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QUARTERLY REPORT, JANUARY 1980 TO MARCH 1980

# MATHEMATICAL SIMULATION OF SEDIMENT AND CONTAMINANT TRANSPORT IN SURFACE WATERS

FIN Number B2271

Prepared for the
U.S. Nuclear Regulatory Commission

Pacific Northwest Laboratory
Richland, Washington 99352

MATHEMATICAL SIMULATION OF SEDIMENT AND CONTAMINANT TRANSPORT IN SURFACE WATERS

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## SUMMARY

During the second quarter of FY-1980, we have completed the topical report, "Critical Review: Radionuclide Transport, Sediment Transport and Water Quality Mathematical Modeling, and Radionuclide Sorption/Desorption Mechanisms," NUREG/CR-1322, PNL-2901. The report describes the detailed literature review on radionuclide transport models applicable to rivers, estuaries, coastal water, and lakes. Some representative sediment and water quality models were also reviewed to evaluate if they can be readily adopted to the radionuclide transport modeling. In addition, radionuclide adsorption/desorption mechanisms were discussed in depth, including compilation of available distribution coefficients. We are going to print this report for the RE distribution. For Task B (Transport of Sediment and Radionuclides in Oceans), available data on the Windscale Plant along the coast of the Irish sea have further been obtained through a literature search. These data will be used for the FETRA model application to the site. For Task C (Transport of Sediment and Radionuclides in Estuaries), data of channel geometry and flow, sediment and radionuclide distributions on Hudson River estuary and Montsweag Bay were also collected through published and unpublished documents. They were used to determine which site should be selected for the estuarine radionuclide transport modeling. Indian Point Nuclear Power Plant discharges its effluent to the Hudson River, and the Maine Yankee Nuclear Power Plant discharges its effluent to the Montsweag Bay. The evaluation of data for these two sites led to the conclusion that the Hudson River estuary should be selected as the modeling site, because more critical data are available in the Hudson River estuary than those collected in the Montsweag Bay.

## LITERATURE REVIEW

Both the state-of-the-art of mathematic~l modeling of radionuclide transport and the present understanding of radionuclide adsorption/desorption mechanisms were critically reviewed. Study results were documented in the report, "Critical Review: Radionuclide Transport, Sediment Transport and Water Quality Mathematical Modeling, and Radionuclide Sorption/Adsorption Mechanisms," NUREG/CR-1322, PNL-2901, by Y. Onishi, R. J. Serne, E. M. Arnold, C. E. Cowan, and F. L. Thompson.

Most radionuclide transport models are based on the advection/diffusion equation. These models range from simple analytical solutions to sophisticated numerical models. For every simplified case, analytical solutions provide useful information on radionuclide distributions with very minor efforts. Numerical models, however, can accommodate a wide variation of channel geometry, flow distribution, and sediment and radionuclide distributions. The study reveals that the important mechanisms of radionuclide transport and fate are: 1) advection and dispersion of radionuclides by current, surface waves, and mixing, 2) radionuclide decay, 3) radionuclide contributions and subsequent mixing from outside sources, and 4) interaction between radionuclide and sediment.

As shown in Table 1, most available radionuclide transport models were developed for rivers and include the first three mechanisms. These models are best suited to short-term radionuclide migration cases where: 1) radionuclides have small distribution coefficients, Kd, and 2) sediment concentrations in receiving water body is very low. However, in cases where: 1) the distribution coefficient is large, 2) sediment concentrations in receiving water body is high, or 3) a long-term migration and accumulation are under concern, the last mechanisms (radionuclide-sediment interactions) must be included in the analysis. Radionuclide-sediment interactions involve radionuclide adsorption/desorption and transport, deposition and scouring of particulate radionuclides.

## TABLE 1. Summary of Radionuclide Transport Model

| Author and/or Radionuclide Transport Models | Modeling Substances: Dissolved Radionuclide Transport | Particulate Radionuclide Transport | Sediment Transport | Mechanisms: Advection | Diffusion/Dispersion | Adsorption of Radionuclides | Radioactive Decay | Hydrodynamics Simulation | Dimensionality: No Spatial Dimensions | One-Dimensional | Two-Dimensional | Three-Dimensional | Time Dependent: Steady-State | Dynamic | Solution Technique: Analytical | Numerical Solution Technique* | Applicable Water Body** | Field Application |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fletcher and Dotson 1971 | x | x | x | x | | | x | | | x | | | | x | | FD | R,L | |
| Bramati et al. 1973 | x | | | x | | x | | | | x | | | x | | x | | R,L | x |
| Soldat et al. 1974 | x | | | x | | x | x | | | x | | | x | | | | C,E,R,L | x |
| Watts 1976 | x | | | x | | | x | | | x | | | x | | x | | R | x |
| Martin et al. 1976 | x | | | x | | | x | | | x | | | | x | | | R,L | x |
| Buckner and Hayes 1976 | x | x | | x | x | x | x | | | x | | | | x | | FD | R | x |
| Shih and Gloyna 1976 | x | | | x | x | x | | | | x | | | | x | x | | R | |
| Armstrong and Gloyna 1968 | x | | | x | x | x | | | | x | | | | x | | FD | R | |
| White and Gloyna 1969 | x | | | x | x | x | | | | x | | | | x | | FD | R | |
| Shull and Gloyna 1968 | x | x | | x | | x | | | | x | | | x | | x | | R | |
| Onishi, et al. 1976, 1977, 1978, 1979 | | | | | | | | | | | | | | | | | | |
| FETRA | x | x | x | x | x | x | x | | | | x | | x | x | | FE | C,E,R, | x |
| SERATRA | x | x | x | x | x | x | x | | | | x | | | x | | FE | R,L | x |
| | x | x | x | x | x | x | x | x | | | | | x | x | | FE,FD | R | |
| Fields 1976 (CHMSED) | x | x | x | x | | x | | | | x | | | x | | | FD | R | |
| Eraslan, et al. 1977 | | | | | | | | | | | | | | | | | | |
| RADONE | x | | | x | x | | | | | x | | | | x | | FD | E,R | |
| RADTWO | x | | | x | x | | | | | | x | | | x | | FD | C,E,L | |
| HOTSED | | x | | | | x | | x | | x | | | | x | | FD | E,R, | |
| Chapman 1977 | | x | | x | x | x | x | | | x | | | | x | | FD | R | |
| Smith et al. 1977 | x | x | | x | x | x | x | | | x | x | x | | x | | FD | R,L | |
| Vanderploeg et al. 1976 | x | x | | | | x | x | | x | | | | | | x | | L | x |
| Booth 1976 | x | x | | | | x | x | | | x | | | | x | x | | L | |
| USNRC 1978 | x | x | | x | x | x | x | | | x | | | | x | x | | E | x |

* FD - Finite Difference
  FE - Finite Element
** C - Costal Systems and Great Lakes
  E - Estuarine Systems
  R - River Systems
  L - Lakes and Impoundments

## TASK B. TRANPSPORT OF SEDIMENT AND RADIONUCLIDE IN OCEANS

As reported in the first quarterly report of FY-1980, the sediment-radionuclide transport model, FETRA, will be applied to the Irish Sea to examine the applicability of FETRA to coastal waters. The shaded area in Figure 1 indicates the modeling area. Data required by FETRA which consists of sediment, dissolved radionuclide and particulate transport submodels, are as follows:

All of the input data required to operate FETRA are listed below for each submodel of FETRA:

- Channel geometry or bathymetry
- Depth and velocity distributions which will be obtained by a hydrodynamic code (e.g., CAFE) with field data.
- Longitudinal and lateral dispersion coefficients.

