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USE OF RADIOISOTOPES FOR OPEN-CHANNEL FLOW MEASUREMENTS

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Abstract — Résumé — Аннотация — Resumen

USE OF RADIOISOTOPES FOR OPEN-CHANNEL FLOW MEASUREMENTS. With techniques based upon the salt-dilution method, radioisotopes can be used for discharge measurements in open channels such as canals, streams and rivers. Field measurements with radioisotopes in canals discharging up to 8000 ft^3/s have been made by the Bureau of Reclamation. The conditions of the field measurements are described in this paper, and important observations are made relating the results to the use of these methods for discharge measurements in rivers.

The field tests were performed to study the general feasibility of the use of isotopes for discharge measurements in open channels and to investigate some of the important field problems which are still under study. These include the field requirements for necessary transverse mixing of the isotopes with the flowing water; sorption of the isotopes by suspended sediments, channel flow surfaces and aquatic plants; and improvement of field procedures and equipment. Results of present laboratory and field tests lead to a proposed method for employing radioisotopes in river-discharge measurement to provide continuous or periodic discharge determinations.

EMPLOI DES RADIOISOTOPES POUR LA MESURE DU DÉBIT D'EAUX S'ECOULANT A CIEL OUVERT. Avec les méthodes fondées sur la dilution des sels, on peut utiliser les radioisotopes pour la mesure du débit d'eaux s'écoulant à ciel ouvert: canaux, rivières et autres cours d'eau. Le «Bureau of Reclamation» a fait des mesures à l'aide de radioisotopes dans des canaux débitant jusqu'à 230 m^3/s. Les auteurs exposent les conditions dans lesquelles se sont déroulées ces mesures et font des observations importantes concernant l'interprétation des résultats dans le cas où l'on voudrait utiliser ces méthodes pour des mesures du débit dans les rivières.

Les expériences avaient pour but de déterminer s'il était possible d'employer des radioisotopes pour la mesure du débit d'eaux s'écoulant à ciel ouvert, et d'élucider certains des importants problèmes pratiques qui sont encore à l'étude, notamment: les conditions qui assurent le brassage transversal indispensable pour que les isotopes se mélangent à l'eau courante; la sorption des isotopes par les sédiments en suspension, les parois du lit et les plantes aquatiques; l'amélioration des méthodes pratiques et le perfectionnement du matériel. Les résultats des expériences qu'ils ont faites en laboratoires et sur le terrain ont conduit les auteurs à mettre au point une méthode d'emploi des radioisotopes pour les mesures, continues ou périodiques, du débit des cours d'eau.

ИСПОЛЬЗОВАНИЕ РАДИОИЗОТОПОВ ДЛЯ ИЗМЕРЕНИЯ РАСХОДА ВОДЫ В ОТКРЫТЫХ РУСЛАХ. С помощью технических приемов, основанных на методе растворения соли, можно использовать радиоизотопы для измерения расхода воды в открытых руслах - каналах, ручьях и реках. Управлением мелиорации были проведены полевые измерения с использованием радиоизотопов в каналах, пропускающих до 230 куб.метров воды в 1 сек. Дается описание условий полевых измерений и сообщаются важные наблюдения, касающиеся результатов использования этих методов при измерениях расхода воды в реках.

Полевые испытания были проведены с целью изучения общей возможности использования изотопов для измерений расхода воды в открытых руслах и для исследования некоторых наиболее важных полевых проблем, которые изучаются в настоящее время. К ним относятся поперечное смешивание изотопов с потоком воды; поглощение изотопов суспензиями дном и берегами каналов, а также водяными растениями; улучшение техники полевых опытов и оборудования. Результаты настоящих лабораторных и полевых испытаний привели к предлагаемому методу использования радиоизотопов при измерении расхода воды в реках. Метод обеспечивает постоянные или периодические определения расхода воды.

EMPLEO DE RADIOISÓTOPOS PARA MEDIR LA CIRCULACIÓN EN CANALES ABIERTOS. Cuando se trabaja con técnicas basadas en el método de dilución salina, los radioisótopos permiten medir el caudal en canales abiertos, corrientes y ríos. El Bureau of Reclamation los ha utilizado para determinar en canales un caudal de hasta 8000 pies^3/s. La memoria describe las condiciones en que se realizaron las mediciones sobre el terreno y, basándose en los resultados obtenidos, formula observaciones relativas al empleo de estos métodos en la medición de caudales fluviales.

Los ensayos sobre el terreno se realizaron con miras a estudiar la posibilidad de emplear isótopos para medir el caudal en canales abiertos y para investigar algunos de los problemas más importantes que se plantean en la práctica y que se están estudiando todavía. Se trate, entre otros, de las condiciones que en la práctica deben cumplirse para que se produzca la necesaria mezcla transversal de los isótopos con el agua en circulación, de la sorción de los isótopos por sedimentos en suspensión, por las superficies laterales y del fondo del canal y por las plantas acuáticas; también es importante mejorar los procedimientos y el equipo que se emplean sobre el terreno. Los resultados obtenidos inducen a los autores a proponer un método que utiliza radioisótopos para medir el caudal de ríos en forma continua o periódica.

BASIC CONCEPTS

Chemicals were first used in large-scale flow measurements approximately 100 years ago, and their importance has increased considerably since that time. The use of radioisotopes as a special form of chemical measurement was first introduced by Joly in 1922, but only in recent years have large-scale measurements, involving both open and closed conduits, been performed [4]. Improved instrumentation and the need for more accurate discharge measurements have been responsible for this renewed and increased interest.

