Distribution of Radionuclides in the Columbia River Streambed, Hanford Reservation to Longview, Washington

GEOLOGICAL SURVEY PROFESSIONAL PAPER 433-O

Prepared in cooperation with the U.S. Atomic Energy Commission

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By W. L. HAUSHILD, G. R. DEMPSTER, JR., *and* H. H. STEVENS, JR.

TRANSPORT OF RADIONUCLIDES BY STREAMS

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1 inch = 2.54 centimetres 1 foot = 0.305 metre 1 mile = 1.61 kilometres

DISTRIBUTION OF RADIONUCLIDES IN THE COLUMBIA RIVER STREAMBED, HANFORD RESERVATION TO LONGVIEW, WASHINGTON

By W. L. HAUSHILD, G. R. DEMPSTER, JR., and H. H. STEVENS, JR.

ABSTRACT

Until all the eight reactors at Hanford Reservation, cooled by once-through flow of treated Columbia River water, were shut down in 1971, their cooling-water effluent was the main source of dissolved and particulate radionuclides in the Columbia River. The distribution and quantities of radionuclides accumulated in the riverbed were investigated; reconnaissance surveys were made of radionuclide concentrations, particle size of surficial sediment, and sediment at depth; radionuclide discharges were defined at two locations; and radionuclide concentrations in surficial sediment were observed semimonthly at three river locations.

The pattern of seasonal variation of radionuclide concentrations in surficial sediment of the Columbia River generally was independent of location, radionuclide species, and sediment composition. The variations were attributable to seasonal changes in concentration of suspended-particulate and dissolved radionuclides at Pasco, Wash., and changes in hydrodynamic and transport characteristics of the river. Radionuclide concentrations were at a maximum during November–early January and late March–early May, and at a minimum during June–July and late January–early March.

At all river locations, radionuclide concentrations in coarse surficial sediment (mostly sand with some fine gravel) of main channels were significantly lower than concentrations in fine surficial sediment (mixtures of sand, silt, and clay) of secondary channels and shallow areas. Chromium-51 and scandium-46 usually had a greater affinity for fixation to fine sediment, relative to coarse sediment, than did zinc-65 or cobalt-60. Radionuclide concentrations in both coarse sediment and fine sediment did not vary significantly (95 percent confidence level) within relatively long river reaches. However, within the reach from the reactors to Longview, Wash., radionuclide concentrations in surficial sediment did attenuate with distance downstream; respective concentrations of chromium-51, zinc-65, scandium-46, and cobalt-60 at Vancouver, Wash., Columbia River mile 106 (km 171), averaged 4, 2, 1, and 1 percent of levels at Pasco, Wash., Columbia River mile 330 (km 531).

The stratigraphic distribution of radionuclides varied considerably. Differences were distinguishable between coarse sediment of main channels and fine sediment of secondary channels and shallow areas, but differences were not distinguishable within these sediment-size classes. Radionuclides tended to be distributed equally throughout relatively great depths (more than 60 in. (1.5 m) in some places) in sand beds of main channels; this was attributed to the mixing of sediment when dunes migrate downstream. Radionuclide concentrations in fine-sediment beds usually were highest at or a few inches below the surface and generally attenuated to negligible values within the upper 12 inches (0.3 m) of the streambed.

The monthly mean quantities of eight radionuclides accumulated in the streambed between Pasco and Vancouver generally decreased linearly from January 1964 to September 1966. Seasonal variations of monthly mean accumulations of zinc-65, cobalt-60, antimony-124, and manganese-54 were small, whereas monthly mean accumulations of chromium-51 varied greatly during each year—the higher of two seasonal maximums was five to six times greater than the lower of two seasonal minimums.

In 1965 the estimated mean amount of five radionuclides accumulated in the streambed from Hanford Reservation to Longview, Wash., was 37,100 curies. This consisted of 12,800 curies of zinc-65, 22,300 curies of chromium-51, and 2,000 curies combined of cobalt-60, scandium-46, and manganese-54. Forty percent of the radionuclide accumulation was in the Pasco-to-McNary Dam reach, 52 percent was in sediment-depositing reaches below The Dalles Dam, and the remaining 8 percent was in thin-sediment deposits in the lower part of The Dalles Reservoir and various armored-streambed reaches.

In June 1965, 28,900 curies of these radionuclides were estimated to be in the Columbia River streambed from the reactors to the ocean: 20,200 curies in the riverbed, and 8,700 curies in the estuary bed (Hubbell and Glenn, 1973). A predominance of chromium-51 over zinc-65 in the estuary bed and an opposite predominance in the riverbed probably indicate less seasonal variation in the accumulation of radionuclides (especially chromium-51) in the estuary bed than in the riverbed. It also suggests that the main source of particulate radionuclides discharged to the ocean during June was the riverbed rather than the estuary bed.

INTRODUCTION

From 1944 to 1971, the Columbia River received radionuclides derived partly from natural radioactivity and nuclear fallout on its drainage basin, but mostly from low-level radioactive waste discharges from facilities at the U.S. AEC (Atomic Energy Commission) Hanford Reservation (fig. 1). The low-level wastes were produced primarily by neutron activation of chemical constituents in the treated river water used to cool the nuclear reactors on the Reservation. Dissolved radionuclides that entered the river either remained in solution or became associated with sediment or aquatic

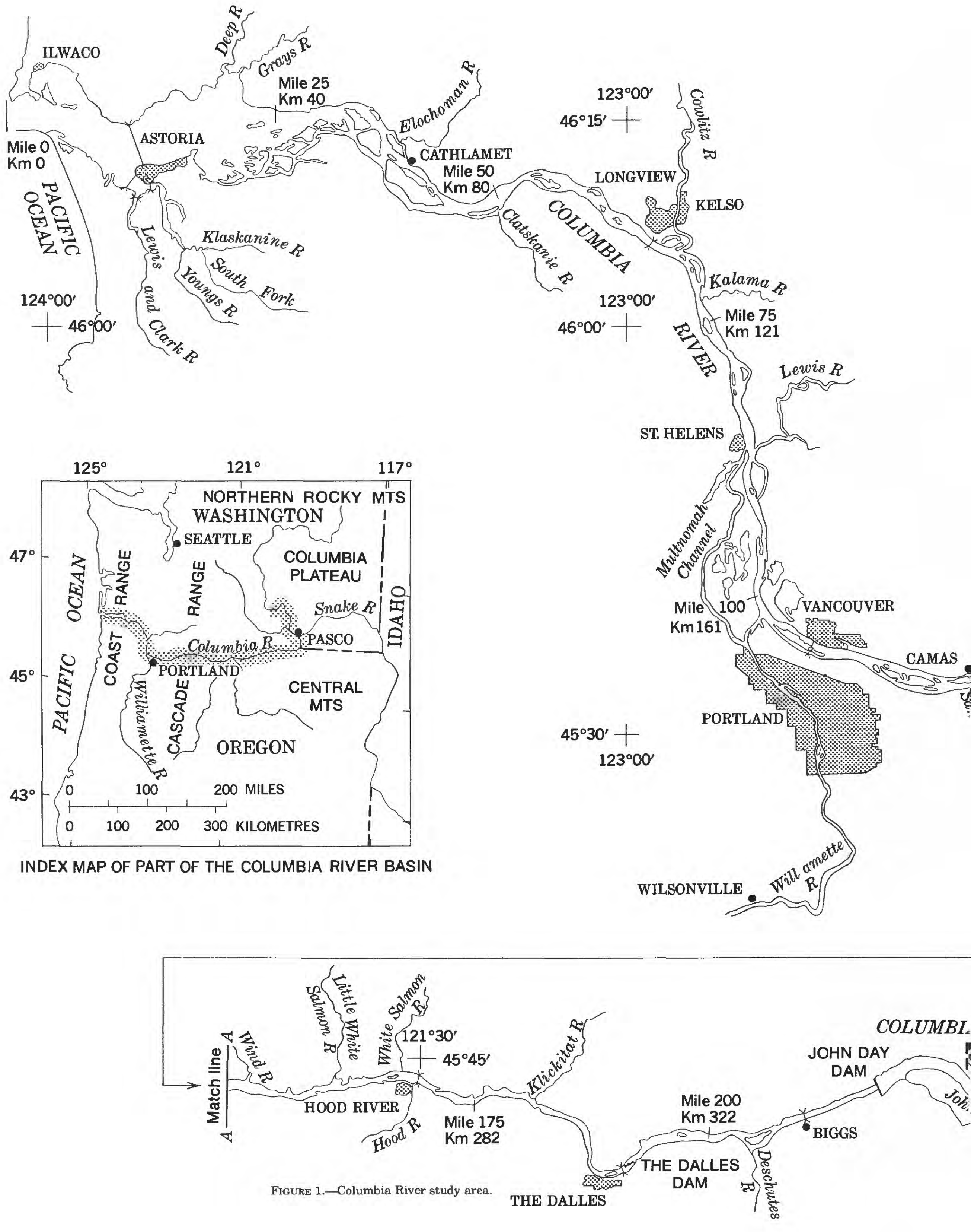
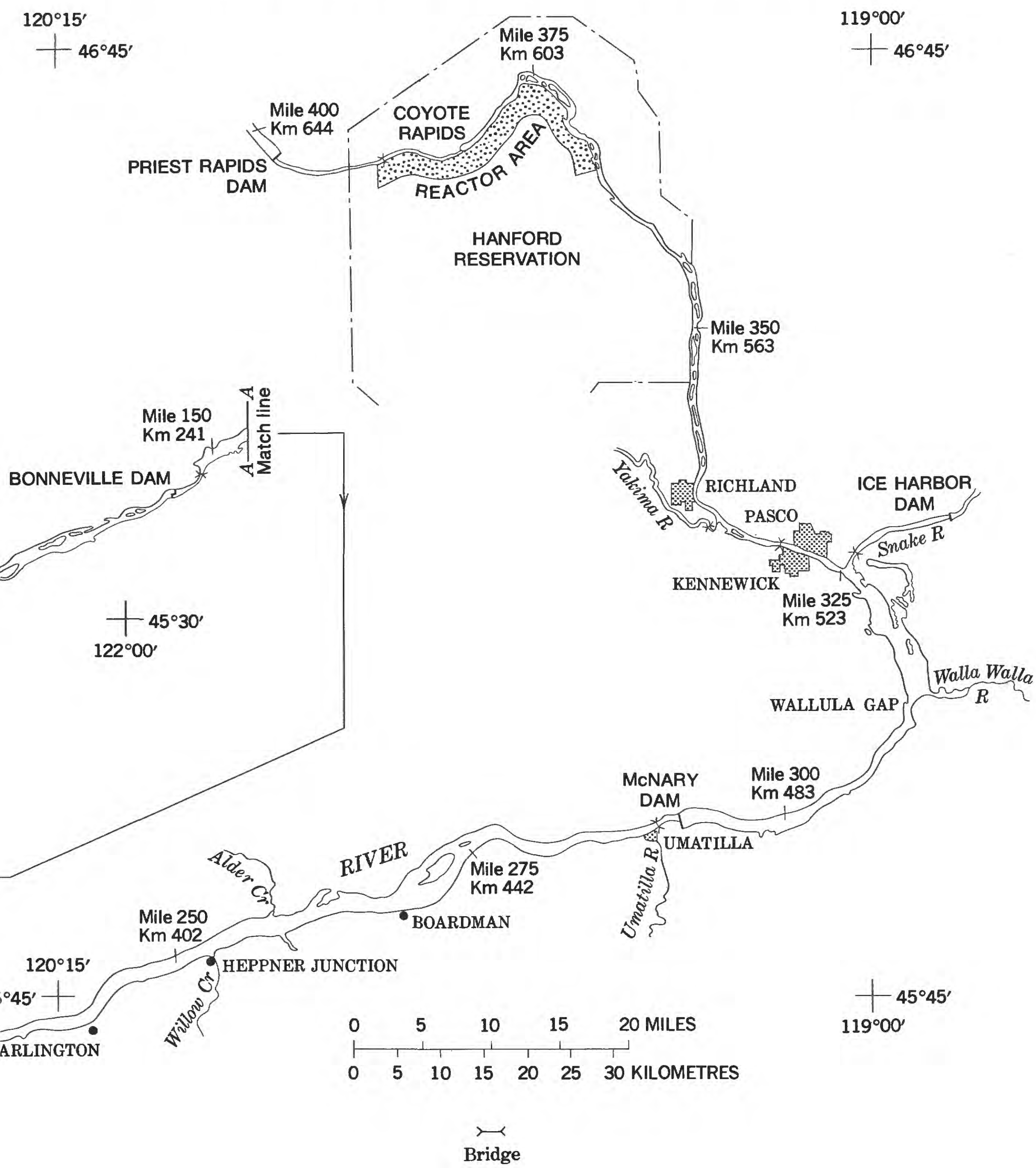


FIGURE 1.—Columbia River study area.

biota. Mainly as a result of uptake and transport by sediment, the longer lived radionuclides were distributed in the streambed from the reactors to the Pacific Ocean. The number of operating reactors increased from one in 1944 (the first reactor went into operation on September 26, 1944) to nine in 1963–64, and decreased thereafter to none in 1971.

General levels of radionuclides in the river were monitored at various locations by radiological health groups of companies under contract to AEC, and by Washington and Oregon State agencies. Before 1962, investigations of interactions between the radionuclides and elements of the river environment were confined mainly to reaches in the vicinity of the Hanford Reservation. In 1962, the U.S. Geological Survey in cooperation with AEC began a detailed investigation of the transport and storage of radionuclides in the Columbia River between the reactors and Longview, Wash. (fig. 1). Through the Richland Operations Office of the AEC, one of its prime contractors[1] cooperated in the investi-

[1]General Electric Co. until about January 1965, and Battelle Memorial Institute thereafter.



gation by arranging for and performing radiochemical analyses of water and sediment samples, by providing scientific expertise, and by participating in a survey of the sediments and radionuclides in the streambed between the reactors and McNary Dam (fig. 1).

The purpose of the investigation was to determine the decay, distribution, and movement of radionuclides in the Columbia River. In particular, information was desired on (1) the spatial and temporal distributions of radionuclides, (2) the influences of the hydrodynamic and sedimentation characteristics of the river on the distribution of radionuclides, and (3) the major processes involved in disposition of radionuclides in a fluvial environment. One objective of the study was to complement and supplement results from related studies of radioactivity in the Columbia River estuary and adjacent ocean.

As part of the investigation, surveys were made of the distribution of radionuclides and sediment in the streambed between the reactors and The Dalles Dam in September 1965; between The Dalles and Bonneville Dams in October and November 1964; and between Bonneville Dam and Longview, Wash., in April 1965. (See fig. 1 for these locations.) In addition, radionuclide concentrations and particle-size distributions of surficial sediment were observed for samples collected semimonthly during 1963, and intermittently at other times during 1962-1965, from the streambed at Pasco, Wash., Hood River, Oreg., and Vancouver. This report presents the results from the surveys and the observations at the three river stations. The data have been used to determine the spatial and temporal distributions of radionuclides and particle size in the streambed. The quantities of several radionuclides in the streambed (radionuclide inventories) from the reactors to Longview were estimated from the spatial distributions of radionuclides and sediment. For the period January 1964 through September 1966, monthly mean inventories for the Pasco-to-Vancouver reach also were estimated by using inflow and outflow of eight radionuclides reported by Haushild, Stevens, Nelson, and Dempster (1973).

Between April 21 and May 12, 1966, surficial-sediment samples were collected at seven locations along the Columbia River between Pasco, Wash., and about CRM 86[2] (Columbia River mile 86, km 138), and from locations above the mouths of the Snake and Willamette Rivers (fig. 1). Data from these samples were used by Glenn (1973) in a study of the relations among radionuclide content, particle size, cation exchange capacity, mineralogy, and carbon content of sediment from the Columbia River.

[2]Distance in miles (also converted to kilometres) along the river is that given in a river mile index compiled by the Hydrology Subcommittee of the Columbia Basin Inter-Agency Committee (1962).

ACKNOWLEDGMENTS

All radiochemical analyses were performed under the direction of Dr. Julian M. Nielsen at the Hanford Radiological Sciences Department, which was operated initially by General Electric Co., and later by Battelle Memorial Institute. The work was performed for the Division of Reactor Development and Technology, U.S. Atomic Energy Commission.

Much of the equipment used to measure radioactivity in place and to obtain cores of deposited sediment was developed by D. W. Hubbell, E. A. Prych, and J. L. Glenn, U.S. Geological Survey, for investigating radionuclides in the Columbia River estuary.

EQUIPMENT AND METHODS

Several methods were used to sample the various types of sediment deposits in the Columbia River. Divers sampled the sediment from holes they dug at several locations in the gravel streambed in the upper part of McNary Reservoir (fig. 1). A gravity corer was used to obtain a few cores from clay and silt deposits upstream from McNary Dam and a split-core barrel with a Mylar liner was hand driven to obtain cores of sandy and silty deposits in shallow parts of McNary Reservoir (Nelson and Haushild, 1970). However, most cores were taken with a portable vibro corer (Prych and Hubbell, 1966), which satisfactorily cored sand deposits or deposits of sand, silt, and clay throughout the study reach. The cores were collected and retained in plastic liners. Sediment in the cores was relatively undisturbed although some interior warping may have occurred, and small quantities of water may have percolated upward in cores of coarse sand.

Sediment in the surface layer of the streambed (surficial sediment) was sampled with a USBM-54 bed-material sampler (U.S. Inter-Agency Committee on Water Resources, 1966). This sampler can collect a 300–400-semicylindrical slice from the bottom, retaining any fine sediment and interstitial water contained in the slice. Whenever sediment completely filled the sampler, approximately 62 percent of the sample was from the top 1 inch (2.5 cm) of the streambed and about 38 percent was from the adjacent lower 1 inch. Occasionally, the sampler did not completely fill with sediment because the deposits were either less than 2 inches (5.1 cm) thick or they were so compacted that the sampler did not achieve maximum penetration.

Levels of gross-gamma radioactivity in the streambed were monitored with a single-channel radiation detection system adapted for in-place measurements (Prych, and others, 1967). A scintillation counter was encased in a waterproof aluminum housing that mounted into and formed the bottom of a towing sled. A single-conductor armored cable served as both the signal conductor and the towline. In-place measurements of radioactivity were made by lowering the unit to the bed while the boat hovered, or was anchored, in essentially a fixed position.

The reaches that were surveyed, during separate continuous periods, were: reactors to McNary Dam, McNary Dam to The Dalles Dam, The Dalles Dam to Bonneville Dam, and Bonneville Dam to Longview, Wash. Before the survey of each reach, cross sections spaced at fairly regular intervals and other locations (such as mouths of tributaries) were selected from maps and U.S. Coast and Geodetic Survey charts of the river. These preliminary selections were modified during the survey when necessary.

At several points along each cross section, gross-gamma radiation from the streambed was measured in place and surficial sediment was sampled. Water depth along the cross section was defined with a recording sonic depth finder. Between the cross sections, the depth finder was used to obtain a continuous record of bottom topography along courses parallel to the flow direction. Data on gross-gamma radioactivity, sediment texture and location of sampled sediment deposits, and the configuration of the streambed between cross sections were plotted on maps and charts in the field. These plots were used to find where additional surface-sediment samples and measurements of gross-gamma radioactivity would be most desirable, and to select coring sites.

Although many more cross sections were surveyed, only in 64 was enough sediment found on the streambed for surficial-sediment samples to be taken with the USBM-54 sampler. Thirty-eight cores were collected at or near some of these cross sections.

The general stratigraphy of the cores was logged immediately after collection. Cores were then kept frozen until processed. Freezing facilitated handling and suppressed biological and chemical activity. The sediment contained in the driving head of the corer below the plastic liner was extruded and placed in plastic containers.

Cores were processed by cutting the liners and frozen sediment into segments, ½ to 1 inch (1.3 to 2.5 cm) long for the upper parts and 2 inches (5.1 cm) long for the lower parts of the cores. After the plastic liner was removed the core segments were trimmed to remove sediments that might have migrated with percolating water. The trimmed core segments and the sediment from the driving head were ovendried and then inspected to estimate the relative contents of gravel, sand, silt, clay, and organic material.

Some surficial-sediment samples were analyzed for radiochemical content. These samples were divided into a small portion, kept wet for analysis of particle-size distribution, and a large portion that was ovendried for radiochemical analysis. Samples that were not analyzed for radiochemical content were kept wet for possible analysis of particle-size distribution.

Concentrations of specific radionuclides in core segments and surficial-sediment samples were determined at a radiochemical laboratory on the Hanford Reservation. At the laboratory, the dried sediment was crushed, weighed, and placed in an appropriate holder. Samples containing particles as large as 5 cm could be analyzed. Radionuclide concentrations of the samples were computed from multidimensional gamma-ray spectra data obtained with a 400-channel analyzer (Perkins, 1965).

In determining particle-size distribution of sediment, samples containing little or no silt (less than 0.062 mm) were ovendried and then analyzed, by sieving for particle sizes greater than 2 mm and by the visual-accumulation tube method for particle sizes between 0.062 and 2 mm (U.S. Inter-Agency Committee on Water Resources, 1957a). Samples containing clay, silt, and sand were analyzed by a combination of wet sieving, visual-accumulation tube, and the pipette method for particle sizes less than 0.062 mm (U.S. Inter-Agency Committee on Water Resources, 1941, 1943). The methods involved chemical and mechanical dispersal of sediment particles, and chemical elimination of organic material. Particles smaller than 2 mm were measured by a settling-velocity method; particle sizes greater than 2 mm, determined by sieving, were adjusted to represent sizes based on settling velocity (U.S. Inter-Agency Committee on Water Resources, 1957b).

THE COLUMBIA RIVER

DESCRIPTION OF THE STUDY REACH

STREAMBED CHARACTERISTICS

From Priest Rapids Dam to about 5 miles (8 km) downstream from the Snake River, fine gravel and sand filled the interstices in the coarse gravel that formed an essentially armored streambed. Several gravelly islands, some of which supported vegetation, were in this reach. Sand, silt, and clay was deposited in and near the mouth of the Yakima River at the upstream end of McNary Reservoir (fig. 1), but the streambed in the lower reach of the Snake River was armored with gravel.

The source and characteristics of streambed sediment downstream from the Snake River mouth in McNary Reservoir depend on the mixing of the Columbia and Snake Rivers in the reservoir. Dispersion of dye released in the Snake River in September 1966, when flow in both rivers was low, showed that although the lateral mixing of water from the two rivers progressively increased downstream from the Snake River mouth to Wallula Gap (fig. 1), the rivers were still more separated than mixed. In this reach, the deep (30–60 ft, 9–18 m) channel that occupied the western one-third of the river carried mostly Columbia River water. The streambed of this channel, to within about 5 miles (8 km) above Wallula Gap, was armored with gravel similar to the streambed upstream; sand was deposited on the streambed for the remaining distance to Wallula Gap. The eastern two-thirds of the river from about 5 miles (8 km) below the Snake River mouth to Wallula Gap was relatively shallow and carried mostly Snake River water. The sand, silt, and clay deposited in this part of the river probably was derived principally from the Snake and Walla Walla Rivers (fig. 1) since April 1953, when water was first impounded in McNary Reservoir.

