dimensional model is limited to the zone of upstream salinity intrusion region while two and even three dimensional models have to be used at the lower reaches of the estuary due to the circulation pattern existing there. In spite of the difficulties in justifying the validity of the tidally averaged approach, the model has been used effectively in studies of pollutants in several estuaries. These models require data on sectionally averaged longitudinal velocity, fresh water advective flow, suspended sediment load, and  $K_d$  for different nuclides.

E. Sites on Impoundments<sup>19</sup>:

The impoundment situations should take into account the effect of hot discharge of the NPP release. The hot water input results in layering of the flow and in the production of secondary layer caused by density differences. The thermal discharge flow together with wind and pumping effects may determine the flow pattern which in turn affect the dispersion

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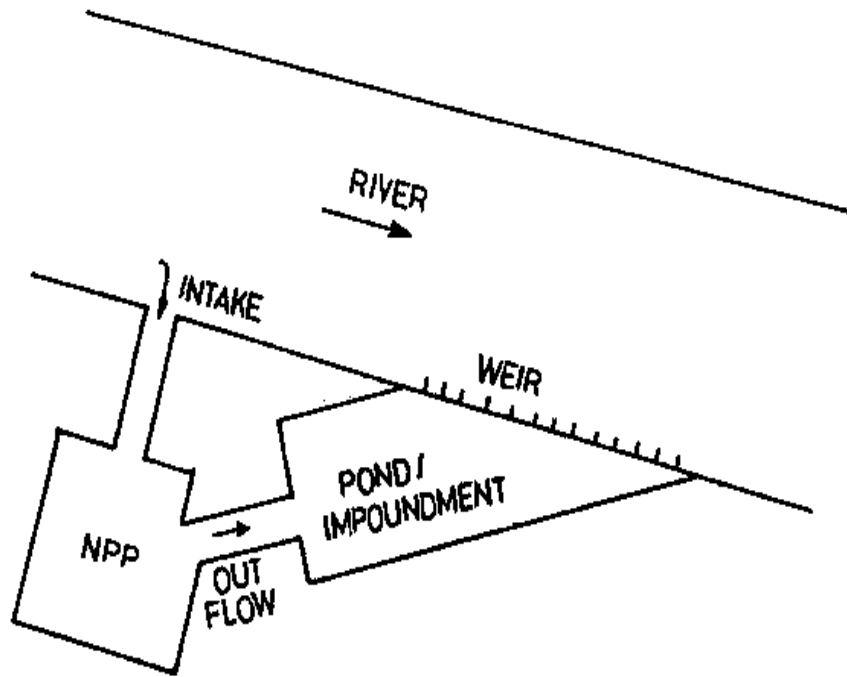
<sup>18</sup> An estuary is a semi-enclosed coastal body of water that has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.

<sup>19</sup> A dam like structure built across a river downstream which stores water for subsequent use.

of the radionuclides. Thus the cooling ponds or impoundments are either fully mixed or stratified.

NPPs can be located either on the banks of the (i) impoundment or (ii) upstream on a river feeding into the impoundment connected to the river (Fig. 3.1). Prediction of concentration of radionuclide within or at the outlet of the impoundments require appropriate information on impoundment geometry, effective volume, inflow and outflow rates (equal to make up flow rate, except for evaporation) and sediment characteristics such as suspended load, its settling rate and distribution coefficients for different radionuclides. The choice of effective volume is crucial for evaluating estimates of radionuclide concentration. Additional information on fluctuation of water level (on monthly basis), stratification and its seasonal variations is required for the study of worst-case situation.

The suspended silt load in the pond would scavenge the radionuclide concentration from the water phase. The data on depth of the pond, suspended silt load, its sedimentation rate and distribution coefficient are needed to compute fractional removal rate by the suspended material.



**Fig. 3.1 : PICTORIAL REPRESENTATION OF POND IMPOUNDMENT AS THE RECIPIENT MEDIUM OF THE EFFLUENT**

### 3.3.2.2 Data on Dispersion Coefficient

Many physical processes are involved in the transport of substances released into the surface water bodies and one of the most important parameters among them is the eddy diffusion coefficient or usually called as dispersion coefficient. The dispersion generally tends to carry the substances from places of higher concentration to those having lower concentration. Thus the dispersion coefficients in three directions viz.  $K_x$ ,  $K_y$  and  $K_z$  are derived from Fickian theory as proportionality coefficients between the components of concentration gradient and the flux of matter per unit area. However, the Fickian theory is not without deviation in coastal waters, since the regions considered for dispersion is small enough requiring the use of non-Fickian theory. The importance of this dispersion and the value of corresponding coefficient may be quite large depending on the system and its flow condition. A summary of values used in different water bodies is given in Annexure-I.

The dispersion coefficients are not measured but obtained from the literature at the site evaluation stage. In some situations, these coefficients may differ by an order of magnitude. The coefficients  $K_x$  and  $K_y$  range between  $1.0E6$  to  $1.0E8$   $cm^2/s$  for the open sea. The same for coastal sea varies from  $1.0E4$  to  $1.0E6$   $cm^2/s$ . The value of  $K_z$  is usually in the range of  $1-30$   $cm^2/s$  and the stratification reduces  $K_z$  to the lower part of the range. The concentration values are generally predicted using the mean values and the uncertainty band is evaluated through ranges. However an investigation of dispersion in a region of interest (upto 16 km around) should be based as much as possible upon data collected in that particular region. This study is needed especially where the hydrological situation is complex and the simple conservative model cannot be applied. In such cases, certain non-toxic fluorescent dyes or isotopic tracer techniques, including stable as well as radioactive isotopes, or float bottle experiments facilitate measurement of dispersion parameters (Annexure I).

### 3.3.2.3 Data on Sediment Distribution Coefficient ( $K_d$ )

The  $K_d$  value is needed for finding the partitioning effect of the radionuclide between the sediment and the water phase. Sediment distribution coefficient for a nuclide is a function of sediment characteristics (particle size, clay component, mineral composition, etc.), its load and the physico-chemical characteristics of the nuclide in a medium. The knowledge on sediment distribution coefficient is needed in following cases:

- i) When there is a potential for exposure to man from sediment; and
- ii) When the concentration of any nuclide in water phase may be significantly decreased by sediment scavenging either due to physico-chemical characteristics or due to the high suspended sediment load.

The sediment distribution coefficient,  $K_d$ , is the ratio of radionuclide concentration in sediment per unit weight to that in water per unit volume when equilibrium has reached. The methodology for estimating this parameter is described in Annexure - II.

Laboratory determination of  $K_d$  values for different nuclides on sediments involves collection of sediment samples from specified locations alongwith water from the same media. The sediment sample is dried in an oven at 100 deg. C, cooled, powdered and sieved into different particle size. The  $K_d$  value for a particular particle size is determined using the procedure described in Annexure II. The product of weighted fraction of a particular particle size and its  $K_d$  value for nuclide will yield weighted mean value for the  $K_d$  of the nuclide. The weight fraction of a particular particle size can be evaluated using sieving method of a wet sediment sample. Alternatively,  $K_d$  values are also determined using the distribution of stable element in sediment and water collected from the same location.

The laboratory measured  $K_d$  value with a sediment for a nuclide yields reproducible values and a variation of about +/- 30 % could be expected. However,  $K_d$  values for a nuclide with sediments collected from different locations can vary by orders of magnitude for the reasons mentioned below. Thus adequate number of sediments collected from different locations should be used for evaluating the mean value using a statistical distribution analysis. This mean is generally used as default value for modelling purpose.

The estimates on sediment distribution coefficients for different nuclides are available in literature for different medium. These default values can be employed in site evaluation stage. However measurement of parameters for site-specific situations could be carried out during pre-operational phase by methodology described in Annexure - II.

#### 3.3.2.4 Data on Water Use

The concentration of radionuclides in water expose man both externally and internally. The internal exposure is due to the consumption of

drinking water and aquatic food materials derived from water body. The external exposure results from the recreational practices such as swimming, fishing and boating. Irrigation practices also lead to radioactivity entering the terrestrial environment and subsequently causing exposure to man. For radioactivity which is concentrated in sediments, the usual exposure route is by external exposure to people who spend time on these sediments deposited on the banks of rivers, lakes, estuaries and sea. Resuspension of contaminate sediments in air could also cause internal exposure through inhalation. If sediments become distributed on agricultural land, the food-chain pathway may also become more important than external exposure. Thus, information on present and projected uses of water that could be affected by radioactive releases from the NPP together with location along downstream upto a distance of 16 km, nature and extent of usage need to be collected at this stage.

In general, for NPPs on river banks all main users of the river (upto 16 km) should be identified. For NPPs on lakes, users anywhere on the lake and at all the locations where water is drawn off should be listed. For NPPs on the sea coasts, a distance of 16 km along the shore on either side of discharge point will need to be investigated for potential users.

The information on the users of water should include average and maximum rates of water intake by users, distance of the intake from the sources of release and the mode of water consumption. For the water use through irrigational practices, information is needed on the rate of water usage, area of irrigated land, types of agricultural yields and their mean consumption rates. The information on the amount of commercial and recreational fish catch, type of species, concentration factors of these species for relevant radionuclides and their consumption rates are also required to evaluate the contribution of water use to exposure through the intake of fresh water and marine food stuffs. Information on the frequency of utilisation of water for recreational purposes is also essential.

Further, the uses of water by some industries and their releases may influence the dispersion characteristics of the water body. Hence, information on uses of water and the discharges from the industries in the region (of 16 km around) such as chemical plants, paper mills, mines etc. are also required to be taken for dispersion calculations.