The Bureau of Reclamation is engaged in a research and development programme to investigate the use of radioisotopes for discharge of flow measurements. The programme is broad in scope and covers the study of the basic concepts of several methods of using isotopes; refinement of isotope injection and counting equipment; development of techniques suitable for measurements of flow in natural waterways, canals and through pumps and turbines; and identification and solution of problems arising from field use of the method. The subject of this paper is the use of radioisotopes in discharge measurements in large canals.

Salt dilution using radioisotopes

In one method of using radioisotopes the techniques are directly related to the salt dilution method. In the dilution method a salt solution of known concentration C_1 is introduced into the flow at a constant rate q . At a point sufficiently distant downstream to assure adequate transverse mixing of the salt solution with the flow the measured salt concentration is C_2. From considerations of conservation of material, $C_1 q = C_2 Q$, where Q is the flow being measured; hence $Q = (C_1/C_2) \times q$

Isotope dilution

Radioactive salt in solution can safely be substitued for ordinary chemical salts to achieve equal or better accuracy. With radioisotopes smaller volumes of the chemical tracer need to be handled and injected, and measurement of the downstream concentration is a simpler field pro-

cedure. These and related advantages come from the high degree of detectability of radioactive materials by their radioactive properties.

The relationship between the use of non-radioactive and radioactive chemicals in the salt dilution method will be discussed without too detailed attention to the instrumentation or laboratory and field procedures, which can vary depending upon the requirements of the particular test. It will be shown that other related methods can be derived from the basic concepts of salt dilution.

Consider the concentration C_1 and C_2 in the equation for the salt dilution method. When radioactive material is used, these concentrations can be determined by Geiger or scintillation counters which measure the gamma-ray emissions from the radioactive salts introduced into the flow. The emissions sensed by these instruments are counted by a portable battery-operated scaler.

The concentration C_1 and C_2 can be determined in terms of $\mu c/ml$ by proper calibration of the counting equipment. This can be done in the laboratory. For example, the counting rate is determined for a Geiger counter probe submerged in a container filled with a radioactive solution of known concentration. The container is large enough so that gamma rays originating from the outer regions of the container are not counted by the probe in the centre of the volume. This simulates the action of the probe in the field since gamma rays also occur outside the range of the probe. If F is the calibration factor for a given set of equipment or a given probe, then the counting rate R for a solution of concentration C is $R = FC$, or $C = (R/F)$.

In the field, calibrated equipment is used for the determination of the values of C_1 and C_2 in the salt dilution method equation. This gives

$$Q = \frac{C_1}{C_2} \times q = \frac{R_1/F}{R_2/F} \times q$$

$$\text{or } Q = (R_1/R_2) \times q.$$

Thus, it is seen that radioisotopes may be substituted for chemical salt in the salt dilution method of measuring discharge. When radioisotopes are used, the technique is known as the isotope dilution method. It is also to be noted from the above equation that the discharge can be determined without a knowledge of the exact value of the calibration factor. The calibration factor need be only sufficiently accurate for the determination of the quantity of radioisotopes necessary to give counting rates large enough for accurate determination of the discharge.

The field procedure in the isotope dilution method is the determination of the concentration C_1 of the isotope being introduced into the flow. It is introduced at a constant rate q by a Mariotti flask or constant-flow pump. At a sufficient distance downstream from the point of introduction of the isotope to assure adequate mixing, the concentration of the stream C_2 is determined by immersion of a counter, such as a Geiger counter, into the stream. The counting rates obtained for the original solution C_1 and the diluted solution C_2 provide the data necessary for determination of the discharge for the flow Q.

Pulse or total count method

From the basic considerations of the salt dilution method another technique of using radioisotopes which eliminates the need for continuous application of the tracer at a fixed rate q can be derived. In the total count or pulse method a known amount of tracer A is introduced to the flow in a comparatively short time, producing a pulse of radioactivity in the flowing water.

At the measurement point downstream the concentration of the tracer is determined as previously discussed for the isotope dilution method. However, the constant C_2 in the salt dilution equation is now a variable and a function of time. Again, from considerations of conservation of matter,

$$A = C_1 q = Q \int C_2 dt$$

$$\text{or } Q = C_1 q / \int C_2 dt.$$

The latter equation is similar to the equation for the isotope dilution method.

Since A is known, the rate of introduction q and the initial concentration C_1 need not be determined. Since $C_2 = R/F$,

$$Q = C_1 q / \int (R/F) dt = C_1 q / (1/F) \int R dt.$$

The total number of counts N obtained during the passage of the tracer is $N = \int R dt$. By substitution, the quantity of flow (discharge) is then found to be $Q = FA/N$.

FIELD STUDIES

Field measurements in canals were made with the use of the pulse or total count method and the general procedures described above. In addition, specific procedures were as described below.

The quantity A, or the amount of radioisotope to be introduced for each measurement, was determined by measurement of the radioactivity of the solution in a portable standardized counting system which was calibrated in the laboratory. The radioisotope gold-198 was then introduced into the canal stream in a solution of gold chloride poured from a plastic bottle onto the surface of the canal water.

The total number of counts N was determined by means of a probe consisting of four Geiger counters encased in a plastic tube and submerged in the canal water. The "counting rate" was determined with a companion portable, battery-operated scaler.

Several series of discharge measurements were performed at different times in various canals carrying flows from a few to over 200 m^3/s (few hundred to over several thousand cubic feet per second).

Demonstration tests

The first series of measurements was made in April 1961 as a demonstration for exploration of the use of radioisotopes for canal flow

measurements. These tests were carried out co-operatively with United States Geological Survey personnel, who made precise, independent measurements of discharge using the current-meter traverse method.

