Water Resources Engineering
Prof. R Srivastava
Department of Civil Engineering
Indian Institute of Technology, Kanpur

Lecture No. 20

In the previous lecture we had looked at various aspects of precipitation. We have seen how to design a network of rain gauges to measure the precipitation. The rain gauges may be recording or non-recording where the non-recording gauges measure the amount of precipitation in a day and recording rain gauges maintain a continuous record of the precipitation. We have seen how to decide the density of rain gauges which is given by code specific to that country. For example in India in plane areas one rain gauge in about 500 kilometers square is recommended. We have also seen how to analyze the data. For example the data collected from a rain gauge may be missing. If it is missing for a day or for a month or for a year we may have to obtain those values or estimate those values based on the neighbouring rain gauges. After getting all the data we have to check for the consistency whether the data is consistent or not. There may be some relocation of the rain gauge station in which case the data may not be consistent. So we will check for the consistency after that and then we have seen how to obtain aerial average precipitation from a few point measurements and how to analyze the frequency of precipitation intensity.

Today we will take up some examples to clarify some of these points. Let's take an example where we have a non-recording rain gauge at a location and let's look at what kind of record it will have. This data shows month and the date. Some records have been omitted here but date 1, 2, 3, 4, 5, up to 31 and similarly the month going from January to December. For everyday we have the corresponding precipitation. This is all in millimeters. For example on the 1st January of this particular year, this year may be 1974, 1975 or 1990; for that particular year on January 1st we had a rainfall of 1.2 millimeter. Similarly on January 2nd we had 2.8 and then the important things which we note down are the total precipitation in that month. In this case for the month of January the total precipitation was 25 millimeter and we can look at the monsoon months July and August, the precipitation is quite high 220 millimeters and 200 millimeters.

The other important thing to note is the maximum daily precipitation because this is an information which is very useful to us in deciding what will be the maximum amount of flood which can be expected due to a one day rain. 51 millimeter was the maximum one day or maximum 24 hour precipitation for this particular year. Similarly we can have data for other years. We can get the average or the total precipitation in the month and then suppose we have a long period of record let's say 30 years. If we have 30 years of such record then for each year January may not have 25 millimeter of rain every year. It will have sometimes 20, sometimes 15, sometimes 30; so we can find out an average. The 30 year average is known as the normal precipitation. We can say that in the month of January normally the precipitation will be let's say 27. At least a 30 year record is generally used but sometimes smaller periods may also be used. Mean monthly precipitation or normal monthly precipitation for a record is important. Annual precipitation is the other important parameter. Here we see that sum of all these monthly precipitation is 850 millimeters. In this particular year on the station the rainfall recorded was 850 millimeters.

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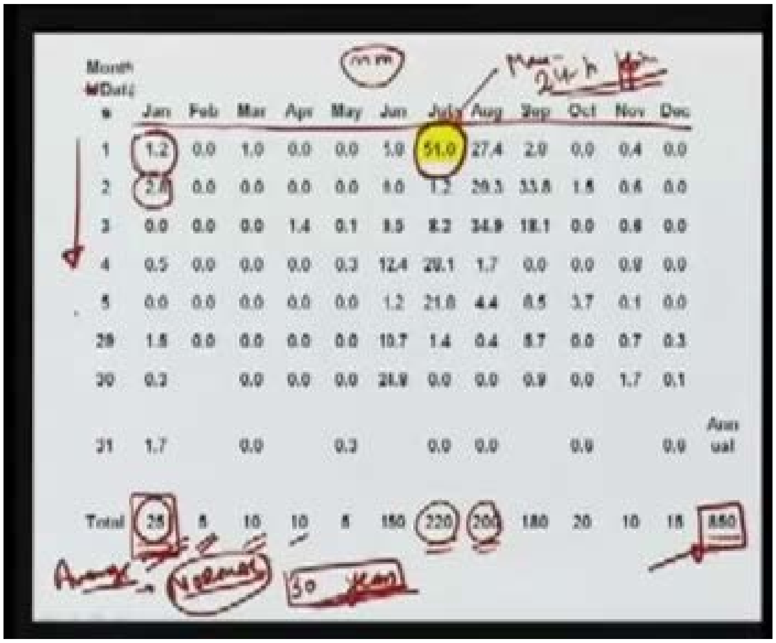

Month / Date	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
1	1.2	0.0	1.0	0.0	0.0	1.0	51.0	27.4	2.0	0.0	0.4	0.0	
2	2.8	0.0	0.0	0.0	0.0	8.0	1.2	20.3	33.8	1.5	0.6	0.0	
3	0.0	0.0	0.0	1.4	0.1	8.5	8.2	34.9	18.1	0.0	0.8	0.0	
4	0.5	0.0	0.0	0.0	0.3	12.4	28.1	1.7	0.0	0.0	0.9	0.0	
5	0.0	0.0	0.0	0.0	0.0	1.2	21.8	4.4	8.5	3.7	0.1	0.0	
29	1.8	0.0	0.0	0.0	0.0	10.7	1.4	0.4	8.7	0.0	0.7	0.3	
30	0.3		0.0	0.0	0.0	21.9	0.0	0.0	0.9	0.0	1.7	0.1	
31	1.7		0.0		0.3		0.0	0.0		0.0		0.0	
Total	25	5	10	10	5	150	220	200	180	20	10	15	850

Now let’s take an example a hypothetical catchment area which is 60 kilometer by 30 kilometer size and for sake of presentation we can idealize it as a rectangular area all though in practice it will not be so. Now as per the IS code, IS:4987, for plane area 1 station for 520 kilometer square is the recommended requirement and if we do this then our area is 60 by 30 which is 1800 square kilometers. We say that we would need roughly 4 stations and let’s put these stations as S_1, S_2, S_3 and S_4 and in this case we may decide to put it at 20 kilometers and similarly 10, 10 and 10. Once we have put these 4 stations there we have to see whether these stations are adequate or not. We will collect the data for a few years and analyze that data to see what is the variance or the typical variation within these stations.

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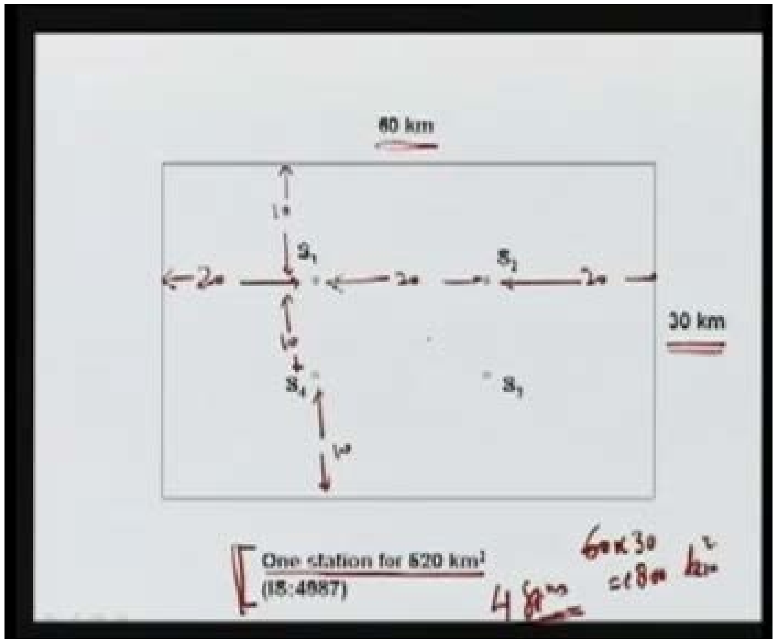

For example rainfall at S_1, S_2, S_3 and S_4 are they very similar or is there a wide variation? For this we need to analyze; let's look at this data. We have annual precipitation required at S_1, S_2, S_3 and S_4 where this is S_1, S_2, S_3 and S_4 and the annual precipitation is obtained for a particular year or a mean of a few years as 800, 1150, 1000 and 650 millimeters giving a mean of 900 millimeters for these 4 stations. We can find out what is the standard deviation which we can obtain from the variation or the variance of the actual rainfall at that station. P is the actual rainfall and Pm is the mean of all the stations which is 900. These quantities represent the deviation of the rainfall at the station from the mean and the square; the sum of those deviations, square of the deviations comes out to be 145000 and then the standard deviation can be calculated as the square root of sigma P minus Pm square over n minus1. This gives us a value of 219.85 and the coefficient of variation is nothing but a standard deviation divided by the mean. So 219 divided by 900 will give us 0.244. The allowable error typically is taken as 0.1 or 10% variation. If we take allowable error as 0.1, the required number, N is the required number of stations which is given by C_V over epsilon square where epsilon is the allowable error and C_V is the coefficient of variation. In this case it turns out to be 5.97.

