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A SALT TRACING METHOD FOR MEASURING CHANNEL VELOCITIES IN SMALL MOUNTAIN STREAMS*

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Abstract: Measuring or calculating channel velocities in small mountain streams is very difficult due to the high variability of the channel geometry parameters and roughness characteristics. A salt tracing procedure has been examined for small streams. The technique is simple and quick, using materials that are commonly available at most research watersheds and water resource centers. The velocity *through* the channel reach using the salt tracing method was found to be a better representation of the average stream velocity than that computed by the continuity equation at three channel cross sections.

1. Introduction

This paper describes an effective and economical method for measuring channel velocities over a reach of stream channel using a salt tracing technique. In spite of its importance in hydrologic and geomorphic studies, information on channel velocities in small mountain streams is rare. Hydrologists must have information on channel velocities in order to develop and test flood routing techniques or mathematical models for predicting runoff from mountainous watersheds. Ragan (1967) and Dunne (1969) have demonstrated in humid areas that the major part of summer storm runoff is generated on small areas near the stream channel where the response of runoff to rainfall is rapid. Storage and transmission characteristics of stream channels are therefore an important control of the shape of the hydrograph and of the "effect area" than can contribute flow to the hydrograph. Geomorphologists studying the relationships of channel geometry, sediment transport

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and flow characteristics of stream channels would also benefit from better data on channel velocities.

The study area is a part of the Sleepers River Research Watershed in northeastern Vermont, a facility of the Agricultural Research Service, USDA. The study reach covered 1500 ft of a stream channel draining approximately 2.05 square miles. The mean annual flow for five years of record is approximately 3.5 cfs. Channel-bank widths in this particular reach ranged from 6.2 to 21.3 ft with an average width of 12.2 ft, (Zimmermann *et al.*, 1968). The average slope of the water surface during periods of low flow for the 1500 ft of channel is 0.0315 foot per foot. In the reach, there are also three carefully surveyed cross sections, for which relationships between discharge and velocity have been developed using the continuity equation. Data for this report were collected during the summer months of 1968. Flows sampled during the three month period were in the range of those that occurred between 4 percent and 93 percent of the time.

2. Methods of measuring channel velocities

The more common methods of determining stream velocities are: (1) direct measurements with a current meter, Corbett (1945); (2) computations by the Manning equation, Barnes (1967); and (3) determinations using the continuity equation

$$Q = AV. \tag{1}$$

There are limitations to all of these methods. The velocity determined by these three methods is for a particular cross section only, and in the calculations an area term must be evaluated. Mountain streams usually have such variable geometry and roughness characteristics that it is nearly impossible to determine the "representative cross section." Zimmermann *et al.*, (1968) in their study on channel form certainly indicated this fact. The use of the Manning equation also requires an estimate of the roughness coefficient "n", which itself may or may not vary with discharge.

In recent years, tracing techniques have been developed for measuring channel velocities where it is not feasible to use more conventional methods. Fluorescent dyes have been used as tracers to measure travel time in the Potomac River (Wilson, 1965), the Great Miami River (Bauer, 1968) and many other streams. Radioisotopes have been used successfully to trace water from one location to another in a 96-acre basin, (Pilgrim, 1966). Fluorometric or radioisotope detection equipment used in tracing are not generally available for research centers and individuals with small budgets because of expense and licensing requirements. Salt-dilution methods have been successfully used to measure the discharge of streams (Allen, 1923) and (Ostrem, 1964).

This paper describes a method of measuring average channel velocities over a reach of stream, using equipment already available at many experimental watersheds and water resources centers. The only equipment required is a portable pH meter, equipped with a sodium-ion electrode. The tracer is common salt (NaCl), which is inexpensive, easily obtainable, and causes no significant pollution of the stream. Measurement is rapid and easily accomplished by one person, even in rough terrain under stormy conditions. The average time necessary to perform one measurement was 15 min, but depended on the length of channel and discharge. The method can therefore be used to obtain valuable data for hydrologic and geomorphic studies of small streams without undertaking an expensive and time-consuming program of fluorometric or isotopic measurement. The technique also has the advantage of being usable in streams that are too rocky, sluggish, or too shallow for current-meter measurements or for measurements of their cross-sectional area.