After flowing through the constriction of the channel at Wallula Gap, the waters of the Columbia and Snake Rivers were completely mixed. During the survey of September 1965, thin (about 6 in., 15.2 cm) intermixed deposits of clay, silt and very little sand were found at most cross sections below Wallula Gap in McNary Reservoir. Only in one cross section near McNary Dam, and in parts of a few other cross sections, were sediment deposits notably thicker. The thinness and small particle size of the deposits in McNary Reservoir agree with Whetten and Fullam's (1967) findings from a study of the extent of sedimentation in Bonneville, The Dalles, McNary, and Ice Harbor (Snake River) Reservoirs by means of a boat-towed seismic profiler. They found relatively little sediment in all reservoirs except Bonneville, and attributed the scarcity of sediment to "the relatively high current velocities and small particle size of the sediment in these reservoirs."

The streambed from McNary Dam to about 16 miles (26 km) upstream of The Dalles Dam was either bedrock or armored with gravel. (Water was not impounded in John Day Reservoir (fig. 1) until after the survey of September 1965.) There were many gravel islands in this reach. Sand, silt, and clay sediments tended to be transported through the reach; deposits of fine sediments were found only in one pool (CRM 262.8, km 422.8) and near the upstream end of one island (CRM 205.4, km 330.5). Silt with some sand and clay was deposited in the downstream part of The Dalles Reservoir. As in McNary Reservoir, the sediment deposits generally were relatively thin, and were thicker only in localized areas.

Except in the 5-mile (8 km) reaches immediately below The Dalles Dam and above Bonneville Dam where the bed was generally bedrock (basalt) and for about 14 miles (23 km) below Bonneville Dam where it was armored with gravel or bedrock, the bed of the Columbia River below The Dalles Dam was generally sand. Sediment on the bottom and sides of the deep (main) channels that convey a large percentage of the water was generally fine to coarse sand; in some places gravel was present. The sediment in the smaller shallow anabranches and nearshore areas generally was various mixtures of sand, silt, and clay.

DUNES

Often the sandy bottom sediment was formed into trains of dunes. Depending on local flow conditions, dunes were as small as 6 inches (15 cm) high and 4 feet (1.2 m) long, or as large as 10 feet (3 m) high and 800 feet (240 m) long. The diversity in the heights and lengths of dunes is shown by the depth-finder records in figure 2 for various locations downstream from The Dalles Dam. Whetten and Fullam (1967) reported that approximately 45 percent of the main channel between Bonneville Dam and Vancouver, and 80 percent between Vancouver and Longview, was covered with sand waves (dunes).

During times of high and medium flow, dunes progressed downstream by erosion of the upstream face and deposition on the downstream face; therefore, the streambed surface at a particular location alternately rose and fell as the dunes traveled by. Sediment that moved along the upstream faces of large dunes often formed small dunes (fig. 2) that usually migrated faster than the large dunes. When the flow was low, little if any sediment transport occurred along the bed, dunes migrated slowly if at all, and silt and clay sometimes accumulated enough to change the particle-size distribution of the surficial sediments. Fine-sediment layers covered the sand bed in some dune areas observed during low-water periods. Whetten and Fullam (1967) observed that silt deposits formed on the sand bed in some dune areas of Bonneville Reservoir in March 1966.

The U.S. Army Corps of Engineers has built flood-protection and channel-improvement works along much of the Columbia River from Bonneville Dam to Longview. These works generally have caused or increased deposition of sediment (sand, silt, and clay mixtures) along the Columbia River shores and in the smaller anabranches. Dunes formed in the shallower parts of these areas during high flows were exposed to the air during low flows. The action of rainfall, tides, and alternating inundation and exposure modify the migration, spacing, and shape of these dunes. Dunes exposed on some nearshore flats after the recession of high flow in late summer diminished gradually until by late fall–early winter the streambed there was relatively flat. Dunes formed underwater at the head end of shallow anabranches tended to decrease in height and to develop longer upstream slopes during exposure. Whetten and Fullam (1967) present quantitative data on the modification of dune shapes during all stages of emergence at the head end of a shallow anabranch at about CRM 127 (km 204).

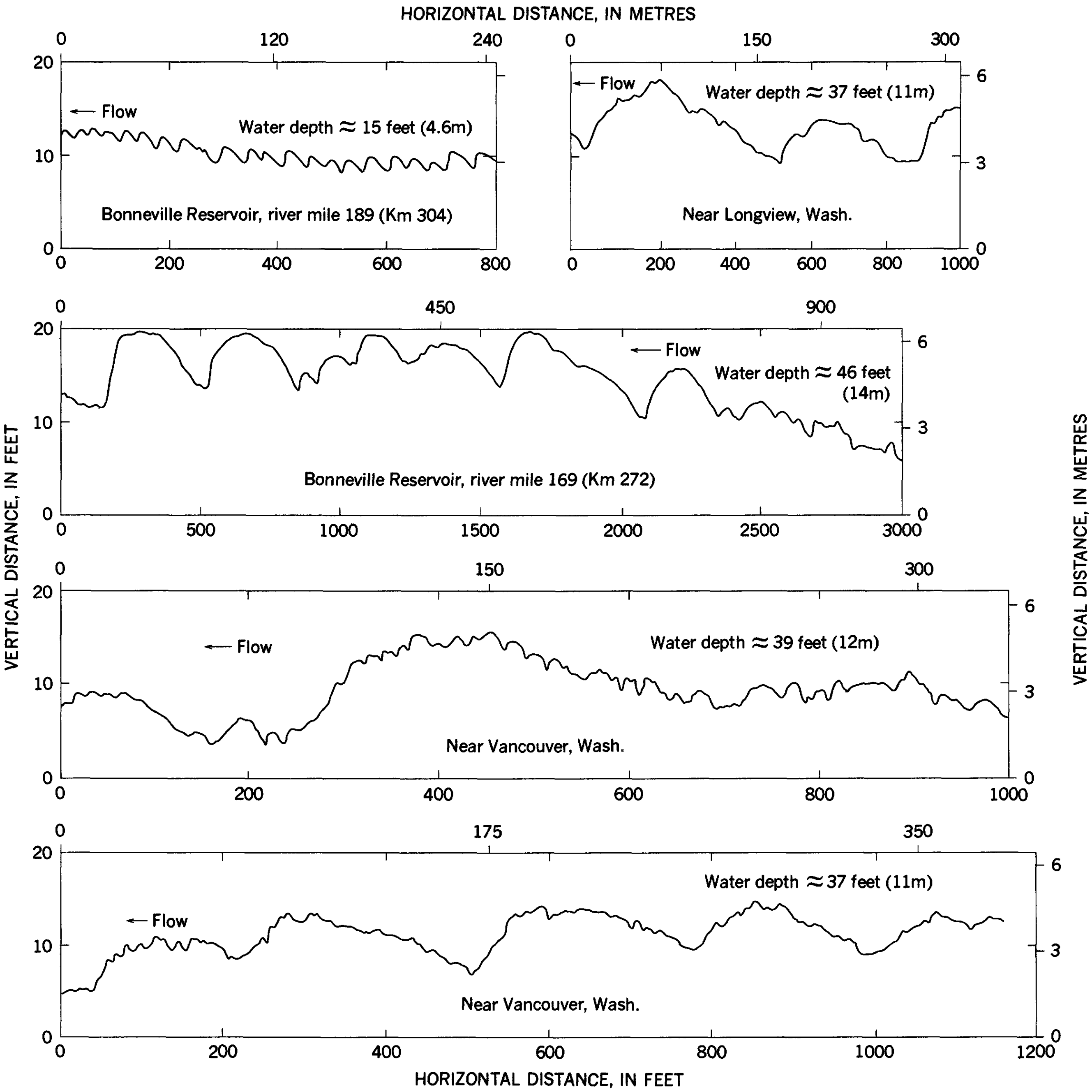


FIGURE 2.—Depth-finder profiles of streambed dunes at four Columbia River locations.

HOMOGENEITY OF SEDIMENT CHARACTERISTICS

Studies by several investigators indicate that mineralogic characteristics of sediment deposited along the Columbia River downstream from Pasco are consistently homogeneous. Knebel, Kelley, and Whetten (1968) studied the spatial variations in clay minerals in the "clay-size" (≤0.002 mm) fraction of surficial sediment by analyzing samples obtained as near midchannel as possible in Columbia River reservoirs and in Ice Harbor Reservoir on the Snake River. They found that the relative quantities of three clay mineral groups (montmorillonite, illite, and chlorite plus kaolinite) in surficial sediment from McNary, The Dalles, Bonneville, and Ice Harbor Reservoirs were indistinguishable from one another. They attributed the similarity of clay-mineral quantities in surficial sediment from the three Columbia River reservoirs to the relatively large quantity of sediment contributed by the Snake River.

Kelley and Whetten (1969) statistically analyzed sediment-sample data from the Columbia River and quantitatively determined which of five river reservoirs deviated most and which were most similar with respect to four measured variables: bulk chemistry, trace-element chemistry, bulk mineralogy, and heavy-mineral content. They concluded: "The general impression produced by the multiple discriminant analyses is that of quite homogeneous and independent source reservoirs upstream [Grand Coulee—dam located at CRM 596.6, 959.9 km,—and Ice Harbor] and more variable and less distinct reservoirs downstream [McNary, The Dalles, and Bonneville]; although different from the upstream reservoirs, the downstream reservoirs seem not very different from one another."

Glenn (1973) also found more sameness than difference in physical, chemical, and mineral characteristics of streambed sediment from seven locations between the Hanford Reservation and Longview, Wash. He reported that (1) no statistically significant differences in cation exchange capacity were noted between the upper and lower ends of the study reach, (2) no longitudinal trends in carbon or nitrogen content were apparent, (3) the mineral suite in less-than-2-μm and 2–4-μm separates from the Snake River was not appreciably different from the suite in these separates from the Columbia River, (4) highly significant differences in mineral assemblages of the less-than-2-μm and 2–4-μm separates along the Columbia River were not evident, (5) no highly significant longitudinal changes in mineralogy of sand separates occurred along the Columbia River, and (6) when regression coefficients for the logarithms of zinc-65 concentrations versus the logarithms of particle diameters were compared, no significant differences existed among sample locations.

The homogeneity of the mineralogic and chemical characteristics of surficial sediment below the reactors indicates that particle size may be a good indicator of radionuclide concentrations in the surficial sediment. Glenn (1973) confirms this by his finding that the logarithms of zinc-65 concentrations were inversely related (regression coefficient of -0.6) to the logarithms of particle diameters. He was able to pool data for samples from seven locations along the Columbia River because covariance analyses indicated that regression coefficients at all locations were statistically the same. The homogeneity of sediment characteristics also suggests that radionuclide uptake by similar-size sediments in the Columbia River should be homogeneous. If so, differences in radionuclide concentrations in similar-size surficial sediment should not be distinguishable over relatively long distances along the Columbia River; differences may only be distinguishable over distances long enough so that further dilution, decay, and uptake by sediment have attenuated base levels in the river more than the variation of the radionuclide concentrations in surficial sediment. In other words, radionuclide concentrations in surficial sediment should (and did) attenuate downstream from the nuclear reactors but attenuation within relatively long reaches should not be (and was not) determinable within credible confidence levels. These presumptions are the basis for the later division of the Columbia River into environments that had deposits of similar-size sediment and for the pooling of radionuclide concentrations in surficial sediment over relatively long reaches.

CONCENTRATIONS OF RADIONUCLIDES IN SURFICIAL STREAMBED SEDIMENT

SEASONAL VARIATION

Concentrations of radionuclides were determined for surficial-sediment samples obtained about semimonthly during 1963 from cross sections at Hood River, Oreg., and Vancouver, Wash., and during February 1963 through May 1964 from a cross section at Pasco, Wash. (table 1). The yearly cycle of radionuclide concentrations was estimated from these data. Observation periods were too short for evaluating year-to-year concentration changes at the three locations.

The flow, sedimentation, and channel characteristics differed at the three cross sections. Water velocities were low during low flows but were quite high during high flows at the Pasco cross section, in the upstream part of McNary Reservoir. Sediment finer than gravel either moved in thin layers or formed thin intermittent deposits on the gravel-armored streambed. Surficial-sediment samples from the middle section of the river channel were mostly coarse sand and fine gravel, whereas samples from the shoreward sections contained more fine sand, some silt, and frequently some clay (table 2).

At the cross section in the middle part of Bonneville Reservoir at Hood River, Oreg., most water flowed in a deep main channel that occupied nearly two-thirds of the river's width; the other third was relatively shallow. The particle-size composition of surficial-sediment samples from the main channel varied, from about a 1:1 mixture of fine sand and coarse sediment (sand with some fine gravel) during high and medium flows to a mixture of fine and coarse sands, silt and fine gravel during low flows (table 2). Sand dunes in the main channel migrated slowly downstream during high and medium flows but were stationary (or nearly so) during low flows. Some silt usually was deposited on the dunes during low flows. Surficial-sediment samples from the shallow section contained fine sand, silt, and small quantities of clay and coarse sediment—the amounts of each particle-size component varied somewhat erratically during the sampling period (table 2).

A main channel at Vancouver conveyed about 90 percent of the river discharge; the remainder flowed through a deep and comparatively narrow secondary channel along the Oregon side of the river.

TABLE 1.—*Mean concentrations of four radionuclides in surficial-sediment samples from river subsections at three Columbia River stations*

[Concentrations in picocuries per gram]

Pasco, Wash.

Date	Middle section of channel				Shoreward sections of channel			
	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}
1962								
Aug. 14	60	420	20	36	140	310	16	18
Oct. 30	----	----	----	----	1,300	710	85	40
1963								
Feb. 13	----	510	17	33	------	1,600	90	95
Mar. 4	----	504	16	34	------	1,400	59	77
Mar. 18	----	500	23	33	------	2,800	270	90
Apr. 3	----	560	22	36	------	2,900	450	81
May 6	----	640	24	33	------	----	----	----
May 21	----	550	19	35	------	1,300	81	50
June 4	----	300	9.5	24	------	510	15	32
June 17	----	340	8.1	29	------	----	----	----
July 9	----	370	11	25	------	----	----	----
July 22	----	400	13	26	------	----	----	----
Aug. 6	53	440	15	32	1,100	820	81	54
Aug. 26	92	370	13	25	500	500	26	27
Sept. 10	120	440	20	31	1,000	1,900	63	170
Sept. 25	210	420	20	26	2,200	1,200	100	77
Oct. 7	640	470	39	30	6,900	1,600	320	56
Oct. 21	620	480	38	29	6,000	1,600	290	59
Nov. 5	900	1,300	49	71	13,000	3,900	630	100
Nov. 18	1,400	770	77	36	------	----	----	----
Dec. 2	1,800	940	95	38	12,000	3,300	540	92
Dec. 16	580	730	45	32	8,700	3,400	540	87
Dec. 30	790	1,300	92	41	6,600	2,300	420	110
1964								
Jan. 13	1,500	1,100	130	58	4,100	2,600	300	110
Feb. 11	460	810	160	42	1,700	1,200	130	58
Feb. 26	300	820	23	59	3,500	2,300	280	86
Mar. 10	600	620	44	30	7,300	3,700	640	100
Mar. 24	480	570	41	30	4,400	2,200	360	77
Apr. 7	890	790	80	37	2,700	1,800	240	65
Apr. 21	390	610	40	29	2,100	1,400	160	44
May 5	260	540	27	31	590	1,100	69	49
1965								
Jan. 7	770	360	39	14	3,000	1,700	230	38
Mar. 10	1,400	1,400	140	16	1,800	1,300	160	26

Hood River, Oreg.

Date	Main channel				Shallow section			
	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}
1962								
July 31	16	27	0.8	1.0	50	76	2.0	4.3
Oct. 15	68	41	2.7	1.1	230	120	8.1	5.9
1963								
Jan. 8	58	56	4.1	1.7	----	----	----	----
Feb. 12	33	57	2.3	1.2	----	----	----	----
Mar. 13	----	140	7.7	3.2	----	----	----	----
Mar. 26	----	160	11	3.5	----	----	----	----
Apr. 10	----	160	8.1	3.4	----	220	10	7.2
May 1	----	190	10	4.0	----	470	32	11
May 21	----	36	1.4	1.8	----	180	7.2	4.5
June 4	----	24	.4	.7	----	200	9.0	5.4
June 18	----	24	.4	.7	----	----	----	----
July 9	----	16	.3	.5	----	130	3.6	3.2
July 23	----	19	.5	.6	----	71	3.7	2.8
Aug. 6	69	29	1.5	.9	150	50	3.5	1.8
Aug. 26	100	34	1.9	.9	190	83	4.1	3.5
Sept. 10	120	41	2.6	1.1	150	53	3.2	2.4
Sept. 24	160	44	3.0	1.1	400	120	5.4	5.0
Oct. 8	190	49	3.6	1.3	420	91	5.0	2.9
Oct. 22	210	49	4.1	1.4	270	83	4.5	3.2
Nov. 5	290	67	6.3	1.9	640	170	8.1	6.8
Nov. 19	180	51	4.2	1.4	220	86	3.2	3.9
Dec. 3	300	82	8.1	2.3	400	120	5.0	5.0
Dec. 17	230	100	7.2	2.3	300	100	5.4	4.5
1964								
June 24	200	16	1.4	.7	260	150	9.5	5.0
Sept. 22	200	35	3.9	1.1	310	120	7.2	5.0

Vancouver, Wash.

Date	Main channel				Secondary channel[1]			
	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}
1962								
July 24	----	11	0.2	0.2	----	7.2	0.1	0.1
Oct. 8	15	8.6	.2	.1	25	12	.6	.3
1963								
Jan. 16	8.2	16	.2	.2	21	27	.8	.5
Feb. 19	5.4	10	.2	.2	20	24	.7	.5
Mar. 12	----	17	.3	.3	----	30	.7	.5
Mar. 25	----	25	.5	.4	----	44	1.3	.7
Apr. 9	----	29	.6	.4	----	83	2.0	1.0
Apr. 30	----	21	.4	.4	----	42	1.1	.6
May 28	----	14	.3	.4	----	110	2.3	5.2
June 11	----	11	.3	.3	----	17	.8	.8
July 8	----	12	.2	.2	----	17	.3	.3
July 22	----	12	.2	.2	----	23	.7	.5
Aug. 5	18	12	.3	.3	63	23	.9	.6
Aug. 27	23	11	.2	.2	69	30	1.2	.6
Sept. 9	24	10	.2	.2	120	27	1.3	.6
Sept. 23	36	10	.3	.2	190	40	2.4	.9
Oct. 7	28	9.0	.2	.2	220	37	2.1	.9
Oct. 21	26	9.6	.2	.2	140	35	2.2	.9
Nov. 4	43	12	.5	.3	210	40	2.4	1.0
Nov. 18	68	14	.8	.3	210	41	2.4	1.1
Dec. 2	34	10	.4	.2	290	63	4.1	1.7
Dec. 16	64	17	1.1	.4	330	81	6.6	1.8
1964								
June 12	66	10	.1	<.1	68	6.5	.1	<.1
1965								
Jan. 19	25	13	.2	.3	50	29	1.6	.7
Apr. 15	9.8	25	<.1	<.1	85	86	2.6	1.0
June 16	4.5	8.8	<.1	<.1	----	----	----	----

[1]Samples from the vertical from July 1962 through May 1963 and from three verticals thereafter.

TABLE 2.—*Mean particle-size distributions of surficial-sediment samples from river subsections at three Columbia River stations*

[Tabulated values are percent in class: clay, <0.004 mm; silt, 0.004–0.062 mm; fine sand, 0.062–0.25 mm; coarse sediment, >0.25 mm]

Date	Clay	Silt	Fine sand	Coarse sediment	Clay	Silt	Fine sand	Coarse sediment
Pasco, Wash.								
	Middle section of channel				Shoreward sections of channel			
1962								
Aug. 7	----	----	3	97	----	28	28	44
Oct. 11	----	1	5	94	1	16	43	40
1963								
Jan. 30	----	----	3	97	1	14	39	46
Mar. 21	----	1	7	92	1	22	39	38
June 14	----	----	6	94	----	4	31	65
Sept. 3	----	----	2	98	2	6	46	46
Dec. 30	----	1	3	96	1	13	47	39
1964								
June 29	----	1	6	93	----	4	34	62
1965								
Jan. 7					3	30	33	34
Mar. 10					2	14	30	54
Hood River, Oreg.								
	Main channel				Shallow section			
1962								
July 10	----	----	40	60	1	33	64	2
July 31	----	----	49	51	----	----	----	----
Sept. 11	----	1	27	72	1	17	79	3
Oct. 15	----	1	50	49	----	----	----	----
1963								
Jan. 8	----	2	36	62	1	11	84	4
Apr. 4	----	6	38	56	2	23	71	4
June 4	----	----	44	56	3	35	59	3
Dec. 17	----	3	42	55	4	24	70	2
1964								
Mar. 31	3	15	42	40	4	22	71	3
June 24	----	----	52	48	3	38	55	4
Sept. 22	----	----	47	53	4	51	44	1
Vancouver, Wash.								
	Main channel				Secondary channel			
1962								
July 5	----	----	13	87	----	11	46	43
July 24	----	----	14	86	----	----	----	----
Sept. 7	----	----	19	81	----	----	----	----
Oct. 8	----	----	15	85	----	----	----	----
Dec. 27	----	----	23	77	1	11	46	42
1963								
Apr. 3	----	----	24	76	1	10	51	38
June 11	----	----	17	83	1	11	43	45
1964								
Apr. 1	----	1	19	80	1	8	53	38
June 6	----	----	24	76	----	6	46	48
1965								
Jan. 19	----	2	13	85	----	----	----	----
Apr. 15	----	----	7	93	----	11	45	44
June 16	----	3	19	78	1	8	34	57

Surficial-sediment samples from the main channel contained more coarse sand and fine gravel than did the main channel at Hood River; they seldom contained silt or clay. Samples from the secondary channel generally were mixtures of about equal parts of coarse and fine sand but the samples usually contained some silt and clay (table 2). Although sand dunes in both channels moved more slowly downstream during low flows than during high flows, they probably never ceased to migrate.

The surficial sediment in a main channel at each cross section was relatively coarser (coarse-sediment segment) than the surficial sediment in a secondary channel (fine-sediment segment). For a 95 percent confidence level, analyses of covariance using radionuclide data for sediment samples from each cross section indicated that (1) the mean concentrations of specific radionuclides in samples from the coarse-sediment segment were significantly lower than for samples from the fine-sediment segment (table 1); and (2) the concentrations of specific radionuclides at a specific time were not significantly different among samples from within either segment.

