Course Name: Watershed Hydrology

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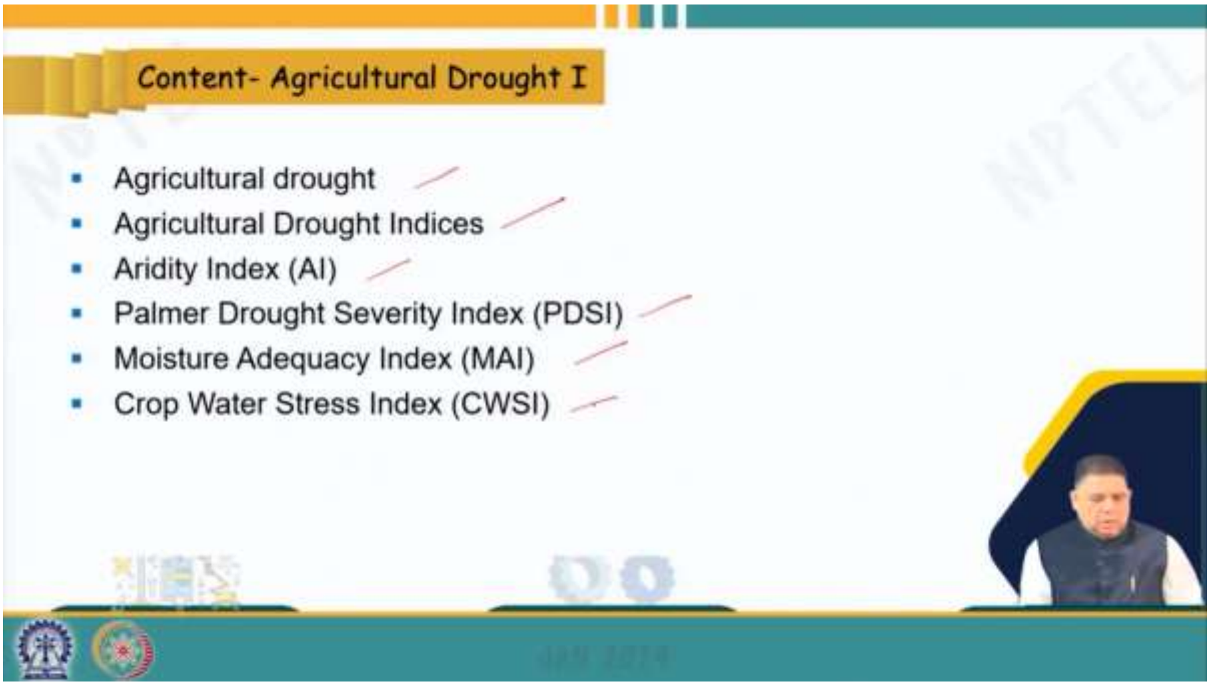
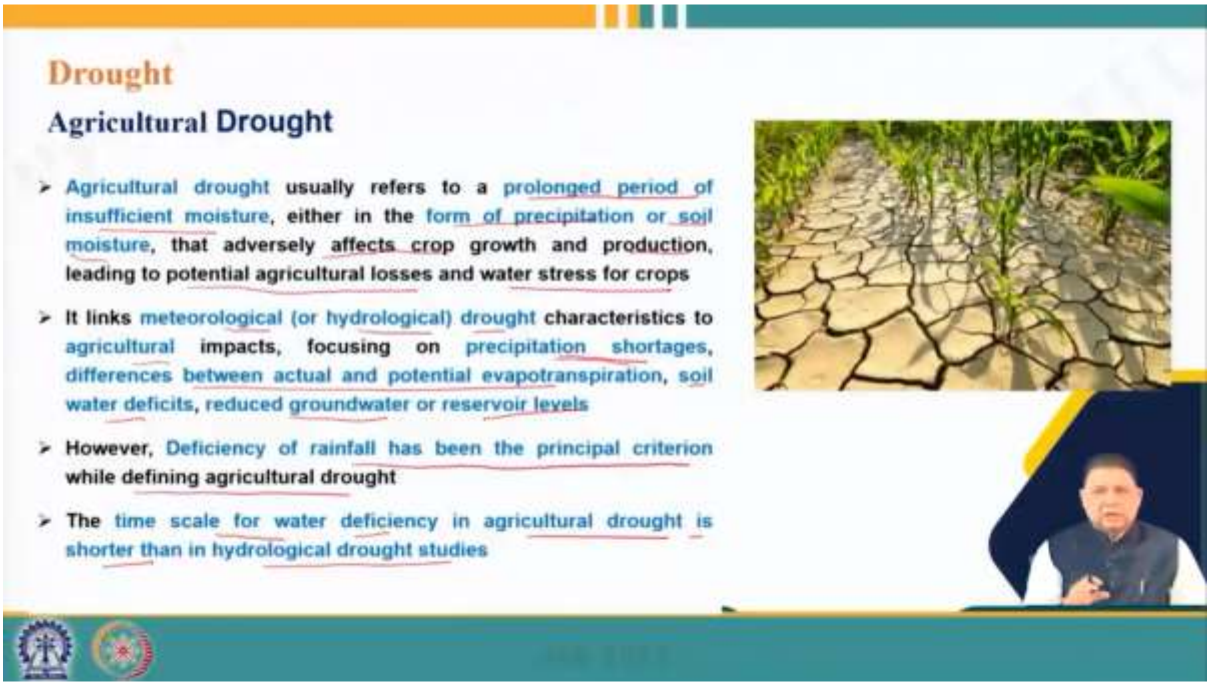
Week: 11

Lecture 53: Agricultural Drought I

Hello friends, welcome back to this online certification course on Watershed Hydrology. I am Rajendra Singh, professor in the department of agriculture and food engineering at Indian Institute of Technology Kharagpur. We are in module 11, and this is lecture number 3, where we will be starting with agricultural drought part 1.



In this lecture, we will introduce agricultural drought. Of course, we have already defined that, but we will be talking about agricultural drought indices like the aridity index, Palmer Drought Severity Index, moisture adequacy index, and crop water stress index.



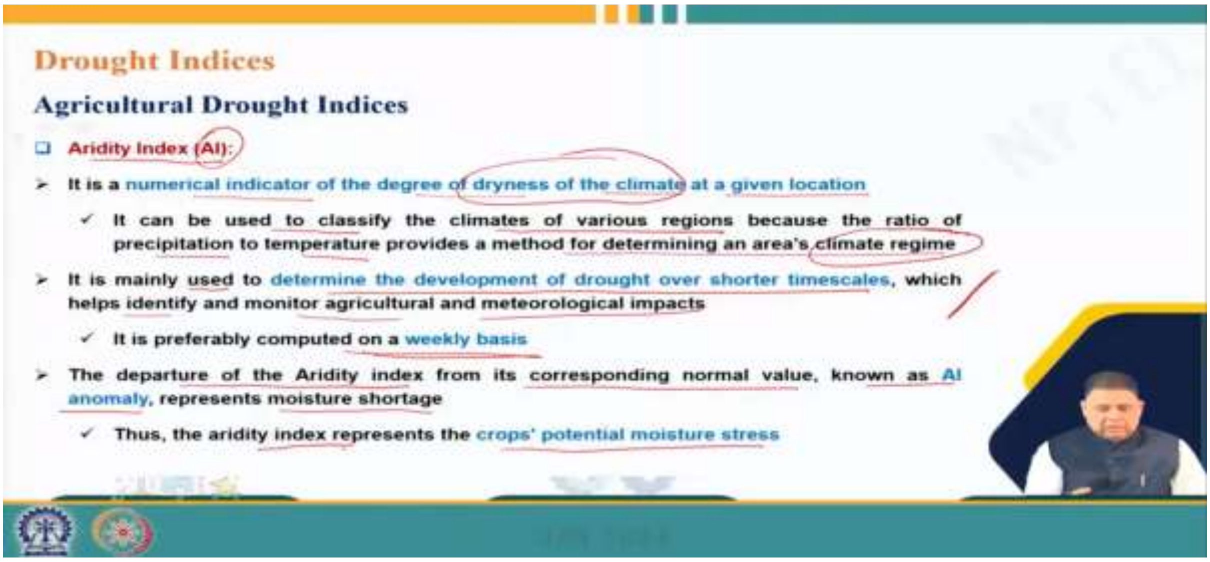
Now, coming to agricultural drought, we have already defined this and we saw that deficiency of rainfall is the principal criterion that defines agricultural drought because it usually refers to a prolonged period of insufficient moisture either in the form of precipitation or soil moisture that adversely affects crop growth and production, leading to potential agricultural losses and water stress for crops. It links meteorological or hydrological drought characteristics to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, and reduced groundwater or reservoir levels. So, basically, as we discussed in the previous lecture, we discussed various kinds of drought like meteorological drought, where it is related to only rainfall deficit or precipitation deficit.