The April 1961 demonstrations were performed on the Gila Gravity Main Canal and its branches, the Yuma-Mesa Branch and the Wellton-Mohawk Canal. At the point of bifurcation the Gila Gravity Main Canal discharge was 34 m^3/s (1200 ft^3/s); velocity, 0.70 m/s (2.3 ft/s). The flow division was Wellton-Mohawk discharge 22.7 m^3/s (800 ft^3/s); velocity, 0.09 m/s (0.3 ft/s); and Yuma-Mesa Branch discharge, 11.4 m^3/s (400 ft^3/s); velocity, 0.76 m/s (2.5 ft/s).

The locations of the measurements are briefly described in Table I, and Table II describes demonstration tests. It is to be noted that some of the measurements were made at, or across, engineering structures for a study of the influence of the structure or for use of the turbulence introduced by the structure for mixing.

The current-meter flow measurements were made with special care for the best possible evaluation of the radioisotopes measurements. A comparison of the results and an error analysis are given in Table III. The probable error in the current-meter measurements, estimated by the experienced technicians using the current meters, has been used to indicate the outside limit of accuracy of the radioisotope flow measurements achieved. This does not represent a statistical error analysis either on the basis of the results or the total number of counts N. A statistical evaluation on the basis of the total number of counts, $100/(N)^{1/2}$, is also included and found to be almost always less than the limits of error from the current-meter measurements.

Additional field measurements

Because of the encouraging results from the demonstrations at Yuma in April 1961, additional measurements were made, with essentially the same techniques, at other locations. These subsequent measurements are summarized in Table IV.

In general, these subsequent tests confirm the encouraging nature of the earlier demonstrations performed on the Gila Gravity Main Canal. The tests were usually performed without great difficulty, effort and preparation; and most tests gave reasonably consistent results one with another and with operational determinations of the discharge.

However, many procedures and details remain to be explored before the full utility of the technique is achieved and minimum requirements for successful discharge determinations are established. Some of the additional measurements were designed to bring out some of the field problems. In other cases unforeseen problems arose.

Transverse mixing

For example, one of the most critical factors is the determination of the necessary length of canal for achievement of thorough transverse mixing. Unless adequate transverse mixing is achieved, inaccurate discharge values

TABLE I

DESCRIPTION OF TEST LOCATIONS FOR APRIL 1961 DEMONSTRATIONS, YUMA, ARIZONA

Test No.	Canal	Canal description	Engineering structures
1	Gila Gravity	Trapezoidal, earth-lined, approximate base = 6.7 m (22 ft), depth = 4.1 m (13.54 ft), side slopes = 2 : 1	Injection at sluice gate discharge to canal, flow very turbulent; counting at Station 30
2	Gila Gravity	Trapezoidal, earth-lined, approximate base = 6.7 m (22 ft), depth = 4.1 m (13.54) ft), side slopes = 2 : 1	Injection near entrance to Tunnel 2, 6.10 m (20 ft) diameter and 880 m (2900 ft) long. Counting at tunnel exit
3A	Gila Gravity	Trapezoidal, earth-lined, approximate base = 6.7 m (22 ft), depth = 4.1 m (13.54 ft), side slopes = 2 : 1	Injection at upstream end of Gila River Siphon, 5.94 m (19 5 ft) diameter, 610 m (2000 ft) long. Counting at siphon exit
3D	Wellton-Mohawk	Trapezoidal, earth-lined, base = 13.41 m (44 ft), depth = 2.68 m (8.8 ft), side slopes = 2 : 1	Injection above wash siphon approximate 4.0 m (13 ft), diameter 60 m (200 ft) long. Counting downstream 1372 m (4500 ft)
4	Yuma-Mesa Branch ("A" Canal)	Trapezoidal, concrete-lined, base = 2.44 m (8 ft), depth = 3 07 m (10.08 ft), side slopes = 1.5 : 1. Straight section	
5	Wellton-Mohawk	Trapezoidal, concrete-lined at injection base 4.88 m (16 ft), depth = 3.9 m (12.8 ft), side slopes = 1.25 : 1	Injection 304 m (1000 ft) upstream from pumping plant. Counting 320 m (1050 ft) downstream from pumps

TABLE II

DEMONSTRATION TESTS OF FLOW MEASUREMENTS WITH RADIOISOTOPES

Discharge measurements at various locations of the Gila Gravity Main Canal and Yuma Mesa Canal were made with radioisotopes. The results are given in metric units with the English equivalents in parentheses.

Test No.	Location	Au^{198} (mc)	Injection to count distance (km (mi))	Duration of count (h : min)	Total time (h : min)	N C/S net	Q (m^3/s (ft^3/s))
1	Station 30	166	0.56 (0.35)	0 : 12	0 : 22	2 710	39.45 (1393)
2	Tunnel 2	406	1.37 (0.85)	1 : 45	2 : 08	7 041	37.21 (1314)
3A-1	Gila River Siphon	576	0.69 (0.43)	0 : 32	0 : 42	10 674	34.86 (1231)
3A-2	Gila River Siphon	498	0.69 (0.43)	0 : 50	0 : 48	9 436	34.13 (1205)
3D	Wellton-Mohawk	553	1.40 (0.87)	2 : 10	1 : 25	15 961	22.37 (790)
4	Yuma-Mesa Pumping Plant ("A" Canal)	301	1.29 (0.80)	1 : 20	1 : 25	17 374	11.19 (395)
5	Wellton-Mohawk Pumping Plant No. 1	395	0.77 (0.48)	1 : 49	1 : 43	11 367	22.46 (793)

