Course Name: Watershed Hydrology

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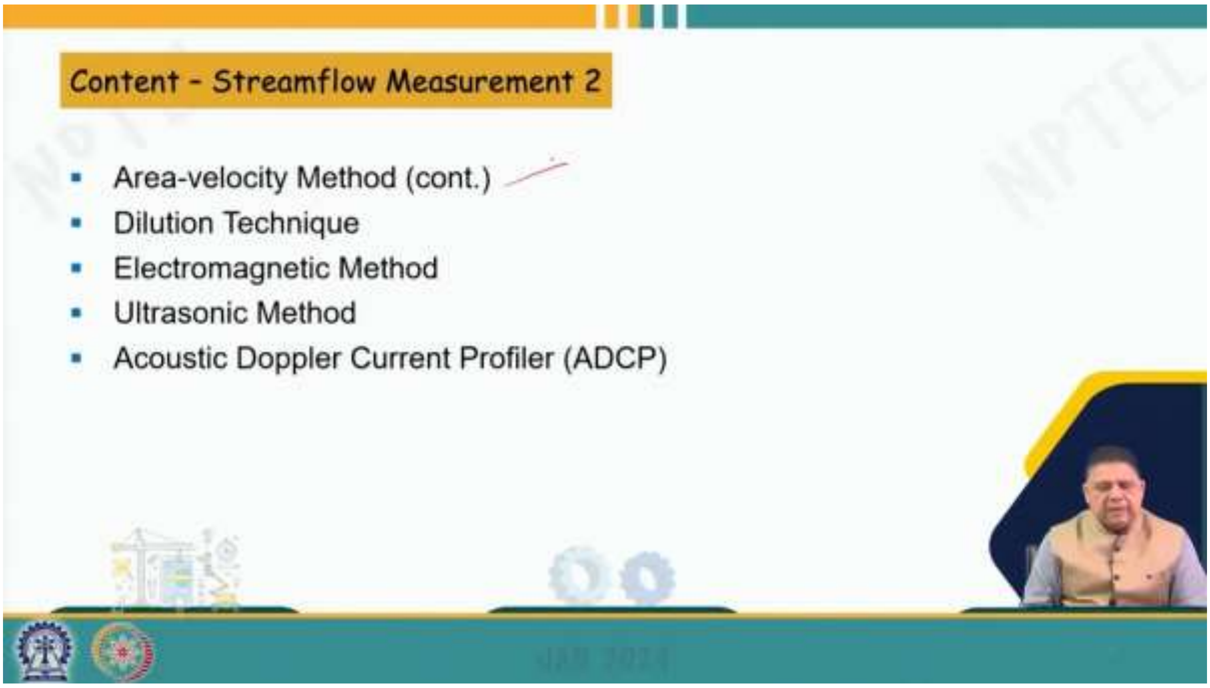
Week: 03

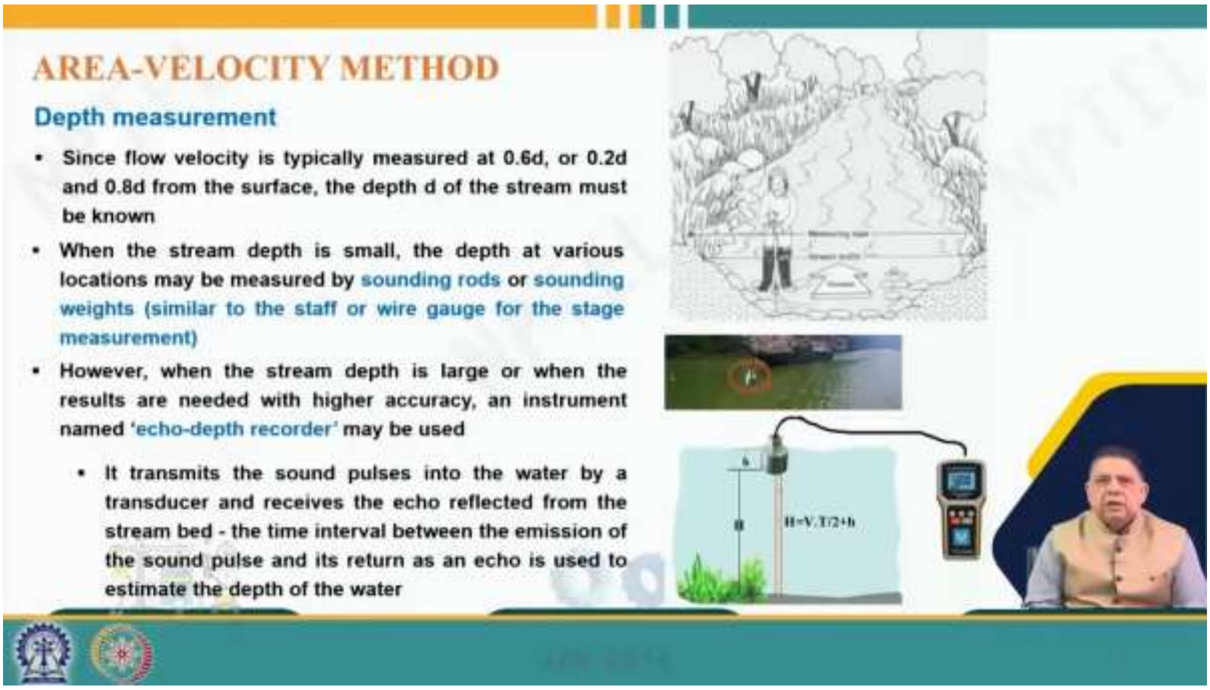
Lecture 13: Streamflow Measurement 2

Hello, friends! Welcome back to this online certification course on Watershed Hydrology. I am Rajnath Singh, a professor in the Department of Agriculture and Food Engineering at the Indian Institute of Technology Kharagpur. We are in Module 3, this being Lecture 3 and we will continue with streamflow measurement. Specifically, Part-2 of streamflow measurement. In this lecture, we will proceed with the area-velocity method, which we initiated in the previous lecture. Then, we will deal with the dilution technique, discuss the electromagnetic method of streamflow measurement, the ultrasonic method of streamflow measurement and also touch upon the acoustic Doppler current profiler (ADCP).



Now, if you recall from the previous lecture, we discussed velocity measurement, stating that a current meter is typically used as the equipment for measuring velocity. We also discussed that if it's a vertical profile, then typically the velocity distribution looks something like this and the reason behind this is because the velocity distribution in the vertical profile is not uniform.

So, we either employ the 6:10 rule, where we measure velocity at 0.6D (D being the depth measured from the top) or we take two measurements at 0.2D and 0.8D and then average them out. Since flow velocity is typically measured at 0.6D, 0.2D and 0.8D from the surface, the depth (D) of the stream must be known. Therefore, we must have a fair idea about the depth at which we are making the measurement. When the stream depth is shallow, the depth at various locations may be measured by sounding rods or sounding weights. We can use a rod or a weight to immerse; if it's a weight, then we use a cable to immerse and then measure the depth. This process is very similar to the staff or wire gauge discussed in the previous lecture for measuring the stage. The only difference is that for the stage. We measure with reference to a certain datum from the bottom. Whereas for depth we measure from the water surface to the bottom of the channel bed.

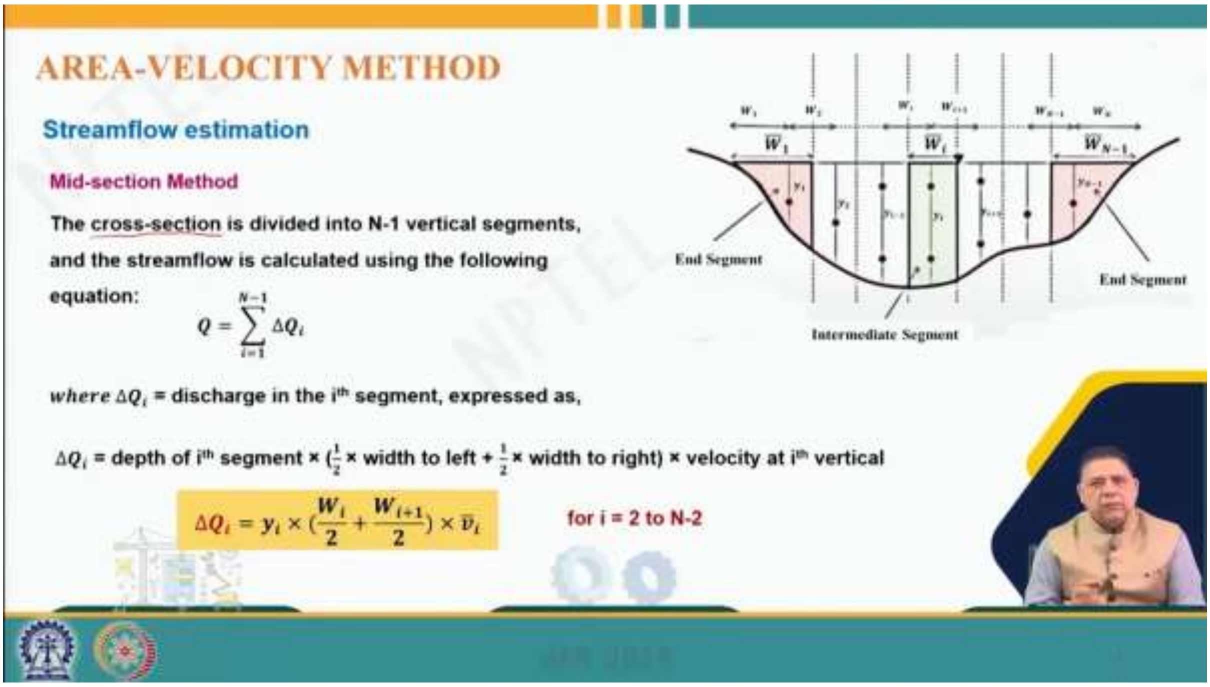


However, when the stream depth is significant or when higher accuracy is required in the results, we employ an instrument called an echo depth recorder. As the name suggests, it is a sound-based device. This device transmits sound pulses into the water by a transducer and receives the echo reflected from the stream bed.