Percent departures of sample-mean concentrations from a period-mean concentration for chromium-51, zinc-65, scandium-46, and cobalt-60 in surficial sediments are plotted in figures 3 and 4. This normalization of the data suppresses the effects of differences between (1) river locations, (2) sediment compositions at a station, and (3) absolute concentrations of specific radionuclides. The general seasonal variation patterns were nearly the same for all radionuclides and for the coarse- and fine-sediment segments. Concentrations of specific radionuclides generally were lowest during June–July, increased somewhat gradually to peaks during November–early January, were low again in late January–early March, peaked again during late March–early May, and then decreased to the low values during June–July. The few chromium-51 data during January through July suggest that the peak concentrations during late March–early May may be much less than the peak concentrations during November–early January at all river locations.

Most of the seasonal variation of radionuclide concentrations in the surficial sediment of the Columbia River streambed can be attributed to changes in the concentrations of the dissolved and particulate (associated with material coarser than 0.30 μm) radionuclides at Pasco and to changes in source and concentration of suspended sediment in the river. Haushild, Stevens, Nelson, and Dempster (1973) classified dissolved and particulate radionuclides at Pasco into four classes according to the seasonal variation patterns of their concentrations (fig. 5). Dissolved cobalt-60 is a class 1 radionuclide; dissolved zinc-65 and scandium-46 are in class 4; particulate zinc-65, scandium-46, and cobalt-60 are in class 2; and dissolved and particulate chromium-51 are in class 3. The seasonal variation patterns for suspended-sediment concentrations and water discharges at Pasco and Vancouver are also shown in figure 5.

The June-July low in radionuclide concentrations in surficial sediment coincided with a period of low concentrations of dissolved and particulate radionuclides (fig. 5), and of high transport of sediment derived mostly

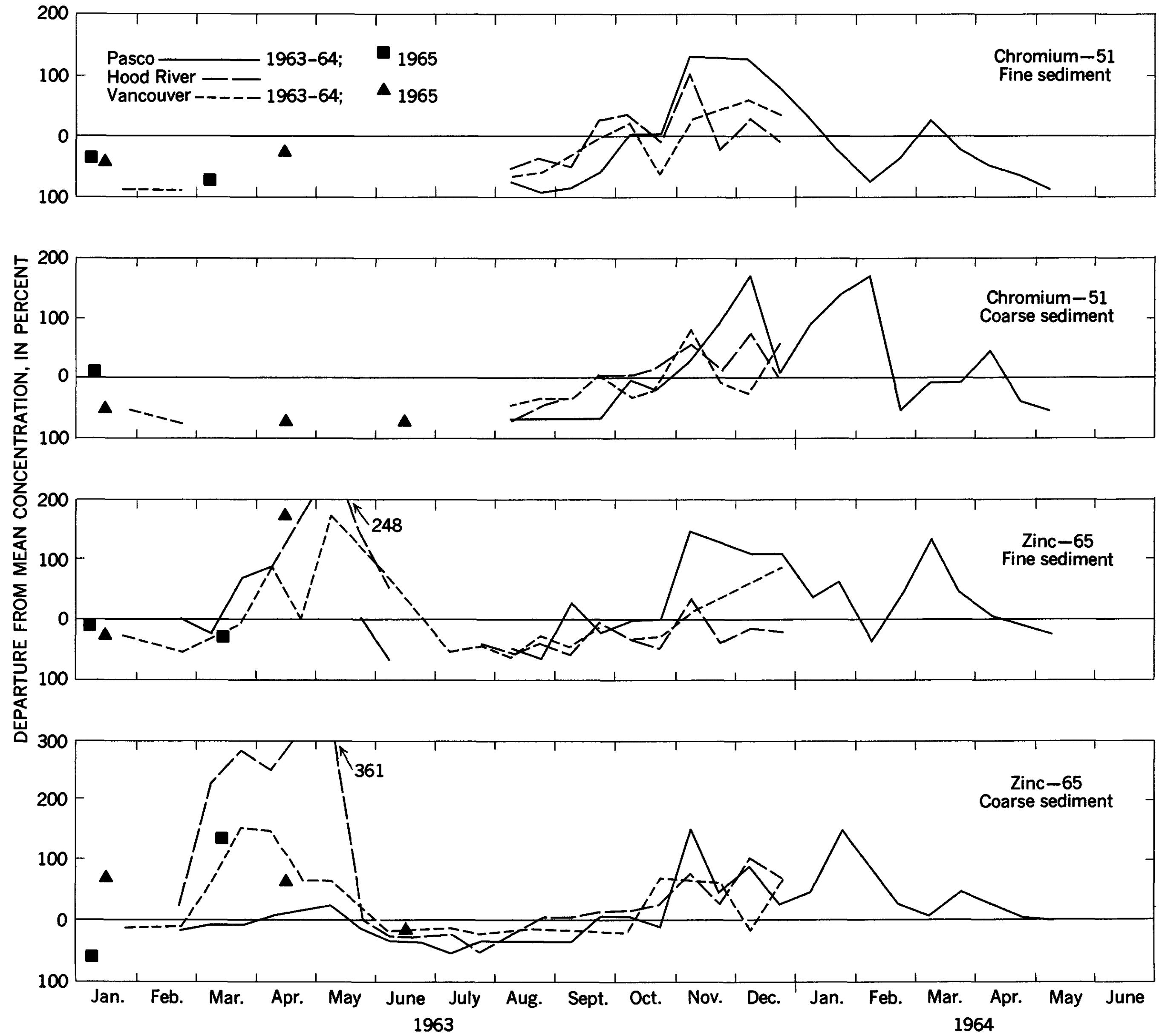


FIGURE 3.—Departures of sample-mean concentrations from period-mean concentrations of chromium-51 and zinc-65 for the coarse- and fine-sediment segments of cross sections at three Columbia River locations. Period means were computed from concentrations observed in samples of surficial sediment during August through December 1963 for chromium-51 and during May through December 1963 for zinc-65.

from the river channel and flood plain (Haushild and others, 1973). Relatively fast downstream migration of streambed dunes contributed to low radionuclide concentrations in surficial sediment. Dunes migrated by the erosion of upstream dune slopes and deposition on the downstream slopes. In this manner, surficial sediment became a mixture of recently deposited sediment and sediment that had been buried in the streambed for various periods. Because of radionuclide decay, buried sediment generally had lower concentrations of radionuclides than recently deposited sediment. Therefore, the mixed surficial sediment had relatively low concentrations of radionuclides.

During November through early January, finer sediment supplied to the Columbia River by tributary inflow caused most of the increase in suspended sediment (Haushild and others, 1973). Deposition occurred because water discharges usually were relatively low. Sorption of radionuclides by the sediment during suspension and deposition probably was enhanced by the increasing availability of most dissolved radionuclides (fig. 5). Consequently, concentrations of radionuclides in the surficial sediment peaked during November–early January.

Suspended-sediment concentrations fell to a minimum during late January through early March. These

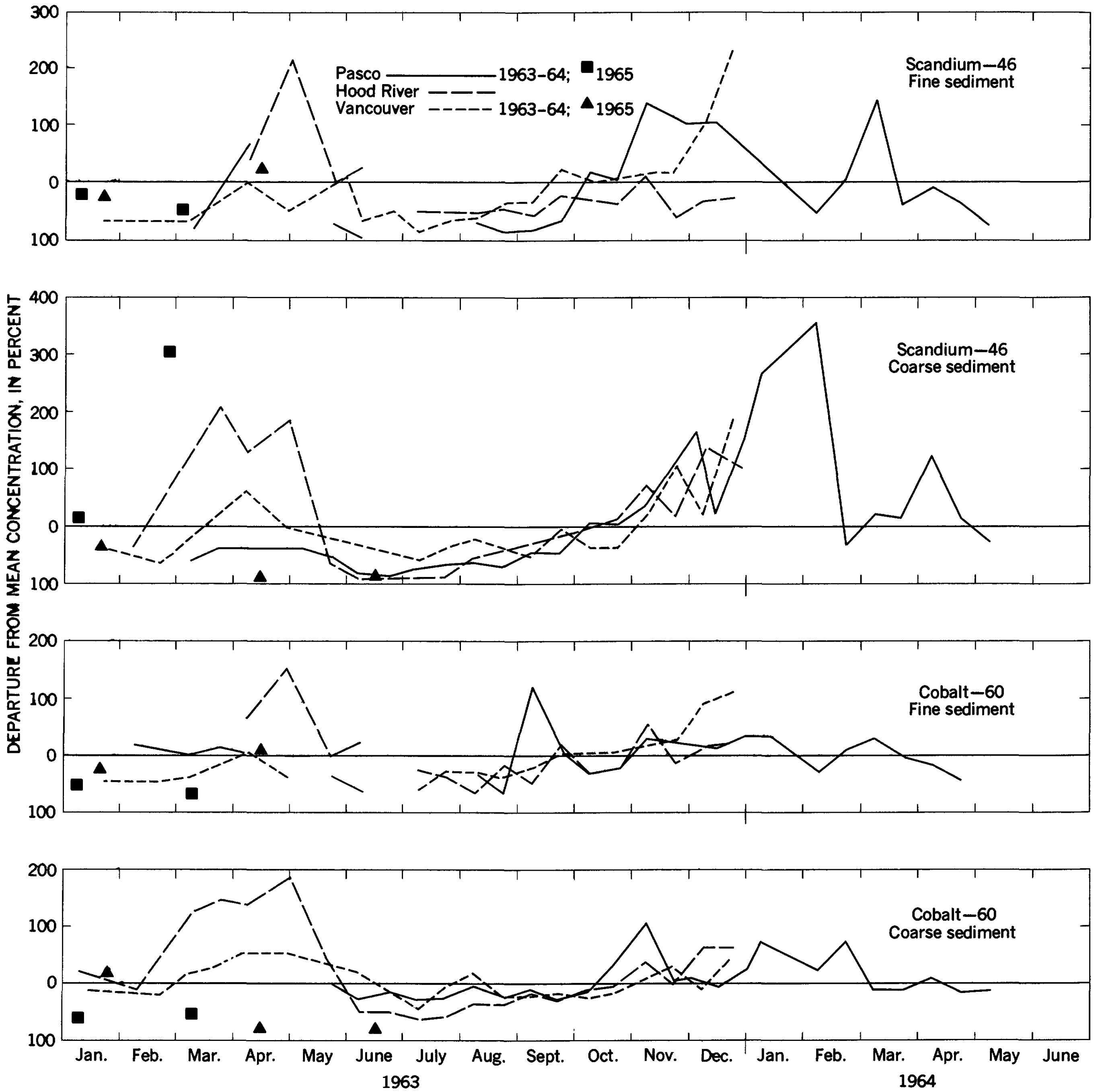


FIGURE 4.—Departures of sample-mean concentrations from period-mean concentrations of scandium-46 and cobalt-60 for the coarse- and fine-sediment segments of cross sections at three Columbia River locations. Period means were computed from concentrations observed in samples of surficial sediment during May through December 1963.

changes occurred at the same time that radionuclide concentrations in the surficial sediment were decreasing or at a minimum. However, at this time of year, the concentrations of dissolved zinc-65, scandium-46, and cobalt-60 usually remained at high levels and concentrations of dissolved and particulate chromium-51 usually decreased but were above mean concentrations (fig. 5). The lesser availability of suspended fine sediment to take up radionuclides and deposit them on and in the streambed may have contributed most to the low radionuclide concentrations.

For zinc-65, scandium-46, and cobalt-60, the peak of radionuclide concentrations in surficial sediment during late March through early May coincided with the usual increase in dissolved and particulate radionuclides then.

DOWNSTREAM ATTENUATION

Differences in radionuclide concentrations in

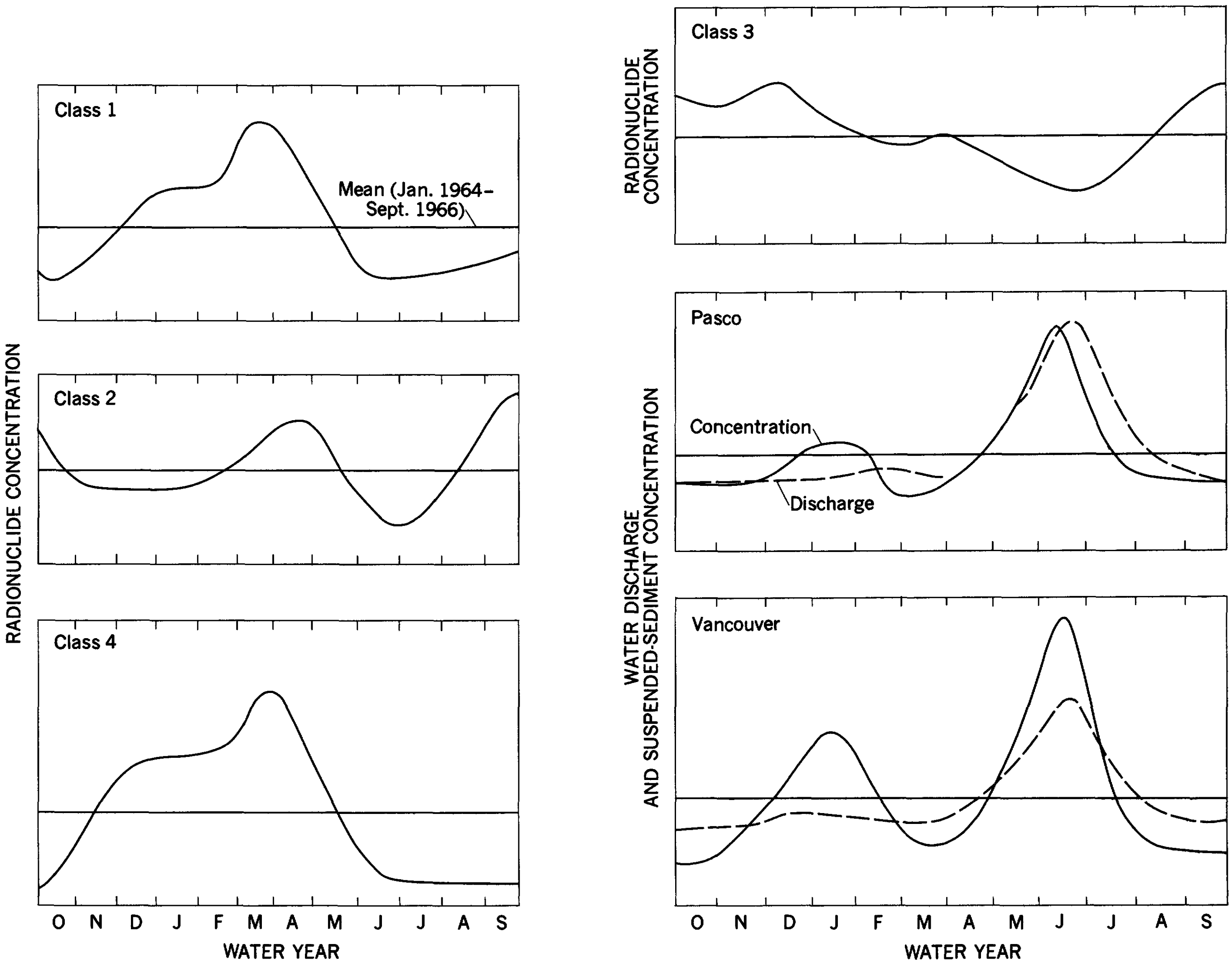


FIGURE 5.—Seasonal variation patterns in concentration of four classes of radionuclides, concentration of suspended sediment, and water discharge of the Columbia River. (Curves reproduced from those given by Haushild and others, 1973, figs. 9 and 10; scales and units of concentrations and discharges are not shown because only the variational patterns are important in this report.)

surficial sediment among the three locations on the Columbia River can be evaluated from the data in table 3. Radionuclide concentrations were compared for periods when data from semimonthly observations were complete enough to compute means at the three river locations. Concentrations for the fine- and coarse-sediment parts of the streambed were compared at each river location and also between river locations.

TABLE 3.—*Ratios of period-mean radionuclide concentrations in coarse- and fine-sediment parts of the streambed at Columbia River locations*

[Observation periods: chromium-51, August-December 1963; other radionuclides, May-December 1963]

	Pasco, Wash.				*Hood River, Oreg.*				*Vancouver, Wash.*			
Radionuclide-concentration ratios	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}	Cr^{51}	Zn^{65}	Sc^{46}	Co^{60}
Fine-sediment parts to coarse-sediment parts of streambeds at indicated station	8.9	3.1	7.4	2.2	1.7	2.5	2.0	3.1	5.1	3.5	5.4	3.1
Indicated station to Pasco, fine-sediment part of streambed	1.0	1.0	1.0	1.0	.05	.07	.03	.06	.03	.02	.01	.01
Indicated station to Pasco, coarse-sediment part of streambed	1.0	1.0	1.0	1.0	.28	.09	.10	.04	.05	.02	.01	.01
Indicated station to Pasco, from data collected between April 21 and May 12, 1966[1]	1.0	1.0	1.0	1.0	----	[2].08	[3].06	[3].07	----	[2].07	[3].03	[3].04

[1]Data from table 25, p. 96 of Glenn (1971). Values shown for Hood River, Oreg., are average of values reported by Glenn for locations in Bonneville Reservoir upstream from Hood River and from Bonneville Dam.
[2]From average of concentrations for particles <0.5 mm.
[3]From concentrations for particles <0.002 mm.

Inspection of table 3 indicates that type of radionuclide affected the ratios between concentrations in fine- and coarse-sediment parts of the streambed at a station. The ratios for zinc-65 and cobalt-60 averaged 2.9 and were about the same at the three stations, whereas the ratios for chromium-51 and scandium-46 ranged from 1.7 to 8.9 and were highest at Pasco and lowest at Hood River. The comparisons among stations show that concentrations of chromium-51 and scandium-46 in the fine-sediment part of the streambed at Hood River decreased to only 5 and 3 percent, respectively, whereas concentrations in the coarse-sediment part decreased to 28 and 10 percent, respectively, of concentrations at Pasco. The relatively small particle-size composition (table 2) and relatively favorable conditions for deposition of particulate radionuclides in the coarse-sediment part of the streambed at Hood River may have contributed to this apparent selective sorption and deposition of chromium-51 and scandium-46.

Glenn (1973) analyzed the downstream attenuation of radionuclide concentrations in surficial sediment as part of a study of the relations among radionuclide content and physical, chemical, and mineral characteristics of Columbia River sediments. His study included data for particle-size separates from samples obtained at six cross sections between Hanford Reservation and Vancouver, Wash., during April 21 to May 12, 1966. Some of Glenn's data for zinc-65, scandium-46, and cobalt-60 are given in table 3. His results showed that (1) the average zinc-65 concentration from a station near McNary Dam was 20 percent of the zinc-65 concentration from a station just upstream from Pasco, and (2) zinc-65 concentration decreased gradually from McNary Dam to Vancouver; at Vancouver, it was about 7 percent of the concentration just upstream from Pasco. The results from the semimonthly sampling at the three stations during 1963 indicated that the average zinc-65 concentration at Vancouver, Wash., was 2 percent, scandium-46 and cobalt-60 were 1 percent, and chromium-51 was 3–5 percent of respective concentrations at Pasco (table 3).

The smaller decrease in zinc-65 concentrations between Pasco and Vancouver for 1966 (Glenn, 1973) than for 1963 (this study) might be attributable to the different times of year the data were obtained. Less attenuation normally would be expected during late April–early May when zinc-65 concentrations usually are much greater than period-mean concentrations at stations downstream of Pasco (fig. 3). This reasoning helps explain the differences between Pasco and Vancouver, but is contradicted by the fact that attenuation of zinc-65 concentration between Pasco and Hood River during both 1963 and 1966 was the same. This evidence precludes explanations of differences in the attenuations by differences in sample locations and sample makeup (particle-size separates versus total-sediment samples). Either attenuation of zinc-65 concentrations between Hood River and Vancouver was different in 1966 than it was in 1963 or the error in determining the attenuation between Pasco and Vancouver is on the order of the differences between the attenuations noted in the two studies.

RADIONUCLIDE INVENTORIES

INVENTORY COMPUTED FROM RADIONUCLIDE BUDGET

A radionuclide inventory is the quantity of a radionuclide accumulated in a specific reach of a stream at a given time. Inventories of specific radionuclides can be estimated by combining (1) the quantities of the radionuclides accumulated in the reach at some initial time; (2) the discharges of the radionuclides into and out of the reach after the initial time; and (3) the decay rates of the radionuclides.

An equation for computing the quantity of a radionuclide accumulating in a river reach from such data is:

$$A_i = A_0 exp-\lambda t_i + \frac{R}{\lambda}(1-\exp-\lambda t_i), \quad (1)$$

where

A_i is the amount of a specific radionuclide accumulated at end of time t_i,

A_0 is the quantity of the radionuclide stored in the reach at $t = 0$,

λ is the decay rate for the radionuclide expressed in terms of $1/t$,

t_i is the ith time period, and

R is the input (inflow minus outflow) of the radionuclide to the reach during t_i.

If λ and t are expressed in the same units of time (weeks) and R is a weekly input, inventories can be computed from the following form of equation (1):

$$A_n = A_0\exp-n\lambda + \frac{(1-\exp-\lambda)}{\lambda}\sum_{T=1}^{n} R_T\exp(T-n)\lambda, \quad (2)$$

where

A_n is the amount of a specific radionuclide accumulated in the reach at the end of n weeks,

T is a dummy variable that represents the number of weeks after some initial time when A_0 is known,

R_T is the input of the specific radionuclide during the Tth week.

Weekly mean discharges of eight radionuclides at Pasco and Vancouver, Wash., for the period January 1964 through September 1966 were used as inflow and outflow discharges. The weekly discharges were used by Haushild, Stevens, Nelson, and Dempster (1973) to determine monthly mean discharges. For the computations, values of A_0, the amount of a radionuclide stored in the Pasco-to-Vancouver reach as of January 1964, had to be known. These values were determined by solving equation (2) for A_n with n equal to 10 half-lives. If n is set equal to 10 half-lives, the term $A_0 \exp -n\lambda$ in equation (2) equals $A_0/1{,}024$, which is negligible compared with other terms in the equation. Thus, values of A_0 as of January 1964 could be computed solely from radionuclide inputs for periods of 10 half-lives before January 1964.