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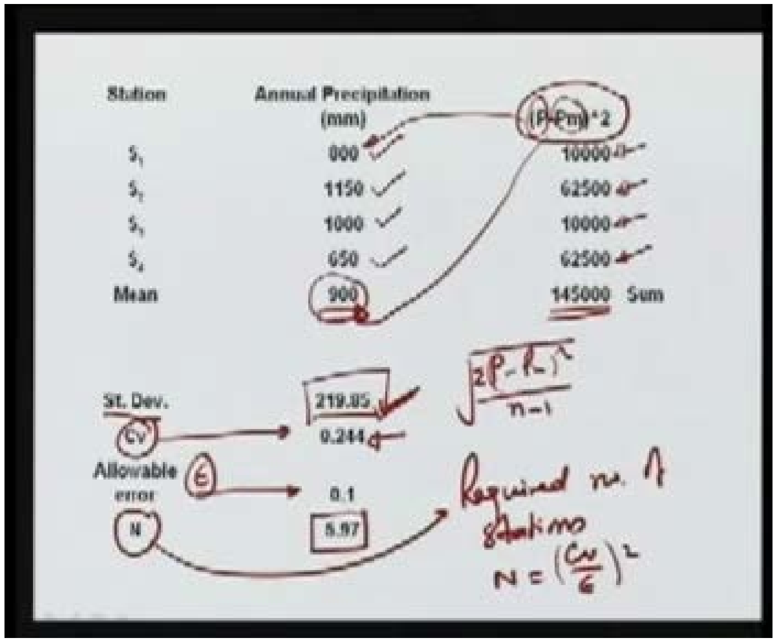

That means we can say that we need 6 stations in that area to bring the variation within the acceptable limits. We already have 4 stations. We need to put two more stations and let's put them at S_5 and S_6 where S_5 may be 10 kilometers from here and 5 from here. We decide that these 6 rain gauges S_1, S_2, S_3, S_4, S_5 and S_6 are sufficient for our required accuracy and then we will analyze the data at these 6 stations. We will assume that they are all non-recording gauges; all six are. The data which is available is daily data; daily precipitation data is available to us.

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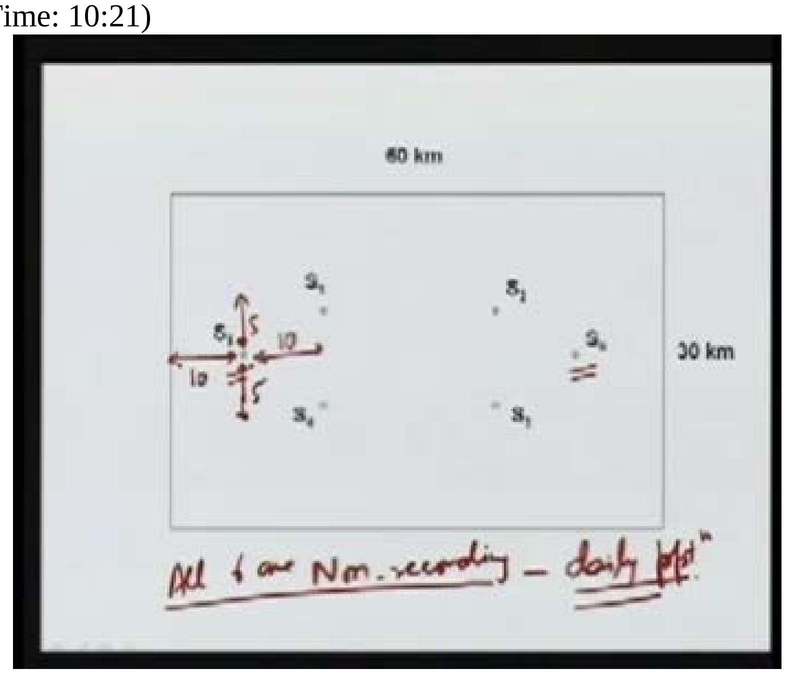

We can analyze that daily data to find out what is the mean precipitation at each of these stations for different years. For example this table shows that at station S_1 the 30 year mean value of precipitation in January is 24.6 millimeters.

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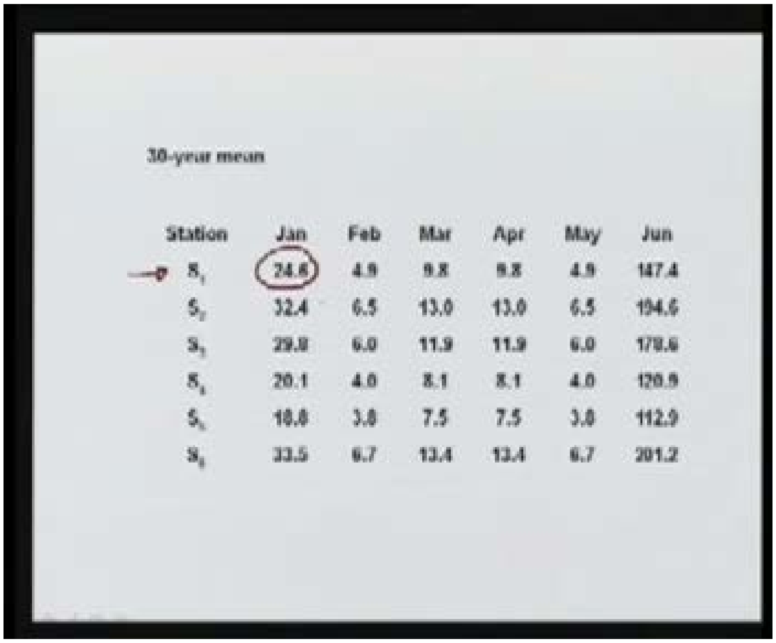

30-year mean

Station	Jan	Feb	Mar	Apr	May	Jun
S_1	24.6	4.9	9.8	9.8	4.9	147.4
S_2	32.4	6.5	13.0	13.0	6.5	194.6
S_3	29.8	6.0	11.9	11.9	6.0	178.6
S_4	20.1	4.0	8.1	8.1	4.0	120.9
S_5	18.8	3.8	7.5	7.5	3.8	112.9
S_6	33.5	6.7	13.4	13.4	6.7	201.2

Similarly for the month of February, March, April, May and June and we have here July. As expected the monsoon months July, August and September has higher precipitation compared to the months of March, April and May. All these stations S_1, S_2, S_3, S_4, S_5 and S_6 have data from the period of 1976 to 2005. Using this 30 year data we can find out the mean monthly precipitation as well as the mean annual precipitation. This shows us the mean annual precipitation at the stations S_1, S_2 up to S_6.

Suppose we have some missing day for example in this case we have assumed that for the year 1990 may be station S_6 was moved in let's say January 1990. Because of this relocation we were not able to collect data from station S_6 during the entire period of January 1990. Now the question which may be asked is what is the precipitation in January 1990 on the station S_6 or for the whole year 1990? Since we don't have the data for January we don't have the entire annual rainfall. So what will be the annual rainfall in 1990? For other stations these values will be known. Let's look at one day; for January 12 we have the measurement of all the other stations S_1, S_2, S_3, S_4 and S_5 but S_6 we don't have. Similarly for the entire month of January 90 we have record or the sum of the daily values available at all other stations but not at S_6 and for the year 1990 also we have all the records available but not at S_6. We need to estimate these values based on the values measured at other 5 stations. If more stations are there its better but we will now analyze that there are only 5 other stations and we want to estimate the missing values as well as see whether the data is consistent or not.

If we look at one day January 12, 1990 we want to estimate what would be the rainfall on this date at station S_6 which we could not measure. This is not advisable because for a single day the rainfall will occur because of a storm which may not be uniform over the area. That storm may be occurring like this. Whatever data we are getting at S_1, S_2, S_3, S_4 and S_5 may not hold good for S_6.

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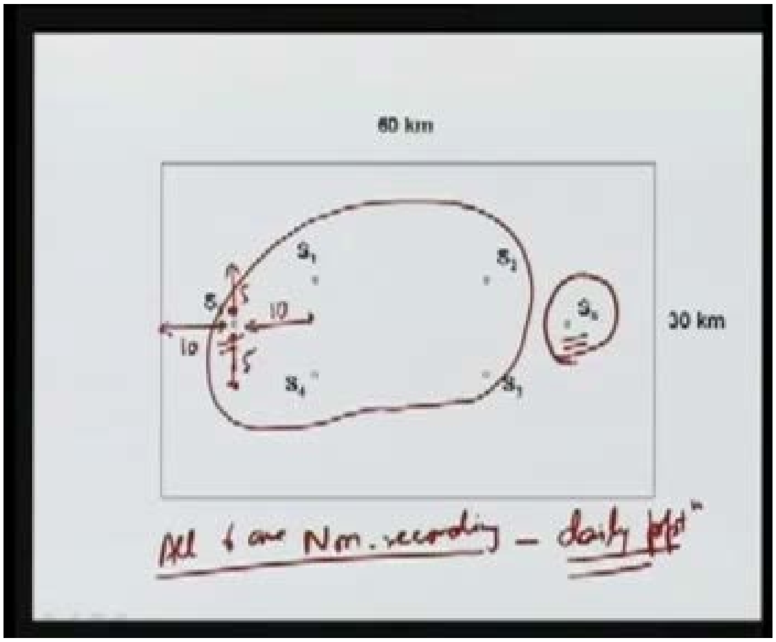

For a small duration we should not use the other stations to estimate the missing data. For one day rainfall it is generally not advisable to use the surrounding station data to estimate the data because of the non-uniformity or special non-uniformity of the storm data. But for a month we may assume that there may be different storms occurring and overall on an average sense they will satisfy the spacial uniformity requirement. For a month we can still use our missing data estimation method to estimate this value which is nothing but saying that P_x over N_x is equal to mean of P over N at all the surrounding stations where P is the precipitation and N is the normal precipitation.

