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RADIOACTIVITY TRANSPORT IN WATER--
CONTINUOUS RELEASE OF RADIONUCLIDES IN A SMALL SCALE ECOSYSTEM

Technical Report--21

to the

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by

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ABSTRACT

Model rivers were simulated in two channels of a research flume. The control channel of the model river system contained a typical bottom sediment and received a potable water supply. The second channel, in addition to bottom sediment, contained a lush community of rooted aquatic plants in one end and received water which was rich in phytoplankton. Both channels were subjected to a continuous release of ^{134}Cs and ^{85}Sr for periods up to thirty-five days. The distribution of the radionuclides in the bottom sediment, plants, algae and water was determined.

Under the conditions of the release, less than maximum permissible concentration, the radioactivity continued to increase on the surface of bottom sediments until a quasi-equilibrium level was reached at approximately 25 days after initiation of release. At this condition or saturation, the specific activity of bottom sediments associated with ^{134}Cs and ^{85}Sr approached 55 $\mu\mu c/cm^2$ and 3.34 $\mu\mu c/cm^2$ respectively, and sediment concentration factors were 275 ml/cm^2 and 85 ml/cm^2. In the case of rooted plants, quasi-equilibrium for ^{134}Cs (89 $\mu\mu$ c/gm of plant) and for ^{85}Sr (25 $\mu\mu$ c/gm of plant) was reached within two days. The plant weight was based on oven dried mass. Plant concentration factors averaged 400 and 600 ml/gm respectively for ^{134}Cs and ^{85}Sr. In the phytoplankton rich water, it was found that as much as 27% of the radioactivity of the water was actually contained on or in the phytoplankton. The rate of ^{134}Cs uptake by the phytoplankton was related to net photosynthetic oxygen production.

The experimentally determined parameters were applied to predictive models and these relationships were checked against some observed data.

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CONCLUSIONS

1. Under continuous release of radionuclides into an aquatic system, bottom sediment and plants will concentrate radioactivity until such time as an equilibrium state is reached. Plants reach equilibrium much faster than bottom sediments. In ^{134}Cs and ^{85}Sr, under identical conditions of flow, equilibrium was reached in less than 36 hours for plants as compared to about 30 days for the bottom sediment.

2. Radionuclides are extracted from the water phase and are concentrated by bottom sediments or aquatic plants at a rate which is directly proportional to the difference between the saturation concentration (concentration at equilibrium) and the concentration in sediments or plants at a given point in time.

$$\frac{dC}{dt} = K(GC_w - C)$$

where

K	= transfer rate coefficient
G	= concentration factor at saturation
C_w	= specific activity of the water at equilibrium condition
C	= specific activity of sediments or plants at time t

3. The transfer rate coefficients for plants were much higher than those for bottom sediments. Plant transfer rate for ^{134}Cs was 0.0293 hr^{-1} and for ^{85}Sr was 0.0378 hr^{-1}. In the case of sediments, the transfer rate coefficients for ^{134}Cs varied between 0.0014 hr^{-1} and 0.0018 hr^{-1} and for ^{85}Sr varied between 0.0010 hr^{-1} and 0.0013 hr^{-1}.

4. The amount of radioactivity per cm^2 of bottom surface (concentration factor) to the radioactivity per ml of water above the sediment is dependent in part on the radionuclide involved. The concentration factor of Lake Austin sediment ranged from 250 to 300 ml/cm^2 for ^{134}Cs and from 70 to 90 ml/cm^2 for ^{85}Sr.

5. The bottom sediments of Lake Austin have higher affinity for ^{134}Cs than ^{85}Sr, but the opposite is true in the case of aquatic plants. The concentration factor for ^{85}Sr and for ^{134}Cs in plants averaged 600 ml/gm dry weight and

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400 ml/gm dry weight respectively.

6. In a continuous release of ^{134}Cs and ^{85}Sr, wherein the specific activity remained relatively constant in the water phase, it was found that the following existed:

$$[C_{so} \text{ for } ^{134}Cs] = 26.2\ [C_{so} \text{ for } ^{85}Sr]^{0.66}$$

$$[C_p \text{ for } ^{134}Cs] = 6.18\ [C_p \text{ for } ^{85}Sr]^{0.76}$$

where

C_{so} = concentration of ^{134}Cs activity in $\mu\mu c/cm^2$

C_p = concentration of ^{85}Sr activity in $\mu\mu c$/gm oven dry weight.

7. Suspended phytoplankton contribute to the surface concentration of radionuclides on bed sediments. In the West channel suspended phytoplankton concentrations averaged about 20 mg/liter and this mass of plants resulted in transfer rate coefficients to bed sediments which were about 25% higher as compared to the East channel.

8. Suspended phytoplankton, unlike rooted plants, showed a higher concentration factor (CF) for ^{134}Cs than for ^{85}Sr. The CF for ^{134}Cs varied from 4,000 ml/gm to 13,000 ml/gm, while the CF for ^{85}Sr varied from 200 to 700 ml/gm. In the case of ^{85}Sr the CF on phytoplankton was about the same as the CF for rooted plants.

9. The uptake of ^{134}Cs by suspended phytoplankton in the flume varied from 12 $\mu\mu c$/liter in the early morning to approximately 50 $\mu\mu$ c/liter during the late afternoon. The uptake of ^{134}Cs by suspended phytoplankton followed a pattern similar to the diurnal cycle and photosynthetic oxygen production. A linear correlation was found to exist between the change in rate of ^{134}Cs uptake and the rate of photosynthetic oxygen production:

$$y = A + Bx$$

where

y = change in rate of concentration of ^{134}Cs, ($\mu\mu c$/liter/hr)/hr

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x = rate of photosynthetic oxygen production, mg/liter/hr

$A+B$ = constants

During a described 36-hour experiment, the equation of best fit (correlation coefficient = 0.953) was:

$$y = -.42 + 5.57x$$

10. The amount of ^{85}Sr uptake associated with suspended phytoplankton varied from 0.2 μμc/liter to 0.8 μμc/liter; however, no cyclical diurnal relationship was noted between photosynthetic oxygen production and the rate of uptake of ^{85}Sr.

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CHAPTER I

INTRODUCTION

The demand for electrical power in the past has grown at an exponential rate, roughly doubling every ten years. Generating capacity in this nation will increase from the present 325 million kilowatts capacity to approximately 1.5 billion kilowatts by the year 2000 (1).

The extent to which the environment will be affected and courses of remedial action can be determined by either experience or experimentation. Since the beginning of nuclear power development, safety to man and his environment has been of prime consideration. Highest standards of engineering practice and "fail safe" principles have been employed in reactor design and effluent standards have been set at conservative levels. As a result, no body of experience exists from which to deduce the spectrum of hazards involved under various degrees of accidental release, environmental reaction, and types and extent of remedial action. Likewise the threshold limits of controlled released can not be determined. Without experience, knowledge and logical decisions must depend upon controlled experimentation.

Experimentation on real rivers, while valuable, is not always practical. Limits are controlled by the actual physical, chemical and biological characteristics of the river and by safety considerations. On the other hand, experimentation in small scale ecosystems offers great flexibility. The experimentor can establish and control the parameters of his research. The results of experimentation in small scale ecosystems which simulate stream processes can be most helpful in giving a qualitative and quantitative insight into ecological responses to radioactive stress.

The objective of this series of investigations has been to develop a mathematical model which can be used to predict the behavior and transport of radionuclides in small scale ecosystems. The various facets of this research have been designed to determine the effects of specific environmental

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factors on transport, to estimate the uptake and release of radionuclides by bed sediments and plants, to establish the effects of organic and inorganic pollution loads on radionuclide movement and to relate all of these factors into a basic prediction transport model. Investigation included accumulation of field data obtained from river systems, laboratory tests, aquaria studies, and flume experiments. Various stages of this research have been completed and published in progress reports (2-21).

Further studies were needed to evaluate the long-term effects resulting from continuous releases of radionuclides and to verify the prediction model. Therefore, experimentation described in this report has been designed to include:

1. Continuous release of ^{134}Cs and ^{85}Sr in the flume for a period over one month to determine the dynamic balance of water, sediment and plants in an ecosystem.

2. Detailed studies and refinement of mass transfer coefficients for retention and release of ^{134}Cs and ^{85}Sr by sediments and biomass.

3. The mutual relationship between radionuclides in solution and suspended algae including the factors that influence this relationship.

4. The investigation of the locus and nature of contaminated sediments be areal distribution of radionuclides retained by bed sediments.

5. Refinement of the existing computer program and its use as a predictive tool for transport of radionuclides. A comparison of specific predicted activities in water, sediments and plants to the measured values are discussed.

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CHAPTER II

EQUIPMENT AND PROCEDURES

A series of experiments were conducted in a research flume in which small scale ecosystems (Model Rivers) were established. These ecosystems simulated river processes typical of the southwestern region including bottom sediment obtained from nearby Lake Austin and plants obtained from a stretch of the San Marcos River, approximately 30 miles south of Austin. Radionuclides were introduced into the ecosystems under continuous release conditions and the uptake and concentration of radioactivity by the various elements of the ecosystem were monitored. The experimental conditions are summarized in Table 2-1.

The Model River

The Model river in which the river processes were simulated consisted of a metal flume 200 feet in length, 2.5 feet in width, and 2 feet in depth. A center partition divided the flume into two identical channels each 1.25 feet in width, Fig. 2-1 and 2-2. Flow in the East channel consisted of potable water supplied from the municipal water system. Into the West channel, water rich in phytoplankton was pumped from a supply reservoir. Flow conditions were maintained by pumping the water from the reservoir into a constant head tank and controlling flow through a valved outlet at the bottom of the tank so as to maintain a predetermined head over a "V" notched weir at the inlet box. Water depth was controlled by setting the end gate or overflow weir to provide the depth desired. Approximately 4 inches of bottom sediment were placed in both channels. Plant growth was established in the last 50 feet of the West channel, stations W150 to W200.

Instrumentation consisted of dissolved oxygen probes (galvanic) to which stirring mechanisms had been attached to insure sufficient velocity across the face of the probe, thermistors, and pH meters. A dosing box Fig. 2-3 was designed and fabricated to control the radionuclide release.

In part of the experimentation oxygen was removed from the ecosystem in both channels from stations 100 to 200 using Na_2SO_3 as the reducing agent and cobaltous chloride as a catalyst. The method used in dosing the Na_2SO_3 is illustrated in Fig. 2-4. A nitrogen environment was maintained

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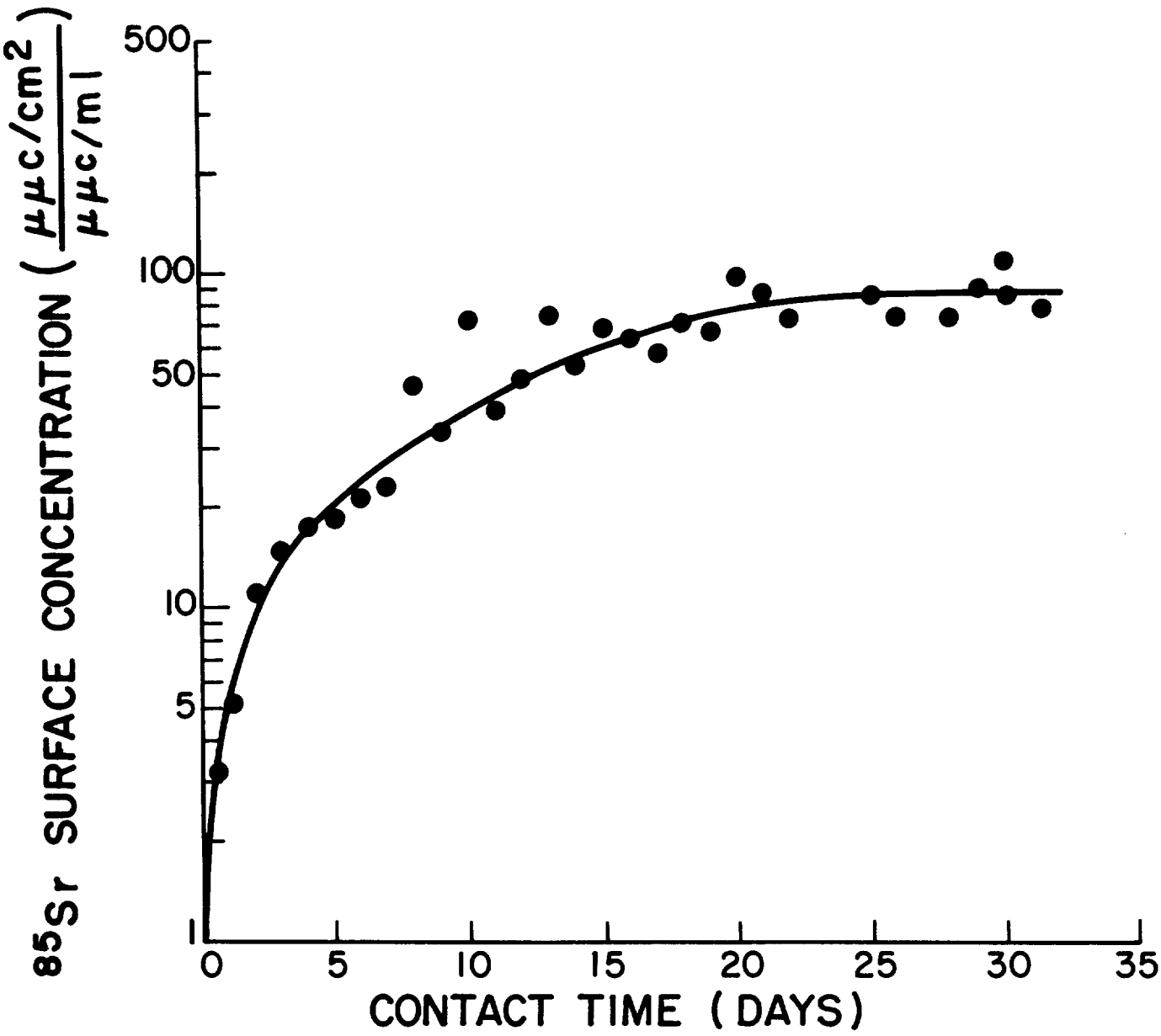

FIG. 3-4 AVERAGE SURFACE CONCENTRATION OF STRONTIUM-85 BY BED SEDIMENTS IN THE FLUME RELATED TO CONTACT TIME.

Table 2-1. Summary of Experimental Conditions

Variable	East Channel	West Channel
Water	Tap	Storage Reservoir
Sediment	Lake Austin	Lake Austin
Plants	None	From 150 ft - 200 ft
Flow		
Rate	10 l/min	10 l/min
Depth	6 inches	6 inches
Average Velocity	0.55 ft/min	0.55 ft/min
Radionuclides		
Cesium-134	2.16 μc/min	2.08 μc/min
Strontium-85	0.46 μc/min	0.44 μc/min
Dosing Rate	54 ml/min	52 ml/min
Release Period	35 days	21 days
Rhobamine "B"		
Dosing Rate	54 ml/min	52 ml/min
Concentration	0.80 mg/min	0.78 mg/min
Release Period	36 hours	36 hours

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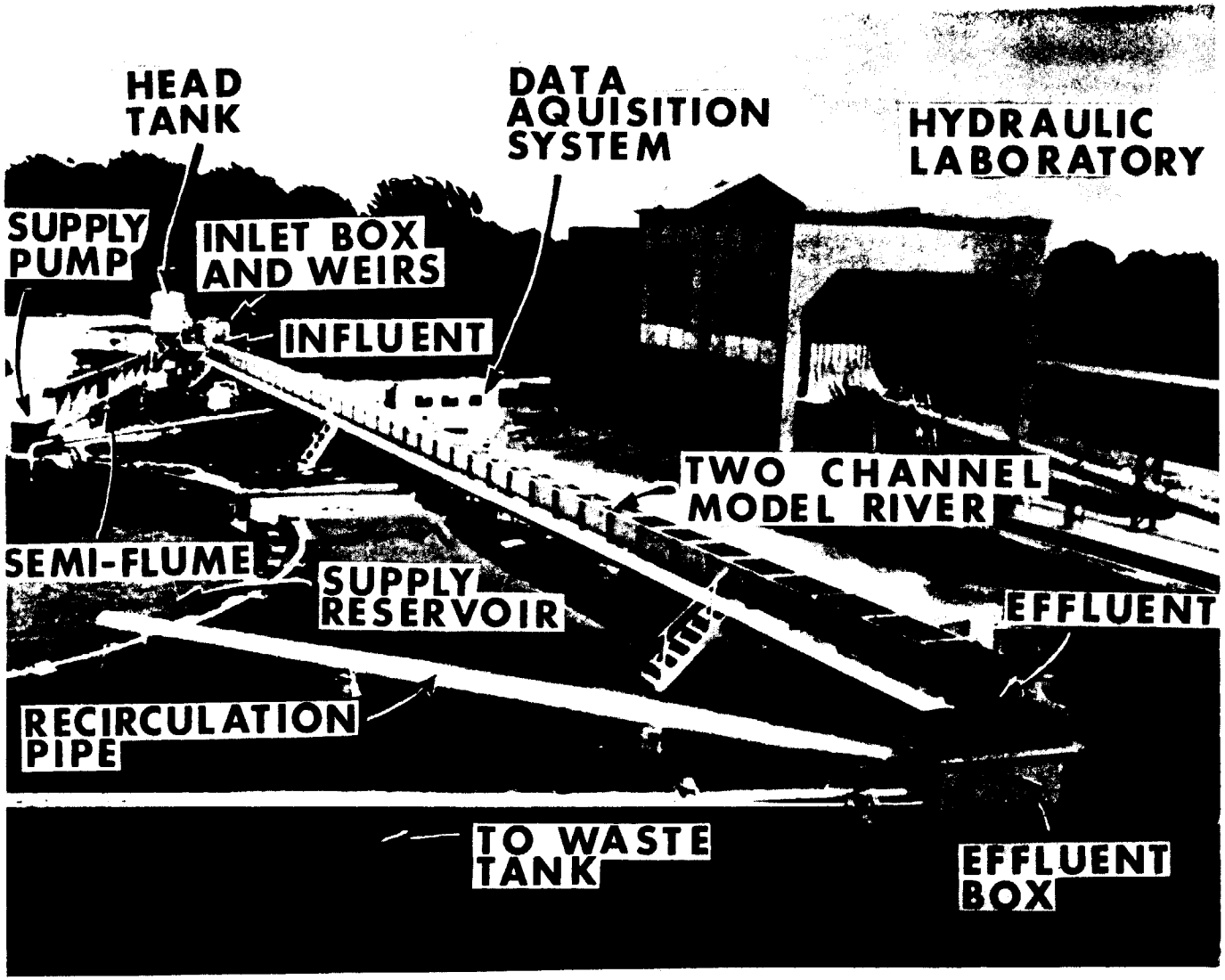

FIGURE 2-1. THE MODEL RIVER

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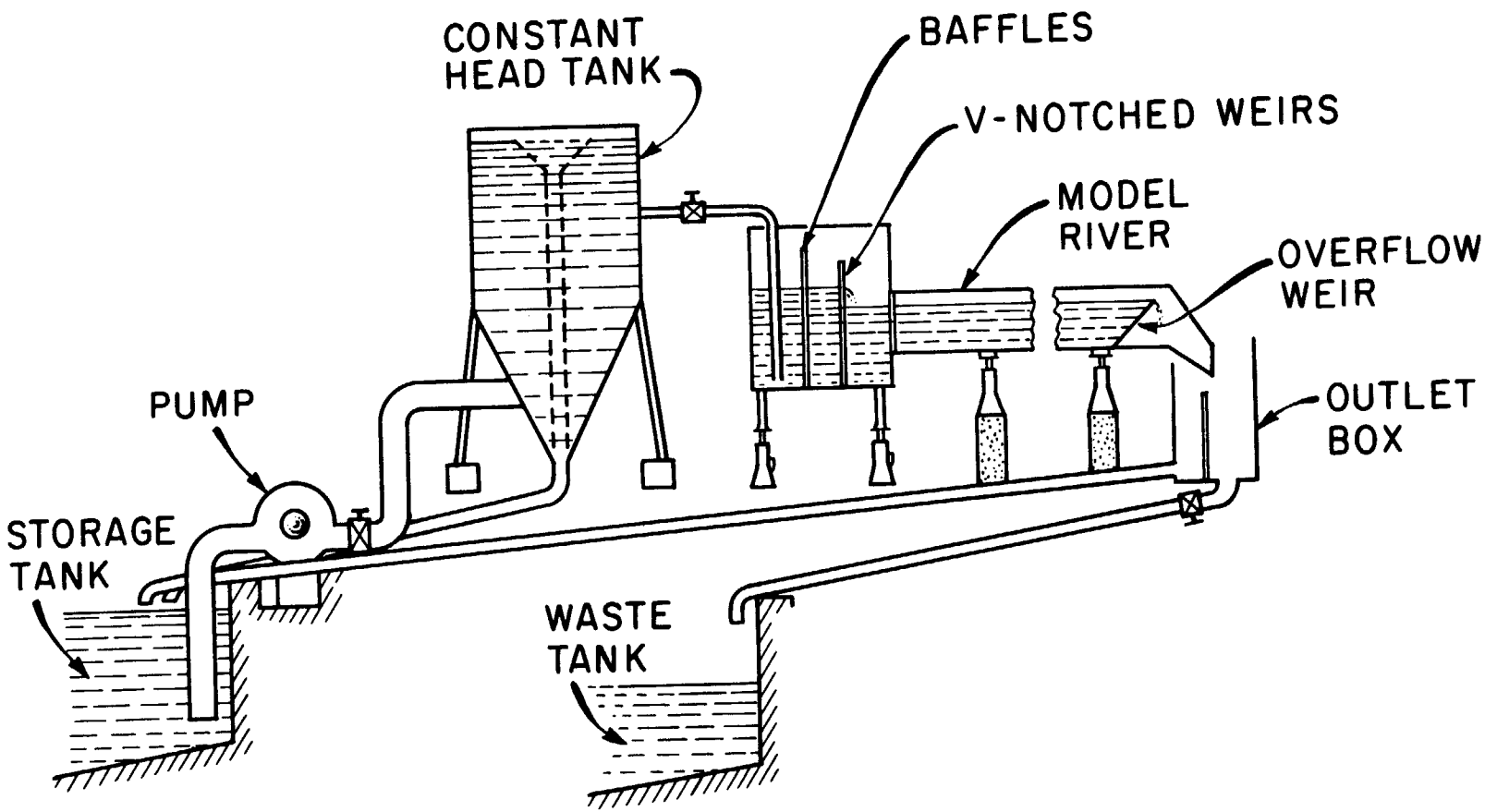

