Water Resources Engineering

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Lecture No. 16

In today’s lecture we will look at various components of the water cycle which describes the movement of water on the ground, in the atmosphere and below the ground surface. This is commonly called the water cycle or the hydrologic cycle. Then we will look at various components for example the rainfall evaporation, transpiration and filtration. These various components can be described in terms of the mechanism, how can they be measured and what is of interest to us as water resources engineer. Let’s first look at the water cycle or the hydrologic cycle and let’s say we have these hilly areas; so mountains here then we have some streams and we have the ocean here. There may be some small depressions on the ground surface, there will be some trees, other vegetations and there may be some buildings. When the process of evaporation starts from the ocean since this is a cycle we can start anywhere. We can start from raindrops falling on the surface, their precipitation or we can start with evaporation.

Let’s start with the evaporation because this is the driving force behind the water. First it will evaporate from the ocean. It will condense as it goes up because of adiabatic cooling and form clouds. These clouds will rain; some rain will fall on the ocean. Then the clouds will be moving. There will be some clouds over the land surface and there will be what is known as precipitation. We are familiar with the precipitation of solids in liquids during chemical reactions. This precipitation can occur in various forms. For example on the mountains it can take the form of snow otherwise it can have rain or it may have hails. We will look at various forms of precipitations also. Once the precipitation occurs part of it will directly evaporate. Solar radiation is the agency or the source of the heat energy. So the solar radiation in the form of heat energy from the sun will cause the evaporation. The same energy will also cause some evaporation from the rainfall directly. So this rain will not reach the ground. Even before that there will be some evaporation from the rain. The part which reaches the surface some of it will be intercepted by the buildings and may be other vegetation. So this part will not reach the ground. It will be intercepted before it reaches the ground and from the interception it may evaporate back to the atmosphere without reaching the ground. Some part of the interception will fall down to the ground after sometime. The part which reaches the ground can go in the ground known as infiltration. It may evaporate from the ground surface or it may runoff over the ground and the runoff is one component in which we are very interested because this is what will govern the flow in the streams and if we are designing a project, let’s say an irrigation project or water supply project we should know how much water is available in the streams or if we are interested in the flood control structures we should know what is the maximum flood expected. So runoff is a very important component of the hydrologic cycle and we should know how to obtain this component. The part which goes into the ground as infiltration some part of it may be retained near the soil surface and is called the soil moisture. Part of this moisture will be taken up by the plants through their roots and then it will be transpired back to the atmosphere. We will call it transpiration.

There will be some water under the ground. Let’s say that there is some ground water table. Ground water table denotes the top of the water inside the ground which would be at atmospheric pressure. There will be a rock base. This will be rock above which this water will be standing and the water which infiltrates into the ground water some part of it may percolate very deep into the rocks and may be lost for all practical purposes and is called deep percolation. Some part the water which infiltrates may again reappear on the surface. For example if we have an impermeable layer let’s say here then the water which is falling here, infiltrating inside the ground may join the runoff or may appear on the surface again. This is known as interflow and depending on how fast or how slow it appears it may be a delayed appearance on the surface or it may come very fast. The depressions on the ground surface will also store some of the precipitation. So before the runoff can start we should have some storage in the depression and that is also counted towards losses. Once we have precipitation we will have some depression storage and once we fulfil all these depression storage requirements then there will be runoff over the surface and going to the streams. Finally the streams will runoff to the ocean. From ocean it will be evaporated back and the whole cycle will repeat. Various components of the hydrologic cycle can be thought of as precipitation which can be thought of as driving all the flow. Although the precipitation comes from evaporation we can start from anywhere in the cycle. Let’s start from the precipitation.

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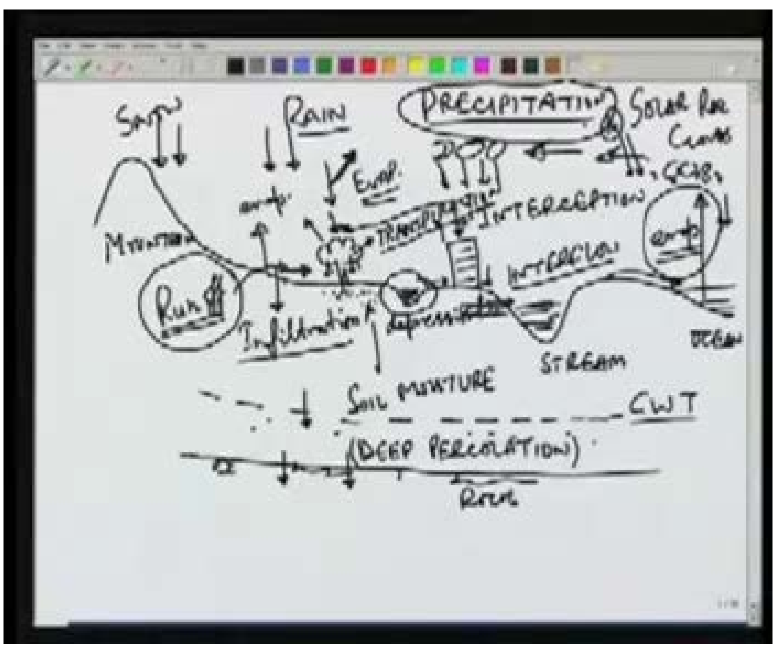

Precipitation as we have seen can be in the form of snow or it can be in the form of rain. Let’s first look at various forms of precipitation. In the first classification we can classify the precipitation which is falling as liquid form or solid form. In the liquid form we have rain. But depending on what is the rate at which it is falling we can classify this into different categories for example a drizzle or we can call it rain depending on what is the intensity at which they are falling. Drizzle for example as an intensity which is very small and typically we use less than about 1 millimetre per hour. The rainfall or the precipitation is measured in terms of depth, in depth units. When we say that there is a precipitation of 1 millimetre or1 centimetre it indicates that over a certain area if the entire precipitation which is falling stands on that area uniformly it will have a depth of that much. For example 1 centimetre or 1 millimetre and the intensity of precipitation is measured in terms of depth per unit time, typically millimetre per hour or sometimes centimetres per hour or millimetres per day, centimetres per day whatever units we want to use but millimetre per hour is the conventional unit. If precipitation is falling at rate of less than 1 millimetre per hour we can just call it a drizzle. There is not really a rain it is just drizzling at a very small rate.