The time interval between the emission of the sound pulse and its return is used to estimate the depth of water. So, this is a typical setup: there's a transducer, a recorder and obviously the sound waves are sent towards the bed. When they hit the bed, they return and based on the time gap between sending and receiving the depth is estimated. Of course, the equipment is calibrated in a particular way.

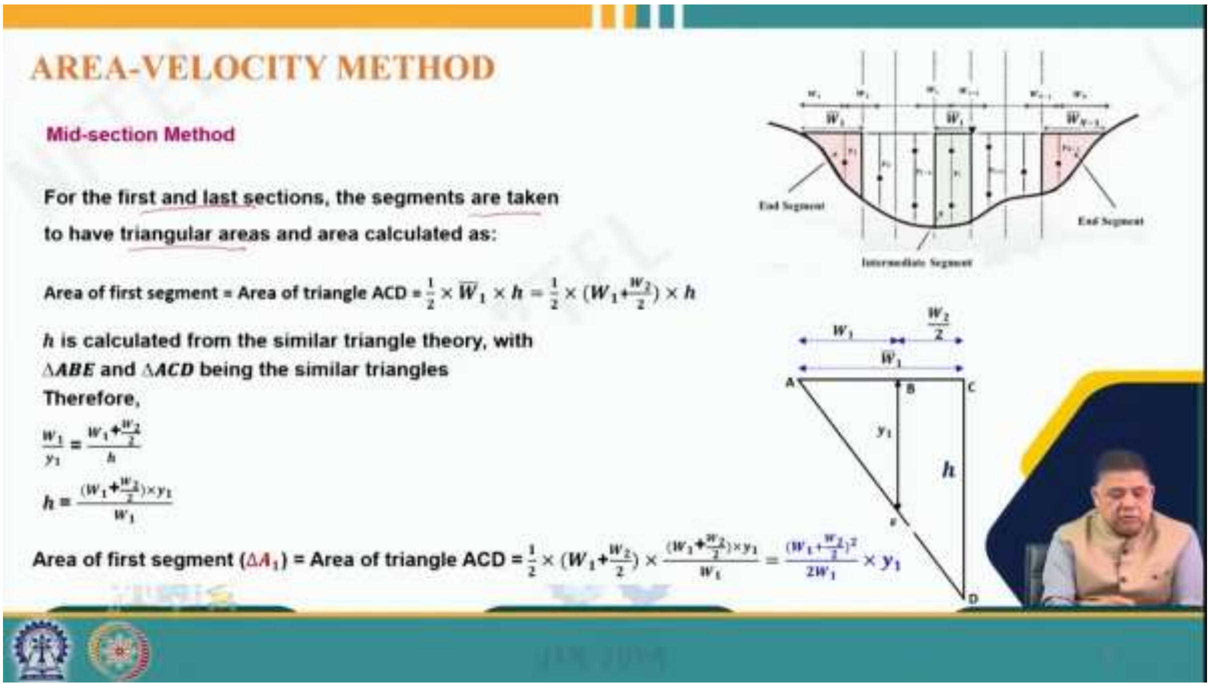
In the area velocity method, another important aspect is the cross-section. We must have a clear idea about the cross-section and where we are going to measure the velocity and depth. All these factors are crucial. Typically, we use a method called the mid-section method. In this method, the river cross-section is divided into $n-1$ vertical segments. At depths w_1, w_2 and so on, we divide the entire cross-section into $n-1$ segments and the stream flow is calculated using the following equation, which is simply the sum of the discharges in these segments.

If we are able to estimate the discharge in all $n-1$ segments, the sum of those will give us the total stream discharge. Essentially, for all segments except the two end ones, we use a formula to calculate the discharge. For i from 2 to $2n-2$, the discharge (δQ_i) in the i^{th}segment is the depth of the i^{th} segment multiplied by half the width to the left plus half the width to the right. All multiplied by the velocity at the i^{th} vertical (v_i). So, it's $2y_i+2w_i+1\times 2v_i$.

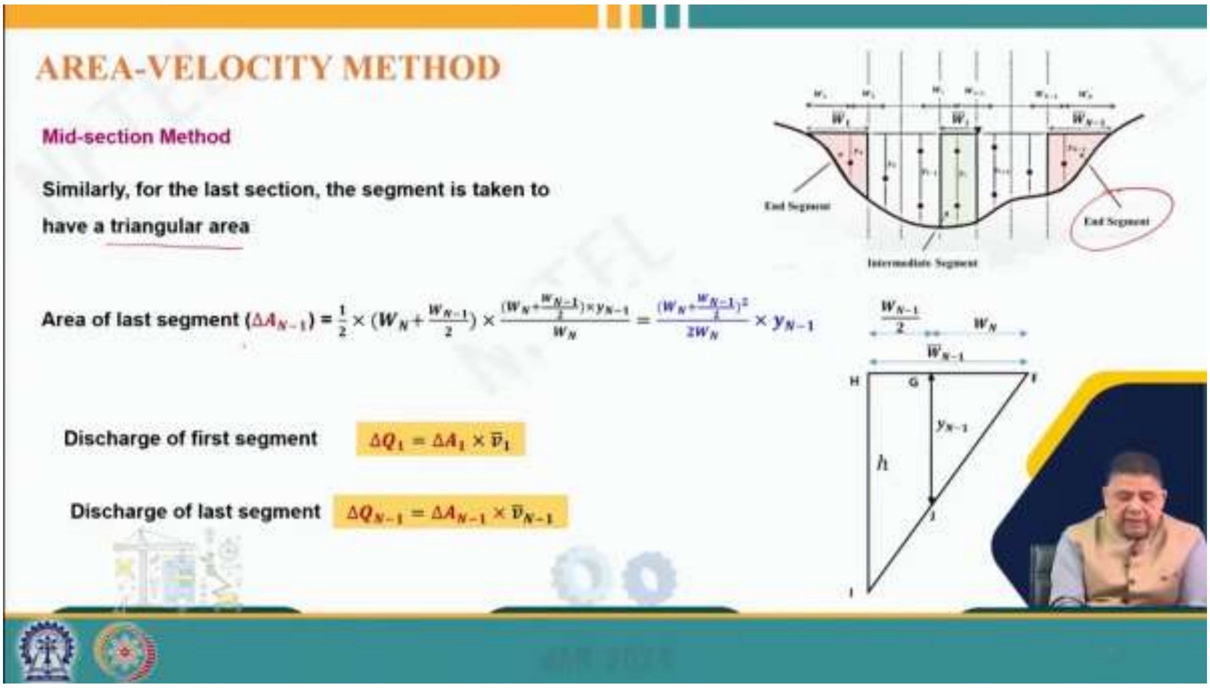


What's happening here is that we're dividing each segment, marking its midpoint for measuring the depth and velocity. Depending on the depth, we measure the velocity at specific points. For example, at points 2 and 8 or points 6 and 8, we find the average velocity for that segment. Essentially, this equation is derived from the trapezoid equation, considering half-widths and velocity at the i^{th} point. For each intermediate segment, from 2i=2 to 2i=n−2, we use this formula.

In the case of end segments, specifically the first and last sections, they are treated as having triangular areas and then the area is calculated accordingly. So, if we consider the area of the first segment. It is essentially the area of triangle ACD. Here, you can see that it is represented as w_1'. This is w_1' and this is y_1' here. So, this is the triangular area we are considering, shaded in pink here, representing $\frac{1}{2} \times w_1'$, which is $\frac{1}{2}$ times the width multiplied by the depth (h). So, it's $\frac{1}{2}$ times w_1', where w_1' is $\frac{w_1 + w_2}{2}$, as you can see from here. So, half of that, which is $\frac{w_1 + w_2}{4}$.