Because actual radionuclide discharges prior to 1964 were not measured, they were simulated with a model based on discharges measured during 1964–66. Such a model should be valid unless there were major changes in the river system or in the operation of reactors during the 10 half-life periods preceding 1964. During 1955–64, eight operating reactors contributed radionuclides directly to the river in their cooling-water effluent. The last major change in the Columbia River system prior to January 1964 was the beginning of storage in McNary Reservoir and regulation of water outflow at McNary Dam in April 1953. Ten half-life periods for seven radionuclides were shorter than the 9-year period 1955–63. Therefore, inputs for these seven radionuclides were estimated from simulated discharges and used directly in equation (2). However, discharges of cobalt-60, which has a half-life of 5.27 years, were simulated for only two half-lives (10.54 years) prior to January 1964; this period started after the closing of McNary Dam in April 1953, but included a period from mid-1953 through 1954 when six instead of eight reactors were operating. Setting the storage of cobalt-60 in the Pasco-to-Vancouver reach two half-lives before January 1964 at zero would introduce considerable error, because cobalt-60 accumulating in the reach since September 1944 would not have completely decayed by mid-1953. Annual storages of cobalt-60 therefore were roughly estimated for the period September 1944 through mid-1953 by considering the number of reactors operating each year and the probable lesser storage of cobalt-60 in the reach (McNary Reservoir did not then exist). Summation of these estimated annual storages, corrected for decay losses to January 1964, suggested that the initial storage of cobalt-60 on January 1964 would have been about 40 curies greater than if cobalt-60 storage two half-lives before January 1964 was zero. The additional initial storage of 40 curies was used in computing cobalt-60 inventories for January 1964 to September 1966.

The discharges at Pasco and Vancouver for periods prior to 1964 were simulated by use of the following model:

$$X(t) = T(t)+S(t)+f\left[Q(t)\right], \quad (3)$$

where

$X(t)$ = time series of simulated weekly mean discharges of particulate or dissolved radionuclides,

$T(t)$ = secular trend in $Y(t)$,

$S(t)$ = pattern of seasonal variation for $Y(t)$, and

$f\left[Q(t)\right]$ = influence of water discharge on $Y(t)$,

in which

$Y(t)$ = time series of weekly mean discharges of particulate or dissolved radionuclides observed at Pasco or Vancouver during January 1964 to September 1966, exclusive of the period in July and August 1966 when all reactors were shut down, and

$Q(t)$ = time series of weekly mean water discharges observed at Pasco or at Vancouver during the period January 1964 to September 1966.

Secular trend, $T(t)$, and seasonal variation pattern, $S(t)$, were determined for each particulate and dissolved radionuclide by using techniques described by Waugh (1943). The logarithms of weekly values of $\left[Y(t)-T(t)-S(t)\right]$ were related to the logarithms of weekly values of $Q(t)$; if there was a significant linear relation, it was called $f\left[Q(t)\right]$. In this manner, models were determined for simulating the particulate and dissolved discharges of each of the eight radionuclides at Pasco and at Vancouver—a total of 32 models. The weekly mean total discharge of a radionuclide at each river station was determined by adding the simulated weekly mean discharges of dissolved and particulate radionuclides.

Subtraction of the simulated output discharges at Vancouver from the simulated input discharges at Pasco provided net weekly simulated inputs of the radionuclides to the Pasco-to-Vancouver reach. Observed and simulated inputs of chromium-51 and of cobalt-60 for the period January 1964 through September 1966 are shown, respectively, in figures 6 and 7. Being mostly anionic, about 92 percent of chromium-51 remained dissolved in the river water at Pasco and Vancouver, whereas an average of 60 percent and 88 percent, respectively, of the generally cationic cobalt-60 was particulate at Pasco and Vancouver (Haushild and others, 1973; Nelson and others, 1966). The general agreement indicated in figures 6 and 7 between observed and simulated inputs for two dissimilar radionuclides was typical of the agreement for the other six radionuclides.

Weekly inputs observed from January 1964 through September 1966 and estimated initial storages for January 1, 1964, were used to compute weekly inventories. Monthly mean inventories, determined from the weekly values, are shown in figures 8 and 9.

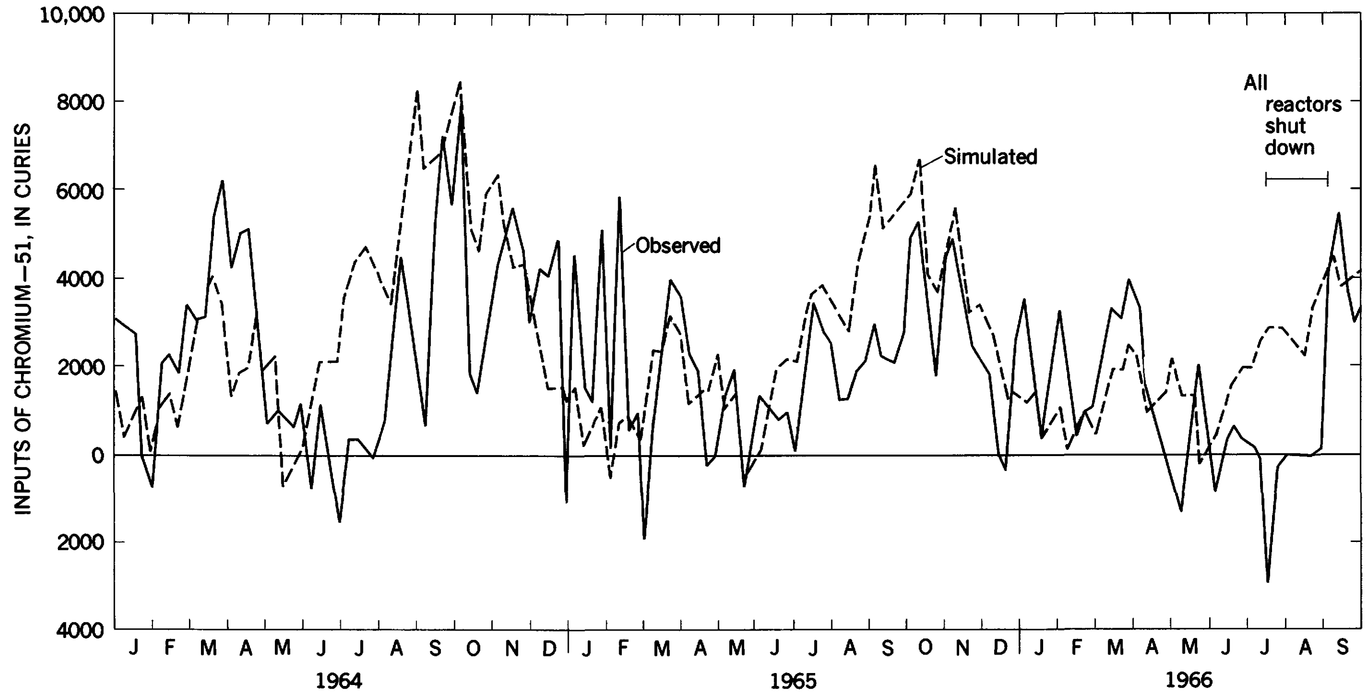


FIGURE 6.—Weekly mean inputs (inflows minus outflows) of chromium-51 into the Columbia River from Pasco to Vancouver, Wash., January 1964 through September 1966.

A generally linear decrease in the radionuclide inventories during the observation period (figs. 8 and 9), agrees with the decreasing trend in discharges of radionuclides reported by Haushild, Stevens, Nelson and Dempster (1973). The pattern of the small seasonal variation in monthly mean inventories showed a maximum in spring and a minimum in summer–early fall for antimony-124, manganese-54, cobalt-60, and zinc-65 (fig. 8). The March-April peaks in monthly mean inventories of chromium-51 usually were little greater than the February-March minimums, whereas maximums during October-December were five to six times greater than the minimums in June or July. Variations in monthly inventories of cobalt-58 and scandium-46 were anomalously large in 1964 (fig. 9). After 1964, scandium-46 inventories had about equal maximums in May and November-December and about equal minimums in July and February, and cobalt-58 inventories varied slightly about the decreasing trend. Iron-59 inventories were maximum in May and October-November and were minimum in February-March and July-August.

Computed antimony-124 and chromium-51 inventories had small negative values during the shutdown of all reactors in July-August 1966. Because these radionuclides are mainly dissolved, even relatively small inaccuracies in the data can make it impossible to determine accurate and credible values of small positive inventories of chromium-51 and antimony-124 by the methods defined in equation (2). Inventories deter-

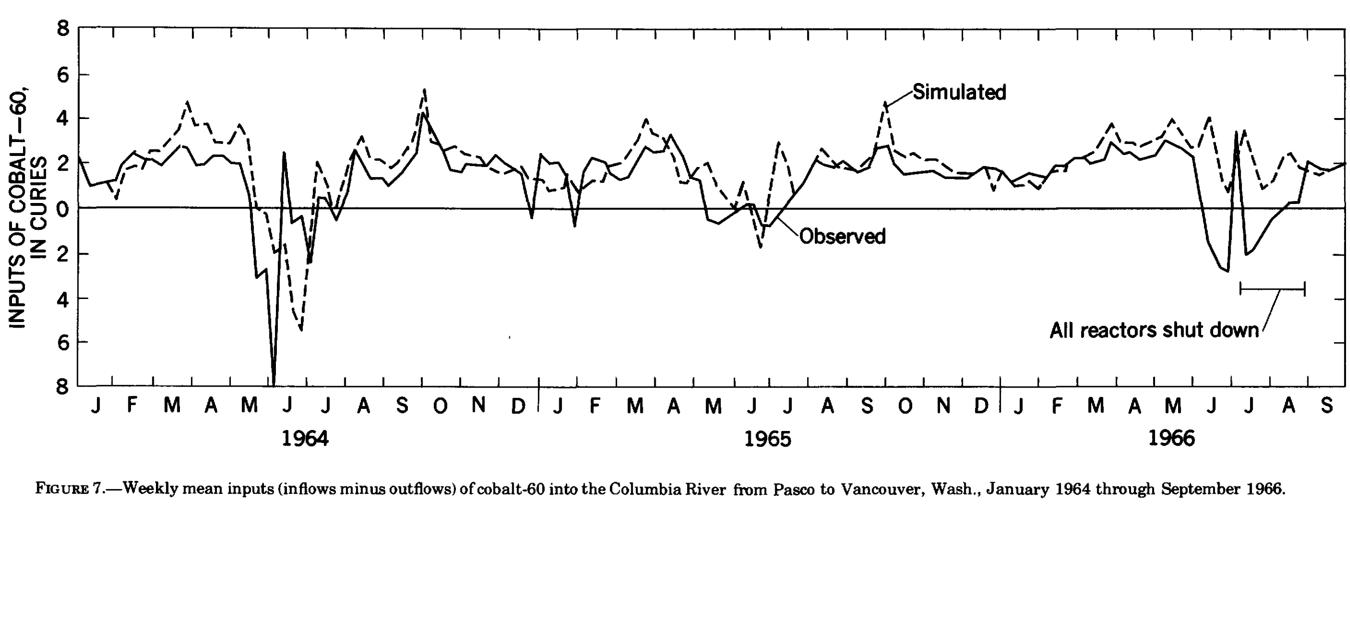


FIGURE 7.—Weekly mean inputs (inflows minus outflows) of cobalt-60 into the Columbia River from Pasco to Vancouver, Wash., January 1964 through September 1966.

mined by using simulated inputs (see figs. 6 and 7 for inputs of chromium-51 and cobalt-60) for the eight radionuclides from the beginning of the shutdown period through September 1966 are shown in figures 8 and 9. These data are estimates of inventories for the Pasco-to-Vancouver reach had the reactors not been shut down.

INVENTORY COMPUTED FROM RECONNAISSANCE-SURVEY DATA

COMPUTATION METHOD, DATA AND RIVER DIVISION

In general, inventories were computed by dividing the river into reaches, reaches into subreaches, and

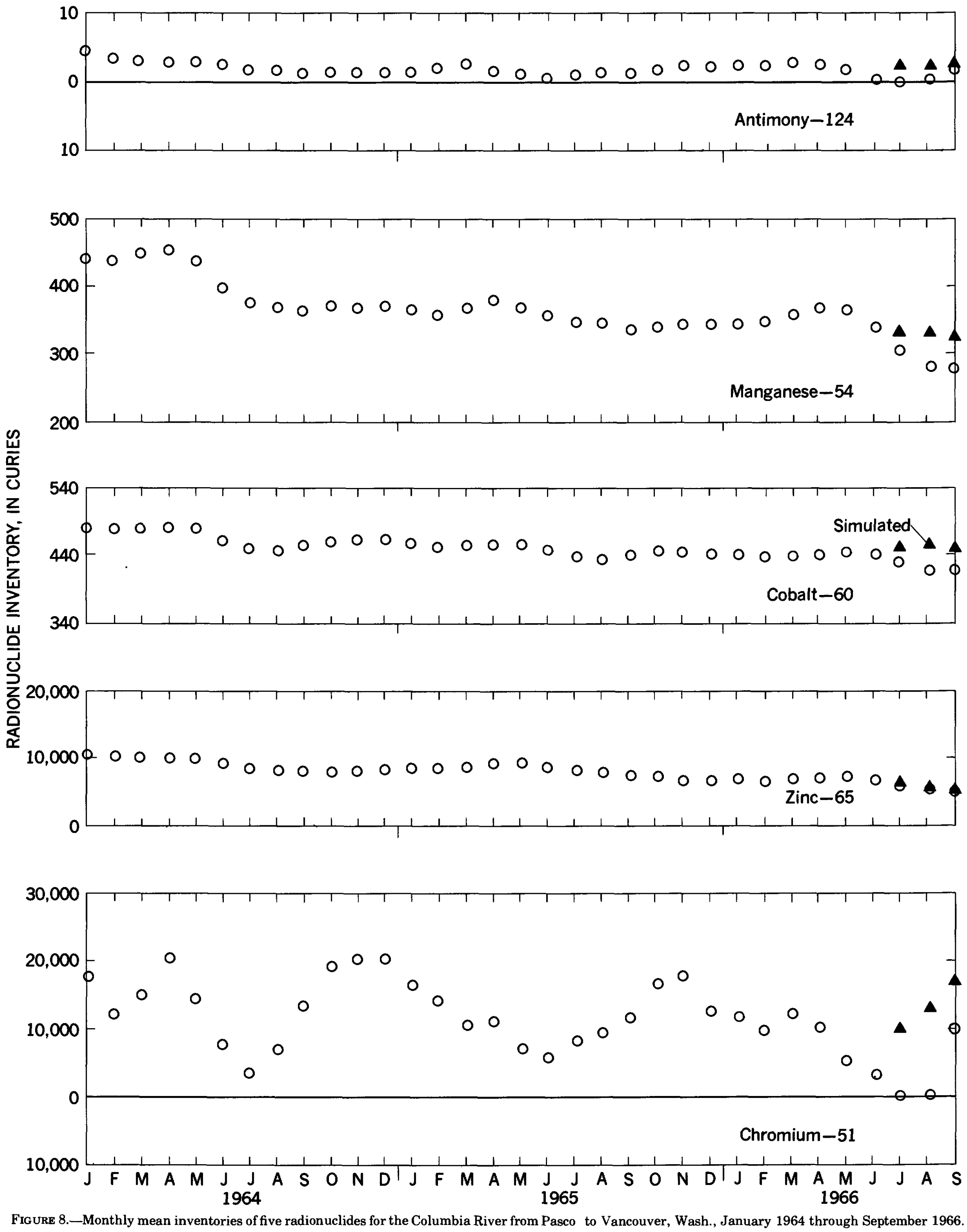


FIGURE 8.—Monthly mean inventories of five radionuclides for the Columbia River from Pasco to Vancouver, Wash., January 1964 through September 1966.

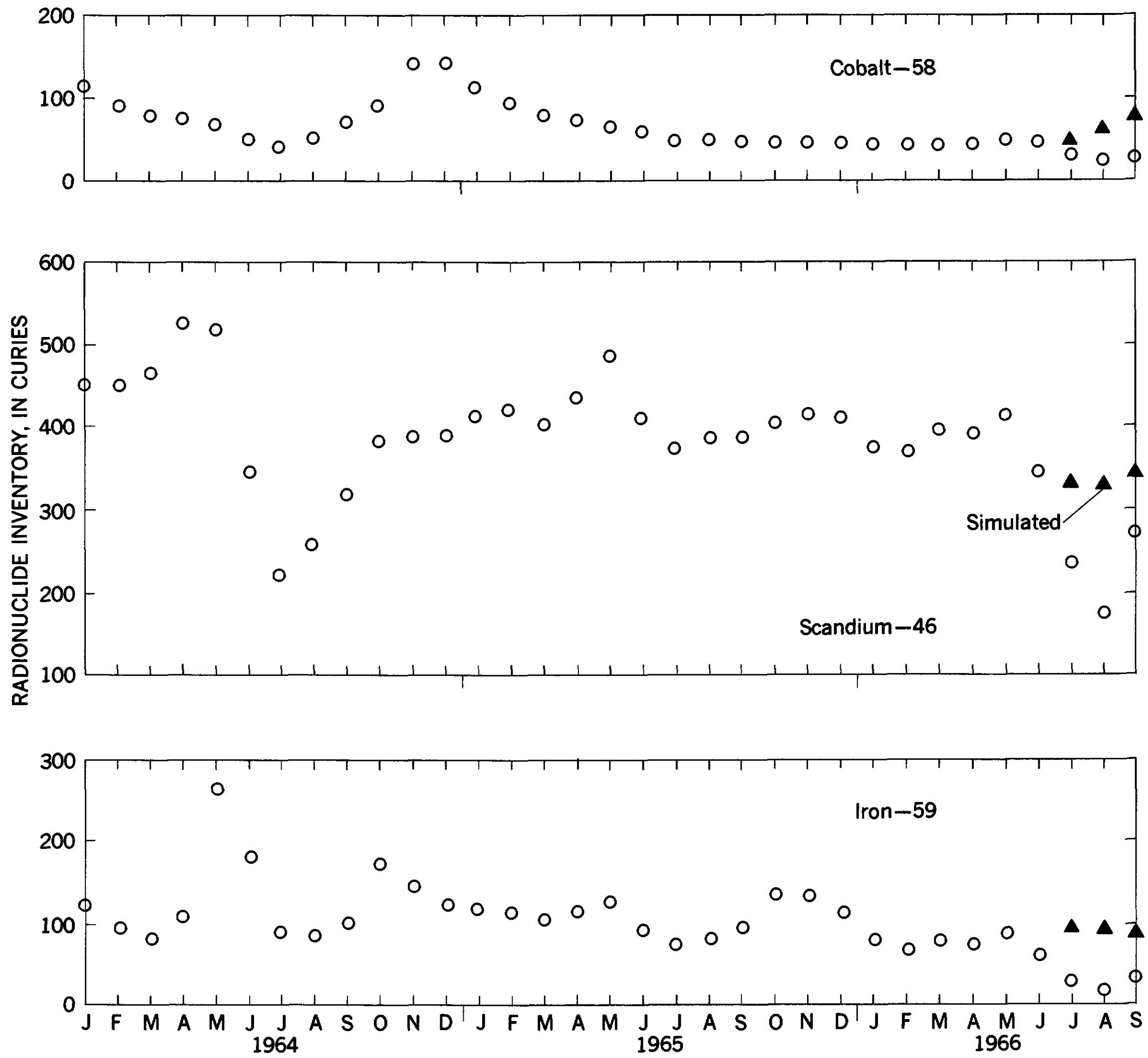


FIGURE 9.—Monthly mean inventories of three radionuclides for the Columbia River from Pasco to Vancouver, Wash., January 1964 through September 1966.

some subreaches into environmentally similar areas, as based on the composition of surficial sediment. Then, the radionuclide contents in the streambed of each subreach or environmental area were computed as the product of mean radionuclide concentrations in surficial sediment, factors to express distribution of radionuclide concentrations with depth in the streambed, specific weight of bed sediment, and extent of the subreach or environmental area. (Of course, all factors must be expressed in compatible units.) Inventories in a river reach were the sum of the inventories for the subreaches and environmental areas within the reach.

Table 10 shows the concentrations of five major radionuclides in surficial-sediment samples obtained from reconnaissance surveys. (See "Basic Data" section.) Particle-size distribution of the samples, water depths at sample locations, and gross-gamma count rates from in-place sediment are also given in this table. Radionuclide concentrations in core segments are presented in table 11. (See "Basic Data" section.) Particle-size distributions of surficial-sediment samples from many locations other than those shown in table 10 are available from U.S. Geological Survey files. In addition to this body of data, Nelson (1965) reported concentrations of radionuclides in streambed sediment from the Columbia River upstream of McNary Dam. His data include radionuclide concentrations for (1) particle-size separates of samples obtained by divers, (2) segments of a 2-inch-diameter (5.1 cm) core from a sand deposit on the downstream side of an island downstream from Pasco, (3) segments of cores of a fine-grained sediment deposit located near McNary Dam and a silty-sediment deposit located about 4 miles (6.4 km) below the Snake River mouth, (4) segments of a core from a compacted clay deposit beneath about 50 feet (15 m) of water between Richland and the Yakima River mouth, and (5) a core of sediment from the river flood plain downstream of the reactors but within the Hanford Reservation.

The first step in using the reconnaissance-survey data for computing radionuclide inventories was to divide the Columbia River into reaches of similar environment. The main division was into reaches where the streambed was armored with gravel (bedrock in a few short reaches), and where sediment (fine gravel, sand, silt, and clay) was deposited. (See "Description of the Study Reach" section.) Computation of inventories was different for each main stream environment.

ARMORED-STREAMBED REACHES

For the armored-streambed reach between the reactors and McNary Dam, Nelson and Haushild (1970) reported the average content of zinc-65, chromium-51, scandium-46, cobalt-60, and manganese-54 contained in the sediment beneath each unit area of streambed. The contents they reported were based on concentrations from samples obtained by divers. Armored-streambed reaches below McNary Dam were not sampled; therefore, contents of radionuclides in these reaches were estimated by applying a downstream attenuation to the observed contents of the five radionuclides in the armored-streambed reach above McNary Dam. That is, radionuclide contents in armored streambeds were assumed to decrease linearly downstream at the same rate as the radionuclide attenuation in surficial sediment (sand) in the river's main channels. (See table 4 in the following section.) For example, the average concentration of zinc-65 in surficial-sand samples decreased by 60 percent (from 120 to 48 pci/g) between the reach upstream of Walla Walla River and the Bonneville Reservoir reach; the average zinc-65 concentration was 26 pci/g (another 18 percent lower) in surficial sand samples from the reach between Bonneville Dam and Longview, Wash. Zinc-65 content beneath each unit area of an armored streambed located midway between the midpoints of the reach upstream of Walla Walla River and the Bonneville Reservoir reach, therefore, was estimated to be 70 percent ($100 - 60/2$) of the zinc-65 concentration in the armored-streambed reach above McNary Dam.

Radionuclide inventories for armored-streambed reaches above McNary Dam were reported by Nelson and Haushild (1970). Inventories for armored-streambed reaches below McNary Dam were computed from streambed areas, determined by planimetry from U.S. Coast and Geodetic Survey maps, and the estimated radionuclide contents beneath each unit area of streambed.