Sediment transport submodel:

- Sediment size distribution and density
- Sediment fall velocity (It can be estimated by sediment size and density)
- Critical shear stresses of erosion and deposition of cohesive sediments (silt and clay) (They are usually selected through a model calibration process)
- Erodibility coefficient for erosion of cohesive sediment (It is usually selected through a model calibration process)
- For marine environments:

  a) Wave characteristics of deep water:

| | |
|---|---|
| Wave number<br>Wave height<br>Wave frequency<br>Direction of wave propagation | They are used to calculate wave characteristics, (of offshore and surf zones) in a study area by the Wave Refraction Model (Dobson 1967, Ecker and Dogracа 1974) |

or

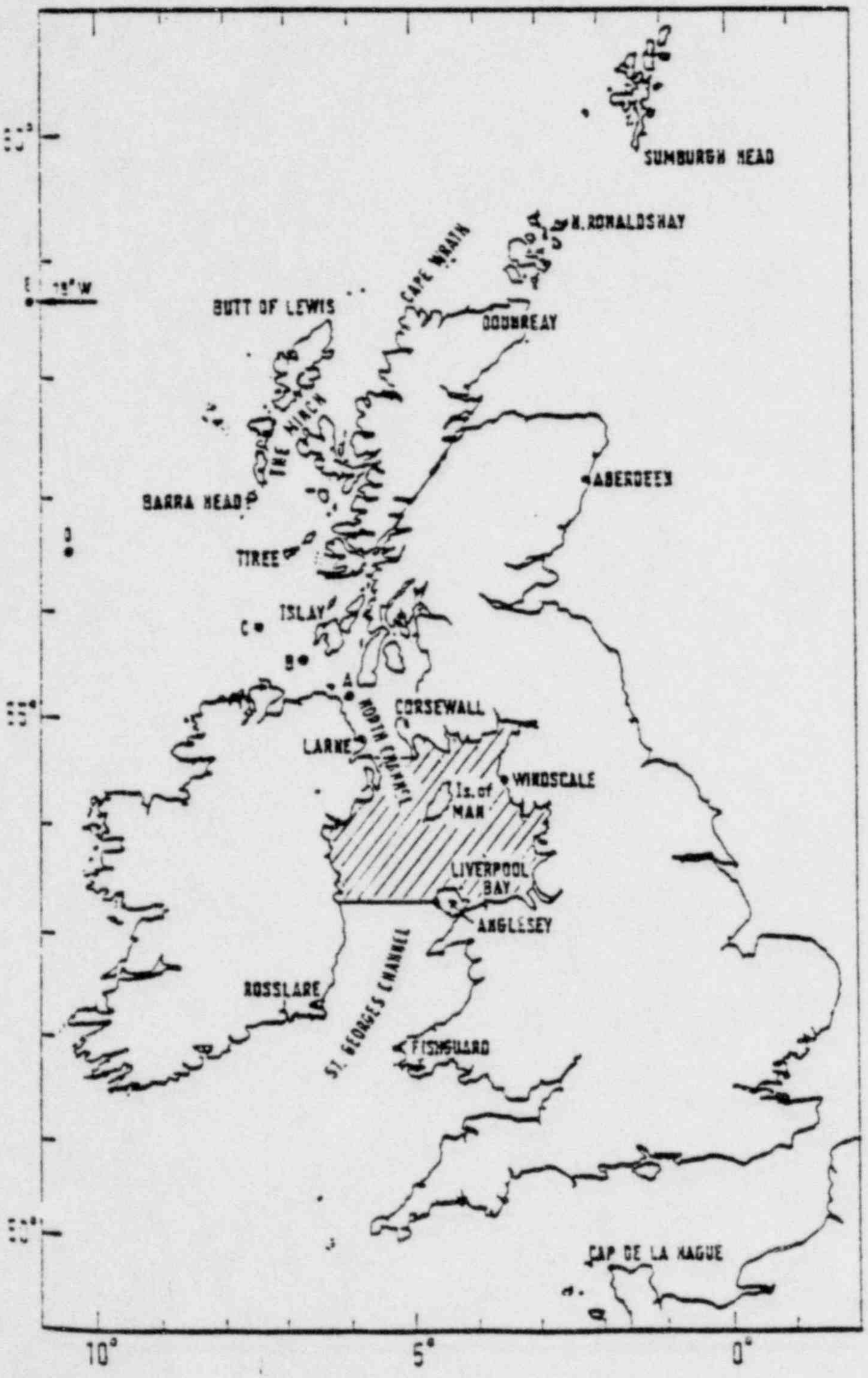


FIGURE 1. Irish Sea Modeling Area

b) Information for wind-generated waves:
   Wind velocity
   Mean fetch depth
   Effective fetch length

- Initial conditions:
  Sediment concentrations for each sediment size fraction
  Bottom sediment size fraction

- Boundary conditions:
  Concentration or lateral influx of sediment at the boundaries

Dissolved and particulate contaminant (radionuclide) transport submodels:

- Distribution coefficients of radionuclide with marine sediments for each sediment size fraction

- Initial conditions:

  Dissolved radionuclide concentration

  Particulate radionuclide concentration associated with sediment in water for each sediment size fraction

  Particulate radionuclide concentration for each sediment size fraction within ocean bed

- Boundary conditions:

  Concentration or lateral influx of dissolved radionuclides at the boundaries

  Concentration or lateral influx of particulate radionuclide at the boundaries for each sediment size fraction.

