APPLICATION OF RADIOACTIVE TRACERS IN THE STUDY OF SEDIMENT MOVEMENT

by

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ABSTRACT

Radioactive tracer techniques were employed in order to investigate the dispersion and transport of bed material in a test reach of the North Loup River near Purdum, Nebraska. Sand particles, labelled with Iridium-192, were used as tracers to enable observation of the natural dispersion and transport processes.

The amount of radioactivity and the number of tracer particles required for the experiment was determined by considering the sensitivity of the radiation-detection system, the characteristics of the test reach, and radiological safety considerations.

In the experiment, the tracer particles were released from a line source which extended across the bed of the stream. As the tracer particles were transported and dispersed downstream, their longitudinal and lateral distributions in the bed were observed by periodic surveys with a sled-mounted scintillation detector, and their vertical distribution in the bed was observed by monitoring core samples. Information obtained from a laboratory calibration of the radiation-detection system under simulated field conditions was used to reduce the field data to a set of tracer-particle concentration-distribution curves.

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[1] For presentation at Federal Inter-Agency Sedimentation Conference, Jackson, Mississippi, January 28-February 1, 1963.

The results of the field study indicate a potential for the wide application of radioactive tracer in sediment studies.

INTRODUCTION

One relatively new measuring technique that is being applied more and more frequently in studies of sediment transport is the radioactive tracer technique. This technique is essentially different from more conventional methods in that the displacement of individual particles or groups of particles is measured rather than such characteristics as the flux of sediment particles past a cross section, the net volumetric change in a reach, or the displacement of channel boundaries. As a result, the radioactive tracer technique is particularly useful in studies of the dispersion of sediment, the rate of travel of sediment particles, and in other studies concerned with the fundamental mechanics of sediment movement.

Although radioactive tracers can be extremely useful, a number of factors must be considered in their application. In general, the accuracy of measurements increases as the level of radioactivity increases. However, the higher the level of radioactivity, the greater is the possibility for harmful contamination and radiation exposure. As a result, in order to achieve a satisfactory balance between the level of accuracy and the level of radioactivity, all aspects of an experiment must be considered in detail. The fundamental factors for consideration include (1) the kinds and required accuracy of measurements to be made, (2) the radionuclide to be used as a tracer and the means for labelling the sediment particles, (3) the amount of the tracer to be used, (4) the method of introduction of the tracer into the flow system, (5) the method of detection of the radioactivity, and (6) the reduction of the data.

The purpose of this paper is to discuss briefly some of these factors as they were considered in the design and implementation of a field experiment on the North Loup River, Nebraska, that was conducted by the U. S. Geological Survey in November, 1960.

EXPERIMENTAL DESIGN

The primary object of the field experiment was to study the dispersion and transport of bed material particles in a natural stream. Hence, it was decided to release radioactive tracer particles as a line source and then to monitor the longitudinal distribution of the particles at various times after release. The site on the North Loup River near Purdum, Nebraska, was selected because of favorable experimental conditions. In particular, the North Loup River, which is in the sand hill region of north-central Nebraska, maintains a relatively constant water discharge of about 250 cfs for prolonged periods of time, draws from rather than contributes to the ground water, has a bed normally composed of large dunes approximately 1.5 ft high and 15 ft long, and has bed material having a median diameter of about 0.29 mm. The specific reach used for the experiment is a man-made cutoff about 1,800 ft long and 50 ft wide that is fairly straight except for two minor bends, has stable banks, and is isolated from any community.

It was concluded that optimum results would be obtained by using a single, narrow, size range of tracer particles having a median fall diameter that was slightly coarser than that of the bed material. Such a size range was selected to insure that the tracer particles would not be in suspension any significant part of the time, but, that the particles in the size range containing the greatest proportion of the bed material would be represented. The selected tracer particles had a median particle size of 0.305 mm and a distribution as illustrated in figure 1.

Figure 1.--Size distributions of measured suspended sediment, labelled Ottawa sand, and bed material.

A comparison of the distribution of the tracer particles with those of the suspended sediment and the bed material, which are also presented in figure 1, shows that most of the tracer particles could have been in suspension at one time or another, but that suspension probably occurred only infrequently.

Because the tracer particles would move primarily as bed load, "in situ" measurements seemed to be the most feasible means of defining the longitudinal dispersion of the particles. Such measurements virtually necessitated the use of a gamma-emitting radionuclide because the penetration range of alpha and beta radiation is limited to only a few centimeters in water. A scintillation detection system was selected to monitor the gamma radiation because of its versatility and its inherently high sensitivity. The system consisted of a scintillation detector, pulse-height analyzer, count rate meter, strip chart recorder and scaler. With this system the number of gamma rays (photons) which interact with the crystal in the detector can be counted and displayed as a count rate or a count accumulation. Inasmuch as the number of gamma rays emitted from a source is directly proportional to the amount of radioactivity, within statistical limitations and provided all other factors are the same, the count rate also is proportional to the amount of activity. Hence, if the amount of activity on each particle is proportional to the particle weight, measured count rates indicate the weight of tracer particles near the detector provided, of course, suitable calibrations have been made.

For the experiment, the scintillation detector was housed in a water-tight aluminum casing and mounted on a sled (see figure 2) that was dragged along the stream bed. The detector was attached to the sled by a four-bar parallelogram linkage and supported on the bed by a wooden dish. This system allowed the detector to remain in continuous contact with the stream bed during transport and to move vertically independently of the sled.

Figure 2. --Sled and scintillation detector. Note the parallelogram linkage that allows the detector to move independently from the sled and the wooden dish-shaped piece that supports the detector on the bed.

Iridium-192 was selected as the tracer because it (1) emits gamma rays having energies that are readily detectable underwater (0.14 to 0.90 mev); (2) has a half-life of 74 days, hence, it would decay slowly enough to be readily detectable during the entire experiment, but rapidly enough to preclude long-term contamination of the stream; and (3) could be procurred commercially already plated onto sand particles. The plating process consisted of wetting the sand in a solution containing the Iridium-192 and then baking the sand at 700°F for several hours. Tests showed that with continuous agitation of the particles immersed in water approximately 25 percent of the activity was abraded from the particles in 24 hours. Although it is impossible to relate the amount of abrasion the particles received in the tests to that likely to occur in a natural stream, 24 hours of agitation no doubt is equivalent to a relatively long time. Krone[2] also plated the radionuclide onto the sediment by an adsorption process. However, other methods of producing tracer particles have been used. For instance, Inose and others[3] incorporated the radionuclide into

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[2] Krone, R. B., first annual progress report on the silt transport studies utilizing radioisotopes. California Univ. Inst. Eng. Research, 118 p., 1957.