For January 1990 station S_1 had a precipitation of 28.3. That goes as P for S_1. The normal 30 year mean for January is 24.6 at station S_1. So 28.3 divided by 24.6 will be the P by N value at station one. Similarly we get the P by N at all the other stations. S_2, S_3, S_4 and S_5 finding out all these five P by N values we take the mean. Nx is the mean for January at station S_6 which is known to us as 33.5. Based on this we can estimate the missing record at station S_6 and we can say that the rainfall at station S_6 in January 1990, which we were not able to measure, can be estimated as 36.7 millimeter. If you look at the January 90 precipitation at station compared to the normal values you can see that at all 5 stations the normal value is smaller than the actual value or in other words the actual rainfall was higher than the normal rainfall. So we would expect that at station S_6 also the actual rainfall will be higher than the normal rainfall; 36.7 compared to 33.5. Same philosophy can be used to obtain the annual rainfall at station S_6. For example in 1990 annual rainfall at station S_1 was 852 while normal is 835. Similarly for station S_2 actual rainfall is 1120; normal is 1103.

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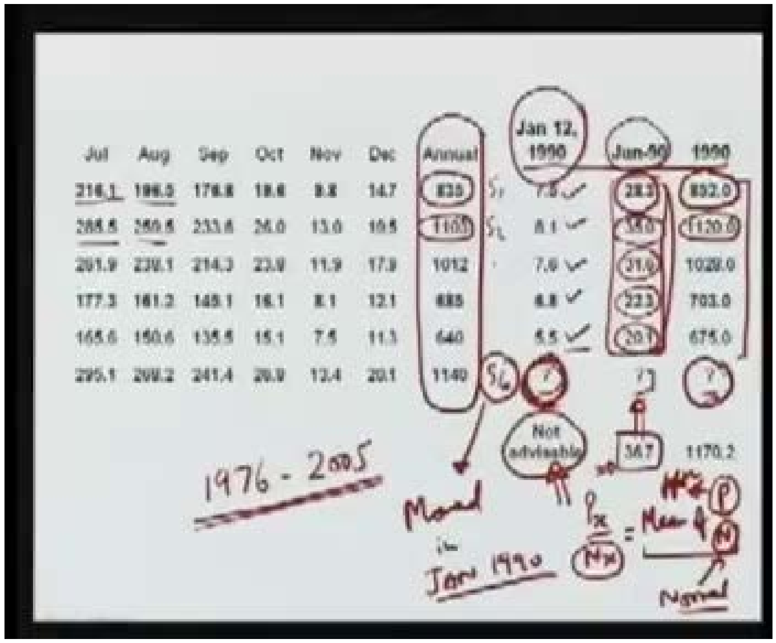

So using this data again using the same equation we can estimate that the annual rainfall at station S_6 during 1990 was 1170.

Once we get this missing data filled in we can now do an analysis which is known as double mass curve analysis as we have discussed to see whether the data is consistent or not and for that purpose we need to plot the lets say the annual rainfall at each station for this period of record which is available to us may be 30 years in this case as we said 76 to 2005. This data is starting from 1976 up to 1990 and then 91 up to 2005. This 30 year data values are shown here. These are the annual precipitation for the corresponding year at the stations S_1, S_2, S_3, S_4, S_5 and S_6. Using this data we can find out the mean of 5 stations because at S_6 we want to check the consistency. S_6 was moved in 1990. So we are not sure whether the data is consistent or not. We want to check consistency of S_6 comparing it with the mean of the other 5 stations. That’s why in this S_1, S_2, S_3, S_4 and S_5 we can take the mean, annual mean. This gives us mean annual precipitation at the 5 neighbouring gauges. This gives us the annual precipitation at S_6 for each year.

In double mass curve we do cumulative analysis. This is the cumulative value; mean means again at stations S_1 to S_5 and this is in meters. This 898 actually becomes about 0.9 meters and then this is cumulative. We add the next year. So 898 plus 859 will give us 1.8 meters. Then 1.8 plus 169 this will give us 2.6 meter. What this line tells us is starting from 2005 which is giving us 0.9 what is the cumulative annual rainfall, mean rainfall, at all the 5 stations? For first year it was 0.9, second year it became 1.8, third year 2.6 and so on.

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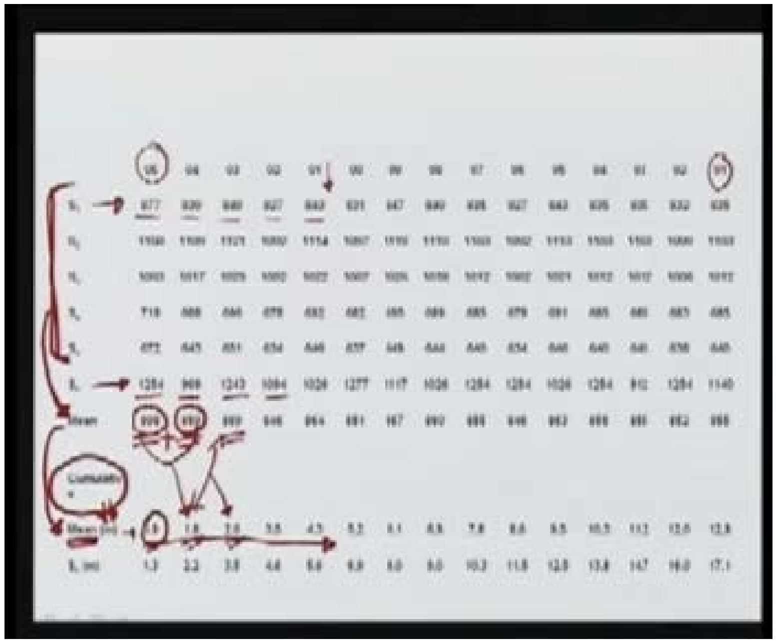

Naturally it will keep on increasing because this is accumulated starting from the most recent record which is 2005 and going up to the last year for which we have record which is 1976. This cumulative mean it reaches up to 25.7 which indicate that in this 30 year period we have total of about 25 meters or 25.7 meters of rainfall as the mean of the 5 surrounding stations. Similar analysis we can do for S_6. For S_6 the 2005 data is 1254 which is shown as 1.3 meters. This 2.2 is nothing but adding 1254 plus 969. Same way we have this cumulative rainfall at station S_6 and if you plot this data and you also see that this is 36.7 meters precipitation occurring at station S_6.

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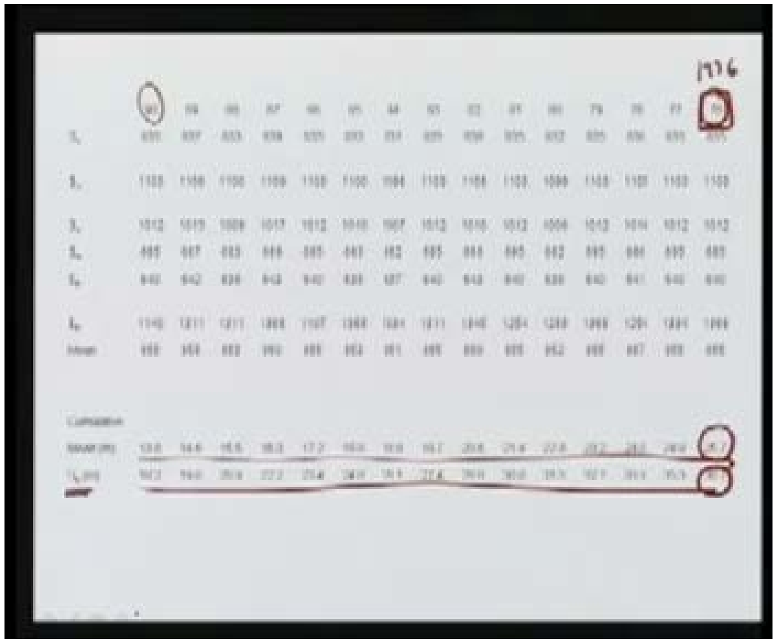

If we plot this data here it shows accumulated mean. This is S_1 to S_5 and this is accumulated at S_6. If the data is consistent at S_6 then we would get a straight line, a single straight line through all the data. But as you can see here we have a straight line up to about 1990 and then we have deviations from the straight line. The straight line is going like this but the data deviates from the straight line. This is 1976, 1990 and 2005. It indicates that due to the change of location of gauge S_6 there was some inconsistency introduced in the data. Since the most recent data were assumed to be correct or required we have to make it consistent with respect to the recent record we will modify the previous record. That is data before 1990 should be modified so that all of them come on this straight line and to bring it on the straight line what we need to do is this is 17.1 from here to here and this is 14.6 from here to here. We have a correction factor of 14.6 divided by 17.1 which come out to be 0.85. All this data before 1990 has to be multiplied by 0.85 to bring it down to this line and make it consistent.

