Application of Isotopes in Hydrologic Measurements

Dr. S. P. Rai
Scientist 'D',
National Institute of Hydrology,
Roorkee-247667
sprai1966roorkee@gmail.com

1. Introduction

Isotope methods were introduced into catchment hydrology research in the 1960s as complementary tools to conventional hydrologic methods for addressing questions of where water goes when it rains, what pathways it takes to the stream and how long water resides in the catchment (McDonnell, 2003). Despite slow incorporation into routine research applications, the last decade has seen a rapid increase in isotope-based catchment studies. These have been mainly carried out in small well-instrented experimental catchments, on the order of 0.01 to 100 km and located typically in headwater areas (Buttle, 1998). In contrast, little has been done in terms of application and transfer of these concepts and methodologies to large (>100s to 1000s of km^2), less instrumented basins.

In the past few decades, sophisticated nuclear-hydrological instruments have been developed to measure accurately both radioactive as well as stable isotopes and accordingly various nuclear methods have been evolved. It is therefore, now very easy to solve many hydrological problems related to planning of water resources, agriculture, industry, and habitation using isotope techniques which were very difficult, sometimes impossible to tackle in the past.

Isotopes have wide applications in hydrological investigations and provide vital information for the better management of water resources. Since Oxygen and hydrogen isotopes ratio provide conservative tracers, uniquely intrinsic to water molecules that elucidate the origin, phase transitions and transport of H_2O. Therefore, isotopes help in understanding various hydrological processes and identification of source. For example, study of the isotopes of oxygen and hydrogen in water, or in elements contained in dissolved salts which have the same behaviour as water, enable exact recording of phenomena affecting the occurrence and movement of water in all its forms. The use of these techniques is also increasing worldwide, but still it requires momentum and training of the field persons in this subject.

The major applications of isotopes in the field of surface hydrology are (i) River discharge measurements (ii) Hydrographs separation (iii) Dynamics of lakes and reservoirs (iv) Surface water and groundwater interaction (v) Leakage through dams/lakes (vi) Evaporation/Evapotranspiration (vii) Sources and tracing of pollutants (viii) estimation of snow and glacier melt runoff in snow dominated catchment.

2. Discharge Measurement Using Isotope

Non-conventional techniques of discharge measurement including radiotracers, basically dilution techniques, are used where conventional methods of flow measurement of rivers and streams are not suitable due to higher degree of turbulence. Dilution techniques are based on the use of various suitable water tracers and detection of tracer dilution in minute quantity at the appropriate distance of the stream/river. Mainly, three types of tracers are employed for measuring low flows using dilution techniques.

(i) Chemical tracers ii) Fluorescent dyes iii) Radioactive tracers

The outstanding advantage of tracer dilution gauging is that it measures the flow in an absolute way because the discharge is calculated from measurements of volume and time only; tracer concentrations need be determined only in dimensionless relative readings. Dilution methods may provide the only effective means of estimating the flows in shallow rock-stream rivers or when rivers are in extreme condition of flood or drought.

Dilution gauging has gradually developed as a method in widespread use over the past 50 years or so. A very detailed account of the methods using common salt was given by Groat (1915). He and his colleagues identified many pitfalls in the method as a result of experimental work more than half a century ago.

Principle of the techniques, type of water tracers, selection of tracer and measuring reach, tracer quantity and its injection techniques, sampling techniques, preparation and field activities, empirical formulae for the estimation of mixing length, analysis of the water samples, determination of discharge, advantages and drawbacks of various dilution techniques are discussed in this lecture.

2.1 Principle

The basic principle of the dilution technique is to mix a suitable tracer with the flowing water at a point and to observe its dilution at some other appropriate distance after its homogeneous mixing with river/stream water. There are three basic criteria, which should be followed in order to get the correct information about discharge.

(1) The tracer should not be lost in the way and it should have the flow characteristics near to water.

(2) There should not be any inlet or outlet for the river/stream water in between the injection and sampling point.

(3) The sampling should be carried out after the proper mixing of tracer with flowing river/stream water (the distance at which proper mixing of a tracer with flowing water of a river/stream (from the injection point) takes place is known as mixing length.

The first two criteria can be taken care at the time of selection of suitable tracer and site for conducting the experiment, but the third criterion is most significant which requires considerable experience in order to have rough estimate of the mixing length for selecting the sampling point. In most of the cases, the sampling point is decided either by conducting a separate experiment using some tracers which can be detected in-situ and provide the information of mixing length or empirical formulae are used to have a rough idea of mixing length.

There are two basic methods of dilution gauging. The constant rate injection method and the integration or instantaneous (gulp) method. The details of tracer injection are discussed/ illustrated below.