FIG. 2-2 SCHEMATIC OF MODEL RIVER SYSTEM

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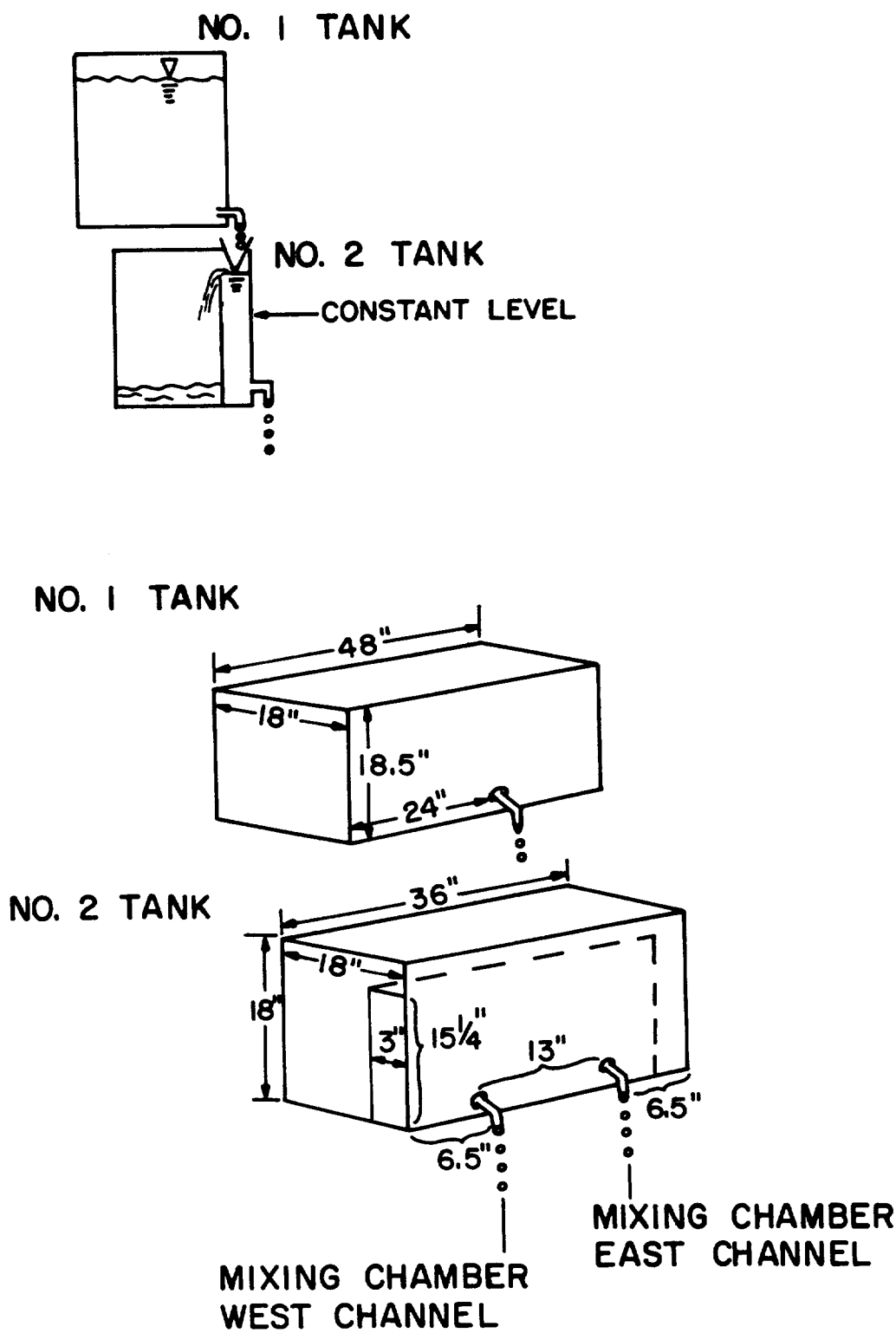

FIG. 2-3 CONSTANT FEED RADIO-NUCLIDE DOSING BOXES.

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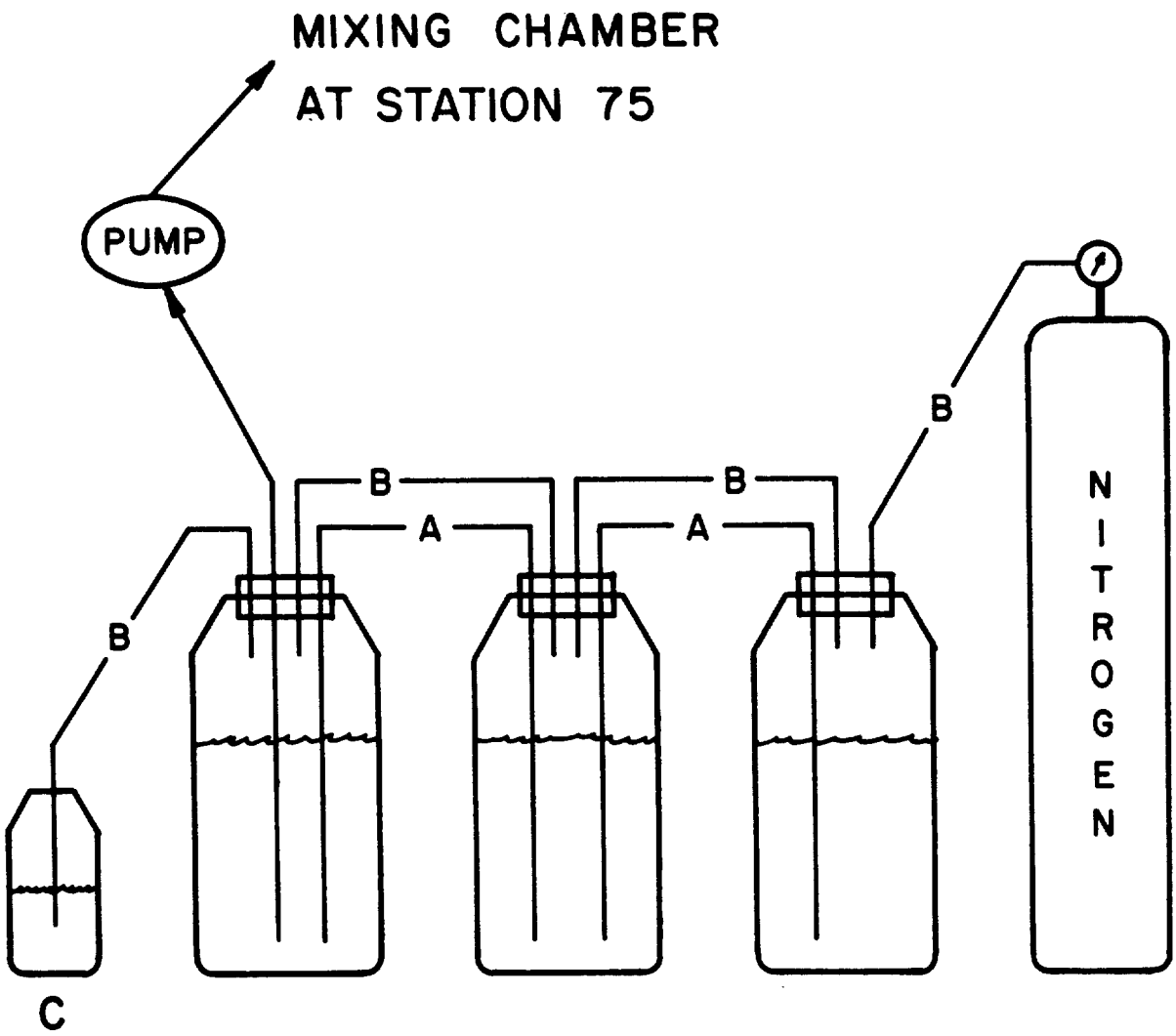

A = SIPHONS B = NITROGEN LINES

C = BUBBLING TO INSURE NITROGEN IS FLOWING

FIG. 2-4
METHOD USED TO DOSE FLUMES WITH SOLUTION OF SODIUM SULFITE AND COBALTOUS CHLORIDE.

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over the reducing solution to preserve its strength.

Acclimatization of Plants

In late February plants were brought from the San Marcos River and transplanted in the West channel, between stations W150 and W200, to provide a lush community typical of central Texas streams. The plants included Vallisneria, Potamogeton, Myriophilum, Utricularia, and Chara. Difficulties were encountered in growing the plants probably due to the considerable diurnal changes in water temperature that occurred in the West channel during the months of March and April. Also, during part of this period, the pump which supplied water from the reservoir to the West channel brokedown and as a result it was necessary to substitute potable water. The potable water had a pH of 10 which probably contributed to plant die off. Finally at the end of April the plants were harvested and replaced by fresh plants from the San Marcos River. The new growth was dominated at the beginning by Potamogeton and Vallesnaria. One month later, when the experiments were initiated the predominant species was Chara. Chara had not been noticeable when the plant community was established at the end of April.

Plankton Community

Before beginning the experimentation, the plankton community was studied to better evaluate the role of plankton in the transport of radionuclides. Accordingly, diurnal changes in numbers and species of organisms at various depths of the supply reservoir and at various locations along the flume were determined.

Samples from the supply reservoir were taken every three hours over a twenty-four hour period, May 14-15 at depths of 0.5, 1.5, 3.5, and 5.5 feet, measured from the water surface. The total count of organisms remained relatively uniform throughout the depth of the reservoir and averaged 3500 organisms/ml. Temperature and pH remained relatively constant within the entire depth of the reservoir throughout the twenty-four hour period. Maximum temperature differential between top (6" from surface) and bottom was less than 1°C, and maximum pH change was less than 0.40 units.

The species present in the samples taken from the West channel were the same as observed in the supply reservoir and distribution of total plankton population was fairly uniform. Diurnal changes in plankton count were

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measured at stations W0, W50, W100, W150, W195 (west channel, 0, 50, 100, 150 and 195 feet from inlet end) on May 15-16 before starting experimentation and on June 8-9, June 12-13 and June 26-28 during experimentation. Table 2-2 indicates the relative abundance by species in the West channel on the above days and Table 2-3 indicates the organism count and the experimental conditions prevailing at the time of sampling.

Dispersion Studies

During the initial two days of radioactivity release, Rhodamine B dye was also simultaneously released through the same dosing apparatus Fig. 2-3. Samples were taken at stations 2, 22, 52, 102, 152 and 197 feet from the inlet in both channels. The samples were prepared for counting in a multichannel analyzer for radioactivity and for Rhodamine B measurement in a Turner Fluorometer. In the case of radioactivity, corrections were made for decay, self-sorption and efficiency. In the case of Rhodamine B, corrections were made for temperature and decay by sunlight. Correction determinations were obtained by placing aquaria containing known concentrations of Rhodamine B alongside the flume at the same time as the experiment was being run and measuring the decrease in concentration with time.

In the previous experimentation on the flume (21) dispersion has been shown to be directly related to velocity. However wind and temperature may have an exaggerated effect on dispersion. Temperature effects may stimulate mixing in one case and in another case establish a stratified flow regime. Wind in all cases will stimulate mixing. Thermal effects could not be eliminated short of insulating the metal sides of the flume. Since the flume was not insulated, some error will result in the experimental determination of a longitudinal coefficient of dispersion and in the prediction of concentration at a location and point in time. Wind effects, however, were eliminated by covering the top of the flume with a clear plastic material.

Pollutional Stresses

The effects of pollutional stresses on the transport characteristics and equilibrium levels of ^{134}Cs and ^{85}Sr were studied. In one experiment spanning two days dissolved oxygen was lowered by the use of a solution of Na_2SO_3 and $CoCl_2.6H_20$ as a catalyst. The solution was injected in both East and West channels respectively at stations E75 and W75. Water samples, sediment samples and plant samples were taken every four hours and analyzed for radionuclides.

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Table 2-2. Relative Abundance of Organisms in the West Channel of the Flume

Order	Species	Observation Dates			
		May 14-15	June 8-9	June 12-13	June 26-29
A	Merismopedia	++*	++	+	+
Cyanopyceae	Gloeocapsa	++	++	++	+
(blue-green Algae)	Chrococcus	+++	+	-	-
	Oscillatoria	+	+	-	-
	Gloeotrichia	+	+	-	+
	Cyclotella	++	+++	+	+
	Stephanodiscus	++	++	++	+
B	Pinnularia	+	-	-	-
Bacillariaceae	Navicula	+++	++	++	++
	Cymbella	+	+	-	-
	Fragilaria	++++	++++	++	+++
	Tabellaria	++++	++++	+++	+++
	Campylodiscus	+	+	-	-
C	Chlamydomonas	+	+	-	-
Chlorophyceae	Staurastrum	+++	++	+	+
(green Algae)	Scenedesmus	+++	+	+	-
	Pediastrum	++	+	-	-
	Pachycladon	+	-	-	-
D	Euglena	++	+	-	+
Euglenaceae					
(animal)					

*Number of "+" indicates relative abundance
(the more "+" the greater the frequency)

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Table 2-3. Summary of Plankton Count in West Channel Under Different Conditions of Pollutional Stress

Date	Pollutional Stress	*Number of Organisms per ml			
		W0	W50	W100	W200
May 15	None	1790		1870	1900
June 8	Continuous Release of ^{134}Cs and ^{85}Sr	5190		4510	4990
June 9	Continuous Release of ^{134}Cs and ^{85}Sr	3500		5400	5300
June 12	Continuous Release of ^{134}Cs and ^{85}Sr with Na_2SO_3 added at W175	2300	2230	1410	490
June 26	Continuous Release of ^{134}Cs and ^{85}Sr with Milk Solution Added at W75	4000		5700	5000

*Average Count over 24-hour period

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In a second experiment, dissolved oxygen was reduced by biological activity. A solution prepared with powdered milk and sewage seed, obtained from an aeration tank of the local activated sludge treatment plant, was injected at stations E75 and W75. As in the previous experiment, samples were taken every four hours. The experiment was conducted for three days.

Areal Distribution of Radionuclides Along the Bed Sediment

Bed sediments concentrate radionuclides from overlaying water through sorption, deposition of suspended solids, movement of contaminated sediments and bottom organisms, and through precipitation resulting from chemical and physical interactions within the water. The cumulative efforts of these mechanisms could be visualized through a survey of the amount and distribution of radioactivity on the sediments. Radioactive contamination was expected to be on the surface of bottom sediment since migration through bed sediments is a slow process (18). Therefore, two core samples of diameter 7/8" were taken every foot along the entire length of the East channel after drainage of all the overlaying water. The upper 1/2" of the sediment cores was collected and composited in 10 core groups providing a total of 40 composite samples. Each composite sample represented a 5-foot length along the flume. The composite samples were processed, homogenized and prepared for counting and finally a profile of radioactivity or areal distribution of ^{134}Cs and ^{85}Sr was established for the flume sediments.

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CHAPTER III

RETENTION AND RELEASE OF RADIONUCLIDES

When radioactivity is released into streams,part of this radioactivity will be extracted by bed sediments, by suspended solids, and by the stream's biota. Some of this retained activity may subsequently be released and some may be stored for indefinite periods of time. The mechanisms involved in retaining and storing radioactivity include sorption, sorption and sedimentation, chemical precipitation, and biological uptake. However, the activity stored in a hydrological environment may be released by changes in dynamic, physical, and biochemical conditions. An increase in velocity will scour bottom sediment and return radioactivity to the flowing portion of the stream. Toxic material introduced into the stream will upset normal biological balance, will alter the numbers and types of aquatic flora and fauna and may cause sudden releases of stored radioactivity.

As a first step in understanding the role of bed sediments and biota in the retention and transport of radionuclides, steady-state conditions were considered. Described in this chapter are steady-state or quasi-steady-state experiments.

Bed Sediment

Cesium 134 and Strontium 85 were continually released at a uniform rate into both East and West channels of the flume. The East channel contained potable water flowing at the rate of 10 liter/min or a velocity of 0.44 ft/min with average depth of flow of 7 inches. Flow in the West channel was identical to that in the East channel except that the water was from the storage reservoir and was rich in phytoplankton. Cesium 134 was released into the East channel at the rate of 2.6 μc/min and into the West channel at 2.08 μc/min. Strontium 85 was released into the East at the rate of 0.46 μc/min and into the West at 0.44 μc/min. Six sediment samples were taken from each channel each day. The samples were distributed evenly along the channel length. Radioactivity associated with ^{134}Cs and ^{85}Sr was determined for each sample. Fig. 3-1 is a plot of the average concentration with time of ^{134}Cs by bed sediment at six stations along the flume. Fig. 3-2 is a similar plot for ^{85}Sr. Radioactivity increased with time to an equilibrium level after a period of approximately 25 days or equivalent to 100 times the hydraulic flow through time. In Figs. 3-1

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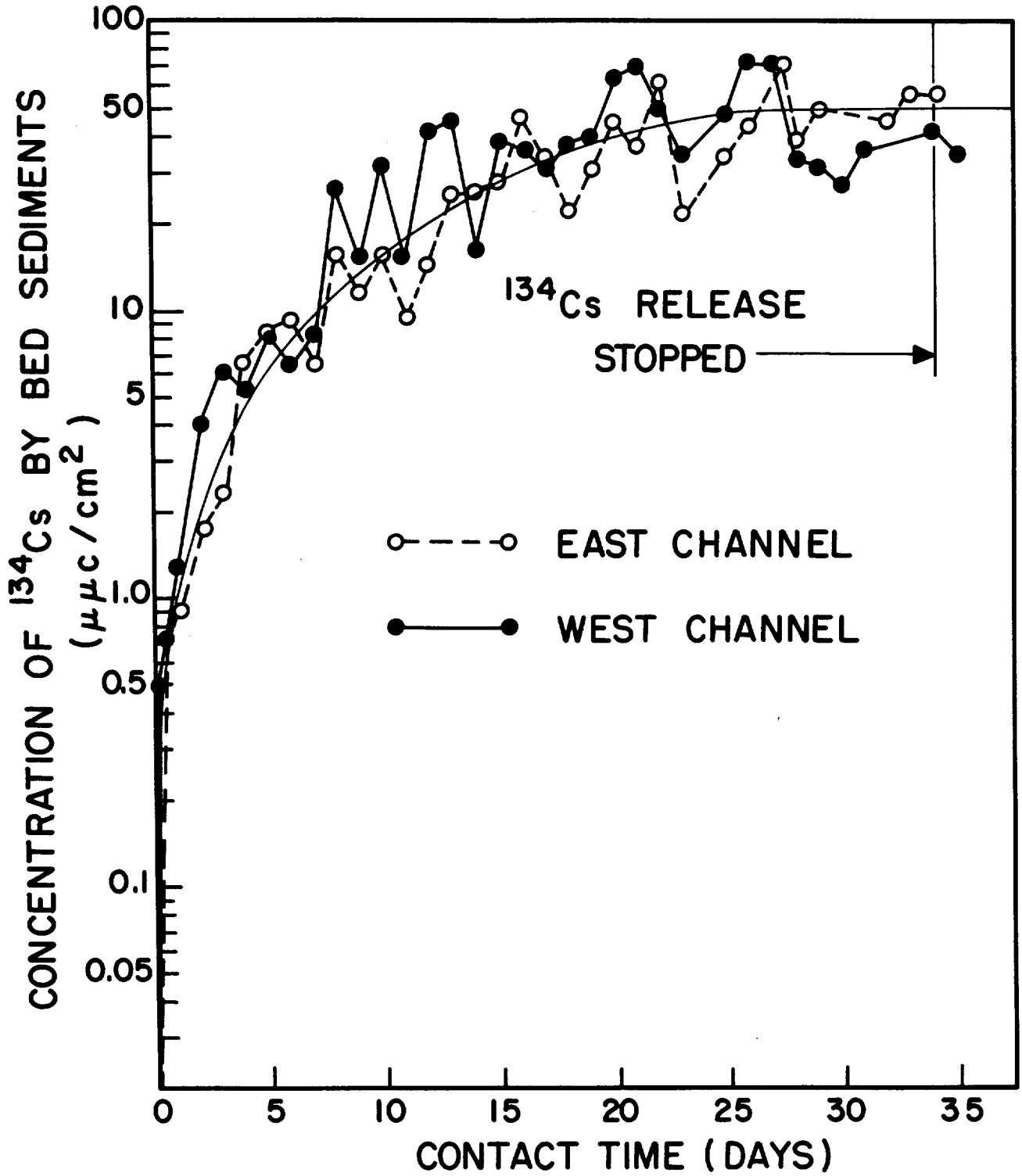

FIG. 3-1 CONCENTRATION OF CESIUM-134 BY BED SEDIMENTS IN THE FLUME RELATED TO CONTACT TIME (AVERAGE OF SIX STATIONS).