[3] Inose, S., Kato, M., Sato, S., and Shiraishi, N., the field experiment of littoral drift using radioactive glass sand. Proc. 1st U.N. Int. Conf. on the Peaceful Uses of Atomic Energy, v. 15, p. 211-219, 1956.

glass particles that simulated the sediment, and Lean and Crickmore[4] irradiated natural sand in a nuclear reactor. A summary of the various labelling techniques that have been used is given by Feely and others.[5]

One important factor in connection with sand plated with a radionuclide is that the measured activity is proportional to the surface area of the particle rather than to its weight. If a wide range of particle sizes is labelled, this factor must be considered in converting a measured count rate to a weight of tracer particles; however, if the particles are relatively uniform in size, the count rate is also approximately proportional to particle weight.

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[4] Lean, G. H., and Crickmore, M. J., the laboratory measurement of sand transport using radioactive tracers. Dept. of Sci. and Ind. Res., Hydraulics Research Station, Wallingford, England, 26 p., 1960.

[5] Feely, H. W., Walton, A., Barnett, C. R., Bazan, F., the potential applications of radioisotope techniques to water resource investigations and utilization. AEC Res. and Dev. Rpt NYO 9040, 340 p., 1961.

The amount of radioactivity required for the experiment was determined by considering the natural background radiation, the volume of sand throughout which the particles would be dispersed, the decay rate of the activity, the adsorption characteristics of the sand and water, the efficiency of the detection system, and the geometrical orientation of the detector to the tracer particles. The effects of the latter three items can be characterized by the "sensitivity" of the detection system, which is the count rate per unit of activity per unit volume under specific experimental conditions. The sensitivity of a detection system to a uniformly distributed source such as sand tracer particles can be estimated by defining a count-rate attenuation function through measurements of the count rate from a weak point source buried at different locations and distances relative to the detector and then integrating the attenuation function over the volume through which the tracer particles will be distributed.

Once the sensitivity is determined, the amount of radioactivity, M, required for experiment can be computed from

$$M = \frac{(R_o - R_b)\,V\,e^{0.693\,t/T}}{S}$$

in which

$R_o - R_b$	is the minimum net counting rate over background that is required during the experiment for statistical significance.
V	is the estimated volume through which the tracer particles will be dispersed at the end of the experiment.
S	is the sensitivity of the detection system for the conditions of the experiment.
$e^{0.693\,t/T}$	is a correction factor for radioactive decay.

where

t	is the duration of the experiment.
T	is the half-life of the radionuclide.

In the design of this experiment, a net minimum counting rate equal to one-half of the background rate was considered acceptable for the condition of a uniform distribution of tracer particles throughout the test reach. By assuming that the experiment would last for one month, it was determined that 40 millicuries of Iridium-192 would be required.

When radioactivity is labelled on sediment particles, each particle is a separate source and the count rate measured by the detection system depends not only on the amount of radioactivity, but also on the distribution of the tracer particles. As a result, sufficient particles must be used in order to minimize the possibility of significantly non-uniform distributions within the bed. If the distribution of tracer particles throughout the bed is random, as the concentration of tracer particles increases, the relative distribution of the tracer particles tends to become more even and random variations in the number of tracer particles per unit volume of bed material tend to have less affect on the count rate. The random variations in the number of particles in a given volume can be characterized by the coefficient of variation or the relative standard deviation. If the variation in the number of tracer particles in a given volume is assumed to follow the Poisson distribution, the coefficient is $100/\sqrt{N}$, where N is the mean number of tracer particles in the given volume of bed material. For experimental desigh, a coefficient of about ± 6 percent seems to be adequate when the volume associated with N is defined as that volume of the bed from which 50 percent of the measured gamma rays (counts) emanate when the sand bed contains a uniformly distributed source of infinite extent, and N is taken as the required number of tracer particles within the volume at the end of the experiment when the tracer particles are distributed over the test reach. Of course, the coefficient of variation provides only an index to the expected variation in count rate attributable to random variation in the number of tracer particles. However, if a relatively long rate meter time constant is used and the detector is moved along the bed, the fluctuations in count rate due to local variations in the distribution of tracer particles are damped appreciably. Sensitivity measurements for the Iridium-192 and the detection system used in the experiment indicated that 50 percent of the counts emanate from within 4.4 in. of the center of the 2 in. x 2 in. detector crystal, which is equivalent to a volume of 116 cu in. The coefficient of variation with this volume for the total reach volume of 1,800 x 50 x 1.5 cu ft and the 40 lbs of sand (approximately 4.6 x 10^8 particles) used in the experiment was 6.6 percent.

In order to establish the exact relationship between count rates and the weight of tracer particles, the detection system was calibrated under conditions that simulated the actual experimental environment. The calibration was made in a 4 ft diameter by 4 ft high tank in which known weights of tracer particles were mixed with known volumes of natural bed material similar to that in the North Loup River. Count rates were measured for different depths of uniformly distributed particles and for different ratios of the weight of tracer particles to the volume of natural sand (concentrations). In order to reduce the background count rates a depth of 9 in. of water was maintained over the sand bed throughout the calibrations.

The results of the calibrations, which were for two different instrument settings, are shown in figure 3. This figures shows that

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Figure 3.--Variation in adjusted count rate with the depth to which different concentration of tracer particles are uniformly mixed.

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the adjusted count rate, which is a count rate adjusted for radioactive decay, varies with depth, as well as with concentration, for all depths less than about 8 in.; for depths greater than about 8 in. the adjusted count rate varies only with concentration. In the experiment it was anticipated and eventually borne out that the particles would be distributed to depths greater than 8 in. As a result, the only portion of the calibration curves required for converting the count rates observed in the field to concentrations were those portions for an 8 in. depth.

DATA COLLECTION AND RESULTS

In order to study longitudinal dispersion, the tracer particles were introduced essentially as a line source by depositing the 40 lbs of tracer particles in 2-lb lots at 2-ft intervals across the width of the channel. Each 2-lb lot was labelled with 2 millicuries of Iridium-192. The labelled particles were placed on the stream bed by using the apparatus and technique shown in figure 4. The apparatus consisted of an electric can opener and a movable funnel tube which were mounted to the stern of the boat. In the placement (dosing) operation, the funnel tube was lowered until the bell at the bottom of the tube rested on the stream bed, then, a can containing the tracer particles was opened with the can opener and poured down the funnel tube to the stream bed.

Figure 4.--The dosing operation.