We have been gathering field data required by FETRA. Windscale data found in the open literature is tabulated in Table 2. Past routine monitoring programs for the Irish Sea have focused on three radiation exposure pathways: 1) internal exposure resulting from the consumtion of laverbread manufactured from the seaweed Porphyra, 2) internal exposure resulting from the consumption

## TABLE 2. Irish Sea Data

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Barnes and Goodley 1961 | | Hydrographic information for the North Channel | |
| Belderson and Stride 1969 | | Hydrographic information for the Northeastern Irish Sea | Includes bed-transport paths; locations of sand wave and mud zones |
| Craig 1959 | | Water movements in the North Channel | |
| Dunster 1958 | 1953-1958 | Discharge of $^{106}Ru$ and $^{90}Sr$ during experimental periods | |
| | | Sea bed concentration of $^{106}Ru$ | |
| Dunster et al. 1964 | | Description of area | |
| | 1953-1962 | Mean monthly discharge rates for $^{106}Ru$, $^{90}Sr$ | |
| | | Description of sea bottom sampling program | |
| | 1959-1962 | Mean annual discharge rate for several beta emitters | |
| Hetherington 1976a | July 1973 | | |
| | July 1974 | Concentration contours for $^{239}Pu$ - filtered seawater | Irish Sea (30 sampling points) |
| Hetherington et al. 1975 | July 1973 | Concentration contours for $^{137}Cs$ - filtered seawater | Irish Sea (30 sampling points) |
| | 1973, 1974 | Fraction of $^{239}Pu$ in seawater retained on a 0.22 micron millipore filter as a function of the total suspended load | 15 stations within a 30 km radius of Windscale |
| | 1974 | Filtered seawater and seabed surface concentration of $^{239}Pu$ and concentration factors | |
| | | $^{239}Pu$ and $^{137}Pu$ concentrations in core samples | |
| | | Concentrations of $^{239}Pu$ and $^{137}Pu$ Cs in filtered seawater | <10 km, 75-100 km from Windscale outfall |
| Hetherington et al. 1976 | | Concentration of $^{238,239,240}Pu$ and $^{241}Am$ in surface sediments | 8 stations ranging from 1-110 km from Windscale outfall |
| | 1974 | Distribution of $^{238,239,240}Pu$ and $^{241}Am$ is a seabed sediment core sample | |
| | 1974 | Concentrations of $^{238,239,240}Pu$ and $^{241}Am$ in sediment and seawater within 10 km of discharge | |
| Hetherington and Jefferies 1974 | 1966-1971 | Concentrations of $^{106}Ru$, $^{95}Zr/^{95}Nb$, $^{144}Ce$ in surface sediment samples | Eskmeals (1966-1971), Walney (1966-1968), Whitehaven (1969-1971) |

## TABLE 2. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| | 1967-1973 | Distribution of $^{106}Ru$, $^{95}Zr/^{95}Nb$, $^{144}Ce$ $^{137}Cs$, $^{134}Cs$ in core samples | Ravenglass Estuary (Eskmeals) |
| | 1970-1971 | Particle size distribution of sediment | Mud from the Ravenglass Estuary |
| Hunt 1979 | 1977 | Concentration in sediment of $^{60}Co$, $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{144}Ce$, $^{238}Pu$, $^{239}Pu + ^{240}Pu$, $^{241}Am$ | 14 coastal locati[illegible] (intertidal sediments) |
| | Sept 1977 | $^{137}Cs$ concentration contours - filtered seawater | |
| Jefferies, 1968, 1970 | 1965-1967 | Concentration in furface silt of $^{95}Zr/^{95}Nb$ $^{106}Ru$, $^{144}Ce$, $^{137}Cs$ | Ravenglass Estuary mud flats (intertidal zone) |
| | | Distribution of same radionuclides in core samples | |
| | | Accumulation factors for surface silt and surface sand for $^{95}Zr + ^{95}Nb$, $^{106}Ru$, $^{137}Cs$ | Weekly seawater samples were taken during 1965-1966 and filtered through 0.22 micron millipore filters for analysis |
| Jefferies et al. 1973 | May 1972 | Concentration of $^{137}Cs$ in filtered seawater | Sampled at surface, mid-water and bottom at 58 stations in the Irish Sea<br>Found >90% of $^{137}Cs$ water sample content to be in the filtrate |
| | | Information on circulation | |
| Jones 1960 | | Specific gravity of sea bed material from off the Cumberland coast | |
| | Nov 1956 | Uptake of $^{106}Ru$ by particles of different diameter | |
| Longley and Templeton 1965 | 1962 | Concentration on shore silt of $^{106}Ru$, $^{137}Cs$, $^{144}Ce$ | |
| | | Seabed concentration of $^{106}Ru$ | |
| Mauchline 1963 | 1959-1960 | Concentration in sea water [illegible] $^{144}Ce$, $^{106}Ru$ $^{95}Zr/^{95}Nb$, $^{98}Sr$, $^{90}Sr$, $^{137}$[illegible] | Locations near Sellafield |
| | | Limited information on circulation and winds | |
| | | Composition of the bottom material in the northeastern Irish Sea | |
| Mauchline and Templeton 1963 | | Hydrographic information | |
| Mitchell 1969 | 1968 | Concentration in silt of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{144}Ce$ | Ravenglass Estuary, Walney Island, Whitehaven Harbor |
| | 1968 | Concentration in sea water of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{137}Cs$, $^{40}K$ | 8 coastal sites in the vicinity of Windscale |

## TABLE 2. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| | 1968 | Concentration in seabed samples of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{144}Ce$ | Off St. Bees |
| Mitchell 1971a | 1969 | Concentration in silt of $^{95}Zr/^{95}Nb$, $^{106}Nb$, $^{144}Ce$ | Ravenglass Estuary, Whitehaven Harbor |
| | 1969 | Concentration in foreshore silt of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{137}Cs$, $^{144}Ce$ | Garlieston |
| | 1969 | Concentration in coastal sea water of $^{106}Ru$, $^{137}Cs$, $^{40}K$ | St. Beas, Seascale |
| Mitchell 1971b | 1970 | Concentration in silt of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{137}Cs$, $^{144}Ce$, $^{241}Am$ (1971 only) | Ravenglass Estuary (Eskmeals), Whitehaven Harbor<br>1972-1973: Mary Port Harbor, Workington Harbor, Walney Harbor |
| Mitchell 1973 | 1971 | Concentration in sea water of $^{134}Cs$, $^{137}Cs$ | Irish Sea and northwestern approaches (5-6 locations) |
| Mitchell 1975 | 1972-1973 | Concentration in silt and sand of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{137}Cs$, $^{144}Ce$, $^{134}Cs$ (1972-1973) | Foreshore materials around the Irish Sea and western Scotland (Garlieston silt, Heysham sand, Fleetwood sand) |
| Hetherington 1976b | 1974 | Concentration of $^{137}Cs$ in filtered sea water | Irish Sea - contours |
| Mitchell 1977a | July 1975 | Concentration in silt and sand of $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{144}Ce$ | Garlieston (silt), Heysham (sand), Feetwood (sand) |
| Mitchell 1977b | Jan 1976 | | |
| Pentreath et al. 1980 | 1977, 1978 | Kd values for particulate material in surface water samples: $^{239/240}Pu$, $^{241}Am$, $^{242}Cm$ $^{244}Cm$ | 0.22 micron filters used |
| | 1976, 1977 | Kd values for sediment from the surface of muddy areas of the Irish Sea: $^{239/240}Pu$, $^{241}Am$ | |
| | 1978 | Value of $^{241}Am/(^{238}Pu + ^{239/240}Pu)$ for shore-line sea water - filtrate and particulate | 0.22 micron filters used |
| | 1978 | Values of $(^{238}Pu + ^{239/240}Pu)/^{244}Cm$ and $^{241}Am/^{244}Cm$ for the particulate phase of shore-line sea water | |
| | | Values for $^{137}Cs$ concentration and $^{99}Tc/^{137}Cs$ in Ravenglass silt | |
| | 1977 | Plutonium profiles in core samples | 1 km, 15 km from Windscale pipeline |
| Perkins et al. 1964 | | Hydrographic and wind information | Northeast Irish Sea and Solway Firth |