Integration Method In integration method of dilution, a quantity of tracer of volume V_1 and concentration C_1 is added to the river in one step i. e., by a simple, steady emptying of a flask of tracer solution at a site in river so called the injection station, and at the sampling station the passage of the entire tracer cloud is monitored to determine the relationship between concentration and time. The discharge is calculated from the equation,

$$M_1 = C_1 V_1 = Q \int_{t_1}^{t_2} (C_2 - C_0)\, dt = Q.\, A$$

$$\text{or} \quad Q = C_1 V_1 / \bar{C}\,(t_1 - t_2) = C_1 V_1 / A \qquad (1)$$

where M_1 is the quantity of tracer, t_1 is a time before the leading edge of the tracer cloud arrived at the sampling point and t_2 is the time after all the tracer has passed the point. V_1C_1 is the total quantity of tracer injected into the stream, C_0 is the background activity in river water and $\bar{C}$ is the average concentration during time interval t_2 and t_1. A is the area under the concentration time curve. This has been illustrated in *Figure 1*.

Equation (1) corresponds exactly with experimental practice and integration of the curve of (C_2-C_o) plotted against t gives the flow. However, the criterion of mixing is not that the plot of $\bar{C}$ against t is symmetrical, but that the plot of $\bar{C}$ against x is symmetrical.

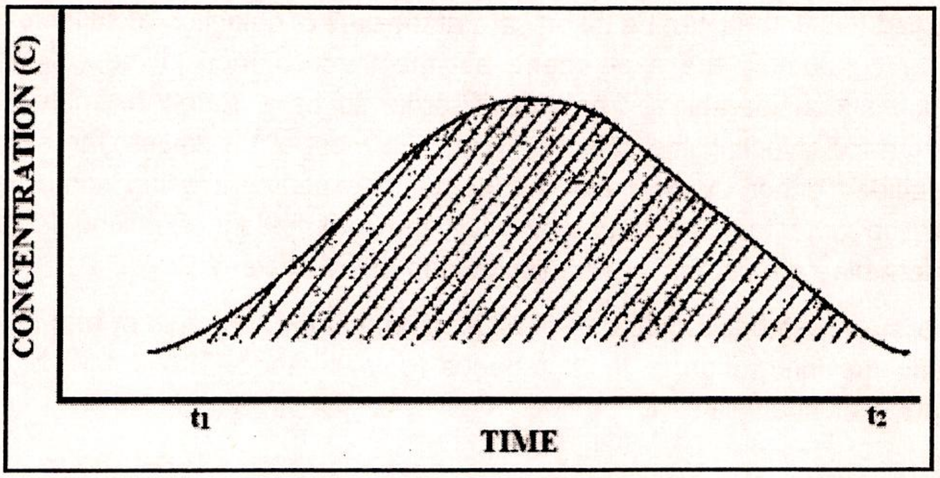

Figure - 1: Concentration curves

Constant Rate Injection Method: In constant-rate injection method, a tracer solution of concentration q, is injected continuously, at a volumetric rate q, for a period such that an equilibrium concentration C_2 is established for a finite time at a sampling station downstream. Then the mass rate at which tracer enters the test reach is (qC_{1i} + QC_o), where Q is the discharge of river and C_o is the background tracer concentration in the river water. On the assumption that satisfactory mixing of the tracer with the entire flow across the section has taken place by the time the water has reached the sampling station (discussed later), the rate at which the tracer leaves the test reach is $(Q+q)C_2$. Equating these two rates gives the discharge

$$(qC_1 + QC_o) = (Q + q)C_2.$$

$$Q = q(C_1 - C_2)/ C_2 - C_o) \quad (2)$$

An approximate form of this equation is often quoted in the literature but should not be used unless it can be shown that q compared with Q, and C_2 compared with C_1, are so small that the desired accuracy will not be affected. The reason for some caution here is that C_2, represents the absolute plateau level, including the background contribution C_o, and a correction for this background must not be made in the numerator. Also, the background referred to in the above equation is solely the concentration present in the water before the addition of tracer, and this contribution must be distinguished from the so-called background components of analytical measurements which arise within the instruments or are caused by other external influences.

Thus, if we are sure that C_o is very less in comparison to C_1 and C_2 is very less in comparison to C_1, we can rewrite equation 1 in the following way.

$$Q = qC_1/ C_2 \quad (3)$$

Although the tracer concentration profile does not have to be integrated in the constant-rate injection method, the dispersion characteristics of the channel define the period of injection necessary to establish plateau conditions at the sampling station. A constant-rate injection may be considered as a series of gulp injections, as shown in *Figure* 2. The injection (1 to n) will give a series of overlapping tracer profiles, which will lead to an integrated resultant tracer form by adding ordinates. Without presenting the mathematics it is clear that, in the limiting case where the elementary injections follow continuously, the minimum period of injection to obtain plateau condition will be T, because in the period T after the arrival of tracer the concentration of tracer will increase from the addition of tracer elements, but subsequently each gain from an elementary profile will be matched by a corresponding loss from an earlier profile. A similar argument will apply, at the end of the plateau, before the start of distribution n. The value of T may not be known when planning the gauging exercise and it is therefore important to note from Figure 2, that to establish plateau conditions for a time period T the duration of the injection must be at least (T+T_p).