Then we talked about hydrological drought, which is related to water shortages in storage, be it surface storage or groundwater storage. And then the third one is agricultural drought, that if there is deficient rainfall or deficiency in soil moisture, then obviously for a prolonged period, the crop will start suffering, and in that case, agricultural yield or the crop yield will get reduced because of the water stress, and then it is referred to as agricultural drought.

And of course, the primary reason is of course rainfall, which basically starts with meteorological drought or hydrological drought because you do not have water either in the form of rainfall or you have stored water for irrigating the crops. So obviously, that is why there could be precipitation shortage, there could be a difference between actual and potential evapotranspiration that will happen when you are not able to irrigate. So, actual transpiration will be much lower, then soil water deficit will be there, and of course, there will be reduced groundwater and reservoir levels because of the hydrological drought.

The timescale for water deficiency in agricultural drought is shorter than the hydrological drought studies because what happens is that agriculture, for agricultural crops, the deficit crops can survive deficit for only a limited period of time. So obviously, once there is a moisture deficit and irrigation is not provided, and that means the soil moisture reaches the wilting point, then obviously, the crops will suffer irreversible loss or damage. And that is why even for a shorter duration if there is a lack of soil moisture or lack of precipitation or irrigation to the crop or the soil moisture, then obviously it will immediately damage the crop, whereas in the case of hydrological drought, the water levels go down slowly in the water bodies or the groundwater. So that is why the impact of hydrological drought is felt after a prolonged period, whereas agricultural drought could make an impact even in a short period of time. That is a major difference between the other types of droughts and agricultural drought.

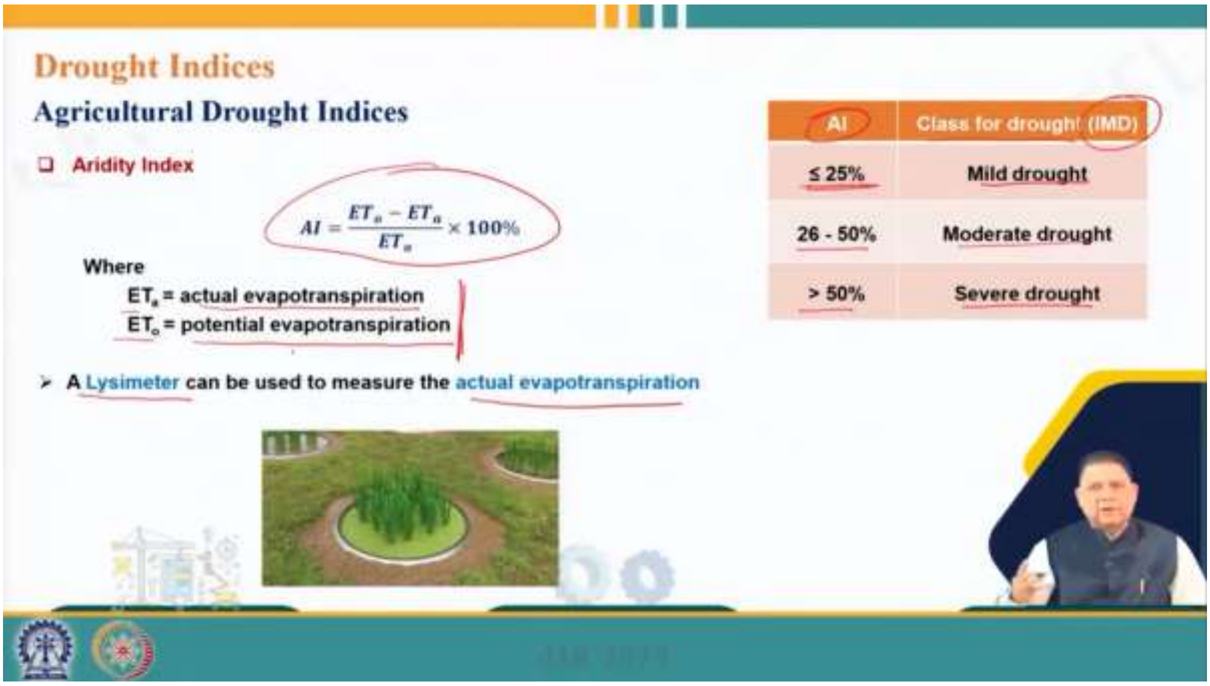
Now, coming to indices, there are various kinds of indices available for studying agricultural drought like the aridity index, the Palmer Drought Severity Index (PDSI), the moisture adequacy index (MAI), the crop water stress index (CWSI), and of course, there are plenty of remote sensing-based research which have come up in recent times and are very popularly being used nowadays, like NDVI, TVI, EVI, VCI, TCI, and a long list which we will be covering in the next lecture. Today, we will be focusing more on these indices from the aridity index to the crop water stress index. The remote sensing-based ones we will take in the next lecture.



Now, let us start with the aridity index (AI). Of course, nowadays AI refers to artificial intelligence, but here AI refers to the aridity index, which is a numerical indicator of the degree of dryness of the climate at a given location. The dryness of the climate is reflected by the aridity index and it can be used to classify the climates of various regions because the ratio of precipitation to temperature provides a method for determining the climate regime of areas.

It is mainly used to determine the development of drought over shorter time scales, which helps identify and monitor agricultural and meteorological impacts. So, it is very important from an agricultural perspective because, for agricultural drought, the time span is very vital. Thus, any study or idea that shows there are drought chances or the area is becoming drought-prone must be on a shorter scale. This is where the AI is useful, as it determines the development of drought over short time scales. It is preferably computed on a weekly basis, so a weekly idea of aridity gives us a fair idea about agricultural drought. The departure of the aridity index from its corresponding normal value, known as the AI anomaly, represents the moisture shortage.

So obviously, over a long period of time, if you have data, then you know what the normal aridity index of a particular place is in a particular week. So, if there is any departure from that, then it will be called an anomaly, and that will represent whether there is any moisture shortage. The aridity index represents the crop's potential moisture stress. So obviously, if the aridity index, if aridity goes up, that means soil moisture shortage is more, and that means there is potential moisture stress. That is how the aridity index indicates agricultural drought.