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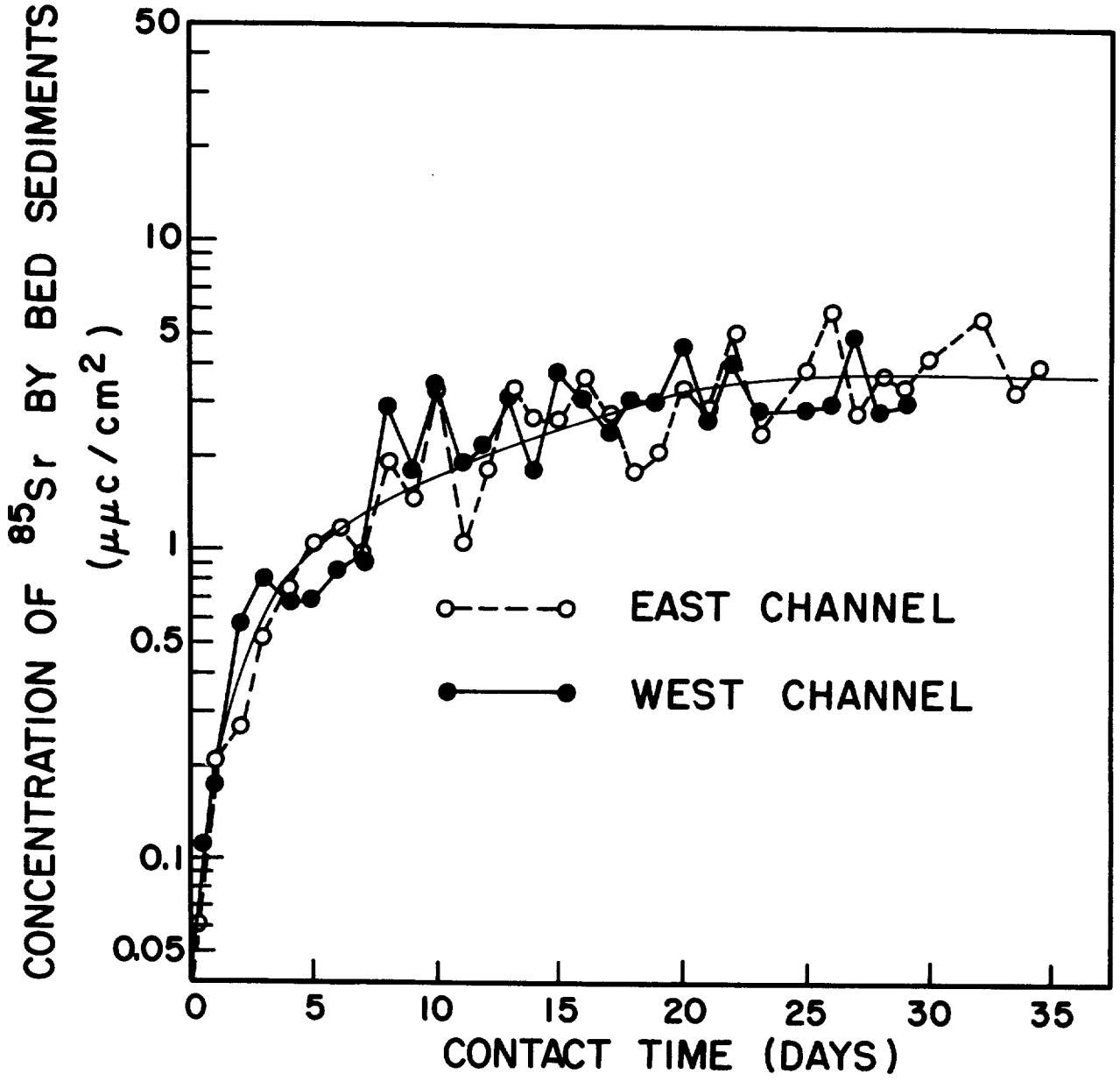

FIG. 3-2 CONCENTRATION OF STRONTIUM-85 BY BED SEDIMENTS IN THE FLUME RELATED TO CONTACT TIME (AVERAGE OF SIX STATIONS).

and 3-2, as might be expected, the bed sediment in the West channel exhibited higher concentrations of radionuclides than did the sediment in the East channel. The radionuclide activity in the West channel sediment was increased by sorption and biological uptake of phytoplankton that deposited and attached to the bottom sediment.

Sediment Surface Concentration Factors

A meaningful and useful expression for the radioactivity retained by the bed sediment is surface concentration factor (K_s). Surface concentration factor is the ratio of the radioactivity retained by the bottom sediment per cm^2 of bottom surface area to the radioactivity contained in one ml of water flowing in the system. Figs. 3-3 and 3-4 indicate the surface concentration factors (K_s) obtained in the experiment. The surface concentration factor at equilibrium in the case of ^{134}Cs was approximately 275 and for ^{85}Sr was approximately 85. In other words, each cm^2 of bottom area contained 275 times the radioactivity associated with ^{134}Cs and 85 times the radioactivity associated with ^{85}Sr than did each ml of flowing water. Bottom sediment had a greater affinity for ^{134}Cs than for ^{85}Sr.

Areal Distribution of ^{134}Cs and ^{85}Sr

At the end of the experiment, after 35 days of continuous release of radioactivity, water in the East channel was drained off. Two sediment cores were taken at each foot along the channel. The top half inch of each of ten cores was composited and prepared for counting. Each composited sample represented a 5-foot length of the channel. The concentration of ^{134}Cs and ^{85}Sr in each composited sample is shown in Fig. 3-5.

The uptake of both ^{134}Cs and ^{85}Sr follow the same general pattern. Radionuclide concentration was relatively higher at both ends of the channel with lower concentrations at the mid-section between 70 and 150 feet. Just why this distribution occurred can only be conjectured. It may have been caused by thermal stratification in which a higher velocity underflow resuspended and relocated deposited radioactivity. Thermal stratification and under-flow was noted in previous experiments (24). The area that had the highest concentration was from 150 feet to 180 feet. This could be due to the end weir effect. The end weir established a settling area which was

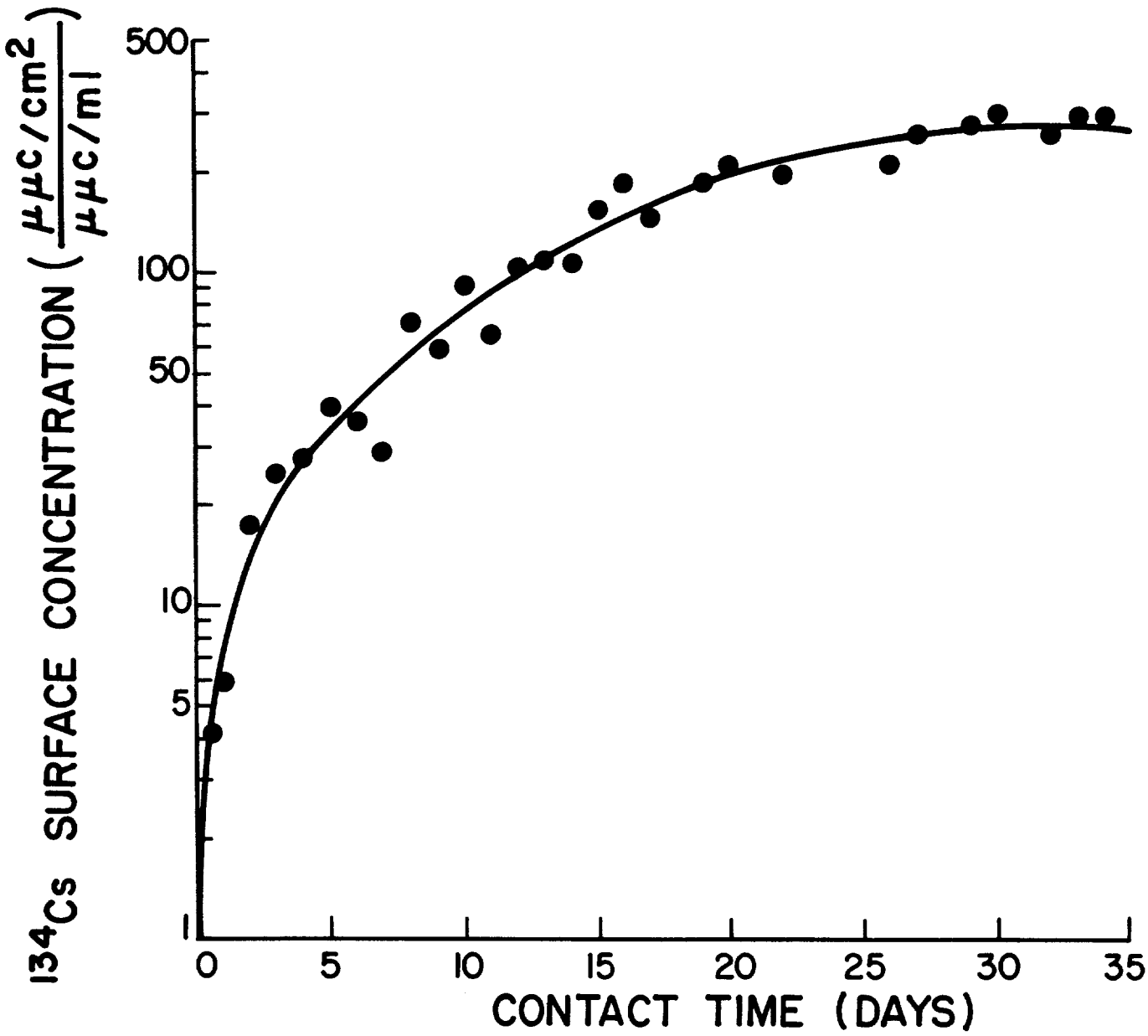

FIG. 3-3 AVERAGE SURFACE CONCENTRATION OF CESIUM-134 BY BED SEDIMENTS IN THE FLUME RELATED TO CONTACT TIME.

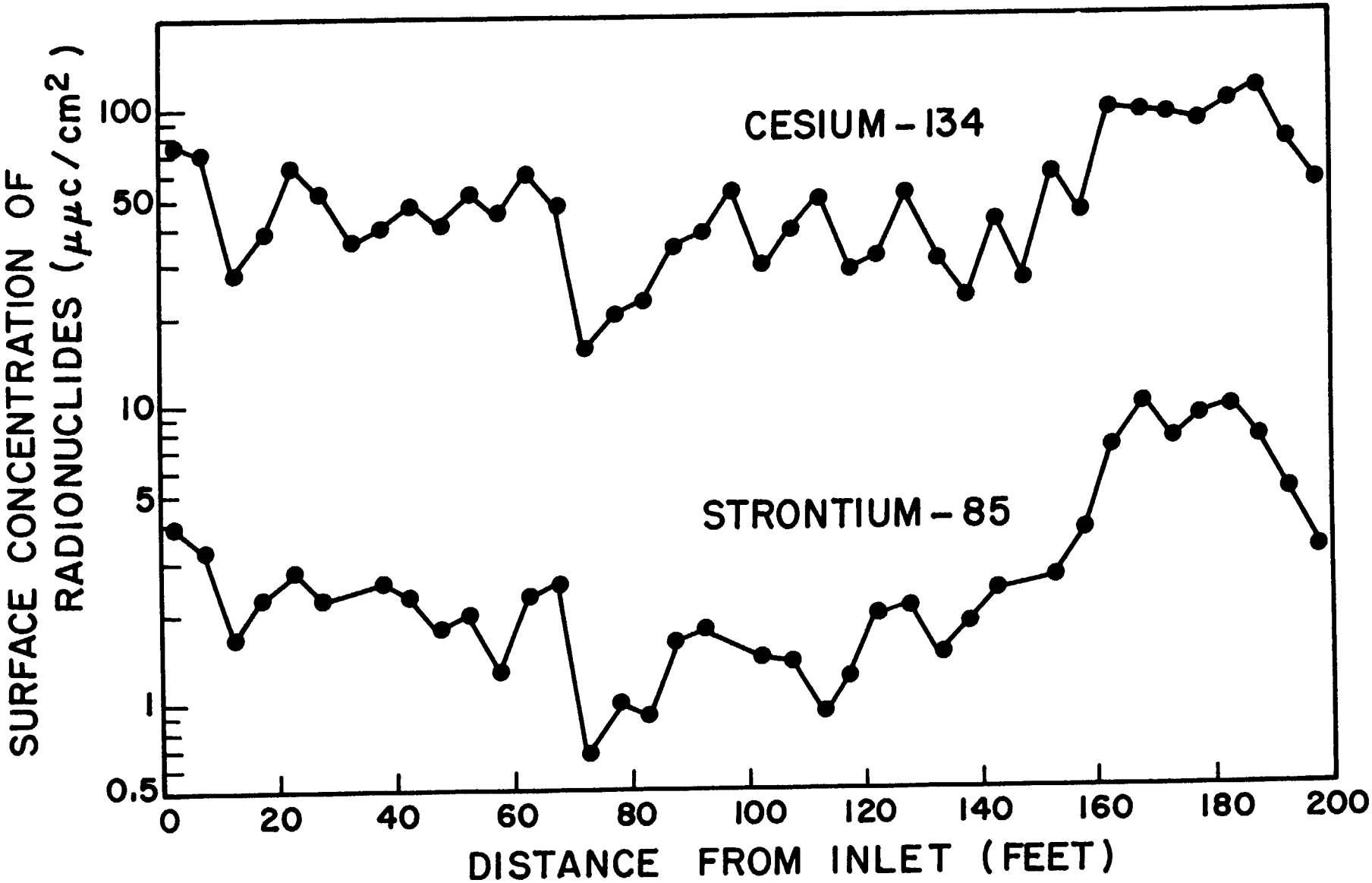

FIG. 3-5 CONCENTRATION OF RADIONUCLIDES BY BED SEDIMENTS ALONG THE LENGTH OF THE FLUME.

1139006

the recipient of all of the particles moving along the bed sediment.

Since ^{134}Cs and ^{85}Sr activity followed the same pattern,it was decided to correlate the ^{134}Cs and ^{85}Sr activity at each 5 foot station on a log-log scale. The result was a straight line relationship, Fig. 3-6. An expression for this relationship is

$$[C_{so} \text{ for } ^{134}Cs] = 26.2\ [C_{so} \text{ for } ^{85}Sr]^{0.66}$$

where

$$C_{so} = \text{concentration at surface in } \mu\mu c/cm^2$$

The average areal concentration of ^{134}Cs by bed sediment in the East channel was 55.1 $\mu\mu c/cm^2$. This is consistent with the equilibrium level of activity in Fig. 3-1. The average concentration of ^{85}Sr was 3.34 $\mu\mu c/cm^2$, which value is consistent with the equilibrium level of activity in Fig. 3-2. In calculating the average values the standard deviations were 25.7 $\mu\mu c/cm^2$ for ^{134}Cs and 2.55 $\mu\mu c/cm^2$ for ^{85}Sr.

Plants

Studies such as those on the Clinch River indicated that while biota living in a river contaminated with radioactive wastes concentrate radionuclides, their effect may be neglected in a mass balance analysis of radionuclide transport (22). However, when the plant growth is extensive, as it is in some slow moving and enriched streams, a significant immediate uptake of radionuclides is noticed and may thereby influence initial transport predictions. Species of rooted plants, Potamogeton, Vallisneria, Myriophyllum, Utricularia, in the West channel of the flume between stations W150 and W100 were plants typical of the Southwest. In the beginning of the experiment of May 28, the predominant species were Potamogeton and Vallisneria. One month later toward the end of the experiment the macro algae Chara dominated the plant area and the species Myriophilum and Utricularia disappeared. On July 3rd, the distribution of the plant species was as follows:

Chara: 20.7 gm/ft^2
Potamogeton: 11 gm/ft^2
Vallisneria: 5.4 gm/ft^2

The above distribution was based on air-dry weight; however, oven dry weight was found to average 5.7 percent of the air dry weight.

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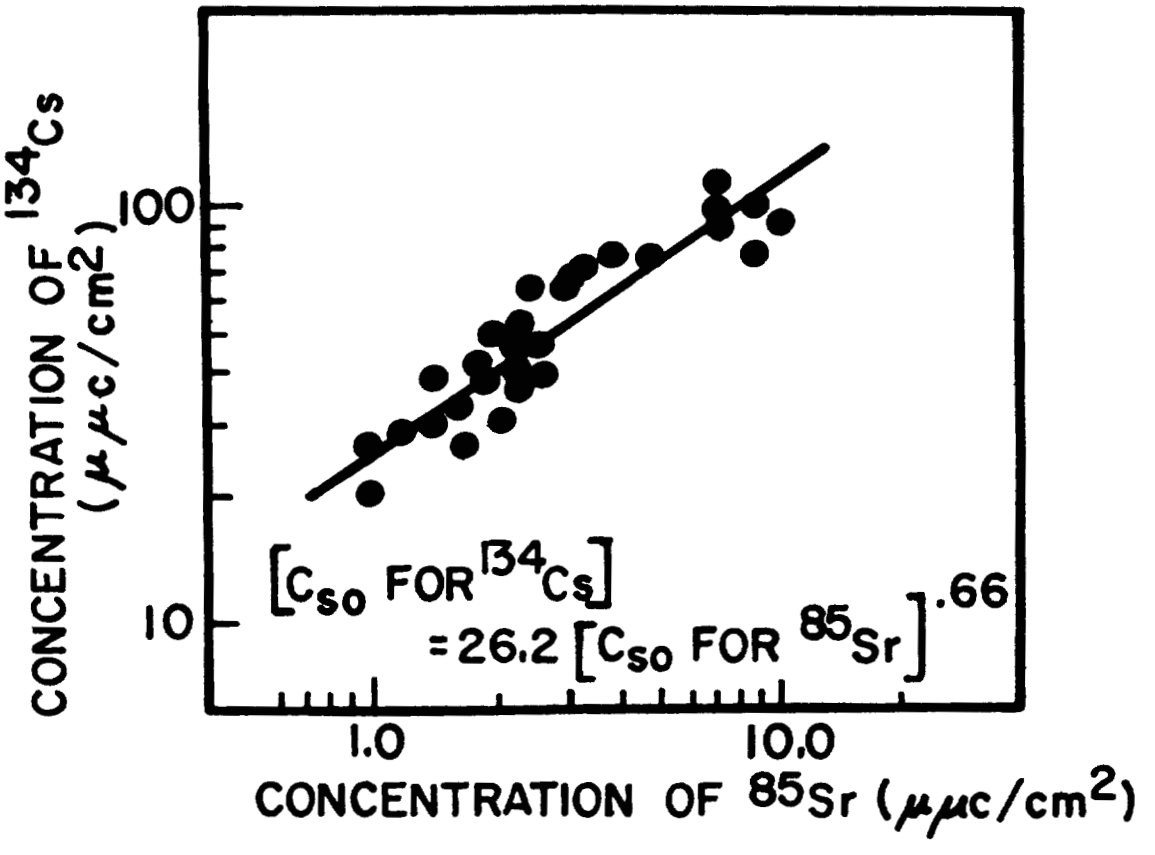

FIG. 3-6 CORRELATION BETWEEN CONCENTRATIONS OF CESIUM-134 AND STRONTIUM-85 BY BED SEDIMENTS IN THE FLUME.

Retention of ^{134}Cs and ^{85}Sr by Plants

Fresh water plants accumulate radionuclides in varying amounts depending on the radionuclide, presence of stable element, biological availability of the element and the plant species. On continuous releases of ^{134}Cs and ^{85}Sr, plants accumulated radionuclides to an equilibrium level, Fig. 3-7. The immediate uptake of ^{134}Cs and ^{85}Sr by plants was relatively high and a quasi-equilibrium state was reached in the first two days.

It is interesting to note that ^{134}Cs and ^{85}Sr increased or decreased at the same time. A linear relationship on a log-log scale existed between the retention of ^{134}Cs and the retention of ^{85}Sr by the plants, Fig. 3-8. This relationship can be expressed as follows:

$$[C_p \text{ for } ^{134}Cs] = 6.18\ [C_p \text{ for } ^{85}Sr]^{0.76}$$

where

C_p = retention of radionuclides by plants in $\mu\mu c$/gm dry weight. The linear correlation coefficient is 0.86.

It would seem that the retention of ^{134}Cs by the plants was greater than the retention of ^{85}Sr; however, the specific activity of the ^{134}Cs in the water flowing in the West channel was almost five times that of the ^{85}Sr. The above equation obviously is only applicable for the experimental conditions.

Concentration Factors of Plants

In the case of plants the concentration factor K_p is the ratio of the specific activity of plants in $\mu\mu c$/gm oven dry weight to the specific activity of water in $\mu\mu c$/ml. The average concentration factors for ^{134}Cs and ^{85}Sr for the predominant species of plants were determined over a 21 day period following the initiation of the continuous release, Fig. 3-9. From the 2nd to 21st day concentration factors for ^{134}Cs varied between 220 ml/gm and 580 ml/gm with an average of 400 ml/gm. During this same time concentration factors for ^{85}Sr varied from 430 to 860 ml/gm with an average of 600 ml/gm. In other words, the radioactivity associated with ^{134}Cs in one gram oven dry weight of plants is equal to the ^{134}Cs radioactivity in 400 ml of water and the radioactivity associated with ^{85}Sr in one gram oven dry weight of plants is equal to the ^{85}Sr radioactivity in 600 ml of water. These data agree with previously reported studies (25).

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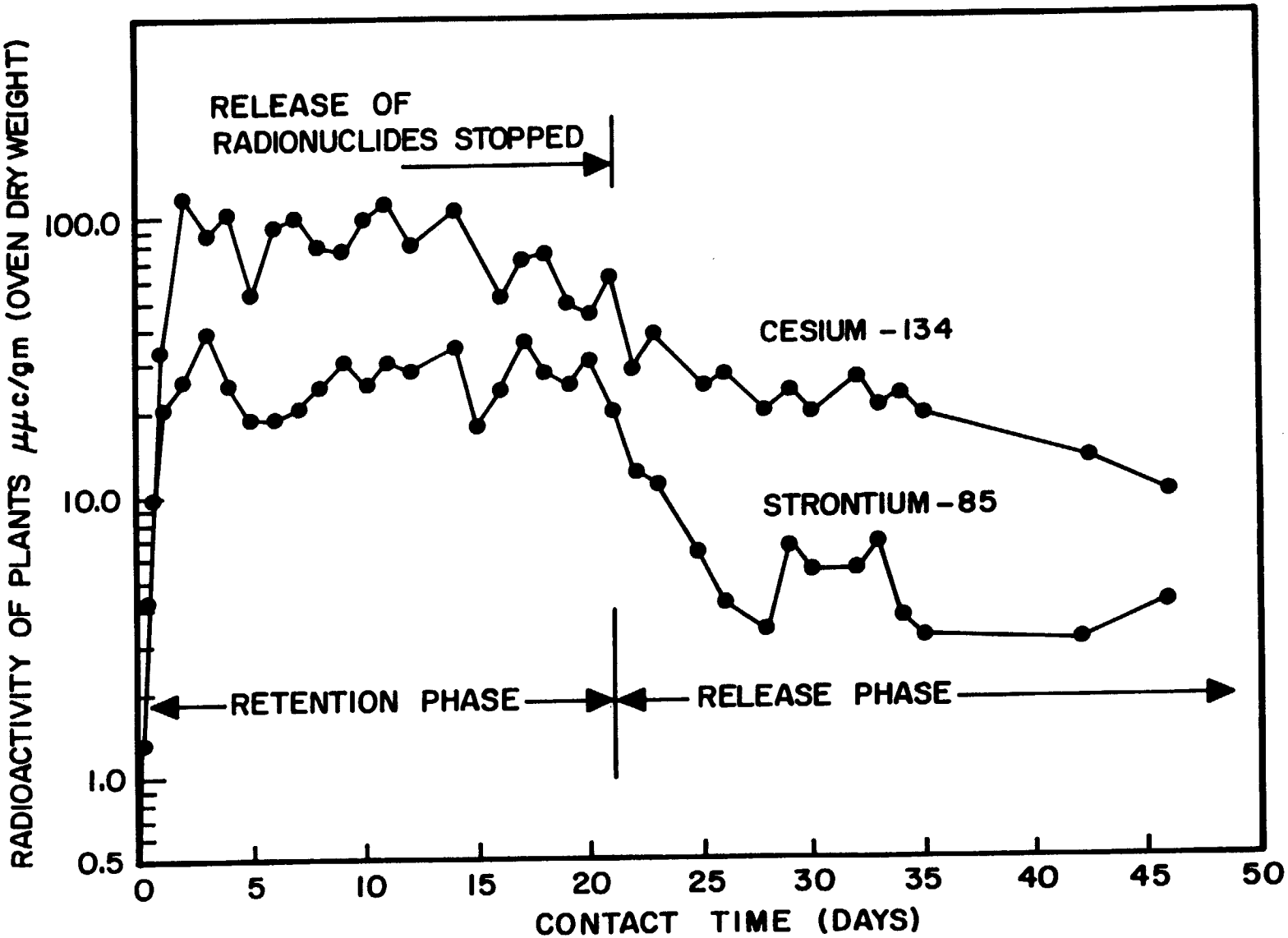

FIG. 3-7 CONCENTRATION OF ^{134}Cs AND ^{85}Sr BY AQUATIC PLANTS RESULTING FROM CONTINUOUS RELEASE OF RADIONUCLIDES IN THE FLUME.