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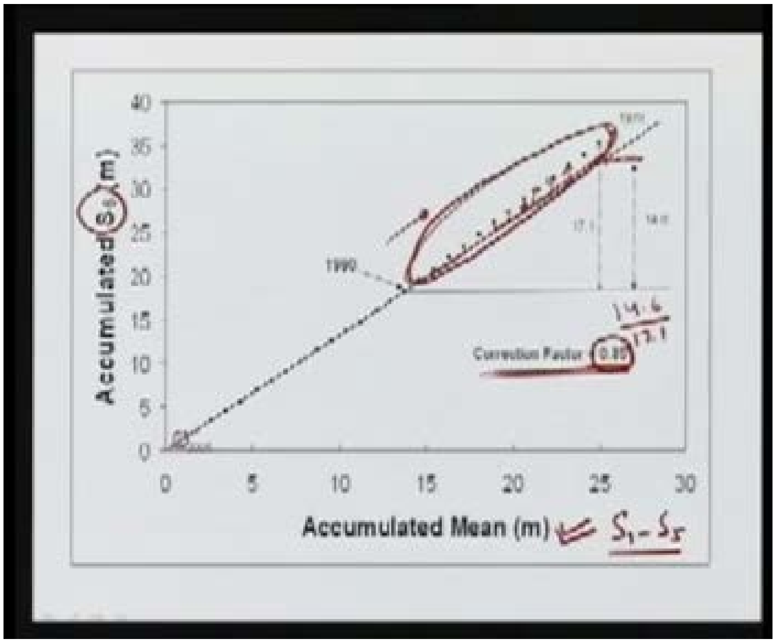

This is known as the double mass curve analysis. Mass curve is nothing but accumulated value; so cumulative and since you are plotting cumulative mean versus cumulative S_6 this is the double mass curve which indicates how the data on station S_6 should be modified to make it consistent.

Once we analyze the data, fill in all the missing records and make it consistent then we need to see how the point values which are the rainfall at the stations can be modified to make them real values. Suppose this is the area 60 kilometer by 30 kilometers. Our aim is to find out what is the average rainfall over this entire area of 1800 square kilometers. But the values which is available in this case is 640 here, 835 here, 1103 here, 1140 here, 1012 here and 685 here.

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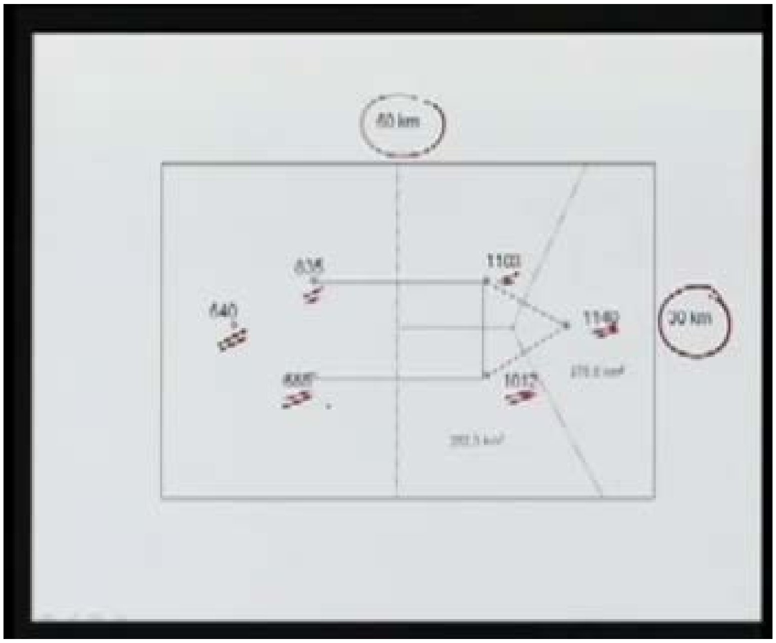

These are the values available to us of the point rainfall data. This 640 for example these values come from this data.

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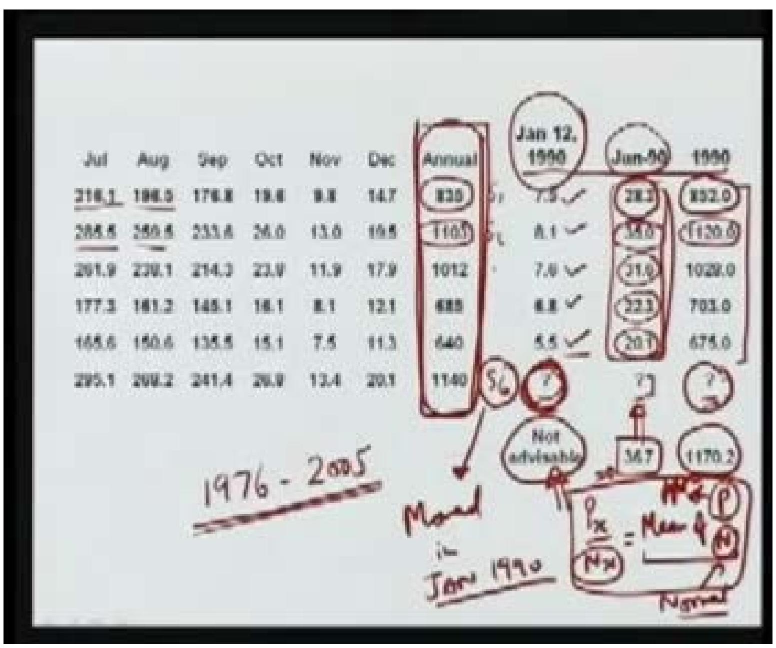

This is our mean annual precipitation based on this 30 year record. What we are saying is that the 30 year mean value of precipitation at all these stations is given by S_1 835, S_2 1103. These are the mean values of precipitation at the station S_1, S_2, S_3, S_4, S_5 and S_6

for 30 year period. Over this entire area what is the depth of rainfall if we want to compute it then we have different methods.

For example we have arithmetic mean method which just takes the mean of the annual precipitations. In this case we have these values already available from the record. Mean of that gives us 902.5. Based on this we can say that the average annual precipitation over the entire area can be taken as 902.5 millimeters.

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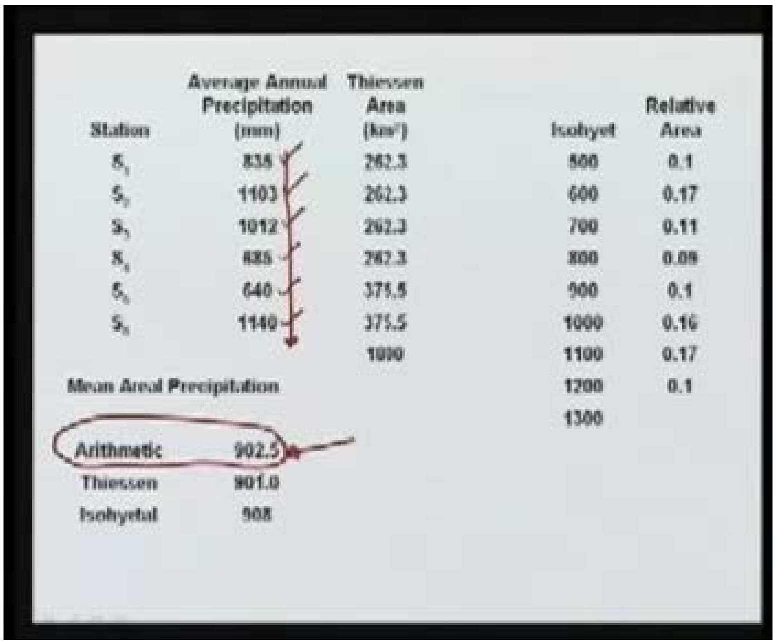

But as we have seen arithmetic mean method doesn't account for relative location of the gauges. So the Thiessen polygon method is preferred in which we divide the area into effective area for a particular gauge by drawing perpendicular bisectors between the gauges. In this case we have these two gauges joined by a straight line and this line is the perpendicular bisector of this line. Similarly we join these two gauges and this is the perpendicular bisector and we do the same thing for other gauges. Once we do this the effective area for the gauge S_6 will be all this area because in this area any point we take suppose I take a point here it will be closer to the gauge S_6 than any other gauge. If I take a point exactly on this line it would be equidistant from S_6 and S_2. Any point here or here or here would be closer to S_6 than any other gauge. This effective area of the gauge S_6 can be plotted and measured and the area comes out be 375.5 kilometers square.