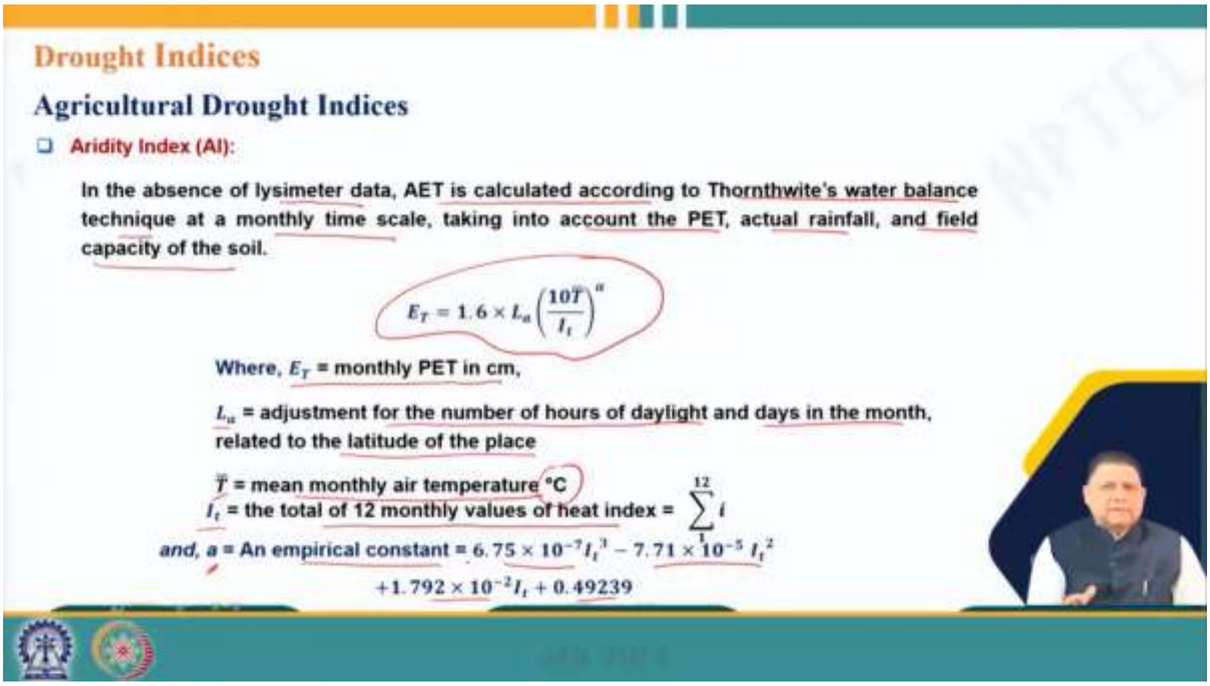


Now, as far as numerical estimation is concerned, it is expressed by this relationship:

$$AI = \frac{ET_0 - ET_a}{ET_0} \times 100\%$$

, where ET_a is actual evapotranspiration and $ET_0$is potential evapotranspiration. So of course, we have studied evapotranspiration in great detail. So if we have the actual and potential evapotranspiration data value on a weekly basis or whatever time scale you choose, then the aridity index could be calculated. And once the aridity index is calculated, then drought can be classified. This classification, which is shown here in this table, is given by the India Meteorological Department. That is why if the AI is less than or equal to 25 percent, that is, there is an anomaly, then it is considered a mild drought. If it is 26 to 50 percent, then it is referred to as moderate drought, and if it is greater than 50 percent, then it is considered severe drought.

So, three different classes of drought could be identified based on the aridity index. And of course, we know that for studying evapotranspiration, we have studied in great detail that a lysimeter could be used to measure the actual evapotranspiration, and for potential evapotranspiration, we have seen that we have many hydrometeorological equations available, starting from Blaney-Criddle to Thornthwaite. We also talked about the Penman-Monteith equation earlier, and of course, we also saw that we earlier studied what a lysimeter is and how it is used in field conditions for measuring evapotranspiration.

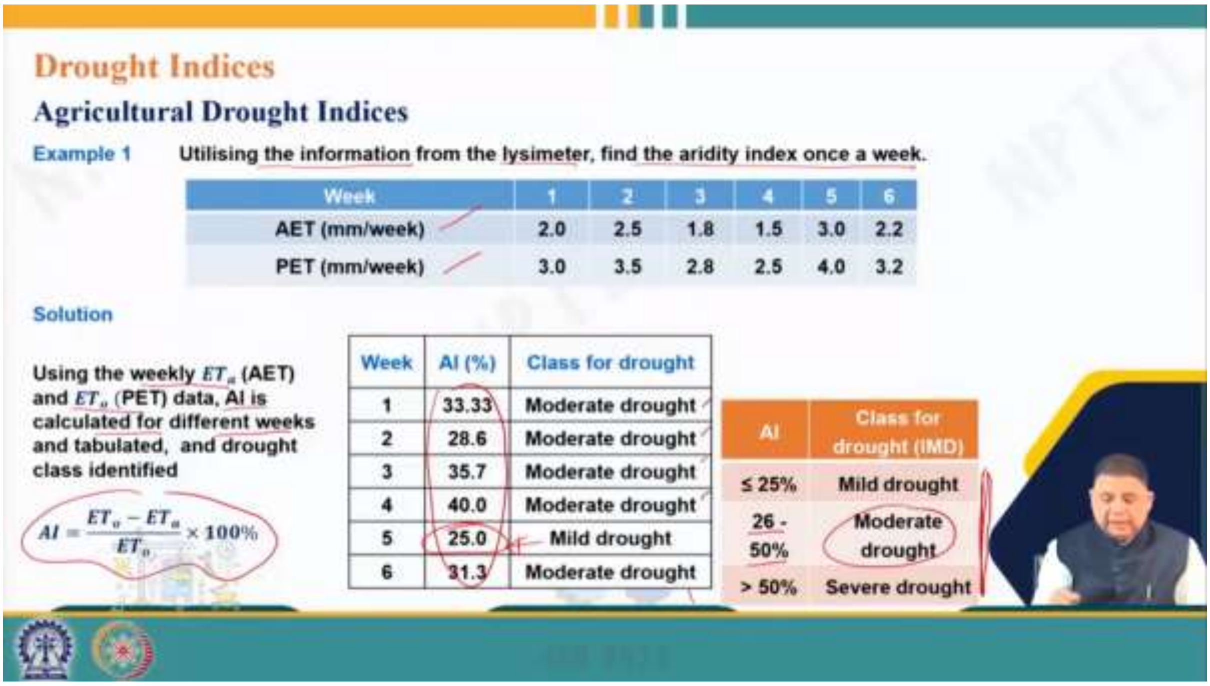


Now, in the absence of lysimeter data, that is, if you do not have lysimeter data available, then AET can be calculated according to Thorton's water balance technique at a monthly time scale. Of course, then it can be only done at a monthly time scale, taking into account the PET, actual rainfall, and field capacity of the soil. In that case,

$$E_T = 1.6 \times L_a \left(\frac{10\bar{T}}{I_t}\right)^a$$

where E_T is the monthly PET in centimetres. L_a is the adjustment for the number of hours of daylight in days in the month and related to the latitude of the place. T bar is the mean monthly air temperature in degrees Celsius, and $I_t$is the total of 12-month values of heat index. Here, it is given as 1 to 12 I, and A is an empirical constant, which is given in terms of I_t. It can be calculated by this relationship.