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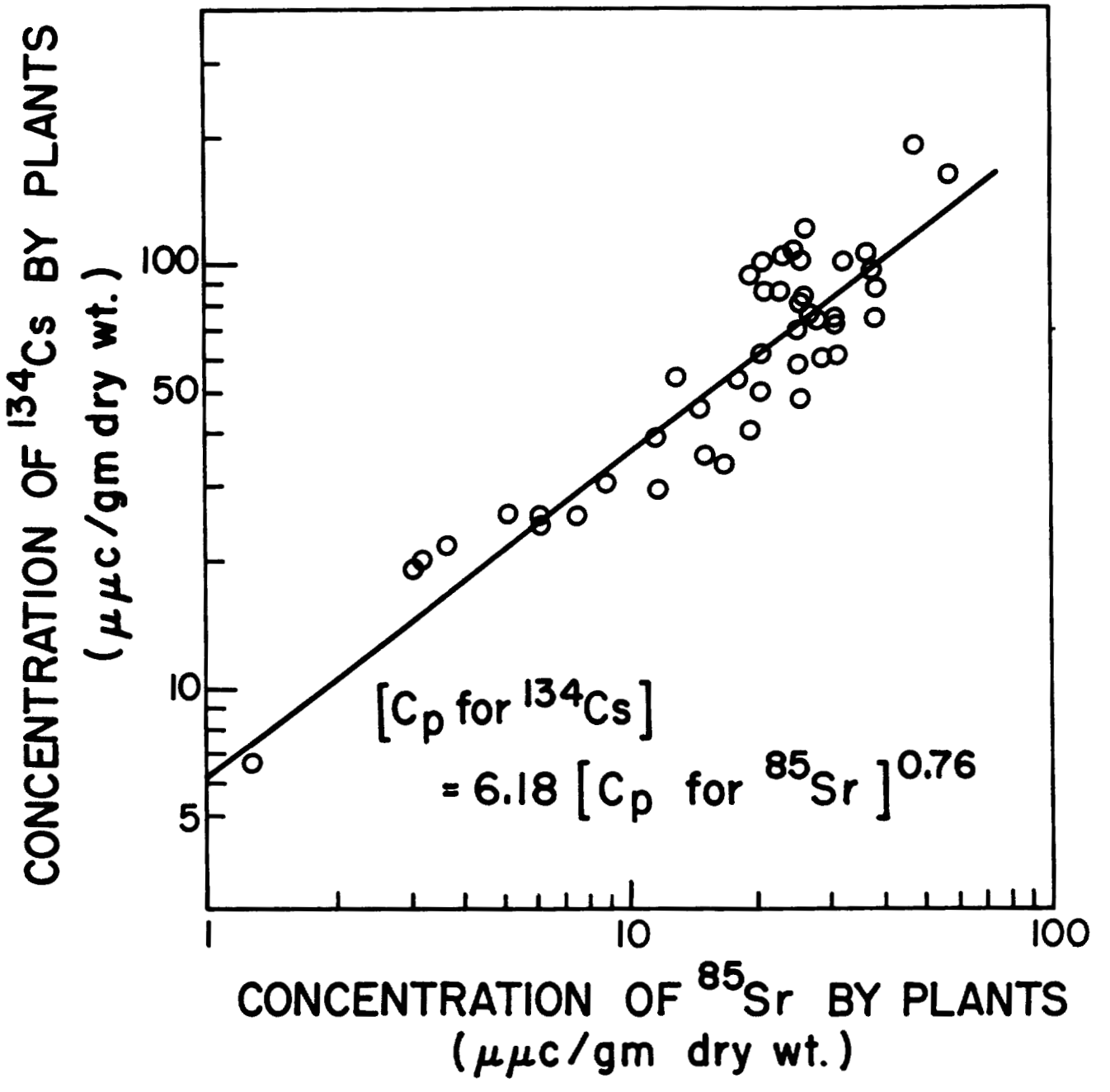

FIG. 3-8 CORRELATION BETWEEN CONCENTRATION OF ^{134}Cs AND ^{85}Sr BY AQUATIC PLANTS IN THE FLUME.

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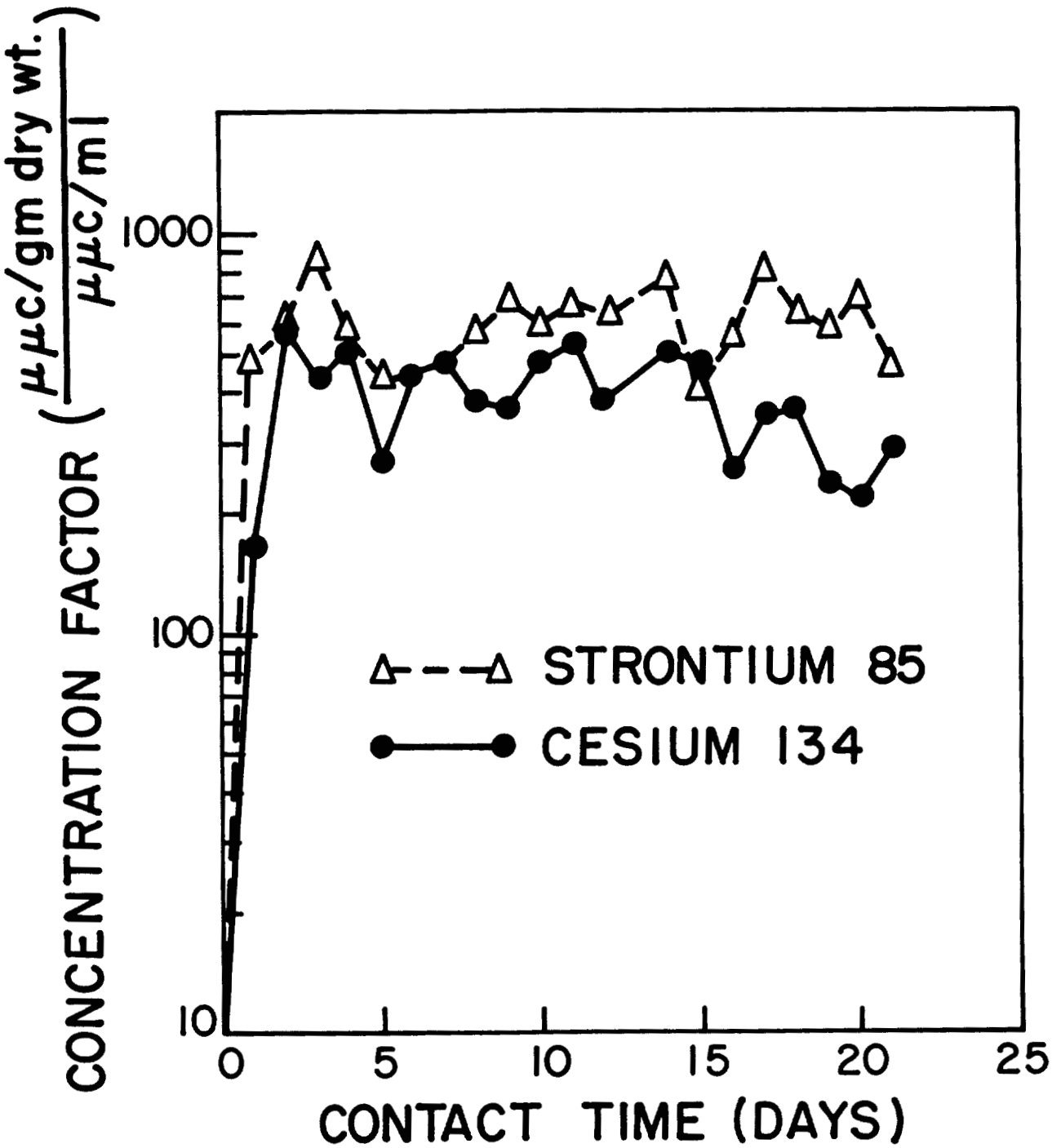

FIG. 3-9 AVERAGE CONCENTRATION FACTORS FOR ^{134}Cs AND ^{85}Sr BY AQUATIC PLANTS.

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Loss of ^{134}Cs and ^{85}Sr by Plants

After three weeks release, the flow of ^{134}Cs and ^{85}Sr was discontinued in the West channel and the radioactivity of the plants continued to be monitored. Initially the plants released activity at a relatively high rate which continued for approximately a week. Thereafter, release was at a much slower rate, Fig. 3-7. At one point the specific radioactivity associated with ^{85}Sr increased for a period of 5 days. There was no readily available explanation for this phenomenon.

The specific activity of the plants, related to time after the source of radionuclide release was discontinued, is shown in Fig.3-10. The linear relationship of the semi-log plot can be expressed as follows:

$$C_p = A10^{-BT}$$

where

T = time in days after discontinuance of the radionuclide source. The specific activity related to ^{134}Cs can be expressed:

$$C_p = 47.9 \times 10^{-0.061T}$$

and for ^{85}Sr: $$C_p = 18.4 \times 10^{-0.121T}$$

From the above it is seen that ^{85}Sr was released by the plants relatively faster than ^{134}Cs. That is, the percentage of ^{85}Sr in the plants decreases at a faster rate.

The correlation between ^{134}Cs and ^{85}Sr concentration in plants is valid through the whole spectrum of uptake, equilibrium and release. See Fig. 3-10 and Fig. 3-8.

1139013

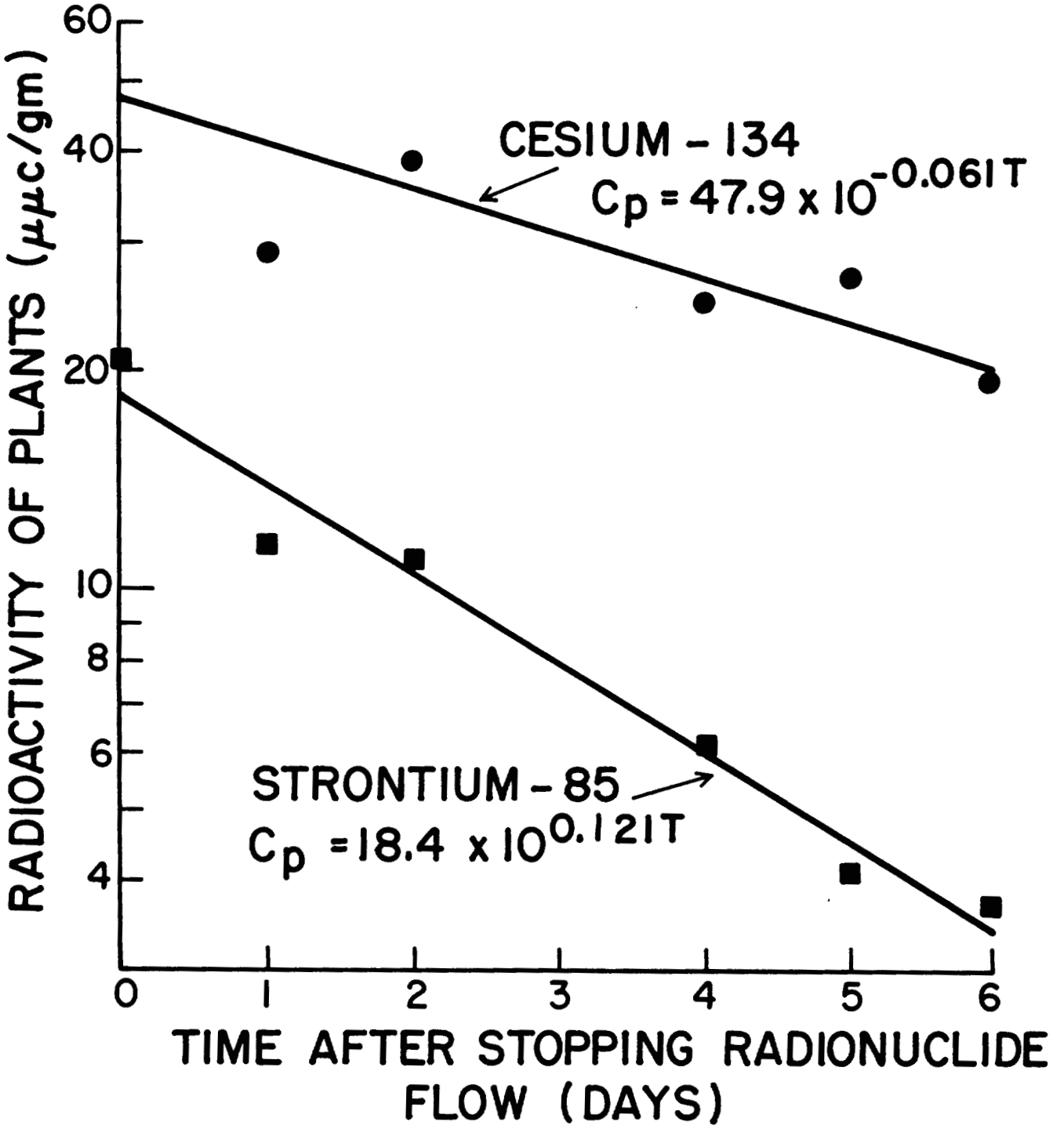

FIG. 3-10 RELEASE OF RADIONUCLIDES BY PLANTS AFTER DISCONTINUING THE SOURCE.

1139014

CHAPTER IV

DISPERSION OF RADIONUCLIDES

Hydraulic mixing and dispersion of dissolved radionuclides are the most important phenomena influencing the rate of movement and concentration of radioactivity released into a stream. The dispersion mechanism is responsible for the mixing that takes place before other phenomena affecting transport of contaminants, such as sorption by sediments and biota, can occur. Dispersion of trace amounts of radionuclides in a flowing stream results from turbulence, molecular diffusion, and convection.

Dispersion characteristics of the flume under the flow conditions of the experiment were studied through the use of dye which was released along with the radionuclides during the initial two days of the experiment.

Dispersion of Rhodamine B

Rhodamine B was released at a constant rate in both channels and the concentration in the water was measured through the use of a Turner Fluorometer. The fluorometer was calibrated with samples of known Rhodamine B concentration, Fig. 4-1.

Since Rhodamine B is known to decay as a result of sunlight and high temperature, aquaria containing known concentrations of Rhodamine B were set along the side of the flume at mid length and during the dye experiment the decrease in concentrations was measured with time in order to determine the necessary correction factors.

Samples of water were taken from six stations in both channels at 2, 22, 52, 152 and 197 feet from two levels, one inch below the water surface and one inch above the bed sediments. The average time concentration curves of the dye at these stations in the East and West channel are shown in Figs. 4-2 and 4-3. The plotted points from which the curves were constructed were average values considering top and bottom samples. Stratification occured from time to time. Also, it was found that East and West channels did not behave exactly the same. Figure 4-4 illustrates stratified flow in the West channel and non-stratified flow in the East channel at the two-foot station.

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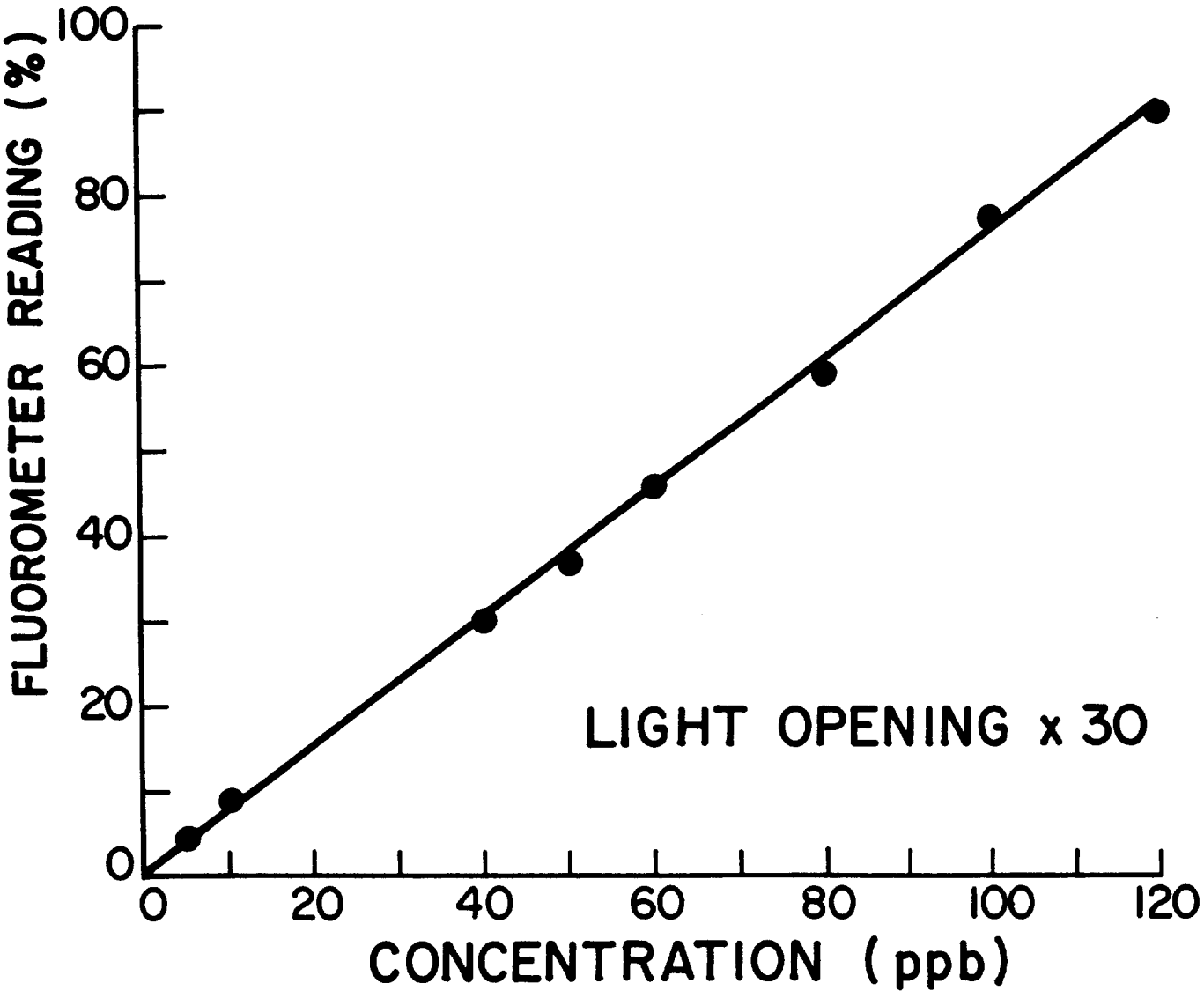

FIG. 4-1 CALIBRATION OF FLUOROMETER FOR DETERMINING RHODAMINE B CONCENTRATIONS.

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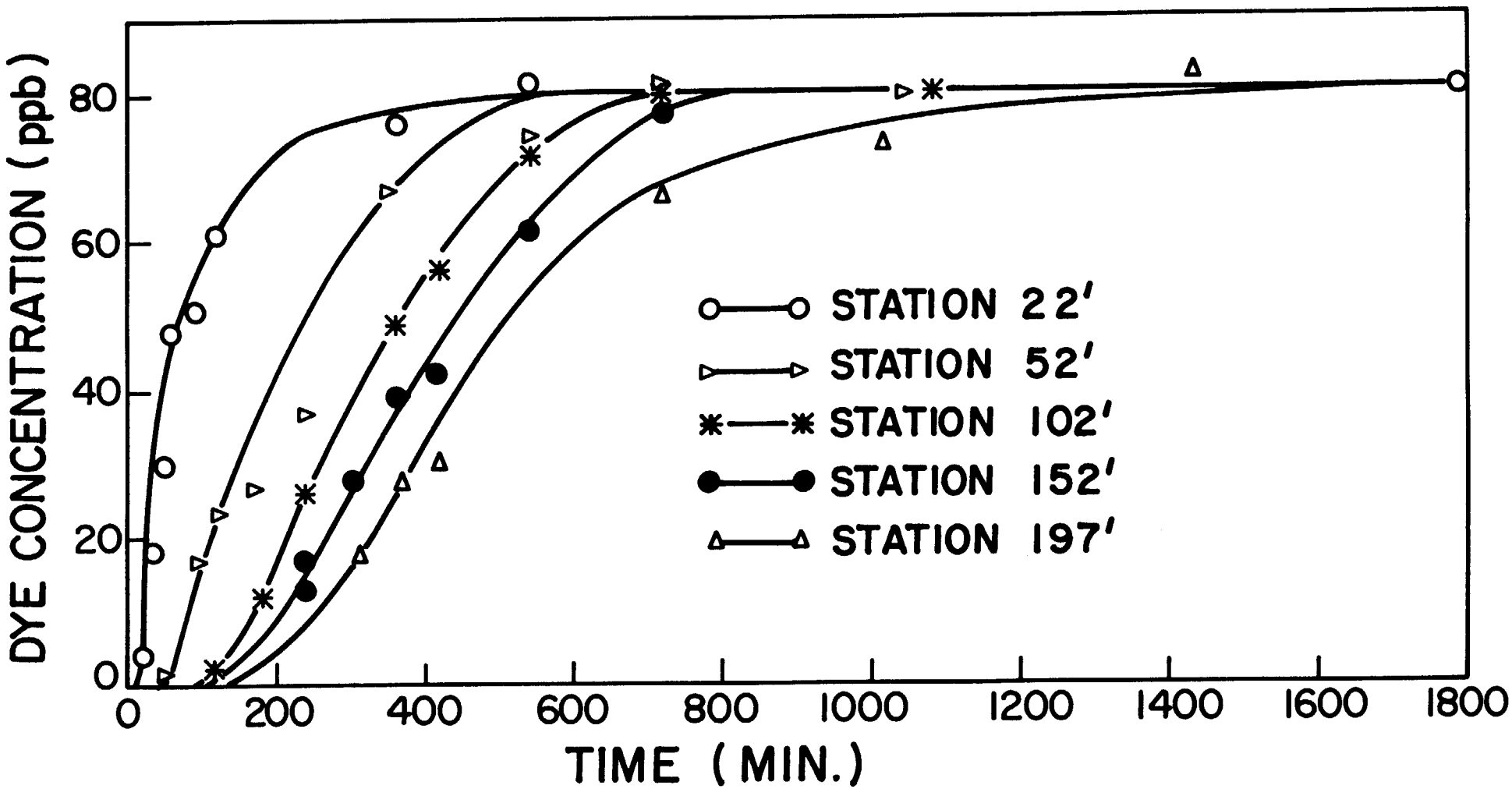

FIG. 4-2 TIME CONCENTRATION CURVES FOR CONTINUOUS DYE RELEASE IN THE EAST CHANNEL.