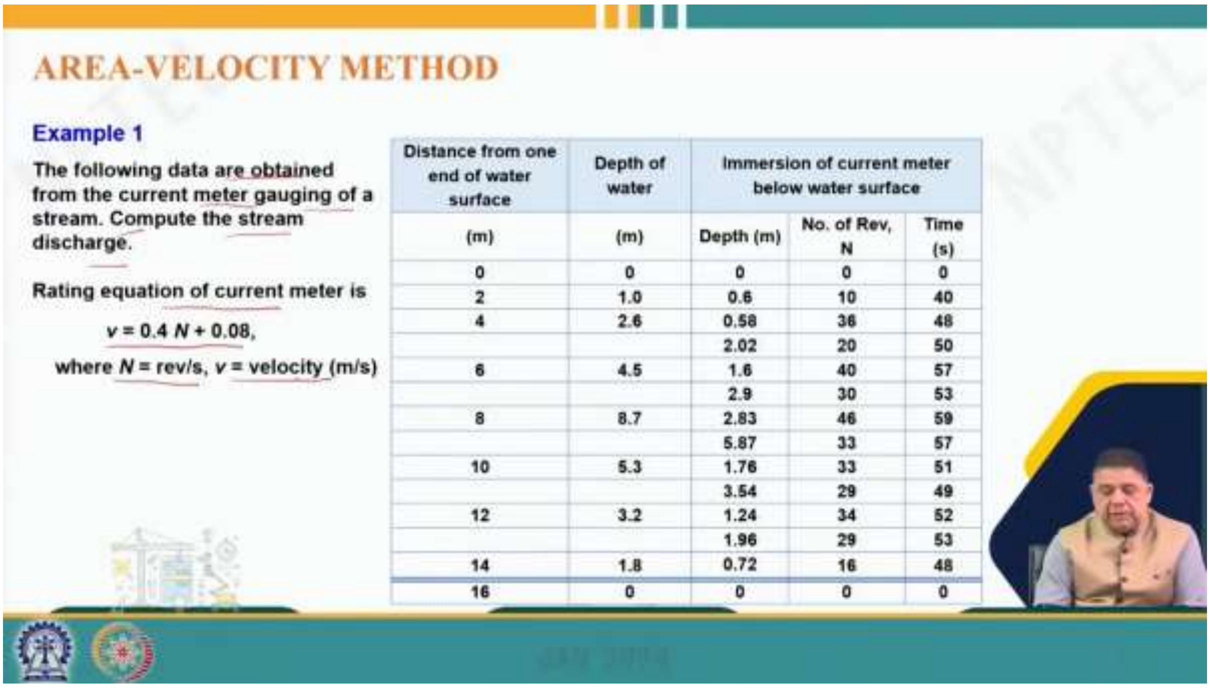


Now, to calculate h, we utilize the similar triangle theory. We consider that triangle ABF and triangle ACD are similar triangles. Therefore $\frac{w_1}{y_1}$, which is this side divided by this side of ABF is the same as $\frac{AC}{CD}$ for triangle ACD. We are interested in finding out CD, which is h. So, from here, $\frac{w_1}{y_1} = \frac{w_1 + w_2}{2h}$ and that will give us the value of h. If we substitute this value of h in this equation, then the area of the first segment will finally be in this form: $\frac{(w_1 + w_2)^2}{8} \times \frac{w_1}{y_1}$, which is a manipulation of this entire multiplication terms.



Similarly, for the last segment, it is also considered to have a triangular area. The area of this particular segment, $\Delta\, y_{n-1}$, will also be found out in a similar fashion, using the similarity theory. Here, it will come out to be $\frac{(w_n + w_{n-1})^2}{8} \times \frac{w_n}{y_{n-1}}$.

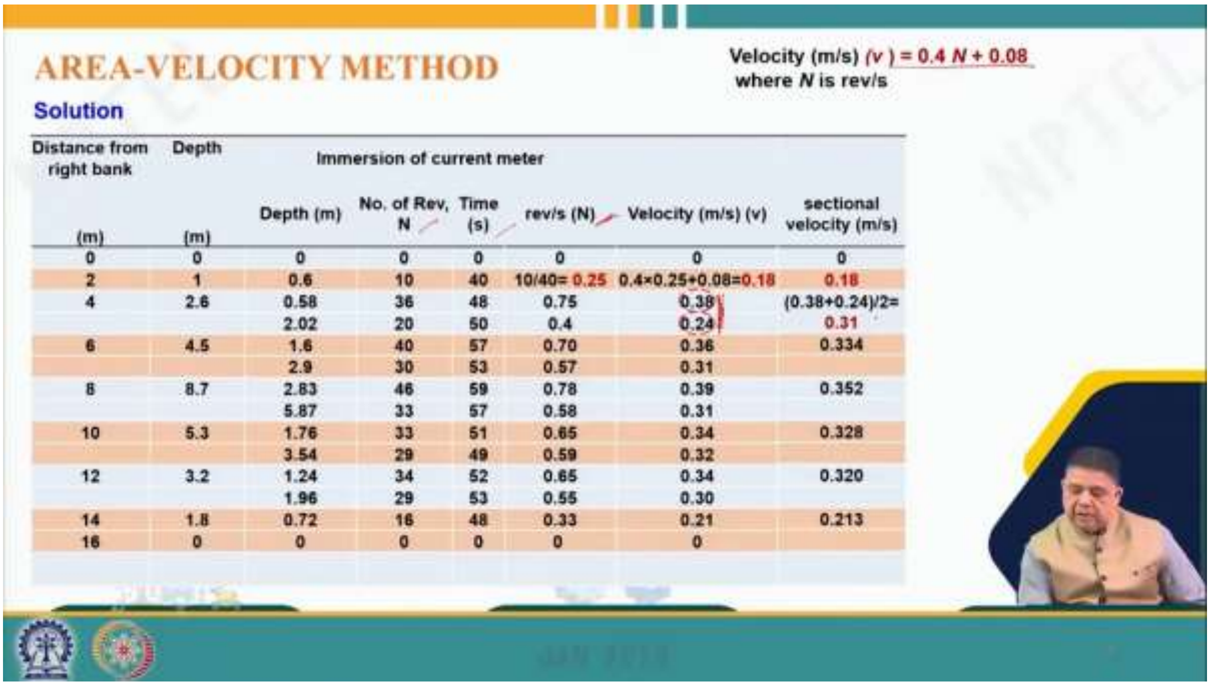
So, this is y_{n-1}, where we are measuring y_{n-1}. The discharge of the first segment will be $\Delta\, A_1$ times $\bar{v}_i$, which is the average velocity in the first segment. Then, the discharge of the last segment will be $\Delta\, Q_{n-1}$, which will be the area times the average velocity in that particular segment. So, the total, obviously, we know because we have calculated earlier the discharges in all other segments. The sum of all these will give us the total discharge by the midsection method.



Now, let's take an example. The following data are obtained from the current meter gauging of a stream. The stream discharge rating equation of the current meter is $v = 0.4n + 0.08$, where n is revolutions per second and v is the velocity per meter per second. As you can see in the data, distances from one end of the water surface across the stream at different depths are mentioned. Also, current meter data like depth and number of revolutions are recorded.

If you notice at smaller depths there is just a single measurement but when the depth is more. There are two measurements as indicated by 0.2+0.8d measurements. This needs to be taken into account while finding out the discharge.

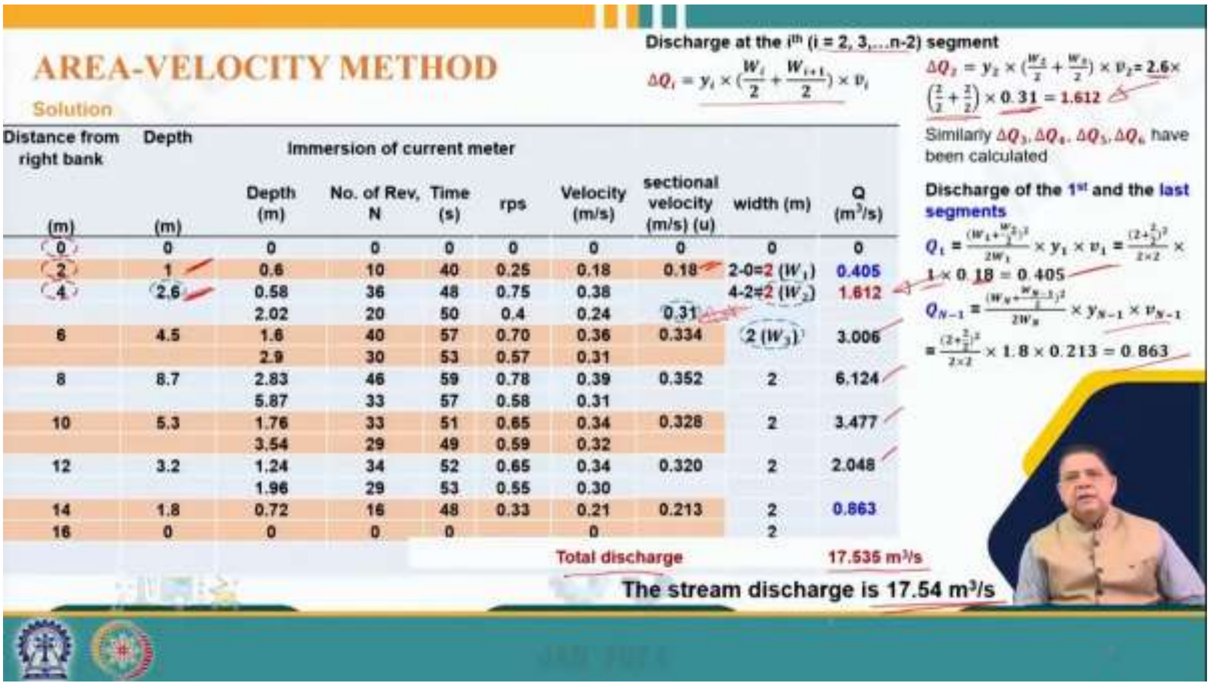
So, this is the raw data we just saw and we know that velocity is $4n$+0.08, as given by the equation. Obviously, we have to find out the value of n since revolution and time are given. Once we know the value of n, we can plug it into the equation to find the velocity at different depths or distances where the current meter readings have been taken.