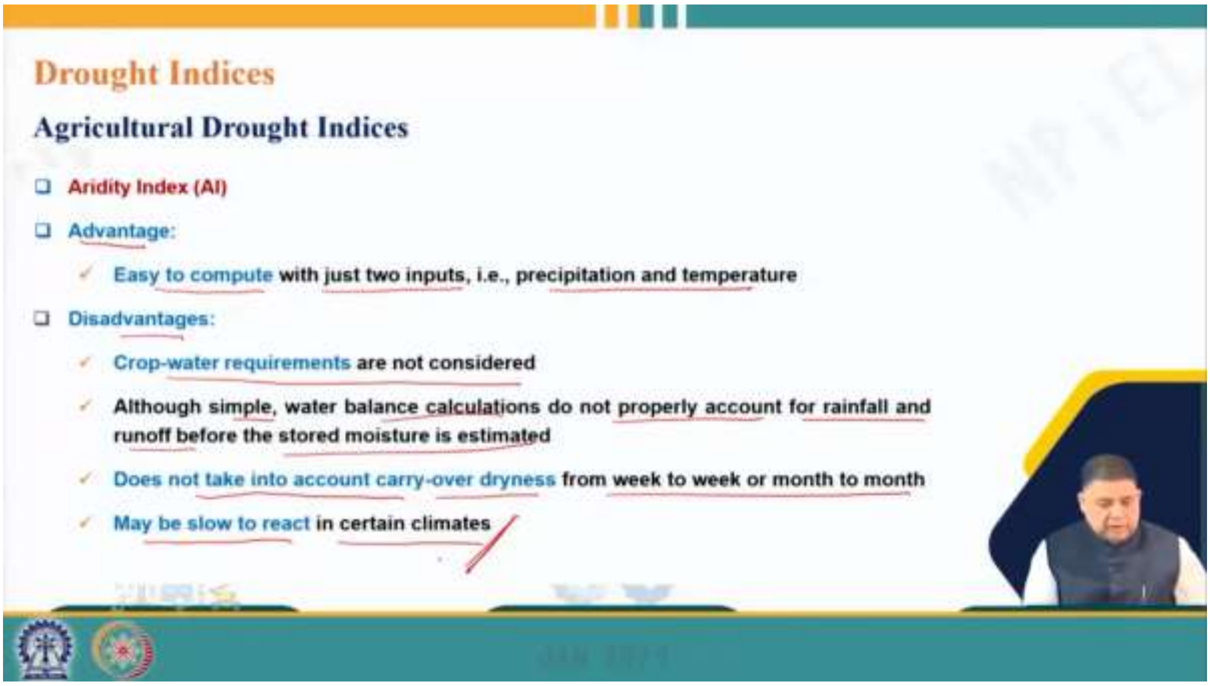
So, if you do not have lysimeter data, then we will estimate evapotranspiration using Thorton's water balance equation. I mean, this is just a recommendation; you can use any other method because you need actual ET and potential ET. So, by any method, if you have these values available, you can estimate the aridity index.



Let us take a problem here on agriculture dot index, that is, on AI, utilizing the information from the lysimeter, find the aridity index once a week. So, actual ET and potential ET values in millimetres per week are given over a 6-week period, and these are the values.

So, obviously, we know that using the weekly ETA and ETO, AI can be calculated for different weeks. It is calculated here and tabulated. These are the values that are calculated using this relationship, which is ETO minus ETA divided by ETO. So, PET is ETO, and ETA is actual ET, which is shown here. So, using these values, AI is calculated here, and of course, we know that this scaling is as per IMD. So, if the AI value is less than or equal to 25, then it is mild drought. So, this value one value in week number 5 is 25.

So, it is a mild drought, but the rest of the values are between 26 and 50 percent. So, they indicate moderate drought. That is why in week numbers 1, 2, 3, 4, and 6, there is a moderate drought in the area as per the data provided here. So, that is how we know that there is a possibility of drought or not based on the calculation of AI values.

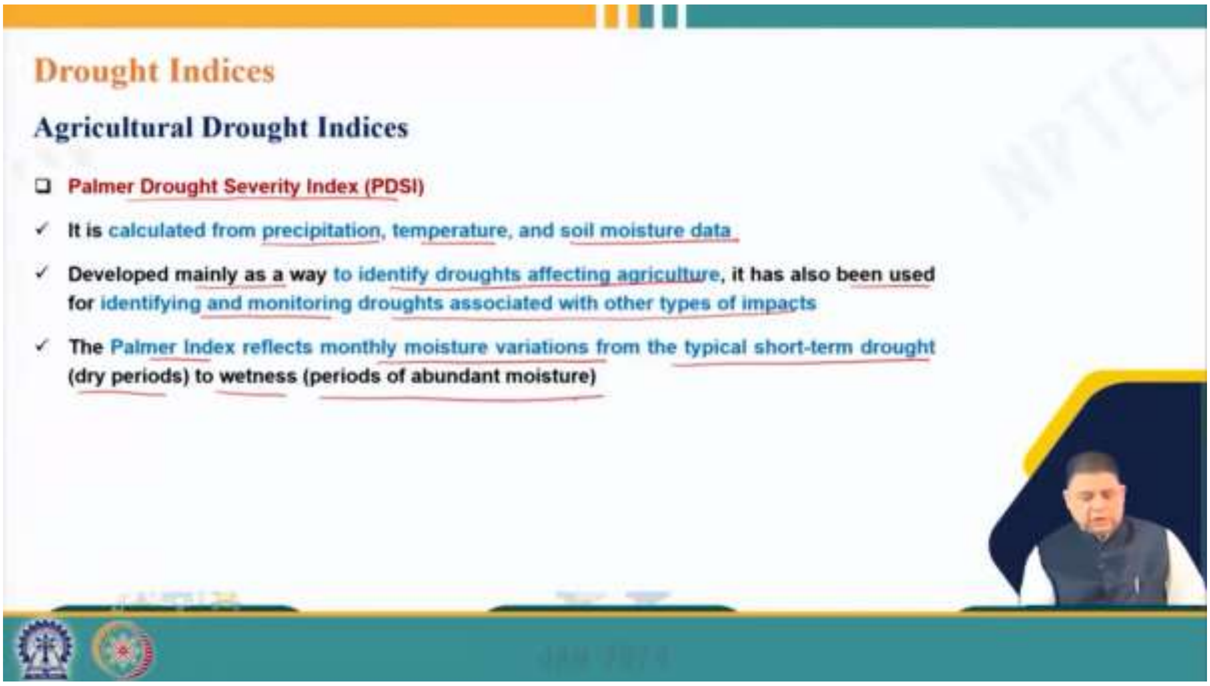


Then, coming to the advantages of this, the advantage of AI EI is that it is easy to compute with just 2 inputs, precipitation and temperature, and the disadvantages include that its crop water requirements are not considered directly. Although simple water balance calculations do not properly account for rainfall and runoff before the stored moisture is estimated.