TABLE III

ERROR ANALYSIS OF DEMONSTRATION TESTS

Test No.	Current meter		Radioisotopes	Error from current meter	Statistical error from $100/(N)^{1/2}$
	Q (m^3/s (ft^3/s))	Error (%)	Q (m^3/s (ft^3/s))	(%)	(%)
1	39.53 (1396)	1	39.45 (1393)	- 1 + 1	1.9
2	37.89 (1338)	3	37.21 (1314)	- 5 + 1	1.2
3A-1	34.89 (1232)	3	34.86 (1231)	- 3 + 3	0.97
3A-2	34.27 (1210)	3	34.13 (1205)	- 3 + 3	1.0
3D	22.23 (785)	3	22.37 (790)	- 2 + 4	0.79
4	11.70 (413)	3	11.19 (395)	- 7 - 1	0.76
5	22.34 (789)	3	22.46 (493)	- 2 + 4	0.94

are indicated. The series of tests on the A canal, performed 7 and 8 February 1962, were designed to investigate this problem, both visually and with counting equipment. By injection of fluorescene dye into the canal, it was found that a gentle bend in the canal caused the dye to remain along one side of the canal for greater distances than the casual observation of the flow would indicate. To help evaluate the transverse distribution, measurements were made with separate counting probes located in the left, centre and right portions of the canal and at two locations downstream from the bend. The degree of mixing was evaluated by the relationship

$$\% \text{ mixing} = \frac{1 - (|N_L - N_m| + |N_c - N_m| + |N_R - N_m|)}{3N_m} 100\%$$

where N_L = total counts at the left counter, N_c = total counts at the centre counter, N_R = total counts at the right counter and N_m = means total counts for all three counters.

The results of the tests are shown in Table VI.

From the per cent mixing and the discharge measurements, it is seen that inadequate distribution of the radioisotopes occurred even for a distance

TABLE IV

ADDITIONAL FIELD TESTS

Description of location

Date	Location	Structure description	Remarks
19/10/61	Gila River Siphon	Siphon: diameter, 5.94 m (19.5 ft); length, 610 m (2000 ft)	Concrete-lined invert and siphon
19/10/61	Gila Gravity Main Canal, Station 5+64	Earth-lined canal: base, 6.7 m (22 ft); depth, 4.1 m (13.54 ft), side slope = 2:1	Maximum capacity 62.3 m^3/s (2200 ft^3/s)
19/10/61	Gila Gravity Main Canal, Tunnel 2	Tunnel: diameter, 6.10 m (20 ft); length, 880 m (2900 ft)	Concrete-lined
20/10/61	Gila Gravity Main Canal, Tunnel 2	Tunnel: diameter, 6.10 m (20 ft); length, 880 m (2900 ft)	
20/10/61	Gila River Siphon	Tunnel: diameter, 6.10 m (20 ft); length, 880 m (2900 ft)	

TABLE IV cont.

Date	Location	Structure description	Remarks
6/2/62	Yuma Mesa "A" Canal, Station 5+00	Concrete-lined canal: trapezoidal base = 2.44 m (8 ft); depth = 3.07 m (10.08 ft); side slopes = 1.5:1	Gentle S-curve at upstream end of test area; maximum capacity, 17.56 m^3/s
7/2/62	Yuma Mesa "A" Canal, Station 10+00	Concrete-lined canal: trapezoidal base = 2.44 m (8 ft); depth = 3.07 m (10.08 ft); side slopes = 1.5:1	
8/2/62	Yuma Mesa "A" Canal, Station 60+00	Concrete-lined canal: trapezoidal base = 2.44 m (8 ft); depth = 3.07 m (10.08 ft); side slopes = 1.5:1	Test of split flow: 1. Counter above junction with "B" Canal 2. Counter below junction on "A" Canal 3. Counter below junction on "B" Canal
25/4/62	Gila River Siphon	Concrete-lined canal: trapezoidal base = 2.44 m (8 ft); depth = 3.07 m (10.08 ft); side slopes = 1.5:1	
25/4/62	Gila Gravity Main Canal, Station 5+64	Concrete-lined canal: trapezoidal base = 2.44 m (8 ft); depth = 3.07 m (10.08 ft); side slopes = 1.5:1	

TABLE IV cont.

Date	Location	Structure description	Remarks
26/4/62	Coachella Canal, Station 713	Earth-lined canal: depth = 3.15 m (60 ft); base = 18.28 m (10.33 ft); side slopes = 2:1	Maximum capacity = 70.80 m^3/s (2500 ft^3/s)
27/4/62	Coachella Canal, Station 288	Earth-lined canal: depth = 3.15 m (60 ft); base = 18.28 m (10.33 ft); side slopes = 2:1	Maximum capacity = 70.80 m^3/s
28/4/62	All-American Canal, Station 48+50	Earth-lined canal: trapezoidal base = 48.77 m (160 ft); depth = 6.28 m (20.6 ft); side slopes = 1.74:1	Maximum capacity = 429 m^3/s (15 155 ft^3/s)
23/5/62	Consolidated Canal	Concrete-lined canal: trapezoidal base = 12.19 m (40 ft); depth = 1.52 m (5 ft); side slopes = 1.25:1	1920 m (6300 ft) above diversion gates; maximum capacity = 37.52 m^3/s (1325 ft^3/s)
24/5/62	South Canal, Granite Reef Diversion Dam	Concrete-lined canal: trapezoidal base = 19.20 m (63 ft); depth = 2.44 m (8 ft); side slopes = 3/8:1	Incomplete mixing occurred; maximum capacity = 46.73 m^3/s (1650 ft^3/s)
25/5/62	Consolidated Canal, Diversion Gates	Concrete-lined canal: trapezoidal base = 19.20 m (63 ft); depth = 2.44 m (8 ft); side slopes = 3/8:1	