## TABLE 2. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Perkins and Williams 1966 | | Particle size distribution of shore and bottom sediments | Northeast Irish Sea and Solway Firth |
| | | Concentration in core samples of shore sediments of $^{106}Ru$, $^{95}Zr/^{95}Nb$, $^{137}Cs$, $^{144}Ce$, $^{40}K$ | Northeast Irish Sea and Solway Firth |
| Preston et al. 1971 | 1964-1966 | Concentrations of $^{106}Ru$, $^{95}Zr/^{95}Nb$, $^{137}Cs$ in coastal sea water as a function of distance from Windscale | |
| | 1963-1966 | Concentration contours for $^{137}Cs$ and $^{106}Ru$ | Off the Cumberland coast |
| | Sept 1968 | Concentration contours for $^{137}Cs$ | North Irish Sea |
| | 1967-1969 | Concentration in surface silt of $^{144}Cs$, $^{106}Ru$, $^{95}Zr/^{95}Nb$ as a function of distance from the Windscale pipeline | |
| Ramster and Hill 1969 | 1964-1968 | Hydrography of the northern Irish Sea | Based on 4 yr of direct measurements |
| Seligman 1956 | | Limited hydrographic information | |
| Templeton and Preston 1966 | 1960-1966 | Seabed composition - northeastern Irish Sea Concentration of $^{106}Ru$ in seabed cores (9 in. depth) | Indicates existence of profiles for $^{90}Sr$, $^{137}Cs$, Pu |
| | | Concentration of $^{106}Ru$ in estuarine silt as a function of distance from Windscale | Indicates existence of similar data for $^{144}Ce$, $^{95}Zr/^{95}Nb$ |
| | 1964 | Concentration of $^{106}Ru$ and $^{90}Sr$ in unfiltered sea water from the northeastern Irish Sea | In addition, monthly samples were collected for 6 months, filtered (1.2 micron pore diameter) and analyzed for $^{106}Ru$, $^{144}Ce$, Pu, $^{95}Zr/^{95}Nb$, $^{90}Sr$, $^{137}Cs$ |

of fish and shellfish, and 3) external exposure from adsorption of radioactivity by sediment, particularly in the Ravenglass Estuary south of the Windscale plant. The second pathway became more important as a result of the increase in rates of disposal of $^{137}Cs$ and $^{134}Cs$ since 1969, and led to the establishment in 1968 of annual research cruises by the Fisheries Radiobiological Laboratory (FRL). FRL is responsible for fulfilling the responsibilities of the Ministry of Agriculture, Fisheries and Food (MAFF) for the control of radioactive waste discharges in England and Wales. In connection with the basic surveys, FRL has conducted a substantial amount of environmental research.

Data contained in Table 2 do not satisfy all the requirements for the application of CAFE, a hydrodynamic model, and FETRA. Routine sampling for calculation of dose rates for Pathway 3 has been limited to foreshore silt and sand. However, several of the more recent publications indicate the existence of more suitable data obtained through FRL's environmental research programs. The main concern is to obtain sediment and radionuclide concentration information, since such data are not routinely collected (as generally is for bathymetry, hydrography, wind, and tidal information) required for the hydrodynamic model.

As indicated above, required sediment and radionuclide data include concentrations for radionuclides dissolved in the water, adsorbed onto suspended sediment and adsorbed onto bed sediment, concentrations of suspended sediment in the water column, size distributions of suspended and bed sediments, and values of distribution coefficient, Kd.

Dissolved concentrations of $^{137}Cs$, $^{106}Ru$, and $^{239}Pu$ in the Irish Sea have been found in the literature. Between 1963 and 1966, a network of up to 25 stations covering an area of 1000 $km^2$ was sampled at three-month intervals. Samples were collcted at the surface, mid-depth, and bottom, and filtered through 0.22 micron Millipore filters. Concentration contours for $^{106}Ru$ and $^{137}Cs$ within approximately 50 km of the outfall are presented in Preston et al (1971). Hetherington and Jefferies (1974) include concentration contours for $^{95}Zr/^{95}Nb$.

Jefferies et al (19[illegible]) include concentration contours interpolated from data obtained during the May [illegible]2 cruise. Samples were collected at the surface, mid-depth, and bottr[illegible] 3 stations throughout the Irish Sea. In addition, they state that stations are sampled on a regular basis on ferry crossings in the Northern Irish Sea (from Corewall to Larne) and in the Southern Irish Sea (from Fishguard to Rosslare). Samples are filtered through 0.22 micron Millipore filters. Information was not found concerning the extent of analyses made on the filtrate and the residue remaining after filtration. Concentration contours for $^{106}Ru$ and $^{137}Cs$ based on data from the July 1973 cruise has been published in Hetherington et al (1975). Plutonium-239 contours interpolated from 26 surface water samples obtained in July 1973 and July 1974 may also be found in Hetherington et al (1975).

Apparently analyses were also made for $^{144}Ce$. Hetherington et al (1975) give dissolved concentration information for $^{239}Pu$, $^{144}Ce$, $^{137}Cs$, and $^{106}Ru$ at 10 stations within 10 km of the outfall, and at 10 stations between 75 and 100 km of the outfall. These are also based on the 1973 and 1974 cruises.

There is less information regarding particulate concentrations for radionuclides adsorbed onto suspended sediment in the Irish Sea. Pentreath et al (1980) do not show any spatially-distributed values, but do give Kd values for particulate material in surface water samples for $^{239/240}Pu$, $^{241}Am$, $^{242}Cm$, and $^{244}Cm$. The samples were collected during cruises in September 1977 and May 1978. Hetherington (1976a) shows the distribution of plutonium between residue and filtrate, and total suspended loads for 15 stations within a 30 km radius of Windscale. The values were obtained from surface water samples collected during July 1973 and July 1974. The suspended load ranged from 0.5 to 10 μg/g.