Rain can be classified as light medium and heavy again depending on the intensity with which it is falling. Light is typically less than 2.5 millimetres per hour in units and heavy is typically greater than 7.5 and in between we have medium. The liquid precipitation can be classified as drizzle, light rain, medium rain or heavy rain. In solid we can have the precipitation in form of snow or ice. Depending on the atmospheric conditions at the place where the clouds are formed and the rain drops are formed and the place at which they are falling we can have various combinations. Snow has a density which is quiet small. So when we measure the precipitation in terms of snow we typically express it in equivalent water depth. The specific gravity of snow is typically about 0.06 to 0.15 and general value which is taken is 0.1. What it means is that if 1 centimetre of snow falls it will be equivalent to 1 millimetre of water depth. So typically they will be measured in terms of the equivalent water depth and the measurement devices for snow would be different because the depth is very high for the same amount of precipitation.

Ice is not very common under Indian conditions but we can have various different kinds in ice also. For example we can have sleet, glaze and hail. Hail has ice pellets which are typically greater than 8 millimetres in size. Sleet is a freezing rain and glaze is an ice coating which is formed when the rain drops hit a frozen ground, ice coating on frozen ground. These are not very common. We will not study them.

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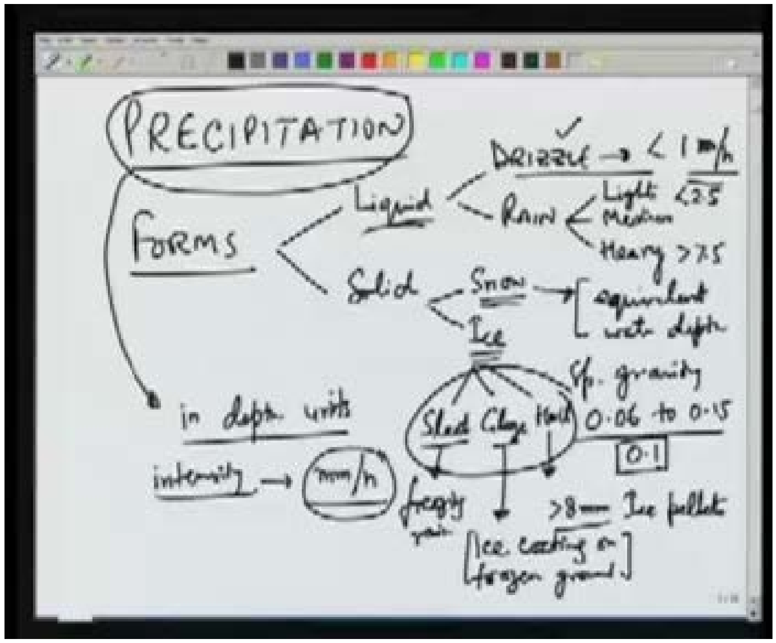

The liquid form which is rain is naturally what will concern us very often. So mostly we will discuss in terms of rain. Sometimes we will talk about snow also but we will concentrate on rain.

Let's first look at what is the mechanism? In rainfall what we require is presence of water vapour and then somehow they should condense and fall to the ground. So if water vapour is present in the atmosphere suppose this is the ground level and there is water vapour present in the atmosphere here this has to cool down in order to precipitate. So if suppose we have some air mass here which contains water vapour and it is lifted to a higher level then this is cooler. As we go higher in the atmosphere the temperature decreases and as it goes to a cooler level there will be condensation and this will fall as precipitation. So there should be some mechanism of creating water vapour and some mechanism of cooling that air mass to a certain temperature so that it can precipitate. The mechanism for cooling will decide what kind of various rainfall types we have. Typically we can classify them as frontal precipitation, convective precipitation, orographic and cyclonic.

Cyclonic also includes anti cyclonic which have different directions of wind. In the frontal there is cold and warm air meeting. So there is a front which has cold air on one side. Let's say this is the cold air and here we have warm air. This warm air may be moving or the cold air may be moving. But the net result is that the warm air gets lifted above the cold air and as it gets lifted it becomes colder and then it will cause condensation and precipitation. So that is the mechanism of frontal rainfall or frontal precipitation. In the convective precipitation there may be a local cooling. If the ground is warm here then the air which is in contact with the ground gets heated and is lifted up because the density becomes smaller and as this air is lifted up cold air from surrounding will come to replace it and therefore it will cause a convective motion here. As this air mass goes up the cooling will result in precipitation. Typically these occur at a small scale for example 10 square kilometres. So the area covered by convective precipitation is generally small.

Orographic, in this the lifting agency is mountains. If the ground surface is like this, this is a mountain here. Air coming in here will get lifted because of the presence of the mountains and as it gets lifted again it will have condensation and precipitation. Typically precipitation is more on the side which is facing the wind and on the other side precipitation will be small because the water vapour has already been taken out of this air. So we have what is known as a rain shadow. In this portion rain would be very small compared to on this side. In cyclonic and anticyclonic, cyclonic has anticlockwise wind movement; very high speed wind and anticyclonic has a clockwise motion and these patterns cyclones and anticyclones they carry a lot of moisture and they cover a very large area. Typically an area up to may be about 200 square kilometres can be covered by cyclonic precipitations.