About 2 hours after the dosing operation was completed the first longitudinal traverse was made. Just before this traverse, as well as all subsequent ones, the detector sled was placed by hand upstream from the dosing section and the natural background radiation was recorded for about 2 minutes. After background counting, the boat was released and maneuvered downstream. The longitudinal traverses were made with the boat and the detector sled arranged in tandem as is shown in figure 5. The boat, which faced upstream and pulled the detector sled, was maneuvered downstream by means of an outboard motor having reverse controls. Mounted on the front end of the boat was a distance-measuring cable and reel which functioned both as a stay line and as the distance marking system. In operation, the cable, which was fixed at the upstream end of each segment of the test reach, was unwound manually so that the boat and sled moved downstream at a uniform controlled rate. When buttons that were located at definite intervals along the cable tripped an event-marking switch, ticks were made on the recorder charts. In this way the recorder charts were provided directly with a distance coordinate.

Figure 5.--Arrangement of boat and sled for the longitudinal traverses.

The tracer particles were tracked daily by making longitudinal traverses with the radiation detection equipment down the left and right sides of the stream along paths that were roughly 1/3 of the channel width away from the bank. Typical data produced by the longitudinal traverses are shown in figures 6 and 7. The distribution curves in these figures were established by adjusting the observed count rates for radioactive decay and then converting the adjusted count rate to a concentration with the calibration curves. One particularly interesting occurrence is indicated by the distribution curve in figure 7. This curve shows that on about the seventh day after dosing a relatively large number of tracer particles appeared just downstream from the dosing section along the left side of the stream. Apparently, tracer particles were trapped in a deep trough and remained buried beyond the range of the radiation detection equipment for several days. About the seventh day after dosing, the trapped particles were released by a train of dunes having deep troughs. The particles then began to disperse in a normal manner. As a result of the temporary storage, the distribution curves for the left side of the test reach were less indicative of the general distribution that applies for the average flow condition than those for the right side.

Figure 6. --Longitudinal distribution of labelled particles along the right side of the channel, Nov. 3-8, 1960.

Figure 7. --Longitudinal distribution of labelled particles along the center of the channel, Nov. 7 and 9, 1960.

In addition to the longitudinal traverses, several traverses were made to define the lateral distribution of the tracer particles. Figure 8 shows the lateral distribution of the particles 185 ft downstream from the source 3 days after dosing and 415 ft downstream from the source 5 days after dosing. The deficiency of particles along the left bank near the source is evident in the distribution for the third day after dosing. The distribution curve for the fifth day after dosing indicates a reasonable uniformity of the tracer particles.

Figure 8. --Lateral distribution of labelled particles downstream from the source on Nov. 5 and 8, 1960.

In order to develop accurate concentration-distribution curves from the observed count rates and the calibration curves, it was essential that the depth to which particles were dispersed generally was greater than 8 in. and that no general vertical concentration gradient persisted throughout the stream bed. Two different methods were used to verify the fact that these two conditions existed. The first method consisted of defining the vertical distribution of tracer particles into the bed. This was done by collecting core samples of the bed material at various lateral and longitudinal positions in the test reach. The core samples were collected with a 1-1/2 in. diameter sampler capable of withdrawing a 3-ft long core. For analysis, the cores were ejected in 2 in. increments with a hand jack attached to the end of the sampler plunger and each increment was counted separately with a scaler by using the scintillation detector and sled in an inverted position. Some typical observed vertical distributions are shown in figure 9. A common characteristic of all of the vertical distributions was that the count rate was highly variable with depth into the bed and no semblance of a continuous vertical distribution pattern was definable. Probably the variations resulted largely from the passage of dunes having different amplitudes, mean elevations, and concentrations of tracer particles. Unfortunately, as a result of these irregularities of the movements of the dunes, neither the distance below the water surface, distance below the bed surface nor depth of activity could be

Figure 9. --Vertical distribution of labelled particles at selected verticals on Nov. 10 and 11, 1960.

used to normalize the vertical distribution of count rate. Hence, the distributions from the separate verticals could not be combined to provide an average gradient. However, the distributions from the separate verticals were combined to show that the average depth of the zone through which the sediment particles moved was about 1.45 ft. Because the average depth of the zone of movement was considerably greater than 8 in. and no discernable vertical distribution pattern appeared to exist, it seems reasonable to assume that the observed longitudinal and lateral distributions generally were representative of the actual distribution of the tracer particles.

The validity of converting the observed count rates to concentration of tracer particles with the calibration curves for an 8 in. depth was further verified by comparing the distribution of observed count rate with records of the bed configuration. The comparisons showed that no correlation existed between the depth of the zone of particle movement, as characterized by a profile of the bed configuration over which the detector passed, and the observed count rate. The apparatus for measuring bed configuration was a dual channel ultra-sonic depth sounder[6] which was mounted on the bow of the boat with one transducer facing upward and another facing downward so that both the water- and bed-surface profiles were recorded. A typical record of the bed configuration is shown in figure 10.[7]

Figure 10.--Water and bed surface profiles defined by the dual channel stream monitor. (From Hubbell and Haushild, 1962.)

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[6] Karaki, S. S., Gray, E. E., and Collins, J., dual channel stream monitor. Am. Soc. Civil Engineers Proc., v. 87, no. HY6, p. 1-16, 1961.

[7] Hubbell, D. W., and Haushild, W. L., discussion of "dual channel stream monitor." Am. Soc. Civil Engineers Proc., v. 88, no. HY4, p. 287-291, 1962.

CONCLUSIONS AND APPLICATION OF RESULTS

The results of the field study and subsequent laboratory flume studies indicate that the concentration of labelled sediment particles at any point in the stream bed at any time can be determined conveniently, accurately, and safely with radioactive tracer techniques. This conclusion is important because it implies the feasibility of determining, by experiment, distributions of labelled particles in a stream channel with respect to space and/or time for a wide variety of conditions. For example, by selective labelling, certain aspects of the behavior and distribution of particles having definite sizes, shapes, specific gravities, and other characteristics can be determined. Furthermore, by using a scintillation detector in conjunction with a pulse-height analyzer, different radionuclides can be distinguished from one another so that several selected labels can be used simultaneously to observe the behavior of different types of particles in the same experiment. For example, the authors currently are conducting laboratory flume experiments in which three different radionuclides are used to trace, simultaneously, the movement of three different sizes of particles in a bed material of naturally graded sand. Measurement of concentration distributions of labelled particles will provide new insights into the phenomenon of sediment transport and will supply the kind of data necessary for analyzing sediment transport as a random phenomenon that can be characterized by probability laws and treated as a stochastic process.

In addition, observed longitudinal distributions of tracer particles released from a uniformly distributed source provide a means for computing sediment discharge directly with a continuity type equation. The computation is based on the idea that (1) the time rate of movement of the mean of the distribution is equivalent to the average particle velocity and (2) the extent of the tracer particle distribution within the bed defines the effective cross-sectional area through which the particles move.

The examples given above indicate only a few of the many possible applications of radioactive tracers in sediment transport research. Probably only a small part of potential value of radioisotope techniques in sediment research has been realized. It is the authors' hope that this paper will serve to assist others with the development of new applications.