For the purposes of collection of data, an area within 16 km of radius from the point of discharge should be covered as regulatory requirement.

However, it is desirable that monitoring is carried out in an area of 30 km radius as mentioned in this Guide.

### 3.3.3 Acquisition of Data

Reliable data on all the above mentioned parameters have to be obtained using appropriate measurement techniques. Some parameters have seasonal dependency and they should be acquired during atleast one full year for different seasons in the region.

Data on flow rates and currents are obtained from measurements taken either continuously or with 10 minutes interval for 3-6 hours on a fortnightly basis. The information may be available with local authorities. If such measurements are not available, the same will need to be generated atleast for a period of 1 year on a fortnightly basis. Vertical and horizontal (surface) temperature profile of the water body should be measured on a seasonal basis for a minimum period of one year.

Data on geometry and bottom configuration of water bodies are commonly obtained from a single survey if the region is not subject to substantial change.

Data on sediment load and water quality are commonly generated from fortnightly survey for a period of one year and this frequency can be altered depending on sediment load and water quality variations. Examples of instrumentation used for the measurement of some of these parameters are shown in Table 3.1.

## 3.4 Information Needed at Pre-Operational Stage

Generally pre-operational stage is a stage of measurement programme. The main objective of this measurement programme is to provide verification of the hydrological information obtained in the site evaluation stage as well as to generate site-specific parameters wherever required (dispersion coefficients, sediment distribution coefficients) The pre-operational investigations should encompass planning of radiological monitoring programme to be carried out during the operational stage of an NPP. This is essential for the validation of the model. The investigations should include compilation of information on the critical nuclides, critical pathways and critical group. The determination of background levels of radioactivity in aquatic environment could also be carried out to facilitate evaluation of the contribution attributable to the NPP releases.



## 4. MODELLING OF RADIONUCLIDE DISPERSION

### 4.1 Type of Models

Generally all the models can be categorised into three groups viz. Numerical, Analytical and Box models.

Numerical models transform the main governing equations of radionuclide dispersion into finite difference or finite element form. These models are the most complex of those available. They take into account all the relevant physical phenomena, atleast partially. Such models are needed only in specially complex situations.

Analytical models are the simplified version of basic equations describing radionuclide transport. The simplifications are made either by disregarding time and/or space terms or by introducing plausible functional relations for these; in some cases the resulting equation may have a closed-form solution. Sometimes additional simplifications are made as to the water body geometry and dispersion coefficients of water body. These simple models that can be easily validated, are preferable for derived discharge limit computations. The complex analytical models take into account realistic situations in a more refined manner, however, the requirement on data base, availability of data and validation of concepts behind the model require considerable effort.

Box models are also known as compartmental models. These models represent a surface water body as one or more homogeneous compartments. In this type of model, average concentrations are computed for each box (compartment) and transfer coefficients are set up to relate the variations in between the compartments. These are used both for local bodies (e.g. ponds) and for global bodies (e.g. the world oceans).

In most cases, simple models (either box or analytical) are adequate for NPP siting purposes. For efficient use of these models, the radionuclide dispersion is divided into three phases viz., Phase-1, Phase-2 and Phase-3 (also called as mixing zones, near-field and far-field).

Phase-1 is the initial mixing of the effluent with the water body. Since the substance is close to the point of release, models to simulate this phase are sometimes called near-field models. Owing to the fact that this phase is short, the radionuclide can be considered as a passive tracer in the effluent and the initial dilution is primarily affected by the jet

velocity of the discharge and its depth and level (at the surface or submerged). It is noted from various studies conducted in international rivers, that Phase-1 stage may cover upto about 100 times the depth of the river channel depending on the volume, the temperature of the effluent and characteristics of the river [2]. The thermal influence in the dispersion will be felt only for a short period (1-2 hrs) and this will be further reduced because of pre-dilution employed prior to the discharge of the effluent. This phase ends once the buoyancy and initial momentum of the effluent has become negligible. For discharges into rivers, the initial mixing takes place in the first few hundreds of metres where a significant density difference exists. For practical purposes this can be assumed 100 times the depth of the water body at discharge point.

Phase-2 covers the process between initial discharge and complete mixing. Depending on the receiving water body, this phase may be associated either with time or distance needed to complete the process. In large lakes<sup>20</sup>, for instance, the time for complete mixing may be months due to stratification. For discharges into rivers, complete mixing may be quickly attained in a few thousands of metres (2 to 3 km) or it may be slow and require upto 10 km distance. The coastal flow (10-30 cm/s) induces rapid equilibrium condition within a few kilometre distance along the coast. Sediment interaction is usually not taken into account in the models used for this phase. For this phase, three dimensional models are not required though they are available. As a result of initial complete mixing, one or two dimensional models may suffice.

- \* Phase-3 covers the long term transport of substances(beyond about 10 km distance) after complete mixing with the receiving water body. In many cases, phase-3 develops over long distances and/or very long periods. In contrast to phase-1, transport during phase-2 and phase-3 is represented by far-field models. These models (phase-3) are usually one-dimensional and take into account sediment interaction.

## 4.2 Selection of the Model

The selection of an appropriate model is dependent on the type of discharge (surface or submerged), the type of water body into which the radioactive materials are released (e.g. rivers, estuaries, impoundments, large lakes or oceans) and the accuracy required in the estimation of concentration of radioactive materials in surface waters at the various

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<sup>20</sup> A large body of water lying on the surface of a continent and unconnected with the ocean with a tank like structure with and without stratification and having river input and output.

locations of the drawal points by the main users. Further technical judgement will be needed in the selection of modelling approach for a particular case.

A general discussion of radionuclide dispersion modelling in surface water with a short description of factors governing their simplifications is presented in Appendix A. Appendix B deals with models for the initial mixing stage (Phase-1) for both surface and submerged releases. Dispersion models are classified according to the water body receiving the liquid effluent. The four groups of models viz. models for rivers, impoundments and small lakes, open coast water bodies and large lakes and estuaries are discussed in Appendices C to F. These are far-field models encompassing phase-2 and phase-3. Application of these models for steady-state releases as well as time-dependent releases are also discussed. The use of models for the different situations are indicated in Table-4.1A alongwith the required data base in Table-4.2A. Appendix-G describes the radiological model for the translation of concentration of radionuclides in water to dose from external exposure pathways through sediment.

### **4.3 Validation of Model**

Radioactive effluents released from the NPP undergo large dilution in the water body and it may not be practicable to measure the low concentrations of radionuclides in the environment. It is therefore necessary to predict these concentrations in the environment by suitable hydrological and environmental models from a knowledge of source terms. In addition, the application of appropriate model will enable formulating the derived working levels for the release of radioactive effluents.

A model is conceptually identical to working hypothesis for the explanation of interactions and processes occurring in the environment. As a hypothesis, the model should be:

- able to predict possible results in a quantitative form; and
- validated if possible with field observations.

The direct verification of predictive model is ideal, however, it may not be practicable to do so in real situations. In such cases, one of the following approaches may be adopted for ensuring application of an appropriate model for a specific case:

- a simple model that has been validated for a similar area elsewhere can be chosen; or

- it should be demonstrated that the approximations and assumptions made in applying the model to the specific case will not lead to an underestimate of the radionuclide concentration at any point of interest.

Both these approaches are only substitutive for model validation. It is always desirable to validate the model employed in radionuclide dispersion with suitable radioactive or chemical tracers during pre-operational or operational stage.

#### **4.4 Model Uncertainty and Sensitivity Analysis**

Many of the important parameters describing the processes in the model are known from experiment or theory only with large margins of uncertainty. Hence an evaluation of uncertainty in the model output is required. Estimation of potential extent of errors in prediction is recommended through the comparison of model prediction against independent sets of observations carried out during operational stage (model validation). In addition, it is also desirable to perform sensitivity and uncertainty analysis to identify the model components that are significant contributors to the uncertainty in the prediction. These procedures are recognised as necessary to improve confidence with which model predictions can be used as tools for decision-making.

Methods of sensitivity analyses are typically performed to identify the effect of model parameters on model predictions. The classical method of sensitivity analysis is to take the partial derivatives of the model response with respect to each model parameter. It is useful to normalise these values by numerically estimating the percent variation in model response resulting from a percent perturbation in the model parameter. These differential sensitivities can also be used as a coarse screening of parameter importance.

A variety of methods of uncertainty analyses have been developed to estimate the effect of variances and covariances of model parameters on model predictions. These techniques provide a statistical method of parameter evaluation and model comparison as well as a quantitative method for recommending data collection to improve parameter estimates. These methods can easily be applied to simple additive or multiplicative models with few parameters. The variance of model response can be strongly influenced by both the sign and size of the correlation among the parameters.

The spatial concentration profile of  $^{137}\text{Cs}$  in coastal waters using tidal model is shown in Annexure VI for varying  $K_x$ ,  $K_y$  and  $U_x$  values. An order of magnitude increase in  $K_x$  value decreases the concentration by a factor of about 3-4 only. The increase of  $U_x$  value makes the peak concentration to appear at a farther distance. The concentration at a specified distance (user's point) can be translated into dose using radiological model. Using the basic or apportioned limit<sup>21</sup>, the corresponding discharge limit for the nuclide can be computed for the radionuclide and compared with that of the actual release rate. The confidence in the model prediction can be obtained from the above mentioned statistical analyses. In addition, this would provide thrust area for further investigations during operational stage.