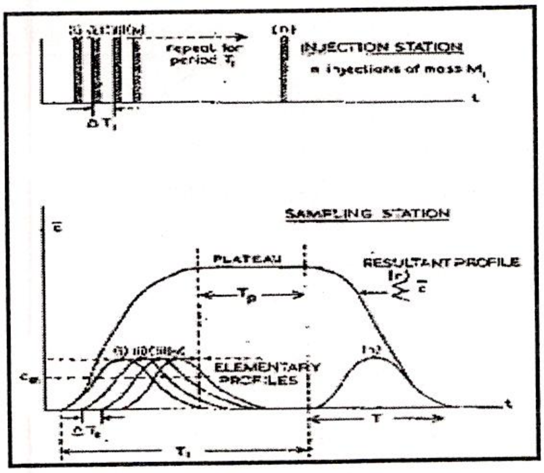

Figure - 2: Constant rate injection simulated by repeated guilp injections to show relationship between plateau duration Tp and flow through period T

2.2 Water Tracers

The various substances chosen to act as water tracers are selected for the possession of properties, which provide ease of detection at low concentrations. It is possible to envisage other forms of tracer, such as heat, which may be introduced without adding any substance to the flow. Also some non-miscible tracers might be possible, such as bacterial or phase tracers (Wimpenny et.al., 1972), if the component cells behave as individual tracer elements and still exist in statistically significant concentrations at the sampling stations. The main types of tracer in use will be discussed below but the choice, in practice, may be decided by the detection apparatus available. For example, many modern water quality laboratories have an atomic absorption spectrophotometer, which may well be very satisfactory for determination of the tracer lithium, whereas access to a fluorimeter or nucleonic counting equipment might prove more difficult and therefore make the application of their tracers less convenient or more costly. The ideal properties of the tracer are as follows:

(a) It should not be adsorbed on suspended solids, sediments, bed and bank materials, sample containers, or piping action or lost by evaporation.

(b) It should not react chemically with any of the surfaces given above, or with substances in solution under the pH and other chemical conditions existing along the channel.

(c) It should be stable under environmental factors existing for the envisaged time-of travel and in particular it should not show photochemical decay in sunlight.

(d) It should not have any harmful effects on human health or adverse effects on flora and fauna in the channel particularly fish.

(e) It should be readily detectable above the background level at concentrations, which are compatible with the accuracy desired and the quantity of tracer it is convenient to inject.

Although the chemical tracers and dyes are beyond the scope of this lectures, but for the benefit of readers, these along with radiotracers of different types and different categories are discussed below.

2.3 Chemical Tracers

The chemical tracers to be considered are simple anions, because most natural mineral surface are negatively charged thereby discouraging losses by adsorption. The traditional tracer is chloride in the form of common salt, but bromide ions may be considered equally suitable from their proven conservative properties. The use of fluoride may be limited to non-calcareous streams because of the low solubility of its calcium salt, whereas iodide has been shown to be unsatisfactory in some applications. In tests reported by Neal and Truesdale (1976) the fraction of iodide, or iodate, at a level of 0.04 mg/l, absorbed by sediments was found to range from negligible quantities to almost total uptake depending on the suspended - sediment loading and the composition of the sediment. Very high uptakes were found to occur on peat and natural peak/clay sediments in their associated fresh water. These tests confirmed indications of a similar nature obtained much earlier by Eden et.al. (1952) when reservoir water containing added Iodine-131 was passed through laboratory-scale slow sand filter. The activity of the effluent rose slow over a period of several days to about half of that in the water before filtration. When filtration of water without tracer was resumed, Iodine-131 was evident for many days. As sand filters trap a layer of organic debris, the implication of these results is that iodide should not be selected for work of high accuracy unless the levels of organic sediments or suspended matter can be shown experimentally to have a negligible effect on tracer recovery. The concentration of the halide ion down to about 0.02 mg/l can be determined by ion-specific electrodes under ideal conditions. The disadvantages being that approximately 10-100 kg of salt per cubic meter per second of discharge, depending on the technique used and accuracy desired, will be required.

Salt (NaCl has a solubility of 357-360 g/l at temperature from 0° to 40°C, respectively, and for concentrations up to about 50 mg/l, relationship between conductivity and concentration is almost linear (approximately 1.86 μ S/cm per mg/l at 18°C). The minimum concentration of NaCl which may be measured with an error of ± 1 percent is given in ISO 555/1 (International Organization of Standardization, 1973) as 1 mg/l when it is 1000 μ S/cm clearly, for accurate work, steady background concentration are required and these may not occur in rivers receiving sewage effluents or in winter months with intermittent chloride in rain may be very variable and may range from a few to several tens of milligrams per litre. It is important to remember that tracer materials in bulk, and common salt in particular, may be chemically impure. Salt may also contain additives to improve its physical properties or for health reasons.