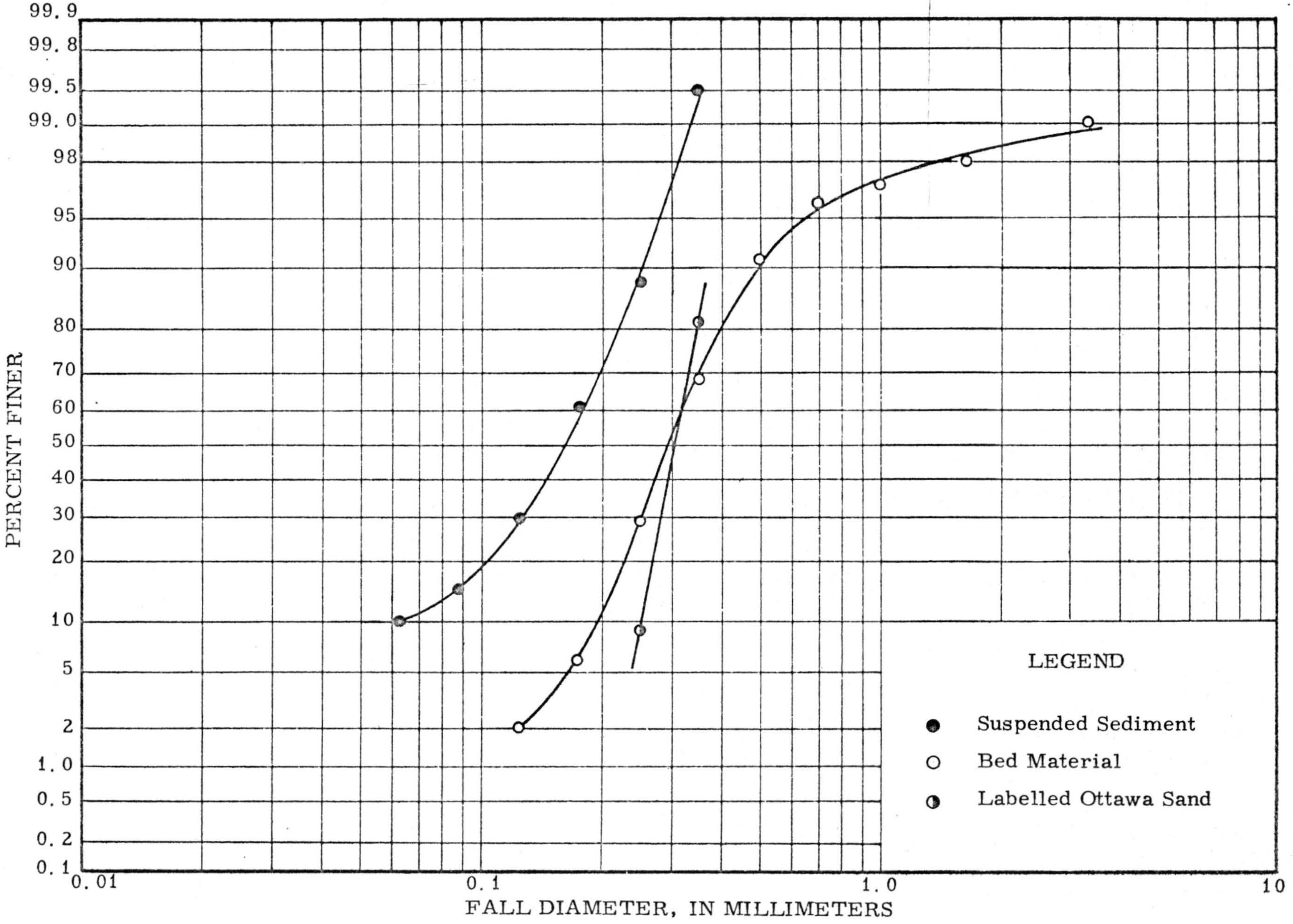


Figure 1.--Size distributions of measured suspended sediment, labelled Ottawa sand, and bed material.

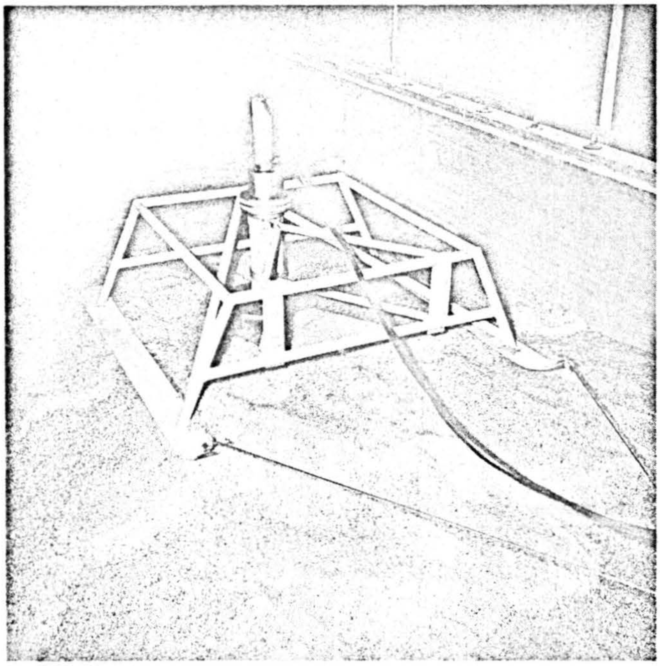


Figure 2. --Sled and scintillation detector. Note the parallelogram linkage that allows the detector to move independently from the sled and the wooden dish-shaped piece that supports the detector on the bed.