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21 The value of dose assigned by the appropriate agencies for the discharges of various radionuclides through air and water route.

**Table - 3.1**

Examples of Instrumentation Accuracy

<b>Parameter measured</b>	<b>Instrumentation or methods used</b>	<b>Characteristics of instrumentation systems Accuracy required</b>
Water depth	Echo sounder	1 m shallow water 3 m deep water
Location	Navigation System	+ 30 m indicated position
Current speed	Current sensors	+ 3% (threshold 0.1 m/s)
Current direction	Current sensors	+10°
Water temperature and water gradient	Thermistor	+ 1° C
Water quality	Chemical Analysis	+ 10%
Suspended load & sedimentation rates	Basket samplers and weight Measurements	+ 10%
Sediment $K_d$ values	Batch techniques Stable element method	+ 10%
Background radioactivity	Liquid Scintillation and Gamma Spectrometer Radiochemical analysis	+ 10%

**Table - 4.1A**  
Application of Hydrological Dispersion Models

Model Name (Applicable Ref. Appendix A-G)	Distance (Sec. 4.1)	Application based on Size and Type of system	Remarks
Dilution Model (B.1.1,B.1.2)	Phase 1	Rivers, open coasts <sup>22</sup> , lakes, impoundments	Bottom interfaces should be minimal, applicable upto jet flow equal to ambient flow (or 10% of it)
Simple model (C.1)	Phases 1 & 2	River/channel with constant linear flow	Instant dilution from continuous release spatial profile determined by U and $\lambda_e$
Steady-state flow model (C.2)	Phases 2 & 3	River/Channel	Applicable to down current indefinitely from the end of Phase 1. Even stratification effect can be incorporated
Time dependent model (C.3,E.2.1)	Phases 2 & 3	River/Channel, Open Coast (C.3) (E.2.1)	Vertically mixed line source, allows for location of discharge spot/batch release
Fully mixed model D.1	Phases 1 & 2	Small lakes/Impound- ments Rivers and Estuaries	Flushing time/turnover time should be high, stratification should be absent
Plug flow model D.2	Phases 1 & 2	Small lakes/Impound- ments with shallow depth	Continuous release, Concentration at outflow point
Stratified Model D.3	Phases 1 & 2	Rivers/channels, small lakes, Impoundments	Flushing time/turnover time should be small compared to residence time of radionuclides in the system
Complete mixing model E.1,F.1	Phases 1 & 2	Tidal Seas/estuaries (E.1) (F.1)	Flushing time should be large enough, continuous release
Time dependent tidal effect induced	Phases 2 & 3	Open coast sea	Routine/spot release
Time dependent tidally averaged dispersion averaged model F.2	Phases 2 & 3	Estuaries/rivers	Aerial Source, Spot release

Note:-The Phases 1,2, & 3 mentioned here are defined under Chapter 4

<sup>22</sup> Coasts which are not bounded by any ridges or valleys like structures. Large water bodies like oceans, seas and large lakes have open coasts.

**Table - 4.1 B**

## Types of Numerical Models

Code	Name	Description
IA	One dimensional tidally averaged	A numerical solution of the 1D tidally averaged dispersion eqn. may be steady state, meaning that the coefficients are constant in time, or the dispersion coefficient and flow parameters may vary between tidal cycles.
IT	One dimensional tidally varying	A numerical solution in which the tidally elevation, velocity, and dispersion coefficient vary during the tidal cycle.
ITB	Branching one dimensional tidally varying	A network of IT models connected at junctions.
2VA 2HA	Two dimensional tidally averaged	A numerical solution of a 2D tidally averaged dispersion equation. V means a model which uses a vertical, X-Z plane and H means a model which uses a horizontal X-Y plane.
2VT 2HT	Two dimensional tidally varying	Similar to 2VA and 2 HA except that the tidal elevation and flow velocity vary during the tidal cycle.
3A 3T	Three dimensional	3D tidally averaged (A) and tidally time varying (T) numerical models
P	Physical	A small-scale physical replica of the prototype geometry with provisions for generating tidal and river flows
NP	Hybrid numerical physical	A combination of a physical and a numerical model, using one model to generate input information for the other



**Table - 4.2A**  
Requirements of data base depending on stages of Siting

Information on	Related Parameters	Remarks
Site Selection Stage: Source Terms	Quantity/composition of radionuclides	Estimates based on literature/ past experiences/design data if available
Hydrological systems	Description of water bodies in the region (30 km around)	Estimate of dilution factor capacity based on characteristics of water body where effluent will be discharged
Radiological	Location of water use, fish catch, crop yield, dietary/ dwelling habits	Estimates to be made based on data from local authorities
Site Evaluation Stage: Source Terms	Quantity/Composition/ Physico- chemical data of radionuclides	Estimates based on NPP design (PSAR)
Hydrological	Measured Parameters: Geometry of aquatic body, Mean width, Mean depth, Mean flow, input/output of water, Temperature depth profile, tidal amplitude, Tidal velocity vectors, Depth gradient in coastal sea, Flow characteris- tics Silt/sediment load, sedi- mentation rate and $K_d$ for nuclides.	These parameters are worked out based on field measurements or available data suitably extrapolated for site conditions.
	Computed Parameters: Residence time of nuclides, Flushing time for lake/ Impoundment and Dispersion Characteristics	These are computed values.
Radiological	Intake parameters for water, fish and other food materials consumed by the critical group	Estimates to be made based on data from local authorities
Hydrological	Geometry of water bodies, Dispersion and flow characteristics and sedimentology	Refined parameters based on measurements and computation carried out during plant design and construction stage
Radiological	Identification of critical group, CF for food materials, intake/ occupancy factors.	Refined analysis specific to the critical pathway, site.

Legend: PSAR - Preliminary Safety Analysis Report ;  
FSAR - Final Safety Analysis Report ; CF - Concentration Factor

**Table - 4.2B**

Data Format for Hydrological Information

Parameters	Hydrological Information
Type of Water Body	
Distance from Site	
Cross Section	
Width	
Distance	
Slope	
Flow : Max. Min. Ave.	
Sediment Load: Max. Min. Ave.	
Connected Water: Upstream Downstream	
Tidal Information: Amplitude Period	

**Table – 4.2C**

Data Format for Water Use

Parameters	Hydrological Information
Type of Water Body	
Quality of Water	
Direct Water Use: Drawal Point Drawal Rate Purpose of drawal	
Indirect Water Use : Fish Yield Molluscan Fishing Salt Production	
Time of Occupancy in the Water Body/Shores: For swimming For Recreation and other activities For Intertidal Fishing	

## APPENDIX - A

### GENERALISED HYDRODYNAMIC DISPERSION MODEL (SURFACE WATERS)

#### A.1 Model:

The models for radioactive dispersion in water bodies solve either the following basic equation or a simplified version of it:

$$\frac{\partial C}{\partial t} = - \{ U(\frac{\partial C}{\partial X}) + V(\frac{\partial C}{\partial Y}) + W(\frac{\partial C}{\partial Z}) \} + \{ \frac{\partial}{\partial X} (K_x \frac{\partial C}{\partial X}) + \frac{\partial}{\partial Y} (K_y \frac{\partial C}{\partial Y}) + \frac{\partial}{\partial Z} (K_z \frac{\partial C}{\partial Z}) \} - \lambda C - R + Q \quad (A.1)$$

The first term in the bracket represents advection of the material by water movement; U, V and W are the three components of water velocity in the X, Y and Z directions respectively.

In the classical context, the second term in bracket would represent diffusion. For the surface water transport of interest, it accounts, however, for dispersion in general. The hydrological macroscopic processes, as mentioned earlier, overshadow other mechanisms such as diffusion. It is assumed for the purpose of this model and the scale dependence is ignored so that the dispersion coefficients  $K_x$ ,  $K_y$  and  $K_z$  are independent of position, i.e., constant along each direction.

The third term  $\lambda_c$  represents radioactive decay, where  $\lambda$  is the physical decay constant and C is the concentration. When a substance is non-radioactive,  $\lambda = 0$ . For substances subject to chemical changes, an additional depletion term can be included; usually such a term would be a function of kinetic rate constants.

The term R represents the rate of pick-up of radionuclides by the sediments. The relation of R with C can be represented by the relation :

$$R = K_d S (dC/dt), \quad (A.2)$$

where  $K_d$  is the distribution coefficient of a radionuclide for the sediment and S is the suspended sediment load. Finally, Q represents any other source/sink terms including all releases of the radionuclides to the water body.

#### A.2 Factors Governing Simplifications:

The equation (A.1) is a quasi-conservative equation for the dispersion of radionuclide in the aquatic environment. The non-conservative elements are

introduced by the radioactive decay and source/sink terms. The equation can generally be solved by numerical analyses only owing to the complexity of flow characteristics and boundary interactions. However, the equation can be simplified for specific situations from a knowledge of the flow characteristics.

Experience gained in the operation of NPPs reveal that the radionuclide concentrations from routine and most of the accidental releases are extremely low and seldom exceed the stipulated limit set by the Regulatory Body. This has led to the development of many simple analytical models based on conservative/and or realistic assumptions. The simplifying assumptions are generally made in relation to straight shore-line, uniform flow, constant dispersion coefficients and simple bottom geometries etc. These simple models require only little information in terms of input data, but they are sensitive to the values of the data.