SEDIMENT-DEPOSITING REACHES

The sediment-depositing reaches were further divided into stream subenvironments—main channels where deposits were mostly sand or secondary channels and shallow areas where deposits were mixtures of sand, silt, and clay. Mean radionuclide concentrations and particle-size distributions of surficial-sediment samples, and mean count rates of gross-gamma radioactivity of in-place sediment for these two subenvironments in each reach are shown in table 4.

Each sediment-depositing reach (except for the small deposit at CRM 263, km 423) was further divided longitudinally into subreaches. As an example, core sites, cross-section locations, and subenvironments for the

TABLE 4.—*Mean radionuclide concentrations and particle-size distributions of surficial-sediment samples, and mean in-place count rates of gross-gamma radioactivity at sample sites for stream environments in sediment-depositing reaches of the Columbia River from 27 miles (43 km) upstream of McNary Dam to Longview, Wash.*

Reach or location designation: Name	CRM[1]	Stream environment	Number of samples	Concentration (picocuries per gram): Zn^{65}	Cr^{51}	Co^{60}	Sc^{46}	Mn^{54}	Particle-size distribution (percent in class): <0.004 mm	0.004–0.062 mm	>0.062 mm	In-place count rates (per minute)
Upstream of Walla Walla River in McNary Reservoir[2]	319–314	Main channel	4	120	220	8.1	9.5	8.1	0	0	100	31,000
	319–314	Secondary channels and shallow areas	14	260	660	10	35	12	7	48	45	90,000
Downstream of Walla Walla River in McNary Reservoir	314–292	Entire Streambed	26	470	580	14	54	14	14	55	31	190,000
29 mi. (47 km) downstream of McNary Dam[2]	263	Sediment deposit in pool of rapids-and-pools reach	4	54	140	2.7	3.6	4.5	4	29	67	30,000
Downstream part of The Dalles Reservoir[2]	208–193	Entire streambed	12	130	300	3.4	17	8.1	7	43	50	79,000
Bonneville Reservoir[3]	187–140	Main channel	22	48	110	1.8	4.1	3.2	0	3	97	------
	187–140	Secondary channels and shallow areas	6	140	380	5.9	12	7.7	6	50	44	------
Bonneville Dam to Longview Wash.[4]	132–66	Main channel	44	26	34	.5	.6	.7	0	0	100	10,000
	132–66	Secondary channels and shallow areas	30	130	190	1.7	6.6	3.8	5	38	57	33,000

[1]Multiply by 1.61 to compute river kilometre.
[2]Data collected in September 1965.
[3]Data collected in October and November 1964.
[4]Data collected in April 1965.

sediment-depositing subreach from CRM 65.5 to 78.0 (km 105 to 126) are shown in figure 10. Radionuclide concentrations, particle-size distributions, and in-place count rates for surficial sediment in the subreaches from 14 miles (23 km) below Bonneville Dam to Longview, Wash., are given in table 5.

Their large standard deviations (table 5) indicate that concentrations of radionuclides in surficial-sediment samples varied greatly. Thus, differences in radionuclide concentrations in surficial-sediment samples from adjacent similar stream subenvironments usually were not significant (95 percent confidence level). Differences between concentrations in samples that were collected long distances apart usually were significant.

Semidiurnal ocean tides frequently cause flow in the river to reverse direction from the mouth upstream to near CRM 66 (km 106)—actual location of the farthest extent of flow reversal depends on tide height and river flow. Because hydrodynamic conditions generally favor deposition in tidal river reaches where flow reverses, the higher concentrations of radionuclides between river miles 66 and 77 (km 106–124) (see table 5) may have been caused by the deposition of more fine sediment there than was deposited in nearby upstream reaches. Zinc-65 concentrations in surficial-sediment samples between CRM 66 and 123 (km 106–198) were significantly lower than concentrations between CRM 123 and 132 (km 198–212); reasons for this difference are unknown. Radionuclide concentrations in surficial

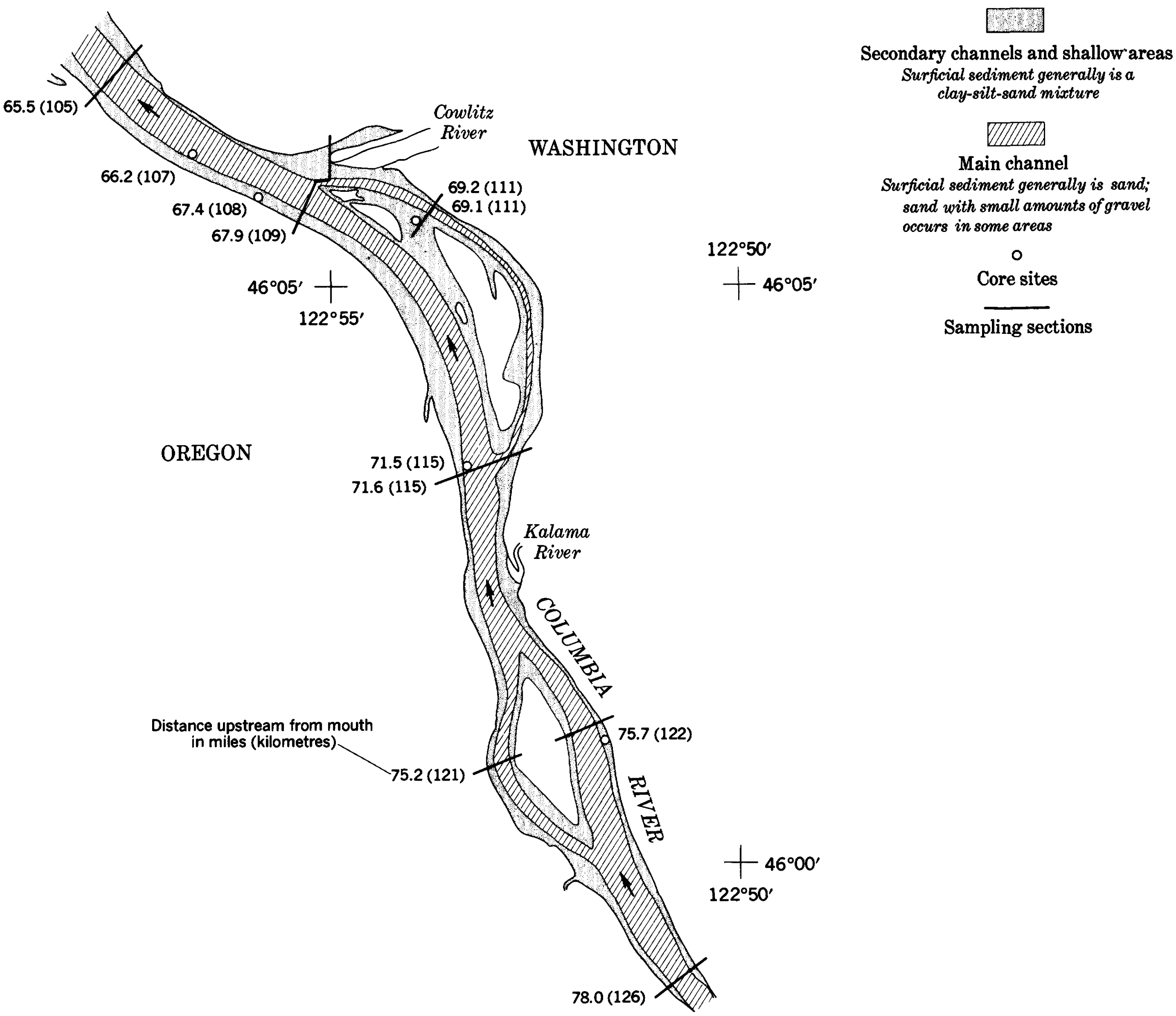


FIGURE 10.—Stream environments and locations of core sites and sampled cross sections in the Columbia River between CRM 65.5 and 78.0 (km 105 and 126).

TABLE 5.—*Mean radionuclide concentrations and particle-size distributions of surficial-sediment samples and mean in-place gross-gamma count rates for two stream subenvironments in sediment-depositing subreaches of the Columbia River from 14 miles (23 km) below Bonneville Dam to Longview, Wash.*

Reach designation by CRM[1]	Number of samples	Concentration (picocuries per gram) Zinc-65 Mean	Zinc-65 SD[2]	Chromium-51 Mean	Chromium-51 SD	Cobalt-60 Mean	Cobalt-60 SD	Scandium-46 Mean	Scandium-46 SD	Manganese-54 Mean	Manganese-54 SD	Particle-size distribution (percent in class) <0.004 mm	0.004–0.062 mm	0.062–0.25 mm	>0.25 mm	In-place count rate (per minute) Mean	SD
Secondary Channels and Shallow Areas																	
132–118	6	120	58	100	66	1.5	0.5	4.4	2.9	2.9	1.4	6	52	38	4	33,000	14,000
118–109	7	140	99	150	130	1.5	.9	5.8	4.9	3.4	2.9	6	49	39	6	33,000	12,000
109–77	11	80	53	130	71	1.4	.8	4.1	2.8	2.6	1.5	3	18	42	37	24,000	15,000
[3]77–66	6	220	87	440	180	2.8	1.0	14.3	9.3	7.2	2.9	8	44	27	21	51,000	15,000
[3]132–77	24	110	71	130	98	1.5	.8	4.7	3.6	2.9	2.0	5	37	40	18	29,000	14,000
Main channel																	
132–123	11	50	18	34	24	0.5	0.1	0.6	0.2	0.9	0.3	----	1	40	59	15,000	6,200
123–106	7	23	13	37	13	.5	----	.6	.4	.6	.2	----	----	29	71	6,800	3,000
106–89	8	14	7.7	28	10	.5	----	.5	.2	.5	.1	----	----	16	84	7,600	3,200
89–73	9	15	6.3	28	8.6	.5	----	.5	----	.5	.1	----	----	38	62	7,000	2,600
73–66	9	22	9.0	41	18	.5	.2	.8	.8	.9	.5	----	1	41	58	11,000	4,400
[3]132–66	44	----	----	34	16	.5	----	.6	.4	.7	.3	----	----	33	67	10,000	5,500
[3]132–123	11	50	18	----	----	----	----	----	----	----	----	----	----	----	----	----	----
[3]123–66	33	18	10	----	----	----	----	----	----	----	----	----	----	31	69	8,200	3,800

[1]Multiply by 1.61 to compute river kilometre.
[2]Standard deviation.
[3]Mean concentrations for these subreaches were used in computing inventories.

sediment of subreaches were determined for all the sediment-depositing reaches of the Columbia River between the reactors and Longview, Wash. The areas to which the concentrations apply were measured from U.S. Coast and Geodetic Survey maps by planimetry.

The core-segment data (table 11) were used in estimating the vertical distributions of radionuclide concentrations required for computing inventories in the sediment-depositing reaches. For each of five radionuclides, ratios of concentrations at depth to adjusted concentrations in the top 2 inches (5.1 cm) of each core were computed. The concentrations were adjusted to represent concentrations that would have been obtained in a surficial sample; they were determined by weighting concentrations in the top inch (2.5 cm) and next-lower inch of cores with the percentage of sediment obtained from these streambed layers with a USBM-54 sampler. (See "Equipment and Methods" section.) Thus, a ratio at a specific depth reflects the radionuclide concentration there relative to the concentration in the surficial sediment. The data from the appropriate cores within relatively long reaches of the Columbia River were combined to determine the vertical distributions of radionuclide concentrations in streambeds of main channels or the secondary channels and shallow areas in these reaches. The following techniques for determining the vertical distributions of zinc-65 concentration in the sediment-depositing streambeds are applicable to all radionuclides.

For the reach from Bonneville Dam to Longview, Wash., two vertical distributions of zinc-65 concentrations are shown in figure 11 for each subenvironment. In the sand beds of the main channel, zinc-65 concentrations in a few cores were nearly the same throughout the core depth (left group of data), whereas concentrations below the top 2 inches (5.1 cm) of most cores averaged about 70 percent of the adjusted concentrations (right group of data). In the secondary channels and shallow areas, zinc-65 concentration decreased rapidly with depth in some cores (right group of data); concentrations generally decreased with depth in other cores (left group of data) in an erratic manner—several ratios were equal to or greater than one. Other variables or combinations of variables—such as core location, particle-size distribution of surface sediment at core sites, and in-place count of gross-gamma radioactivity at core sites—did not prove to be reliable indicators of where the right or left distributions of zinc-65 concentrations occur in the two stream subenvironments. Therefore, vertical distributions of zinc-65 concentrations within each stream subenvironment for the Bonneville Dam-to-Longview reach were determined by combining the two groups of data for the specific subenvironment.

For two types of beds in McNary Reservoir, for secondary channels and shallow areas in the Bonneville Dam-to-Longview reach, and for local deposits in The Dalles Reservoir, the data in figure 11 define the vertical distribution of zinc-65 concentration to depths in the streambed where concentrations were negligible. Nelson and Haushild (1970) used the vertical distributions in the two types of beds in McNary Reservoir to compute a zinc-65 inventory there. Summation of the average ratios for 2-inch (5.1 cm) increments from the

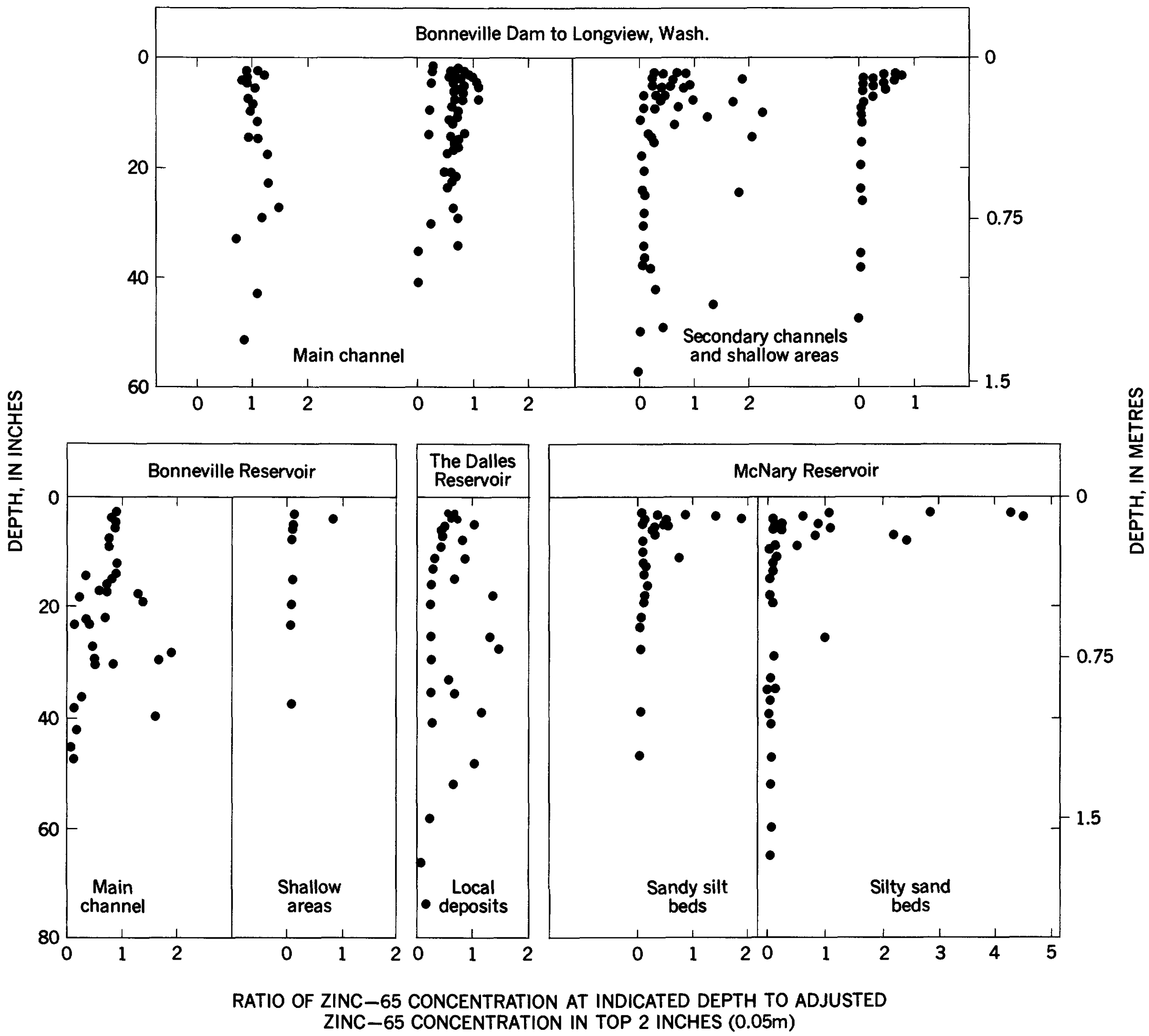


FIGURE 11.—Variation of normalized zinc-65 concentrations with depth in cores from streambed of the Columbia River.

streambed surface to the depth where concentrations became negligible provided a vertical-distribution factor to apply to the previously determined zinc-65 concentrations in surficial sediment of the secondary channels and shallow areas of the Bonneville Dam-to-Longview reach. The factor for this reach was also used in computing accumulations of radionuclides in streambeds of the similar subenvironments of Bonneville Reservoir. This was necessary because data were available for only one core taken in October 1964 from the shallow areas of Bonneville Reservoir. Sustained high winds and waves, which are typical for the Columbia River gorge, made it impossible to obtain cores during two later surveys.

The vertical distribution of zinc-65 concentrations for the one core from a shallow area probably was representative only of that site, and vertical distributions in secondary channels and shallow areas of Bonneville Reservoir were assumed to be similar to those in this subenvironment below Bonneville Dam. The thick deposits cored in The Dalles Reservoir were small in extent; deposits elsewhere were less than 1 foot (0.3 m) thick. For The Dalles Reservoir, factors to account for vertical distribution of zinc-65 concentrations were computed for (1) thick deposits, from the distributions (fig. 11) for The Dalles Reservoir, and (2) thin deposits, from the distributions (fig. 11) for sandy-silt beds in McNary Reservoir.

Factors to account for vertical distribution of zinc-65 in the sand beds of the main channel in Bonneville

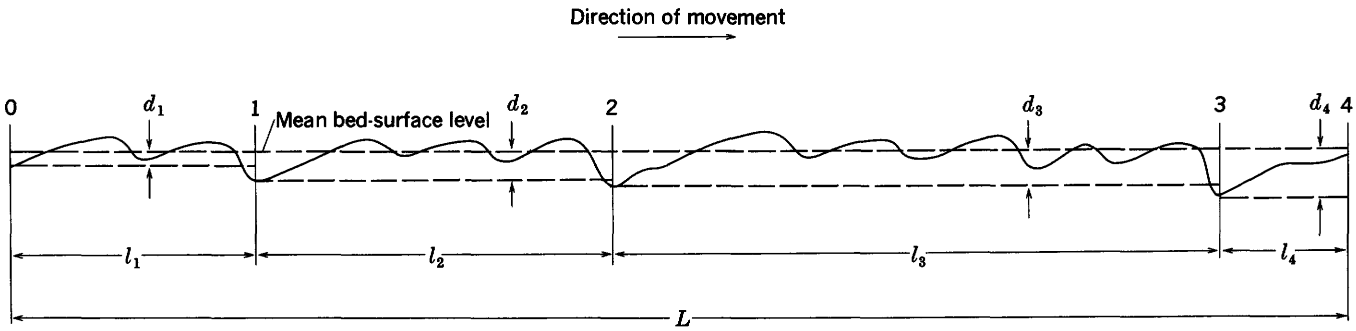


FIGURE 12.—Method for estimating average depth of zone of particle movement d, where $d = \frac{1}{L}\sum_{i=1}^{n} l_i d_i$. (From Sayre and Hubbell, 1965, fig. 41.)

Reservoir and below Bonneville Dam were computed from the data shown in figure 11. The constancy of zinc-65 concentration with depth in main-channel beds below Bonneville Dam resulted from the continual mixing of streambed sediment as the dunes migrated downstream. The gradual attenuation of zinc-65 concentration with depth in main-channel beds of Bonneville Reservoir may be attributed to the slow average rate of migration of dunes during medium and high river flows and the nonmigration of dunes during low river flows. The depth over which the vomputed factors apply should be the same as the depth d of the zone of particle movement. Sayre and Hubbell (1965) present a method for estimating d for dune beds from a depth-sounder record. The geometrical definitions and mathematical expression that they used for computing d for a reach are shown in figure 12. Sayre and Hubbell's method was used to estimate depths of the zone of particle movement in sand-bed reaches in Bonneville Reservoir and below Bonneville Dam, where many depth-sounder data (fig. 2) were available.

The specific weight, expressed in units of weight per unit volume, of in-place sediment in the sediment-depositing reaches was estimated from a relation between median particle size and specific weight of reservoir deposits (Hembree and others, 1952). Specific weight, concentration of radionuclides in surficial sediment, factors to account for vertical distributions of radionuclide concentrations, and areas were then used to compute inventories (accumulations of radionuclides at a specific time) for the sediment-depositing reaches.

Estimated radionuclide inventories at times when data were collected for various reaches of the Columbia River from the reactors to Longview, Wash., are given in table 6. The inventories shown in table 6 for the two reaches between the reactors and McNary Dam are those reported previously by Nelson and Haushild (1970).

DISCUSSION

Inventories estimated from the reconnaissance-survey data indicate the locations and amounts of the five major radionuclides accumulated within the streambeds of the reaches only at the times of the surveys. Because of the temporal variations in inventories shown in figures 8 and 9, any comparisons between reaches of inventories surveyed during different seasons or years may be considerably in error. To correct this deficiency, the inventories given in table 6 were adjusted for temporal variations (seasonal and trend) so that mean inventories for 1965 were estimated (table 7). The adjustment factors were computed from the inventory data given in figures 8 and 9. The seasonal variation and trend in the inventories for the Pasco-to-Vancouver reach were assumed to represent the temporal variations in inventories for the other Columbia River reaches. The adjustment factor for a specific

TABLE 6.—*Estimated radionuclide inventories at times of the reconnaissance surveys for various reaches of the Columbia River from the reactors, Hanford Reservation to Longview, Wash.*

Reach designation		Quantities, in curies				
Description	CRM[1]	Zinc-65	Chromium-51	Cobalt-60	Scandium-46	Manganese-54
Reactors to Pasco, Wash.[2]	384–330	630	600	80	40	80
Pasco, Wash. to McNary Dam[2]	330–292	3,600	10,000	250	330	130
McNary Dam to Biggs, Oreg.[2]	292–208	110	160	12	7	13
Biggs, Oreg., to The Dalles Dam[2]	208–192	710	320	18	50	37
The Dalles Dam to Bonneville Dam[3]	192–146	2,700	7,000	130	230	200
Bonneville Dam to Vancouver, Wash.[4]	146–106	3,300	3,300	53	64	70
Vancouver, Wash. to Longview, Wash.[4]	106–66	1,800	3,500	53	58	73

[1]Multiply by 1.61 to compute river kilometre.
[2]Data collected in September 1965.
[3]Data collected in October and November 1964.
[4]Data collected in April 1965.