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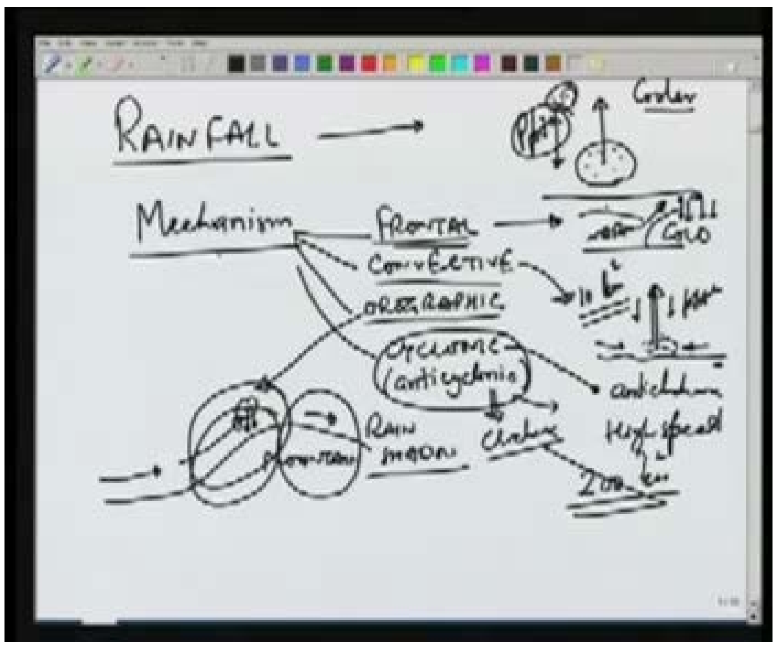

These are some common mechanisms which cause precipitation. After looking at various forms of precipitation let's look at how to measure it and then how to analyse the data which is collected by measurement. So let's first look at the measurement.

Broadly we can classify the measuring instruments as non-recording and recording depending on whether they get the values continuously for example in recording or at some particular fixed time like in non-recording. In non-recording they don't record continuously with time and in recording they maintain a continuous record with time about the depth of rainfall. We have already seen that measurement is typically done in terms of depth and generally in millimetres. The site for the rain gauge Suppose we have some area here and we want to install a rain gauge here. The rain gauge should be located properly and when we say proper location there are some requirements. For example the location should have a clear area about 5 meters by 5 meters; some times higher than this which should be fenced so that it is not distributed. The rain gauge which we install here is not distributed by animals or other people. This area should be clear means there should not be any objects in that area. It should be fenced so it is not easily accessible to others. Then the height; if this is the ground level the rain gauge may be installed at some height so the water falls here, the rain falls here or we can have a lower height. This height has to be decided based on various considerations. For example if the height is very large then wind will affect the measurement. If it is very small then chances are that the rain drops falling here may cause some splashing into the rain gauge and whatever data we record here may not be correct; so small height may lead to splashes or flooding. Sometimes if the rain gauge height is small then the nearby area may get flooded and it may spill over into the rain gauge causing a higher amount than the actual rainfall. Typically the height is kept at above 30 centimetres to balance the wind effects and also to prevent the splashing.

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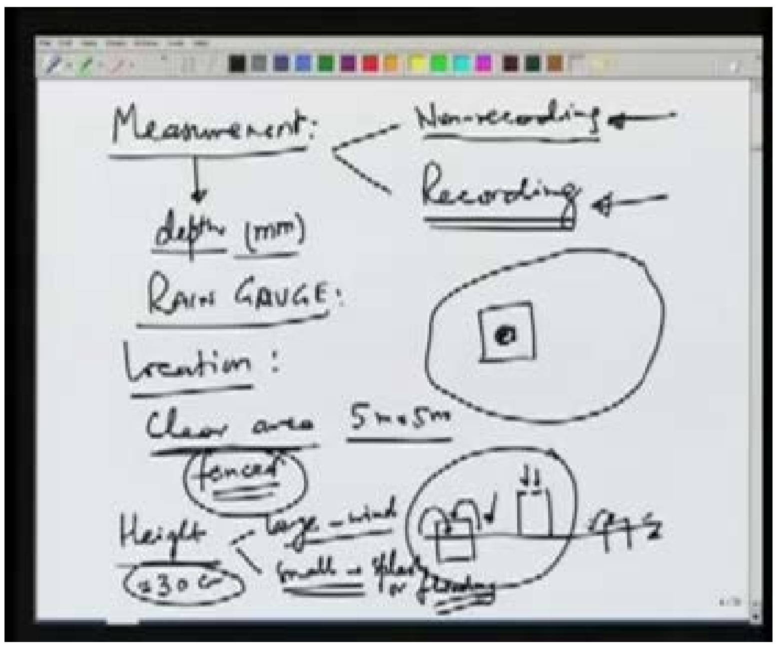

The other parameter which has to be decided is what should be the area of the opening and typically it is about 100 to 200 square centimetres. Then there is a funnel which collects the water falling on this area and deposits it in a bottle. We have a bottle kept here which will collect the rain water falling and with time the water level will go up. These are non-recording gauges because a continuous record of the water level with time is typically not kept in these and what is generally done is once a day the person who is maintaining this rain gauge will go look at the water level and report that as the depth of rain during that time period. Typically in the morning around 8 or 9 or about 8.30a.m in India the measurements are made and whatever rainfall is measured is reported as occurring in the previous day. This bottle which is kept here can store about 10 centimetre depth of water and if there is a severe thunder storm and we expect that this water may over flow then the person has to go more frequently. Frequent measurements during severe storms have to be made so that the bottle does not over flow.