An illustration on the type and magnitude of simplification is cited below. The effect of sediment removing the radioactivity is ignored generally in simple models and hence they tend to overestimate the concentration in the water phase. Scavenging within the bed is a process of suspension-sedimentation-resuspension cycle and requires a detailed knowledge of hydrology of the system and sedimentology. The approximation to this process is represented by  $K_d$  which is a nuclide-dependent parameter. The reduction factor (F) for the concentration of a radionuclide in water is obtained from the relation:

$$F = 1/(1+K_d S) \quad (A.3)$$

However, it should be realised that the concentration of a radionuclide in drinking water at the time of ingestion is lower than that in the water body due to water-treatment processes and time delay prior to consumption. Thus, adequate representation of real situations can be built-in in the radiological model depending on the phases of requirement.

## APPENDIX-B

### NEAR FIELD INITIAL DILUTION MODEL (PHASE 1)

#### B.1 Models:

Initial dilution models are necessary to know the radionuclide concentration near the point of effluent discharge. These models for initial mixing viz.: near-field models/and phase 1 models, deal with dispersion near the point of effluent discharge where the dilution is primarily affected by turbulent jet mixing. The primary mechanisms for dilution for these models are provided by momentum and buoyancy of the Plant effluent, and to a smaller extent by the velocity and temperature of the recipient water body. The dilution occurring in the near-field is generally approximated by means of steady-state flow conditions since the effluent discharge from NPPs maintain a steady-state flow and the dilution is the result of momentum and buoyancy differences between the discharges and the ambient medium.

These Phase 1 models are also applicable to rivers, estuaries, open coasts and impoundments. They can be categorised into two groups based on the nature of discharge i.e., surface discharge or submerged discharge.

#### B.1.1 Dilution Models For Surface Discharge:

The mathematical models available for thermal plumes from surface discharge fall into three categories viz.: Integral; Phenomenological and Numerical models. A list of commonly used Integral and Phenomenological models [3-8] is shown in Table-B1 along with the field sites where validation studies have been performed for the models.

Most of the models used for thermal plumes are either Integral or Phenomenological. The Integral models employ equations of conservation of mass, momentum and energy and treat the plume dispersion of buoyant plumes similar to that of non-buoyant jets. The Phenomenological models for thermal plumes are derived from empirical expressions based on field or laboratory data. The Numerical models are needed only when the concentration distribution near the point of effluent discharge is required and /or geometry and recirculation patterns are complicated. Generally Numerical models are not field-tested and verification may be needed if they are to be used for a specific site.

The application of both the Integral and Phenomenological models for continuous releases from NPPs require data on the characteristics of discharge and receiving environment. The data needed on the discharge characteristics are the discharge at outfall, and outfall exit temperature and velocity. The characteristics of the

receiving water body should include information on the geometry of water body such as bottom contours, geometry of near and far shore- lines and the flow pattern like current speed and direction and the temperature of the water. The best results from these models could be obtained with the application of appropriate parametric values in situations where the discharge largely controls the dispersion in near-field and boundary interferences are minimal. Because of the underlying assumptions and changing of environmental conditions the above models provide estimates of dilution accurate to within a reliability factor of 2.

#### B.1.2 Dilution Models For Submerged Discharge:

Dilution models for submerged dispersion of heated water are based on integral approach of employing an entrainment hypothesis. These are also derived from the basic equations of conservation of mass, momentum and energy. Shirazi-Davis model [6] of Table-B1 gives the best results and can be used for a wide range of angles between direction of discharge and that of ambient currents. The interaction of the merging jet with the bottom limits the application of the model for shallow water systems and often overestimates the dilution factor for shallow-water conditions.

Additional information needed for the submerged dilution model, other than those mentioned for surface discharge models, is on the discharge configuration. This includes data on number of ports, their sizes and spacings, their angles of discharge with the bottom and depth of water at the discharge.

**Table-B1**

List of commonly used Dilution Models

Model	References of model					
Site of Validation	3	4	5	6	7	8
Kewaunee						X
Oskarshamnsverkt			X			
Palisades	X	X	X	X	X	
Pilgrim	X	X			X	
Point Beach		X	X	X	X	
Zion						X

References:

(3) Motz-Benedict

(5) Prych

(7) Pritchard, Model No:1

(4) Stolzenbach-Harieman

(6) Shirazi-Davis

(8) Pritchard, Model No:2



## APPENDIX - C

### FAR FIELD RIVER DISPERSION MODEL

#### C.1 Simple Model:

Frequently, there is a continuous routine release of substances into a river. After sometime, such discharges lead to uniform concentration at any river cross section located downstream from the point of discharge. Uniform mixing may be obtained in short distances when the discharge method provides for initial mixing. The spatial variation of steady-state concentration (C) can be represented by the simple relation:

$$dC/dX = -\lambda_e C/U \quad (C.1)$$

where X is the downstream distance (m) and U is the linear flow velocity (m/s) and  $\lambda_e$  is the effective removal rate coefficient. The solution for this equation is of the form:

$$C(t) = C_o \{ \exp -(\lambda_e X/U) \} \quad (C.2)$$

where  $C_o$  is the well mixed concentration in Phase-1 of the water body assuming steady effluent discharge into the flow channel with constant linear velocity, U. The value for  $C_o$  can be obtained from the relation [8]:

$$C_o = PM_p Q/F \quad (C.3)$$

where P is the conversion factor for units; Q is the input rate of radionuclide into the river (Bq/y);  $M_p$  is the mixing ratio, a dimensionless reciprocal of dilution factor; F is the effluent flow ( $m^3/y$ ). The spatial concentration of radionuclide in Phase-2 can be evaluated by using this equation and the term X/U represents the decay term during transit in the downstream distance.

The input rate, Q, for a radionuclide is treated as an average annual discharge rate from a continuous release. Because of the averaging effect, batched releases can in many cases be treated as a continuous release. The mixing ratio,  $M_p$ , is the dimensionless reciprocal of dilution factor and this factor has a value of unity for undiluted effluent. For complete mixing  $M_p = F/R$  where R is the annual river flow.

The effective removal rate coefficient,  $\lambda_e$ , should include all mechanisms leading to depletion of concentration. In this case,

$$\lambda_e = \lambda_s + \lambda \quad (\text{C.4})$$

where  $\lambda_s$  is the removal rate coefficient derived from sedimentation process and  $\lambda$  is the radioactive decay. The exact function of  $\lambda_s$  depends on the sedimentation model. A simple derivation for  $\lambda_s$  can be obtained from the relation [9]:

$$\lambda_s = K_d S_r / [h(1 + K_d S)] \quad (\text{C.5})$$

where  $S_r$  is sedimentation rate ( $\text{te/m}^2/\text{s}$ ) and  $h$  is the depth of water column (m) and  $S$  is the suspended sediment load ( $\text{te/m}^3$ ).

This simple model assumes that the activity discharged per unit time is diluted by the volume flow rate of the river. While this assumption is too simplistic for the area immediately downstream, it becomes a more reasonable approximation as the downstream distance increases. This simple model is useful for calculating annual exposure resulting from routine release of radioactive effluents. The model can be employed for discharges in rivers/channels, however, more a sophisticated model given below (Sec. C.2) can be utilised when higher accuracies in concentration estimates are needed.

Generally, all the required parameters are available except  $\lambda_s$ . UNSCEAR [10] suggests using  $K_d$  as an independent parameter to classify and model interactions between sediment and the nuclide. For river velocity of 2 m/s,

$$\lambda_s = 2.0\text{E}-5 \text{ s}^{-1} \text{ for } K_d > 1.0\text{E}3 \text{ m}^3/\text{kg} \text{ (strong interaction)}$$

$$\lambda_s = 4.0\text{E}-6 \text{ s}^{-1} \text{ for } 1 < K_d < 1.0\text{E}3 \text{ m}^3/\text{kg} \text{ (medium interaction)}$$

$$\lambda_s = 0 \text{ for } K_d < 1 \text{ m}^3/\text{kg} \text{ (weak interaction)}$$

## C.2 Steady-State Flow Model:

Alternatively, the steady state concentration of radionuclides in river water beyond Phase 1 can also be evaluated using the Steady State Flow Model. The simplest river model for continuous release of liquid effluents considers longitudinal advection and lateral dispersion. A two-dimensional steady-state equation of mass balance for the concentration of radionuclide can be written for this situation using certain simplified assumptions for the convective-diffusive equation depicted in Appendix A as :

$$U_x (\partial C / \partial X) = (\partial / \partial Y [ K_Y (\partial C / \partial Y)] - \lambda C \quad (C.6)$$

It should be noted that longitudinal dispersion is neglected in this equation since longitudinal advection dominates the longitudinal dispersion.

In some situations, the depth (d) of the river may be irregular and a function of Y only. The velocity,  $U_x$ , along the stream can also be assumed to be a function of Y. When the depth of the river changes in lateral direction, as usually is the case, the depth dependence can be incorporated as:

$$U(Y) d(Y) (\partial C / \partial X) = \partial / \partial Y [K_Y d(Y) \partial C / \partial Y] - \lambda d(Y) C \quad (C.7)$$

Since U and d are functions of lateral co-ordinate Y, this equation cannot be solved in an analytically closed form; numerical method needs to be employed for arriving at spatial concentration of radionuclide in river water. Vertical mixing upto a water depth of d(Y) is assumed for computation.

The input data required for this model are the channel geometry, the cross-stream flow distribution for determining U and the dispersion coefficient at the representative cross-sections of the river. Though it is preferable to measure the velocities at each cross-section of interest with current meter, it is a common practice to estimate the distribution U(Y) across a river cross-section from known stream bottom profiles.