TABLE V

ADDITIONAL FIELD TESTS RESULTS

Date	Location	Injection to counter distance (m (ft))	Au^{198} (mc)	Net counts (N)	Q radioisotope (m^3/s (ft^3/s))	Q operational (m^3/s (ft^3/s))
19/10/61	Gila River Siphon	640 (2100)	308	7 325	37.78 (1334)	-
19/10/61	Gila Gravity Main Canal Station 5+64	1829 (6000)	303	6 744	40.41 (1427)	-
19/10/61	Gila Gravity Main Canal Tunnel No. 2	1298 (4260)	310	5 645	50.24 (1744)	-
20/10/61	Gila Gravity Main Canal Tunnel No. 2	1298 (4260)	311	4 886	57.17 (2019)	-
20/10/61	Gila River Siphon	640 (2100)	289	6 648	39.08 (1380)	-
6/2/62	Yuma Mesa "A" Canal Station 5+00	411 (1350)	287	15 665	9.20 (325)	9.35 (330)
6/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	287	16 200	8.89 (314)	9.35 (330)
6/2/62	Yuma Mesa "A" Canal Station 5+00	1146 (3760)	286	15 500	9.46 (334)	9.35 (330)

TABLE V cont.

6/2/62	Yuma Mesa "A" Canal Station 5+00	2438 (8000)	283	15 500	9.15 (324)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	259 (850)	295	8 830	16.8 (593)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	539 (1770)	294	18 350	8.04 (284)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	990 (3250)	294	17 110	8.61 (304)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	259 (850)	406	10 280	19.82 (700)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	539 (1770)	404	26 190	7.73 (273)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 10+00	990 (3250)	404	24 070	8.55 (302)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	244	11 630	10.70 (278)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	244	12 040	10.16 (359)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	244	15 780	7.96 (281)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	301	15 120	10.14 (358)	9.35 (330)

TABLE V cont.

Date	Location	Injection to counter distance (m (ft))	Au^{198} (mc)	Net counts (N)	Q radioisotope (m^3/s (ft^3/s))	Q operational (m^3/s (ft^3/s))
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	301	15 760	9.54 (338)	9.35 (330)
7/2/62	Yuma Mesa "A" Canal Station 5+00	692 (2270)	301	18 790	8.04 (284)	9.35 (330)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	209	12 460	8.55 (302)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	209	12 440	8.41 (297)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	209	12 280	8.55 (302)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	200	12 280	8.33 (394)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	200	11 660	8.61 (304)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	200	12 180	8.27 (292)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	229	14 010	8.18 (289)	8.64 (305)

TABLE V cont.

8/2/62	Yuma Mesa "A" Canal Station 60+00	1348 (4425)	228	13 580	8.55 (302)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	1353 (4440)	228	13 950	8.18 (289)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	771 (2530)	231	14 060	8.24 (291)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	1348 (4425)	231	14 160	8.33 (294)	8.64 (305)
8/2/62	Yuma Mesa "A" Canal Station 60+00	1353 (4440)	231	13 870	8.35 (295)	8.64 (304)
25/4/62	Gila River Siphon	640 (2100)	507	6 667	38.80 (1370)	-
25/4/62	Gila River Siphon	640 (2100)	507	6 982	36.45 (1286)	-
25/4/62	Gila Gravity Main Canal Station 5+64	1829 (6000)	502	5 736	43.90 (1550)	-
26/4/62	Coachella Canal Station 713	1615 (5300)	391	8 147	24.47 (864)	24.79 (875)
26/4/62	Coachella Canal Station 713	1615 (5300)	391	8 310	23.59 (833)	24.79 (875)
26/4/62	Coachella Canal Station 713	1615 (5300)	391	7 504	25.17 (924)	24.79 (875)
27/4/62	Coachella Canal Station 288	457 (1500)	453	9 099	25.37 (896)	25.54 (902)

TABLE V cont.

Date	Location	Injection to counter distance (m (ft))	Au^{198} (mc)	Net counts (N)	Q radioisotope (m^3/s (ft^3/s))	Q operational (m^3/s (ft^3/s))
27/4/62	Coachella Canal Station 288	457 (1500)	453	8 905	25.49 (900)	25.54 (902)
27/4/62	Coachella Canal Station 288	457 (1500)	453	9 004	25.23 (892)	25.54 (902)
28/4/62	All-American Canal Station 48+50	2100 (6900)	1876	4 338	220.64 (7791)	227.49 (8033)
28/4/62	All-American Canal Station 48+50	2100 (6900)	1876	3 828	245.87 (8682)	227.49 (8033)
28/4/62	All-American Canal Station 48+50	2100 (6900)	2048	4 762	219.37 (7746)	227.49 (8033)
28/4/62	All-American Canal Station 48+50	2100 (6900)	2048	4 417	232.56 (8212)	227.49 (8033)
23/5/62	Consolidated Canal - 6300 ft above diversion dam	1800 (5900)	453	19 927	11.67 (412)	-
23/5/62	Consolidated Canal - 6300 ft above diversion dam	1950 (6300)	454	19 785	11.70 (413),	-

TABLE V cont.

23/5/62	Consolidated Canal - 6300 ft above diversion dam	1950 (6300)	454	16 043	13.28 (469)	-
24/5/62	South Canal Granite Reef Diversion	397 (1300)	434	15 556	13.20 (466)	-
		397 (1300)	434	11 601	19.23 (679)	-
		397 (1300)	434	6 989	31.75 (1121)	-
25/5/62	Consolidated Canal - Diversion Gates	305 (1000)	418	21 466	9.20 (325)	-
25/5/62	Consolidated Canal - Diversion Gates	305 (1000)	418	23 142	9.26 (327)	-
25/5/62	Consolidated Canal - Diversion Gates	305 (1000)	448	23 620	8.95 (316)	-
25/5/62	Consolidated Canal - Diversion Gates	305 (1000)	448	23 878	8.86 (313)	-