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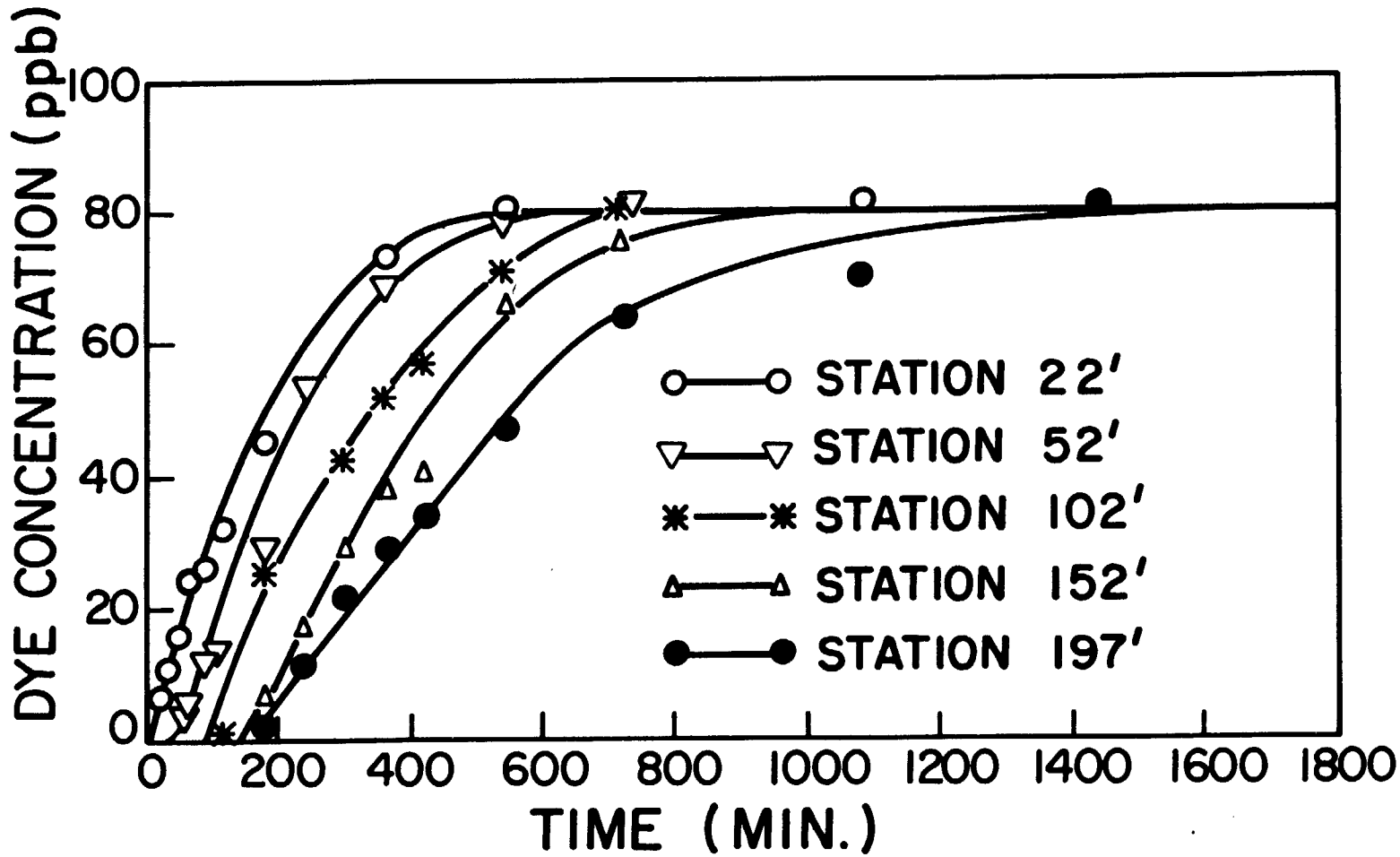

FIG. (4-3) TIME CONCENTRATION CURVES IN THE WEST CHANNEL FOR CONTINUOUS DYE RELEASE.

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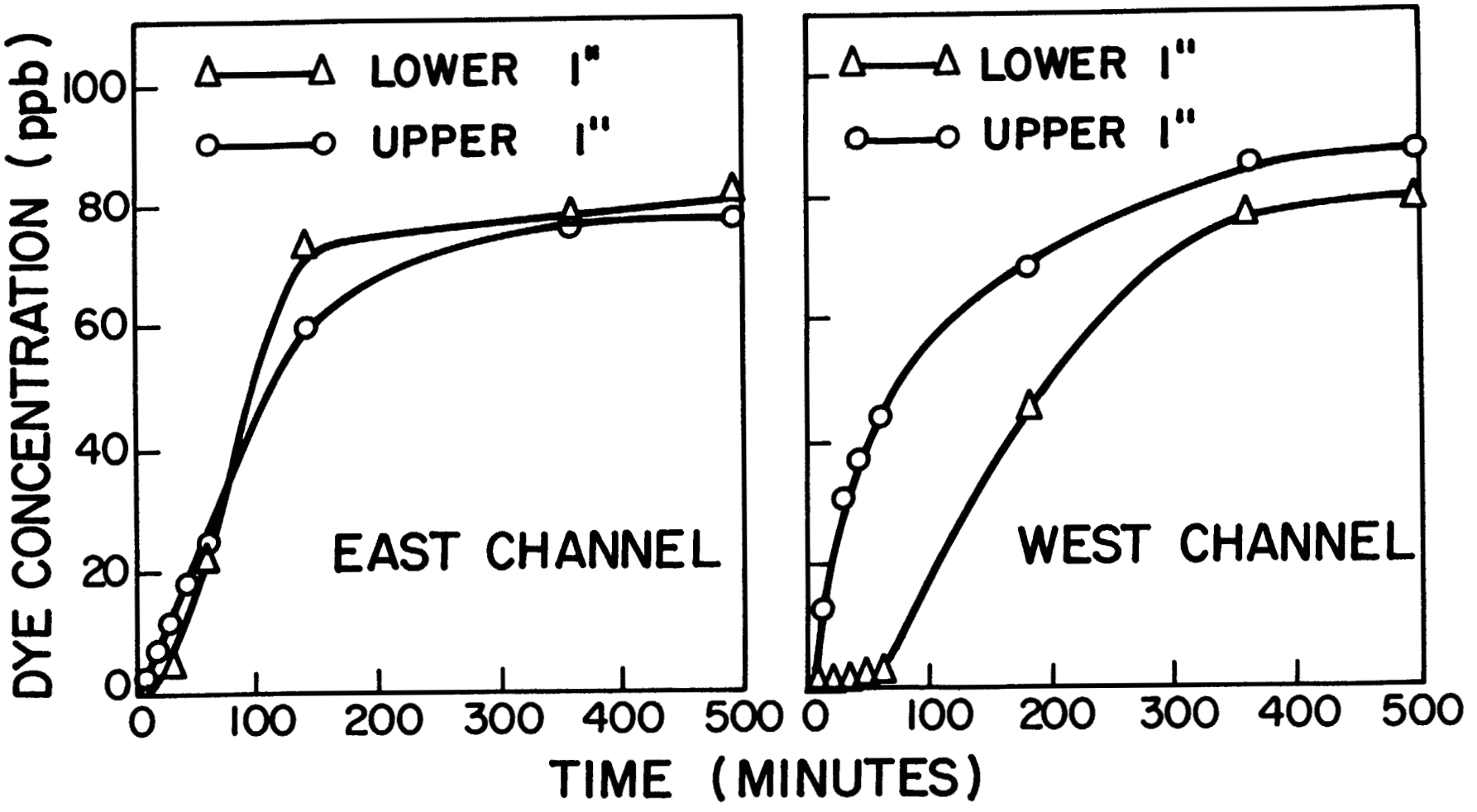

FIG. 4-4 TIME CONCENTRATION CURVES AT STATIONS E2 AND W2 FOR CONTINUOUS RELEASE OF DYE.

1139019

In general, the upper layers of water had higher dye concentrations in daylight hours than did the lower layers. However, at night the dye concentrations were evenly distributed from top to bottom.

From the dye concentration curves the flow through time of the dye can be estimated as the time elapsing until 50% of the equilibrium dye concentration had reached the effluent end of the flume. From Figs. 4-2 and 4-3 the flow through time in the East channel would be estimated at 445 minutes and in the West channel at 460 minutes. This would establish the velocity of flow at approximately 0.44 ft/min, a reasonable figure, considering depth to bottom sediment varied from approximately 6 to 7.5 inches, channel width was 1.25 ft, and quantity of flow was 10 liters/min.

Dispersion of ^{134}Cs and ^{85}Sr

Whenever radionuclides are continuously injected into a waterway, concentration gradients are created within the water and across the water solid interface. Several diffusive mechanisms will act to reduce the concentration gradient until a steady state condition is achieved. This steady state condition is often upset by physical, chemical, and biological processes which change the characteristics of the water and sorbing surfaces.

Cesium 134 and Strontium 85 were continuously released at a uniform rate in the East and West channels of the flume. Water samples were collected at time intervals and the specific activity of water as related to time is shown in Figs. 4-5 and 4-6. The specific activity increased rapidly for the first two days; thereafter, only occasional increases and decreases in the specific activity of water were observed.

Most of the radionuclides released were discharged through the flume. On a mass balance basis, the amount of ^{134}Cs and ^{85}Sr that was discharged with the water flowing through the flume is shown in Table 4-1. A higher fraction of strontium than cesium was discharged through the flume, hence, relatively more cesium was retained in the flume system than strontium. East channel discharge was greater than West channel because of the presence of plants and phytoplankton in the West channel.

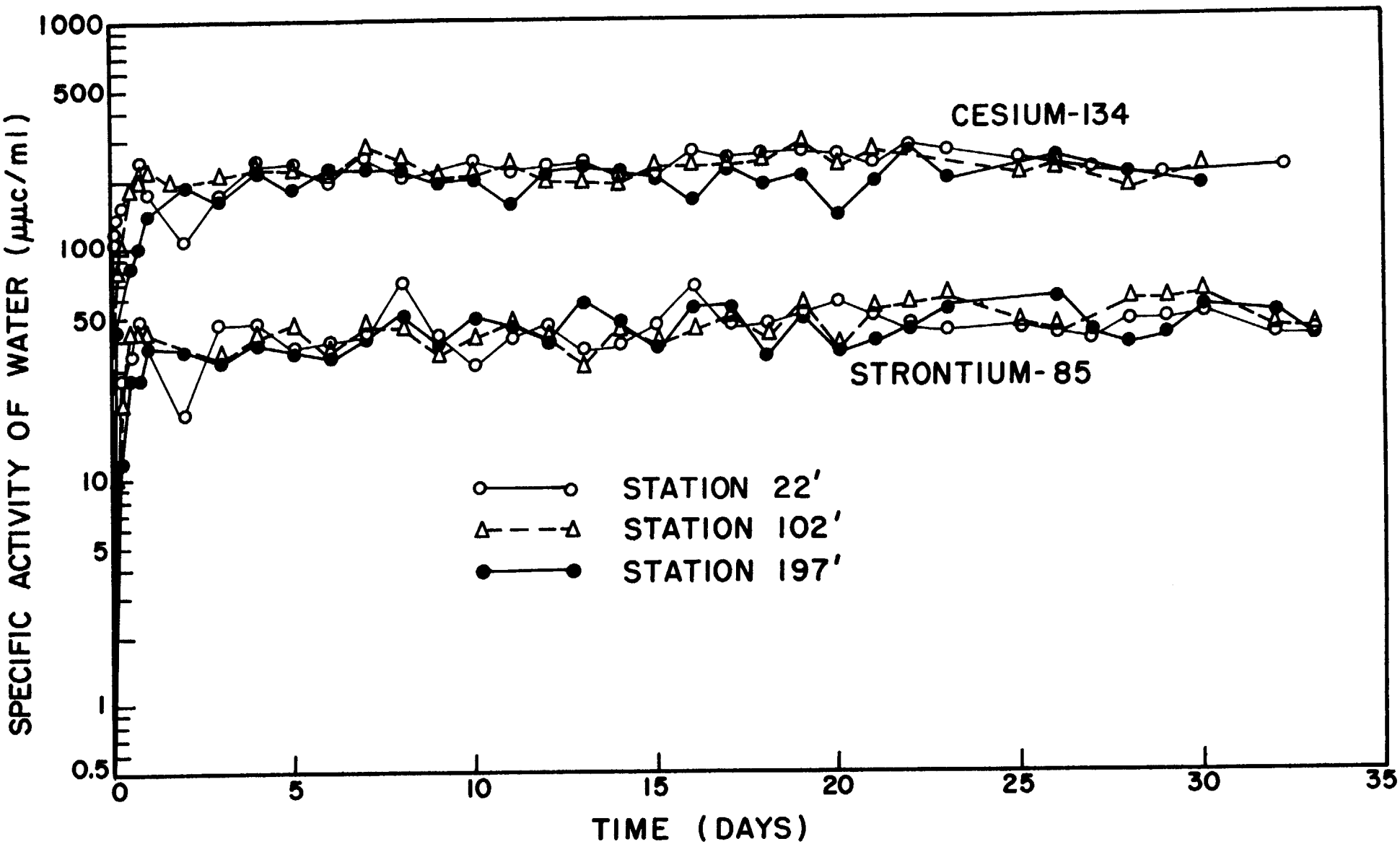

FIG. 4-5 SPECIFIC ACTIVITY OF WATER IN THE EAST CHANNEL RELATED TO CONTACT TIME.

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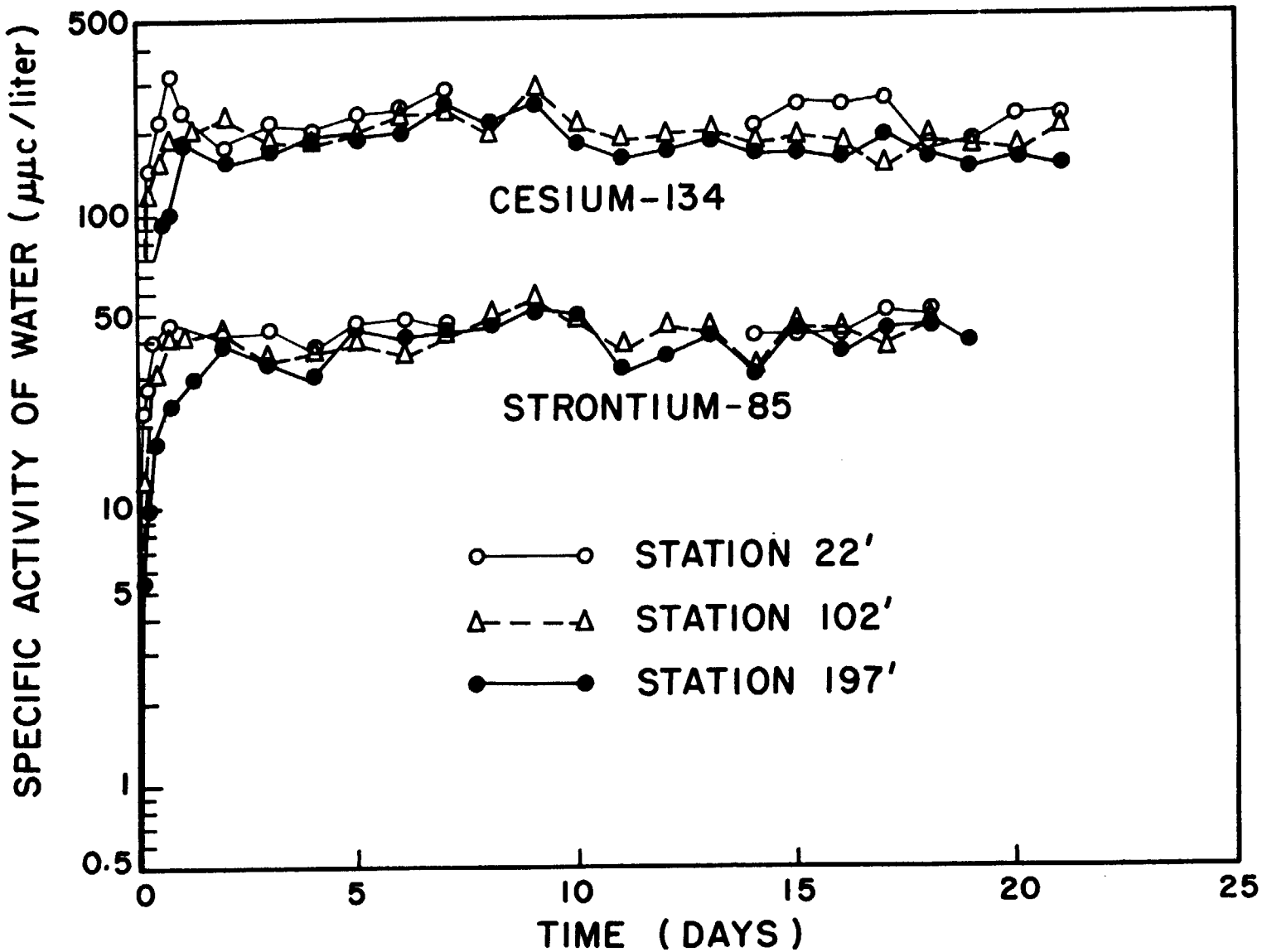

FIG. 4-6 SPECIFIC ACTIVITY OF WATER IN THE WEST CHANNEL RELATED TO CONTACT TIME.

1139022

Table 4-1. Radionuclides Discharged Through the Flume

Time After Initiation of Release (days)	Fraction Discharged through Flume (%)			
	Cesium-134		Strontium-85	
	East Channel	West Channel	East Channel	West Channel
1.0	85.4	81.4	87.2	88.0
2.0	90.3	78.3	92.7	86.2
3.0	88.8	79.8	94.1	87.2
4.0	86.0	87.5	92.6	91.4
5.0	85.8	85.2	92.2	93.7
6.0	87.6	90.5	91.0	93.7
7.0	92.4	73.1	93.8	93.9
8.0	85.7	76.8	90.2	86.2
10.0	88.4	78.5	86.9	87.3
12.0	90.6	76.7	93.4	92.9
15.0	85.8	81.0	92.7	90.9
20.0	83.0	78.2	93.7	91.0
25.0	90.0		95.0	
30.0	87.6		95.2	
34.0	87.3		96.6	

1139023

Distribution of ^{134}Cs and ^{85}Sr Between Solution and Suspension

The overall radioactivity transported through the West channel of the flume is made up of the radioactivity of the ions dissolved in the water and the radioactivity associated with suspended solids. Radioactivity associated with suspended solids was determined by filtering out the suspended solids on millipore filters (0.45 μ pore size) and measuring the radioactivity thus collected. The suspended solids in the West channel consisted of phytoplankton, the concentration of which varied between 15 and 25 mg/liter.

Twelve days after continuous release of radionuclides, when the system was thought to be fairly stable, the role of phytoplankton in the transport of radioactivity was examined. Water samples were taken every four hours over a period of 36 hours between June 8 and 9, 1970, at the 100, 150 and 197 ft stations. A 50 ml portion of each sample was immediately filtered through a millipore filter for radionuclide assay. Another portion of each sample was used for identity counting of organisms. The predominant species are indicated in Table 2-2 and the total organism count is presented in Table 4-2. Dissolved oxygen and temperature measurements were also taken.

The portion of radioactivity in the water flowing through the West channel that was associated with suspended phytoplankton is shown in Table 4-3. The activity related to phytoplankton indicates uptake in traversing through the flume to the station indicated. The percent of the activity related to ^{134}Cs in the phytoplankton averaged between 8.9% and 26.7% of the total activity in the water samples depending upon the time of day during which the samples were taken. The percentage is low early in the morning and high late in the afternoon. On the other hand there was no similar recognizable diurnal relationship to ^{85}Sr activity. The percent of the activity related to ^{85}Sr in the suspended algae as compared to water averaged between 0.4 and 1.5%.

Figure 4-7 shows diurnal variation along the flume, during 36 hours of sampling of water, in the activity of ^{134}Cs associated with the phytoplankton in a liter of water, the dissolved oxygen, and temperature.