The above steady-state model would give a closed form solution for constant  $K_Y$  and can be applied appropriately to sites with ideal boundary and initial conditions.

### C.3 Time-Dependent Model:

The temporal and spatial concentration of a radionuclide in a river with straight rectangular channel with steady flow parallel to the shore can be evaluated from the following two-dimensional equation for spot release:

$$\partial C / \partial t = K_x (\partial^2 C / \partial X^2) + K_Y (\partial^2 C / \partial Y^2) - U_x (\partial C / \partial X) - \lambda C \quad (C.8)$$

where  $K_x$  and  $K_Y$  are the dispersion coefficients in the X and Y directions. This equation accounts for turbulent dispersion in the direction of flow which cannot be disregarded for obtaining time dependent concentration. Further, this representation assumes full mixing in the vertical direction and constant  $K_x$  and  $K_Y$ .

The analytical solution for concentration ( $C_i$ ) to this time-dependent dispersion equation in X and Y direction can be obtained for an instantaneous release of unit activity as:

$$C_i = [1/4\pi H[K_x K_y t^2]^{1/2}] \exp[-(\lambda t)] \cdot \exp[-(X-Ut)^2/4K_x t] \cdot \exp[-(Y^2/4K_y t)] \quad (C.9)$$

Computation of concentration for continuous release can be obtained from the convolution integral as:

$$C_c(t) = \int_0^t f(\tau) \cdot C_i(t-\tau) d\tau \quad (C.10)$$

where  $C_i$  is the concentration of a radionuclide at time  $(t-\tau)$  for an instantaneous release,  $f(\tau)$  is the rate of release as a function of time,  $\tau$ , and  $C_c$  is the concentration of the radionuclide at time  $t$ .

The above model provides solution for radionuclide distributions when the sediment effects are neglected. However, this effect could also be introduced by the use of  $\lambda_s$  as mentioned earlier (eqn. C.4). The values for  $K_x$  and  $K_y$  should be selected appropriately to provide conservative predictions. It is preferable to obtain these values from tracer experiments at the site, however, rough estimate of  $K_x$  and  $K_y$  can be obtained [2] from the relation  $K_y = K_x = (U^* \beta d)$  where  $\beta$  is the dimensionless constant,  $U^*$  is the shear velocity and  $d$  is the river depth. The shear velocity,  $U^*$ , is related to mean velocity,  $U_m$ , by the relation :

$$U^* = U_m \sqrt{C_f / 2} \quad (C.11)$$

where  $C_f$  is friction coefficient depending on the Reynolds number of the flow and bottom roughness. The value of  $\beta$  is larger for curved channels and in that case, it is better to determine  $K_x$  and  $K_y$  by field studies.

## APPENDIX - D

### MODELS FOR SMALL LAKES AND IMPOUNDMENTS

#### D.1 Fully Mixed Model:

Inland Power Plants use small lakes and impoundments for cooling purposes, either isolated or connected to rivers. In either case, these water bodies may become the first recipient of the release of liquid effluent. It is typically assumed that complete mixing in Phase 1 is quickly attained in these systems. Further, this can be used to derive the maximum concentration of radionuclide at the input point of the river.

For completely mixed small lakes/impoundments receiving a volumetric flow rate of  $q$  of the effluents whose concentration is  $C_0$ , assuming that the initial concentration of the effluent in the water body was zero, the time-dependent radionuclide concentration in the same is obtained from simple mass balance relation as :

$$dC/dt = [qC_0/V] - KC = Q/V - KC \quad (D.1)$$

where  $C$  is the concentration in the water (also represents the concentration in the outflow),  $Q$  is the radioactivity discharge rate computed from effluent flow rate,  $q$ , and its concentration,  $C_0$ ,  $V$  is the effective volume of the system and  $K$  is the effective removal rate coefficient.

The solution for this equation is :

$$C(t) = [qC_0/KV] \{ 1 - \exp(-Kt) \} \quad (D.2)$$

where  $K$  is the effective removal rate coefficient and is given by :

$$K = (\lambda + r/V) \quad (D.3)$$

The effective removal rate coefficient,  $K$ , contains both depletion by radioactive decay and net advective losses  $r/V$ , where  $r$  represents outflow rate. The effective volume,  $V$ , represents the part of the water body actually taking part in the dilution of the effluent. Generally total volume of the water body is used, however, if the water body is thermally stratified, the effective volume as mentioned above needs to be employed. Likewise  $r$  is the net outflow rate which is equal to water inflow rate ( $q$ ), minus any evaporational losses.

It follows from the above equation that the concentration  $C$  builds up until a steady state concentration,  $C_s$ , is reached in the water body. The steady state concentration is given by setting  $t=\infty$  in eqn. (D.2) as :

$$C_s = [qC_o/KV] \quad (D.4)$$

The parameter of importance is the flushing time of the water in the system by the make up and outflow streams defined by  $V/r$ . For large impoundments with small outflow rates, the flushing time is large and hence the time taken to reach the steady-state would depend upon the half-life of radionuclide and the flushing time (Annexure-IV).

## D.2 Plug Flow Model:

This model assumes that the lake/impoundment receives the plant effluent at a particular location and subsequently moves as a plug in the receiving water without significant mixing. The effect of mixing due to recirculation is not considered. The concentration equation for such a system is:

$$V_T (dC/dt) = -\lambda C V_T \quad (D.5)$$

where  $V_T$  is the effective volume of the water body involved.

The solution of the above equation is given by :

$$C(t) = C_o \exp(-\lambda t) \quad (D.6)$$

where  $C_o$  is the initial concentration. If  $W$  is the radioactive discharge rate from the plant and  $q_b$  is the outflow rate from the lake (which in this case is equal to plant effluent discharge rate) then :

$$C_o = W/q_b \quad (D.7)$$

In particular, the concentration at the outflow point of the lake/impoundment can be found if we replace  $t$  in eqn. (D.6) by  $V_T/q_b$  which represents the effluent travel time from plant discharge point to lake outflow point, as :

$$C = C_o \exp(-\lambda V_T/q_b) \quad (D.8)$$

It should be realised that no lake/impoundment either completely mixed or completely plug flow type. The actual performance of any unstratified water body

is somewhere between the two idealised situations. It is possible to obtain only an upper and lower limit using both these models.

### D.3 Stratified Lake/Impoundment Model

For thermally stratified lakes, the simplest approach is to assume complete mixing in each of the compartments. To model a small lake, two components are sufficient, namely, the epilimnion and the hypolimnion i.e., the compartments of above and below the thermocline respectively.

Denoting by  $V_e$  and  $V_h$  the effective volumes of the two compartments (subscript 'e' for epilimnion and 'h' for hypolimnion), the incoming effluent flow rates by  $q_e$  and  $q_h$ , with discharge concentrations of  $C_o(e)$  and  $C_o(h)$ , and letting the initial concentration in each compartment be  $C_e(o)$  and  $C_h(o)$ , a mass balance for each compartment gives the following equations :

$$V'dC'/dt = q'C_o - r'C' - \lambda C'V' \text{ for } 0 < t < t_1 \quad (D.9)$$

The concentration at any time  $t$ , is given by :

$$C'(t) = [q' C_o' / K' V'] \{ 1 - \exp(-K't) \} + C'(o) \exp(-K't), \text{ for } 0 < t < t_1 \quad (D.10)$$

The apostrophe over symbols is used to represent the use of respective epilimnion (e) and hypolimnion (h) parameters for the evaluation of concentration of the respective layers. The effective removal rate coefficients are represented by  $K' = \lambda + r'/V'$  and this means, the effective removal rate coefficient for epilimnion and hypolimnion layers are given by the relation  $K_e = \lambda + q_e/V_e$  and  $K_h = \lambda + q_h/V_h$  respectively.  $C_o'$  is the input concentration of the effluent discharged in either epilimnion or hypolimnion. When one or both  $K$ 's are large, steady state concentration may be reached.

The model is based on the assumption that the lake/impoundment is divided into two layers, each fully mixed and that there is no mixing between these layers during stratified flow period (say stratification continues from time zero to  $t_1$ ). The effluent may flow into each layer and water may be withdrawn from each layer but the inflow and outflow must be equal for each layer. In addition, the model assumes constant volume of water in each layer during the period of stratification and a constant total volume during unstratified flow.

During a seasonal turnover, the thermal stratification is disrupted and the waste effluent is mixed within the entire volume (say stratification terminated at  $t=t_1$ ). The simplest approach assumes that the two layers mix instantly. The resulting

average concentration in the whole impoundment/or lake  $C_a$  is given by a mass balance as:

$$C_a = \{ C_e V_e + C_h V_h \} / [ V_e + V_h ] \text{ for } t=t_1 \quad (\text{D.11})$$

In some cases, immediately following a seasonal turnover, the impoundment/lake may not be thermally stratified for sometime (say upto  $t=t_2$ ); i.e., the whole impoundment volume may be available for dilution of the effluent. For this period ( $t_2-t_1$ ), time-dependent equation (eqn. D.10) can be employed with parameters for the whole water body (e.g.,  $V_T = (V_e + V_h)$ ;  $K_T = (\lambda + q_T/V_T)$ ;  $C_a$ ; and time  $t=(t_2-t_1)$ ).