3. Procedure

Approximately one-half pound of salt (NaCl) was thoroughly dissolved with stream water in a 3-gallon container. The salt solution was injected into the center of the stream as a single slug upstream from the sampling station. Injection sites were chosen where the stream flowed through a constriction with a width of approximately 4 ft. These constrictions would gradually disappear as the discharge increased.

A portable pH meter* equipped with a sodium-ion probe** and a silver chloride ceramic fiber reference junction, was used to measure the sodium-ion activity at the sampling station. (The use of brand names is for the convenience of the reader and does not necessarily imply endorsement by the USDA.) The sodium-ion probe and the reference probe were mounted in a clamp which could be lowered or raised on a small rod. The rod was attached to two planks placed across the channel to support the pH meter. The probes were placed in the center of streamflow with respect to the horizontal plane and immersed approximately 1.5 inch below the water surface.

The sodium-ion activity of the salt solution passing the probes was represented by the millivolt output of the pH meter†. Any change in the electrode potential was due only to changes in sodium-ion activity in the sample

* Photovolt model 125 portable pH meter.

** Corning NAS-11-18 sodium-ion probe (electrode) ADF.

† A conductivity cell was also found to determine adequately the arrival of the salt.

solution (Corning Technical Information Bulletin). The pH of the stream water was in the vicinity of 7 to 8; at this level of hydrogen ion activity, the electrode potential is invariant with the pH changes encountered*.

The response time for the probe in a salt solution constantly flowing past the probe is essentially zero under the test conditions. Exact values are 1 ppm/0.75 sec using 5-50 ppm standards and 1.5 ppm/1.0 sec using the 10-100 ppm standards.** The greatest change in sodium concentration per minute encountered in the field was 25 ppm (0.43 ppm/sec). This value is well within the limits set forth by the Corning Glass Works Company. Therefore, no correction was necessary in the timing of the salt solutions.

The time and corresponding millivolt readings were recorded until the salt solution had completely passed the sampling station. Samples of the stream water, corresponding to different millivolt readings, were taken to construct a calibration curve to convert negative millivolt readings to concentrations of sodium in ppm.

Standard chloride titrations were performed, and these data were then converted to sodium concentration, assuming a 1 to 1 correspondence between sodium and chloride ions. The titration avoided the need to estimate the activity coefficient of the sodium ion. A semi-logarithmic plot of sodium concentration (titration data) versus millivolt output of the electrode (linear) resulted in the graph presented in Fig. 1.

The calibration curve presented in Fig. 1 is slightly different from the standard curve computed by the Nernst equation. The stream temperature was nearly constant during all measurements. The only other explanation for this deviation is interference by other ions present in the system. For accurate results it is suggested to prepare a calibration curve for the particular stream being studied.

From the meter readings taken at the sampling station a graph of time versus sodium concentration was plotted, which resembled a hydrograph in shape. It will be referred to in the following text as a "salt graph". (Fig. 2). Three points on the salt graph were examined for the computation of the channel velocity; they were the time from injection to: (1) the initial rise in concentration, (2) the peak concentration and (3) the center of mass. These will be referred to throughout the paper as initial, peak and centroid velocities, respectively.

The average velocity of the salt solution as it passes from one section to

* Personal communication with Mr. J. Mowbray, Supervisor, Applications Laboratory, Corning Glass Works, Medfield, Massachusetts.