Distance from right bank (m)	Depth (m)	Immersion of current meter Depth (m)	No. of Rev, N	Time (s)	rev/s (N)	Velocity (m/s) (v)	sectional velocity (m/s)
0	0	0	0	0	0	0	0
2	1	0.6	10	40	10/40= 0.25	0.4×0.25+0.08=0.18	0.18
4	2.6	0.58	36	48	0.75	0.38	(0.38+0.24)/2=
		2.02	20	50	0.4	0.24	0.31
6	4.5	1.6	40	57	0.70	0.36	0.334
		2.9	30	53	0.57	0.31	
8	8.7	2.83	46	59	0.78	0.39	0.352
		5.87	33	57	0.58	0.31	
10	5.3	1.76	33	51	0.65	0.34	0.328
		3.54	29	49	0.59	0.32	
12	3.2	1.24	34	52	0.65	0.34	0.320
		1.96	29	53	0.55	0.30	
14	1.8	0.72	16	48	0.33	0.21	0.213
16	0	0	0	0	0	0	

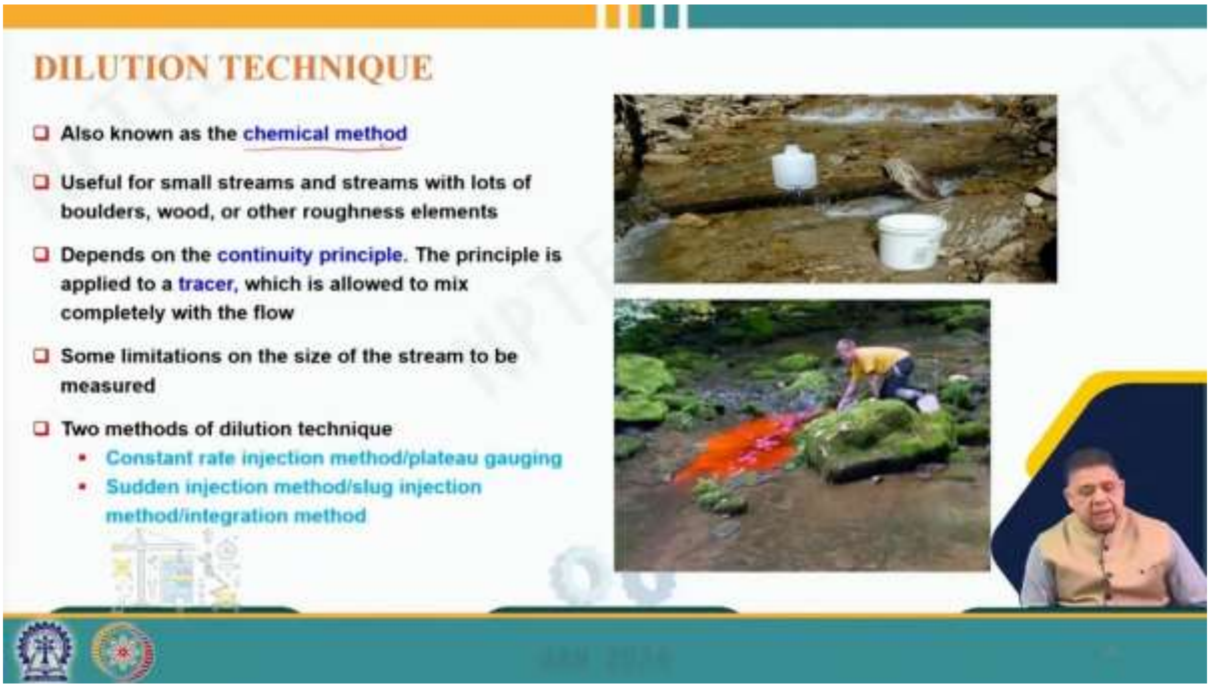
So, all of these data are here. Of course, in sections or depths where only a single measurement is taken. We can directly obtain the velocity. However, in other cases such as this one, we need to take the average of these two to obtain the average velocity. So, the average velocity in this particular section is 0.31 and so on with values like 0.334 and 0.352 for different sections. Now, once we have obtained these sectional velocity values. The next step is to consider the width because if you recall the formula, the width is also taken into account. So, w_1, w_2, ..., w_n, where n-1 comes into the picture. Hence, we need to determine the width, which we already know from the data. Throughout the width of segments is 2 meters.

If we need to find the discharge from section 2 to section n-2 that is from i=2 to n-2. Then obviously, we will utilize the formula. For example, if we consider section 2, then the change in discharge (ΔQ2) is $y_2$times w2/2 plus w_3/2 times v_2. Here, the depth for this section is 2.6 with w_1, w_2 and w_3 being the same value.



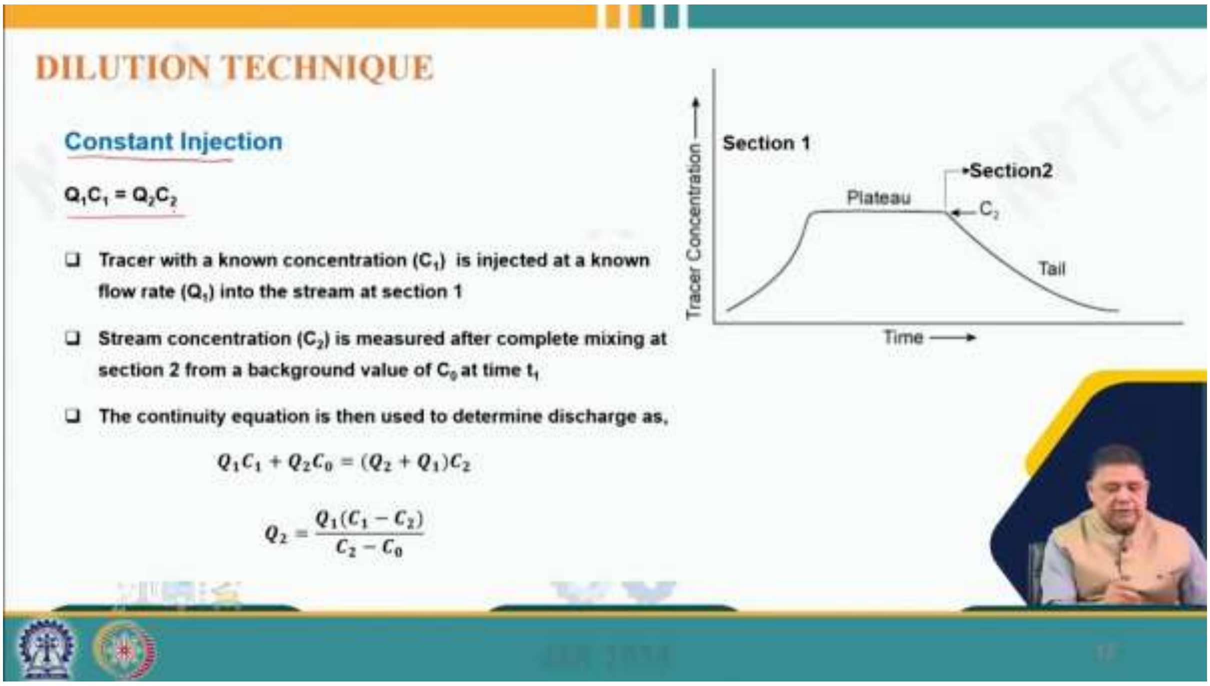
Since all are 2. It doesn't matter and we have to consider the average velocity calculated earlier for this section, which is 0.31. Substituting this value, we obtain the discharge for this particular section as 1.612. Similarly, we will calculate the discharges for all intermediate sections namely Q_3, Q_4, Q_5 and Q_6 for different sections and these are the values we obtain.

So, this is for intermediate sections and for the first and last sections. We know that we have to change the formula, which is as follows: $\frac{w_1 + w_2}{2} \times \frac{y_1 + v_1}{2}$ for the first section. All w's are 2, so that is not a problem putting those values. y_1 represents the depth of section 1, which is 1. Therefore, it is 1 and we found out the velocity to be 0.18. So, using that we get the discharge as 0.405. Similarly, for the last section, we get the discharge as 0.863. So, these are the discharges at different segments and of course as we know the sum of discharges will be the total discharge, which comes out to be 17.535 cubic meters per second. That means the total stream discharge for the given data is 17.454 cubic meters per second.



Then, we move to the next method, which is the dilution method or dilution technique, also known as the chemical method. This particular method is useful for small streams and streams with lots of boulders, wood and other roughness elements where current meters may not be able to work due to obstructions. So, we use this chemical method and this method or dilution technique works on the principle of continuity. The principle is applied to a tracer, which is allowed to mix completely with the flow. A tracer is put into the stream and allowed to mix and then we measure the concentration and use the continuity principle to find out the stream flow or discharge. Of course, there are some limitations on the size of the stream to be measured. This particular technique cannot be used if the stream is too wide because there can be currents and then the tracer mixing may not be uniform resulting in inaccurate data. There are two methods followed in the dilution technique: constant rate injection method, also called plate gauging and sudden injection method, also known as slug injection method or integration method. Slug injection is very common.

So, constant rate injection and slug injection are common terms that essentially refer to the rate at which or the method by which we inject the tracer into the stream. Let's delve into these methods. But before that, there are three main types of tracers commonly used. The first type includes chemicals like sodium chloride. The common salt used at home or sodium dichromate, which can also serve as a tracer. However, in this case we need to use an electrical conductivity mixture because when salt is introduced into water. The electrical conductivity changes. Hence, this conductivity is measured, enabling us to use these chemicals as tracers. Additionally, we can utilize radioactive materials such as bromine 82, sodium 24 or iodine 132. Alternatively, fluorescent dyes like Rhodamine WT (where WT denotes water tracer) or sulphorhodamine can also be employed. These dyes fluoresce, allowing for the observation of different colours, such as red or green.