The other chemical tracer which has been used, mainly in the UK, for dilution gauging in recent years is lithium, mostly as lithium chloride. Cat-ions should, in general, be suspect with regard to cation exchange on many common minerals or bacterial slimes, but lithium behaves in a conservative way, probably because it forms the largest of the simple hydrated alkali cations. Lithium chloride has a solubility of 637 g/l at 0°C and the element lithium can be detected in concentrations down to about 10^{-4} mg/l in the laboratory with specialized flame photometers. The range of the simple portable filter flame photometers will extend to below 1 mg/l, depending on the amount of interference from other alkali ions in the samples.

At the concentrations used for dilution gauging, lithium does not present any hazard to man. It is used in medical practice for its tranquilizing action. However, it could possibly have adverse effects on fish. Tests with yearling rainbow trout in hard water (Department of the Environment, 1971) indicated that the 35-d median lethal concentration was 1.4 mg/l. When dilution gauging is undertaken, tracer concentrations at such levels only exist for transient periods, but some caution in the use of lithium is necessary.

In several tracer studies conducted by the Water Research Centre in UK, where lithium has been used as part of a tracer 'cocktail' in retention studies, it has been shown that its passage may, on occasions, be slightly delayed relative to other tracers such as tritiated water, bromide or chloride, and the explanation may be the occurrence of very short-term adsorption and desorption process. An example is shown in *Figure 3* (Department of the Environment, 1976) for a polluted river. In view of the discussion mixing criteria in the previous section, it is important to note that adsorption and exchange reactions will cause a skew tracer recovery curve, as illustrated in *Figure 3*, even if the mixing characteristics of the channel are otherwise ideal. It is clear that, as with iodide, the use of lithium for accurate gauging work should be considered only after jar tests on sediments taken from the channel have shown that it is unlikely to be adsorbed. Measurements by the Water Research Centre of the concentration of lithium in UK rivers show that most of those into which effluents flow will have background levels ranging up to about 0.05 mg Li/1, whereas springs and unpolluted water will usually contains less than $5x10^{-4}$ mg Li/1.

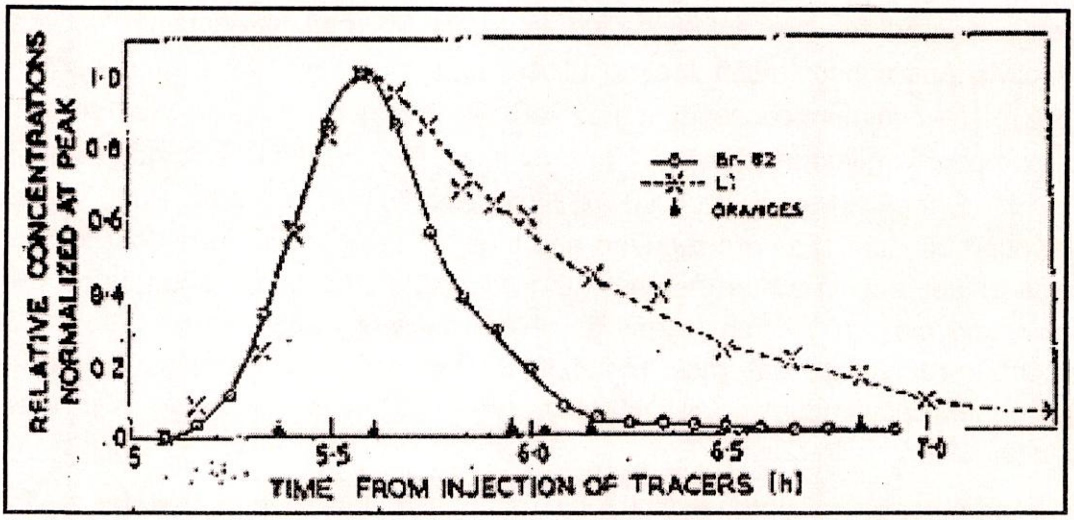

Figure - 3 Example of tracer distributions 12 km downstream of the injection of a tracer cocktail (six oranges also released to assess their effectiveness as time-of-travel indicators)

Another chemical tracer that has been in widespread use, particularly in Switzerland and France, is Chromium in the form of sodium dichromate, which has solubility allowing up to about 600 g/l to be used in practice. Unpolluted natural water mostly contains negligible concentrations of chromium ions and calorimetric analysis permits detection down to about 0.2 mg/l, with further sensitivity provided by Solen extraction techniques. However, chromium is a very undesirable pollutant, as indicated by the proposed limit for concentrations in drinking water of 0.054 mg/l. It my also have an adverse effect on some fish. Tests conducted at the Water Research Centre indicate median survival times for rainbow trout ranging from 10 up to about 50 days at a concentration of 10 mg/l and about 1 day at 100 mg/l. Dichromate may not be a conservative tracer in polluted waters because its reduction to the trivalent state would cause losses by adsorption or precipitation. Other chemicals that have been used for dilution gauging include sodium nitrite and manganese sulphate, although the use of these, as of bromides and fluorides, is not thought to be widespread.