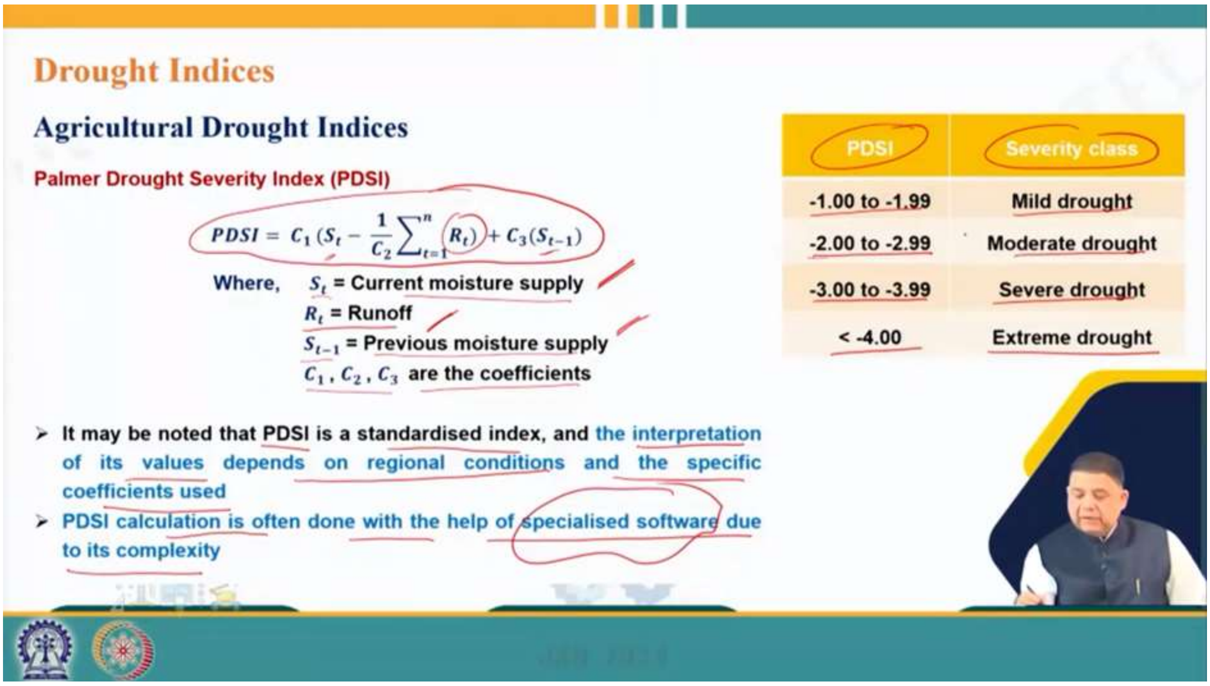
So, obviously, it does not matter as long as you have ETA because of the stored moisture. So, even if there is no rainfall, its impact will not be seen and does not take into account carry-over dryness from week to week or month to month and may be slow to react in certain climates. So, if you do not have frequent lysimeter data, then obviously, estimation will be delayed, and then obviously, a week or two of drought, and the crops may suffer.

And this shows a typical picture of aridity index over India. This is maybe over a week, 11th to 17th May 2022. This just to give you an idea of how aridity could move in the month of May, which is a dry season, high-temperature period in India.

So, this shows that, of course, here, the green colour shows that it is a non-arid place. These are the only green colours. Yellow is mild red, pink is moderate, and red is severe drought. So, these are the scaling we have already seen. That shows that the data shows here that around 78 percent of the total districts across India, that is around 539 of about 691 districts mapped, were facing different degrees of aridity, mild, moderate, and severe, as per IMD during this period in 2022. And I think that could be the scenario almost every year during this period. So, obviously, that is why the onset of monsoon on time is very important because if rainfall does not take place, then you do not have sufficient irrigation facilities to support crop growth, and that is why agricultural drought will happen if meteorological or hydrological drought is there.



Then we come to the next one, that is PDSI, the Palmer Drought Severity Index. It is calculated from precipitation, temperature, and soil moisture data and is developed mainly as a way to identify droughts affecting agriculture. It has also been used to monitor drought associated with other types of impacts. So, of course, mainly focused on agriculture, but it can also directly focus or identify meteorological or hydrological drought. The Palmer index reflects monthly moisture variation from typical short-term drought dry periods to wetness, periods of abundant moisture.