Hence during the unstratified period  $t=t_2-t_1$ , the concentration can be given (similar to eqn. D.10) as:

$$C(t) = q_T C_o / K_T V_T \{ 1 - \exp[-K_T(t-t_1)] \} + C_a \exp\{-K_T(t-t_1)\} \quad (\text{D.12})$$

where,  $q_T$  is the effluent inflow,  $C_o$  is the input concentration for the total lake at time  $t_1$  and  $V_T$  is the total volume of the water body and  $K_T$  the effective removal coefficient.

The input parameters required for the application of the stratified model are : duration of stratification time,  $t_1$ , duration of unstratification,  $t_2$ , effective volume of the epilimnion,  $V_e$ ; effective volume of the hypolimnion,  $V_h = V_T - V_e$  ; inflow rate in the epilimnion,  $q_e$ ; inflow rate in the hypolimnion,  $q_h$ ; and the radionuclide concentration in the inflow to the epilimnion,  $C_o(e)$  and hypolimnion,  $C_o(h)$  respectively. The retention by sediment can be represented by an additional term,  $\lambda_s$ , in the removal rate coefficient  $K$ . In the reservoir, the effect of sedimentation can be disregarded as a conservative approach.



## APPENDIX - E

### FAR-FIELD MODELS FOR OPEN-COAST WATER BODIES

#### E.1 Model For Complete Mixing Situations

The radioactive material is usually released in the near-shore region of open-coast water bodies such as coastal seas and large lakes. The model for complete mixing situations can predict the concentration when discharges are continuous. This means that the effects of tidal currents towards or away from the shore coasts are cancelled in the averaging processes. The simplest model for coastal seas is again box-type where complete mixing is assumed to take place within a volume  $V$ , from which radioactivity is lost by the combination of water exchange, radioactive decay and sediment interactions. The derivation of steady state concentration is similar to those presented for lakes/impoundments. The steady state concentration,  $C_s$ , can be given by a similar relation (as eqn. D.4) :

$$C_s = Q/KV \quad (E.1)$$

where  $Q$  is the discharge rate of radionuclide [ $Q=q(\text{input effluent flow}) \times C_o$  (input concentration)] and  $K$  is the effective removal rate coefficient comprising radioactive decay, fractional loss rate of water from the mixed volume,  $r/V$ , and sediment removal rate coefficient,  $\lambda_s$ . For tidal seas,  $V$  may be described by tidal excursion volume and  $r$  is by net water movement. For non-tidal seas, values for  $V$  and  $r/V$  will be determined by the nature of water movement and hence are likely to be site-specific than for the tidal situations.

The complete mixing model may be applied for time scales larger than one month since flushing time of large lakes and enclosed seas<sup>23</sup> is usually of the order of months. It is recognised that the sedimentation in lakes and enclosed seas partially removes some elements. The time scale for sedimentation is, however, long compared to the mixing time for the system, so that fully mixed model for the entire body of water is still valid without  $\lambda_s$ . However, for non-uniform sedimentation, additional removal term of  $\lambda_s$  can be incorporated in  $K$  as mentioned earlier.

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<sup>23</sup> Continents and island chains more or less separate certain oceanic areas from the open ocean, thus forming adjacent seas. Adjacent seas are called Marginal Seas when they form merely an indentation on the continental coast, and Mediterranean (Enclosed) Seas when they are enclosed to a great extent by land.

## E.2 Transient Model For Line Source

### E.2.1 Instantaneous Release of Source

Coastal seas have the distinct feature that the dispersion of effluent is constrained on one side by the coastline. A continuous release of radioactive effluent to a large lake or coastal sea produces a plume that moves parallel to the shore for many days, sometimes as far as 25 km from the point of discharge. The process may continue until any shift in the wind direction and other factors reverses the current. Though the dispersion within the parallel-to-shoreline plume is rather small, reversal processes, on the other hand, are accompanied by exchange with off-shore water and this mechanism effectively removes the pollutant from the effluent away from the coast.

A parallel-to-shoreline plume can be represented by the convective-diffusive equation assuming complete vertical mixing (similar to eqn. C.8) as :

$$\frac{\partial C}{\partial t} = K_x (\frac{\partial^2 C}{\partial X^2}) + K_y (\frac{\partial^2 C}{\partial Y^2}) - U (\frac{\partial C}{\partial X}) - \lambda C \quad (E.2)$$

The model assumes a straight shoreline and constant water depth,  $h$ , constant water speed,  $U$ , and constant dispersion coefficients  $K_x$  and  $K_y$ . The concentration  $C_i$  of a radionuclide for an instantaneous unit discharge from a vertical line source located at  $X=0$ ;  $Y=Y_d$  is evaluated from:

$$C_i(x,y,t) = [ \exp(-\lambda t) / \{4\pi h (K_x K_y t^2)^{1/2}\} ] \cdot [\exp\{-(X-Ut)^2 / 4K_x t\}] \cdot [\exp\{-(Y-Y_d)^2 / 4K_y t\} + \exp\{-(Y+Y_d)^2 / 4K_y t\}] \quad (E.3)$$

### E.2.2 Continuous Release Model

The concentration of a radionuclide from a continuous source can be derived from the instantaneous release by means of a convolution integral of the form:

$$C_c(t) = \int_0^t f(\tau) C_i(t-\tau) d\tau \quad (E.4)$$

where  $f(\tau)$  is the release rate and  $C_i(t-\tau)$  is the analytical solution at time  $(t-\tau)$  for an instant release (eqn. E.3).

### E.3 Transient Model For a Line Source with Tidal Effect

#### E.3.1 Instantaneous Release

Certain differences exist between dispersion of a plume of radionuclides in large lakes and enclosed seas and in oceans and open seas<sup>24</sup>. In oceans and open seas, there are tidal currents and large waves while in large lakes and enclosed seas the effects of land boundaries that enclose the water body are important. The differential equation for the near-shore dispersion of radioactive materials in coastal ocean [12] from an instantaneous release of unit activity taking into account the advective effects of tides is of the form:

$$\frac{\partial C}{\partial t} = K_x (\frac{\partial^2 C}{\partial X^2}) + K_y (\frac{\partial^2 C}{\partial Y^2}) - \{ U_x + U_{xt} \sin (2\pi t/\tau) \} \frac{\partial C}{\partial X} - (U_y + U_{yt} \sin (2\pi t/\tau)) \frac{\partial C}{\partial Y} - \lambda C$$

(E.5)

where  $U_x$ ,  $U_y$  are the wind induced current components in X and Y directions (cm/s),  $U_{xt}$ ,  $U_{yt}$  are the tidal current components in X and Y directions and  $\tau$  is the period of tide (s). The symbols for other terms have already been defined.

The tidal vector of the current in coastal waters is given by  $\{(g/h)^{1/2} A\}$  where  $g$  is the acceleration due to gravity,  $h$  is the water depth at discharge point and  $A$  is the amplitude of the tide. Depending upon the topography of the coast, the angle of incidence of tidal vector has to be generated from field observations.

The solution for the above equation (E.5) for an instantaneous discharge is obtained by using mass balance equation :

$$\int_0^\alpha C dV = M \exp(-\lambda t)$$

(E.6)

Therefore solution is given by :

$$C_i = \{ M \exp(-\lambda t) / 2\pi H (K_x K_y t^2)^{1/2} \} \exp -\{ [X - U_x t + U_{xt} (\tau/2\pi) \cos(2\pi t/\tau)]^2 / 4K_{xt} \} \exp -\{ [Y - U_y t + U_{yt} (\tau/2\pi) \cos(2\pi t/\tau)]^2 / 4K_{yt} \}$$

(E.7)

where  $C_i$  is the concentration of radionuclide at time  $t$ ,  $H$  is the mixing depth and  $M$  is the amount of discharge.

#### E.3.2 Continuous Release

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<sup>24</sup> An open expanse of salt water on the face of the globe.

The continuous release of radioactivity may be considered as consisting of an infinite numbers of instantaneous puff releases sequentially arranged, with a vanishingly small time interval between the puffs, such that  $M = Q t$ . Thus, the concentration distribution from a continuous release of source at a rate of  $M$  (Bq) for time interval of  $t$  is obtained from the convolution integral :

$$C_c(t) = \int_0^t Q(\tau) C_i(t-\tau) d\tau \quad (E.8)$$

where  $C_i(t-\tau)$  is the concentration due to a point source at time  $(t-\tau)$  and  $Q$  is the release rate (Bq/s). The analytical solution for this integral is difficult to obtain and hence recourse to numerical summation technique may have to be undertaken. The steady-state concentration in the water body can be evaluated by replacing the integration limit to infinity.

The physical description of the near-shore dispersion of plumes in this section applies to simple situations of straight shoreline geometry, and this approximation can be assumed even when irregular features are present. Measurements of current should be performed at the site over a sufficient time to characterise the flow variability for studying the effect of irregular coast-lines. These measurements can also determine the pattern on reversal of currents and their frequency. Reasonable values of dispersion coefficients may be obtained for site-specific conditions by tracer studies during pre-operational or operational stage.

## APPENDIX - F

### ESTUARY MODELS

#### F.1 Model for Complete Mixing Situations

The simplest model for an estuarine system is based on complete mixing within a plug of water across the whole width of the estuary. The plug is assumed to move up and down the estuary under the influence of the tide. The factors which determine equilibrium concentration in this tidal plug water are : dilution in the plug water and removal by sediment and the radioactive decay. The equation for the steady-state concentration,  $C_s$ , of a radionuclide introduced at a uniform rate,  $Q$ , into the tidal plug (of volume  $V$ ) is given by:

$$C_s = Q/KV \quad (F.1)$$

where  $K = (\lambda + \lambda_s + r/V)$ ;  $r$  is the fresh water input rate ( $m^3/y$ ) to the head of the estuary. The approach has been found adequate in sections where the estuary is narrow in relation to its length. As the width of estuary increases, mixing across the width becomes less likely and hydraulic conditions may become similar to that proposed for coastal seas.