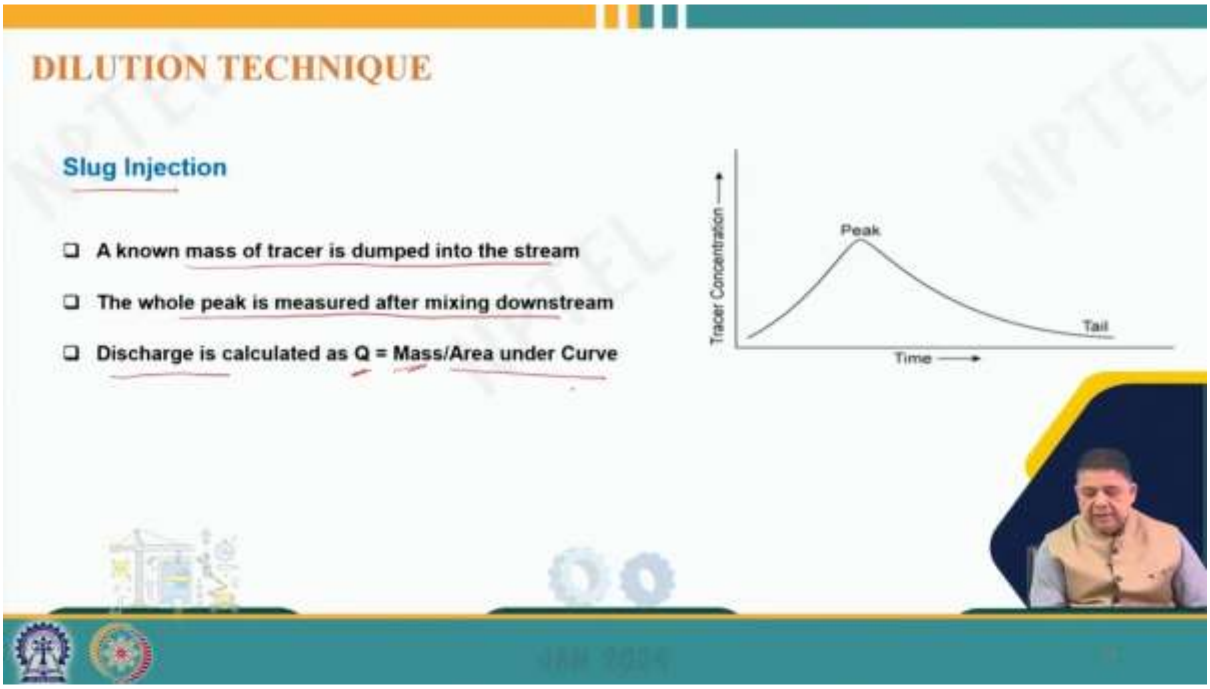


Now, let's focus on the constant injection method, which is one of the methods of injecting tracers. As we already know, the entire procedure is based on the continuity principle. Here's how it works: a tracer with a known concentration C_1 is injected at a known flow rate Q_1 into a stream at section 1. So, if this is our section 1, we introduce a tracer with a known concentration and at a constant rate into the water stream. We know both the concentration and the rate at which we are introducing the tracer into the stream.

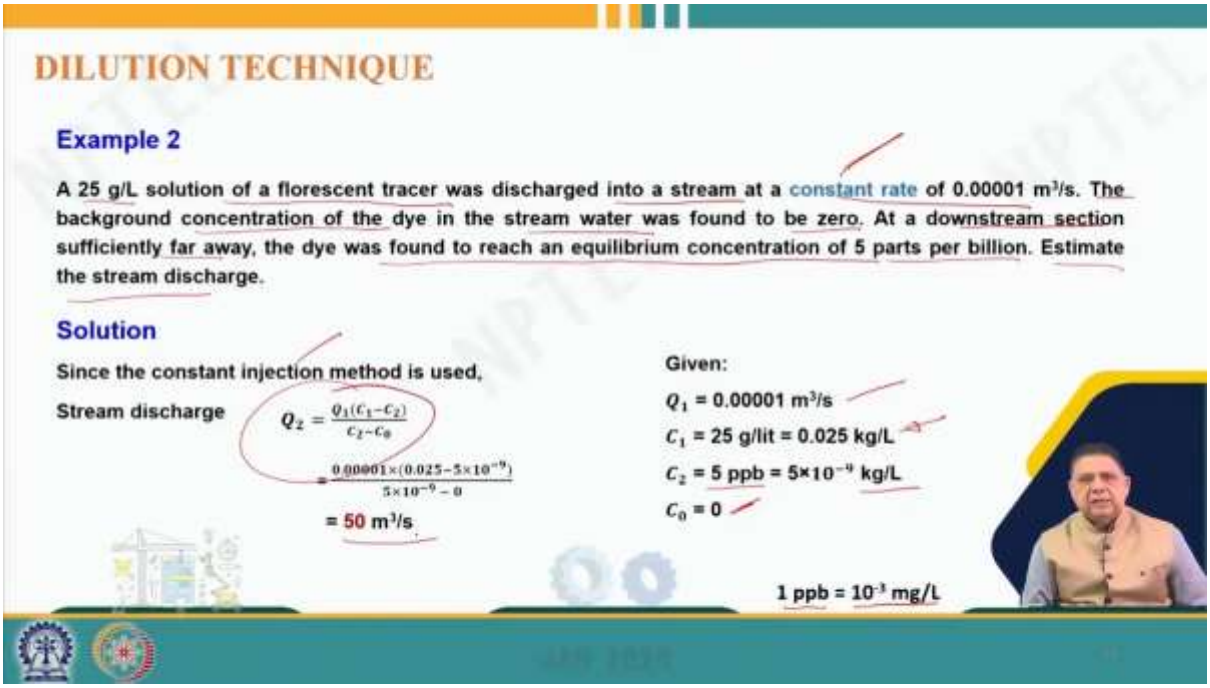
The concentration C_2 in the stream is measured after complete mixing at section 2, which is situated a little further away. This stage often referred to as the plateau method occurs because once complete mixing has taken place. It is expected that the tracer concentration will stabilize resulting in a constant concentration level. Therefore, we measure C_2 from a background value of C_0 at time t_1. Prior to experimentation, we initially measure the concentration denoted as C_0.

Subsequently, we have values for C_1, C_2, C_0 and Q_1. By utilizing the continuity equation, we can determine the discharge represented as $Q_1C_1 + Q_2C_0 = Q_2 + Q_1C_2$. This equation accounts for the flow occurring with a certain discharge.

Considering the background concentration, and the known discharge poured during the experiment, we can calculate the discharge. When measuring, we factor in both the sum of the two discharges ($Q_2 + Q_1$). With these values known, including Q_1, C_1, C_2 and C_0, we can ascertain the discharge. This method is known as the constant injection method.



The other method is slug injection. In this case, a known mass of tracer is introduced into the stream. Here, our dependency lies on the mass rather than the rate. We introduce the known mass into the stream and then the entire peak is measured after downstream mixing. We measure the complete peak tracing its origin, ascent and subsequent descent to the initial value. Discharge is then calculated using the relationship where Q equals the mass of the known tracer divided by the area under the curve.



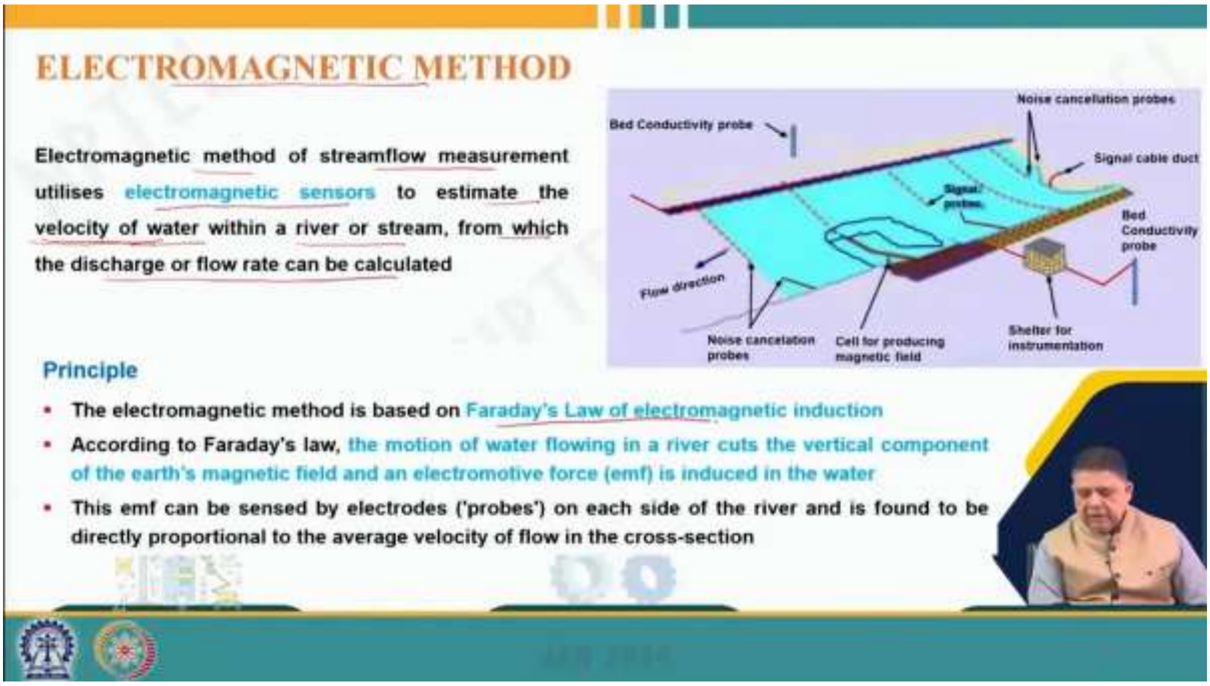
Let's consider a straightforward example: a solution containing 25 grams per litter of a fluorescent tracer was discharged into a stream at a constant rate of 0.0001 cubic meters per second. The background concentration of the dye in the stream water was found to be 0. At a downstream section sufficiently far away, the dye was observed to reach an equilibrium concentration of 5 parts per billion. We need to estimate the stream discharge.