TABLE VI

PER CENT MIXING DETERMINED FOR TOTAL COUNT FLOW MEASUREMENTS
Yuma-Mesa "A" Canal

6 to 8 February 1962

Test No.	Counter location	Mixing distance (m (ft))	Q operational (m^3/s (ft^3/s))	Q radioisotopes (ft^3/s)	Q radioisotopes (m^3/s)	Total count	Mixing (%)	Remarks
2A-1	Left	696	9.35	281	7.96	15 780		Drop 2 m (7 ft) downstream from point of tangency of bend in canal
	Centre	(2283)	(330)	259	7.33	12 040	87	
	Right			378	10.70	11 630		
2A-2	Left			284	8.04	18 790		Drop 2 m (7ft) downstream from point of tangency of bend in canal
	Centre	696	9.43	338	9.57	15 760	91	
	Right	(2283)	(333)	358	10.14	15 120		
	Left	776	8.64	302	8.55	12 460		1679 m (5507 ft) of straight canal upstream from drop
	Centre	(2545)	(305)	301	8.52	12 280	99	
	Right			297	8.41	12 440		
2B-2	Left	776	8.64	294	8.33	12 280		1679 m (5507 ft) of straight canal upstream from drop
	Centre	(2545)	(305)	292	8.27	12 180	98	
	Right			304	8.61	11 660		

of 700 m (2300 ft) between the points of injection and counting. Inadequate mixing occurred in spite of apparently uniform flow, which demonstrates that visual evaluation of flow conditions can be very misleading. When injection location was moved to a point 1676 m (5500 ft) downstream from the bend, satisfactory mixing was achieved and accurate discharge measurements were obtained, as shown by Table VI. In this second test the injection-to-counting distance was 776 m (2545 ft).

The experiment presents an opportunity for evaluation of the formula suggested for determining the minimum required distance for adequate mixing [13]. This formula is:

$$L = K(Q)^{1/3}$$

where the constant K is equal to 200 for side injection and 50 for centre injection when Q is in ft^3/s. Substituting 330 ft^3/s for Q and 50 for K gives a minimum mixing length of about 350 ft or 107 m. The distance of 107 m (350 ft) was obviously too small in the above tests, and therefore the formula is not applicable to flow measurements in canals.

The simple mixing experiment shows the need for development of accurate criteria for judging the minimum distance required for adequate mixing. This may be especially true for discharge measurements in streams and rivers where the flow patterns are very complex compared with those in canals.

Improving the criteria for determining mixing distances is one approach to the solution of the mixing problem; another is to provide for simultaneous multiple injections across the canal. The latter method tends to produce uniform distribution initially and reduces the required mixing length materially. With the All-American Canal carrying about 225 m^3/s (8000 ft^3/s), five equal injections were made at equally spaced intervals across the canal in an apparently successful attempt to achieve complete mixing more quickly. The average measured discharge was within 1% of the discharge measured at a calibrated gauging station. In these tests made on 28 April 1962 the distance between the counting and injection locations was 2100 m (6900 ft). The advantage of simultaneous multiple injections is realized when these figures are compared with the test results previously discussed.

Split-stream flow

An interesting result from measurements performed in February 1962 on the A and B canals illustrates the principle of split-stream measurement. Injections were made upstream from the bifurcation, and counts were taken above the bifurcation and in each downstream leg. From the principle of split-stream flow measurement, if complete mixing takes place before the split, measurements downstream in either branch will give the flow in the main stream before the split. The following results illustrate this principle:

	A main stream	A branch	B branch
First run	8.18 m^3/s (289 ft^3/s)	8.55 m^3/s (302 ft^3/s)	8.18 m^3/s (289 ft^3/s)

Second run	8.24 m^3/s (291 ft^3/s)	8.33 m^3/s (294 ft^3/s)	8.35 m^3/s (295 ft^3/s)

Isotope sorption

Field observations during measurements in May 1962 in the South and Consolidated Canals indicated that aquatic weeds apparently absorbed and/or adsorbed radioisotopes. Large accumulations of weeds which collected on the probes showed this to be so. In canals containing large quantities of weeds serious errors in discharge determination could occur. One possible solution of this problem would be the use of a chemical form of isotope which is extremely stable and less likely to sustain absorption by plants.

Future applications and general observations

With the development of more precise equipment and field procedures the radioisotope method of flow measurement will be used in many field applications, including the rating of hydraulic structures, the calibration of gauging stations and the measurement of seepage losses from canals. For achievement of these objectives, however, minimum mixing distances must be established for use, and all losses of the isotopes must be minimized and/or accounted for.

The results of the field experiments made in canals provide general information which may be of value in the use of radioisotopes for flow measurement in natural waterways.

1. The pulse or total count method, when properly used, can give accurate and reliable results.
2. The techniques and field procedures are relatively simple and uncomplicated.
3. The principle of split-stream flow measurement offers the possibility of injection at a point of good mixing and the choice of a location downstream which may be more convenient for counting.
4. Great caution should be exercised in the choice of the points of injection and counting to assure that adequate transverse mixing has been accomplished.
5. The question of sorption, not only by aquatic plants by by sediments and channel walls as well, should be taken into account.

PROPOSED AUTOMATIC STATION

With the many encouraging results from the field tests and continuing advancement of nuclear and chemical engineering equipment, it is not too soon to propose an automatic stream gauging station employing the pulse or total count principle. The station would consist of two substations, the injection substation and the counting substation.

The injection substation would periodically inject a known quantity of tracer into the stream. A manifold-type injector possibly would be required to assure adequate mixing in a reasonable distance. The counting substation

would be located downstream where, by trial, adequate transverse mixing was found to occur. A sample of the stream would be continually pumped through a counting chamber containing the Geiger or scintillation counters. The time between a given number of counts would be continuously recorded. For periods between flow measurements the time lapse would be greater, perhaps 100 times or more, than the time between count recordings during a flow measurement. An examination of the record chart would show the exact periods of flow measurements, and by the choice of times before and after the passage of the tracer a gross total count could be obtained. Total counts between flow measurements could be averaged to give an excellent measure of background radioactivity. From this information the net count, and hence the discharge, could be determined.