** Personal communication with Alfred Fussa, Market Development, Corning Glass Works, Medfield, Massachusetts.

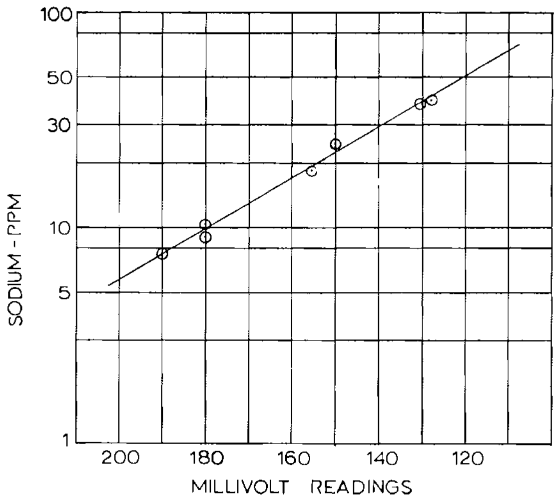

Fig. 1. Calibration curve to convert negative millivolt readings to sodium concentrations in ppm.

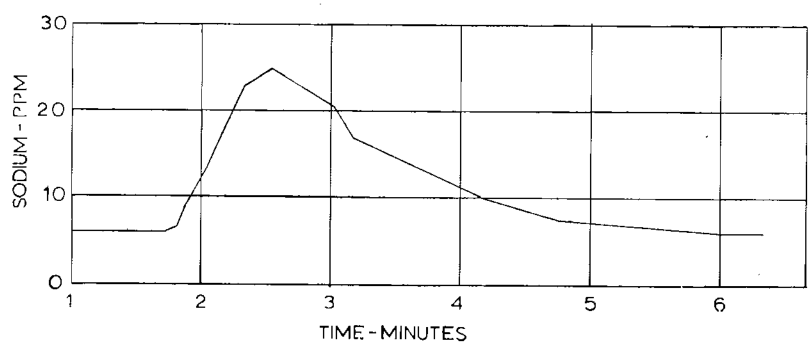

Fig. 2. A typical salt graph with the slug injected at 150 ft.

another in a travel time may be calculated from the equation

$$V = D/T, \tag{2}$$

where V = velocity in feet per second,

T = travel time of the salt solution in seconds,

D = distance from injection site to sampling point in feet.

Seven injection sites and one sampling site were used. The injection sites were located 150, 300, 530, 700, 1000, 1300, and 1500 ft upstream from the sampling station.

Fischer (1967) has suggested that the mixing length for cross-sectional mixing of a slug injection in a natural stream is given by

$$L = \frac{kf^2u}{Ru^*} \tag{3}$$

where L = distance downstream from injection point required for complete mixing,
f = a distance related to approximately one-half the width of the stream,
u = mean velocity,
u^* = shear velocity,
k = constant empirically determined to be approximately 2.0,
R = hydraulic radius.

By substituting $u^* = \sqrt{gRs}$ and using the Manning equation $u = \frac{1.49}{n} R^{2/3} S^{1/2}$ to cancel out the velocity term, Equation (3) may be modified to the following

$$L = \frac{(2.98)\,f^2}{R^{5/6}n}. \tag{4}$$

Relationships have been developed at the three cross sections between discharge and the variables R and n. The stream widths Zimmermann et al. (1968) measured were from one stream bank to the other, thus for periods of flood flow his average value of 12.2 ft would be valid. During periods of low flow the top width of the stream would be considerably less than 12.2 ft. Assuming the stream width at 3.0 cfs to be 8.0 ft, n was found to be 0.13, $R = 0.37$ and the mixing length was 148 ft. Assuming an average width of ten feet for 15.0 cfs, $n = 0.08$, $R = 0.55$, mixing length $L = 153$ ft.

Detection of the leading edge, peak concentration and trailing edge of the salt solution was less accurate as the distance from the sampling station increased, and during periods when the flow was less than 1.5 cfs. This was caused by the longitudinal dispersion of the salt solution as it moved through the channel. It was difficult to obtain velocity measurements from all seven sections at the same discharge during storm conditions. This required sampling several storms and interpolating velocities for flows not measured. When the discharge increased, a greater volume of salt was injected to insure sufficient sodium concentration at the sampling station.