TABLE 7.—*Estimated mean radionuclide inventories for 1965 in various reaches and in the total reach of the Columbia River from the reactors, Hanford Reservation, to Longview, Wash.*

Reach designation		Quantities, in curies					Total	
Description	CRM[1]	Zn^{65}	Cr^{51}	Co^{60}	Sc^{46}	Mn^{54}	Curies	Percent
Reactors to Pasco, Wash	384–330	690	610	83	43	86	1,512	4.1
Pasco, Wash. to McNary Dam	330–292	3,900	10,000	260	360	140	14,660	39.5
McNary Dam to Biggs, Oreg	292–208	120	160	12	8	14	314	.8
Biggs, Oreg., to The Dalles Dam	208–192	780	330	19	54	40	1,223	3.3
The Dalles Dam to Bonneville Dam	192–146	2,800	4,000	130	240	190	7,360	19.8
Bonneville Dam to Vancouver, Wash	146–106	2,900	3,500	52	61	66	6,579	17.7
Vancouver, Wash. to Longview, Wash	106–66	1,600	3,700	52	55	69	5,476	14.8
Total:								
Curies		12,790	22,300	608	821	605	37,124	
Percent		34.5	60.1	1.6	2.2	1.6		100.0

[1]Multiply by 1.61 to compute river kilometre.

radionuclide in a reach then was the ratio, computed from the data in figure 8 or 9, of its mean inventory in 1965 to its inventory at the time of the reconnaissance survey in that reach.

Chromium-51 (60.1 percent) and zinc-65 (34.5 percent) accounted for nearly all of the radionuclide inventory in the Columbia River between the reactors and Longview, Wash. (table 7). Cobalt-60, scandium-46, and manganese-54 each contributed about 2 percent of the total inventory of the five radionuclides. Two main sediment-depositing reaches accounted for 92 percent of the radionuclide inventory—40 percent was in the 38 miles (61 km) from Pasco, Wash., to McNary Dam and 52 percent was in the 126 miles (203 km) from The Dalles Dam to Longview, Wash. The remaining 8 percent was divided among a 54-mile (87 km) armored-streambed reach above Pasco (4 percent), an 84-mile (135 km) armored-streambed reach below McNary Dam (1 percent), and a sediment-depositing reach, 16 miles (26 km) long, from near Biggs, Oreg., to The Dalles Dam (3 percent).

Two mean inventories for 1965 in the Pasco-to-Vancouver reach, estimated from both adjusted reconnaissance-survey data (table 7) and radionuclide discharge data at the two stations (like that shown in figs. 6 and 7), are shown in table 8. For every radionuclide, the estimated mean quantity is higher for the inventory computed from the reconnaissance-survey data. The total inventory estimated by this method exceeds that estimated from the radionuclide-discharge data by 47 percent. Because there is no way to reliably estimate the error in either inventory, reasons for the consistent disagreement between the two inventories cannot be determined. However, the errors in both inventories may be large enough so that the disagreement between the two inventories is reasonable; both inventories probably are reasonably good estimates.

Hubbell and Glenn (1973) estimated radionuclide inventories for June 1965 in the Columbia River estuary (between CRM 0 and 66, km 0–106). To complement their data and to provide inventories for the entire river and estuary downstream from the reactors, inventories for June 1965 in the Columbia River between the reactors and the head of the estuary (CRM 66, km 106) also were estimated. Inventories for June 1965 in the Pasco-to-Vancouver reach were obtained from the data in figures 8 and 9. Inventories in reaches above and below this reach were obtained by adjusting inventories estimated from reconnaissance-survey data (table 6) to June 1965, using a method similar to the one described previously for adjusting inventories to 1965 means. The estimated inventories for the estuary and the river are shown in table 9.

The predominance of zinc-65 over chromium-51 for June inventories in the river was forecasted by the seasonal variations in inventories for these radionuclides (see fig. 8). The predominance of chromium-51 over zinc-65 for June 1965 in the estuary (table 9) may indicate that seasonal variations of these radionuclides are much less in the estuary than in the river. Possibly, high river flows in June transported more particulate radionuclides (especially chromium-51) out of the river reach than out of the estuary, where the tides counteracted the high flows. More particulate radionuclides may have been transported to the ocean during spring high flows than during lower flows in other seasons, but their source during the high-flow periods was more likely the riverbed rather than the estuary bed.

Seventy percent of the radionuclide inventory for

TABLE 8.—*Estimated mean radionuclide inventories for 1965 in the Columbia River from Pasco to Vancouver, Wash.*

	Inventory			
	Reconnaissance-survey data[1]		Radionuclide discharge data[2]	
Radionuclide	Curies	Percent	Curies	Percent
Zinc-65	10,000	34	8,000	40
Chromium-51	18,000	61	11,000	54
Cobalt-60	470	2	450	2
Scandium-46	720	2	420	2
Manganese-54	450	1	360	2
Total	29,640	100	20,230	100

[1]From table 7.
[2]From data like those shown in figures 6 and 7.

TABLE 9.—*Estimated radionuclide inventories for June 1965 in the Columbia River from the reactors, Hanford Reservation, Wash., to the ocean*

		Inventory							
		Zinc-65		Chromium-51		Other radionuclides[2]		Total	
	CRM[1]	Curies	Percent	Curies	Percent	Curies	Percent	Curies	Percent
River[3]	384–66	11,000	38	7,600	26	1,600	6	20,200	70
Estuary[4]	66–0	2,100	7	5,300	18	1,300	5	8,700	30
Total		13,100	45	12,900	44	2,900	11	28,900	100

[1]Multiply by 1.61 to compute river kilometre.
[2]Cobalt-60, scandium-46, and manganese-54 in river; these three radionuclides plus zirconium-95-niobium-95 and ruthenium-106 in estuary.
[3]Inventories from figures 8 and 9 for reach between CRM 106 and 330 (km 171–531) and from table 6 (adjusted to June 1965) for reaches between CRM 330 and 384 (km 531–618), and CRM 66 and 106 (km 106–171).
[4]Inventories from table 10, Hubbell and Glenn (1973).

June 1965 in the streambed from the reactors to the ocean was in the river reach. Computations based on appropriate totals of inventories and distances suggest that the quantity of radionuclides accumulated per unit length of estuary bed was about twice that of the riverbed. Because the average estuary width is at least twice the average river width (see fig. 1), quantities of radionuclides accumulated in sediments beneath a unit area of streambed were probably about the same for both the river and the estuary.

SUMMARY AND CONCLUSIONS

The seasonal variation patterns for the concentrations of radionuclides in surficial sediment of the Columbia River streambed were relatively independent of location (Pasco, Wash., Hood River, Oreg., and Vancouver, Wash.), radionuclide species (chromium-51, zinc-65, cobalt-60, and scandium-46), and stream environment (sand and gravel deposits in the main channel as opposed to mixtures of sand, silt, and clay in secondary channels and shallow areas). The similarity in seasonal variation patterns at three locations between Pasco and Vancouver may be attributable to the homogeneity in chemical and mineral characteristics of stream sediments in this reach. Radionuclide concentrations during January 1963 to June 1964 generally were high in late March–early May and November–early January and were low in June–July and late January–early March. Maximums in radionuclide concentrations in the streambed may have been attributable to some or all of the following factors: (1) High concentrations of suspended-particulate and dissolved radionuclides in the river flow, (2) availability of fine <0.062 mm) suspended sediment in the river; and (3) hydrodynamic conditions favorable to deposition of suspended sediment and particulate radionuclides. Minimum radionuclide concentrations in the streambed in June–July were attributed principally to mixing of streambed sediment by high water flows. The causes of minimum radionuclide concentrations during late January–early March was not known, but the minimums coincided with a time when suspended-sediment concentrations were decreasing or at low values.

Concentrations of zinc-65 and cobalt-60 were 2 to 3½ times greater in fine-sediment streambeds (usually mixtures of clay, silt, and sand) than they were in coarse-sediment streambeds (usually sand with some fine gravel). In relation to their fixation by coarse sediment, chromium-51 and scandium-46 showed a greater affinity for fixation by fine sediment than did zinc-65 or cobalt-60, especially at Pasco, Wash., where respective chromium-51 and scandium-46 concentrations in the fine-sediment part of the streambed averaged 8.9 and 7.4 times greater than in the coarse-sediment part of the streambed. Average concentrations of zinc-65, scandium-46, cobalt-60, and chromium-51 in surficial sediment at Vancouver, Wash., during 5- or 8-month periods in 1965 were 2, 1, 1, and 3–5 percent, respectively, of comparable concentrations at Pasco, Wash. Concentrations in either coarse-sediment or fine-sediment beds were not significantly different (95 percent confidence level) over relatively long distances along the river.

The stratigraphic distribution of radionuclides varied considerably. Differences in the stratigraphic distribution of radionuclides were distinguishable between coarse sediment of the main channel and fine sediment of secondary channels and shallow areas. Radionuclides tended to be distributed equally throughout relatively great depths (more than 60 inches, 1.5 m, in some places) in sand beds of the main channel. The uniform distributions of radionuclide concentration in sand beds was attributed to the mixing of the sediment by the downstream migration of dunes found there. Radionuclide concentrations in fine-sediment beds were highest at the surface, or a few inches below, and usually attenuated to insignificant values within the upper 12 inches (0.3 m) of the streambed.

Monthly mean radionuclide inventories of chromium-51, zinc-65, cobalt-60, manganese-54, antimony-124, cobalt-58, scandium-46, and iron-59 in the Pasco-to-Vancouver reach were determined for the period January 1964 through September 1966 from estimated initial storages of radionuclides and observed radionuclide discharges at Pasco and Vancouver, Wash., during the period. Monthly-mean radionuclide inventories generally decreased linearly with time. Seasonal variations of zinc-65, antimony-124, manganese-54, and cobalt-60 inventories were small; inventories of these radionuclides were maximum in spring and minimum in summer-early fall. Seasonal variation of chromium-51 inventories was large; maximums during October-December were five to six times greater than minimums in June or July; whereas, March-April maximums were not much greater than February-March minimums. Iron-59 and scandium-46 inventories seasonally varied considerably less than did chromium-51 inventories. Cobalt-58 inventories did not vary seasonally.

The mean inventory of five radionuclides in the streambed from Hanford Reservation, Wash., to Longview, Wash., in 1965 was estimated to be 37,100 curies. This quantity was determined by adjusting inventories estimated from data collected in a different reach during each of several reconnaissance surveys; the inventories were adjusted for seasonal variations and trends as indicated by the monthly inventories computed from radionuclide-discharge data. Chromium-51 contributed about 60 percent, zinc-65 about 34 percent, and cobalt-60, scandium-46, and manganese-54 each about 2 percent of the 37,100 curies. Approximately 40 percent of the inventory was in the Pasco-to-McNary Dam reach of the river; another large portion (52 percent) of the inventory was in the sediment-depositing reaches below The Dalles Dam. The remaining 8 percent of the inventory was located in the thin sediment deposits in The Dalles Reservoir and two relatively long armored-streambed reaches.

A total of 28,900 curies was estimated to have accumulated in the streambed between the reactors and the ocean in June 1965: 8,700 curies in the estuary (Hubbell and Glenn, 1973) and 20,200 curies in the river. Nearly equal amounts (13,000 curies) of zinc-65 and chromium-51 were accumulated in the streambed of the whole reach; however, much less zinc-65 than chromium-51 was accumulated in the estuary bed, whereas the reverse was true for the riverbed. The predominance of chromium-51 over zinc-65 in the estuary bed may indicate less seasonal variation in radionuclide inventories—especially chromium-51 inventory—in the estuary than in the river. Also, the riverbed rather than the estuary bed was probably the principal source of particulate radionuclides transported to the ocean during high flows in June.

REFERENCES

Glenn, J. L., 1973, Relations among radionuclide content and physical, chemical, and mineral characteristics of Columbia River sediments: U.S. Geol. Survey Prof. Paper 433–M, 52 p.

Haushild, W. L., Stevens, H. H. Jr., Nelson, J. L., and Dempster, G. R., Jr., 1973, Radionuclides in transport in the Columbia River from Pasco to Vancouver, Washington: U.S. Geol. Survey Prof. Paper 433–N, 43 p.

Hembree, C. H., Colby, B. R., Swenson, H. A., and Davis, J. R., 1952, Sedimentation and chemical quality of water in the Powder River drainage basin, Wyoming and Montana: U.S. Geol. Survey Circ. 170, 92 p.

Hubbell, D. W., and Glenn, J. L., 1973, Distribution of radionuclides in bottom sediments of the Columbia River estuary: U.S. Geol. Survey Prof. Paper 433–L, p. L1–L63.

Hydrology Subcommittee, Columbia Basin Inter-Agency Committee, 1962, River mile index, main stem Columbia River: 17 p.

Kelley, J. C., and Whetten, J. T., 1969, Quantitative statistical analyses of Columbia River sediment samples: Jour. Sed. Petrology, v. 39, no. 3, p. 1167–1173.

Knebel, H. J., Kelley, J. C., and Whetten, J. T., 1968, Clay minerals of the Columbia River: A qualitative, quantitative, and statistical evaluation: Jour. Sed. Petrology, v. 38, no. 2, p. 600–611.

Nelson, J. L., 1965, Distribution of sediments and associated radionuclides in the Columbia River below Hanford, *in* AEC research and development report BNWL–36 3: Richland, Wash., Pacific Northwest Lab., p. 80–88.

Nelson, J. L., Perkins, R. W., Nielsen, J. M., and Haushild, W. L., 1966, Reactions of radionuclides from the Hanford reactors with Columbia River sediments: Internat. Atomic Energy Agency, Vienna, May 16–20, 1966, Symposium on the disposal of radioactive wastes into seas, oceans, and surface waters, Proc., SM–72/8, 22 p.

Nelson, J. L., and Haushild, W. L., 1970, Accumulation of radionuclides in bed sediments of the Columbia River between the Hanford reactors and McNary Dam: Water Resources Research, v. 6, no. 1, p. 130–137.

Perkins, R. W., 1965, An anticoincidence shielded-multidimensional gamma ray spectrometer: Nuclear Industry Methods, v. 33, p. 71–76.

Prych, E. A., and Hubbell, D. W., 1966, A sampler for coring sediments in rivers and estuaries: Geol. Soc. America Bull., v. 77, no. 5, p. 549–556.

Prych, E. A., Hubbell, D. W., and Glenn, J. L., 1967, New estuarine measurement equipment and techniques: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., v. 93, no. WW2, Proc. Paper 5219, p. 41–58.

Sayre, W. W., and Hubbell, D. W., 1965, Transport and dispersion of labeled bed material, North Loup River, Nebraska: U. S. Geol. Survey Prof. Paper 433–C, 48 p.

U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1941, Methods of analyzing sediment samples, *in* A study of methods used in measurement and analysis of sediment loads in streams: St. Anthony Falls Hydraulic Lab., Minneapolis, Minn., rept. 4, 203 p.

———1943, A study of new methods for size analysis of suspended-sediment samples, *in* A study of methods used in measurement and analysis of sediment loads in streams: St. Anthony Falls Hydraulic Lab., Minneapolis, Minn., rept. 7, 102 p.

———1957a, The development and calibration of the visual-accumulation tube, *in* A study of methods used in measurement and analysis of sediment loads in streams: St. Anthony Falls Hydraulic Lab., Minneapolis, Minn., rept. 11, 109 p.

———1957b, Some fundamentals of particle-size analysis, *in* A study of methods used in measurement and analysis of sediment loads in streams: St. Anthony Falls Hydraulic Lab., Minneapolis, Minn., rept. 12, 37 p.

———1966, Catalog instruments and reports for fluvial sediment investigations, *in* A study of methods used in measurement and analysis of sediment loads in streams: St. Anthony Falls Hydraulic Lab., Minneapolis, Minn., rept. M. 14 p.

Waugh, A. E., 1943, Elements of statistical methods: New York, McGraw-Hill, p. 267–349.

Whetten, J. T., and Fullam, T. J., 1967, Columbia River bed forms: Internat. Assoc. Hydraulic Research Conf., Fort Collins [Colorado], 12th, Proc., v. 1, p. 107–114.

BASIC DATA

TABLE 10.—*Radionuclide concentrations and particle-size distributions of surficial-sediment samples and gross-gamma count rates of in-place sediment of the Columbia River*

Date	CRM[1]	Number of samples	Water depth (ft)[2]	Concentration (picocuries per gram)					In-place count rate (counts per minute)	Particle-size distribution (percent in class)			
				Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}		<0.004 mm	0.004–0.062 mm	0.062–0.50 mm	>0.50 mm
McNary Reservoir													
1965													
Sept. 5	318.8	1	42	226	60.3	3.38	8.59	5.40	10,600	0	1	98	1
		2	56	574	200	11.3	20.8	13.2	41,800	2	11	87	0
		3	34	1,510	408	27.4	68.9	28.0	17,700	1	4	22	73
Sept. 4	317.2	1	12	411	120	5.36	22.6	9.46	59,100	2	13	85	0
		2	55	220	133	10.4	10.8	8.11	89,000	0	0	100	0
		3	41	323	433	17.6	33.8	22.4	363,000	5	22	73	0
		4	18	561	741	31.8	67.2	15.4	277,000	6	41	53	0
Sept. 5	315.5	1	13	320	80.7	2.88	8.02	1.5	10,000	4	30	66	0
		2	22	657	135	3.11	21.0	4.69	18,300	19	76	5	0
		3	23	751	150	3.65	27.1	6.26	13,900	18	73	9	0
		4	10	81.9	50.4	2.61	2.61	4.10	3,900	0	0	100	0
		5	29	611	256	13.4	23.8	13.6	23,100	2	12	86	0
		6	57	339	230	15.3	16.6	14.9	20,500	0	0	100	0
Sept. 4	314.0	1	12	377	31.1	.45	8.02	1.98	32,500	8	66	7	19
		2	32	960	144	3.24	43.4	6.26	62,000	10	89	1	0
		3	70	1,050	202	4.60	57.3	7.26	53,600	12	85	3	0
		4	43	604	136	4.28	29.5	10.9	130,000	10	81	9	0
		5	22	370	615	14.7	53.2	19.7	197,000	16	61	23	0
Sept. 4	310.5	1	21	204	94.1	2.34	11.5	3.56	74,800	5	53	42	0
		2	41	558	1,600	31.6	185	38.1	404,000	16	67	17	0
Sept. 4	304.9	1	25	116	127	3.42	10.9	5.09	110,000	----	----	----	----
		2	55	1,640	673	13.6	112	21.7	259,000	12	75	13	0
		3	48	1,170	380	16.6	62.6	3.42	177,000	1	10	89	0
		4	84	552	232	4.67	46.4	7.34	102,000	38	55	7	0
		5	17	141	384	13.7	28.4	9.15	179,000	11	51	38	0
Sept. 4	301.7	1	34	386	228	12.0	21.4	5.95	145,000	6	35	59	0
		2	78	869	885	17.2	94.7	45.4	474,000	11	60	29	0
		3	65	303	611	16.2	47.8	19.3	231,000	21	68	11	0
Sept. 4	298.4	1	48	986	507	9.78	59.5	13.6	255,000	18	80	2	0
		2	33	367	463	15.5	67.6	11.9	147,000	12	59	29	0
Sept. 4	296.2	1	85	563	590	13.6	67.6	20.1	318,000	26	69	5	0
		2	51	645	581	22.2	50.8	14.2	235,000	6	67	27	0
Sept. 3	294.2	1	14	483	503	11.9	69.3	12.7	188,000	16	79	5	0
		2	93	1,420	681	13.8	102	29.0	400,000	18	80	2	0
		3	----	342	266	12.2	20.2	8.47	130,000	7	34	59	0
		4	----	148	213	6.39	13.2	5.44	69,800	9	16	75	0
Sept. 3	292.6	1	15	89.2	102	3.78	6.43	3.29	71,800	8	28	64	0
		2	41	1,050	648	11.9	70.7	19.3	233,000	16	83	1	0
		3	81	704	557	20.4	50.0	18.7	145,000	17	59	24	0
		4	78	1,140	582	21.7	62.7	19.0	130,000	12	69	19	0
		5	13	295	198	8.47	17.3	5.04	75,400	5	23	71	1
		6	19	425	468	16.6	33.2	13.0	158,000	27	71	2	0
		7	37	112	86.9	5.94	6.06	2.25	69,200	5	13	76	6
		8	25	434	637	22.3	53.1	17.0	183,000	16	79	5	0
McNary Dam to the Dalles Reservoir													
1965													
Sept. 12	262.8	1	15	222	66.2	2.88	4.18	6.79	22,200	5	32	63	0
		2	19	105	24.6	2.21	2.79	2.66	47,700	15	75	10	0
		3	27	81.0	50.4	2.52	1.98	3.02	21,700	0	1	99	0
		4	14	150	78.3	3.20	5.58	5.36	30,300	0	7	93	0
The Dalles Reservoir													
1965													
Sept. 16	205.4	1	33	<2	91.4	3.20	7.03	6.43	88,000	1	3	96	0
		2	17	280	128	3.33	16.3	10.4	107,000	2	10	88	0
Sept. 16	201.0	1	15	189	61.2	1.62	8.73	4.50	34,100	10	78	12	0
		2	27	343	68.9	2.93	10.5	8.92	16,900	5	44	48	3
Sept. 16	198.4	1	75	102	156	4.32	20.4	8.02	125,000	6	38	56	0
		2	52	35.6	11.3	.32	.36	1.85	13,700	----	----	----	----
		3	28	102	29.8	.90	3.56	2.48	54,600	----	----	----	----
Sept. 14	194.4	1	27	274	200	4.19	22.2	7.66	126,000	6	67	27	0
		2	100	339	168	3.92	19.6	10.6	114,000	6	19	75	0
		3	31	288	117	3.47	13.4	5.85	110,000	9	77	14	0
Sept. 14	193.0	1	84	1,470	346	9.73	69.4	25.5	65,200	15	35	10	40
		2	28	180	142	2.93	12.6	6.98	94,900	8	62	25	5
Bonneville Reservoir													
1964													
Oct. 30	190.0	1	32	139	79.7	2.49	7.25	4.50	------	2	7	73	18
Oct. 31	186.6	1	86	119	53.6	1.83	4.04	3.09	------	0	1	78	21
Oct. 30	182.6	1	23	590	194	7.17	21.2	11.9	------	6	40	53	1
		2	55	73.8	25.0	.60	2.34	1.50	------	0	0	87	13
		3	57	126	54.9	1.87	5.58	3.04	------	0	1	64	35
		4	30	79.7	32.7	.96	3.13	1.50	------	0	1	91	8

Notes are at end of table.