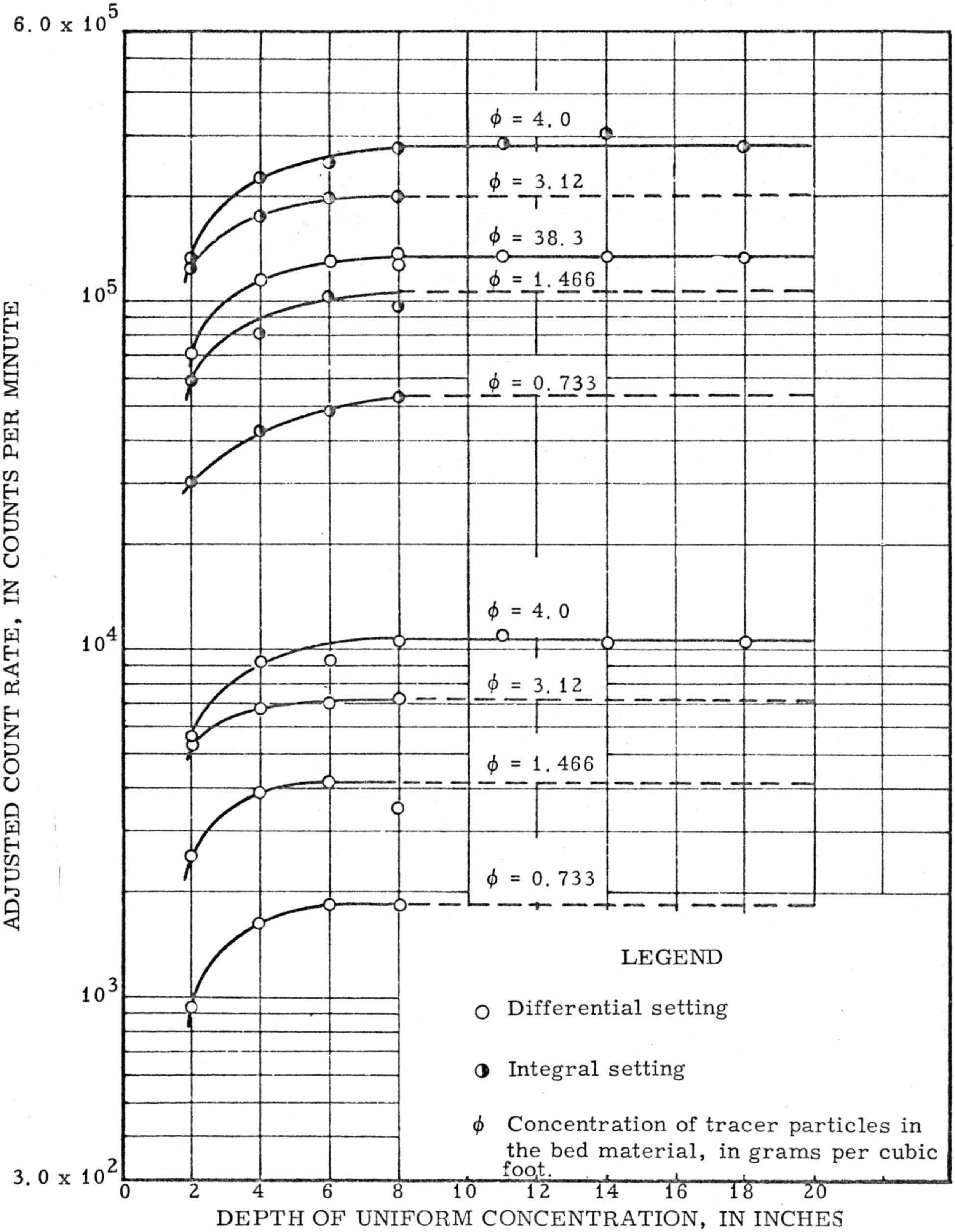


Figure 3. --Variation in adjusted count rate with the depth to which different concentration of tracer particles are uniformly mixed.

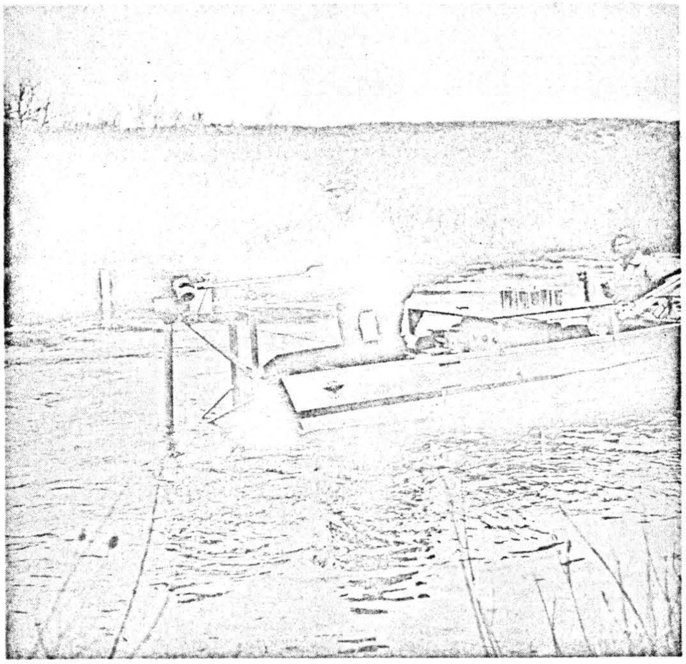


Figure 4. --The dosing operation.

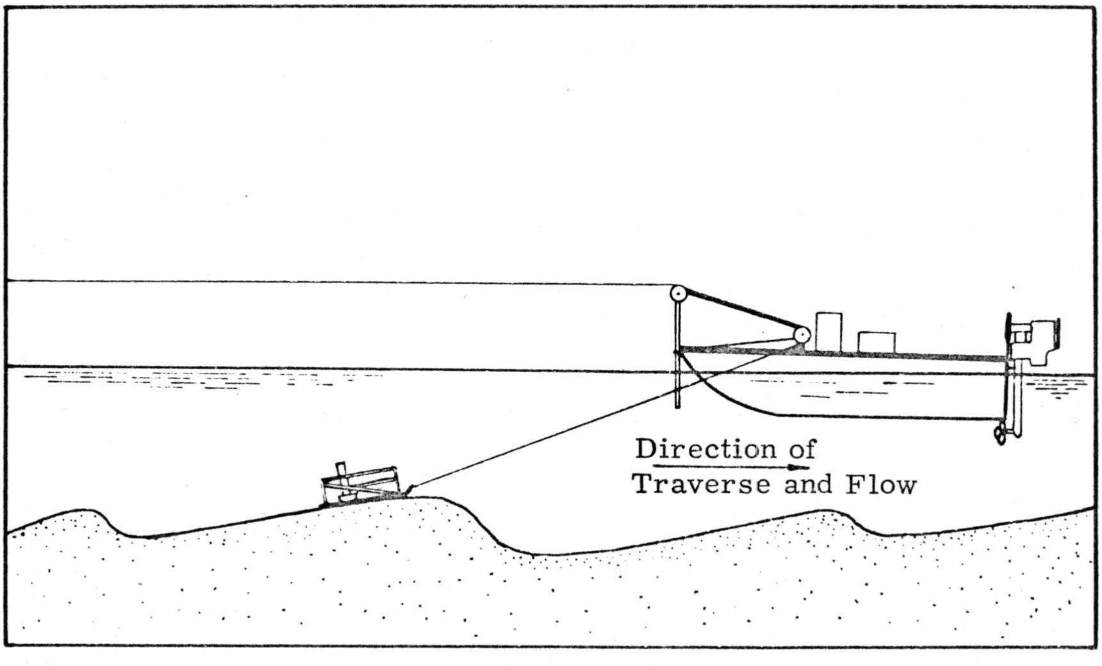


Figure 5. --Arrangement of boat and sled for the longitudinal traverses.