The streamflow was measured at two weirs, before and after each salt tracing run. One hundred feet below the sampling site another stream entered the main channel. Weir #1 measured the flow below the confluence and Weir #2 measured the discharge of the stream entering 100 feet below the sampling site. By subtracting the discharge at Weir #2 from that at

Weir #1, one obtains the flow in the channel reach studied. An average of the flows before and after each tracing run was used.

4. Results and discussion

The basic assumption is that no significant increase in discharge would occur between the injection site and the sampling station when making a tracing measurement. A maximum channel length of 1500 ft was chosen to be the upper limit. Each investigator would have to decide on an upper limit pertaining to the particular stream in question.

Three measures of flow velocity were computed. The travel time of the leading edge of the salt wave was a measure of the maximum velocity through the channel reach. The peak concentration is usually a well-defined point on the salt graph which is commonly used to calculate the travel time, (Wilson, 1965). The center of mass or centroid represents the mean time of passage of the salt cloud. Figure 3 illustrates the relationship found in this particular reach between measured discharge and the velocities computed from the three different time intervals over a distance of 1500 feet.

Leopold and Maddock (1953) and Wolman (1955) working on channels in the northwestern United States and the Brandywine Creek in Pennsyl-

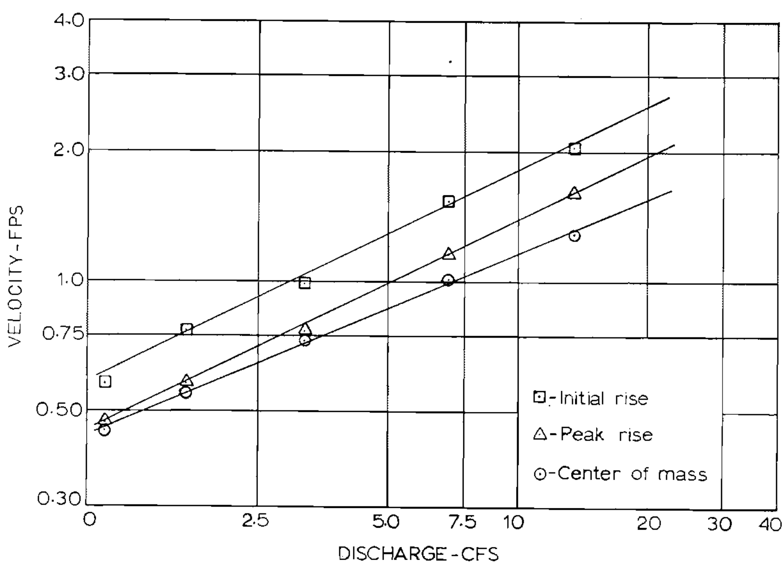

Fig. 3. Relationship between discharge and velocity over a channel length of 1500 ft, using the time intervals of initial and peak concentrations and the center of mass of the salt graph.

vania, respectively, found that velocity and discharge could be related by a power function. A power relationship was found to exist "at-a-station" between velocity and discharge such that

$$V = aQ^m \tag{5}$$

where V = velocity in feet per second
Q = discharge in cubic feet per second
a, m = constants.

Table 1 gives the intercepts, exponents, and coefficients of determinance of the power functions of reach velocity and point discharge for the seven channel lengths in which the salt velocity measurements were made.

The length of the reach between injection site and sampling station had an important effect on some of the velocity measurements. Velocity measurements were made from each of the seven injection sites at three different stages when the flow was practically constant at each stage. The three flows were 1.10, 1.70 and 3.20 cfs, and represented flow occurring greater than

TABLE 1

Intercepts, exponents and the coefficient of determinances for the seven channel lengths using the power function relationship $V = aQ^m$.