Hetherington et al (1975) cite plans to measure the plutonium in suspension and solution near the sea bed. Hetherington refers to plans to examine the relationship betwen grain size and uptake of plutonium by suspended sediment during the summer of 1975 research cruise.

Some information was found for radionuclide concentrations in bed sediment. Hetherington and Jefferies (1974) present information on the distribution of various radionuclides in sea and estuarine sediments in the vicinity of the Windscale Plant, based on samples collected between 1968 and 1971. Their sampling was restricted to the northeast Irish Sea. Hetherington et al (1975) present data on $^{239}Pu$ concentrations in bed surface sediment and sediment core samples at stations up to 110 km from the outfall. The samples were collected during the July 1974 cruise. Hetherington et al (1976) present similar information for $^{241}Am$.

Information on bed sediment composition was found in Mauchline (1963), Perkin and Williams (1966), and Templeton and Preston (1966), but data are limited to those for the northeast Irish Sea.

Kd values based on bed surface silt and sand were found in Jefferies (1968, 1970) for $^{95}Zr/^{95}Nb$, $^{106}Ru$, $^{137}Cs$, in Jones (1960) for $^{106}Ru$, in Hetherington and Jefferies (1974) for $^{95}Zr/^{95}Nb$ and $^{106}Ru$, in Hetherington et al (1976) for $^{239}Pu$, and in Pentreath et al (1980) for $^{239/240}Pu$ and $^{241}Am$. As already stated, Kd values based on suspended sediment in surface water samples may be found in Pentreath et al (1980) for $^{239/240}Pu$, $^{241}Am$, $^{242}Cm$, and $^{244}Cm$.

Although the Irish Sea near Windscale has most adandant data, as compared with other sites, many detailed required data for modeling have not been found in published documents. We have requested FRL further information on measured data, especially sampling locations, and radionuclide and suspended sediment concentrations at each location.

## TASK C. TRANSPORT OF SEDIMENT AND RADIONUCLIDES IN ESTUARIES

In addition to further development of the three-dimensional radionuclide transport model for estuaries we have also collected field data in the Montsweag Bay near the Maine Yankee Nuclear Power Plant through a literature search. The Montsweag Bay data were collected, to be compared with available data for the Hudson River estuary near the Indian Point Nuclear Power Plant, to determine which area is more suitable for the estuarine model testing.

Table 3 summarizes the acquired data for the Maine Yankee Atomic Power Company plant site that is 6.4 km south-southwest of Wiscasset, Maine. Primarily these data consist of concentrations of various radionuclides in the surface bed sediments near the power plant (within 13 km, see Figure 2). Data on dissolved radionuclide concentration are also included.

The data collected and reported on by Churchill (1976, 1979) have the best spatial resolution. This study contains measurements of up to 70 surface bed sediment samples for three different occasions. The samples were collected mainly in Bailey Cove with up to 17 samples collected along the shore of Montsweag Bay.

The power company has collected the data with the best temporal resolution. These data are collected for use in their annual environmental surveillance reports. Typically, they contain radionuclide concentration in bed sediment and estuary water on a monthly or quarterly basis. These data are collected at five to eight locations near the power plant. The annual environmental surveillance reports present this information either as yearly averages for all the sample stations or as plots for the individual station. Personal communication with personnel at the Maine Yankee Atomic Power Company indicated that we could obtain copies of the individual measurements.

Although there appears to be a fairly large amount of data collected in the vicinity of the Maine Yankee

## TABLE 3. Montsweag Bay Data

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Maine Yankee Atomic Power Company Annual Radiological Environmental Surveillance Report | 1977 | Yearly average concentration (pci/liter) $^{7}Be$, $^{40}K$, $^{54}Mn$, $^{58}Co$, $^{59}Fe$, $^{60}Co$, $^{65}Zn$, $^{95}Zr$, $^{103}Ru$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{140}Ba$, $^{141}Ce$, $^{144}Ce$, $^{3}H$ in estuary water (average of 6 stations within 10 km of the plant) | Underlined radionuclides were below the lower limit of detection (LLD) |
| 1 Jan. 1977 - 31 Dec. 1977 | 1977 | Yearly average concentration (pci/G, dry) of $^{89}Sr$, $^{90}Sr$, $^{7}Be$, $^{40}K$, $^{54}Mn$, $^{58}Co$, $^{59}Fe$, $^{60}Co$, $^{65}Zn$, $^{95}Zr$, $^{103}Ru$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{140}Ba$, $^{141}Ce$, $^{144}Ce$ in bed sediment/silt (average of 6 stations within 13 km of plant) | Underlined radionuclides were below the LLD |
| | 1977 | Plots of $^{3}H$ activity on a monthly basis for each of the 6 estuary water stations for 1977 | |
| | 1974 to 1977 | Plots of $^{137}Cs$ and $^{60}Co$ in bed sediments on a quarterly basis for each of the sediment stations for 1974-77. | |
| | 1974 to 1977 | Plot of $^{60}Co$ in liquid effluents on a monthly basis for 1974-77. (No other effluents tabulated) | |
| Maine Yankee Atomic Power Company Annual Radiological Environmental Surveillance Report | 1978 | Yearly average concentration (pci/liter) of $^{131}I$, $^{7}Be$, $^{40}K$, $^{54}Mn$, $^{58}Co$, $^{60}Co$, $^{65}Zn$, $^{95}Zr$, $^{95}Nb$, $^{103}Ru$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{140}Ba$, $^{141}Ce$, $^{144}Ce$, $^{228}Th$, $^{3}H$ in estuary water (average of 8 stations within 11 km of plant) | Underlined radionuclides were below the LLD |
| Jan. 1, 1978 - Dec. 31, 1978 | 1978 | Yearly average concentration (pci/G, dry) of $^{131}I$, $^{7}Be$, $^{40}K$, $^{54}Mn$, $^{58}Co$, $^{60}Co$, $^{65}Zn$, $^{95}Zr$, $^{95}Nb$, $^{103}Ru$, $^{106}Ru$, $^{134}Cs$, $^{137}Cs$, $^{140}Ba$, $^{140}La$, $^{141}Ce$, $^{144}Ce$, $^{228}Th$ in bottom sediments/silts (average of 5 stations within 13 km of plant) | Underlined radionuclides were below the LLD |