TABLE 10.—*Radionuclide concentrations and particle-size distributions of surficial-sediment samples and gross-gamma count rates of in-place sediment of the Columbia River*—*Continued*

Date	CRM[1]	Number of samples	Water depth (ft)[2]	Concentration (picocuries per gram) Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	In-place count rate (counts per minute)	Particle-size distribution (percent in class) <0.004 mm	0.004–0.062 mm	0.062–0.50 mm	>0.50 mm
Bonneville Reservoir—Continued													
1965													
Sept. 17	182.5	1	48	74.8	19.6	.54	1.17	.90	19,900	0	0	73	27
1964													
Oct. 30	180.4	1	9	146	62.2	2.58	4.08	4.25	------	0	2	98	0
		2	60	53.2	26.4	.96	2.21	1.44	------	0	0	97	3
		3	16	63.5	14.6	.70	1.37	1.10	------	0	1	80	19
Oct. 31	178.9	1	15	240	69.8	2.12	10.8	5.86	------	6	50	44	0
Oct. 31	175.0	1	12	171	99.1	4.49	6.43	5.41	------	1	6	93	0
		2	34	64.8	35.4	1.05	2.59	2.87	------	1	1	98	0
		3	68	72.5	27.0	.92	2.37	1.73	------	0	1	92	7
		4	74	123	63.1	3.12	3.41	3.84	------	1	6	92	1
Nov. 2	169.1	1	12	162	127	4.12	7.92	4.38	------	7	31	62	0
		2	35	147	59.0	1.77	6.85	4.46	------	1	1	89	9
		3	33	261	111	6.98	6.58	6.12	------	7	48	45	0
Nov. 2	168.6	1	13	49.2	25.2	.66	1.89	1.47	------	0	1	97	3
		2	16	120	49.6	1.44	5.94	3.80	------	1	3	75	21
Oct. 29	168.2	1	11	90.9	40.0	1.24	4.21	2.79	------	1	1	96	2
		2	16	134	42.5	1.11	5.36	3.16	------	1	2	83	14
		3	21	54.9	22.1	.49	1.72	1.13	------	0	0	98	2
		4	58	59.0	26.1	1.11	1.88	1.33	------	0	0	99	1
Nov. 4	155.4	1	10	278	105	5.13	7.52	7.84	------	1	3	94	2
		2	40	68.8	30.2	.99	2.87	2.35	------	0	2	96	2
		3	16	643	176	8.92	15.7	10.1	------	3	26	71	0
Nov. 5	154.2	1	77	91.0	46.4	2.02	3.54	4.40	------	2	4	88	6
		2	16	364	124	4.86	11.7	7.78	------	9	65	26	0
Nov. 5	151.0	1	32	141	67.5	2.61	7.12	4.91	------	3	5	90	2
Bonneville Dam to Longview, Wash.													
1964													
Nov. 5	137.9	1	22	157	66.2	3.27	3.57	3.63	------	0	5	63	32
1965													
Apr. 21	131.8	1	10	77.7	65.1	1.49	1.22	1.23	22,400	3	29	68	0
		2	9	77.4	55.4	.45	.86	1.21	11,000	0	0	97	3
		3	14	21.8	29.2	<.5	<.5	.55	16,100	0	0	82	18
		4	34	47.8	42.7	.46	<.5	.80	18,200	0	0	98	2
		5	46	9.60	53.3	.59	.48	.79	27,100	0	0	72	28
Apr. 21	128.9	1	28	23.0	48.4	.59	.93	1.03	9,700	2	13	84	1
		2	45	43.1	72.2	.53	.48	.91	26,200	0	0	76	24
		3	26	9.68	40.2	.48	.56	.59	8,800	0	0	89	11
		4	14	42.7	80.8	.66	.58	1.19	16,600	0	0	82	18
		5	14	40.2	111	1.89	3.19	3.06	38,400	9	78	12	1
Apr. 21	125.1	1	12	1,150	69.9	.81	1.11	.84	11,200	0	4	94	2
		2	25	14.5	13.7	<.5	<.5	<.5	6,800	0	0	94	6
		3	33	66.4	47.6	<.5	<.5	.67	15,200	0	0	79	21
		4	17	105	129	1.37	4.91	3.34	38,700	4	42	54	0
		5	19	5.86	52.0	.78	.52	1.44	12,400	0	4	90	6
		6	10	127	171	1.78	6.94	3.80	32,500	7	68	25	0
Apr. 22	120.5	1	12	216	216	2.11	9.23	5.10	54,700	11	80	9	0
		2	12	64.6	29.8	.51	1.65	.99	9,800	0	3	78	'9
Apr. 23	[a]0.0	1	10	<5	1.06	<.5	<.5	<.5	1,800	0	1	94	5
		2	21	109	128	1.21	4.96	3.13	46,500	7	64	29	0
Apr. 23	114.8	1	25	32.0	17.2	<.5	<.5	.51	4,500	0	0	58	42
		2	17	28.8	17.9	<.5	.80	.54	10,500	8	33	58	1
Apr. 20	114.8	3	30	42.2	18.9	<.5	<.5	.51	8,500	0	0	34	66
		4	16	58.6	67.1	1.35	2.63	2.02	27,800	6	39	54	1
Apr. 19	110.2	1	21	42.8	72.5	.58	1.29	1.38	23,200	1	17	81	1
		2	32	32.1	33.4	<.5	<.5	.63	11,800	0	0	72	28
		3	31	16.9	42.9	<.5	.55	.55	4.400	0	0	91	9
		4	13	423	187	1.93	6.73	3.24	38,700	9	74	17	0
Apr. 19	106.6	1	32	36.4	5.29	<.5	<.5	<.5	3,500	0	0	97	3
		2	30	234	342	3.39	10.1	16.2	41,900	5	58	36	1
		3	32	34.7	10.0	<.5	<.5	<.5	4,900	0	0	81	19
		4	21	185	153	1.53	3.49	7.97	40,800	8	60	23	9
Apr. 24	[b]3.0	1	56	82.7	13.7	<.5	1.30	1.20	12,400	5	13	82	0
Apr. 24	[b]0.2	1	54	154	56.8	.89	3.06	1.64	27,600	1	8	88	3
Apr. 24	[b]0.0	1	60	220	202	2.04	10.6	5.48	41,500	2	26	68	4
Apr. 24	101.5	1	77	29.9	4.33	<.5	<.5	<.5	3,800	0	0	56	44
		2	52	18.1	25.5	<.5	<.5	.51	13,100	0	0	89	11
Apr. 24	97.8	1	48	19.5	6.02	<.5	<.5	<.5	3,500	0	0	25	75
		2	58	33.8	8.42	<.5	<.5	<.5	6,700	0	0	60	40
		3	34	27.1	19.0	<.5	.50	.64	10,500	0	0	44	56
		4	8	50.3	22.0	<.5	1.09	.72	10,100	0	2	84	14
Apr. 26	91.6	1	6	15.6	7.44	<.5	.53	<.5	5,900	0	0	56	44
		2	39	33.4	18.5	<.5	<.5	.50	7,400	0	0	75	25
		3	38	119	9.85	1.60	3.68	2.66	12,000	2	11	86	1
Apr. 26	87.5	1	15	211	112	1.96	5.95	3.60	34,900	3	22	70	5
		2	18	145	40.0	1.12	1.98	1.96	11,300	5	24	64	7
Apr. 26	[c]18.3	1	43	22.7	3.39	<.5	<.5	<.5	3,600	0	0	99	1
Apr. 26	[c]19.5	1	29	85.3	17.1	1.60	.50	1.19	6,600	7	14	74	5
Apr. 26	[d]0.1	1	18	59.1	32.0	.68	.97	2.00	14,400	3	11	68	18
Apr. 26	[d]0.2	1	21	29.9	4.93	<.5	<.5	<.5	2,600	0	0	51	49
Apr. 26	86.5	1	48	23.4	14.8	.49	.87	.61	9,800	21	43	36	0
		2	25	35.6	19.9	<.5	<.5	.61	8,400	0	0	94	6
		3	55	16.9	14.6	<.5	<.5	.48	4,900	0	0	96	4
Apr. 27	85.8	1	7	64.6	29.8	.51	1.65	.99	11,200	1	10	69	20

TABLE 10.—*Radionuclide concentrations and particle-size distributions of surficial-sediment samples and gross-gamma count rates of in-place sediment of the Columbia River—Continued*

Date	CRM[1]	Number of samples	Water depth (ft)[2]	Concentration (picocuries per gram) Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	In-place count rate (counts per minute)	Particle-size distribution (percent in class) <0.004 mm	0.004–0.062 mm	0.062–0.50 mm	>0.50 mm
				Bonneville Dam to Longview, Wash.—Continued									
1965													
Apr. 27	85.1	1	15	143	82.0	1.98	4.27	2.71	19,800	3	14	83	0
Apr. 27	84.5	1	20	83.7	55.6	1.01	3.69	1.84	48,200	6	36	57	1
Apr. 27	82.2	1	44	20.6	6.22	<.5	<.5	<.5	2,700	0	0	93	7
		2	44	37.1	15.5	<.5	<.5	.53	7,700	0	0	93	7
		3	52	15.4	12.9	<.5	<.5	<.5	6,400	0	0	80	20
Apr. 28	81.1	1	13	39.6	18.5	.50	.61	.72	4,500	3	4	21	72
Apr. 28	79.6	1	23	246	117	3.30	6.56	4.48	32,600	5	31	53	11
Apr. 28	78.0	1	50	35.6	16.0	<.5	<.5	.56	9,000	0	0	97	3
		2	45	150	109	1.38	5.27	3.41	40,300	1	7	53	39
Apr. 28	75.2	1	27	35.7	21.4	.45	.45	.54	11,100	0	0	91	9
		2	12	34.4	4.38	<.5	<.5	<.5	4,100	0	0	96	4
		3	50	23.4	22.4	.51	.46	.63	9,100	0	0	51	49
		4	29	248	130	1.56	8.48	4.27	30,400	9	57	32	2
		5	28	790	374	4.09	30.0	11.7	100,000	13	82	5	0
Apr. 28	71.6	1	48	17.3	8.20	.45	<.5	<.5	9,300	0	0	58	42
		2	48	35.0	19.9	<.5	<.5	.53	12,900	0	0	96	4
		3	28	46.4	23.2	<.5	<.5	.72	12,600	0	0	96	4
		4	18	31.1	25.5	.91	1.06	1.24	7,500	0	2	26	72
Apr. 29	68.8	1	13	407	210	3.01	14.4	7.09	67,700	7	50	43	0
		2	35	47.1	18.3	<.5	.54	.60	6,700	0	1	99	0
Apr. 29	67.9	1	26	44.6	18.5	.54	.56	.95	18,000	0	0	100	0
		2	50	31.5	13.7	<.5	<.5	<.5	8,100	0	0	52	48
		3	14	12.8	1.52	<.5	<.5	<.5	2,500	0	0	74	26
Apr. 30	67.7	1	50	254	133	1.40	7.72	3.20	------	----	----	----	----
Apr. 29	65.5	1	20	474	294	3.57	22.6	8.42	49,300	9	36	53	2
		2	38	447	202	3.21	2.76	8.83	5,700	0	0	84	16
		3	46	31.1	20.4	<.5	<.5	.68	6,600	0	0	69	31
		4	20	84.3	44.9	.73	2.91	1.89	18,800	0	4	96	0

[a]Sandy River.
[b]Willamette River.
[c]Multnomah Channel of Willamette River.
[d] Lewis River.

[1]Multiply by 1.61 to compute river kilometre.
[2]Multiply by 0.305 to compute water depth in metres.

TABLE 11.—*Radionuclide concentrations in selected sections of sediment cores from the Columbia River*

CRM[1]	Depth (in.)[2]	Concentration (picocuries per gram) Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}	Depth (in.)[2]	Concentration (picocuries per gram) Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}
							McNary Reservoir (9/7/65 to 9/11/65)									
325.8	0–1	275	125	18.4	10.0	8.1	8.11	2.2	9–10	----	6.4	5.3	<0.2	<0.2	18.5	3.5
	1–2	231	140	17.6	6.8	8.9	11.1	1.6	11–12	75	7.2	5.1	<.2	<.2	8.4	1.6
	2–3	1,200	48.5	12.7	<.2	2.5	3.6	10.5	13–14	----	3.6	1.3	[3].9	<.2	5.1	1.4
	3–4	1,150	57.3	14.8	<.2	2.1	5.4	15.6	15–16	243	19.5	4.1	<.2	<.2	8.2	3.2
	4–5	------	54.7	14.5	[3].9	1.0	10.1	3.9	17–18	----	12.2	3.0	[3].3	<.2	12.1	4.3
	5–6	748	36.7	10.7	<.2	<.2	8.5	16.5	20–22	<2	1.4	.6	<.2	<.2	1.6	<.2
	6–7	1,110	37.8	11.8	<.2	<.2	7.1	11.5	22–24	----	<.2	.7	<.2	<.2	1.5	2.2
	7–8	<2	5.0	2.7	<.2	<.2	4.1	.5								
315.4	0–1	2,060	45.3	1.8	3.1	2.3	2.7	17.7	7–8	----	1.2	1.3	<.2	<.2	6.4	2.7
	1–2	795	28.7	2.7	<.2	2.2	3.1	10.5	11–12	<2	.9	.3	<.2	<.2	1.5	<.2
	2–3	1,230	53.5	5.1	<.2	3.2	2.5	8.6	17–18	[3]18	1.0	.5	<.2	<.2	1.3	<.2
	3–4	53.2	71.7	6.2	.8	2.3	3.7	3.4	26–28	<2	.6	<.2	<.2	<.2	1.2	<.2
	4–5	------	21.0	5.0	.8	<.2	5.82	1.9	38–39	<2	.7	<.2	<.2	<.2	.8	<.2
	5–6	<2	7.9	2.7	<.2	<.2	1.7	1.0	45–47	----	<.2	.6	----	<.2	2.5	1.9
315.0	0–1	139	43.0	1.6	3.5	2.0	3.5	.5	7–8	101	100	9.8	<.2	2.6	5.4	4.1
	1–2	65.7	35.5	1.5	1.9	1.4	2.6	<.2	8–9	----	19.2	4.1	<.2	<.2	6.1	4.5
	2–3	488	117	4.2	13.2	4.7	6.0	2.8	10–11	5.0	.9	.4	<.2	<.2	1.5	.7
	3–4	940	185	5.5	100	6.9	13.7	7.5	12–13	19	.9	.4	<.2	<.2	.7	.2
	4–5	86.1	6.1	.7	.7	.2	2.3	2.2	18–20	<2	.5	<.2	<.2	<.2	<.2	<.2
	5–6	<2	8.6	.7	<.2	.6	1.3	.3	34–36	<2	.3	<.2	<.2	<.2	<.2	<.2
	6–7	------	90.6	7.3	2.1	2.2	9.5	4.5								
314.4	0–1	677	97.7	1.7	16.9	4.9	6.9	2.4	8–9	<2	<.2	<.2	<.2	<.2	<.2	<.2
	1–2	80.2	14.9	.5	1.4	.6	6.3	1.4	11–12	5	<.2	<.2	<.2	<.2	.2	.2
	2–3	36	1.9	<.2	<.2	<.2	.3	<.2	20–22	----	<.2	<.2	<.2	<.2	.2	.7
	3–4	14	2.9	<.2	<.2	.3	.3	<.2	22–24	<2	<.2	[3]6.0	<.2	.3	.4	<.2
	4–5	------	<.2	<.2	<.2	<.2	<.2	1.4	24–26	----	<.2	<.2	<.2	<.2	.3	.8
	5–6	<2	<.2	<.2	<.2	<.2	.2	<.2	46–48	<2	<.2	<.2	<.2	<.2	<.2	.4
313.9	0–1	1,490	37.8	.8	4.5	1.8	6.6	10.5	5–6	<2	.6	<.2	<.2	<.2	.6	<.2
	1–2	1,370	37.0	.7	3.9	1.9	2.8	12.5	6–7	<2	.3	<.2	<.2	<.2	.7	.5
	2–3	1,160	<.2	<.2	<.2	.3	<.2	8.9	7–8	<2	.4	<.2	<.2	<.2	.5	<.2
	3–4	<2	2.3	<.2	<.2	<.2	.9	1.1	8–14	<2	28.1	.9	<.2	.7	1.3	2.6

Notes are at end of table.

TABLE 11.—*Radionuclide concentrations in selected sections of sediment cores from the Columbia River*—Continued

CRM[1]	Depth (in.)[2]	Concentration (picocuries per gram)							Depth (in.)[2]	Concentration (picocuries per gram)						
		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}
McNary Reservoir (9/7/65 to 9/11/65)—Continued																
313.9	4–5	<2	12.3	<.2	<.2	.2	.7	.6								
312.1	0–1	1,130	381	7.7	88.5	12.3	28.2	14.3	10–11	----	32.0	11.7	<.2	<.2	12.4	5.2
	1–2	<2	55.6	1.1	1.5	2.4	2.2	1.5	11–12	[3]145	21.2	8.2	<.2	<.2	7.8	2.3
	2–3	<2	282	14.7	4.5	5.9	17.1	14.4	13–14	----	12.8	3.2	----	<.2	10.7	2.9
	3–4	<2	158	11.1	<.2	4.5	9.9	9.3	17–18	[3]7.2	.9	.3	<.2	<.2	.9	<.2
	4–5	------	242	18.6	<.2	4.0	24.8	15.1	32–34	[3]13.1	.6	.4	<.2	<.2	1.1	.3
	5–6	120	287	25.8	<.2	4.0	12.8	10.4	34–36	----	1.1	1.0	<.2	<.2	5.3	3.0
	6–7	------	211	22.8	<.2	2.6	25.4	12.7	38–40	----	2.3	1.3	<.2	<.2	6.8	1.0
	8–9	43.7	40.4	12.8	<.2	.5	5.4	3.0								
305.0	0–1	[3]2,910	[3]11.0	[3]<.2	[3]<.2	[3]1.1	[3].7	[3]45.4	5–6	<2	.5	<.2	<.2	<.2	<.2	.3
	1–2	110	26.6	.9	2.9	1.0	10.0	2.1	8–9	8.1	.3	<.2	<.2	<.2	<.2	.3
	2–3	472	192	3.5	17.2	4.6	6.4	3.1	11–12	<2	<.2	<.2	<.2	<.2	.9	7.3
	3–4	428	208	10.1	21.4	4.6	11.7	5.1	24–26	<2	<.2	<.2	<.2	<.2	<.2	<.2
	4–5	------	11.7	1.4	<.2	<.2	4.4	1.9	48–50	<2	<.2	<.2	<.2	<.2	<.2	<.2
304.9	0–1	200	135	3.0	12.4	3.6	4.6	3.4	24–26	----	101	15.6	----	2.7	16.1	5.5
	1–2	1,240	70.0	1.7	6.8	2.3	2.9	10.3	28–30	130	10.9	5.4	<.2	<.2	9.0	1.8
	2–3	564	436	10.9	47.6	14.7	222	27.3	34–36	----	14.3	2.4	<.2	<.2	9.6	3.2
	3–4	1,000	6.7	<.2	<.2	.8	.3	10.0	40–42	100	7.0	2.6	<.2	<.2	5.1	1.2
	4–5	------	20.4	.6	----	.5	2.4	2.4	46–48	----	<.2	.4	----	<.2	1.9	1.7
	5–6	<2	16.0	.4	<.2	.5	1.4	1.4	52–54	----	6.0	1.5	<.2	<.2	7.1	2.1
	9–10	------	1.4	.2	<.2	<.2	1.6	2.6	58–60	----	<.2	.4	<.2	<.2	1.7	1.8
	13–14	6.3	1.9	<.2	<.2	<.2	.6	.3	64–66	----	<.2	<.2	<.2	<.2	1.4	1.3
	18–20	23.0	4.8	.4	<.2	<.2	.7	1.1								
292.7	0–1	705	302	14.9	25.0	6.8	13.8	8.8	11–12	<2	2.1	<.2	<.2	<.2	<.2	<.2
	1–2	36.9	18.2	.9	<.2	.5	.9	.8	17–18	----	2.9	.5	<.2	.2	.4	1.2
	2–3	15.8	9.0	.6	<.2	.5	.5	<.2	18–20	<2	9.8	.9	<.2	.3	1.1	<.2
	3–4	<2	3.5	.3	<.2	.2	.2	<.2	20–22	----	3.6	.6	<.2	.4	<.2	1.4
	5–6	<2	3.4	.3	<.2	.2	<.2	.9	38–41	<2	2.3	<.2	<.2	<.2	<.2	<.2
	8–9	<2	2.9	<.2	<.2	.2	<.2	<.2								
292.7	0–1	417	201	5.6	15.4	3.5	6.3	4.9	5–6	<2	1.8	<.2	<.2	<.2	<.2	<.2
	1–2	322	225	7.2	20.5	4.2	19.9	7.3	8–9	<2	.9	<.2	<.2	<.2	<.2	<.2
	2–3	195	164	6.8	9.7	4.7	6.3	2.0	11–12	<2	.9	<.2	<.2	<.w	<.2	<.2
	3–4	164	117	8.6	4.2	2.8	6.6	2.7	22–24	<2	1.7	<.2	<.2	<.2	<.2	<.2
	4–5	50.9	2.6	.4	.3	<.2	.4	.4	34–36	<2	<.2	<.2	<.2	[3]<.3	<.2	<.2
292.6	0–1	773	231	12.4	17.8	6.7	16.3	7.4	5–6	1,410	448	14.6	44.3	16.2	21.0	15.1
	1–2	943	295	15.3	24.5	8.0	13.0	3.5	6–7	658	457	14.1	35.8	14.2	19.0	12.3
	2–3	913	310	15.4	36.4	7.8	22.8	7.3	7–8	338	379	21.0	16.4	9.9	16.0	15.0
	3–4	922	292	15.4	32.1	7.7	14.3	4.2	8–9	340	294	25.2	1.7	6.5	15.9	15.9
	4–5	777	281	12.7	21.0	7.8	13.1	10.7	9–15	100	12.2	3.6	<.2	<.2	5.0	1.8
The Dalles Reservoir (9/16/65)																
205.4	0–1	87.3	191	3.8	15.1	7.0	15.4	6.1	26–28	----	255	4.2	7.8	5.9	7.3	9.4
	1–2	<2	115	2.0	4.6	4.1	3.1	1.1	32–34	----	104	1.8	2.8	2.6	2.1	2.5
	2–3	<2	102	1.5	2.6	2.2	2.2	<.2	34–36	----	124	2.1	3.2	3.1	2.7	2.8
	3–4	<2	130	2.2	5.9	3.3	3.2	2.1	38–39	<2	210	3.3	15.5	5.3	2.3	3.2
	4–5	<2	184	3.4	11.0	5.4	5.5	4.1	47–49	----	181	3.1	4.6	5.1	4.6	2.6
	7–8	<2	141	2.2	4.1	3.6	4.3	4.1	51–53	----	114	1.9	3.0	2.6	4.4	3.6
	10–11	<2	150	2.4	4.5	4.2	2.7	2.2	57–59	<2	37.7	.6	.5	1.3	1.5	1.5
	14–15	------	124	2.0	4.5	3.2	3.9	4.7	65–67	----	10.6	.3	<.2	.5	1.4	1.5
	17–18	<2	244	3.8	8.2	7.2	9.0	4.5	72–75	----	35.3	3.8	.7	1.3	3.7	2.4
	24–26	<2	229	3.9	9.5	5.9	4.1	1.4								
194.6	0–1	42.8	244	2.8	6.8	6.3	3.6	4.0	10–11	----	79.7	1.0	.9	2.2	1.7	2.1
	1–2	<2	170	1.8	<.2	5.2	1.4	<.2	12–13	----	68.8	1.2	1.3	1.4	5.6	2.2
	2–3	<2	146	1.5	1.1	4.5	.5	.4	15–16	----	60.1	1.0	<.2	1.3	1.9	1.9
	3–4	<2	140	1.5	1.8	5.0	2.4	3.1	18–20	----	49.5	1.5	.9	2.1	1.2	1.6
	4–5	------	120	1.4	.5	3.2	4.1	2.5	24–26	----	52.6	1.2	.9	1.7	1.7	1.3
	5–6	<2	105	1.0	<.2	3.2	1.4	.5	28–30	<2	63.6	1.2	<.2	2.0	.9	<.2
	6–7	------	98.5	1.2	1.1	2.9	3.2	2.6	34–36	----	60.7	1.1	.5	1.6	1.7	1.2
	7–8	------	97.8	1.4	3.9	2.6	3.6	.9	38–44	----	67.1	.8	1.1	1.9	.8	2.3
	8–9	<2	88.4	1.2	<.2	2.4	.7	<.2								
Bonneville Reservoir (10/28/64 and 9/17/65)																
182.5	0–1	<2	17.8	0.4	<0.2	1.1	0.5	<0.2	8–9	<2	12.8	0.4	<0.2	0.9	0.2	<0.2
	1–2	<2	15.2	.3	<.2	.9	.3	<.2	11–12	<2	14.7	.3	<.2	.9	.4	<.2
	2–3	<2	14.5	.3	<.2	.7	.4	.4	13–14	----	14.6	.5	.9	.9	1.1	.4
	3–4	<2	13.3	.3	<.2	.8	<.2	<.2	14–20	----	11.3	.4	<.2	.5	.8	1.1
	5–6	<2	14.2	.4	<.2	.9	.4	<.2								
180.5	0–1	267	107	2.0	14.0	4.4	2.9	3.3	7–8	5.4	6.0	<.2	<.2	<.2	<.2	<.2
	1–2	12.2	10.3	1.3	<.2	.6	.4	<.2	12–13	<2	4.1	.5	<.2	<.2	<.2	<.2
	2–3	13.5	8.1	.5	<.2	.5	.3	.4	18–20	12.6	4.6	.2	.7	<.2	.2	.6
	3–4	121	56.9	1.1	7.9	3.3	3.9	5.9	22–24	4.1	3.9	.3	<.2	<.2	.2	.4
	4–5	25.2	6.6	.4	<.2	.3	.5	1.0	36–38	25.2	4.7	.3	<.2	<.2	.4	1.0
	5–6	15.8	6.6	<.2	<.2	.3	<.2	.6								
169.9	0–10	40.8	16.3	2.2	<1.1	.9	----	----	20–30	52.2	4.4	2.0	1.1	.5	----	----
	10–20	47.7	42.9	3.5	1.7	1.8	----	----								
168.7	0–1	<2	15.7	.3	.5	.7	.5	<.2	17–19	----	2.5	.2	<.2	<.2	4.1	6.2
	1–2	<2	9.6	<.2	<.2	.5	<.2	<.2	22–24	<2	2.1	<.2	<.2	<.2	1.9	2.7
	2–3	<2	11.6	<.2	<.2	.4	.3	.2	28–29	----	25.6	.9	<.2	.3	6.6	9.2
	3–4	<2	11.0	<.2	<.2	.5	<.2	<.2	29–31	----	22.0	.8	.2	<.2	1.9	1.4
	7–8	<2	10.1	.2	<.2	<.2	.4	.4	35–37	<2	3.2	.2	<.2	.3	<.2	.9
	14–15	<2	10.6	<.2	<.2	.4	.2	<.2	41–43	----	2.0	.4	<.2	<.2	<.2	.7
	16–17	------	7.7	<.2	1.0	<.2	.6	2.2	46–48	----	1.6	.4	<.2	<.2	.4	.9
168.7	0–10	16.4	17.4	1.3	1.3	1.1	----	----	26–34	14.1	8.1	.9	.9	.6	----	----
	10–18	<14	5.6	.6	<.7	.5	----	----	34–42	11.3	2.3	.7	.8	.5	----	----
	18–26	12.4	5.9	.6	.6	.5	----	----	42–48	<9	1.1	<.5	.6	<.5	----	----
168.6	0–17	48.2	9.0	<.5	.9	.8	----	----	27–37	35.9	7.3	<.5	.5	.5	----	----
	17–27	30.8	6.0	<.5	.7	<.5	----	----	37–42	14.7	12.5	<.5	<.5	.6	----	----