In this scenario, we know that the tracer is being injected at a constant rate, indicating a constant injection method. Therefore, we employ the following formula:

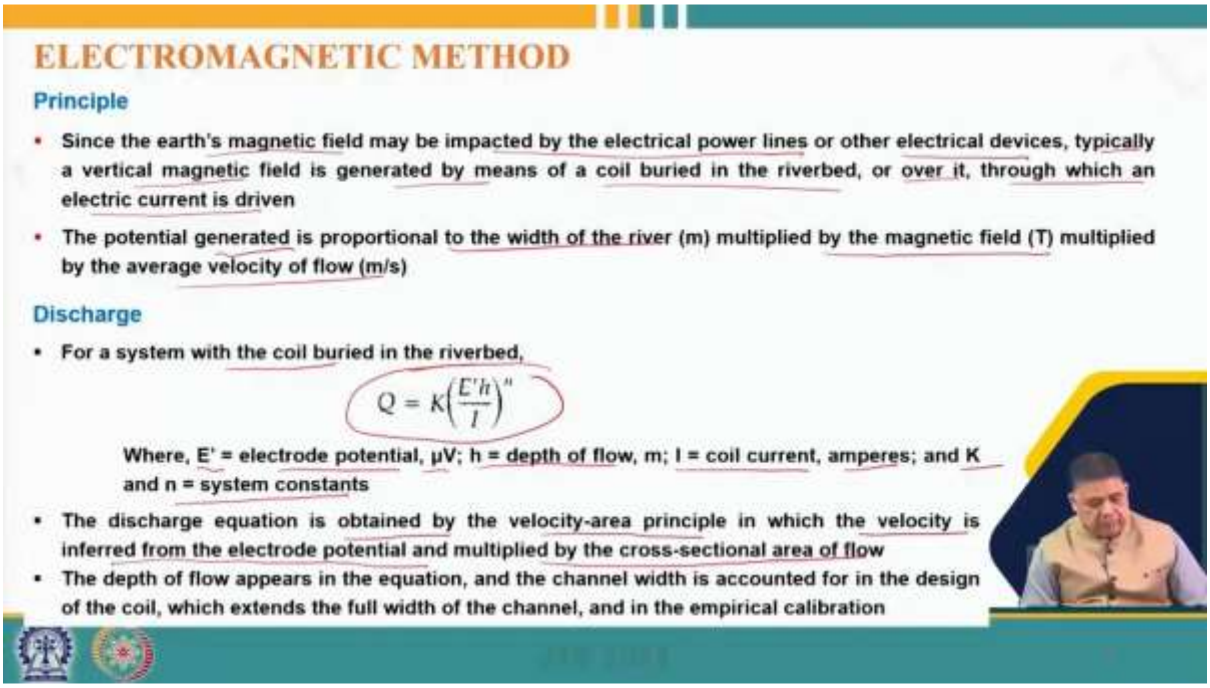
$$Q_2 = \frac{Q_1.C_1.C_2}{C_0}$$

Where Q_1 represents the injection rate of the tracer C_0 is the background concentration (which is 0), C_1 is the known concentration of the tracer (25 grams per litter or 0.025 kg per litter), and C_2 is the equilibrium concentration (5 parts per billion, equivalent to 5×10^{-9} kg per litter).

Given that Q_1, C_1, C_2 and C_0 are known values substituting them into the formula yields Q_2 = 50 cubic meters per second. This indicates that the discharge in the stream using the tracer method is 50 cubic meters per second.



Now, let's move on to the third method: the electromagnetic method. The electromagnetic method of stream flow measurement utilizes electromagnetic sensors to estimate the velocity of water within the river or stream, from which the discharge or flow rate can be calculated. An important point to note here is that the electromagnetic sensors we use measure the velocity. This means that ultimately the area velocity method is employed here. However, instead of using the midsection method in this case the area is taken into account while developing the relationship itself, which we will delve into shortly.



As for the principle behind this method, it is based on Faraday's law of electromagnetic induction. According to this law the motion of water flowing in a river cuts the vertical component of the Earth's magnetic field inducing electromotive force or EMF in the water.

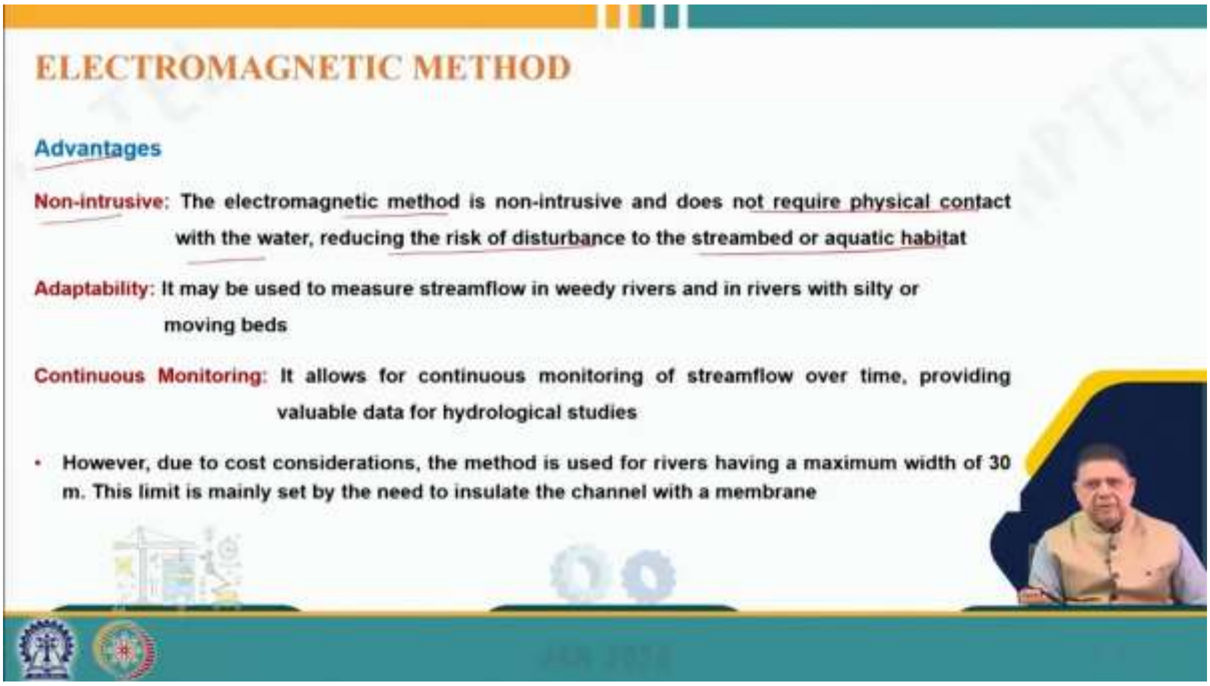
This EMF can be sensed by electrodes or probes on each side of the river and it is found to be directly proportional to the average velocity of flow in the cross-section.

As you can see, a certain setup is required. Cables and probes need to be installed on either side, along with instruments to measure all those signals. All these elements need to be carefully arranged as depicted.

Since the Earth's magnetic field may be influenced by electric power lines crossing the river or stream where this method is being used or by any other electrical devices operating nearby typically a vertical magnetic field is generated using a coil buried in the riverbed or placed over it, through which an electrical current is driven. This process adds a layer of complexity as we may need to bury the cable inside the stream bed or arrange it to move just above the water surface.

The potential generated is proportional to the width of the river multiplied by the magnetic field multiplied by the average velocity of flow. For a system with the coil buried in the riverbed, the discharge can be determined using this relationship, where E' represents the electrode potential (the voltage measured by the probes), H is the depth of flow (meaning we need to measure or know the depth), I is the coil current (the current sent in amperes), and k and n are system constants.

So, *k* and *n* are system constants. That's why I mentioned that although it primarily measures velocity, through these system constants, the area is also taken into account. The discharge equation is obtained through the velocity area principle, in which the velocity is inferred from the electrode potential, as we've demonstrated here, and then multiplied by the cross-sectional area of flow. The depth of flow also appears in the equation. You can observe that the depth of flow *H* is already being used in the equation. The channel width is accounted for in the design of the coil, which extends the full width of the channel, and in the empirical calibration. Since the cable is placed below the bed, the stream width is automatically taken into account by the coil design as well as during calibration. So, these constants *k* and *n* take care of the width aspect.