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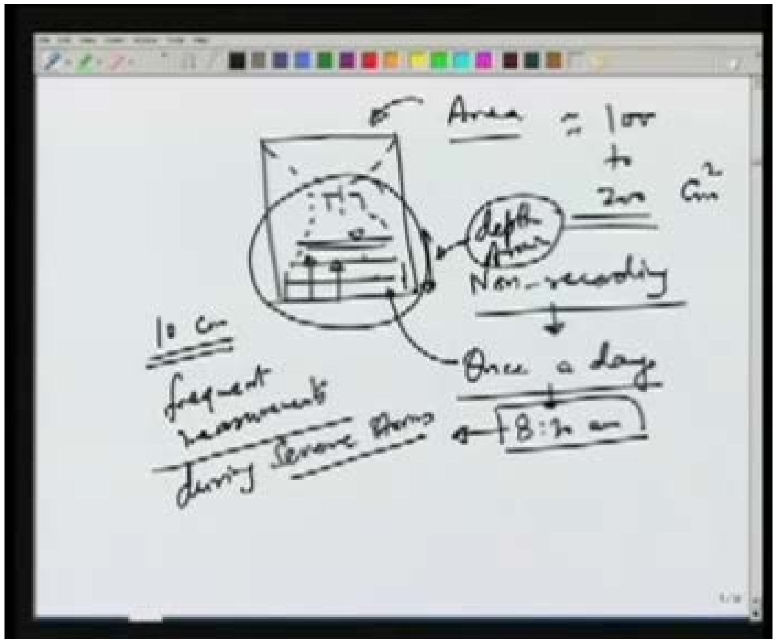

This is the most common non-recording gauge. The disadvantage is that it will not be able to capture the variation with time. We know that in a day there is let’s say 5 centimetres of rain but we don't know when it actually occurred or what the intensity was at different times. For that recording gauge is used and three common types of gauges are tipping bucket, then there could be some weighing gauges or the three different types which we use may be combined or used with some remote device to transmit the data to a far location. If the station is not easily accessible we can use them with some remote device which captures the rainfall recorded by either tipping bucket or weighing or a float mechanism to plot the rainfall record. Let’s look at them one by one.

A tipping bucket typically has a bucket which is balanced at a point. Water will fall in one compartment. There are two different compartments. The rain will fall in one compartment at a time and when it fills this bucket will turn and then this bucket will assume it’s place and then the rainfall will be captured in this bucket. On an average there is some capacity of the bucket. I will draw a bigger figure. As soon as this bucket fills it will tip and that tipping will actuate some circuit and it will record it on a graph paper. This time of filling will be recorded and we will know how much time it will take to fill this bucket capacity and the capacity of the bucket is about 0.01 while filling this much means that one tip represents some amount which may be 0.01. This amount is dependent on the design we make. If we have a very small capacity then there will be more frequent tippings and some amount of rainfall may be lost during tipping. In the time which it takes for this bucket to tip over and the other bucket to come in its place whatever rain is occurring during that time may be lost. That’s why we cannot have very small capacity also and if we have very big capacity suppose the bucket has a large capacity then there is a possibility that it may not be filled completely and it will stop some time. So whatever water is there in the bucket may not be recorded because this rainfall has actually occurred during some time. But it has not filled the bucket so it will not tip it and will not be recorded and when next time there is some rain which occurs it will fill the bucket and will tip it and the rainfall will be recorded as occurring at some other time.

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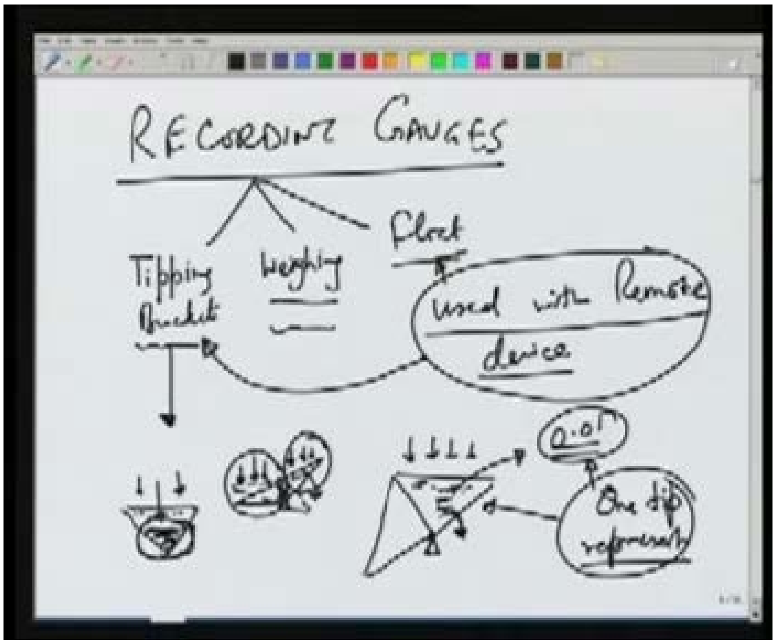

Tipping bucket is a recording type of rain gauge because it will record continuously the time it takes to fill certain capacity. The weighing types of rain gauges are quite simple in mechanism. There is a weight measurement device here. Whatever rain is occurring, it will increase. There is a rain device here which will continuously record the weight of the container and the water in it. With time it will give us a constant record. We can convert or calibrate that weight to give us the depth of rain and this will be accumulated depth. Suppose we start at t equal to 0 with zero depth we will get a curve which will give us temporal variation of the accumulated depth and looking at this curve we can see where the intensity is high. For example the slope is large means the intensity of rainfall will be higher and at some portions the slope may be flatter and here the intensity of rainfall is lower. Weighing type gives us a continuous record of accumulated depth with time.

Similarly a float type works on similar principle. But there is a float and the location of this float will always be at the top of the water level and if the water level rises here then the float will come here. The location of the float at different times will give us the rate of accumulation or the time variation of accumulation of water inside the gauge and it will give us again a continuous record. When the water reaches at the top there is some mechanism which will siphon this water out and then the float will again reset back to the bottom and then will again increase with further rainfall.