2.4 Radioactive Tracer

Long ago, Joly (1922) pointed out the tactical merits of radioactive tracers for dilution gauging. He proposed to utilise radioisotopes in determining river discharge because of the extraordinary accuracy with which radioactive measurements can be effected. A very simple form of electroscope suffices to determine a quantity of radium to the billionth part of a gram. If, now in place of introducing salt by the hundred weight into the river, we flow into the river a few liters of a solution containing a trace of radium, and taking samples downstream examine them by the electroscope, the discharge of the river may be determined.

It took almost half a century for the use of radiotracers to be regarded as part of the normal range of techniques available to the engineers or hydrologists. No one today would consider using radium, as there are dozens of short-lives radiotracers, which have since then developed and tested.

Radioactive tracers have considerable advantages when high discharges are considered. The injection solution may range in concentration up to tens of curies per litre and most isotopes are accurately detectable down to tens of pico curies per litre, so that great dilutions are possible as well as flexibility with regard to injection techniques. When chemicals are used, large systems may require such large volume of saturated solution that tactical difficulties with injection may occur and layering of the dense solutions in the channel may restrict the degree of mixing. Two radioisotopes have proved their value for accurate gauging at any rate of flow; these are bromine-82, which may be obtained as irradiated potassium bromide tablets, and tritium in the form of tritiated water (HTO). Surface waters at the present time contain background levels of tritium of several tens of pico-Curies per litre (about one order of magnitude above natural levels) caused by the contamination of the hydrosphere from nuclear bomb tests in the 1960s.

Background levels of bromine-82 are usually zero, but there may be some variations in the counter background because of fluctuations in the cosmic and terrestrial radiation and the presence in the water of natural or bomb fallout isotopes and possible waste isotopes discharged from hospitals. Radiotracers emitting gamma rays (bromine-82) can be applied for 'dirty' samples to be analysed directly without pretreatment. Additional, factors such as pressure, temperature, and the presence of other substances cannot affect the precision with which tracer concentrations are determined. Even chemical reactions may not matter so long as the tracer stays in solution.

Bromine-82 is short lived, with a half-life of only 35.4h. It is readily detectable in situ and has been used in a wide range of hydrological studies with great success. It disappears at a predictable rate by radioactive decay and cannot cause prolonged radioactive pollution or contamination. However tritium, although it can be considered the ideal water tracer, since it is in the form of a water molecule, is long-lived with a half-life of 12.3 years. It must therefore, be considered as a pollutant and used only for particularly important studies where short-lived isotopes cannot be used or where the time-scale of mixing justifies its use. Since it can not be detected in situ unless very specialized apparatus is available the sampling programme must be adequate to ensure that benefits of its use are secured.

The concentrations of both isotopes, at the sampling station, can be kept less than an order of magnitude below drinking water tolerance levels set for these isotopes by the International Commission on Radiological Protection (1959).

It should be noted that when potassium bromide is irradiated to produce Bromine-82, other isotopes are formed, principally Bromine-81 (half-life 4.6 h), Bromine-80 (half-life 18 min), and Potassium-42 (half-life 12.4 h). In order to reduce the influence of these radioisotopes to a practical minimum, the potassium bromide tablets are removed from the reactor at least three days before the time of injection. Checks of isotope purity are made by gamma-ray spectrometry and by decay measurements.

Other isotopes to consider are sodium-24 (half-life 15h) and Iodine-131 (half-life 8.0 d) but, as mentioned earlier, preliminary tests of both of these would have to be made to assess the possibility of adsorption losses. The use of radioisotope generators for automatic dilution gauging could be attractive for some situations. A long live parent isotope is trapped on an ion-change column and the short-lived daughter may be eluted to form the tracer injection, whenever required. Prototype equipment has been used for pipe-flow measurements by the velocity-area principle using the very short-lived daughter, Barium-137 (half-life 2.6 min), of Cesium-137 which has a half-life of 30 years. For frequent short-terms measurements, or mixing tests, over a period of one to two weeks, excellent in situ detection is possible using Iodine-132 (half-life 2.3h) generated from Tellurium-132, which has a half-life of 78 h.

To summarize, tracers are used on a 'horses for courses' basis and the winning 'horse' would be chosen by the strength of public opinion, the magnitude of the discharge, the sensitivity of instrumentation available, the cost, the remoteness of the site, and the accuracy required. When the highest accuracy is sought, and the field conditions are such that the accuracy will be limited only by the tracer characteristics, there are very few tracer, the best of which are chloride, bromide (Bromine-82), and tritium (or stable isotopes such as Deuterium or Oxygen-18 as a tracer incorporated in the water molecule), which have proved to be reliable. In some countries, particularly India, USSR and UK, where chemical or fluorescent tracers may be in use routinely for local checks, radioactive tracers are used for calibration work where accuracy for long-term application of the results is essential.