A station using radioactive tracers would be particularly useful in a stream where submergence or a shifting bottom profile has made it impossible to establish a stage-discharge relationship, i.e., where a staff gauge will not always indicate discharge.

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This paper describes the results of the efforts of many persons, and it is impossible to recognize by name those who contributed to the study described. However, the contributions of all are acknowledged, including the major participants, C. L. Sweet and M. Hastings of the Bureau of Reclamation's regional office at Boulder City, Nevada, who spearheaded much of the field work, and R. L. Hansen and J. C. Schuster of the Bureau's Research Division, Denver, who not only assisted in many of the field measurements but also greatly assisted in the preparation of the technical material in this paper.

REFERENCES

[1] SCHLOESING, T., Water measurement by the chemical method, C. R. Acad. Sci., Paris (1963) 164.
[2] STROMEYER, C. E., Measurement of feed and circulating water, etc., by chemical means, Trans. Inst. Naval Architects, Lond. 37 (1896) 226.
[3] STROMEYER, C. E., The gaging of streams by chemical means, Proc. Inst. civil Engrs. 160 (1905) 349.
[4] JOLY, J., New method of gaging discharge of rivers (radioactive method), Proc. royal Dublin Soc. 16 (1922) 489.
[5] BARBARAGELETA, A., Chemical-electrical measurement of water, ASCE Proc. 54 (1928) 789.
[6] SPENCER, E. A. and TUDHOPE, J. S., A literature survey of the salt dilution method of flow measurement, J. Inst. Water Engrs. 12, 2 (March 1958) 127.
[7] CAWLEY, W. A. and WOODS, J. W., An improved dilution method for flow measurement, Trans. Amer. Soc. civil Engrs. 123 (1958) 405.
[8] HULL, D. E. and MACOMBER, M., Flow measurements by the total-count method, Proc. 2nd UN Int. Conf. PUAE 19 (1958) 324.
[9] HULL, D. E., Fluid flow measurement, United States Patents No. 2826699 and 2826700, (March 1958).
[10] CLAYTON, C. G., BALL, A. M. and SPENCER, E. A., The measurement of turbulent flow in pipes using radioisotopes, the isotope dilution technique, U. K. A. E. A. Rep. AERE-R 3028 (1959).
[11] HUTTON, S. P. and SPENCER, E. A., Gaging water flow by the salt dilution method, Proc. Inst. civil Engrs. 16 (1960) 395.
[12] CLAYTON, C. G. and SMITH, D. B., Measurement of flow in turbulent motion using radioisotopes, Special Rep. SR. 2, Proc. Hydrology Symp. Water Res. Assn. (October 1962).
[13] HULL, D. E., Dispersion and persistence of tracer in river flow measurements, Int. J. appl. Rad. Isotopes 13 (1962) 63-73.

DISCUSSION

Y. MIYAKE: Dr. Smith mentions in his paper that the loss of phosphorus is due mainly to chemi-sorption, but it seems to me that there is another way in which it can get lost in river waters, namely, as a result of uptake by various organisms. It is possible that the phosphorus in phosphate form is taken up as nutrient matter by the phytoplankton or weeds present in the water.

Although I do not have here any accurate data on the enrichment factor for gold in the organisms, I might mention in this connection that this factor is known to be fairly high in the case of certain of the metallic elements belonging to the transition group. Some of them may therefore not be suitable for tracer studies in river waters.

D.B. SMITH: I agree with your observations on P^{32}. However, I would like to point out that we are not saying that phosphorus is a good river tracer: we used it fully aware of its drawbacks.

I wonder whether you could give us your views on the possibility of using lanthanum-140 as a tracer. What would be its chemical and biological behaviour in streams and the like?

Y. MIYAKE: I think that lanthanum might be unsatisfactory for this purpose because it has a greater tendency to form a hydroxide precipitate.

L.O. TIMBLIN, Jr.: With reference to his remark on the absorption of gold, does Mr. Miyake believe that chemical complexes such as EDTA could be used to decrease biological absorption?

Y. MIYAKE: Yes, if metallic elements are in the form of chelate compounds, they may in some cases be better tracers in water studies.

D.B. SMITH: Gold has been used by Krone in the United States and by the Australian Atomic Energy Commission for the direct labelling of mud and silt. The gold was adsorbed on silt by mixing gold chloride with a silt suspension. It has been our experience that gold is not very stable in dilute neutral solutions. When mixed with mud, almost all the gold was rapidly taken up by the surface of the silt and I think that to a limited extent, this is bound to occur on river beds. Of all the tracers which we have used and with which we have had experience in other work, we think that bromine-82 is the most satisfactory, particularly if it is used with care and in conjunction with sodium thiosulphate, for the conversion of free bromine to sodium bromide.

L.O. TIMBLIN, Jr.: Further to this work by Krone and others, in studies made a few years ago with $Na^{22}Cl$ the Na^{22} was completely absorbed by a column of clay. On the other hand, a chelated form of Na^{22} was not absorbed. It was with the idea that chelated forms of gold might perhaps not be absorbed by clays that I put my question to Mr. Miyake.

F. NEUMAIER: I should like to present some data on our experience in using radioactive tracers for measurement of flow velocity (m/s) and flow rate (m^3/s) in open channels. The tracers used were I^{131}, Br^{82} and Na^{24}. In our method, a known amount of tracer is added to the stream and its concentration-time distribution registered at a measuring point sufficiently far downstream. Depending on the duration of the process, a distinction is made between instantaneous (pulse) and constant-rate (continuous) injection. The tracer is added by means of an injection-rod assembly,

the solution being forced by compressed air from a storage container into the water.