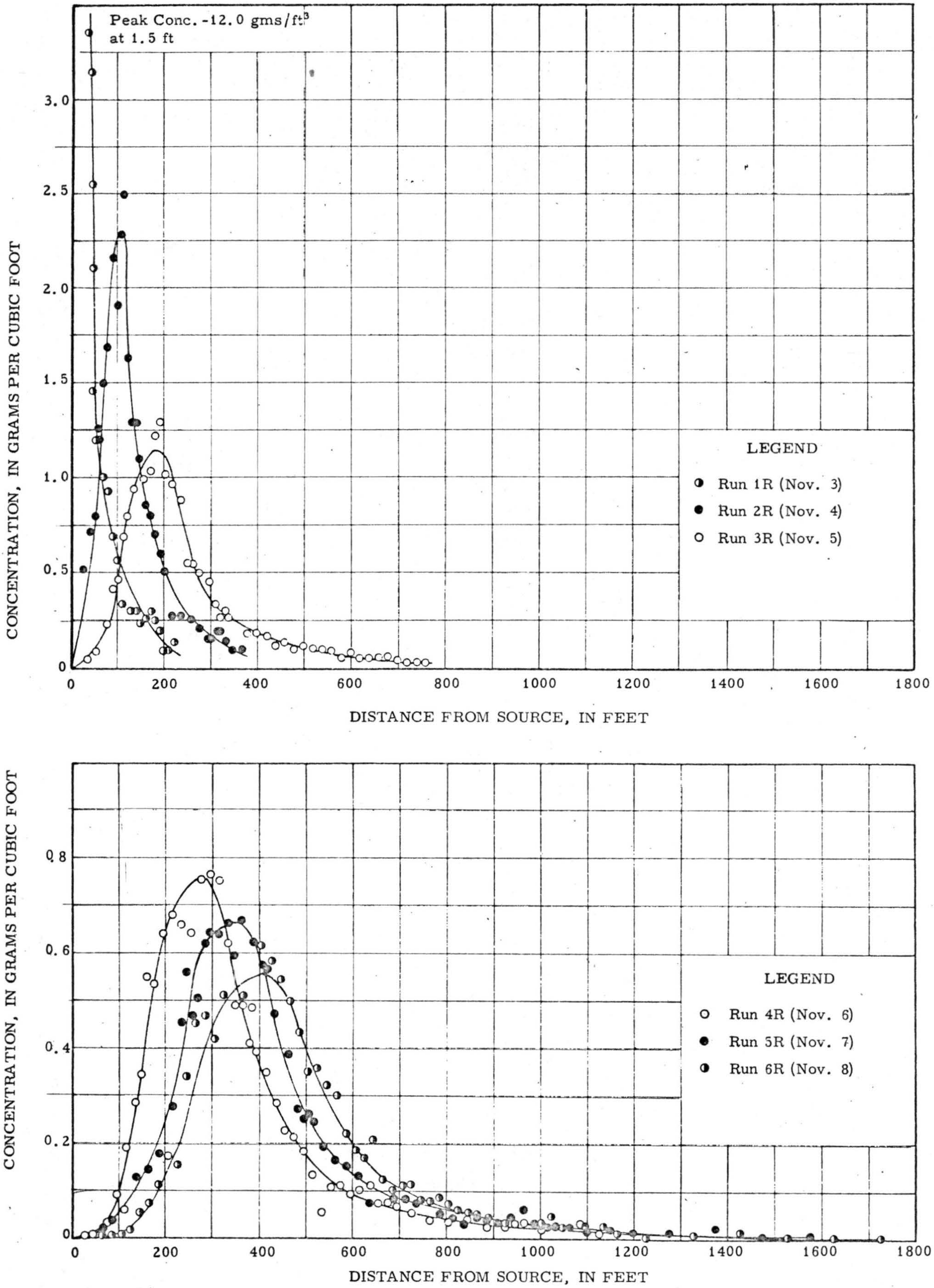


Figure 6 --Longitudinal distribution of labelled particles along the right side of the channel, Nov. 3-8, 1960.