2.5 Selection of Measuring Reach and Mixing Length

The length of the reach required for satisfactory mixing, according to the criteria discussed in the section on principles, can be many kilometers. The criteria are based on the assumption that the dispersion coefficient does not change along the reach between the cross-sections used for the injection of tracer and for sampling. The measuring reach should therefore be of similar form and nature over the whole of its length. For example, if a tracer has become well mixed vertically and laterally at a certain point along a channel which then increases considerably in width, say on the approach to an estuary or weir, and the tracer fronts advance preferentially along a particular axis, then lateral dispersion processes would again become effective in diluting the tracer, and sampling for flow measurement would not be appropriate even though mid-stream samples might indicate a tracer profile approximating a Gaussian distribution. The helical flow induced by a bend may be advantageous in increasing the rate of lateral mixing, thus decreasing the length required for the measuring reach. Meandering reaches may be satisfactory, provided the channel and flow pattern are such that there are no dead zones.

The criteria for mixing also make it clear that there should be no ingress of water along the measuring reach because such an occurrence may be thought of as the introduction of a negative tracer, which therefore must also be mixed completely upstream of the sampling station. However, a mixing reach can be selected independently of the position of the injection station when it is not convenient to make the tracer injection at the head of the reach selected. For example, a reach between two tributaries may be selected as the measuring reach, whereas it may be convenient to inject the tracer into either the main stream, or the tributary, upstream of the confluence. Under these conditions, the tracer-injection geometry and period should be regarded as those existing at the confluence. Loss of water or tracer (e.g. by interaction with sediments) in the reach must be avoided or the basic tracer balance equation will no longer hold. In practice, loss of tracer by seepage through the bed may be most difficult to detect and the effect will be reflected in an erroneous high flow result with not apparent reason why its accuracy should be doubted. It is therefore, necessary on occasions to select a subsidiary measuring, reach downstream of the first, where the flow and surface geology are similar. In addition, there has should be no significant egress of water between the injection and sampling stations and in all probability there has been no ingress and egress of water in the primary reach. Egress of water is equivalent to diversion of some of the flow through a bifurcation and the flow measured, therefore, is representative of the discharge upstream of the zone of egress and not the volume transported to the sampling cross-section.

2.5.1 Empirical Formulae for Estimating Mixing Length

For flow-rate measurement by dilution method, one of the most critical factor is adequate mixing of the tracer, which rather than moving downstream as a slug, gets distributed along the width of the stream, some parts travelling faster and some slower than the velocity of flow. The rate at which the tracer cloud extends and is diluted is of importance to estimate the flow-rate of rivers in mountainous reaches. To avoid too many sampling stations for flow rate measurement by dilution method, dependable prediction of mixing length is essential. In case a single measuring station is located too close to the injection point, inaccurate results may be obtained due to incomplete mixing and if it is too distant, excessive dispersion occurs and tracer gets diluted.

Mixing length depends upon so many factors and it appears that different formulae (*Table 2*) may govern in different conditions. Therefore, it appears to be of interest to observe mixing length in mountainous rivers carrying higher discharges. For flow-rate measurement by dilution method, one of the most critical factor is adequate mixing of the tracer, which rather than moving downstream as a slug, gets distributed along the width of the stream, some parts travelling faster and some slower than the velocity of flow. The rate at which the tracer cloud extends and is diluted is of importance to estimate the flow-rate of rivers in mountainous reaches. To avoid too many sampling stations for flow rate measurement by dilution method, dependable prediction of mixing length is essential. In case a single measuring station is located too close to the injection point, inaccurate results may be obtained due to incomplete mixing and if it is too distant, excessive dispersion occurs and tracer gets diluted.

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Table – 1

Empirical Formulae Developed by Various Research Workers

S. No.	Name of Research Worker	Empirical Formulae
1.	Rimmar	$L = \frac{0.12B^2C(0.7C+6)}{g^D}$
2.	D.E. Hull	$L = a_1 Q^{1/3}$
3.	B.Andre's	$L = a_2 B Q^{1/3}$
4.	N.Yatsukura	$L = \frac{0.032R^{1/6}B^2}{a_3 nD}$
5.	U.P. I.R.I. Roorkee	$L = K B + C'$

where L = Mixing Length
Q = Estimated discharge
R = Hydraulic radius (area divided by wetted perimeter)
a = Manning's coefficient of rugosity
a_1 = 50 for centre point injection
= 200 for bank side injection
a_2 = 27 for small stream with centre point injection

a_3 = 0.3 to 0.8
B = Average water surface width
D = Average depth of flow downstream of injection point
C = Chezy's coefficient (15 - 50)
K = 77 for bank side injection
C' = 120

Rimmar (1960-NEL translation) presented values for the numerical constant applicable to a range of completeness of mixing and some of these values are given in Table- 2. The appropriate value should be selected to replace the value 0.13 when guidance on the mixing length for more or less accurate work is required.