Detection is carried out either by direct measurement in the main stream or in a smaller stream fed from the main flow, or by collection of samples for later analysis. The samples, in turn, can be collected continuously or intermittently and the tracer contained in them measured directly or after enrichment. In one testing arrangement a scintillation counter is immersed directly in the main stream while another is located in a flow tank through which water from the river is pumped.

We sought to determine to what extent the accuracy of the flow rate as ascertained depends on amount of tracer and type of flow. In particular, we established the sensitivities and limits of our detection methods and studied the question of the minimum tracer amounts required to determine flow velocity and flow rate.

For example, to determine the flow velocity of a river having a flow rate of 43 m^3/s, we divided a 60-km section into five subsections. The tracer (I^{131}) was detected by sampling and chemically treating some 400 5-l samples. The average flow velocity over the whole section was 0.6 m/s. The half-widths, as a function of time of the water passage curves measured at the subsections, varied between 30 and 90 min, depending on the type of flow. Only 10 mc of I^{131} were used for the entire 60-km section. The measurements were carried out with a directly immersed scintillation counter and four flow meters placed across the flow cross-section.

Allowing for the limits of error, the measurement results were found to be independent of the location of the sampling points and the flow cross-section, as was to be expected. It was further proved that tracer methods, provided that thorough mixing takes place, can achieve the accuracy obtainable with flow meters.

L. O. TIMBLIN, Jr.: Could Mr. Guizerix give us further details on his work with ion-exchange resins?

J. GUIZERIX: We have done only one experiment with an ion-exchange resin – for the purpose of assessing the factor which might be expected to increase the detection yield. The resin was mixed with the solution in an 18-l tank and then extracted by filtration. Not all the activity was extracted, but from the difference in counting values obtained from the scintillation probe placed in the centre of the tank, we got a value, A_1, which was proportional to the activity localized on the resin. The resin was then placed close to the scintillation crystal and yielded a counting rate A_2. We obtained an A_2-A_1 ratio of 11.5. Further work would be necessary in order to get a quantitative extraction. We have not done this because, as you will recall, our purpose is to measure large flows, for which we shall certainly have to use tritium.

D. B. SMITH: I see that the methods which Mr. Guizerix and I myself propose for river tracing are basically very similar. I would like to ask him whether he considers that the transport of a pump, battery and large container to the site of measurement is more convenient than the method of taking samples at regular intervals and sending these samples to a base laboratory. Is there any great advantage in the continuous pumping method?

J. GUIZERIX: If I remember correctly, studies made by Électricité de France show that a minimum of 25 samples have to be taken in order to construct the activity curve (your first procedure in the continuous sampling method) and to define its area to within 1%. Now, I believe that the volume of the sample used in your method is about 2 l. I therefore wonder whether the taking of 25 samples of 2 l each would not be as cumbersome as sampling by means of a pump. Our equipment is very light, and while not strictly portable, is nevertheless quite easy to transport. It should also be remembered that we make four samplings per section in our measurements.

In the last analysis, however, one has also to face the fact that the gauging of rivers and large channels will always be a cumbersome operation, as far as equipment is concerned.

D. B. SMITH: In our work, we took more than the 25 samples which you mention, but we formed our individual 2-l samples by mixing six samples of about 350 ml each. Hence, all we had to transport from the site were a few 2-l bottles.

R. HOURS: I might mention that a German designer is producing a simple and light plastic device which floats on the river and takes a theoretically perfect average sample. The use of such an apparatus, if necessary with improvements, would doubtless be more convenient than continuous electric pumping or taking numerous samples at regular intervals.

L. O. TIMBLIN, Jr.: In connection with Mr. Guizerix' comments on safety and on the maximum permissible limits (MPL) on the radioisotope, our experiments have shown – and this has probably been your experience as well – that after complete mixing the concentrations were below the MPL's established by the United States Atomic Energy Commission. However, there is some public reluctance to accept the use of isotopes with longer half-lives, even though the MPL's are not exceeded. In the United States, there seems to be a greater willingness to permit the use of an isotope with a short half-life, even though the safety factors may not be any better. This may, in some cases, determine the selection of the isotope with respect to the health question which you discuss.

J. GUIZERIX: In my paper, I emphasized the wisdom of the French regulations with regard to the use of radioactive tracers in hydrology, especially tracers with a half-life of more than one week. Generally speaking, we in France do not like to use long-lived tracers in an extended medium. Since our purpose is to develop tracer applications, it may be assumed that this policy will bear fruit. There is reason to fear the day when large numbers of governmental or private organizations will be using long-lived tracers. I have in mind, in this connection, such things as the use of cobalt to determine blast furnace wear. This is not an application that I personally would favour.

R. HOURS: It is desirable, however, that consideration should be given to the introduction of less conservative regulations, in which greater account would be taken of the half-life of the radioisotope and in which the permissible dose would be calculated in the light of the very short duration of polluted water consumption. But the present regulations have the advantage of already being in existence and of permitting research to be carried on more easily. They are satisfactory for the time being.

J. CAMERON: Mr. Timblin includes in his paper a proposal for an automatic stream-gauging station. Does he consider that we have enough experience at present to predict all the parameters (e.g. vertical and lateral diffusion length, choice and activity of radioisotopes) that would have to be known to design such a station, or would further preliminary experiments have to be conducted?

L.O. TIMBLIN, Jr.: As far as any particular site is concerned, experiments could be performed for the purpose of determining the proper location of the injection and counting station. At present, we do not have sufficient knowledge to predict with certainty, and without experimentation, at what distance complete mixing will have taken place.

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