#### F.2 Tidally-Averaged One-Dimension Model

This model takes into account changes in longitudinal velocity and the dispersion coefficient. A simplified version could be obtained by time averaging the velocity and dispersion terms. Using this assumption, one-dimensional transport equation can be written as:

$$\partial C / \partial t = D_x (\partial^2 C / \partial X^2) - U_f (\partial C / \partial X) - \lambda C \quad (F.2)$$

where  $U_f$  is the fresh water advective flow velocity and  $D_x$  is the apparent longitudinal dispersion coefficient. This dispersion coefficient accounts for dispersion due to motions which have a periodicity similar to tidal period or less and the differences that exist because of the non-uniform mixing. A formulation sometimes used for this longitudinal dispersion coefficient is [13]:

$$D_x (X,t) = 77 n U_t R_h^{5/6} \quad (F.3)$$

where  $X$ , the distance from mouth of estuary;  $n$ , the Manning's roughness coefficient;  $U_t$ , the local r.m.s velocity and  $R_h$ , the hydraulic radius of the cross section as the function of  $X$ . The time dependence is due to tidal effects. Again, this relation is an approximation for situation where the salinity intrusion is negligible.

When the effects of salinity intrusion is significant, the formula of Thatcher and Harleman [14] should provide a better relationship.

As a particular example of this model, the solution for the equation (F.2) for an instantaneous discharge of unit radioactivity entering the estuary having uniform distribution across constant cross section A is given by [similar to the solution of (E.2) as]:

$$C_i(X,t) = \{ 1 / A(4\pi D_x t)^{1/2} \} \exp\{ -[(X - U_f t)^2 / 4D_x t] + \lambda t \} \quad (F.4)$$

For continuous releases, this equation can be used together with the following convolution integral :

$$C_c(X,t) = \int_0^t Q(\tau) C_i(t-\tau) d\tau \quad (F.5)$$

where the symbols have the same significance as given earlier.

The differential equation represented above can also be modified to take into account variation in the cross-sectional area of the estuary. Here, the tidal effects lead to dependency of A on t. However, to apply the equation, a time-dependent longitudinal velocity and cross-sectional area must be specified as input at each distance X. Thus, the variation of the flow field in the estuary must be known to include dependency A(X,t) on concentration profile.

## APPENDIX - G

### ROLE OF SEDIMENT IN HYDROLOGICAL DISPERSION

The affinity of a given radionuclide for a given sedimentary material is usually characterised by the distribution coefficient  $K_d$ . The concentration of radionuclide,  $i$ , in sediments can be described simply by the use of equilibrium model :

$$C_{s,i} = C_{w,i} * K_{d,i} \quad (G.1)$$

where  $C_{s,i}$  is the concentration of radionuclide,  $i$ , in the sediment at equilibrium,  $C_{w,i}$  is the concentration of radionuclide,  $i$ , in water and  $K_{d,i}$  is the distribution coefficient of radionuclide,  $i$  at equilibrium.

The equilibrium model is used to give an upper limit of concentration for a given sediment type and hence may over-estimate the fraction of activity deposited onto sediments. This approach does not take into account time dependent build-up of activity in sediments, the inhomogeneous distribution of activity in sediments and the physical transport of sediments. The time dependence of the accumulation of radionuclide,  $i$ , in sediments can be described by:

$$(dC_{s,i}/dt) = K_{c,i}C_{w,i} - \lambda_i C_{s,i} \quad (G.2)$$

where  $K_{c,i}$  is the transfer rate coefficient from water to sediment (ml/gm/y) and  $\lambda_i$  is the decay constant of the radionuclide  $i$  ( $y^{-1}$ ).

The solution of eqn. (G.2) can be represented as :

$$C_{s,i} = [K_{c,i}C_{w,i} / \lambda_i] \cdot [1 - \exp(-\lambda_i t_b)] \quad (G.3)$$

where  $t_b$  is the exposure time to the contaminated water (usually 15 years). The values of  $K_{c,i}$  have to be generated preferably for each specific site. Both  $K_{d,i}$  and  $K_{c,i}$  are related by  $\lambda_i$  and  $t_b$ .

A number of different external exposure pathways may be considered involving sediment and situations such as occupancy of beach and mud banks etc.

The dose rate due to external radiation is given by the relation :

$$H_i = D_{ip} * U_p \quad (G.4)$$

where  $D_{ip}$  is the whole body dose rate for gamma emitters or the skin dose rate for  $\beta$  emitters and  $U_p$  is the occupancy rate for the external pathway, specific for critical groups of the specific site.



## ANNEXURE - I

### MEASUREMENT OF DISPERSION COEFFICIENTS

The turbulent dispersion coefficients are different for different water bodies. The turbulence generated by wind differs from that generated by flow and this difference inter-alia among others, causes variation of dispersion coefficients of different water bodies. Hence, it is preferable to measure the dispersion coefficients for the specific water body of interest.

The dispersion coefficients are measured by the direct determination of standard deviations  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$  characterising the spatial concentration distribution of a contaminant in water. The standard deviations of the plume can be evaluated by the use of different tracers such as fluorescent dyes, radioactive substances or stable elements. Among the fluorescent dyes, Rhodamine B is one of the sensitive tracers and this can be detected at concentrations of 75 ppm. Radioactive tracers are detectable at concentrations of 40 mBq/ml. Stable elements can be detected at concentrations of about ppb level using Neutron Activation Analysis or in ppm levels using Atomic Absorption Spectrophotometer.

The lateral dispersion coefficient,  $K_Y$ , can be defined in terms of variance,  $(\sigma_Y)^2$ , as:

$$d(\sigma_Y^2)/dt = 2 K_Y \quad (I.1)$$

where the variance  $(\sigma_Y)^2$  can be related to spread of the plume in longitudinal distance.

For flow conditions, the above equation can be replaced by :

$$K_Y = (\bar{U}/2) d(\sigma_Y^2)/dx \quad (I.2)$$

where  $\bar{U}$  is the mean flow velocity and  $X$  is the longitudinal distance from the point of introduction.

The time-concentration profile at different longitudinal distances will give the spread of the plume i.e.,  $\sigma_Y^2$ , the variance in  $Y$  direction. The value of  $K_Y$  can be computed from the relation:

$$K_Y = (\sigma_Y^2)_2 - (\sigma_Y^2)_1 / 2(t_2 - t_1) \quad (I.3)$$

–

If the release is continuous and constant, then  $(t_2-t_1)$  can be replaced by  $(Y_2-Y_1)/U$  and this spatial distribution of concentration will yield the variance.

An approximate relation can be obtained from the spread of the plume such that  $L=4\sigma_Y$  which is the maximum detectable spread and this  $L$  can be substituted in the above equation for the evaluation of  $K_Y$  as :

$$K_Y = \{(L_2)^2 - (L_1)^2\}/32 (t_2-t_1) \quad (I.4)$$

Similar determination of temporal and spatial concentration profiles of the radionuclide in Z direction will yield the values for  $K_z$ .

The use of tracer with no density difference with the ambient is generally recommended so that the rate of spread will become the same for tracer once the initial mixing and buoyancy effects are completed. However, it should be recognised that the basic assumption of this measurement is based on the constancy of dispersion coefficients in space which may be realistic for open channel flow systems like river but is only approximate in other flow environments.

Ocean diffusion studies have revealed that the dispersion coefficients can be represented as a function of the spread of the plume by the relation:

$$K_Y = A L^{4/3} \quad (I.5)$$

This is known as four-thirds power law [16] where  $A$  is the dissipation parameter,  $L$  the spread of the plume ( $L=4\sigma_Y$ ). The values for  $A$  are in the range of 0.01- 0.02  $\text{cm}^{2/3} \text{s}^{-1}$ .

The vertical dispersion coefficient is usually significantly smaller than the lateral/longitudinal dispersion values. If stratification also prevents vertical diffusion, then the vertical dispersion coefficient may be evaluated as a function of local Richardson number.

Some of the best estimate values chosen for different type of water bodies are shown below:

Ranges of Dispersion Coefficients

Systems	Dispersion Coefficients ( $\text{cm}^2/\text{s}$ )		
	$K_x$	$K_y$	$K_z$
Open ocean	1.0(7) [1.0(6)- 1.0(8)]	1.0(7) [1.0(6)-1.0(8)]	1 [0.1-30]
Coastal seas	1.0(5) [ 1.0(4)-1.0(6)]	1.0(5) [1.0(4)-1.0(6)]	5 [1-30]
River	5.9(4)	5.9(4)	1.0(2)

Read 1.0(7) as 1.0E7

Values in the parentheses represent ranges

## ANNEXURE - II

### MEASUREMENT OF $K_d$ FOR RADIONUCLIDES ON SEDIMENT

Adsorption and absorption of specific radionuclides by the suspended and bottom sediments has been recognised as an important scavenging process. This results in exposure pathways viz.; direct shore-line exposure and by transfer to aquatic food chain.