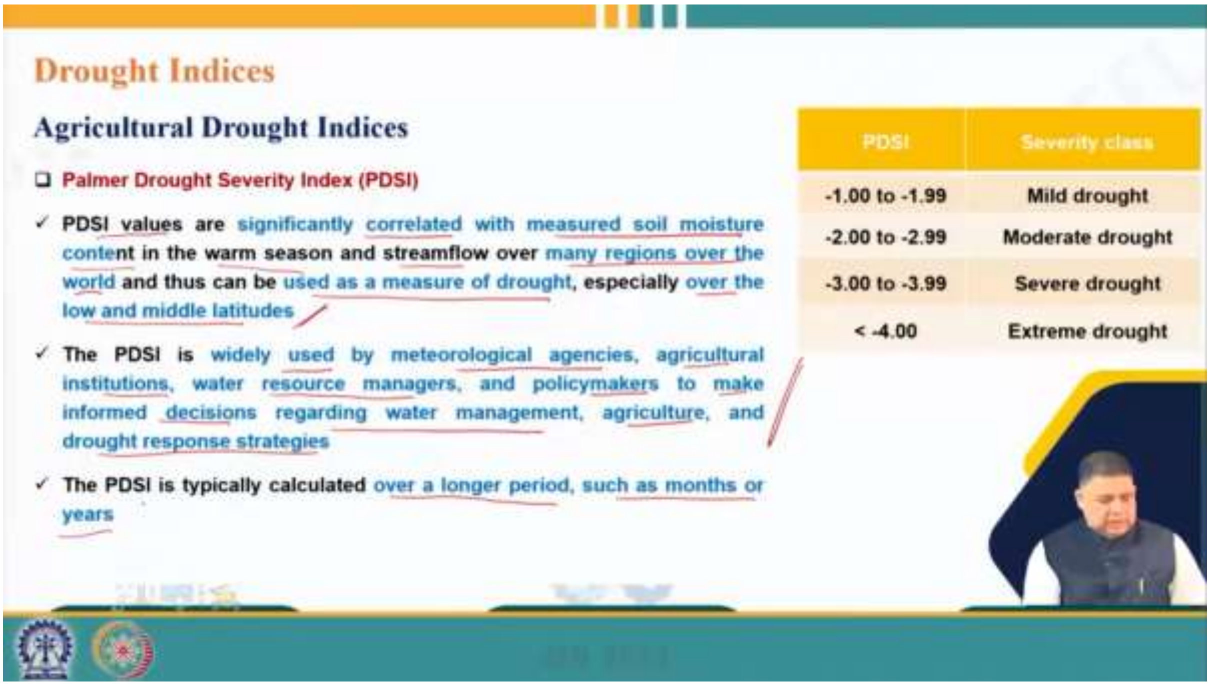


And PDSI is calculated using this little bit of a complex equation

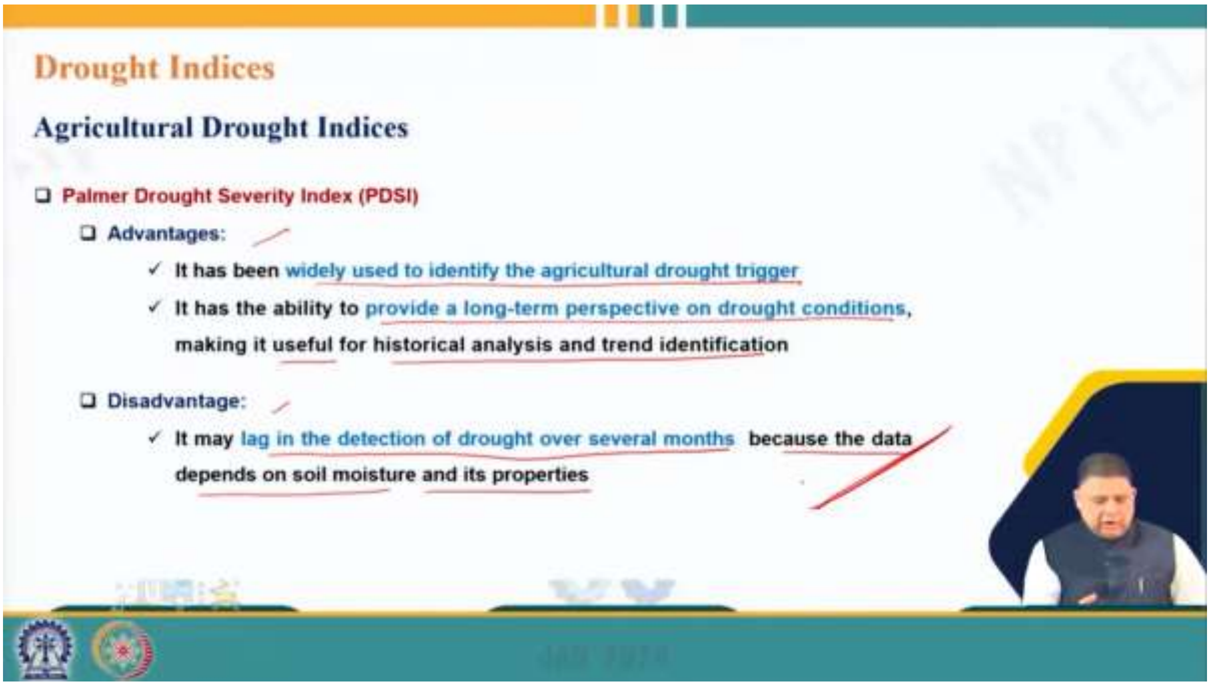
$$PDSI = C_1(S_t - \frac{1}{C_2}\sum_{t=1}^{n} R_t) + C_3(S_t - 1)$$

where S_t and $S_t - 1$ are the current and previous soil moisture supply, respectively. R_t is runoff over the period, andC_1, C_2, $C_3$are the coefficients. So, a little bit complicated equation, but you are using soil moisture supply and runoff value, which means precipitation is also being taken into account. It may be noted that PDSI is a standardized index, and the interpretation of its values depends on regional conditions and the specific coefficients used.

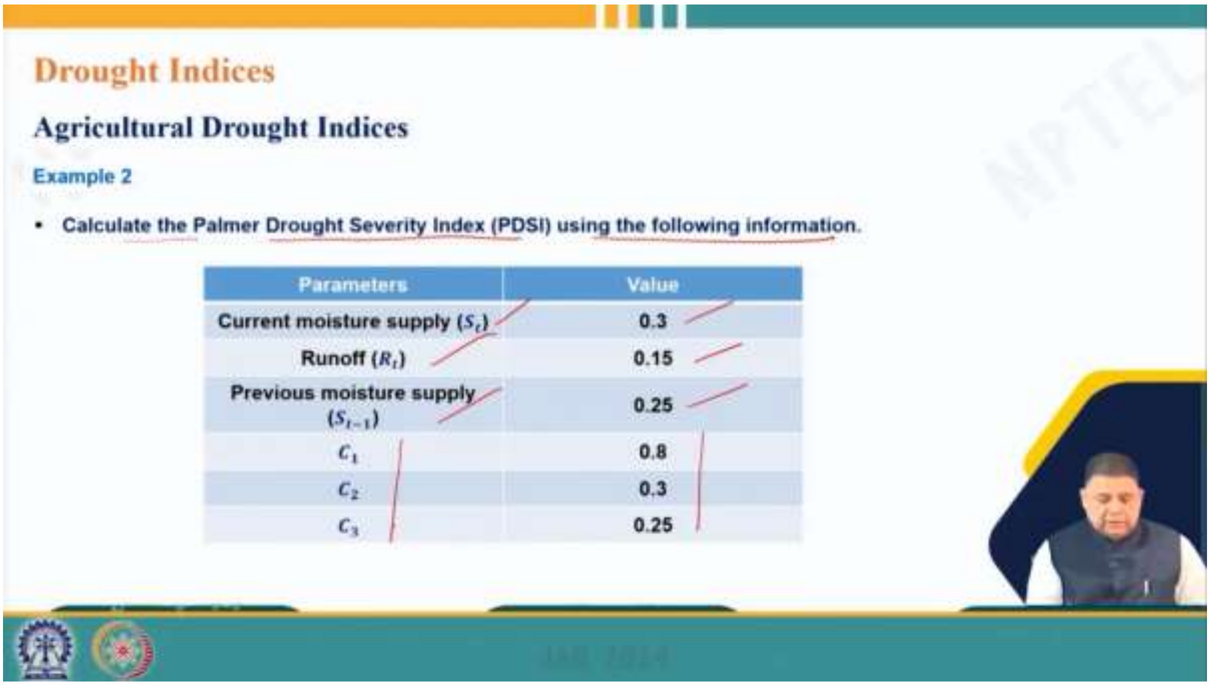
So, C_1, C_2, $C_3$are specific to a particular location, and PDSI calculation is often done with the help of specialized software due to its complexity. As far as the severity class goes, based on PDSI, if the PDSI value is between -1 to -1.99, it is a mild drought; if it is between -2 to -2.99, it is a moderate drought; if it is -3 to -3.99, it is a severe drought, and if it is less than -4, it is an extreme drought. So, again, 4 classes of droughts can be identified based on the PDSI value.



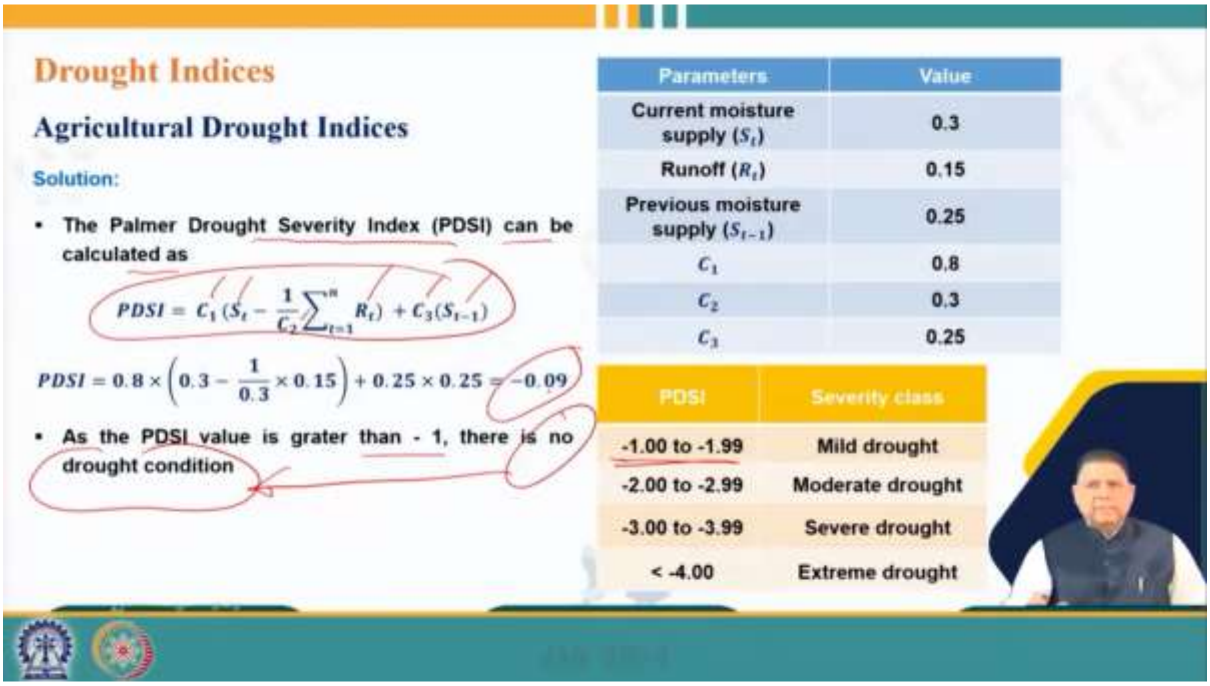
PDSI values are significantly correlated with measured soil moisture content in the warm season and stream flow over many regions worldwide, and thus can be used as a measure of drought, especially over low and middle altitudes. So, that shows that PDSI has been used around the world quite frequently and is widely used by meteorological agencies, agricultural institutions, water resources managers, and policymakers to make informed decisions regarding water management, agriculture, and drought transpository. PDSI is a common agricultural drought index, and it is typically calculated over a longer period such as months or years compared to AAI, which is typically calculated over a weekly period.