Data in Table 4-4, and Fig. 4-7 would seem to indicate a relationship between the oxygen state of the water and the amount of radionuclide sorbed

1139024

Table 4-2. Algal Count Along the West Channel
During Period June 8 to June 9, 1970

Location	Total Count - Organisms/ml							
	← June 8 →					← June 9 →		Average
	0600	1000	1400	1800	2200	0200	0600	
2 ft	5200	4800	6000	7500	4700	3500	3500	5000
102 ft	3300	3000	4000	5100	5400	5800	5000	4500
197 ft	7400	6500	5000	5300	5100	5200	5400	5700
Average	5300	4800	5000	6000	5100	4800	4600	5100

1139025

Table 4-3. Distribution of Radionuclides Between Suspended Phytoplankton and Solution

Date	Time	Variable	Cesium-134			Strontium-85			Average	
			W100	W150	W197	W100	W150	W197	^{134}Cs	^{85}Sr
June 8	0600	Water (μμc/l)	175.0	161.0	178.0	32.0	34.5	29.0		
		SS (μμc/l)	11.7	16.9	17.8	0.5	0.4	0.41		
		%	6.7	10.5	10.0	1.6	1.4	1.4	9.1	1.5
	1000	Water	169.0	143.0	167.0	38.0	30.0	24.5		
		SS	24.1	16.0	12.5	0.16	0.37	0.25		
		%	14.3	11.2	7.5	0.4	1.2	1.0	11.0	0.9
	1400	Water	184.0	176.0	184.0	41.0	36.5	27.0		
		SS	38.1	41.7	30.0	0.34	--	0.2		
		%	20.7	23.7	16.3	0.8	--	0.7	20.2	0.8
	1800	Water	206.0	170.5	156.0	36.0	39.0	29.0		
		SS	45.4	47.0	44.0	0.2	0.18	0.3		
		%	22.0	27.6	28.2	0.5	0.5	1.0	25.9	0.7
	2200	Water	176.0	168.0	152.0	39.0	41.5	45.0		
		SS	33.0	48.0	49.6	0.26	0.24	--		
		%	18.8	28.6	32.6	0.7	0.6	--	26.7	0.7
June 9	0200	Water	194.0	178.5	144.0	45.0	42.0	38.0		
		SS	20.9	28.0	31.3	0.27	0.41	0.38		
		%	10.8	15.7	21.7	0.6	1.0	1.0	16.1	0.9
	0600	Water	175.0	184.0	186.0	41.0	37.0	31.0		
		SS	15.9	17.4	22.6	0.22	0.27	0.27		
		%	9.1	9.5	13.6	9.5	0.7	0.9	10.7	0.7
	1000	Water	192.0	177.0	195.0	46.0	46.5	38.0		
		SS	16.4	17.4	16.2	0.52	0.37	0.17		
		%	8.5	9.8	8.3	1.1	0.8	0.4	8.9	0.7
	1400	Water	193.0	194.0	179.0	37.0	44.5	33.0		
		SS	33.8	30.5	44.6	0.19	0.18	0.06		
		%	17.5	15.7	24.9	0.5	0.4	0.2	19.4	0.4
	1800	Water	189.0	166.0	158.0	37.0	44.5	33.0		
		SS	40.4	47.9	41.5	0.2	0.8	0.51		
		%	21.4	28.9	25.9	0.5	1.8	1.5	25.4	1.3

Note: SS=suspended solids, predominantly phytoplankton. activity associated with SS indicates uptake in traversing from station 0 to stations 100, 150, and 197 feet from 0.

113902b

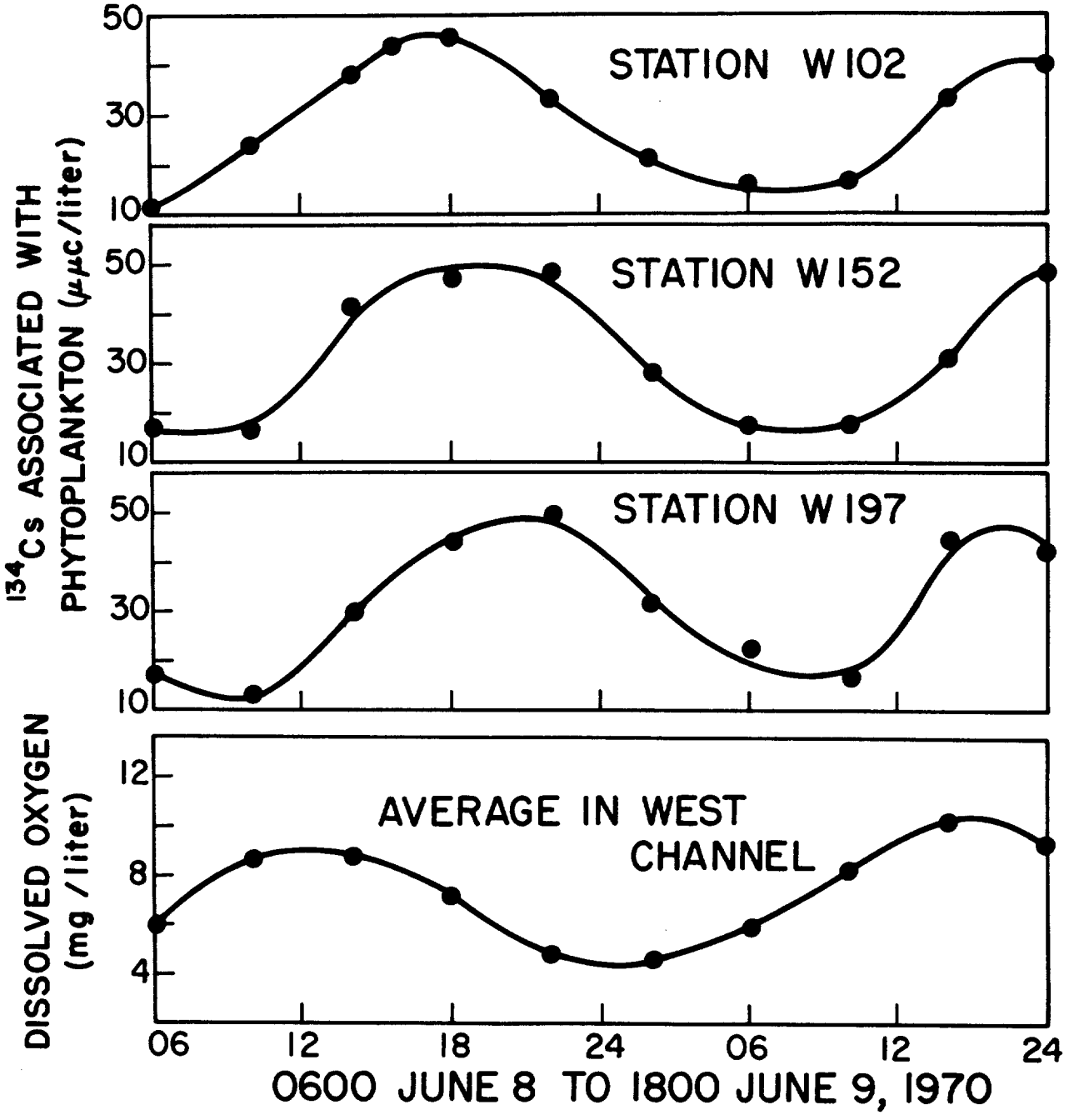

FIG. 4-7 DIURNAL CONCENTRATION OF ^{134}Cs BY SUSPENDED PHYTOPLANKTON AND AVERAGE DISSOLVED OXYGEN IN THE WEST CHANNEL.

1139027

Table 4-4. Calculating Net Photosynthetic Oxygen Production at Station W100 Between 0600 June 8 and 1800 June 9, 1970

Date	Time	$(P-R) = \frac{\Delta D}{\Delta t} - K_2 \frac{D_o + D}{2} + S$								
		D_o (mg/l)	D (mg/l)	ΔD (mg/l)	$\frac{\Delta D}{\Delta t}$ (mg/l/hr)	$\frac{D_o+D}{2}$ (mg/l)	K_2 (hr^{-1})	$K_2\bar{D}$ (mg/l/hr)	S (mg/l/hr)	(P-R) (mg/l/hr)
June 8	06-08	+2.25	+1.85	-0.400	-0.200	+2.050	0.052	+0.1066	0.046	+0.0988
	08-10	+1.85	+0.65	-1.200	-0.600	+1.250	0.052	+0.0650	0.046	+0.5810
	10-12	+0.65	-0.40	-1.050	-0.525	+0.125	0.052	+0.0065	0.046	+0.5643
	12-14	-0.40	-0.65	-0.250	-0.125	-0.525	0.052	-0.0273	0.046	+0.1983
	14-16	-0.65	-0.50	+0.150	+0.075	-0.555	0.052	-0.0289	0.046	-0.0010
	16-18	-0.50	+0.50	+1.000	+0.500	0.000	0.052	0.0000	0.046	-0.4540
	18-20	+0.50	+1.60	+1.100	+0.550	+1.050	0.052	+0.0546	0.046	-0.5586
	20-22	+1.60	+2.40	+0.800	+0.400	+2.000	0.052	+0.1040	0.046	-0.4580
	22-24	+2.40	+2.80	+0.400	+0.200	+2.600	0.052	+0.1352	0.046	-0.2892
June 9	00-02	+2.80	+2.90	+0.100	+0.050	+2.850	0.052	+0.1482	0.046	-0.1522
	02-04	+2.90	+2.90	0.000	0.000	+2.900	0.052	+0.1508	0.046	-0.1048
	04-06	+2.90	+2.60	-0.300	-0.150	+2.750	0.052	+0.1430	0.046	+0.0530
	06-08	+2.60	+2.00	-0.600	-0.300	+2.300	0.052	+0.1196	0.046	+0.2264
	08-10	+2.00	+0.30	-1.700	-0.850	+1.150	0.052	+0.0598	0.046	+0.8362
	10-12	+0.30	-1.20	-1.500	-0.750	-0.450	0.052	-0.0234	0.046	+0.7726
	12-14	-1.20	-2.30	-1.300	-0.650	-1.750	0.052	-0.0910	0.046	+0.6030
	14-16	-2.30	-2.50	-0.200	-0.100	-2.400	0.052	-0.1248	0.046	+0.2708
	16-18	-2.50	-2.00	+0.500	+0.250	-2.250	0.052	-0.1170	0.046	+0.0870

1139028

by the phytoplankton. Possibly a relationship existed between net photosynthetic production of oxygen and the uptake of activity by the phytoplankton.

Determining Net Photosynthetic Oxygen Production

The rate of net photosynthetic oxygen production can be calculated from direct observations of oxygen deficits at stations W102, W152, and W197. The mass balance equation follows:

$$\frac{\Delta D}{\Delta t} = K_1 \bar{L} - K_2 \bar{D} + S - (P-R)$$

where

$\frac{\Delta D}{\Delta t}$ = change in oxygen deficit during time period " Δt" (mg/l/hr)

K_1 = rate constant (log base e) at which BOD is being removed from water by biological activity (hr^{-1})

$\bar{L}$ = average biochemical oxygen demand during time period " Δt" (mg/l)

K_2 = atmospheric (log base e) reaeration rate constant (hr^{-1})

$\bar{D}$ = average dissolved oxygen deficit during time period " Δt" (mg/l)

S = sediment oxygen demand (mg/l/hr)

(P-R) = net photosynthetic oxygen production rate during time period " Δt" (mg/l/hr)

The biochemical oxygen demand L of the water entering the flume was less than 2 mg/l and therefore negligible. Values for K_2 and S were determined, as outlined in a previous study (24), to be 0.052 hr^{-1} and 0.046 mg/l/hr respectively. Substituting this information into equation (4-1), the rate of net photosynthetic oxygen production can be determined:

$$(P-R) = -\frac{\Delta D}{\Delta t} - 0.052\,\bar{D} + 0.046$$

Table 4-5 illustrates the calculation of (P-R) at station W100 during the period of this experiment.

1139029

Table 4-5. Decrease in Dissolved Oxygen and ^{134}Cs Activity in Water After Application of Na_2SO_3 Solution at Station W75

Date	Time	Dissolved Oxygen*				^{134}Cs Activity in Water **			
		W52	W102	W152	W197	W52	W102	W152	W197
12 Jun 1970	1400	7.8	1.4	1.8	2.4	216	143	149	157
	1800	7.9	0.4	1.7	2.6	249	184	178	126
	2200	7.4	1.5		0.7	238	243	159	177
13 Jun 1970	0200	5.0	0.3	0.4	0.4	203	155	139	138
	0600	7.2	0.6	0.5	0.3	216	192	184	136
	1000	7.1	0.1	2.7	2.0	175	186	219	205
	2200	5.3	3.2	1.9	0.9	205	172	149	138
AVERAGE						215	182	168	154

*Dissolved Oxygen in mg/liter

**Activity in μμc/liter

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Relationship Between Net Photosynthetic Oxygen Production and Radionuclide Uptake by Phytoplankton

The changes in the amount of ^{134}Cs radioactivity retained by phytoplankton approximately paralleled the rise and fall of the dissolved oxygen in the water in which the phytoplankton was suspended. It was deduced that there was a relationship between the rate of photosynthetic activity and the rate at which ^{134}Cs was being retained by the phytoplankton.

Figure 4-8 compares the rates of change in ^{134}Cs concentration by the suspended organisms with the rates of photosynthetic oxygen production during the thirty-six hour period of the experiment. The patterns are similar except the phase is different.

If the rate of change in ^{134}Cs concentration is plotted against the rate of net photosynthetic oxygen production, a linear relationship is seen to exist, Fig. 4-9 which can be expressed in the general form:

$$Y = A + B_x$$

where

Y = rate of change in concentration of ^{134}Cs (μμc/l/hr)

x = rate of net photosynthetic production of oxygen in mg/l/hr

A and B = constants.

The data from station W100 showed that A = -0.40 and B = + 6.23 and the linear correlation coefficient is 0.934. The data from station W150 showed that A = -0.46 and B = + 5.17 and the linear correlation coefficient is 0.978. By combining stations W100 and W150, A becomes -0.42 and B becomes +5.57 and the correlation coefficient is 0.953 as shown in Fig. 4-9. The data obtained at station W197 was not used since the area was covered with plants at this location and the role of plants on the overall oxygen balance was not determined.

While there was a relationship between ^{134}Cs uptake by phytoplankton and photosynthesis, there was no relationship in the case of ^{85}Sr. The amount of ^{85}Sr in the suspended phytoplankton remained relatively small throughout the experiment and there was no discernible pattern. The average amount of ^{85}Sr associated with the phytoplankton was 0.31 μμ c/liter.

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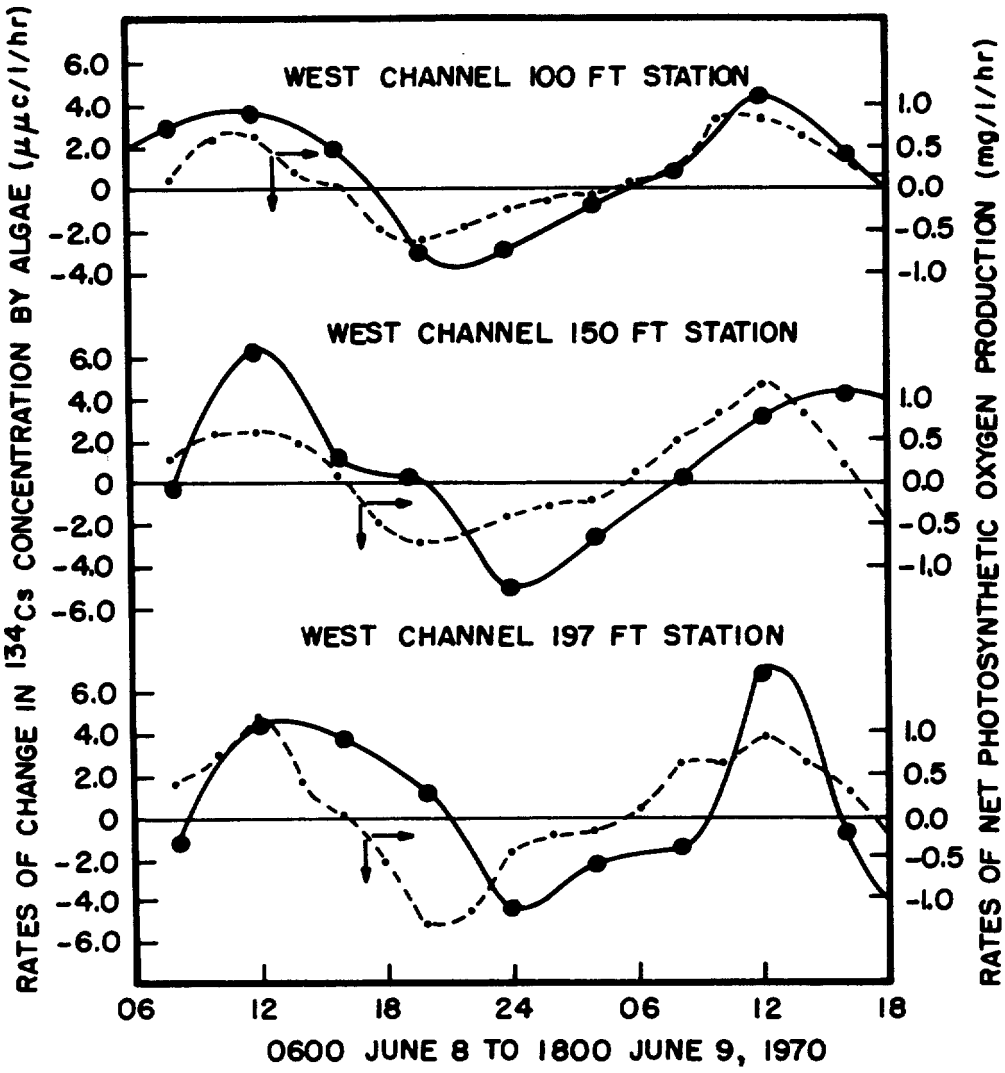

FIG. 4-8 DIURNAL RATES OF CHANGE IN ^{134}Cs CONCENTRATION ASSOCIATED WITH SUSPENDED ALGAE AND RATES OF NET PHOTOSYNTHETIC OXYGEN PRODUCTION.

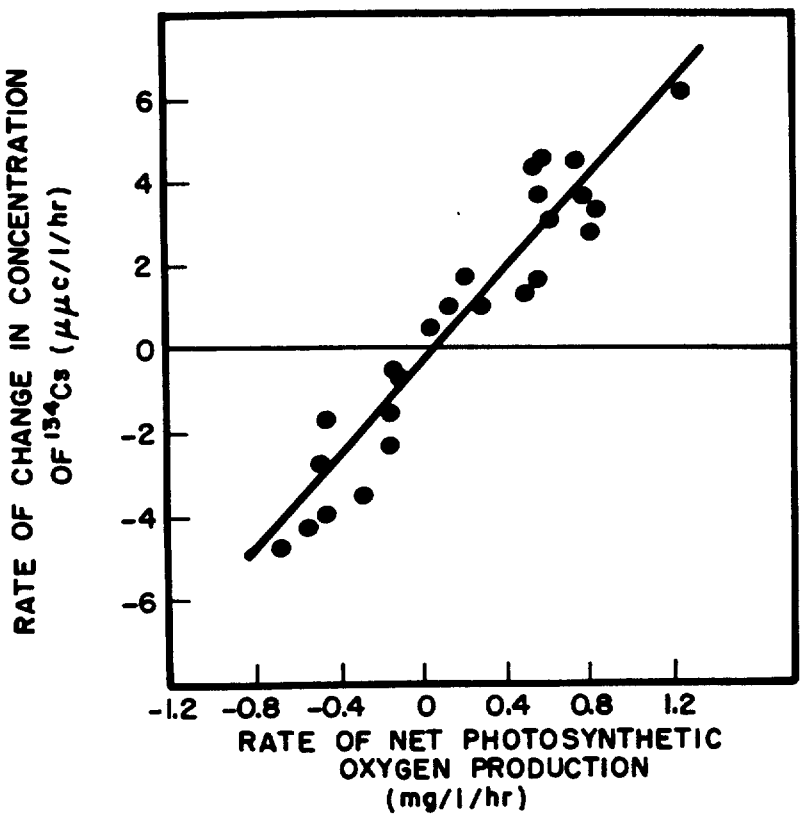

FIG. 4-9 CORRELATION BETWEEN RATE OF CHANGE IN CESIUM-134 CONCENTRATION AND THE RATE OF NET PHOTOSYNTHETIC OXYGEN PRODUCTION.

Concentration Factor of Phytoplankton

As pointed out previously, the amount of suspended solids in the West channel ranged between 15 and 25 mg/l. Assuming an average of 20 mg/l, the concentration factor K_a for the phytoplankton for ^{134}Cs under the maximum condition of ^{134}Cs retention would be 13,000 ml/gm and under the minimum condition would be 4000 ml/gm.

The concentration factor K_a for ^{85}Sr ranged from approximately 200 ml/gm to 700 ml/gm averaging 400 ml/gm. This would indicate that the concentration factor of phytoplankton for ^{85}Sr was very nearly equal to the concentration factor of rooted plants for ^{85}Sr which varied between 430 and 860 ml/gm. (See Chapter III). However, there was no similarity between K_p and K_a for ^{134}Cs. The concentration factor of the phytoplankton for ^{134}Cs was approximately 20 times the concentration factor of the rooted plants.

Effect of Pollutional Stress

The dissolved oxygen was lowered in part in the West channel by adding a continuous source of Na_2SO_3 and $CoCl_2 6H_2O$ as catalyst at the 75 foot station for a two-day period. Comparisons were then made between station W52 and stations downstream of W75.

Table 4-5 illustrates the experimental data obtained between W52 and W197. The specific activity of ^{134}Cs in water was lower at stations downstream of W75 than it was at W52. As indicated in Table 2-3, the number of suspended organisms dropped from 2230 per ml at W50 to 1410 and 490 respectively at stations W100 and W200 in a sampling taken during this experiment. This would account for the reduction of specific activity in the water. Organisms died, settled to the bottom carrying with them radioactivity thus reducing specific activity in water and raising the radioactivity associated with sediments.