	Distance from sampling site – feet						
	150	300	530	700	1000	1300	1500
Initial velocity							
Intercept	0.977	0.835	0.750	0.671	0.648	0.604	0.590
Exponent	0.413	0.468	0.478	0.497	0.479	0.485	0.492
r^2	0.94	0.96	0.96	0.97	0.99	0.99	0.99
Peak velocity							
Intercept	0.630	0.539	0.533	0.477	0.495	0.468	0.458
Exponent	0.465	0.524	0.472	0.515	0.462	0.492	0.474
r^2	0.94	0.97	0.97	0.98	0.99	0.98	0.99
Centroid velocity							
Intercept	0.445	0.414	0.466	0.468	0.422	0.415	0.440
Exponent	0.452	0.444	0.422	0.412	0.444	0.488	0.420
r^2	0.95	0.95	0.98	0.99	0.97	0.99	

93%, 80%, and 55% of the time, respectively. At a flow of 1.10 cfs, the average reach velocity computed from the initial rise of the salt graph decreased as the channel length increased (Fig. 4). The velocity computed using the time to the peak also decreased with increasing channel length. However, the centroid velocity remained nearly constant with increasing channel length. This analysis held true for the other two flows (Table 2).

TABLE 2

The velocities computed from the three points on the salt graph are related to the channel length.

	Distance from sampling site – feet							
Velocity – fps	150	300	530	700	1000	1300	1500	
				$Q = 1.10$ cfs				
Initial velocity	0.81	0.84	0.66	0.65	0.61	0.59	0.58	
Peak velocity	0.57	0.53	0.50	0.47	0.48	0.46	0.47	
Centroid velocity	0.42	0.44	0.44	0.41	0.42	0.44	0.45	Ave = 0.43
				$Q = 1.70$ cfs				
Initial velocity	1.15	0.99	0.85	0.85	0. 2	0.77	0.74	
Peak velocity	0.73	0.68	0.61	0.60	0.61	0.59	0.58	
Centroid velocity	0.53	0.50	0.54	0.56	0.53	0.51	0.55	Ave = 0.53
				$Q = 3.20$ cfs				
Initial velocity	1.50	1.29	1.19	–	1.10	1.01	0.99	
Peak velocity	0.99	0.91	0.84	–	0.82	0.77	0.77	
Centroid velocity	0.73	0.68	0.74	–	0.77	0.71	0.73	Ave = 0.73

The calculated mixing lengths of the salt solution were approximately 150 ft with the possibility of a greater mixing length. Again, the variability of the stream width presents problems in calculating the proper "mixing length." One might conclude that the mixing length was not achieved at a distance of 150 ft because the initial and peak velocities were much greater than their respective velocities at 1000 ft. If this were true, then the centroid velocity over the short distance would be greater than the centroid velocity at 1000 ft, however this did not occur as the centroid velocity remained nearly constant. This indicates that a mixing length of 150 ft was adequate in this turbulent stream.

Theoretically, the center of mass of the salt wave occurs at the mean time of passage of the salt solution, and the computed velocity should be independent of the length of the particular reach chosen for measurement, provided a proper mixing length is obtained and the length of reach is not