As far as advantages go, it has been widely used to identify agricultural drought figures. So, when agricultural drought really begins, one can study using PDSI, and it has the ability to provide a long-term perspective on drought conditions, making it useful for historical analysis and trend identification. However, its disadvantage is that it may lag in the detection of drought over several months because the data depends on soil moisture and its properties. So, obviously, obtaining real-time soil moisture data is not that easy. So, if you are not able to collect real-time soil moisture data, then obviously, there may be a delay in detecting the drought as per PDSI.

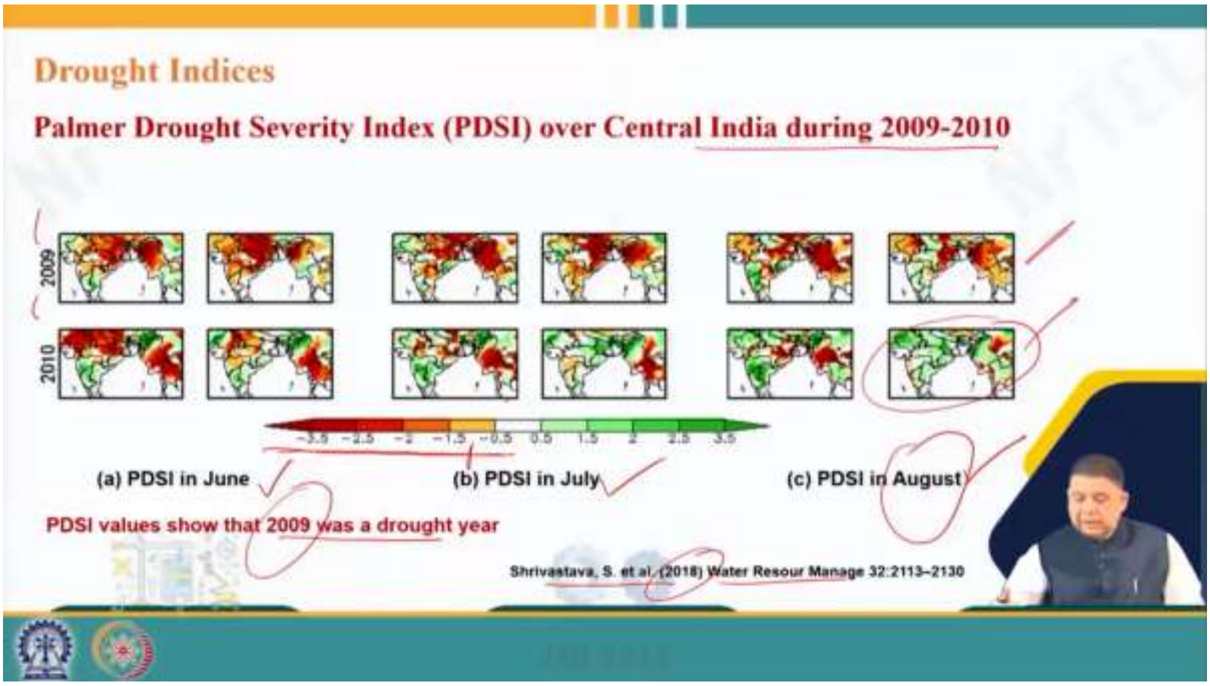


We go to example number 2, which is on PDSI, that says to calculate the PDSI using the following information. So, the current soil moisture supply is given, runoff is given, previous moisture supply is given, C_1, C_2, C_3 are given. So, that means, all the requisite variables are known to us.



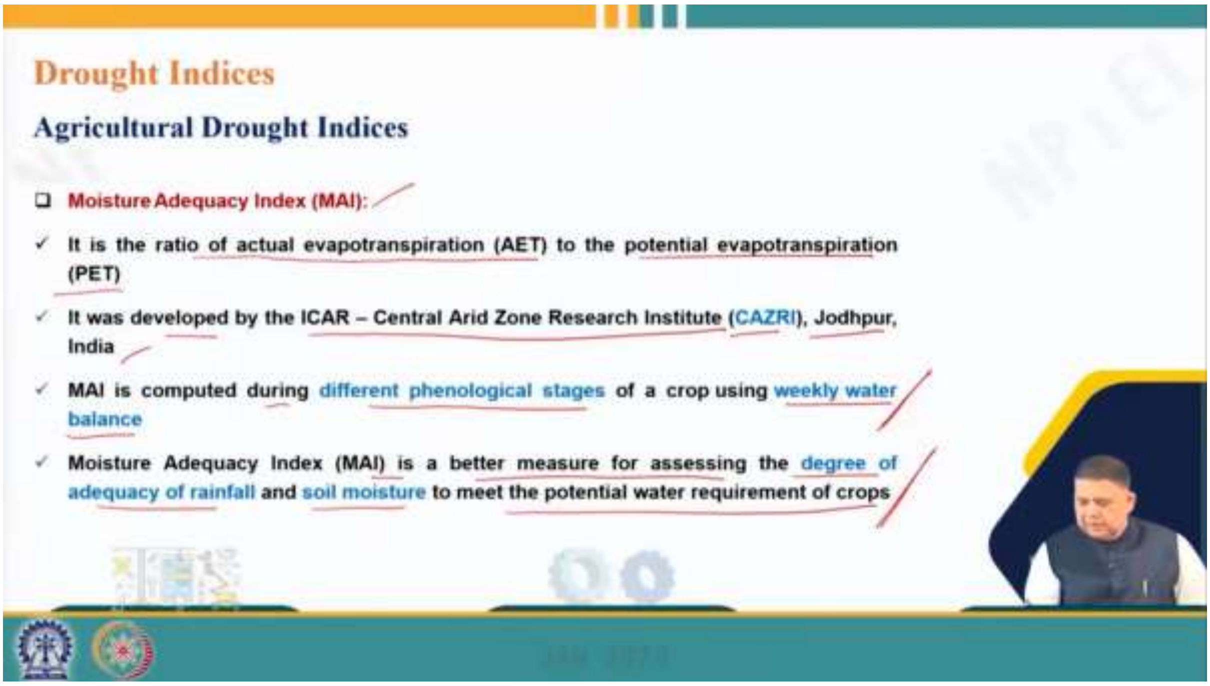
And we know that the Palmer Drought Severity Index can be calculated using this relationship. Here, almost all, likeC_1, C_2, and C_3, are known to us, St and St minus 1 are known to us, and Rt is known to us. So, obviously, we can put the values and then calculate the PDSI value, which comes out to be -0.09 and 0.09. That means, it is below this, so as PDSI values greater than -1, because it starts from -1.