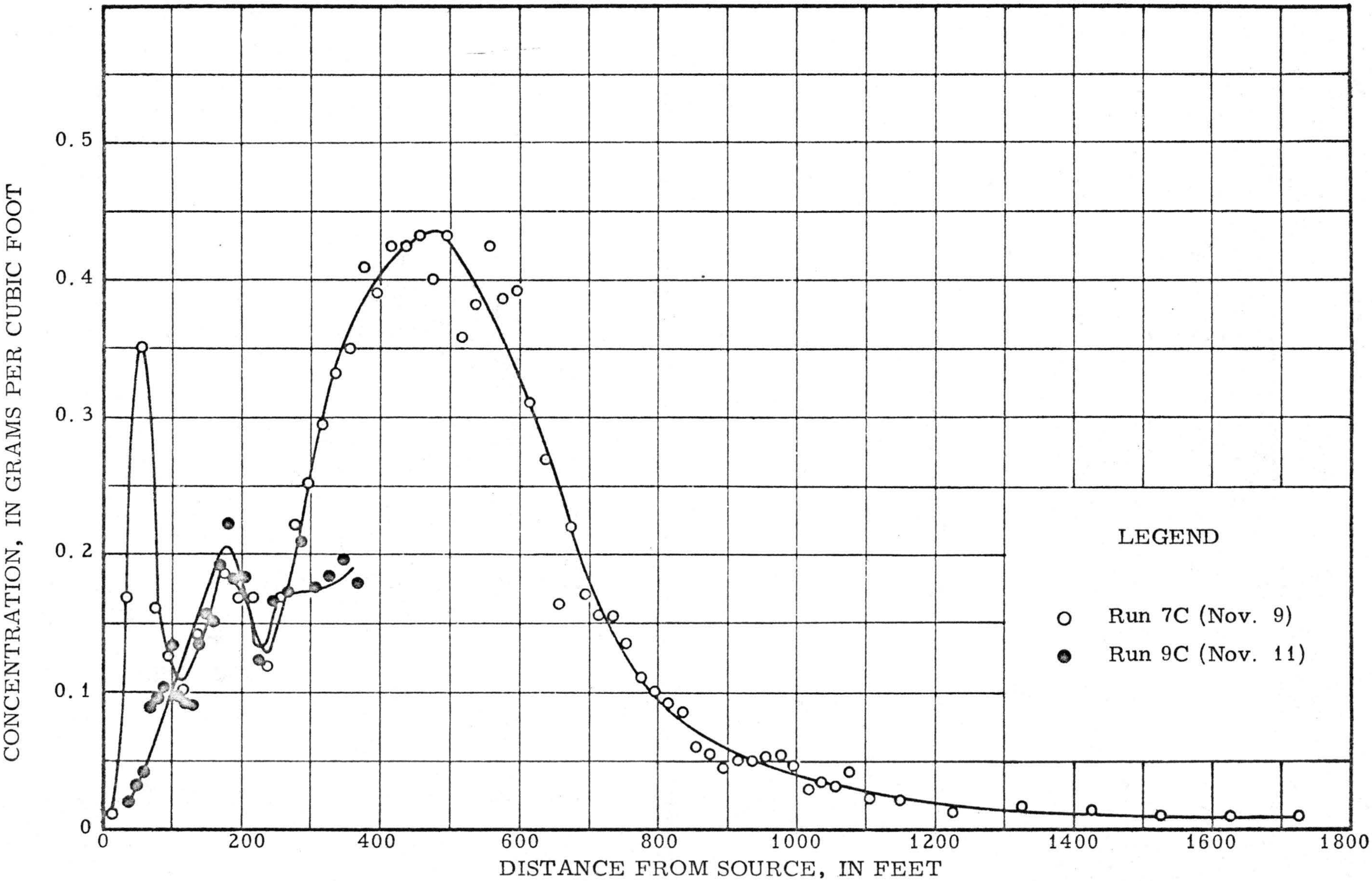


Figure 7. --Longitudinal distribution of labelled particles along the center of the channel, Nov. 7 and 9, 1960.

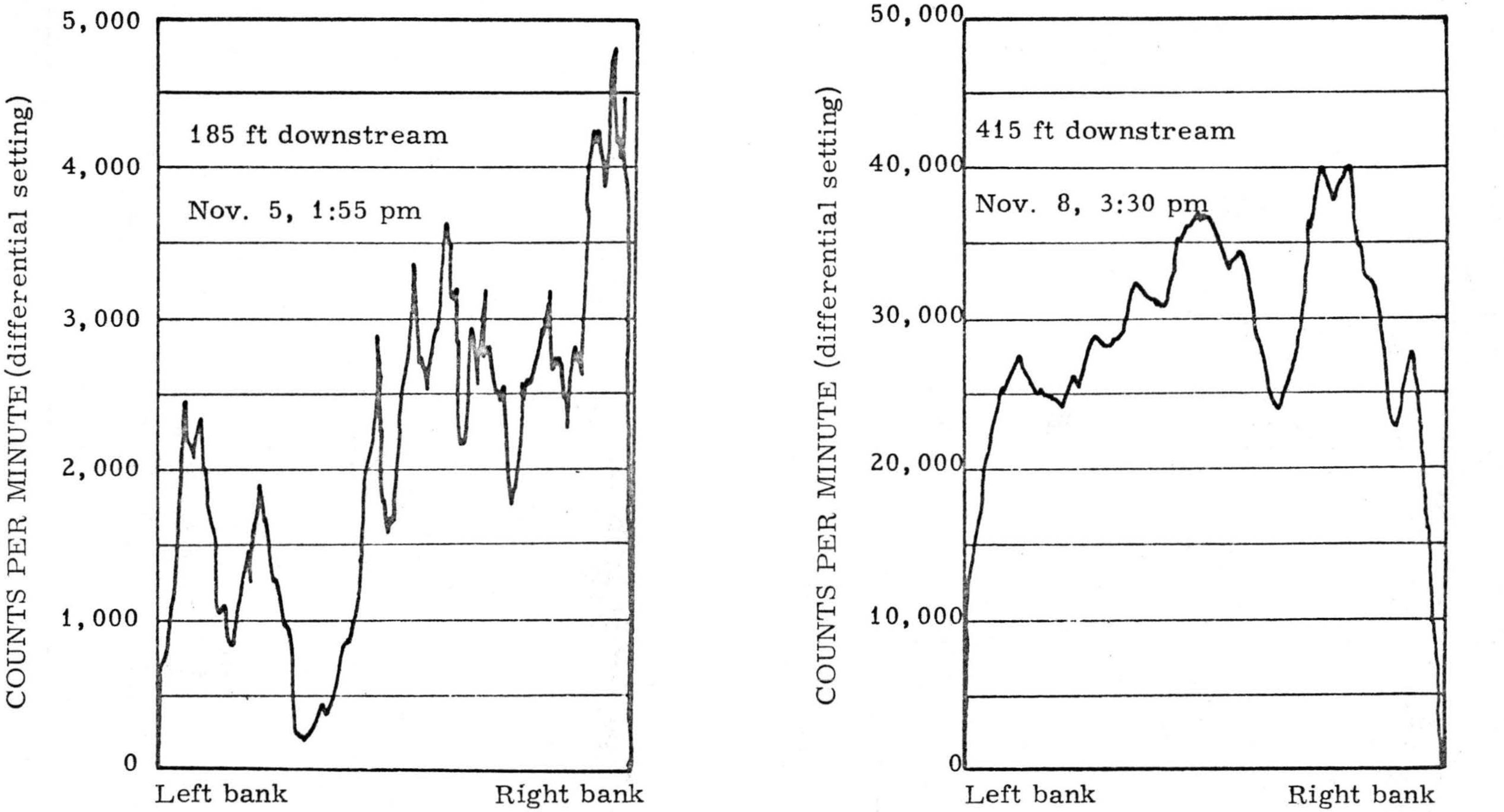


Figure 8. --Lateral distribution of labelled particles downstream from the source on Nov. 5 and 8, 1960.