Similarly for the gauge S_3 this area; any point in this area will be closer to S_3 than any other gauge and this area turns out to be 262.3 square kilometers. Since its symmetric S_2 will also have the same area. S_4 and S_1 will also have the same area and S_5 will have the same area as S_6.

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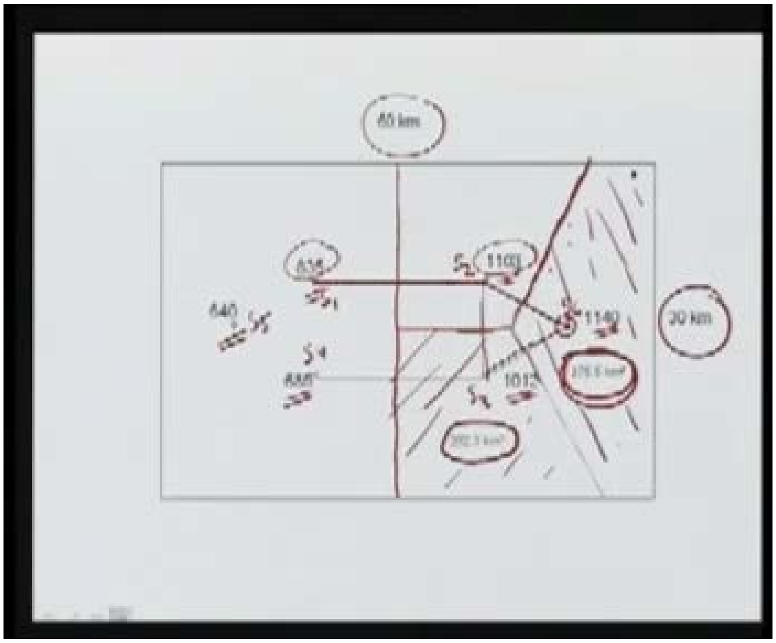

Using these area values these are the areas for S_1, S_2, S_3, S_4 which are the same and S_5, S_6 which are the same. Total area is 1800; we give a weight which is Ai over A. This A is total area, 1800 and Ai is individual S_1, S_2, S_3, S_4, S_5, and S_6. A_1, A_2 up to A_6. This weight is given to the precipitation at each station. This weight multiplied by the precipitation gives us the average precipitation for the whole area and if we do that we get a value of 901 millimeters. Using arithmetic mean we got 902.5, Thiessen polygon 901 which is not very different.

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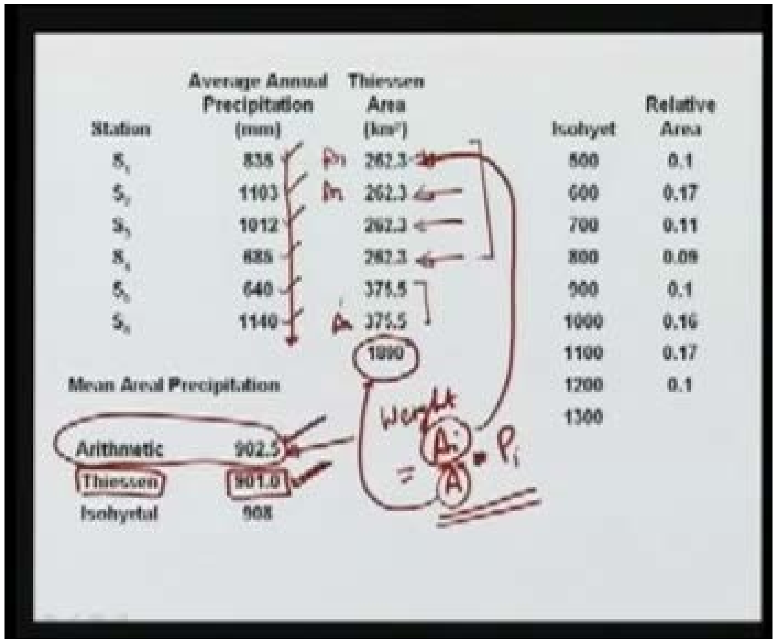

But the method which is the most accurate is the Isohyetal method which is based on the values at stations. This is 640 and this is 835, 1103, 1012 and 1140. Based on these values we can draw lines which have equal precipitation depth. We can draw a line which represents 1100 millimeters of rainfall. That line will pass very close to this point 1100. Similarly if we join these two gauges we can estimate that the 1100 point will be somewhere here. So we can draw an isohyetal line which will represent rainfall of 1100 millimeters. Similarly between these two points we can say that there will be some point of 700 and there will be some point which will have 800. We can draw these isohyets which will represent 700 and 800. These are called the isohyets and between any two isohyets we can find out what is the area and assume that in this area the rainfall is equal to the average of the two isohyets which bound this area.

We can say that in this area, shaded area, the rainfall is equal to 650 millimeters and then we multiply 650 with this area. Similarly in this area we can say that the rainfall is 550. Similarly here we can say 1250.

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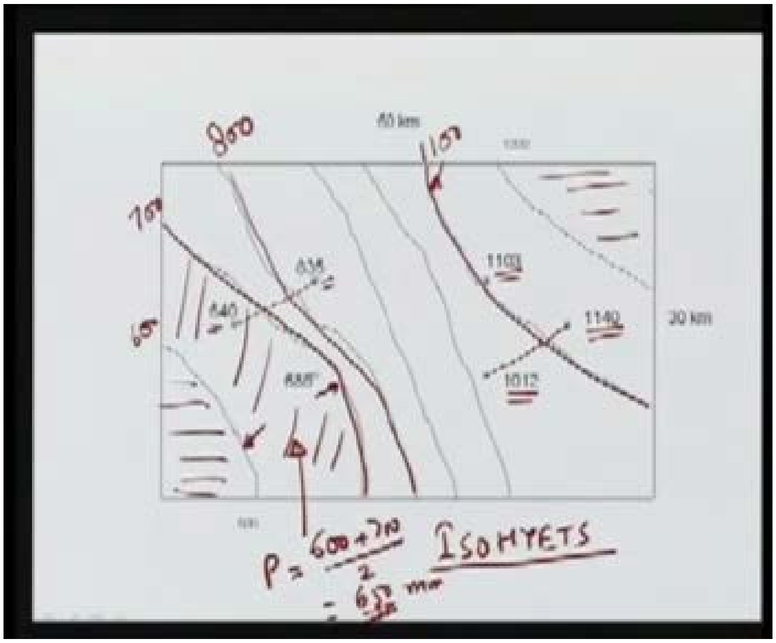

If we do that we have this table here which shows relative area. Between 500 and 600 isohyet the relative area is 0.1, between 600 and 700 0.17. This indicates that this area is one tenth of the total area. This area is 17% of the total area and between 700 and 800 0.11 and so on. A 0.1 weight will be given with a rainfall of which is average of 500 and 600 which is 550; then 0.17 into 650 and so on. The last value 0.1 will be 1250. Adding all these up we get the average precipitation over the area as 908 millimeters. In this case we can see that there is not much difference between the three methods but each has its own advantages and disadvantages.

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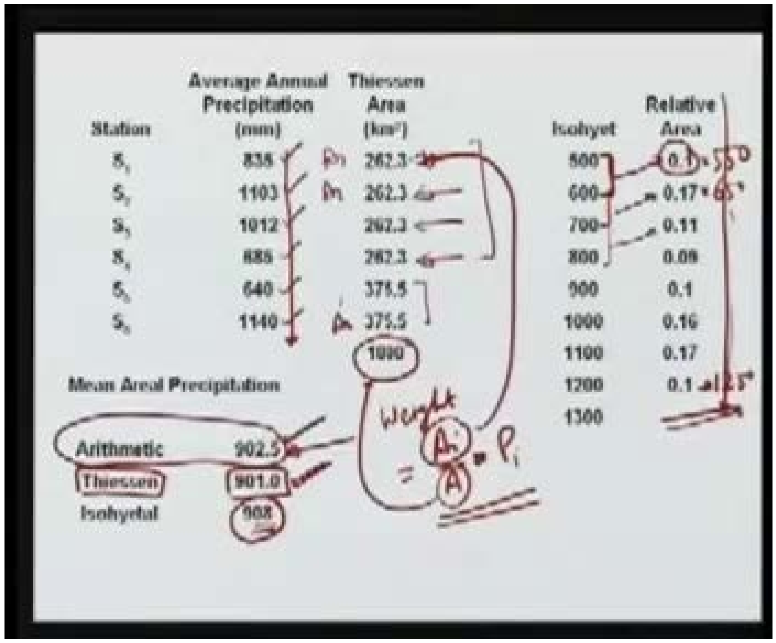

In Theissen polygon if we add one more station suppose here then the entire network has to be redefined and computed again. But if we add a station here, then we need to join this with S_2 and make a perpendicular bisector here. The effective area for S_2 will decrease and become like this. Similarly we have to join this also. This would affect the drawing of the polygons.