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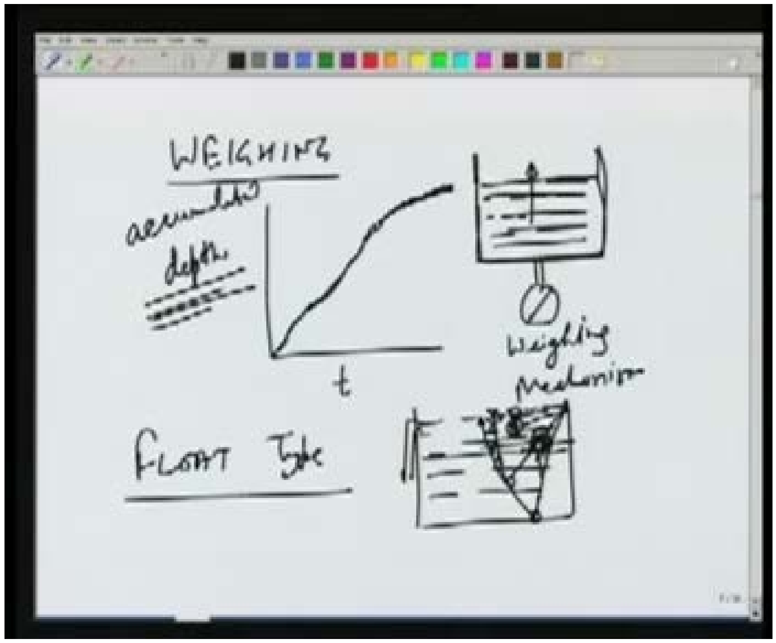

All these three types, tipping bucket, weighing type and float type they are recording gauges which give us continuous record which is very useful for us in analysing at different times what is the amount or what is the intensity of rain.

Once we collect the data we'll have to analyse it using some techniques. So the next thing which we look at is data analysis. First we will see how to present the data. The two commonly used techniques are one in which we plot the intensity of rain and in the other we plot the cumulative depth of precipitation. In the intensity of rain generally we will be using some units like millimetre per hour and cumulative depth we can use millimetres or sometimes centimetres. This is known as a hyetograph and this is known as a mass curve. The hyetograph will look like this. Suppose we have a non-recording gauge where we are measuring the rain fall every day. So this t may be expressed in days. For the first day we know the amount of rain. We can assume that that is the average intensity over that day although it is not a very good assumption. But if we assume that then we can plot a hyetograph like this. The rainfall will not be constant over a period of day. It will be a few hours over which the intensity is constant. The hyetograph shows us the plot of intensity verses time generally in hours while the mass curve shows the accumulation of rain as we have seen for example for a weighing bucket type of gauge. It would show us a curve like this which tells us that there's a very intense rainfall here ah almost no rain here and then again some rainfall here. 3510

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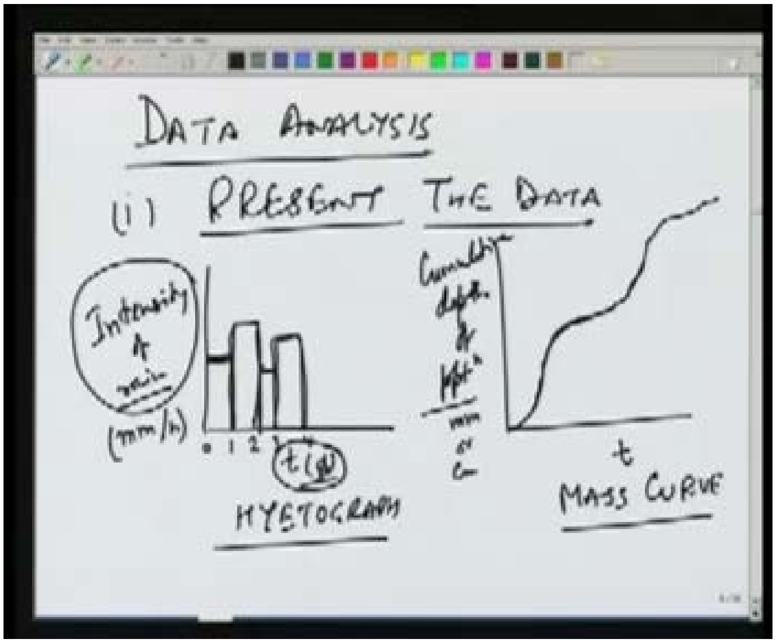

This tells us the cumulative depth and the slope of the mass curve will give us the intensity at that particular time. The location of the gauges as we have seen There are a few limitations on how to locate the gauges. For example open area near that height also has to be decided. But the network of gauges has to be also properly designed. So not only the location but the density also has to be clearly defined. The density is typically defined as number of gauges per unit area where the unit area may be taken as kilometre square or since the area is quite large let's say that we take a unit area of 1000 kilometre square. How many gauges will be put in that unit area will depend on what type of area it is, how the rainfall is varying in that area and there are some guidelines. For example in plain areas typically 2 rain gauges for a 1000 kilometre square are suggested. If we have hilly areas then we may increase the number of rain gauges to about 4 to 8 and in between for example if we have an area which is 1000 meter elevation then we may use 3 to 4 gauges.