1139034

CHAPTER V

MATHEMATICAL SIMULATION

In order to simulate the transport of radionuclides by a numerical model it is necessary to: (1) identify boundary conditions and interrelationships, and (2) formulate physical processes and boundary conditions into algebraic equations. The following equation best characterizes radionuclide transport (12).

$$\frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x} - \bar{u} \frac{\partial c}{\partial x} - \sum_{i=1}^{n} f_i K_i \left[G_i (c) - C_i\right] \qquad (5\text{-}1)$$

where

c = concentration of radioactivity in water at any point (x) at time (t)

D_x = longitudinal dispersion coefficient

$\bar{u}$ = average velocity of flow

f_i = mass or surface area of i-th sorbent affecting a unit volume of the flow zones

K_i = transfer rate coefficient for phase " i "

$G_i(c)$ = a transfer function relating the concentration of activity in the water to the equilibrium level of activity in the phase " i "

C_i = specific activity in the i-th position of the n-sorption phases

The first two terms in equation (5-1) define mixing characteristics and dilution while the third term describes uptake and release by the various sorbent components of the aquatic system. In previous experiments (21) longitudinal dispersion coefficients D_x were calculated for subcritical laminar flow with velocities ranging from 0.33 to 3.30 ft/min using the dye Rhodamine B. From time concentration curves of the Rhodamine B under different velocity conditions in the flume, D_x values were found to be related to the velocity of flow and followed the empricial relationship:

$$D_x = A\bar{u}^{.6} \qquad (5\text{-}2)$$

where A is a constant of proportionality and is expressed in ft/min. The

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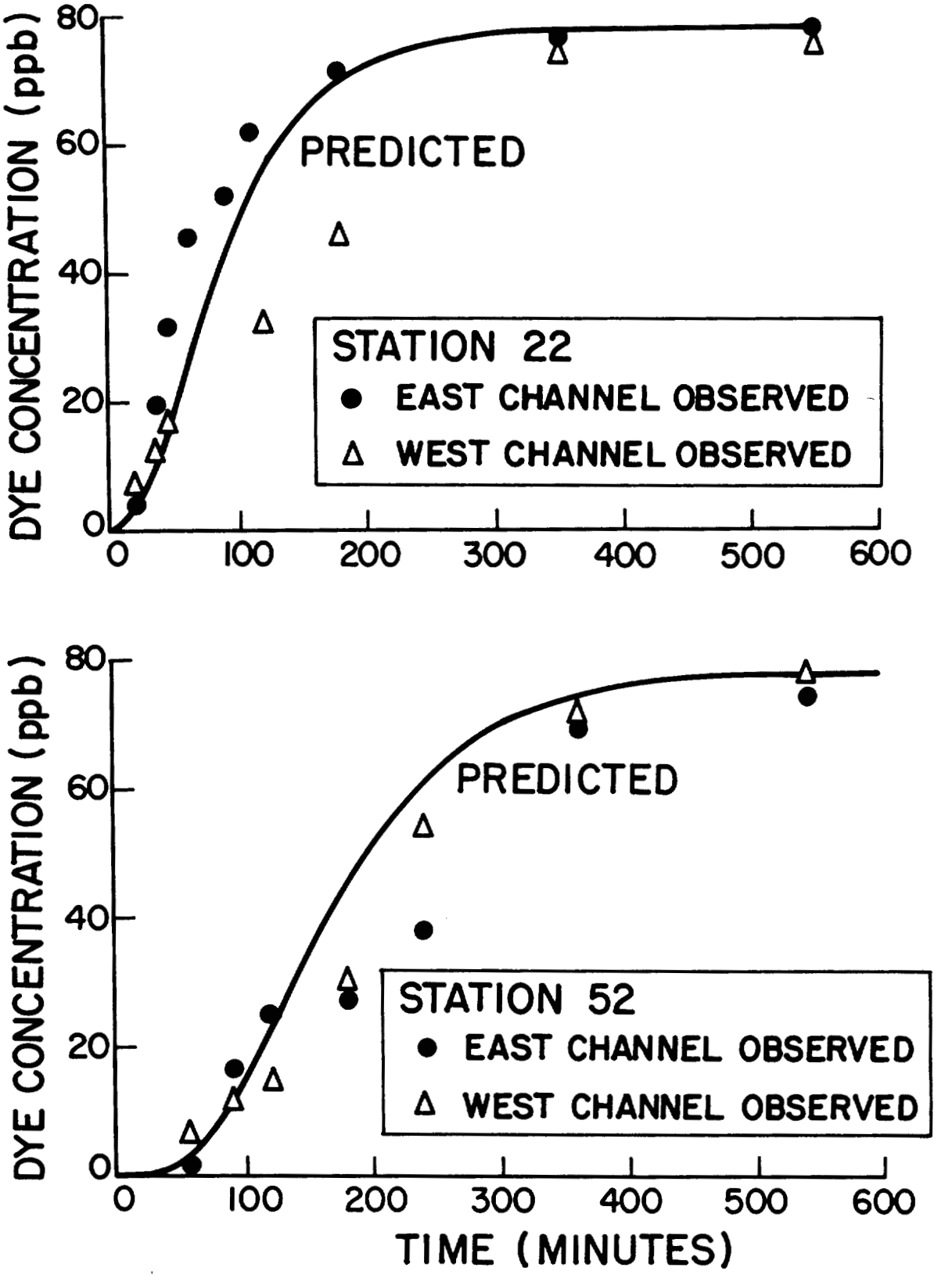

FIG. 5-1 PREDICTED AND OBSERVED TIME CONCENTRATION VALUES FOR CONTINUOUS RELEASE OF RHODAMINE B.

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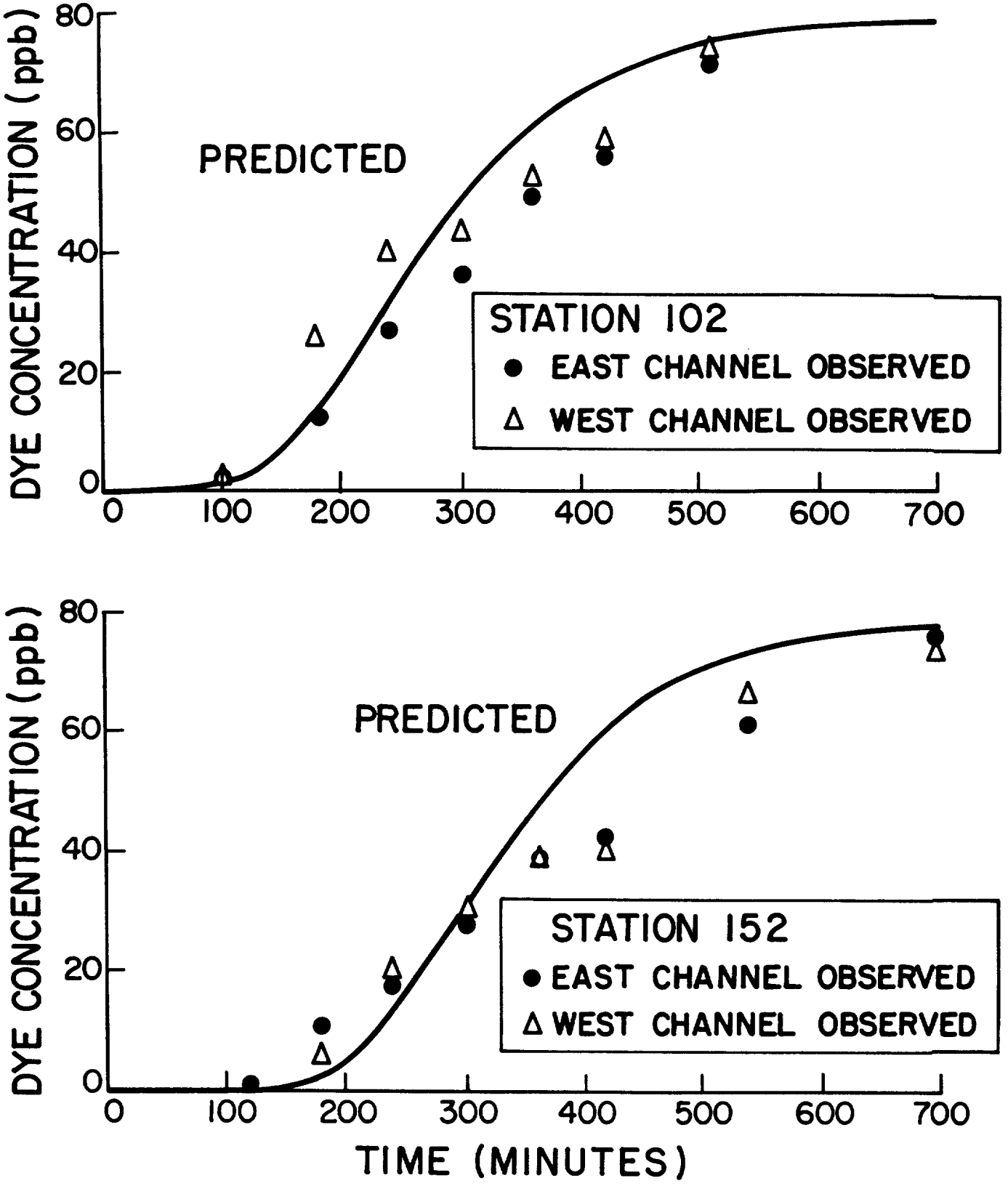

FIG. 5-2 PREDICTED AND OBSERVED TIME CONCENTRATION VALUES FOR CONTINUOUS RELEASE OF RHODAMINE B.

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coefficients for those elements of the system that sorb and remove radioactivity from the water phase (i.e., bed sediment and plants) must be determined. Bed sediments and plants retain and release radioactivity in accordance with the following general relationship:

$$\frac{dC_i}{dt} = K_i \, [G_i C_w - C_i] \qquad (5\text{-}3)$$

where

K_i = transfer rate coefficient for the i-th sorbent

G_i = concentration factor at saturation for the i-th sorbent

C_w = specific activity of the water at equilibrium conditions

C_i = specific activity of the i-th sorbent at time "t"

If the specific activity "C" in the sorbent = 0 when t = 0, the solution of equation (5-3) for concentration or specific activity at any time "t" becomes:

$$C_{i_t} = G_i C_w \, (1 - e^{-K_i t}) \qquad (5\text{-}4)$$

and the solution for the mass transfer coefficient is:

$$K_i = - \frac{1}{t} \ln \frac{G_i C_w - C_i}{G_i C_w} \qquad (5\text{-}5)$$

Mass Transfer Rate Coefficients of Bed Sediment

Detailed analysis of data obtained from retention of radionuclides by bed sediments in the flume indicated that surface concentration increased gradually with time to an equilibrium level after approximately 25 days, Figs. 3-1 and 3-2. As previously discussed in Chapter III, the average areal distribution of ^{134}Cs after 35 days of continuous flow was 55$\mu\mu c/cm^2$ and the distribution of ^{85}Sr was 3.34 $\mu\mu c/cm^2$. In determining the mass transfer coefficients of the bed sediment applicable to ^{134}Cs and ^{85}Sr respectively 55 $\mu\mu$ c/cm^2 and 3.34 $\mu\mu$ c/cm^2 may be used as the $G_i C_w$ term in equation (5-5). Tables 5-1,5-2, and Fig. 5-3 illustrate the calculation of

1139038

Table 5-1. Calculating Mass Transfer Rate Coefficients for Concentration of ^{134}Cs by Bed Sediments in the East Channel

t (day)	G_iC_w ($\mu\mu c/cm^2$)	C_i ($\mu\mu c/cm^2$)	$G_iC_w-C_i$ ($\mu\mu c/cm^2$)	$\frac{G_iC_w-C_i}{G_iC_w}$	$\ln \frac{G_iC_w-C_i}{G_iC_w}$	$-\frac{1}{t} \ln \frac{G_iC_w-C_i}{G_iC_w}$
1	55	1.60	53.40	0.971	-.029	0.029 day^{-1}
2	55	1.79	53.21	0.967	-.034	0.017 day^{-1}
3	55	3.33	51.67	0.939	-.064	0.021 day^{-1}
4	55	6.56	48.44	0.881	-.127	0.032 day^{-1}
5	55	8.52	46.48	0.845	-.169	0.034 day^{-1}
6	55	9.22	45.78	0.832	-.184	0.031 day^{-1}
7	55	6.43	48.57	0.883	-.125	0.018 day^{-1}
8	55	15.25	39.75	0.723	-.325	0.041 day^{-1}
9	55	11.52	43.48	0.791	-.235	0.026 day^{-1}
10	55	15.20	39.80	0.724	-.323	0.032 day^{-1}
11	55	9.21	45.79	0.833	-.182	0.017 day^{-1}
12	55	14.41	40.59	0.738	-.304	0.025 day^{-1}
13	55	24.94	30.06	0.547	-.603	0.046 day^{-1}
14	55	25.89	29.11	0.529	-.637	0.046 day^{-1}
15	55	27.88	27.12	0.493	-.707	0.047 day^{-1}
17	55	32.53	22.47	0.409	-.894	0.053 day^{-1}
18	55	21.90	33.10	0.602	-.508	0.028 day^{-1}
19	55	31.17	23.83	0.433	-.837	0.044 day^{-1}
21	55	37.63	17.64	0.321	-1.136	0.054 day^{-1}
23	55	21.68	33.32	0.606	-.501	0.022 day^{-1}
25	55	33.55	21.45	0.390	-.942	0.038 day^{-1}
					Average	0.033 day^{-1}

$K = 0.033\ day^{-1}$
$= 0.0014\ hr^{-1}$

1139039

Table 5-2. Calculating Mass Transfer Rate Coefficients for Concentration of ^{134}Cs by Bed Sediments in the West Channel

t (day)	G_iC_w ($\mu\mu c/cm^2$)	C_i ($\mu\mu c/cm^2$)	$G_iC_w - C_i$ ($\mu\mu c/cm^2$)	$\frac{G_iC_w - C_i}{G_iC_w}$	$\ln \frac{G_iC_w - C_i}{G_iC_w}$	$-\frac{1}{t} \ln \frac{G_iC_w - C_i}{G_iC_w}$
1	55	1.37	53.65	0.975	-.025	0.025 day^{-1}
2	55	4.01	50.99	0.927	-.076	0.038 day^{-1}
3	55	6.28	48.72	0.886	-.122	0.041 day^{-1}
4	55	5.30	49.70	0.904	-.101	0.025 day^{-1}
5	55	8.60	46.37	0.843	-.171	0.034 day^{-1}
6	55	6.42	48.58	0.885	-.125	0.021 day^{-1}
7	55	8.24	46.77	0.850	-.163	0.023 day^{-1}
8	55	19.32	35.68	0.649	-.432	0.054 day^{-1}
9	55	14.92	40.08	0.729	-.316	0.035 day^{-1}
10	55	26.20	28.80	0.524	-.646	0.065 day^{-1}
11	55	15.52	39.48	0.718	-.332	0.030 day^{-1}
12	55	24.97	30.03	0.546	-.605	0.050 day^{-1}
13	55	22.37	32.63	0.593	-.523	0.040 day^{-1}
14	55	15.90	39.10	0.711	-.341	0.024 day^{-1}
15	55	31.72	23.28	0.423	-.861	0.057 day^{-1}
16	55	29.90	25.10	0.456	-.787	0.049 day^{-1}
17	55	31.85	23.15	0.421	-.866	0.051 day^{-1}
18	55	38.55	16.45	0.299	-1.207	0.067 day^{-1}
19	55	40.48	14.52	0.264	-1.336	0.070 day^{-1}
20	55	35.39	19.61	0.356	-1.035	0.052 day^{-1}
21	55	27.93	27.07	0.492	-.709	0.034 day^{-1}
22	55	38.50	16.50	0.300	-1.204	0.055 day^{-1}
23	55	33.28	21.72	0.395	-.929	0.040 day^{-1}
					Average	0.043 day^{-1}

$K = 0.043$ day^{-1}
$= 0.0018$ hr^{-1}

1139040

the mass transfer coefficient for the concentration of ^{134}Cs by the sediment. The mass transfer coefficient for ^{134}Cs and ^{85}Sr in bed sediments in the East and West channels are given in Table 5-3. From Table 5-3 it is seen that the mass transfer coefficients for the West channel are 33% higher than the coefficients for the East channel in the case of ^{134}Cs and 20% higher in the case of ^{85}Sr. This resulted from the deposition or sorption in the West channel of phytoplankton containing radioactivity on the sediment in addition to concentration of radionuclides from the water by the sediment.

Mass Transfer Rate Coefficients of Plants

The mass transfer coefficients of plants were calculated in the same manner as were the coefficients for bed sediment. For ^{134}Cs the equilibrium concentration, G_iC_w, was 80 $\mu\mu$ c/gm and in the case of ^{85}Sr the equilibrium concentration was 24 $\mu\mu$ c/gm. From Fig. 5-4 the mass transfer coefficients were determined to be 0.696 day^{-1} and 0.912 day^{-1}, respectively, for ^{134}Cs and ^{85}Sr.

Table 5-3. Mass Transfer Coefficients of Sediments and Plants

Location	Mass Transfer Coefficients (day^{-1})			
	Sediments		Plants	
	^{134}Cs	^{85}Sr	^{134}Cs	^{85}Sr
East Channel	0.033	0.030		
West Channel	0.043	0.036	0.696	0.912

Prediction of ^{134}Cs and ^{85}Sr Concentrations

The time concentration curves for ^{134}Cs and ^{85}Sr along the East and West channels of the flume were predicted using the numerical solution (20) for equation (5-1). In the East channel the draw-down of radionuclides by sediments was considered, while plants and sediments were considered in the West channel.

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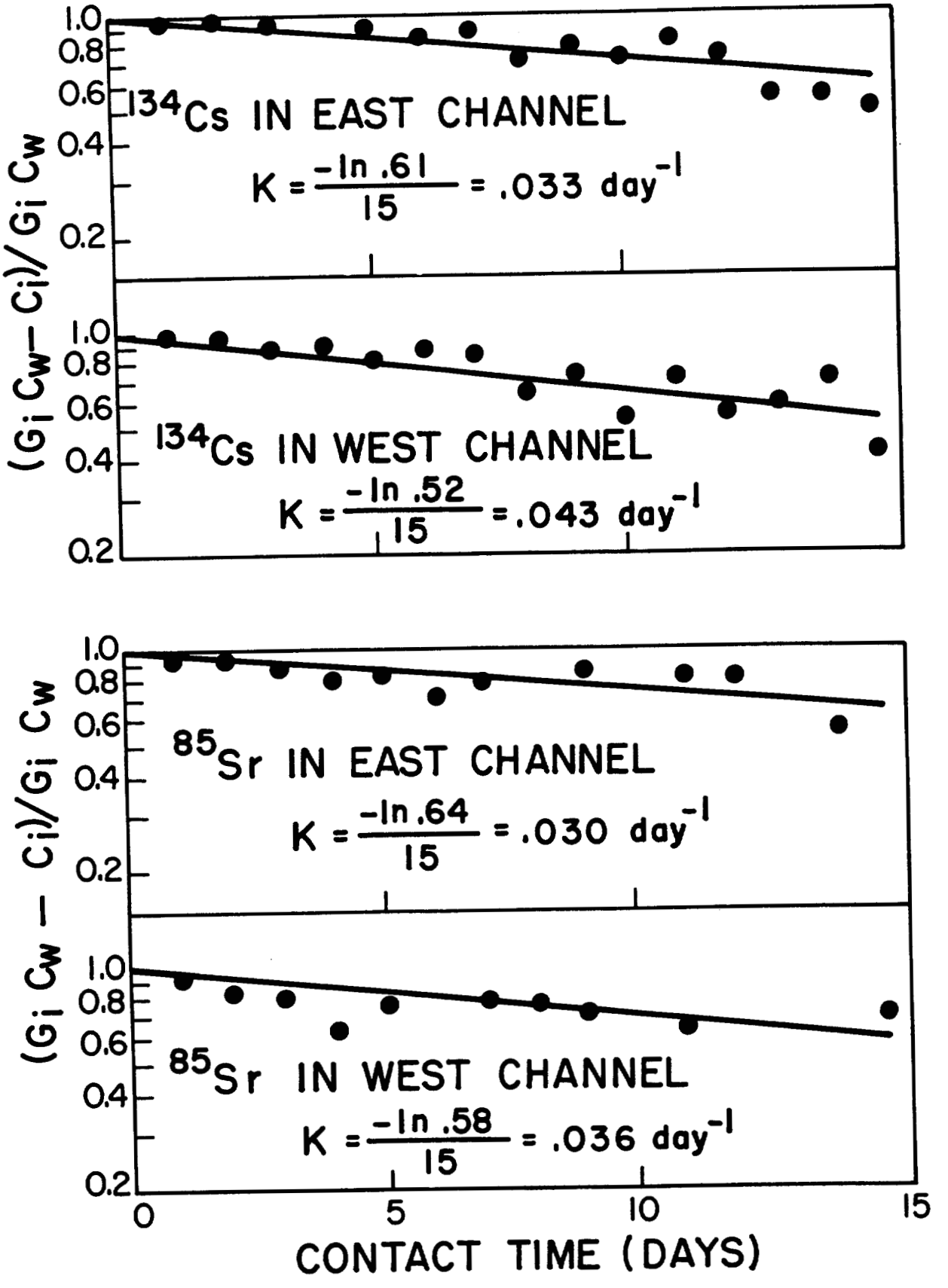

FIG. 5-3 TRANSFER RATE COEFFICIENTS FOR CONCENTRATION OF RADIONUCLIDES BY BED SEDIMENTS IN THE FLUME.