Table – 2

Value of numerical constant in Rimmer's formula

Completeness of mixing	**Numerical coefficient to use in Rimmar's formula**
10	0.074
5	0.091
1	0.130 - value usually quoted
0.1	0.187
0.01	0.244

To summarize, it is necessary to select a length of channel of similar geometrical form from end to end having no ingress of water, pools, or bays and inlets of large magnitude relative to the channel dimensions. Rock sills causing waterfalls without pools upstream or downstream should not matter and in general, bends should advantageous in decreasing the mixing distance. Reaches with bifurcation should not be chosen but island often cannot be avoided, a trivial example being those due to bridge piers. If only rudimentary data on width, depth, and type of channel are available then there is little choice other than to use Rimmar's formula. A valuable compilation of photograph of river channels with their roughness coefficients has been produced by Barnes (1967).

2.6 A Case Study of River Teesta in Sikkim, India

Lachen Chu and Lachung Chu are two streams meeting at Chungthang (at the height of 1600 metres). From the point of confluence onwards the resulting stream is known as Teesta which is a perenial river with substantial flow even in lean season. It is the major river of Sikkim that flows North-South along the state.

River Teesta is an ideal source of hydropower generation because of enormous fall of the order of 3600 metres over a river stretch of 175 kilometers.

Although data for high flow flood discharge are very important, the low flow observations are also equally important for the estimation of firm power draft for hydel power projects. It is necessary to have accurate lean flow data.

At present 12 gauging sites are being maintained by Sikkim Investigation Division (SID) of Central Water Commission (CWC), over Teesta river upto Sirwani. The observations of flow so far are being made by conventional methods only. The float method is mostly used for the measurement of discharge. Hence the chances of erroneous results of discharge are very high. SID of CWC therefore proposed National Institute of Hydrology (NIH), Roorkee for taking up the work of flow measurement of Teesta river using the radio-isotopes. The study was carried out by Bhabha Atomic Research Centre (BARC), Mumbai and NIH, Roorkee jointly.

Selection of Site

Keeping in view the points described above and requirements of NHPC to install the microhydels following four sites were selected at river Teesta -

1. Chungthang
2. Sanklang
3. Dikchu
4. Sirwani

The mixing lengths computed for the 4 sites are as follows:

Site	Expected flow rate (m^3/s)	Mixing length (m)
Chungthana	35	650
Sankalong	70	820
Dikchu	85	870
Sirwani	110	960

Tracer Injection

The tracer was injected at a constant rate using a constant head device and a peristaltic pump. The re-producibility of tracer injection rate was better than 0.5% in repeated measurements.

In Chungthang site ^{82}Br tracer was used to check the mixing length. This was followed with ^{3}H and inactive Iodide tracers. In Sankalong only tritium tracer was used. In Dikchu and Sirwani both tritium as well as iodide tracers were used.

The tracer was first mixed in a known amount of water in a bucket and an aliquot of injection solution was taken for determining the initial conc. Co. The tracers were injected for a fixed duration of a time ranging for 30 min. to 60 minutes.

2.6.1 Chungthang Site

Bromine-82

The ^{82}Br injection was made to examine the proper mixing length required and to find out the duration of the concentration plateau. About 11 GBq (300 m Ci) of ^{82}Br was taken in about 8 litres of water and injected at a constant rate for a period of 30 minutes.

At distance of 600m and 800m downstream from the injection point, water proof NaI(TL) scintillation detectors were kept immersed in water and connected to rate meter/scaler to monitor the passage of the tracer. The count rates obtained have been plotted against time and shown in Fig.1 and 2. At the plateau water samples were collected and counts determined. As the count rate obtained at 600m α 800m were same, hence mixing length of about 800m was adequate. The duration of the concentration plateau was about 15 minutes.

Tritium and Iodide Tracer

About 110 GBq (3 Ci) of ^{3}H as tritiated water and 1 Kg of Potassium iodide were used for the injection. Duration of injection was about 45 minutes. The sampling station was 800m from the injection point.

Tritium Tracer

The tritium concentrations obtained are as follows:

S. No.	Sample identity	Sampling time (Hrs.)	Tritium count rate (Net) cpm
1.	1	9.42	23
2.	4	9.51	67
3.	6	10.00	70
4.	10	10.10	72
5.	12	10.14	72
6.	15	10.20	63
7.	17	10.24	18
8.	22	10.34	9
9.	23	10.45	11

The Net tritium count rate was plotted against sampling time. The maximum count rate obtained was 72 CPM. The initial concentration of the tritium tracer was 570 x 10^6 CPM/m^3. The injection rate of the tracer was 216 ml/minute.

$$\text{Hence } Q = \frac{216x570x10^6}{60x72x10^6} = 28.5m^3/s \qquad (6)$$

Iodide Tracer

The final concentration = 0.0147 mg/ml and

Initial concentration = 0.115 x 10^6 mg/ml

$$Q = \frac{216x0.115x10^6}{60x0.0147x10^6} = 28.2m^3/s \qquad (7)$$

Likewise, discharge measurement was carried out at other sites also.