A simplified approach is adopted to represent the complex scavenging within a bed suspension-sedimentation- resuspension cycle. It makes use of distribution factor,  $K_d$ , which is characteristic of each nuclide and is defined for steady-state conditions at equilibrium as:

$$K_d = C_s/C \quad (\text{II.1})$$

where  $C_s$  is the concentration of radionuclide in sediment in terms of activity per unit weight and  $C$  is the concentration of radionuclide in water in terms of activity per unit volume. Thus, the dimension of this distribution coefficient  $K_d$  is volume divided by weight ( ml/g).

$K_d$  values depend on many parameters viz.; sediment load, particle size, physico-chemical characteristic of the sediment and nuclides and pH of water. Hence, this value should be acquired from laboratory experiments on sediments and water collected at the site. The coefficients may be determined as follows:

A quantity  $M$  of sediment is mixed with a volume  $V$  of water in a beaker and placed on a magnetic stirrer. At time zero, a known amount of a radionuclide is put into the beaker. Then at specified times, aliquots of water samples are taken from the beaker, filtered through filter paper (size 0.45 micron) and assessed for radioactivity. The distribution coefficient,  $K_d$ , is calculated from the relation:

$$K_d = (V/M) \{ (C_0/C_\infty) - 1 \} \quad (\text{II.2})$$

where  $C_0$  is the nuclide concentration in water at zero time and  $C_\infty$  is the nuclide concentration in water when equilibrium has been reached.

The frequency of sampling from the beaker should not significantly alter the initial volume of the water. This can be avoided by giving adequate contact time (overnight) so that equilibrium is attained. The determination should be repeated for each nuclide of interest.

Some typical  $K_d$  values for different radionuclides are given in the table below :-

Distribution Coefficients for Sediments  $K_d$  (ml/gm)

$K_d$			$K_d$		
Element	Marine	Fresh Water	Element	Marine	Fresh Water
H	0		Ag	10000	200
C	100	0	Sn	10000	
Na	100	2000	Sb	10000	300
P	100		Te	10000	30
S	100		I	100	200
Cl	100		Cs	500	30000
Ca	500		Ce	10000	30000
Cr	10000	20000	Pm	10000	
Mn	10000	10000	Sm	10000	
Fe	10000	10000	Eu	10000	
Co	10000	30000	Au	10000	
Ni	10000		Pb	10000	
Zn	10000	1000	Po	10000	
Se	10000		Ra	500	
Br	100		Ac	10000	
Sr	500	2000	Th	5000000	
Y	10000	4000	Pa	5000	
Zr	10000	60000	U	500	
Nb	10000	100	Np	50000	
Tc	10000	200	Pu	50000	30000
Ru	10000	40	Am	50000	30000
Pd	10000	40000	Cm	50000	30000
			Cf	50000	

Note: Values in parentheses indicate that these values have been inferred from analogy, not experimental data.

## **ANNEXURE - III**

### **DEPOSITION OF AIR-BORNE RADIOACTIVITY TO SURFACE WATERS**

A possible source of radionuclides into the surface waters is the deposition of air-borne radioactive materials under accidental radioactive releases. The modelling of surface water concentration profile can be carried out using the transient and/continuous model described in Appendix E. The source term can be evaluated from the deposition of radionuclides on to the surface water. The full-mixing of deposited materials over the depth ( say 10 m) may usually be assumed. Thus, the source term to the surface water can be represented as vertical area source in YZ plane and concentration profile in down stream can be evaluated. It is then possible to compute the concentration in other compartments of the aquatic systems.

## ANNEXURE - IV

### APPLICATION OF FULLY MIXED MODEL FOR AN IMPOUNDMENT

The Fully Mixed model for studying the build-up of radionuclide concentration in an impoundment/lake is discussed in Appendix D.1. The application of the equation in D.1 can be demonstrated using some transformations for time,  $t$ ,  $T_{1/2}$  and flushing time. The relative ratio of radionuclide concentration with respect to its steady-state value in an impoundment/lake as a function of dimensionless time (time/flushing time) is shown in the table below. This gives approximate times required for attaining steady state concentration values as a function of half-life of the radionuclides and flushing time of the system.

TABLE  
Build-up of Radionuclide Concentration

$t/(V_T/q_b)$	$(C(t)/C_\infty$ values for different R values )		
	0.1	1.0	10.0
0.1	0.54	0.16	0.10
0.5	0.98	0.57	0.41
1.0	1.0	0.82	0.66
2.0	1.0	0.97	0.89
10.0	1.0	1.0	1.0

$$R = T_{1/2} / (V_T/q_b);$$

$R < 1$  means half-life short compared to flushing time

$R > 1$  means half-life long compared to flushing time

$t/(V_T/q_b) < 1$  means time considered is less compared to flushing time

$t/(V_T/q_b) > 1$  means time considered is long compared to flushing time

## ANNEXURE V

### APPLICATION OF A SIMPLE AND REFINED MODEL FOR RIVER

This section indicates the application of a simple model (Appendix C.1) for river system and compares with values generated using a refined model [17] incorporating reflection contributions and suspended and bottom sediment effects on the concentration profiles (see table below). The sediment effect in simple model is taken with the use of  $s$  and this will have effect on the concentration profile only at longer distances ( $> 10$  km) for nuclides having high  $K_d$  values. The differences in the results from the models shown in the table below can be explained in terms of reflection contribution and bottom sediment movement considered in the refined model.

Table

Comparison of spatial concentration profile in river water using simple model and 3-dimensional model for a continuous release of 1 Bq/s

Nuclide	Concentration (Bq/m <sup>3</sup> ) based on			
	Model A		Model B	
	1 Km	5Km	1 Km	5 Km
<sup>3</sup> H	1.25E-3	1.25E-3	5.13E-3	4.87E-3
<sup>137</sup> Cs	1.23E-3	1.13E-3	2.18E-3	1.82E-3
<sup>90</sup> Sr	1.23E-3	1.13E-3	4.67E-3	4.37E-3

River Geometry : Width 200 m; Depth 4 m; Flow velocity 1 m/s;  
Model A : Simple model based on river flow dilution  
Model B : Refined Model [17]



## ANNEXURE VI

### PARAMETRIC VARIABILITY IN THE PREDICTION

A tide-induced model developed for coastal discharges [12] has been used to study the effect of parametric variability in the concentration profile of  $^{137}\text{Cs}$  in coastal waters for a continuous release of 1 Bq/d. The concentration of  $^{137}\text{Cs}$  has been computed for different distances along the coast and 5 Km off-shore for varied  $K_x$  and  $U_x$  values (see table below). The increase of  $K_x=K_y$  values by an order of magnitude decreases the concentration by a factor of about 3. The increase in  $U_x$  values allows the peak concentration to appear at farther distances with reduced levels.

Table

Parametric Influence in the prediction of concentration profile of  $^{137}\text{Cs}$  using tidal model (Appendix E.3)

*concentration(Bq/ml) at distances X(Km)				
1.6	5.0	10.0	25.0	Parameters
3.48E-15	3.36E-15	3.06E-15	2.36E-15	$K_x = K_y = 5.0E5$ $U_x = 10; U_y = 1; Y = 0$
1.43E-15	1.52E-15	1.41E-15	9.09E-16	$K_x = K_y = 5.0E6$ $U_x = 10; U_y = 1; Y = 0$
3.45E-16	3.29E-16	3.08E-16	2.47E-16	$K_x = K_y = 5.0E7$ $U_x = 10; U_y = 1; Y = 0$
8.56E-16	9.89E-16	1.02E-15	6.49E-16	$K_x = K_y = 5.0E6$ $U_x = 20; U_y = 1; Y = 0$
3.41E-16	3.83E-16	5.06E-16	3.55E-16	$K_x = K_y = 5.0E6$ $U_x = 50; U_y = 1; Y = 0$
9.21E-17	6.58E-16	1.23E-15	1.33E-15	$K_x = K_y = 5.0E5$ $U_x = 10; U_y = 1; Y = 5$
5.99E-16	7.19E-16	6.77E-16	4.57E-16	$K_x = K_y = 5.0E6$ $U_x = 10; U_y = 1; Y = 5$
1.66E-16	1.62E-16	1.52E-16	1.22E-16	$K_x = K_y = 5.0E7$ $U_x = 10; U_y = 1; Y = 5$
2.82E-16	4.21E-16	4.73E-16	3.16E-16	$K_x = K_y = 5.0E6$ $U_x = 20; U_y = 1; Y = 5$
3.99E-17	9.44E-17	2.09E-16	1.48E-16	$K_x = K_y = 5.0E6$ $U_x = 50; U_y = 1; Y = 5$

\* continuous and constant release rate of 1 Bq/d assumed

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January 9, 1992  
February 10, 14, 1992  
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June 17,26, 1992  
July 3,7, 20, 1992  
November 24,1992

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**PROVISIONAL LIST OF SAFETY GUIDES UNDER SITING CODE**

Safety Guide No.	Title
SG/S-1	Meteorological Dispersion Modelling
SG/S-2	Hydrological Dispersion in Relation to NPP Siting
SG/S-3	Extreme Value Analysis for Meteorological Parameters
SG/S-4	Hydrogeological Aspects Related to NPP Siting
SG/S-5	Calculational Models for Dose from Concentrations
SG/S-6A	Design Basis Floods for Inland NPP Sites
SG/S-6B	Design Basis Floods for Coastal NPP Sites
SG/S-7	Man-Induced Events and Establishment of DBFs
SG/S-8	Influence of Site Parameters on Emergency Preparedness
SG/S-9	Population Distribution and its Analysis
SG/S-10	Quality Assurance in Siting
SG/S-11	Design Basis Ground Motion for NPP Sites