TABLE 3. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| | 1975 to 1978 | Plots of $^{137}$Cs and $^{60}$Co in bed sediments on a quarterly basis for 4 stations for 1975-1978. | |
| Maine Yankee Atomic Power Company Annual Radiological Environmental Surveillance Report, 1976 | 1976 | Yearly average concentration (pci/liter) of $^{7}$Be, $^{40}$K, $^{54}$Mn, $^{58}$Co, $^{60}$Co, $^{95}$Zr, $^{103}$Ru, $^{106}$Ru, $^{134}$Cs, $^{137}$Cs, $^{140}$Ba, $^{141}$Ce, $^{144}$Ce, $^{226}$Ra, $^{228}$Th, $^{3}$H in estuary water | Underlined radionuclides were below the LLD |
| | 1976 | Yearly average concentration (pci/G, dry) of $^{89}$Sr, $^{90}$Sr, $^{7}$Be, $^{40}$K, $^{54}$Mn, $^{58}$Co, $^{60}$Co, $^{95}$Zr, $^{103}$Ru, $^{106}$Ru, $^{134}$Cs, $^{137}$Cs, $^{140}$Ba, $^{141}$Ce, $^{144}$Ce, $^{226}$Ra, $^{228}$Th in bed sediment/silt | Underlined radionuclides were below the LLD<br><br>Note: We don't have a complete copy of this paper. Consequently, information on the number of stations and their locations is lacking. |
| Maine Yankee Atomic Power Company, Effluent and Waste Disposal Semi-Annual Reports | 1976 | Quarterly summary of total and average release of liquid effluents during the quarter for:<br>$^{89}$Sr, $^{90}$Sr, $^{134}$Cs, $^{137}$Cs, $^{131}$I, $^{133}$I, $^{58}$Co, $^{60}$Co, $^{59}$Fe, $^{65}$Zn, $^{54}$Mn, $^{51}$Cr, $^{95}$Zr-$^{95}$Nb, $^{99}$Mo, $^{99m}$Tc, $^{140}$Ba-$^{140}$La, $^{141}$Ce, $^{133}$Xe, $^{135}$Xe | $^{133}$I values for third and fourth quarter only |
| | 1977 | Same as above | No values for $^{133}$I. $^{57}$Co detected during third and fourth quarter. |
| | 1978 | Same as above | $^{133}$I and $^{57}$Co detected for third and fourth quarter. |

TABLE 3. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Churchill, Dec., 1976 | 9-18-74 | The results of three surveys conducted on September 18, 1974 | Causeway in place, outflow over weir into cove; |
| | 6-12-75 | June 12, 1975 | Causeway removed, outflow dammed a few days before (diffuser outflow in Montsweag Bay) |
| | 12-30-75 | December 30, 1975<br>For each survey approximately 70 surface sediment samples were collected and analyzed for:<br>$^{137}$Cs, $^{134}$Cs, $^{58}$Co, $^{60}$Co, $^{54}$Mn | Same as 6-12-75 (above)<br>Most of the samples are in Bailey Cove with up to 17 samples along the shoreline of Montsweag Bay. |
| | 10-13-75 | Three core samples were also collected in Bailey Cove on October 13, 1975 | Note: There was a relatively large discharge into the cove in May, 1975 (May 13-14). The discharge consisted of approximately one-half of the total discharge for May. |
| | | Bed sediment size measurements were performed on most of the samples collected within the cove (% > 64 microns and mean diameter) | Bailey Cove is up to 90% mud flats at low tide. This is where most of the surface sediment samples were collected. |
| Churchill, et al., 1/24/79 | | This is essentially a condensed version of his thesis submitted for a journal article. | |
| Radioactive Isotopic Characterization of the Environment near Wiscasset, Maine . . . May, 1976 | 1972 & '74<br>8-14-75<br>and 6-29<br>to 7-3-72 | Pre- and post-operational surveys<br>Bed sediment - 2 locations within 2.8 km of of plant; 8-14-74 and (6-29-72 & 7-3-72)<br>$^{228}$Ac, $^{214}$Bi, $^{40}$K, $^{137}$Cs, $^{134}$Cs, $^{58}$Co, $^{60}$Co, $^{54}$Mn plus activity map of Bailey Cove sediment based on 50 sample locations<br>$^{58}$Co, $^{60}$Co - no date given | |
| | 8-14-74 | Estuary water - 3 locations within 4 km of plant gross $\alpha$, gross $\beta$, gross $\gamma$ - post operational (8-14-74) | |

TABLE 3. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| | 6-13-72 | $^{228}Ac$, $^{212}Bi$, $^{208}Tl$, $^{214}Pb$, $^{214}Bi$, $^{40}K$ - pre-operational 6/13/72 | |
| | 6-13-72 | Pre- and post-operational measurements of tritium - 8/15/74 and 6/13/72, same locations as above | |
| | 6-13-72 | Plus pre-operational measurements of dissolved radionuclides - 6/13/72 $^{40}K$, $^{137}Cs$, $^{222}Ru$ | |