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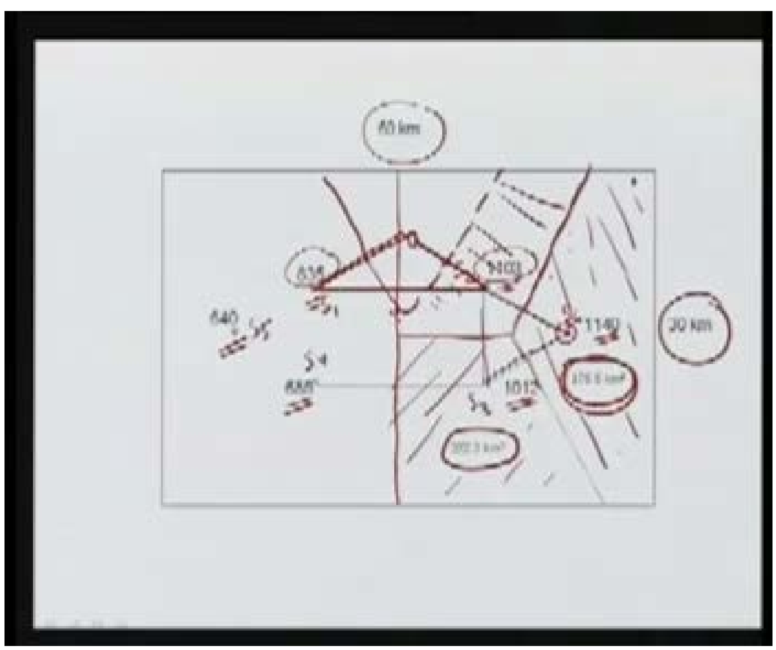

If we add one station somewhere here it will not generally change the isohyets too much. Suppose we have this 800, 900 and 1000 here and we add another station here which has precipitation of 940. It will not change the isohyets much. Even if its let's say more than 1000 suppose it is 1010 then the isohyet will change a little bit. It will go from this side but not very much.

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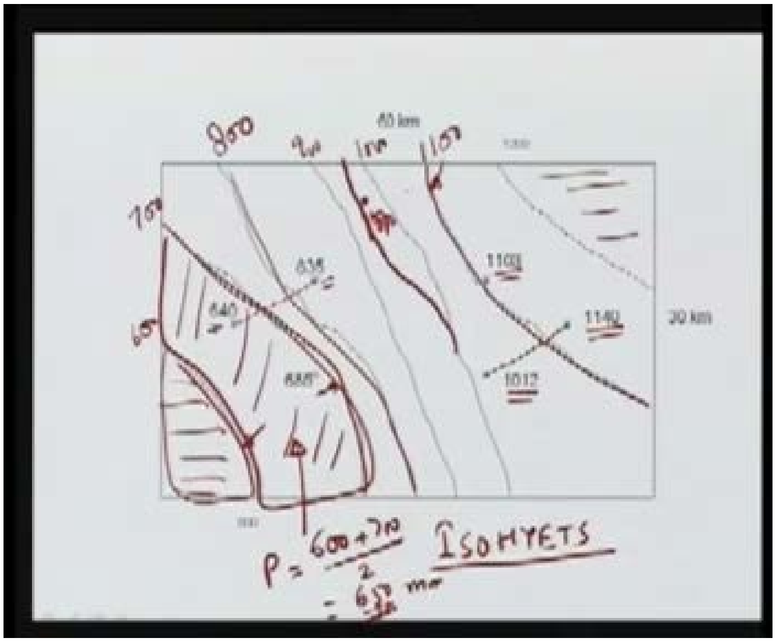

In this way the mean aerial precipitation the three values can be obtained which in this case come out to be very similar.

Once we do the annual precipitation, aerial average we are also concerned about the data which we have which is only 30 years data but sometimes we want to estimate the values for a longer period. We may be interested in finding out the rainfall which will occur once in 50 years or once in 100 years. The data which we have is only for a period of 30 years. In order to analyze this we do what is known as the frequency analysis. This table shows the annual maximum 24 hour precipitation; 24 hour because we have non-recording gauges. The data which is available to us is only a 24 hour data. If we have recording gauges then we may get data which will represent 1 hour or even less than that. We may have 1 hour max precipitation or we may have 1/2 an hour or 15 minutes because for a recording gauge we can analyze the data for a very short period as it maintains a continuous record. But for non-recording 24 period hour is the one which we will be using because the measurement is done once everyday. Based on the maximum annual value of daily precipitation or 24 hour precipitation at station S_1 we can prepare a table which shows this maximum precipitation.

At station S_1 in year 1976 maximum rainfall in a single day was observed as 110 millimeters. These are all millimeters. Similarly in the year 1990 the maximum precipitation observed in a single day at rainfall station S_1 was 70 millimeters.

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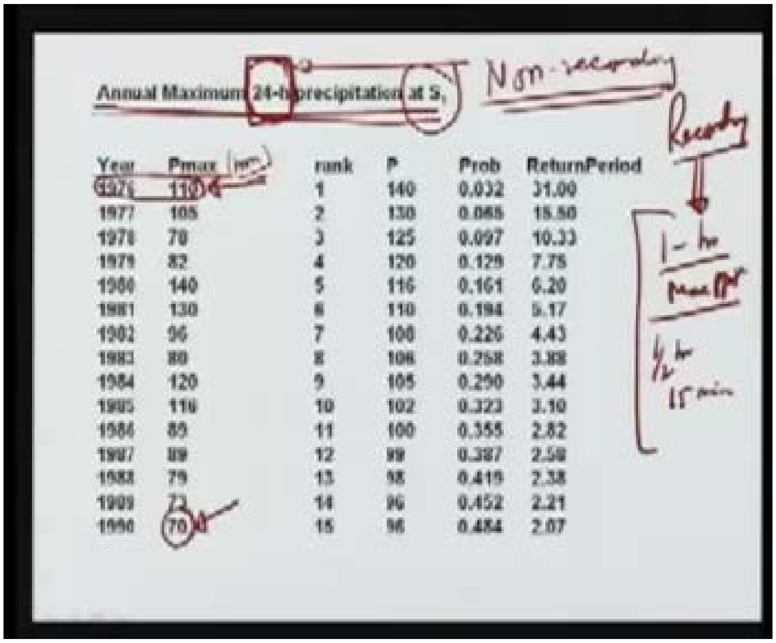

Annual Maximum 24-h precipitation at S_1

Year	Pmax (mm)	rank	P	Prob	ReturnPeriod
1976	110	1	140	0.032	31.00
1977	105	2	130	0.065	15.50
1978	70	3	125	0.097	10.33
1979	82	4	120	0.129	7.75
1980	140	5	116	0.161	6.20
1981	130	6	110	0.194	5.17
1982	96	7	108	0.226	4.43
1983	80	8	106	0.258	3.88
1984	120	9	105	0.290	3.44
1985	116	10	102	0.323	3.10
1986	89	11	100	0.355	2.82
1987	89	12	99	0.387	2.58
1988	79	13	98	0.419	2.38
1989	73	14	96	0.452	2.21
1990	70	15	96	0.484	2.07

This is only up to 1990 we have data up to 2005. We can see that sometimes maximum precipitation in a day is 10 centimeters sometimes it is 125 millimeters or in some years it may go as high as 140 millimeters. We can say that in this 30 year period the maximum daily precipitation in a year was obtained as 140. Based on this 30 year record we want to estimate what will be 50 year maximum daily rainfall or 100 year maximum daily rainfall? We will look at all the data. This is 30 year data and we arrange it in a rank which is decreasing order. The 30 year data which we have of annual maximum precipitation shows us that the overall maximum is 140 over this period. The top value here will be 140 and then this is in decreasing order; so 140 is the maximum. Then we have 130, 125 and 120. We arrange all the data and give it a rank. The first data, the highest value will have a rank 1; second highest rank 2 and so on till we get the last minimum value of 70 which is rank of 30.

The rank we call or we denote by m, total number of data points which we have is 30 because we have a 30 year data. Based on this we can find a probability as m over N plus 1 probability or a plotting position of m over N plus 1. This is a specific way of denoting the plotting position. More general form is m plus some constant a and N plus some constant b. There are number of options for a and b which can be used. But this distribution or this plotting position which is known as the Weibull is the most common. We will be using the plotting position or the probability as m over N plus 1. Return period is nothing but one over probability which represents on an average how much time there will be between occurrence of this rainfall two events of this magnitude. On an average this event will occur once every 31 years as you can see from this. We have N plus 1 which is 31. m is 1 for the first rank; so m over N plus 1 will be 1 over 31 which is 0.032 and return period will be 1 over probability which will be 31.