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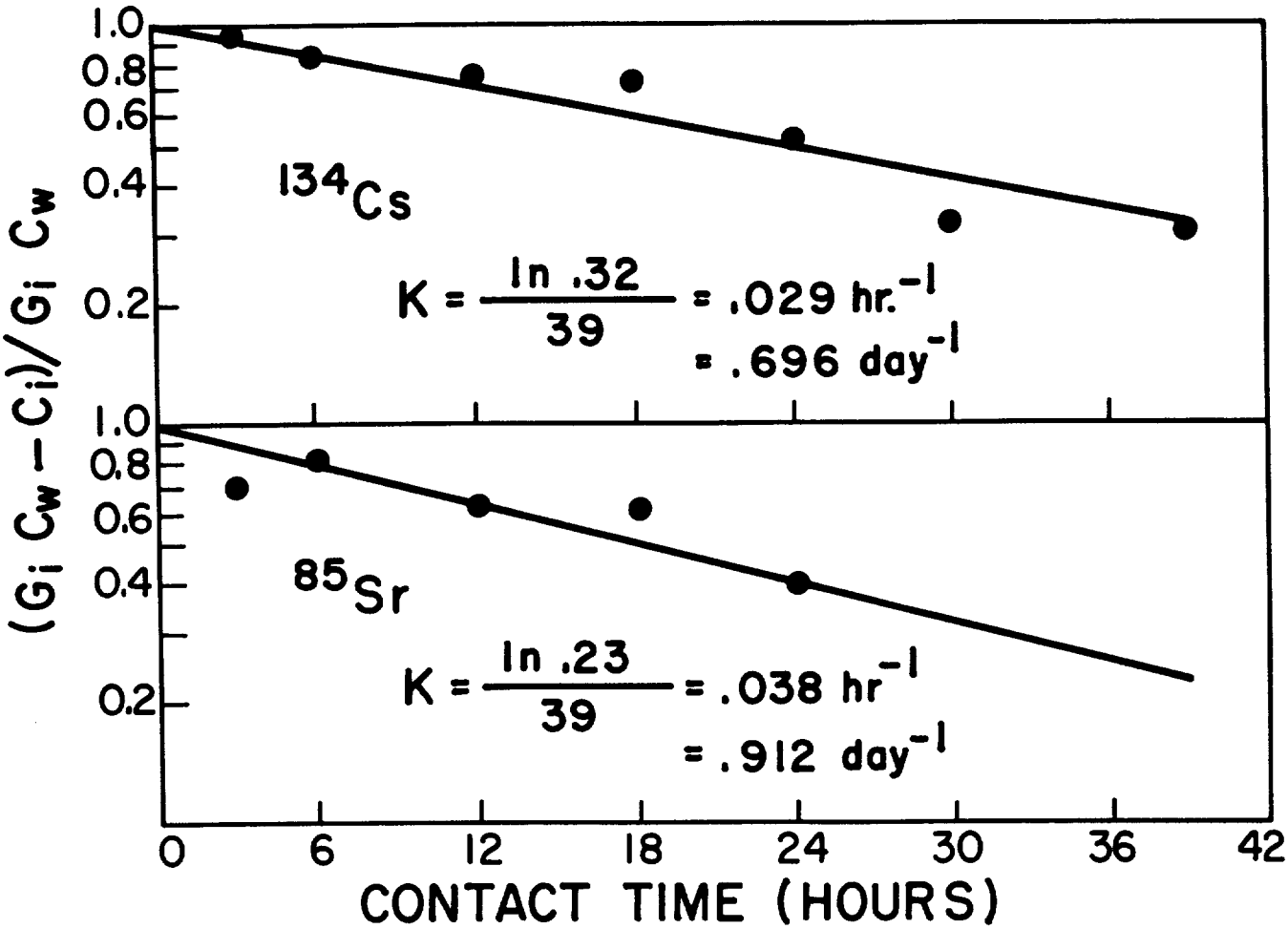

FIG. 5-4 TRANSFER RATE COEFFICIENTS FOR CONCENTRATION OF RADIONUCLIDES BY PLANTS IN THE FLUME.

The data obtained from the transport model predicts that equilibrium levels could be reached within three weeks of continuous discharge of radionuclides. Equilibrium is reached when the specific activity of the inflow water is equal to the specific activity of outflow water through the flume. This period of three weeks was also stated earlier from the observed data. However, the observed data oscillates around an equilibrium level due to changes in physicochemical and/or biological conditions which is not predictable by the transport model.

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CHAPTER VI

DISCUSSION

In the experiments described in the previous chapters, small scale river ecosystems were subjected to continuous releases of ^{134}Cs and ^{85}Sr and the roles played by bed sediment, rooted plants and phytoplankton in radionuclide transport were investigated. Bed sediments concentrated radioactivity on the surface at a rate at any given time directly proportional to the difference between a saturation value and the concentration in the water at that time. In approximately 30 days a quasi-equilibrium period was reached. Once saturation is reached at the sediment surface, radionuclide uptake by the sediment is equal to the radioactivity lost by the surface as a result of migration into the sediment. This migration into the sediment is a slow process.

The concentration of radionuclides in the sediment was affected by sediment movement. Convection currents, underflow, and the impoundment action of the effluent weir caused an areal distribution of radionuclides that was far from uniform. Under real river conditions it can be expected that areal distribution will not be uniform and large areas of bottom sediment will never reach saturation while other areas will be repositories of contaminated sediment.

Under continuous release conditions the extraction of radionuclides from the water phase on a mass balance basis has a minor affect on the specific activity in the water. Figures 6-1 and 6-2 indicate the amount of activity retained in the bottom sediments during the first 22 days of release as being approximately 10% of the released activity even in the flume's shallow system (6-7 inches). With increased depth the relative significance of sediment uptake probably becomes a lesser factor.

The Lake Austin sediment on a cm^2 basis concentrated up to 275 times the amount of ^{134}Cs initially in a cm^3 of flowing water and up to 85 times the ^{85}Sr activity. While this concentration normally has relatively little effect on the amount of radionuclides transported in the water phase, it may be an important factor in further accumulation of radioactivity by bottom feeding fauna.

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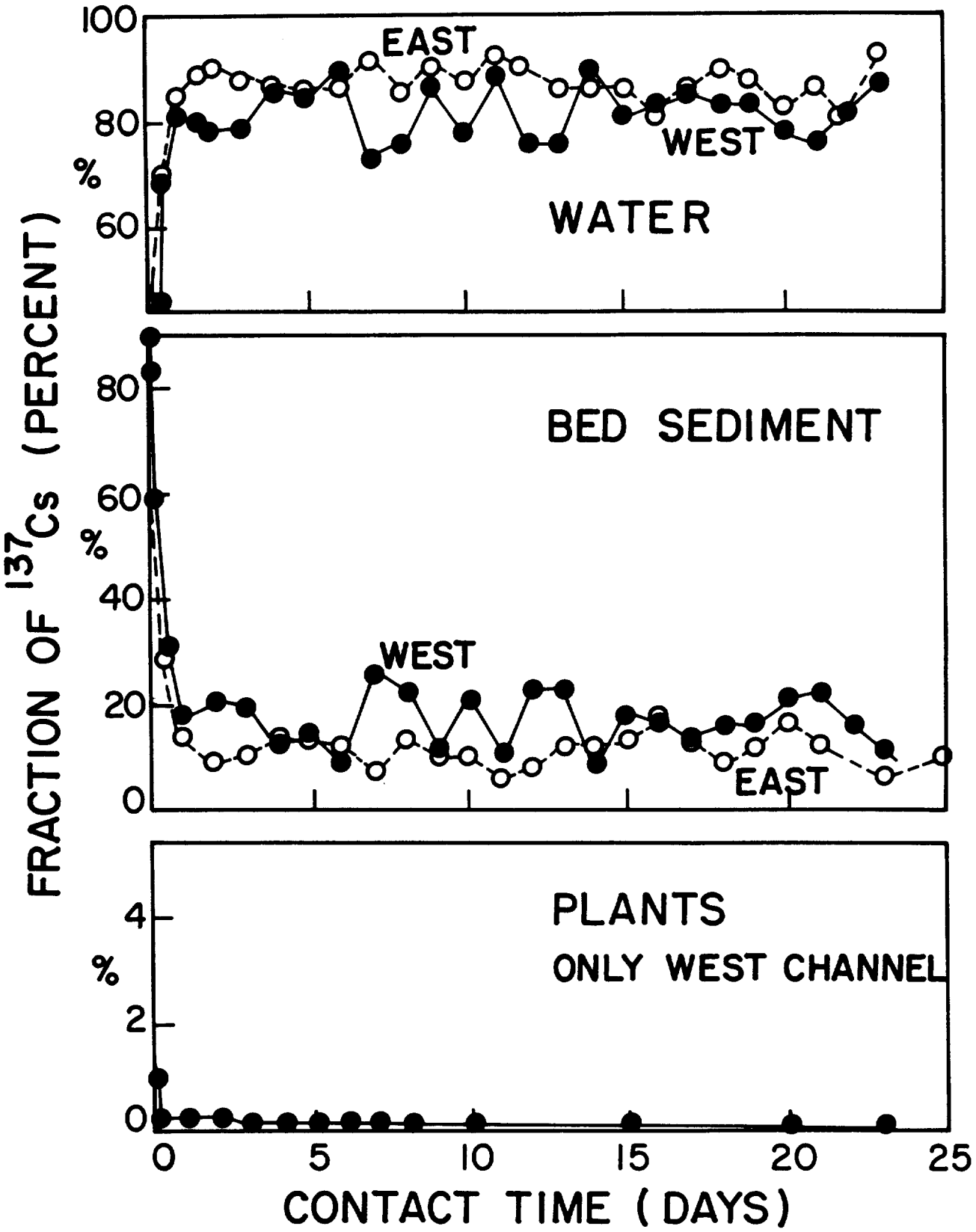

FIG. 6-1 MASS BALANCE OF CESIUM-134 RELEASED IN THE FLUME.

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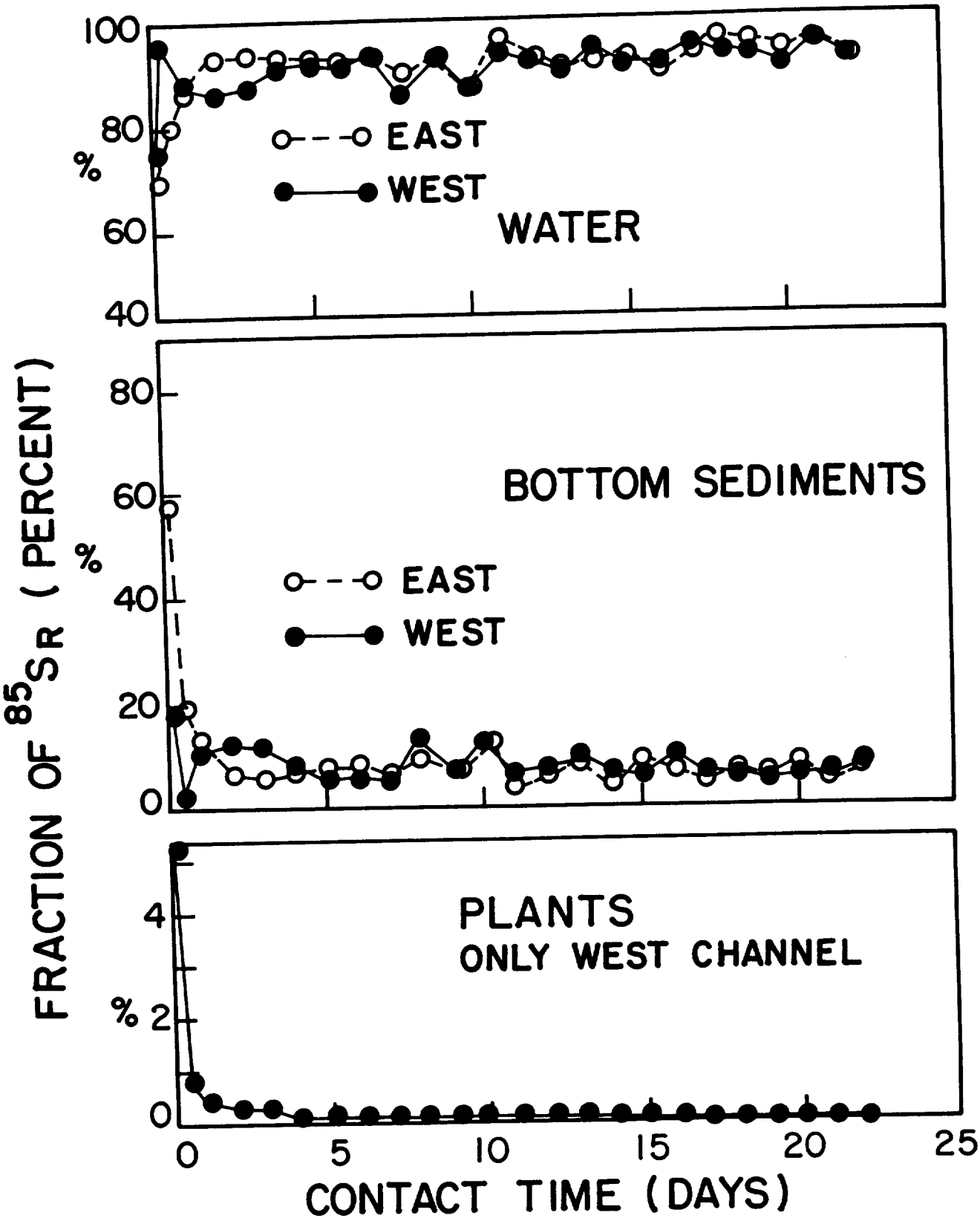

FIG. 6-2 MASS BALANCE OF STRONTIUM-85 RELEASED IN THE FLUME.

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Under continuous release of radionuclides, plants exert little influence on radionuclide transport, Figs. 6-1 and 6-2. As in the case of sediments, plants extracted radionuclides from the water phase until a quasi-equilibrium situation was reached. Where it took the bottom sediment 25 to 30 days to approach this equilibrium situation, plants required less than 36 hours. For plants, the concentration factors for ^{134}Cs and ^{85}Sr respectively averaged 400 to 600 ml/gm oven dry weight. This, as in the case of sediment, could be significant if the plant was through accumulation in the food chain.

Plants and sediment are subject to physical and biochemical upsets. An increase in flow may resuspend the sediment. Pollutional stresses, a reduction in pH and toxic materials may be responsible for sudden releases of radionuclides from both plants and sediment.

The uptake of ^{134}Cs by phytoplankton was related to the diurnal photosynthetic production of oxygen. Uptake in the flume varied from approximately 12 uuc/liter to approximately 48 uuc/liter depending upon the time of day. The large amount of ^{134}Cs uptake was probably due to the fact that the reservoir providing water to the flume was deficient in potassium. Upon entering the flume, the phytoplankton may have found ^{134}Cs as a substitute nutrient for potassium in its metabolic processes. While the lack of potassium probably exaggerated the effect of photosynthesis on ^{134}Cs uptake, it nevertheless demonstrated that there is a correlation between uptake and photosynthetic production of oxygen. On the other hand, no diurnal effect on the uptake of ^{85}Sr was noted. However, the specific activity in the water associated with these ^{85}Sr experiments was small compared to that with ^{134}Cs. Also the water contained an abundant supply of calcium.

1139048

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NUCLEAR SAFETY
SUMMARY OF PROGRESS IN AEC RESEARCH AND DEVELOPMENT PROJECTS
Please Submit All Contributions on These Forms

Due in Nuclear Safety Offices November 15, 1971

Bldg. 9764, P.O. Box Y
Oak Ridge, Tennessee 37830

1. Project Transport of Radionuclides in Water (107 02 52)
2. Organization and Site Department of Civil Engineering, The University of Texas
3. Person to Contact for Further Information Earnest F. Gloyna

4. Objectives for Current Reporting Period (30 words or less, DOUBLE SPACED); use as much of the allowable space as necessary to make the objectives self-sufficient without undue reference to previous Nuclear Safety reports:

To complete the report on biological accumulation of various species of radionuclides by chlorella.

5. Accomplishments During Current Reporting Period (100 words or less, DOUBLE SPACED):

Report on continuous release of ^{85}Sr and ^{134}Cs experiments in a research flume is completed.

6. Plans for Next Reporting Period (30 words or less, DOUBLE SPACED):
To complete the report on biological accumulation of various species of radionuclides by chlorella.

7. Pertinent Reports Published During Current Reporting Period (citations must be complete and accurate; see cover letter for instructions); list periodic reports to the AEC, as well as those published for general distribution:

"Continuous Release of Radionuclides in The Small Ecosystem"

co/ Y. Yousef and T. Padden. Technical Report #21 to AEC

Date November 8, 1971
Phone 471-1166

Prepared by [signature] NOV 1 1 1971
Business Address Taylor Hall 167
Austin, Tx 78712

1139052

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NUCLEAR SAFETY
SUMMARY OF PROGRESS IN AEC RESEARCH AND DEVELOPMENT PROJECTS
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Due in Nuclear Safety Offices July 15, 1971

Bldg. 9764, P.O. Box Y
Oak Ridge, Tennessee 37830

1. Project Transport of Radionuclides in Water (107 02 52)
2. Organization and Site Department of Civil Engineering, The University of Texas
3. Person to Contact for Further Information Earnest F. Gloyna

4. Objectives for Current Reporting Period (30 words or less, DOUBLE SPACED); use as much of the allowable space as necessary to make the objectives self-sufficient without undue reference to previous Nuclear Safety reports: To complete bench scale experimentations on biological accumulation of various species of radionuclides by chlorella.

5. Accomplishments During Current Reporting Period (100 words or less, DOUBLE SPACED):

Report on continuous release of ^{85}Sr and ^{134}Cs experiments in a research flume is completed.

6. Plans for Next Reporting Period (30 words or less, DOUBLE SPACED):
To complete analysis of bench scale experiments on biological accumulation of various species of radionuclides by chlorella.

7. Pertinent Reports Published During Current Reporting Period (citations must be complete and accurate; see cover letter for instructions); list periodic reports to the AEC, as well as those published for general distribution:

"Transport of ^{137}Cs-II, Interaction with Bed Sediments" co/ Akira Kudo, Water Research, Vol. 5, pp 71-79 Pergamon Press (1971). Printed in Great Britain.

Date June 30, 1971
Phone

Prepared by Earnest F. Gloyna
Business Address

1139053

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NUCLEAR SAFETY
SUMMARY OF PROGRESS IN AEC RESEARCH AND DEVELOPMENT PROJECTS
Please Submit All Contributions on These Forms

Due in Nuclear Safety Offices March 15, 1972

Bldg. 9764, P.O. Box Y
Oak Ridge, Tennessee 37830

//

1. Project Transport of Radionuclides in Water (107 02 52)
2. Organization and Site Department of Civil Engineering, The University of Texas at Austin
3. Person to Contact for Further Information Earnest F. Gloyna

//

4. Objectives for Current Reporting Period (30 words or less, DOUBLE SPACED); use as much of the allowable space as necessary to make the objectives self-sufficient without undue reference to previous Nuclear Safety reports:

To complete the report on biological accumulation and desorption of mercurials by Chlorella.

//

5. Accomplishments During Current Reporting Period (100 words or less, DOUBLE SPACED):

The study to evaluate the influence of various environmental factors on the accumulation and desorption of mercurials by Chlorella was completed.

//

6. Plans for Next Reporting Period (30 words or less, DOUBLE SPACED):

NONE

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7. Pertinent Reports Published During Current Reporting Period (citations must be complete and accurate; see cover letter for instructions); list periodic reports to the AEC, as well as those published for general distribution:

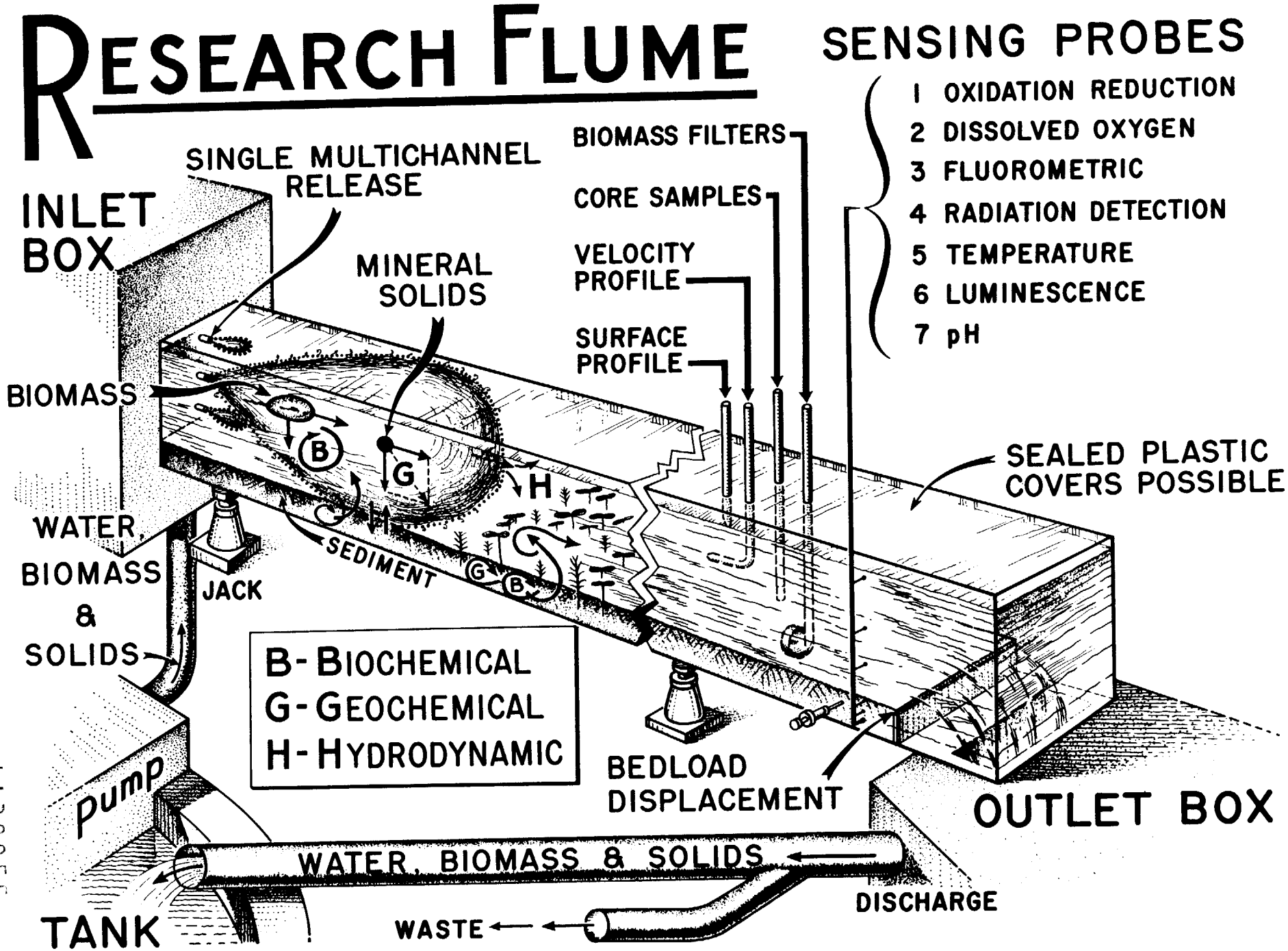
"Model Rivers, An Aid in Decision Making," Conflicts in Water Resources, Water Resource Symposium No. 5, CRWR, Gloyna, E.F., and T. J. Padden (1972)

Date March 1, 1972
Phone (512) 471-1166

Prepared by
Business Address University of Tx at Austin
Taylor Hall 167, Austin, Texas 78712

1139054

RESEARCH FLUME



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