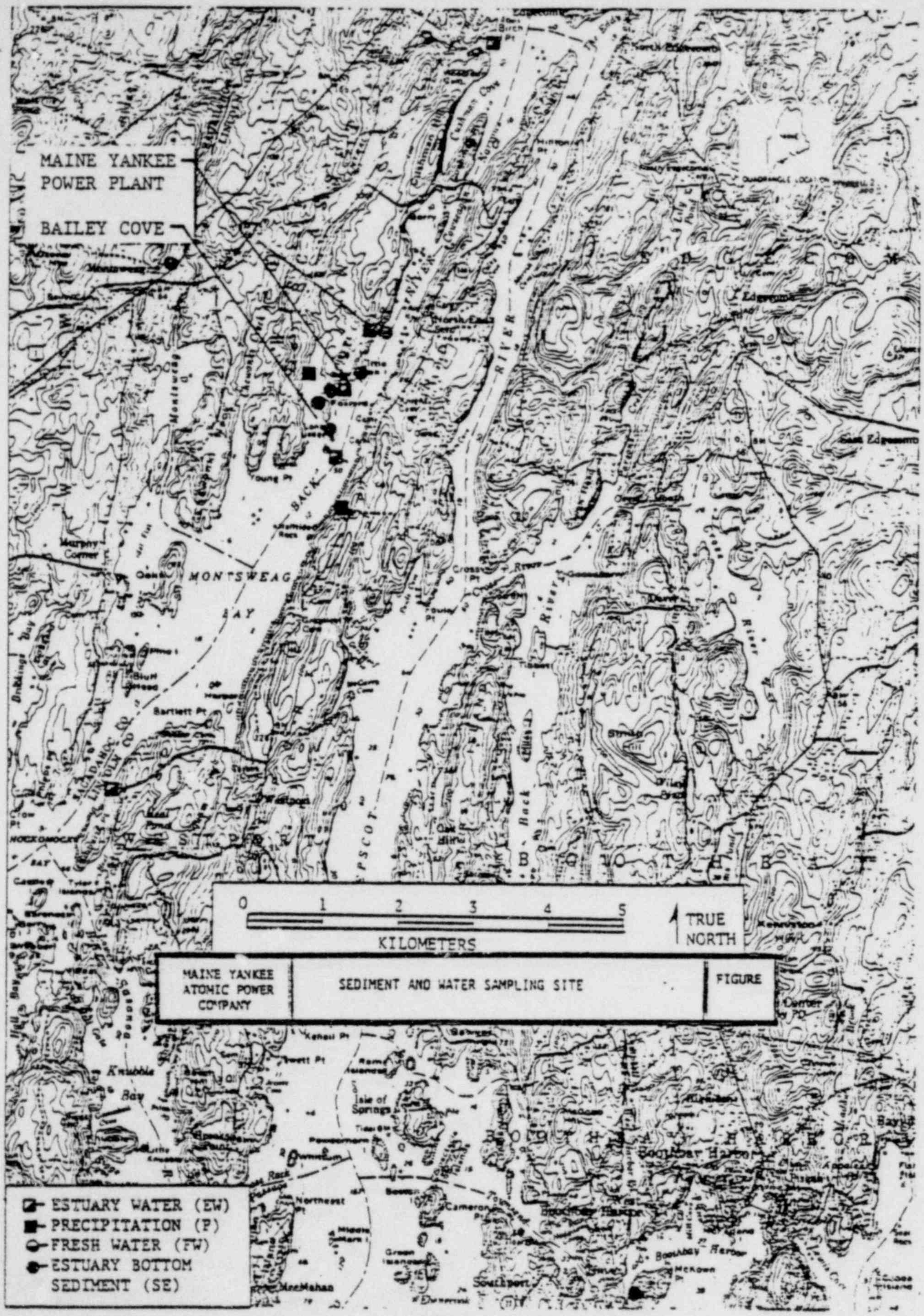


FIGURE 2. Montsweag Bay

Power plant, there are some potential difficulties with using this data for radionuclide transport modeling in the estuary. One problem is that almost all detailed data for radionuclide concentrations associated with bed sediment were collected in Bailey Cove. Approximately 90% of the cove dries up during low tide. If the simulation is to account for the tide flat region, and it should since there is a high sedimentation rate in this region, a difficulty will be encountered when the finite difference computation cells dry up.

The second problem is associated with modeling the geometry of the estuary. Montsweag Bay is a complex estuary with many smaller coves and inlets. Since the finite difference computational cells are rectangular it may be difficult to model the estuarine geometry with satisfactory accuracy.

Other difficulties include the limited data available on suspended and dissolved radionuclide concentrations and the lack of data on the suspended sediment concentrations in the bay. The best information we have on suspended and dissolved radionuclide concentrations are the data from the six to eight estuary water sampling stations maintained by the power company. Six to eight sampling points result in a limited picture of the spatial variations.

The lack of suspended sediment concentration data could be critical. According to Dr. Charles Hess, University of Maine, the water in the bay tends to be quite full of sediment. The amount and size of suspended sediment can greatly affect the adsorption of radionuclides.

Brief summary of available data obtained in 1971 and 1976 in the Hudson River is shown in Table 4. These two sampling periods have the best data. The schematic representation of the Hudson River is shown in Figure 3. Comparison of Hudson River and Montsweag Bay data is shown in Table 5. Because the modeling site must have required data for flow-salinity-sediment-radionuclide transport modeling, (as shown in Table 5) the Hudson River estuary is better suited for the estuarine radionuclide transport modeling.

TABLE 4. Hudson River Data Obtained in 1971 and 1976

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Water resources data for New York, water year 1977, V.1 | 10-14-76<br>11-29-76 | Suspended sediment data (see 1975) | Hudson River at Green Island |
| Wrenn, 1/79 | 1976 and 1977 | Concentrations of $^{137}Cs$, $^{134}Cs$, $^{54}Mn$, $^{60}Co$, $^{58}Co$ from continuous water samples, dissolved and particulate | Measured at Verplanck and Chelsea generally two-week long sample periods from April to October, November, or December |
| | 1976 and 1977 | Quarterly liquid discharges of radionuclides described above from Indian Point | |
| | 1971 to 1977 | Yearly totals of radionuclides described above from Indian Point | |
| | 1976 and 1977 | Concentrations of suspended solids and dissolved chloride | Two-week sample lengths at Chelsea and Verplanck |
| | 1975, 1976, 1977 | Annual average concentrations of radionuclides described above at Verplanck | |
| | 1976 and 1977 | Concentrations of $^{40}K$, $^{137}Cs$, $^{134}Cs$, $^{54}Mn$, $^{60}Co$ on the river bed surface | At Newburgh, Con Hook, Bear Mtn. Bridge, Iona Island, Peekskill Bay, Lents Cove, Indian Point, Tomkins Cove, Greens Cove, Stony Point 5, Buoy 14, Verplanck Beach. Generally monthly or bimonthly samples from April to November or December. |
| | | Radionuclide distribution and total accumulation in core samples for submerged and shoreline sediments in 1976 and 1977 - $^{137}Cs$, $^{134}Cs$, $^{54}Mn$, $^{60}Co$, $^{58}Co$ | At locations mentioned in previous entry. Each location has only one core sample. |
| Simpson and Williams | 12-1-75 to 11-30-76 | $^{137}Cs$, $^{134}Cs$, $^{60}Co$, $^{40}K$, $^{239,240}Pu$, $^{238}Pu$ core samples up to 70 cm deep. Also includes dissolved and suspended Pu data | Up to M.P. 60 |

TABLE 4. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| Jinks & Wrenn, 1975 | 5/71 to 11/73 | Particulate and dissolved concentrations of $^{137}Cs$ | Monthly measurements near Indian Point area |
| Lentsch, et al., 1971 | 8-26-71 | Radiocesium concentrations in core samples | At Croton, Green's cove, Indian Point, Con Hook, Newburgh Bay, Lents Cove. (All locations within 14 miles of Indian Point) |
| | 1966 to 8/71 | Radiocesium liquid waste releases from Indian Point | |
| | 8-10-71 | Longitudinal distribution of radiocesium in Hudson River surface water | M.P. 80 to M.P. 10 |
| Moore, 1974 | | Variation of $^{137}Cs$ concentration with sediment particle size | Newburgh, Buoy 14 |
| | 8-10-71 | Salinity, suspended material, radiocesium concentration (dissolved and particulate) | At Hyde Park, Newburgh, Indian Point, Buoy 14, Buoy 5, Dobb's Ferr[illegible] George Washington Bridge |
| | 5-6-71 to 11-23-71 | $^{137}Cs$ and $^{134}Cs$, salinity particulate and dissolved | Continuous water samples (2 week) at Verplanck |
| | | Variation of $^{137}Cs$, $^{134}Cs$ with salinity | At Verplanck |
| Wrenn, 1/79 | 1971 to 1977 | Yearly totals of radionuclides described above from Indian Point | |
| Wrenn & Jinks, | 1962 to 1977 | Cesium-137 content of bottom sediment and water | Indian Point vicinity (yearly average values) |
| Wrenn, et al., 1976 | 8/71 | Longitudinal distribution of $^{137}Cs$ | From Hyde Park to George Washington Bridge |
| | 8/71, 6/72 | Concentrations of $^{137}Cs$ in sediment (core) | At Indian Point |