Similarly for the second event 31 by 2, 31 by 3, 31 by 4 and for the last value 31 by 30 which is 1.03. This table shows us that a rainfall of 140 has a probability of occurrence of 0.032 in a year. A rainfall of 100 millimeter has a 35.5% chance of occurring in a year and on an average it will occur once every 2.82 years. A rainfall of 70 or more than 70 has a probability of occurrence of 96.8% in a year. On an average it will occur once in every 1.03 years. This table gives us an estimate of the probability of occurrence and the return period for various precipitation events being equaled or exceeded. When we say that this is a probability of 100 millimeter rain that means rainfall equal to 100 or more than 100 will occur with this probability.

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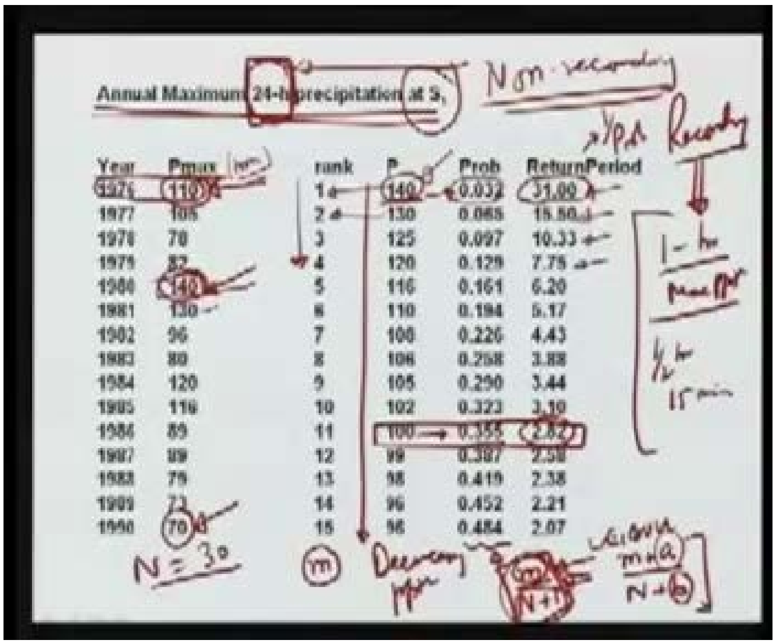

Based on this probability distribution or the frequency distribution we can plot a graph between return period in years and the precipitation in millimeter. This data which we have shown here with the squares is obtained from this table, return period versus the precipitation. For example 140 corresponds to return period of 31. Based on these points we can draw a straight line. We may draw a smooth curve also. We may have probably drawn a curve like this. But in this case it seems that an envelope curve like this may be more suitable. We can draw a line like this and extrapolate the value of rainfall for a return period of 100 years or 50 years say and correspondingly we can read the value from the graph.

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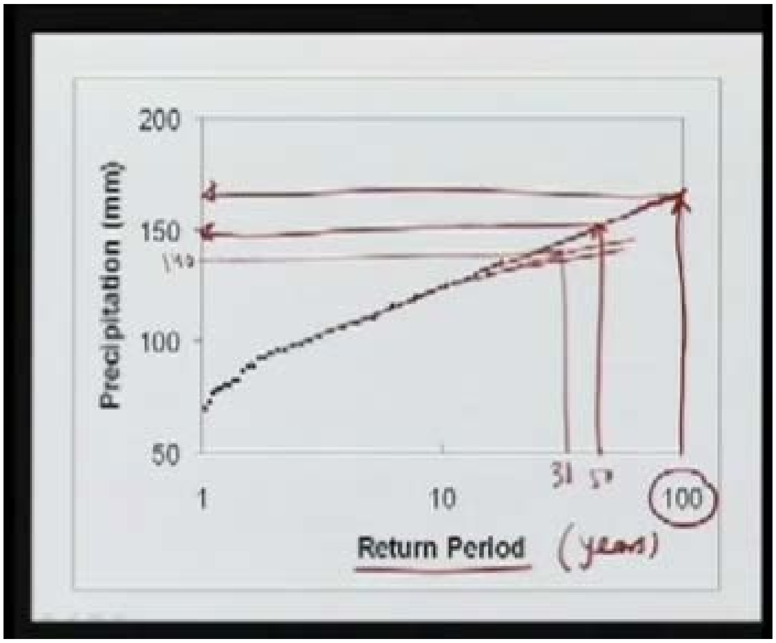

It turns out to be that for T equal to return period of 50 years the precipitation is 150 millimeters and for a return period of 100 years precipitation is 170 millimeter. On an average we can expect precipitation of 170 mm or larger once every 100 years and 150 millimeter or larger once every 50 years.

In addition to these suppose we are designing some structure for 50 year design life; we may like to see what are the chances of its failure in its useful life? We have a 50 year rainfall as 150 millimeter from here. We want to see what is the probability that will occur once or at least once? We can look at either once in 50 years or at least once in 50 years. Atleast once in 50 years means the structure will fail. If we design it for 50 year rain it may fail if it occurs at least once in 50 years. This is exactly once in 50 years. The probability can be obtained by 0.02 which is the probability of occurrence. Since T is 50 years the probability will be 1 by 50. Probability that this event will occur in a year is 0.02 and it will not occur the probability is 0.98; 1-0.02. The probability that it will occur in 1 year and not occur in other 49 years is 0.02 into 0.98 to the power 49 and then 50 because it can occur and that 1 year of occurrence can be anywhere in the 50 years. This gives us a 37.2% probability that the 150 millimeter rainfall will occur once in 50 years. At least once in 50 years means it may occur once, twice or more than that. 1-0.02 is the probability that it will not occur to the power 50. This is the probability of the event not occurring at all in the next 50 years and then 1 minus that will give us the probability of occurrence. 4635

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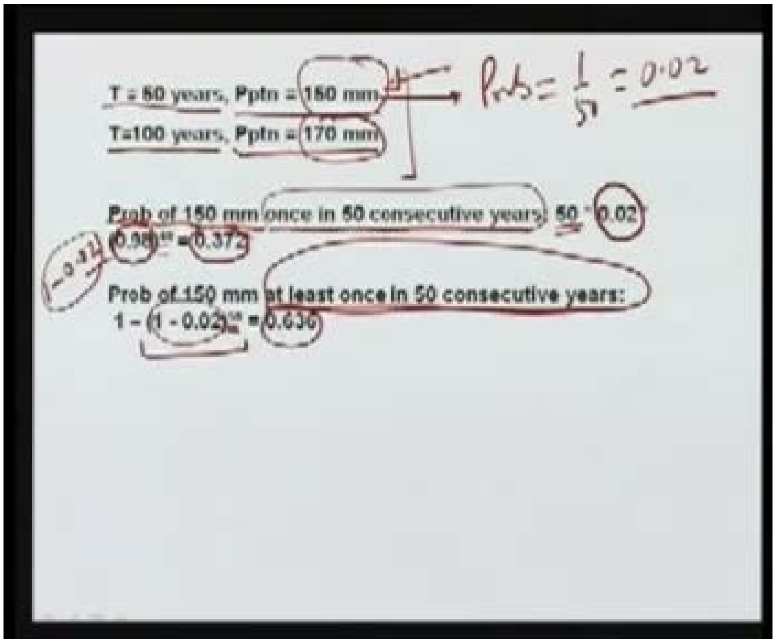

This tells us about the probability of occurrence of any return period rainfall in the next few years. We may not do it in 50 years. We may sometimes look at next 100 years, 150 years and 1000 years. But this is the way we can compute the probability of occurrence or non-occurrence of an event. The frequency of rainfall is important but side by side we have to also look at the intensity of rainfall and the duration of rainfall because they also affect the design of various structures.

In this case let’s look at what are known as intensity duration frequency curves or I-D-F curves. As we have seen the equation which relates the intensity duration and T indicates return period which really depends on the frequency. I, T and D are the intensity, duration and return period. K, X, a and n are constants for a specific area and we may take representative values and see how the intensity duration frequency curves will look like. We have taken here K equal to 70 millimeter, X 0.18, a as 0.5 hours and n as 0.9 for different durations and different time periods. This is a time period of 20 years, 50 years and 100 years. We can compute the intensity in millimeter per hour. This we can assign units millimeter per hour, K millimeter, D is hours, a is also in hours, X is non-dimensionless. Using these values for three different return periods 20, 50 and 100 we have computed the value of i from this equation using these four parameters.