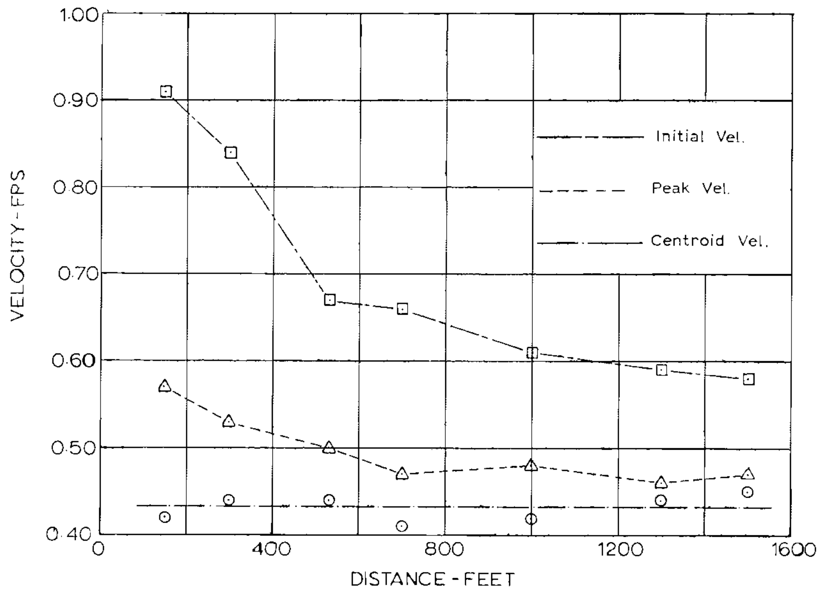

Fig. 4. The effect of increasing channel length with respect to the reach velocity, using the three time intervals initial, peak, and centroid of salt graph, $Q = 1.10$ cfs.

too long. By combining the "centroid velocity" discharge measurements from all the seven channel lengths into one plot, a reasonable relationship exists. The power function equation is $V = 0.477Q^{0.402}$ with a coefficient of determinance of 0.96 (see Fig. 5).

The data supports the above assumption. When the initial velocities and peak velocities from all seven channels lengths were combined into two plots respectively, a reasonable relationship did not exist. If the centroid velocity is assumed to be a measure of the mean velocity through the channel reach, and it appears to be constant in this particular stream, then applying Eq. (1) a mean cross-sectional area could be calculated for this channel length for different flows.

The velocities computed from the centroid of the salt graph were compared with the mean velocity from three surveyed "typical channel" cross-sections (see Fig. 6). The velocity at the surveyed cross-sections was computed independently from the tracing method according to the continuity equation. The centroid velocities were in all cases less than the average velocity of the three cross-sectional velocities. When the flow was 15 cfs, the average cross-section velocity was 38 percent higher than the centroid velocity. Wilson (1965) and Bauer (1968) also found that the velocities of the streams using their travel-time measurements were less than the velocities

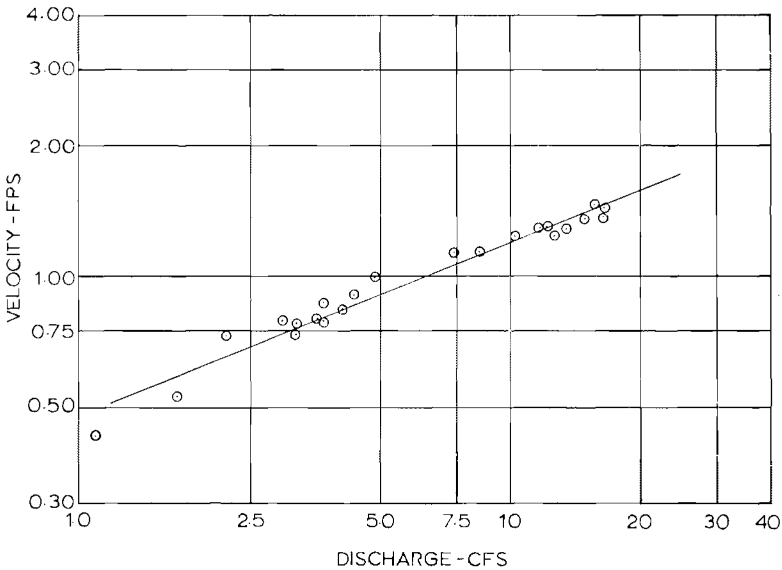

Fig. 5. The relationship of all centroid velocities from all seven channel lengths plotted against their respective discharge.

computed from the continuity equation. Harris and Sanderson (1968), using dyes as the tracer, found that the mean velocity at 18 cross-sections was in close agreement to the velocities found by using the peak and center of mass of the dye-concentration graph.