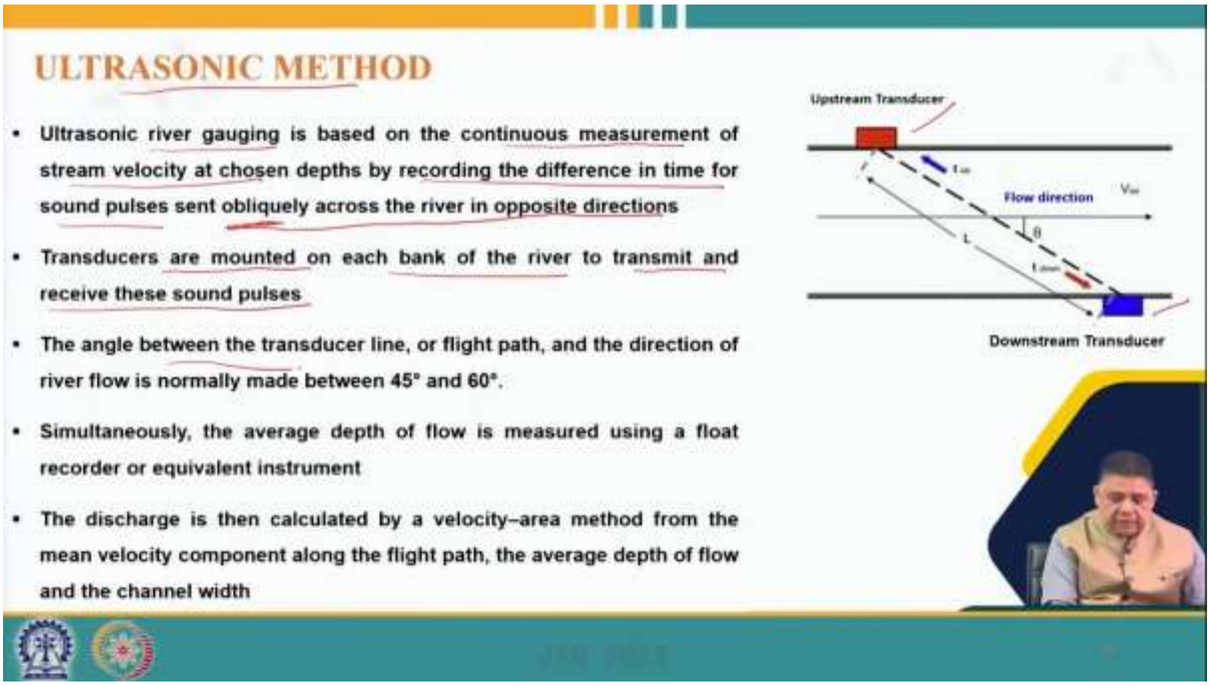


Then, there are certain advantages to this method. For example, it's a non-intrusive method. This electromagnetic method is non-intrusive and does not require physical contact with the water reducing the risk of disturbance to the stream bed or aquatic habitat. In other methods such as using a staff or wire gauge for measuring depth or stage or even employing a current meter for measuring velocity. There's always a risk of disturbance to the stream and of course the aquatic habitat. However, that's not the case with this method.

Adaptability is a crucial factor when it comes to measuring stream flow in various river conditions including those with silty sediment or a moving bed such as VD rivers. In this context the cross-section of the river is not a limiting factor because width is the primary consideration in designing the coil or calibrating the instrument. This means that even if the river's cross-section varies. It doesn't impede the measurement process.

One significant advantage of this method is its capability for continuous monitoring. Unlike other methods that require conducting experiments, which demand time and logistical arrangements once the setup is in place, continuous monitoring of stream flow becomes feasible. This continuous data collection is invaluable for hydrological studies and provides a comprehensive understanding of the dynamics of river systems.

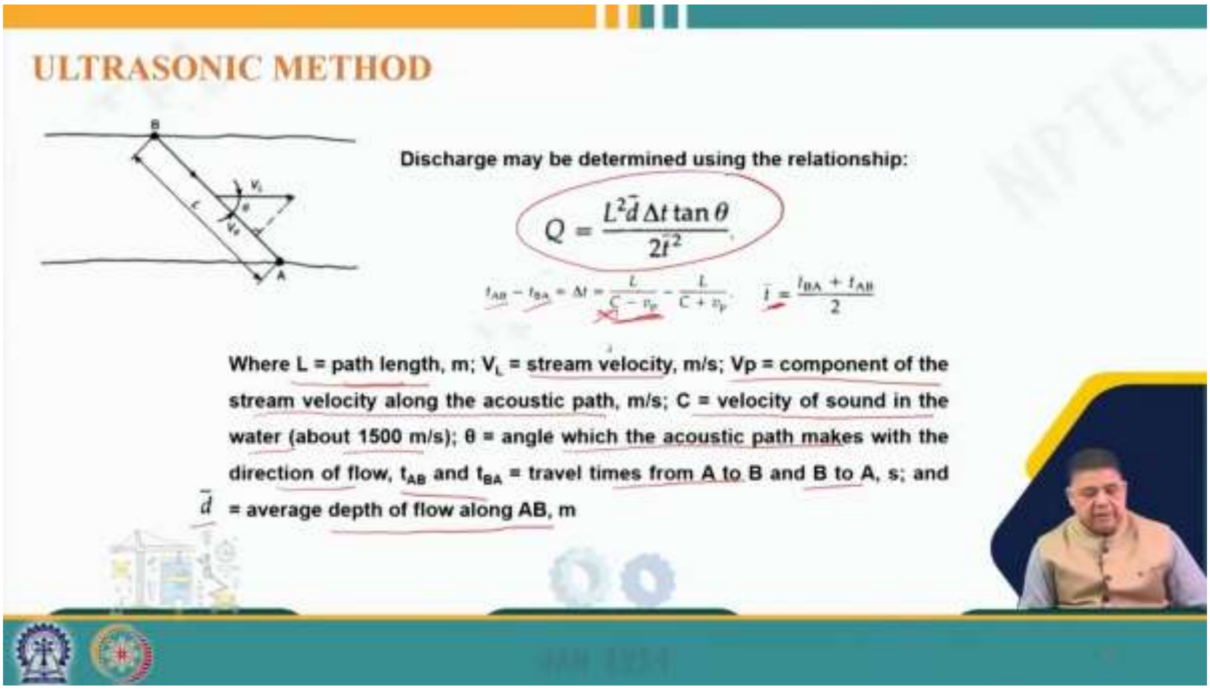
However, it's essential to consider cost factors when employing this method. Typically, it is most practical for rivers with a maximum width of 30 meters. The limitation is primarily dictated by the necessity to insulate the channel with a membrane. Therefore, the cable used for measurement needs insulation or alternatively, the entire channel must be insulated to ensure accurate readings.



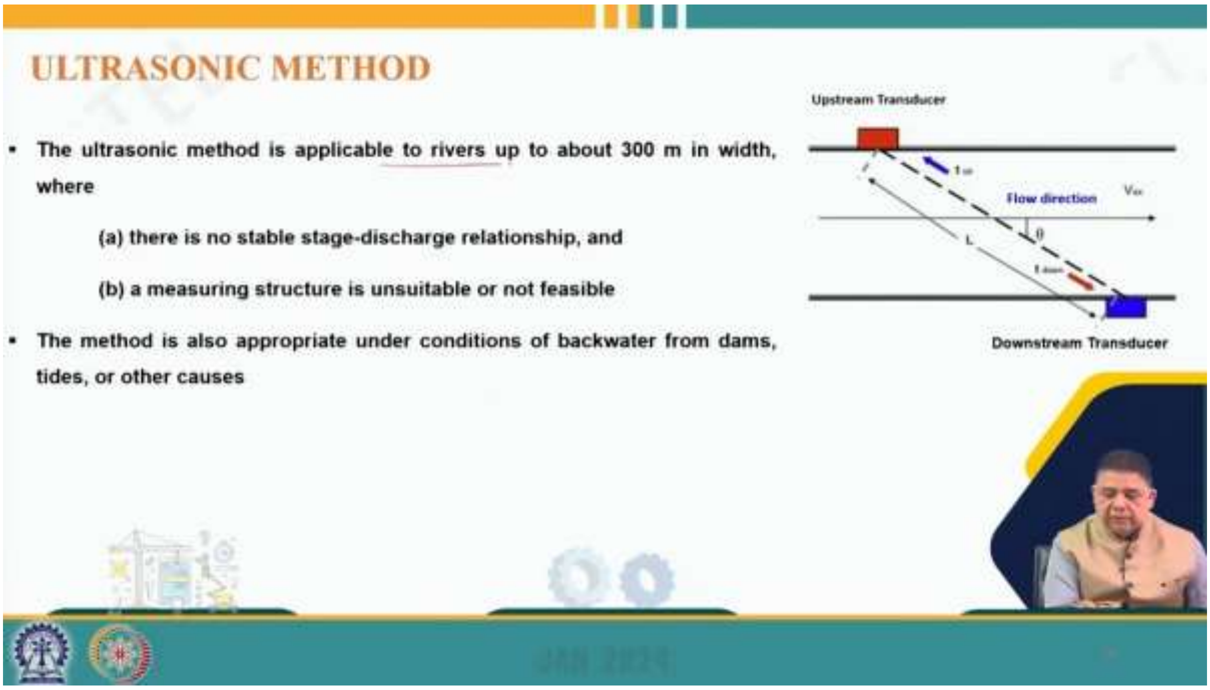
So, there is no danger of current causing any damage to human beings. That's why this becomes a costly affair. Then comes the ultrasonic method, which, of course, is sound-based. Ultrasonic river gauging is based on the continuous measurement of stream velocity at a chosen depth by recording the difference in time for sound pulses sent obliquely across the river in opposite directions. Here, you can see that transducers are installed, and the sound waves are not sent straight across the channel width, but at an oblique angle. The transducers are mounted on each bank of the river to transmit and receive these sound pulses.