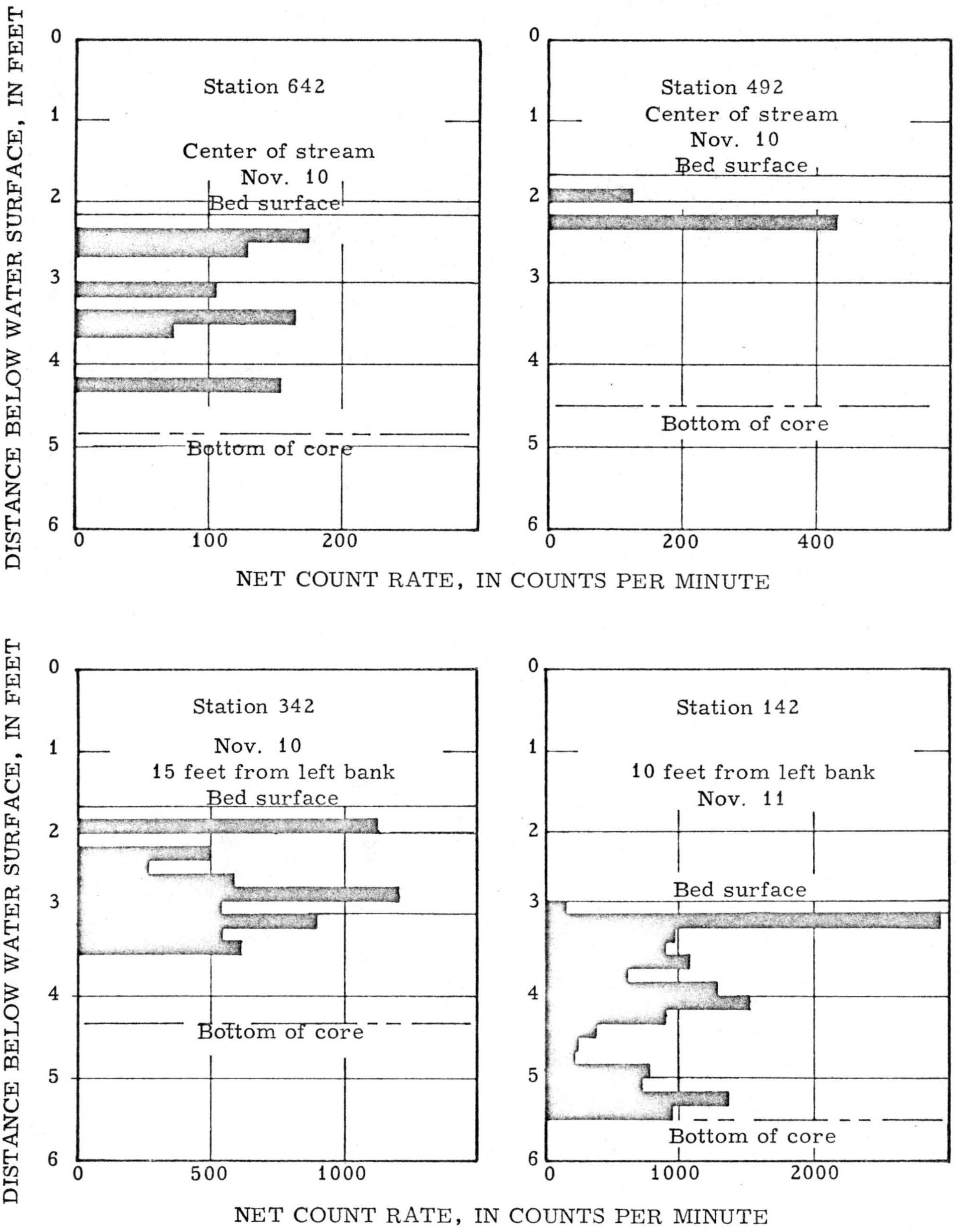
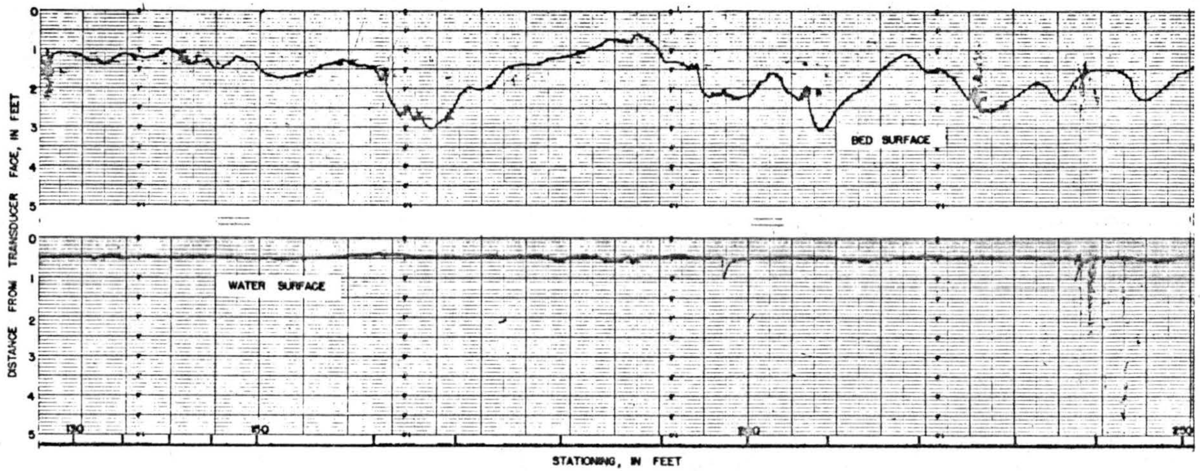
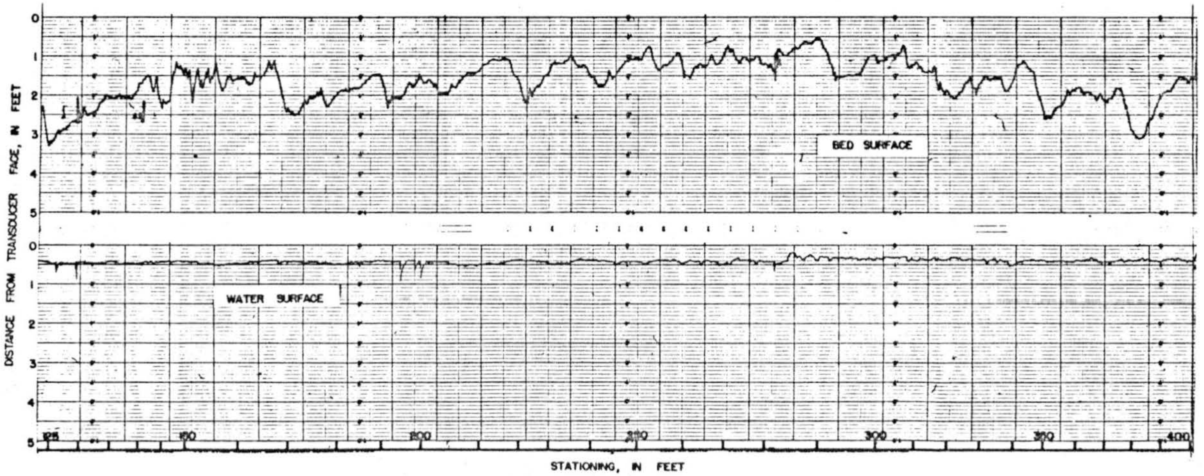


Figure 9.--Vertical distribution of labelled particles at selected verticals on Nov. 10 and 11, 1960.



A. TRAVERSE SPEED OF 15 FEET PER MINUTE



B. TRAVERSE SPEED OF 33 FEET PER MINUTE

Figure 10 --Water and bed surface profiles defined by the dual channel stream monitor. (From Hubbell and Haushild, 1962.)