Errors in Measurements

The relative error in the determination of the discharge of the river Q can be given as

$$\frac{\sigma(Q)}{Q} = 2\sqrt{\frac{(\sigma_q)^2}{q} + \frac{(\sigma_c)^2}{(c)} + \frac{(\sigma_{Co})^2}{(C_o)}} \qquad (8)$$

This is true assuring the complete mixing of the tracer before reaching the sampling point. The relative error is <1% with proper precautions.

The degree of imperfect mixing is usually the main source of error. In the case of constant rate injection method, the % of imperfectness of mixing = $\frac{100}{n\overline{C}}.\sum_{1}^{n} |C - \overline{C}|$ where n is no. of sampling points in a given cross section. The degree of imperfectness in mixing has been computed for Sankalang and Dikchu sites.

For examle:

Net cpm in left Bank = 59.9 cpm (C_i)

Net cpm in the Right Bank = 63.6 cpm (C_i)

Hence, $\overline{C}$ = 61.8 cpm

$$X = \frac{100}{n\overline{C}} \sum_{1}^{n} |C_i - \overline{C} = \frac{100}{2x61.8} \quad 3.7$$

$$= 3.0\%$$

The vast potential of isotope techniques to understand the various complicated hydrological process, has increased the interest among the scientific community. Several research institutions/ organisations are presently using different isotopic techniques for obtaining useful information on the different components of the hydrological cycle in India and world over.

3. Measurement of Precipitation's Isotope for Climate Change Study

The stable isotope ratios of oxygen (180/160) and hydrogen (2H/1H) in past and present precipitation have become an important tool in the field of global change science. In particular, the results obtained from deep ice cores in Greenland and Antarctica, along with studies of other paleo-environmental archives, have confirmed the potential of these natural tracers for reconstructing past climates with improved resolution and reliability.

Precise determinations of stable isotope ratios in meteoric water performed in the early fifties revealed a large variability in the isotopic composition of precipitation, both in time and space (Dansgaard, 1953; Epstein & Mayeda, 1953; Friedman, 1953; Craig, 1961). Since 1961, the International Atomic Energy Agency (IAEA), in cooperation with the World Meteorological Organization (WMO), has been conducting a worldwide survey of the isotopic composition of monthly precipitation.

The programme was launched with the primary objective of collecting systematic data on the isotope content of precipitation on a global scale, characterizing their spatial and temporal variability and, consequently, providing basic isotope data for the use of environmental isotopes in hydrogeological investigations. It quickly became apparent that the collected data are also useful in other water-related fields such as oceanography, hydrometeorology and climatology.

The data gathered during three decades of operation of the global IAEA/WMO network, supplemented by numerous local studies, provide a fairly detailed picture of spatial and temporal variability of the isotopic composition of meteoric waters worldwide. This variability appears to be controlled by numerous, mutually related factors like surface air temperature, relative humidity of the atmosphere, amount of precipitation, latitude, distance from the coast and elevation of the given area above sea level (Dansgaard, 1964; Yurtsever & Gat, 1981; Rozanski et al, 1993). It also became apparent that, like many other atmospheric properties, the isotopic composition of atmospheric water vapour and, consequently, of precipitation exhibits a broad spectrum of temporal variations.

A considerable amount of theoretical and applied work carried out during the past three decades has resulted in a fairly good understanding of the processes Reconstruction of past climates from stable isotope records of palaeo-precipitation controlling the isotopic evolution of meteoric waters at different levels of the global hydrological cycle. It has been demonstrated that the spatial and temporal variations of 2H and 180 isotope composition of precipitation have their origin in isotope fractionation effects accompanying evaporation from the ocean and subsequent condensation during the atmospheric transport of water vapour. It has also become apparent that the isotopic composition of local precipitation, in particular at mid- and high latitudes, is controlled by regional-scale processes, i.e. by average parameters of the evaporation process at source regions of atmospheric moisture, and by average water vapour transport patterns into the continents and the resulting "rain-out history" of the air masses precipitating at a given place (Dansgaard, 1964; Craig

& Gordon, 1965; Merlivat & Jouzel 1979; Rozanske et al., 1982; Siegenthaler & Matter, 1983; Johnsen et al., 1989).

Quantitative interpretation of isotope records preserved in continental archives requires a prior knowledge of the sensitivity of the isotopic composition of precipitation with respect to long-term fluctuations of key climatic parameters (temperature, precipitation amount, relative humidity) over the given area. Unfortunately, the isotopic composition of precipitation has been monitored only for the past three decades. Thus, alternative ways of assessing the long-term climatic sensitivity of the isotopic signature of precipitation are needed.

The link between the isotopic composition of precipitation and climate changes on time scales exceeding instrumental records can be investigated in two ways: (i) through General Circulation Models (GCMs) which simulate the changes in isotopic water cycles (2H'H160, ,H2180) induced by major climatic shifts (Hoffmann & Heimann, 1993; Joussaume & Jouzel, 1993; Jouzel et al., 1997; and (ii) exploring environmental archives in which variations of δ^2H and $\delta^{18}O$ isotope ratios and of climatic parameters (e.g. temperature) are independently recorded (Rozanske et al).