TABLE 11.—*Radionuclide concentrations in selected sections of sediment cores from the Columbia River—Continued*

CRM[1]	Depth (in.)[2]	Concentration (picocuries per gram)							Depth (in.)[2]	Concentration (picocuries per gram)						
		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}
Bonneville Dam to Longview, Wash. (5/1/65 to 5/5/65; 9/20/65; 4/26/66 to 4/30/66)																
128.9	0–1	9.0	14.2	0.4	<0.2	0.3	0.2	<0.2	7–8	8.1	14.7	<0.2	<0.2	0.3	0.3	<0.2
	1–2	9.0	12.5	.3	<.2	.3	.2	.3	9–10	11.3	10.5	.3	<.2	<.2	.2	.4
	2–3	12.2	13.0	.2	<.2	.3	.3	<.2	11–12	9.0	8.0	<.2	<.2	.2	<.2	.5
	3–4	18.5	13.9	.4	<.2	.2	.3	.6	14–15	3.6	10.5	.2	<.2	.3	<.2	<.2
	4–5	2.7	15.7	.4	<.2	<.2	.4	.2	16–18	9.5	10.0	.2	<.2	<.2	.4	.3
	5–6	14.4	15.0	.4	<.2	.2	.3	<.2	18–24	<2	7.1	.3	<.2	.2	<.2	<.2
123.7	0–1	9.5	14.1	.3	<.2	.3	.3	<.2	9–10	16.7	13.7	<.2	.2	.3	<.2	.3
	1–2	11.7	13.5	.5	<.2	.3	.2	.5	11–12	8.1	14.8	.3	<.2	.4	.3	.3
	2–3	14.9	12.9	.4	<.2	.3	<.2	.6	14–15	<2	15.1	.3	<.2	.3	.3	<.2
	3–4	18.5	12.3	<.2	<.2	.3	.2	<.2	17–18	22.5	16.8	<.2	<.2	.3	.3	<.2
	4–5	15.3	12.3	.5	<.2	.2	.4	.3	22–24	15.3	18.4	.3	<.2	.5	<.2	1.0
	5–6	14.4	14.5	.4	<.2	.4	<.2	<.2	28–30	11.3	20.5	<.2	<.2	.5	<.2	.6
	7–8	7.2	13.2	.2	<.2	.4	<.2	.3	30–36	45.5	10.9	.2	<.2	<.2	.4	1.1
120.5	0–1	15.3	25.2	.5	<.2	.6	.5	<.2	11–12	10.4	12.1	.4	<.2	<.2	.3	<.2
	1–2	8.1	13.6	<.2	<.2	.3	<.2	<.2	14–15	5.0	12.5	.4	<.2	.3	.2	<.2
	2–3	8.1	12.7	.3	<.2	.2	.2	.7	17–18	3.2	12.1	.3	<.2	.3	<.2	.6
	3–4	7.6	12.9	.3	.2	.2	.3	.2	20–21	7.2	12.6	<.2	<.2	.3	.4	.5
	5–6	7.2	13.1	.3	<.2	.4	<.2	.3	23–24	8.6	11.8	<.2	.3	<.2	.5	.3
	8–9	<2	12.6	.3	.2	.4	<.2	.3	26–30	5.9	13.1	<.2	<.2	.4	<.2	<.2
114.9	0–1	90.9	102	2.9	2.4	2.0	----	----	6–7	40.2	39.4	.9	1.4	1.5	----	----
	1–2	27.5	25.4	.9	<.5	.6	----	----	7–8	41.9	125	2.8	3.9	2.1	----	----
	2–3	44.6	22.5	.8	<.5	.7	----	----	8–10	36.1	23.8	1.5	<.5	1.2	----	----
	3–4	20.3	20.4	.7	<.5	.6	----	----	10–12	<5	1.4	<.5	<.5	<.5	----	----
	4–5	66.2	36.9	.5	.7	.9	----	----	16–18	<5	.7	<.5	<.5	<.5	----	----
	5–6	46.4	59.4	.7	1.8	1.6	----	----								
114.8	0–1	12.6	10.6	.2	<.2	.3	<.2	.3	11–12	2.3	6.4	<.2	<.2	<.2	.2	<.2
	1–2	4.1	5.7	<.2	<.2	<.2	<.2	.4	14–15	<2	7.4	<.2	<.2	.2	<.2	<.2
	2–3	9.9	5.8	<.2	<.2	.3	<.2	.3	17–18	3.6	6.8	.3	<.2	<.2	<.2	.6
	3–4	14.4	6.3	<.2	<.2	<.2	<.2	.8	20–22	16.7	6.7	.3	.3	<.2	.4	<.2
	4–5	4.1	6.7	.3	<.2	.2	.2	<.2	26–28	<2	5.9	<.2	<.2	<.2	.4	.6
	5–6	3.6	6.4	.2	<.2	<.2	.3	<.2	30–32	17.6	2.5	<.2	<.2	<.2	<.2	<.2
	7–8	2.7	7.5	<.2	<.2	<.2	<.2	<.2	32–38	9.0	<.2	<.2	<.2	<.2	<.2	.5
	9–10	4.1	6.8	.2	<.2	<.2	<.2	<.2	38–44	6.3	<.2	<.2	<.2	<.2	<.2	<.2
[4]107.0	0–1	5.4	.5	<.2	<.2	<.2	<.2	<.2	7–8	4.5	<.2	.3	<.2	<.2	<.2	.3
	1–2	10.8	<.2	<.2	<.2	<.2	<.2	.6	9–10	5.0	<.2	<.2	<.2	<.2	<.2	.4
	2–3	8.6	<.2	<.2	<.2	<.2	<.2	.3	11–12	3.6	<.2	<.2	<.2	<.2	<.2	.3
	3–4	2.3	<.2	<.2	<.2	<.2	<.2	<.2	17–18	12.2	.8	<.2	<.2	<.2	<.2	.4
	4–5	10.4	<.2	<.2	<.2	<.2	<.2	.2	28–30	3.2	<.2	<.2	<.2	<.2	<.2	<.2
	5–6	<2	<.2	<.2	<.2	<.2	<.2	.5	40–42	<2	<.2	<.2	<.2	<.2	<.2	<.2
[5]107.0	0–1	18.5	33.6	1.5	.8	.8	.9	.3	9–10	8.6	3.4	.2	<.2	<.2	<.2	<.2
	1–2	14.9	13.3	.5	<.2	.4	.3	<.2	11–12	9.5	3.2	<.2	<.2	<.2	<.2	<.2
	2–3	9.0	5.0	<.2	<.2	<.2	<.2	.3	14–15	17.6	3.7	<.2	<.2	<.2	<.2	<.2
	3–4	5.0	4.2	<.2	<.2	<.2	<.2	<.2	17–18	8.1	3.9	<.2	<.2	<.2	<.2	.5
	4–5	5.4	4.1	<.2	<.2	<.2	<.2	<.2	20–22	<2	3.8	<.2	<.2	<.2	<.2	<.2
	5–6	6.8	3.5	<.2	<.2	<.2	<.2	.7	23–25	7.6	4.6	<.2	<.2	<.2	<.2	<.2
	7–8	11.3	3.7	.3	<.2	<.2	<.2	<.2	25–31	3.2	4.8	<.2	<.2	<.2	.4	<.2
[4]107.0	0–1	14.9	11.2	.5	.2	.3	<.2	.9	11–12	7.7	5.8	.4	<.2	<.2	<.2	.5
	1–2	11.7	8.3	.3	<.2	<.2	<.2	.6	19–20	<2	<.2	<.2	<.2	<.2	<.2	<.2
	2–3	9.5	7.0	.4	<.2	<.2	<.2	<.2	45–46	4.1	<.2	<.2	<.2	<.2	<.2	<.2
	5–6	4.5	7.5	<.2	<.2	<.2	<.2	<.2								
[5]107.0	0–1	7.6	6.4	.2	<.2	<.2	<.2	<.2	23–24	3.2	6.1	<.2	<.2	<.2	<.2	.5
	1–2	3.6	4.9	.3	<.2	<.2	<.2	<.2	29–30	20.2	7.5	<.2	.5	.3	<.2	.5
	2–3	8.1	3.8	<.2	<.2	<.2	<.2	<.2	35–36	10.8	8.4	<.2	.5	<.2	.2	<.2
	5–6	7.6	8.1	.2	<.2	<.2	.2	<.2	41–42	8.1	8.3	<.2	<.2	.2	<.2	1.4
	11–12	7.6	6.9	.2	<.2	<.2	<.2	1.0	46–47	1.8	8.3	<.2	<.2	<.2	<.2	1.0
	17–18	[3]34.2	6.1	<.2	.8	<.2	.2	1.3	47–48	2.3	10.8	<.2	.5	<.2	.2	1.4
106.6	0–1	134	90.6	1.0	3.5	1.4	----	----	17–18	25.6	8.9	.5	<.5	.5	----	----
	1–2	90.0	64.6	.7	1.9	1.4	----	----	20–21	31.5	8.5	.6	<.5	<.5	----	----
	2–3	------	69.8	.9	2.1	2.1	----	----	23–25	<5	6.9	<.5	.5	<.5	----	----
	3–4	104	154	1.5	6.1	4.1	----	----	27–29	35.1	7.7	.5	<.5	<.5	----	----
	4–5	------	78.2	1.1	4.2	2.5	----	----	29–31	30.6	8.1	<.5	<.5	----	----	----
	5–6	6.8	33.4	.8	1.7	1.0	----	----	33–35	39.6	8.9	.6	<.5	.5	----	----
	6–7	------	28.7	.9	2.7	1.7	----	----	35–37	<5	11.5	.7	<.5	<.5	----	----

TABLE 11.—*Radionuclide concentrations in selected sections of sediment cores from the Columbia River—Continued*

CRM[1]	Depth (in.)[2]	Concentration (picocuries per gram)							Depth (in.)[2]	Concentration (picocuries per gram)						
		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}		Cr^{51}	Zn^{65}	Co^{60}	Sc^{46}	Mn^{54}	Zr^{95} Nb^{95}	Ru^{106}
Bonneville Dam to Longview, Wash. (5/1/65 to 5/5/65; 9/20/65; 4/26/66 to 4/30/66)—Continued																
106.6	7–8	36.0	81.0	1.4	4.0	3.2	----	----	37–39	37.8	18.5	.9	<.5	.7	----	----
	8–9	------	64.1	1.6	3.5	3.4	----	----	41–43	41.9	27.8	1.4	<.5	1.2	----	----
	9–10	36.9	185	3.9	6.8	4.6	----	----	43–46	68.9	111	5.1	1.4	4.1	----	----
	11–12	13.5	50.6	1.8	2.1	1.4	----	----	46–52	8.1	38.7	2.9	<.5	.6	----	----
	13–14	38.2	16.1	.7	.5	.7	----	----								
101.5	0–1	50.0	26.9	.6	1.3	.8	.3	<.2	5–6	<2	<.2	<.2	<.2	<.2	<0.2	<0.2
	1–2	7.2	29.0	.6	.6	.5	.7	1.6	8–9	<2	<.2	<.2	<.2	<.2	<.2	<.2
	2–3	5.4	17.6	.5	<.2	.8	.2	<.2	18–20	4.1	<.2	<.2	<.2	<.2	<.2	.4
	3–4	6.7	<.2	<.2	<.2	<.2	<.2	<.2	37–38	3.2	<.2	<.2	<.2	<.2	<.2	<.2
	4–5	<2	<.2	<.2	<.2	<.2	<.2	<.2								
[6]1.8	0–1	<2	1.4	<.2	<.2	<.2	<.2	.3	8–9	6.8	1.3	<.2	<.2	<.2	<.2	.7
	1–2	2.7	1.1	.3	<.2	<.2	.3	<.2	14–15	<2	1.2	<.2	<.2	<.2	.3	.3
	2–3	4.1	1.4	.2	<.2	<.2	<.2	<.2	28–30	2.3	1.5	<.2	<.2	<.2	<.2	<.2
	3–4	<2	1.5	<.2	<.2	<.2	<.2	.3	42–44	7.2	1.4	.2	<.2	<.2	.4	.5
	4–5	8.1	1.1	.2	<.2	<.2	.2	.4	50–53	<2	1.1	<.2	<.2	<.2	<.2	<.2
	5–6	<2	1.4	<.2	<.2	<.2	<.2	1.0								
84.6	0–1	194	123	2.0	18.1	1.8	----	----	7–8	<5	1.0	<.5	<.5	<.5	----	----
	1–2	128	116	2.4	9.2	1.5	----	----	9–10	<5	<.5	<.5	<.5	<.5	----	----
	2–3	182	96.0	2.0	5.8	2.1	----	----	11–12	<5	<.5	<.5	<.5	<.5	----	----
	3–4	130	78.8	1.5	5.1	2.2	----	----	14–16	<5	<.5	<.5	<.5	<.5	----	----
	4–5	<5	32.2	1.2	3.3	1.2	----	----	22–28	<5	<.5	<.5	<.5	<.5	----	----
	5–6	11.3	2.5	.7	<.5	<.5	----	----								
83.6	0–1	24.8	18.4	.3	.3	.7	<.2	<.2	6–7	19.8	10.6	.3	.4	.4	<.2	.5
	1–2	15.8	11.4	.2	<.2	.5	<.2	<.2	14–15	12.6	11.4	<.2	<.2	.5	<.2	1.4
	2–3	13.1	11.2	<.2	<.2	.7	<.2	<.2	20–22	15.3	10.7	<.2	<.2	.4	<.2	<.2
	3–4	11.7	11.8	<.2	<.2	.5	<.2	.4	26–32	9.9	11.8	<.2	<.2	.5	<.2	.5
	4–5	11.7	11.6	.4	<.2	.4	<.2	.5	32–36	21.2	12.2	<.2	<.2	.5	<.2	<.2
	5–6	12.6	11.4	<.2	<.2	.5	<.2	<.2								
75.2	0–1	11.3	1.7	<.2	<.2	<.2	<.2	.8	5–6	4.1	.6	<.2	.5	<.2	<.2	<.2
	1–2	<2	1.1	<.2	<.2	<.2	<.2	.2	9–10	12.6	.6	<.2	<.2	<.2	<.2	<.2
	2–3	4.1	.7	<.2	<.2	<.2	<.2	.8	14–15	<2	.5	<.2	.2	<.2	<.2	.4
	3–4	<2	.9	<.2	<.2	<.2	<.2	<.2	17–23	5.0	3.0	.3	<.2	<.2	<.2	<.2
	4–5	4.1	.9	.3	<.2	<.2	<.2	<.2	23–25	9.0	2.7	.2	<.2	<.2	<.2	<.2
71.6	0–1	62.2	34.0	1.4	.9	.7	----	----	5–6	7.2	6.4	<.5	<.5	<.5	----	----
	1–2	16.7	10.8	<.5	<.5	.5	----	----	9–11	9.5	6.3	<.5	<.5	<.5	----	----
	2–3	32.4	6.9	<.5	<.5	<.5	----	----	13–15	7.7	5.5	<.5	<.5	<.5	----	----
	3–4	12.6	6.9	<.5	<.5	<.5	----	----								
69.1	0–1	145	110	3.7	5.7	2.4	----	----	9–10	<5	<.5	<.5	<.5	<.5	----	----
	1–2	32.4	75.8	5.4	1.7	1.2	----	----	11–12	<5	.7	<.5	<.5	<.5	----	----
	2–3	65.7	.2.9	4.3	.5	1.3	----	----	23–24	<5	.6	<.5	<.5	<.5	----	----
	3–4	15.8	24.0	5.0	<.5	<.5	----	----	34–36	<5	.6	<.5	<.5	<.5	----	----
	4–5	144	45.9	11.5	<.5	1.8	----	----	46–48	<5	<.5	<.5	<.5	<.5	----	----
	5–6	68.5	47.2	6.3	1.7	.9	----	----	58–60	<5	.5	<.5	<.5	<.5	----	----
	6–7	96.8	24.2	7.8	<.5	1.2	----	----	67–74	<5	.5	<.5	<.5	<.5	----	----
	7–8	10.8	9.5	4.1	<.5	.7	----	----								
67.6	0–1	204	105	1.6	6.2	----	----	----	10–11	20.7	103	3.3	4.5	4.4	----	----
	1–2	57.7	48.7	.9	2.9	1.7	----	----	24–25	<5	11.0	.8	<.5	.7	----	----
	2–3	84.7	60.8	1.1	3.2	2.2	----	----	36–38	6.3	10.2	2.5	.5	.5	----	----
	4–5	20.3	19.2	.7	.9	.8	----	----	48–50	<5	1.1	<.5	<.5	<.5	----	----
	6–7	7.7	8.2	.5	.5	.5	----	----	56–58	<5	1.8	.9	<.5	<.5	----	----
	8–9	<5	5.8	.5	<.5	.5	----	----								
66.7	0–1	9.9	6.3	.3	<.2	.4	<.2	1.1	4–5	2.7	4.6	.2	<.2	<.2	<.2	<.2
	1–2	8.6	3.9	.2	.5	<.2	.2	<.2	5–6	9.0	4.8	.3	<.2	.3	<.2	<.2
	2–3	2.7	4.6	.3	<.2	<.2	<.2	<.2	6–12	3.6	4.0	<.2	<.2	<.2	<.2	<.2
	3–4	13.1	4.7	.4	<.2	.3	<.2	.3	12–18	4.1	3.8	<.2	<.2	<.2	<.2	.5

[1]Multiply by 1.61 to compute river kilometre.
[2]Multiply by 2.54 to compute depth interval in cm.
[3]Concentrations designated as questionable by laboratory.
[4]Trough of sand dune.
[5]Upstream of crest of sand dune.
[6]Distance up Multnomah Channel of the Willamette River.

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