As you can see, two transducers are installed, referred to as upstream and downstream due to the direction or angle they make. The angle between the transducer line or flight path and the direction of river flow is normally kept between 45 and 60 degrees. Simultaneously, the average depth of flow is measured using a float recorder or equipment instrument.

Obviously, we also measure the depth of flow. Discharge is then calculated by the velocity-area method from the mean velocity component along the flight path, the average depth of flow, and the channel width. This means that this ultrasonic method also provides velocity, and then we have to use the area-velocity method to find out the discharge. The equation used for determining the discharge where L is the path length. So, these are the two transducers, and the distance between them is the path length in meters, while V_L represents the stream velocity in the direction of flow.

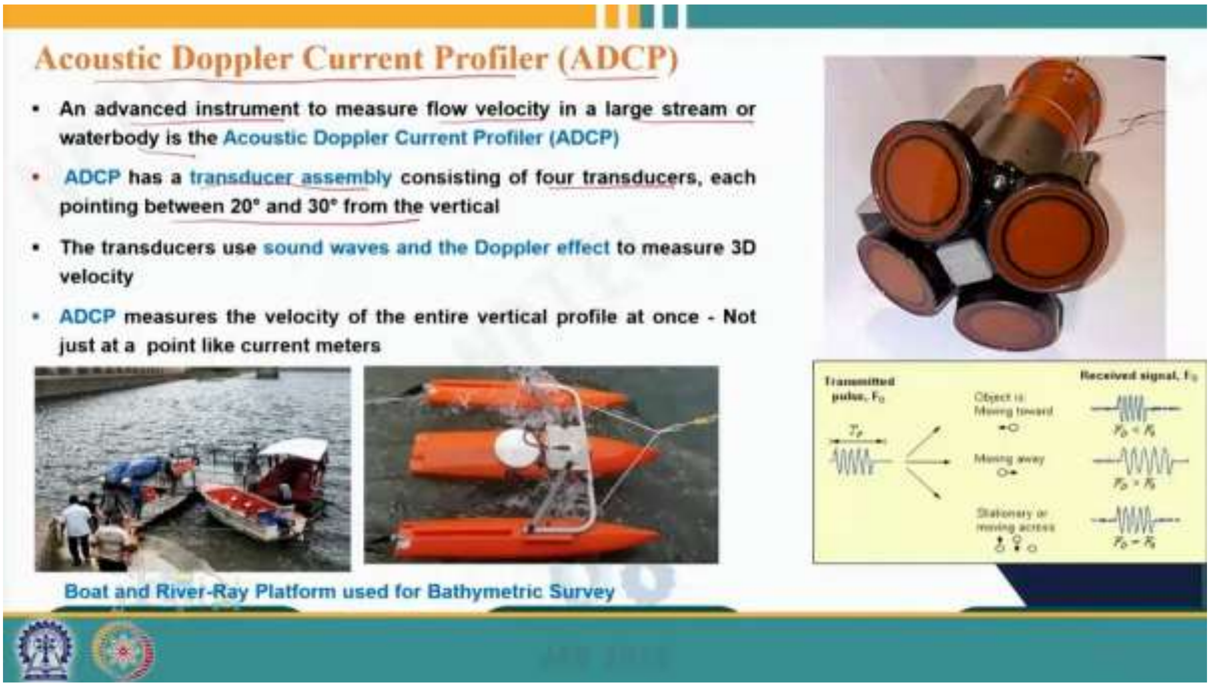


V_p is the component of the stream velocity along the acoustic path, which is being used here to calculate this T bar. C is the velocity of sound in the water, taken approximately 1500 meters per second, also used in calculating T bar. Theta is the angle the acoustic path makes with the direction of flow, as we discussed earlier. TA-B and TB-A are the travel times from A to B and B to A. So, we are calculating TA-B and TB-A, and the difference is giving us delta T, and T bar is being calculated.



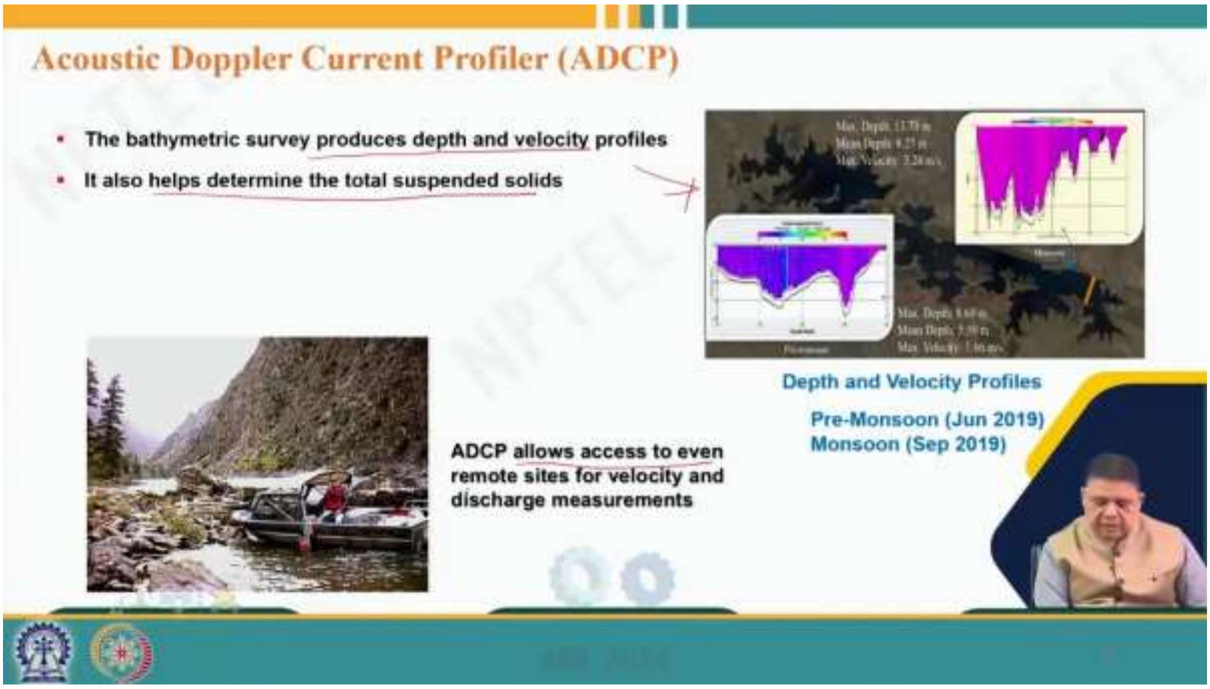
D bar is the average depth of flow along AB. So, D bar represents the average depth of flow along AB. Depth, width, and velocity are taken into account in terms of the path length. This method enables us to find out the discharge. This method is applicable to rivers up to about 300 meters in width. Beyond that, it is found that sound waves are not disturbed, thus providing accurate readings. This method is used where there is no stable stage-discharge relationship and where major structures are unsuitable or not feasible.

This method is suitable where the cross-section is unstable, where installing imaging structures is impractical, or where establishing a reliable stage-discharge relationship or rating curve is difficult. Additionally, this method is appropriate under conditions of backwater from dams, tides, or other causes. If the section of interest is near a dam or a sea where backwater effects may occur, this method works effectively.



Lastly, we will discuss the Acoustic Doppler Current Profiler (ADCP), an advanced instrument for measuring flow velocity in large streams or water bodies. The ADCP includes a transducer assembly consisting of four transducers, each pointing between 20 and 30 degrees from the vertical.

So, as you can see here, this is the Transducer Array of an Acoustic Doppler Current Profiler (ADCP). There are four transducers, making an angle of 20 to 30 degrees with the vertical axis, as mentioned earlier. These transducers emit sound signals or waves, utilizing the Doppler effect to measure 3D velocity. When the sound pulse is transmitted, it is also received upon hitting sediment particles or the riverbed, which is then measured. ADCP measures the velocity of the entire vertical profile simultaneously, unlike a current meter which measures velocity at a single point. This capability is advantageous because, with a current meter, we only obtain velocity data at one point, whereas with ADCP, we get measurements for the entire profile.



Typically, a boat or a platform is used for conducting bathymetric surveys in streams or water bodies. These surveys yield depth and velocity profiles, aiding in determining total suspended solids as sound waves interact with sediment particles. ADCP facilitates access to remote sites for velocity and discharge measurements due to its simple immersion requirement for obtaining 3-dimensional velocity.

Hence, anywhere accessible by boat, ADCP can be employed. With this, we conclude the lecture, having explored various methods of stream flow measurement. We will further delve into indirect methods in the upcoming session, as we've primarily focused on direct methods until now. Thank you for your attention. Please provide feedback and feel free to ask any questions, which we can address in the forum. Thank you very much.