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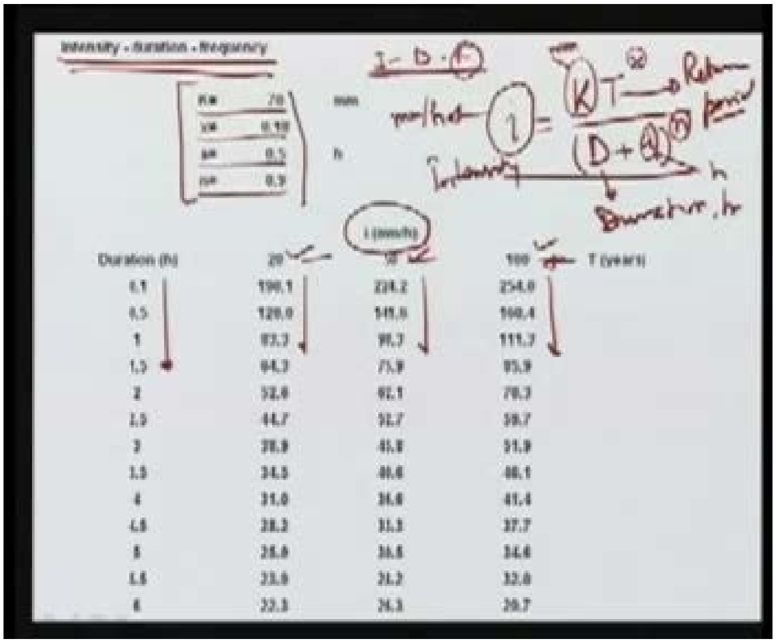

This graph shows the variation for return period of 100 year and 20 year and then 50 years. This shows us that for a particular duration, for a 1 hour rainfall the larger intensity rain will have a higher return period once in 100 years. Smaller intensity rain would be more frequent once every 20 years. Based on this we can estimate what would be the intensity of rainfall of a given duration storm and return period has to be specified. This will give us some idea about the intensity of rain at that particular frequency.

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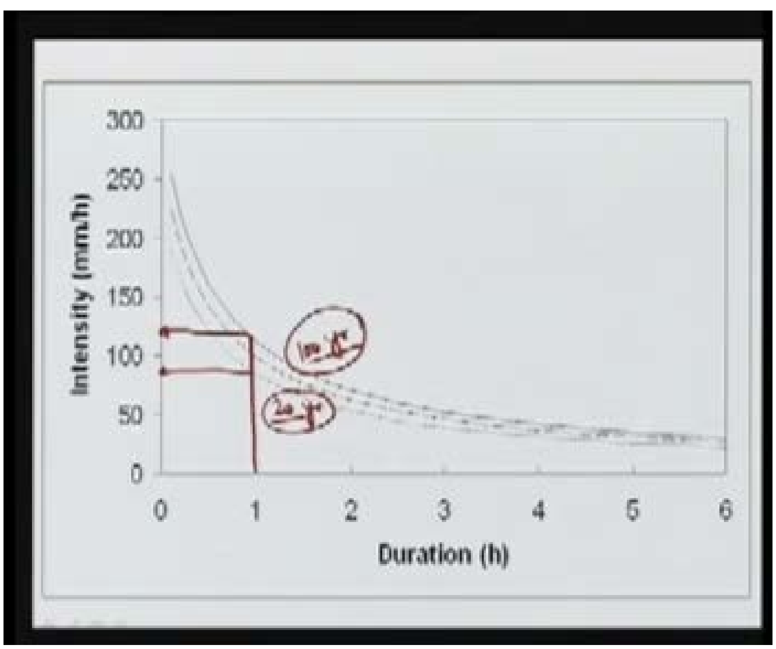

Similarly we can also compute what is the total depth of rainfall in that storm again for different return periods. Here also we have the same thing; 20, 50 and 100 years return period. This is the duration of storm and this is the total depth of precipitation during that storm. This is not intensity; intensity is millimeters per hour but this denotes total depth.

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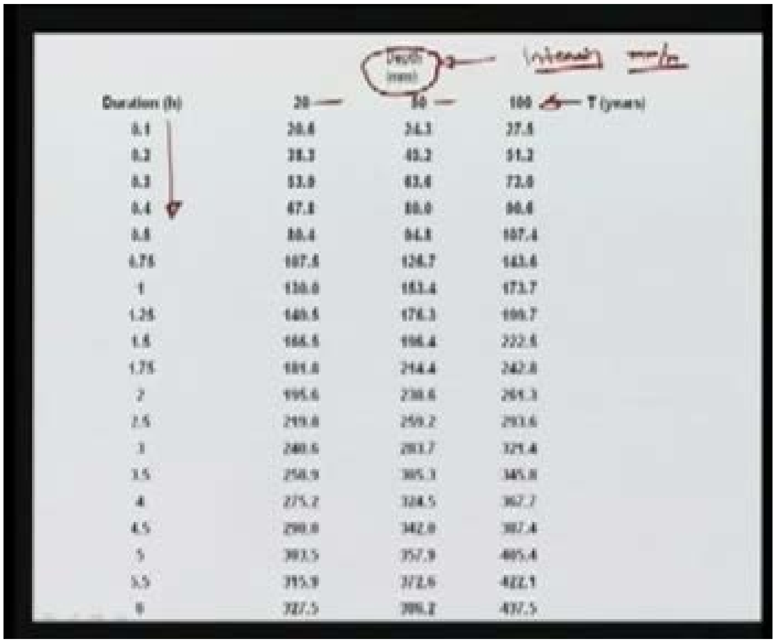

Depth (mm) Intensity mm/hr

Duration (h)	20	50	100 ← T (years)
0.1	20.6	24.3	27.5
0.2	38.3	45.2	51.2
0.3	53.0	63.4	73.0
0.4	67.8	80.0	90.6
0.5	80.4	94.8	107.4
0.75	107.5	126.7	143.6
1	130.0	153.4	173.7
1.25	149.5	176.3	199.7
1.5	166.5	196.4	222.6
1.75	181.8	214.4	242.8
2	195.6	230.6	261.3
2.5	219.8	259.2	293.6
3	240.6	283.7	321.4
3.5	258.9	305.3	345.8
4	275.2	324.5	367.7
4.5	290.0	342.0	387.4
5	303.5	357.9	405.4
5.5	315.9	372.6	422.1
6	327.5	386.2	437.5

If we plot this again this in millimeters for different duration of rainfall 100 year return period, 20 and 50 this gives us total depth of rainfall. As we can see here with the increase in duration the depth is increasing while the intensity was decreasing. This is expected because as the storm duration increases the maximum intensity will occur in the central portion of the storm and then as we move away in time, as the duration increases, then naturally the average intensity will be decreasing. But the depth of rainfall will keep on increasing although at a smaller rate. It will increase at a smaller rate but it will go on increasing. This gives us an idea about the total rainfall depth for any duration storm for any given frequency or return period. This data of intensity duration frequency or depth duration frequency is important in design of various structures as we will see later in the course.

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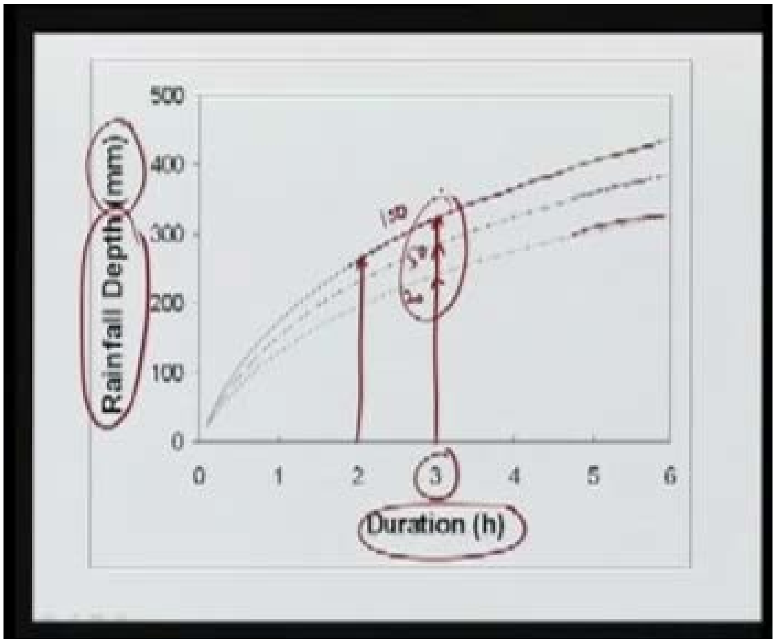

In today's lecture we have taken some examples and analyzed the behavior of precipitation over an area. We have seen how to estimate missing data for some stations, how to check the consistency of the record at various stations, how to compute aerial averages from the point rainfall values in order to get aerial average precipitation from a few rain gauge measurements. Then we have also seen how to analyze frequency distribution of the rainfall in order to predict a longer term rainfall than what the record is available for. Using a smaller period of record we can predict a larger return period rainfall and then we have looked at intensity duration frequency curves and depth duration frequency curves which are helpful in design of structures which depend on rainfall intensity or total depth of rainfall in their design.