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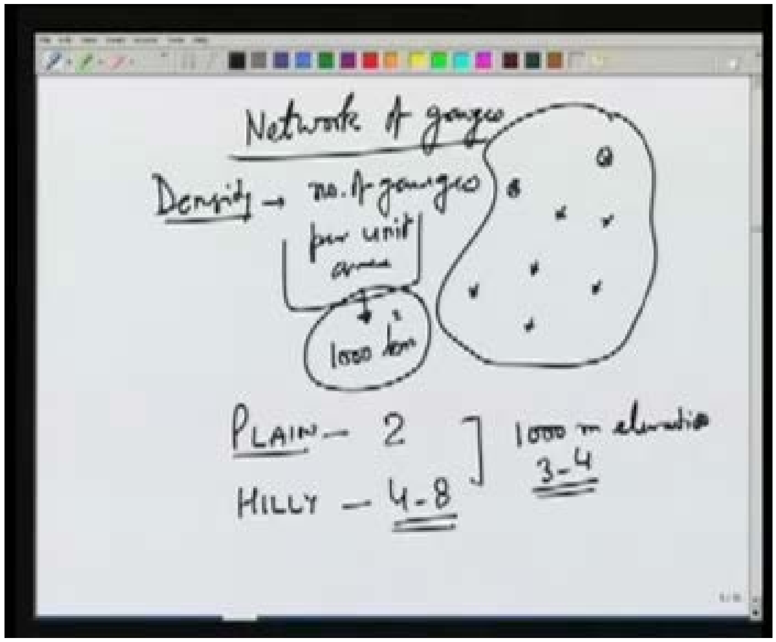

So that decides how many gauges we want in a particular area. In this area how do we locate the gauges? For example there may be one gauge here, one here and one here. Once we decide the density we have to decide where to locate the gauges also and in addition to this empirical guideline there is another technique of deciding the number of rain gauges in an area which depends on what is the variation of rainfall within these gauges. For example if we have an area and we have some existing gauges let's say we have these 'm' gauges. For these m gauges we can find out a coefficient of variation C_v which can be defined as summation over all the stations m Pi minus P bar whole square by m minus one. This coefficient of variation represents how much the precipitation values at each gauge are different from the average. This is the standard deviation sigma divided by the average precipitation P bar.

C_v tells us the standard deviation as compared to the mean precipitation where P bar is the mean precipitation which can be obtained as 1 to m Pi over m. So if we have m number of gauges in the area we can find out the mean precipitation using this formula. We can find out the standard deviation using this and then we can find the ratio of those as the coefficient of variation C_v. There is some allowable error, allowable value, which we call epsilon and generally it would be about 10%. The allowable error or allowable variation which we have in our data or which we can permit in our data is typically taken as about 10%. If C_v is below this value then it's okay otherwise we will have to increase the number of stations. The value of N which is the number of gauges which we want for the error to be less than allowable error is given as C_v over epsilon whole square.

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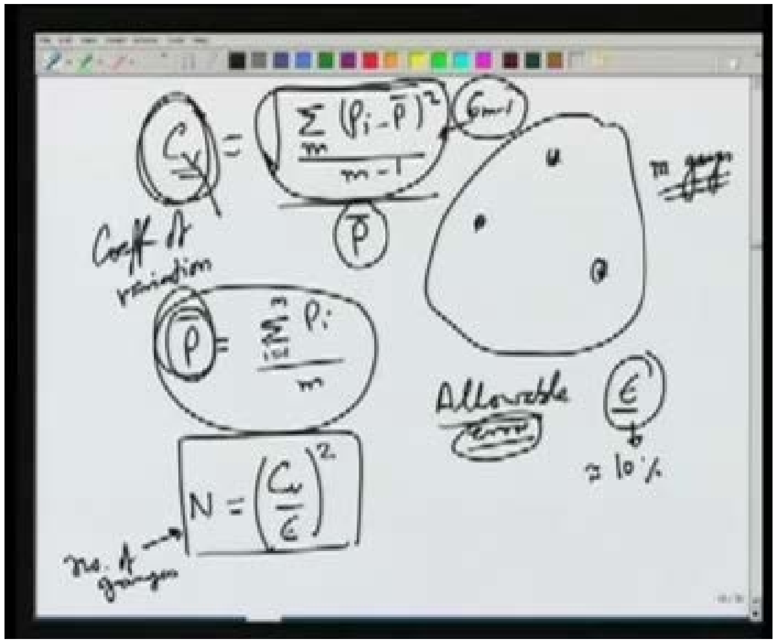

Once we find the coefficient of variation and we know the allowable error value then we can find out the number of gauges required to achieve that error and m gauges is already existing; whatever remaining N minus m that we have to add to get the error within the allowable limit. This is about the network design. This will tell us in this area how many additional gauges have to be put? Once we decide that then there may be some other problems. Once we collect the data we will decide the rain gauge density. We monitor it on a daily basis or continuous recording gauge basis. Then we need to analyse this data. The data has we have seen can be presented as either hydrograph or a mass curve but in analyses of data there may be various problems with the data. For example there may be some data which is missing. There may be data which is inconsistent.

Missing data means that we have a long period of record at a particular rain gauge and surrounding rain gauges also but part of it may be missing. For example in a year we are measuring rainfall every day but one day or two days the data may not be there. Inconsistent data means that inconsistency may be because either a station has shifted or surrounding conditions have changed. A station has shifted means we had a location of the station earlier; but if due to some reasons the station has to be shifted to some other location then the data will be inconsistent because the characteristics of the areas will be different or we may not shift the station but the surrounding area has some change in the condition. For example obstructions may have been created or constructed near the rain gauge or the environmental factors may be some forest was there and there is a fire which changed the nature of the surrounding area. So all these will cause some inconsistency which means that the data before that change and after that change will not be consistent and sometimes we may have observation errors also. For example after plotting the data we may notice that before certain time the data is not consistent. It may be because of some observation error also. So human error also we can add but it’s not very likely but there may be some observation error. So if we have a missing data or inconsistent data we first need to fill in the gaps. We need to either fill in the missing data or we need to correct the inconsistent data.