The variability of stream widths and bed roughness makes it impractical to measure the velocity at a particular cross-section and use it as the average velocity through the stream channel. For flood routing purposes, such an average velocity through a reach is necessary. The other methods, such as the continuity equation and the Manning equation rely on the evaluation of an area term and/or a roughness coefficient. The advantage of the tracing technique is that it measures the average velocity over a reach of stream, thereby overcoming the errors involved in selecting a "representative cross-section".

Data obtained by the salt tracing technique gave consistent relationships between average flow velocity and discharge. The effect of varying channel length on measured velocity was studied and could be minimized or eliminated. A comparison was also made between the flow velocity measured by the tracing technique and that computed from the continuity equation.

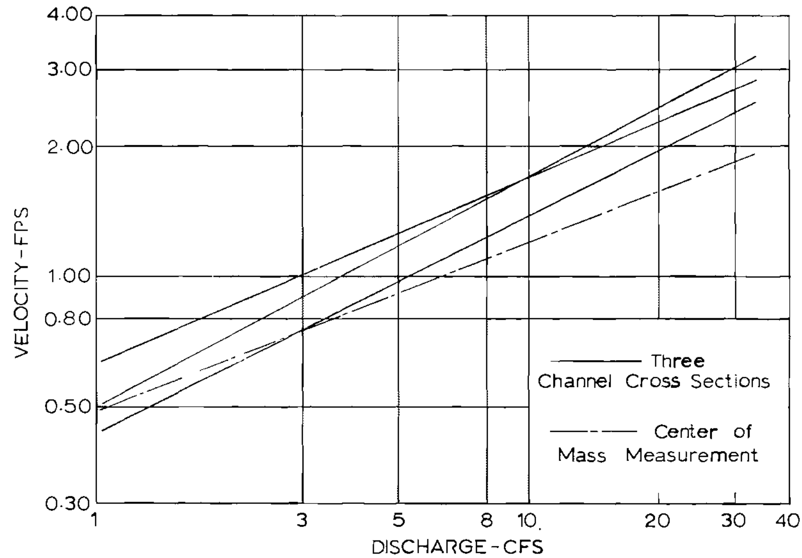

Fig. 6. The velocity computed from the centroid is compared with the average velocity of the three cross-sections.

5. Other applications

The salt tracing method was also used in a 146-acre watershed to trace peak flows from an upstream gaging station to another gaging station 600 feet downstream. The stream was more narrow, had a greater slope, and was deeper than the one previously described. Similarly consistent results were obtained on this stream. The method was also tested in a small watershed (Dunne, 1969) where the stream enters a shallow, swampy depression. These swampy areas seem to be major sources of storm runoff in this area. Because of the physical features of the swamp, conventional methods of determining channel velocities could not be used. The swamp area was covered with a tall, thick grass. Water depths were of the order of 1 to 6 inches. The tracing method was used successfully to determine an average velocity of flow through the swamp at various discharges.

6. Summary

A salt tracing technique was developed for measuring average velocities *through* a channel reach where the geometry parameters were highly variable It proved to be quick, simple, and used readily available equipment found at most research watersheds or laboratories. The economic justifications are quite visible, since the purchase of radioactive or fluorometric equipment is very expensive in comparison to a portable pH meter with a sodium ion probe. Since a portable pH meter is often available at most laboratories, the only cost is the "ion" probe and common salt, a very minimal expenditure. The method was ideal for small mountain streams where light portable equipment is necessary. The mixing length of such streams is generally small due to the turbulence, and the steep slopes.

Average channel velocities over a reach are better represented by velocities computed using the time of passage of the centroid of the salt graph. Channel length did not affect the centroid velocities provided the mixing length was exceeded, and the channel length was not too long to lose the sensitivity of the Na^+ concentration. Velocities based on initial rise and time to peak were unstable as the channel length increased. The section velocities at surveyed cross sections as computed by $V=Q/A$ also did not give a true representation of the average velocities through a channel reach. The salt tracing method would have disadvantages in large streams because the salt requirement would be too great.

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