TABLE 4. (Contd)

| REFERENCE | DATE(S) | DATA | NOTES |
|---|---|---|---|
| | 8/71, 9/73 | Similar types of data as above | At Newburgh |
| | 8/71, 6/72 | Similar types of data as above | At Croton Point |
| Wrenn, et al., 9-4-73 | 1971 to 1972 | Means and ranges of $^{40}K$, $^{137}Cs$, $^{134}Cs$, $^{54}Mn$, $^{60}Co$ concentrations in sediment and water | At Indian Point |

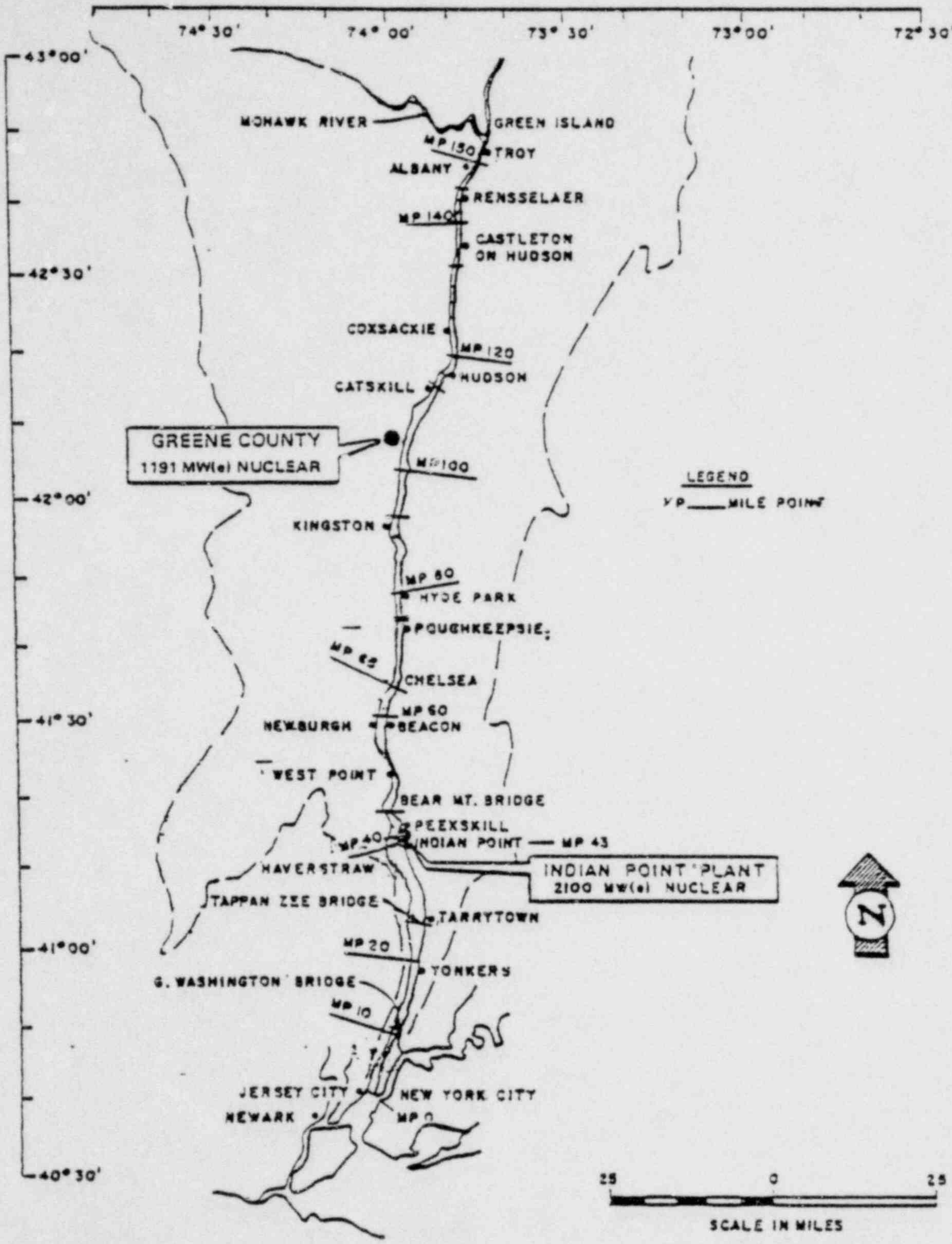


FIGURE 3. Schematic Representation of the Hudson River

TABLE 5. Hudson River and Montsweag Bay Data Comparison

| Data Type | Hudson River | Montsweag Bay |
|---|---|---|
| Radionuclide Concentration: | | |
| • Bed Sediment | Numerous measurements (7-13) from milepoint (MP) 0 to MP 60. | Primarily collected in Bailey Cove (90% exposed tide flat at low tide). Some data collected along the Montsweag Bay shoreline. |
| • Particulate | Measurements taken primarily at MP 40 and MP 65. Six other measurements taken between MP 10 and MP 80. | Bulk radionuclide measurements made at 6-8 stations within 13 km of the plant site. |
| • Dissolved | Same as for particulate data. | |
| Radionuclide Source | Quarterly reported liquid discharges from Indian Point. | Quarterly reported liquid discharges from the Maine Yankee power plant. |
| Sediment: | | |
| • Bed | Measured at MP 60 and MP 35. | Primarily collected in Bailey Cove. Some data collected along the Montsweag Bay shoreline. |
| • Suspended | Measured at MP 65 and MP 40. | No data. |
| Channel Geometry | Fairly simple-long trough with variable cross-section area. | Complex with many small coves and inlets. Difficult to model accurately with finite difference cells. |
| | Note: There are two sets of data for the Hudson River, 1971 and 1976. One can be used to calibrate the code and the other used to verify the code. | Bed sediment and radionuclide data collected primarily by Churchill on 9-18-74, 6-12-75, and 12-30-75. |

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