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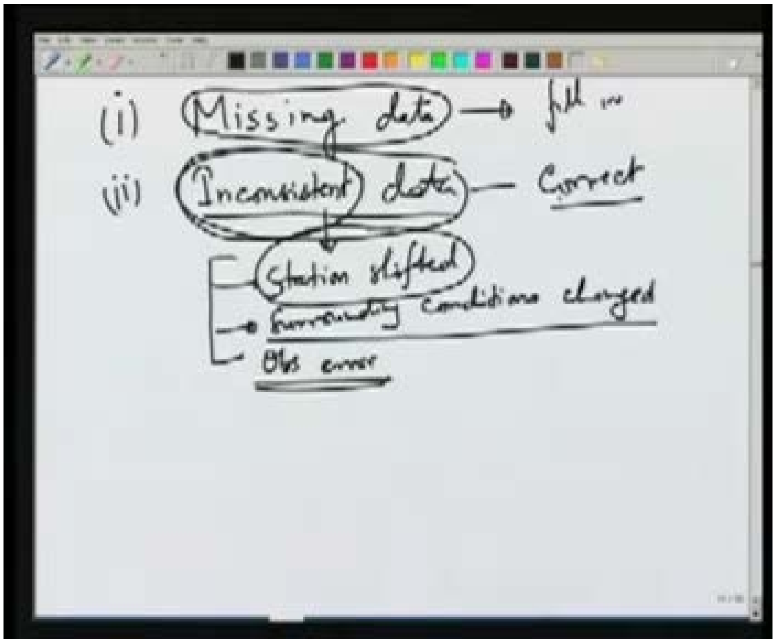

There are methods for correcting the inconsistency or filling in the missing data. For missing data suppose we have this area in which there are stations here and all of these are measuring the rainfall. We did not discuss it earlier but in an area if there are number of rain gauges it is generally thought that about 10% of them should be recording rain gauges so that we can get an idea about the temporal variation also. So if we have some missing data and there are some recording rain gauges or non-recording rain gauges we can take help of the nearby rain gauges. Suppose this is the station at which data is missing for certain period but for the same period data is available at all these other stations. Then the equation which we can use to estimate the missing data here is P_x again going from 1 to m over m. This is the station x at which the data is missing. The precipitation at x can be taken as the mean of the precipitation at all the surrounding or nearby gauges. This normally will work well but sometimes it may create problems. At these gauges and at x the normal precipitation itself may not be identical. Suppose this rain gauge in general receives more precipitation than this then taking an arithmetic mean like this will not be proper and then we will have to modify this as again the summation going from 1 to m.

For all rain gauges we take the ratio of the precipitation divided by the normal value. This normal is typically a 30 year average. For example suppose a data is missing for first of January. Then we say over the last 30 years what is the average precipitation on the first of January at various gauges and that is Ni or Nx for the gauge under consideration. We say that the ratio of precipitation on that day to the normal rainfall on that day should be the arithmetic mean of the similar ratios for the other stations. This will help us identify or fill in the missing value P_x. Once we have completed the record by filling in the missing values we should check on the consistency.

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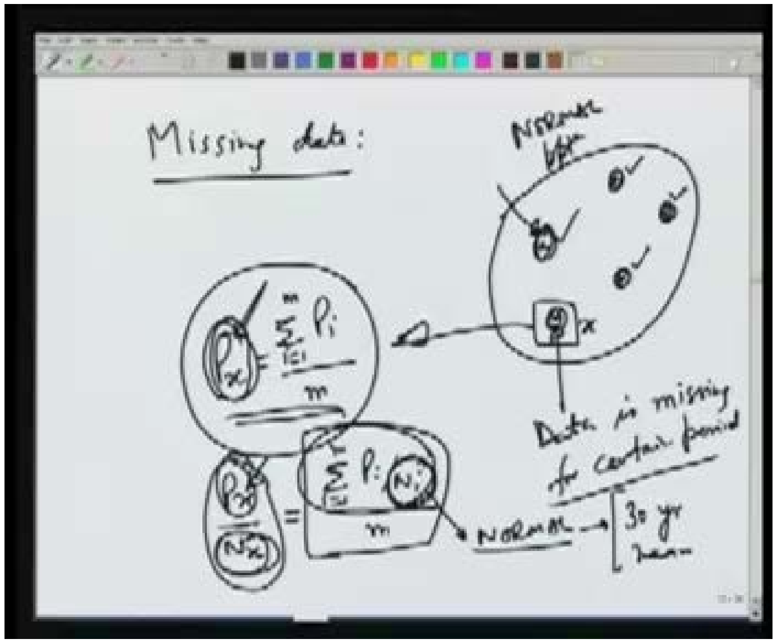

For checking the consistency we use a procedure which is commonly called the double mass curve analysis. We have a gauge here and we want to check its consistency. We have some surrounding gauges also generally about 10 gauges are taken or neighbouring gauges. All these gauges are taken and what we plot is the mass accumulated as average of surrounding stations and what we will do is we'll plot it verses the accumulated mass at x. Suppose x is the station for which we want to check the consistency. Accumulated mass at x will be plotted against the average accumulated mass at the surrounding stations which may be about 10 in number and if the data is consistent then it should plot as a straight line. Let's say we talk about annual values; annual precipitation. We will have here years. Let us say the data looks like this. These will indicate different years and they are plotted in reverse chronological order. These are the nearest values and then time is decreasing. So ideally they should plot on the same line if the data is consistent because then the accumulated mass of precipitation at x should have a certain definite ratio with the surrounding areas. But if the data is not consistent then we may have a deviation may be like this or may be like this. For example the data for 2004 may be here, 2000 may be here and may be let's say 1990 is here. This tells us that in 1990 something changed at the station and the data is not consistent. Either the station was moved or environment around the station was changed and therefore we need to correct the earlier data and bring it in line with the recent data. If the data is here we have to move it here on the line. There is a correction factor which has to applied to all the data before 1990 and that correction factor will depend on what is the value to the line actual value a and the observed value either here or if the observed values are here then it will be up to that line. 'a' is at any time the value to the actual straight line. 'o' is the value on the observed data. If the data is here then 'o' will be smaller, if the data is here 'o' would be larger. All these values have to multiplied by a by o to bring it to the straight line.

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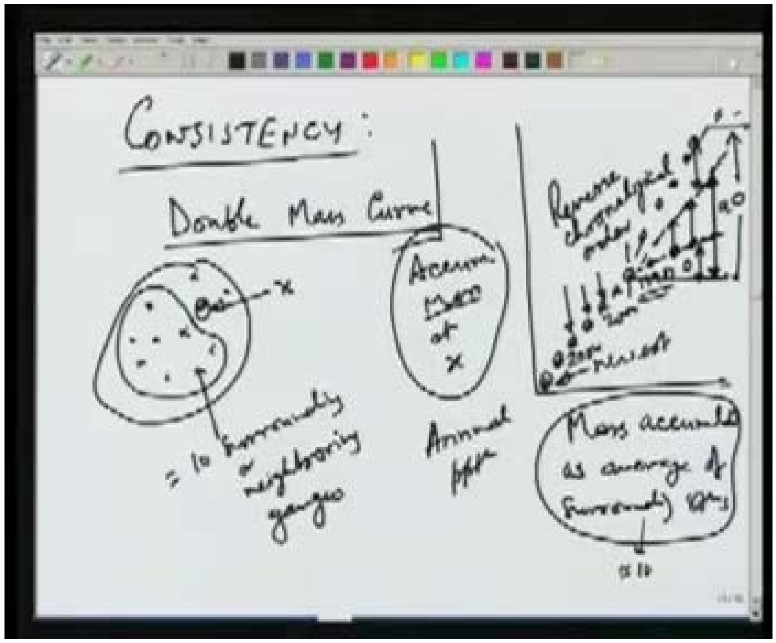

This way we can correct any inconsistency in the data. By filling in missing data and by correcting inconsistent data we can be sure that now we have a record of rainfall over a particular area which represents the actual conditions without many errors. The area which we have taken till now, we have not really defined this catchment area. But whenever we take this area typically it is done in such a way that the boundary corresponds to water shed. The rain drops falling on this side will move towards this side and the raindrops falling on this side will move toward this side. When we say this is a water shed any rainfall falling in this area will move toward this side because this is called the catchment area for a channel. The rain gauge location may not correspond to a catchment area. Suppose this is an area in which there are some rain gauges. These give us a point value at a certain location. When we say we have the precipitation record at this point it represents the precipitation record at a single point. Our aim would be to extrapolate or to find out an average areal precipitation.

The next step which we have to take is how to transform these point values to represent an average depth over the entire area. If this gauge collects 1 centimetre of rain this collects 2 centimetres and this collects 1.5 then over the entire area what could be assumed as an average depth of precipitation? Our next aim would be to look at how to convert the point values. These are the point values to an average depth of precipitation over the entire area.

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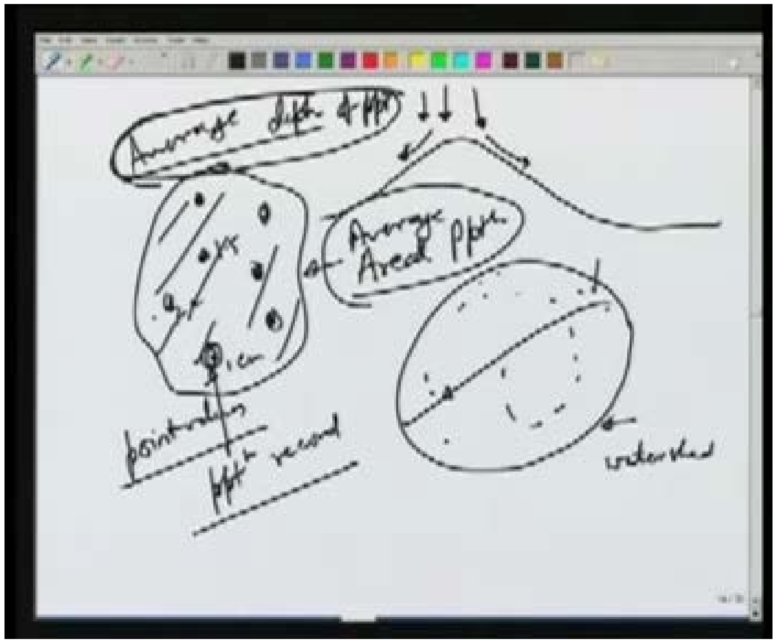

When we talk about this area it should be of uniform characteristics. It may not correspond to the catchment area for a river but it should be of uniform climatological conditions so that we can compare the records of different rain gauges.

In today’s lecture we have looked at the hydrologic cycle in which we discussed various components of the cycle really describing the movement of water in the atmosphere, on the surface of earth and below the surface of earth. Then we have discussed various components of this water cycle which are precipitation, evaporation, transpiration, intersection and depression storage, infiltration, ground water, then runoff, surface runoff and sub surface runoff and interflow. All these components we have described and then we said that some of these components are of importance to us as water sources engineer. For example evaporation from the sea is really driving all the precipitation but precipitation is causing the runoff. Since we are interested in the runoff because we want to see in water supply project or irrigation project how much water is available or as a flood control project how much flood we have to accommodate in the storage reservoirs. We are interested in runoff but since precipitation is causing the runoff we should look at the precipitation and precipitation data is more easily available than the stream flow or runoff data. We have looked at the precipitation, the mechanisms, how it can be measured and some problems with the data which may arise and how to take care of those problems and then we would look at converting these point values to areal values because we want precipitation over certain area what is the average depth of rainfall so that we can convert that into some volume and that will be our next lecture to convert the point values to areal values.