So, its value is only -0.09. So, there is no drought condition in the area as per the data provided, no drought condition. So, because mild drought starts from -1, so its value obtained is only -0.09. So, based on if you have the requisite data, you can calculate PDSI or rather Palmer Drought Severity Index, and you can make a judgment about the agricultural drought in a given area.



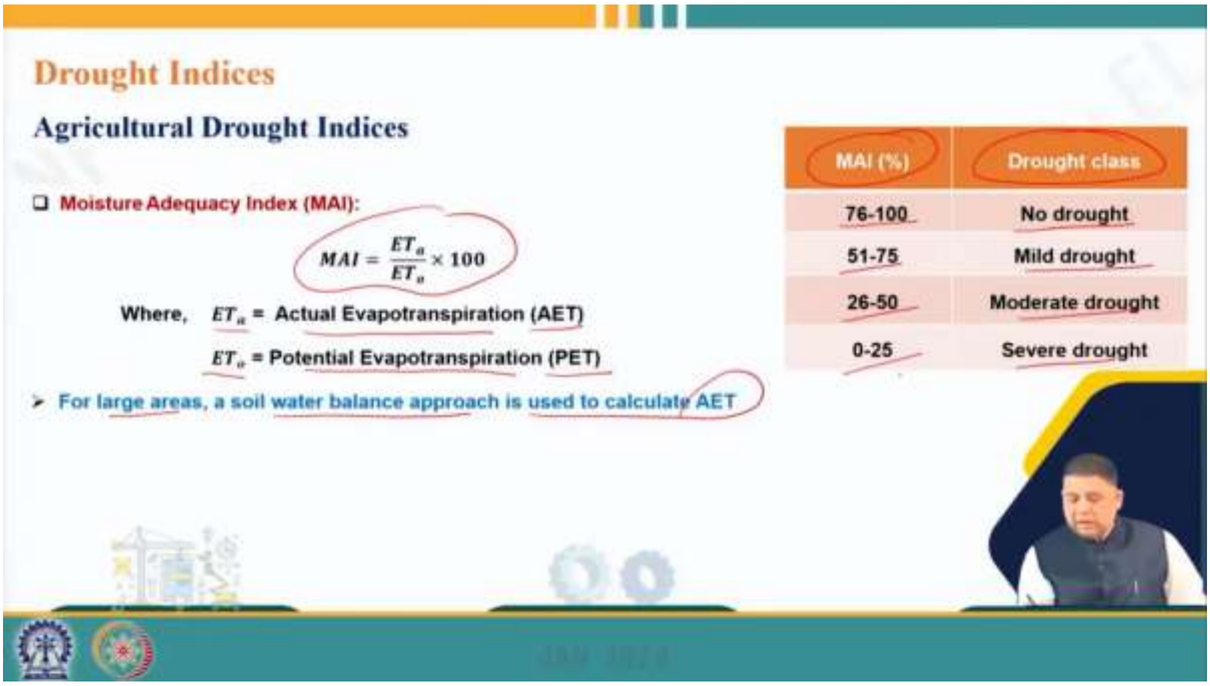
Then, this is a typical Palmer Drought Severity Index over central India during 2009 and 2010, and it is reported in this paper published in Water Resources Management 2018. And, of course, these are over 2 years, 2009, 10, and just taken as a sample value just to show how the picture could vary. And, of course, it is you can see that these are the caution places, and that is from 1 onwards, and these are positive values. So, this is in the month of June, this is the month of July, this is the month of August. As you can see, as the rainfall comes, more green patches you see. But, if you consider 2009 and 2010, even in August, you will find that 2009 was a drought year because you still find a lot of negative values, colours, reddish colours or yellowish reddish colours here in this picture compared to the bottom one, 2010.

So, that is why we can say that based on this analysis, you can say that even historical analysis, you can make and say that 2009 was a drought period in central India for which this data has been procured. So, I mean, this is how you can analyse PDSI, and you can make inferences out of the data that is available with us.



Then the next one comes is MAI, that is, the Moisture Adequacy Index. It is the ratio of actual evapotranspiration to potential evapotranspiration. Like the AI, it also uses actual and potential evapotranspiration in calculation. And it was developed by the ICR Central Arid Zone Research Institute, Jodhpur, India, and it is computed during different phenological stages of a crop using weekly water balance.

So, obviously, if you calculate it on a weekly basis, then you are covering different phenological stages and get a good idea about the impact of moisture shortage or moisture adequacy on the crop growth. MAI is a better measure of assessing the degree of adequacy of rainfall and soil moisture to meet the potential water requirements of crops, and this has been reported by researchers based on their analysis.

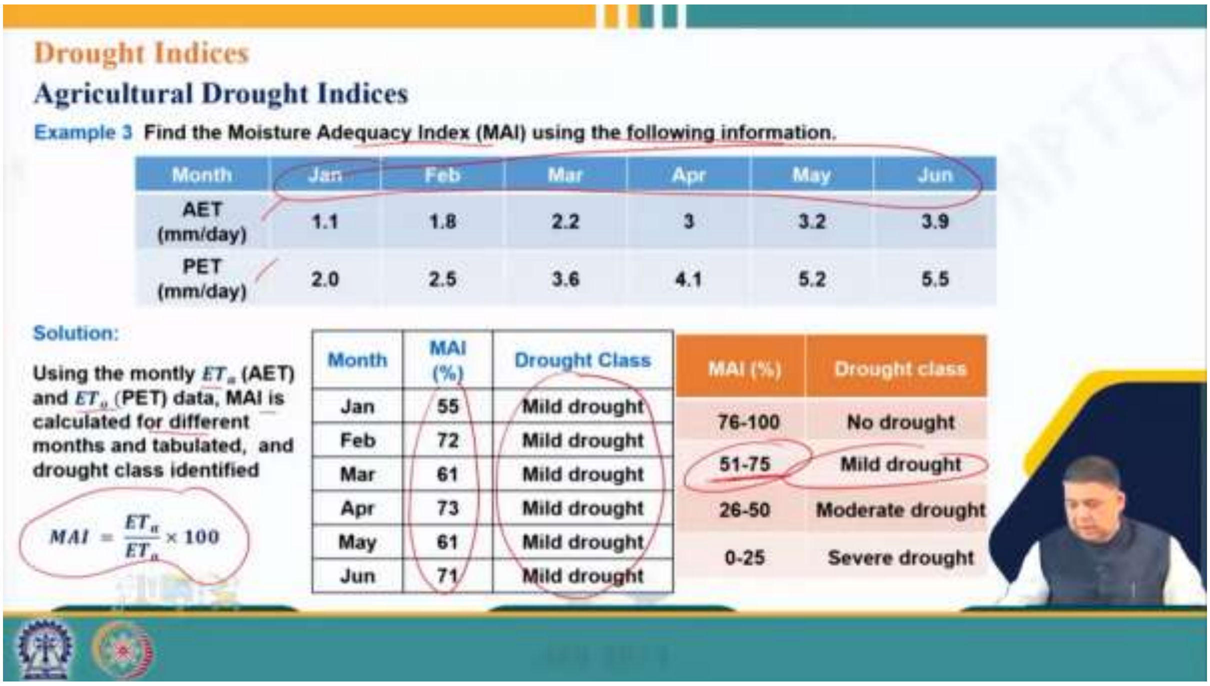


And of course, the calculation, as far as calculation goes, this is a simple calculation:

$$MAI = \frac{ET_A}{ET_0} \times 100\%$$

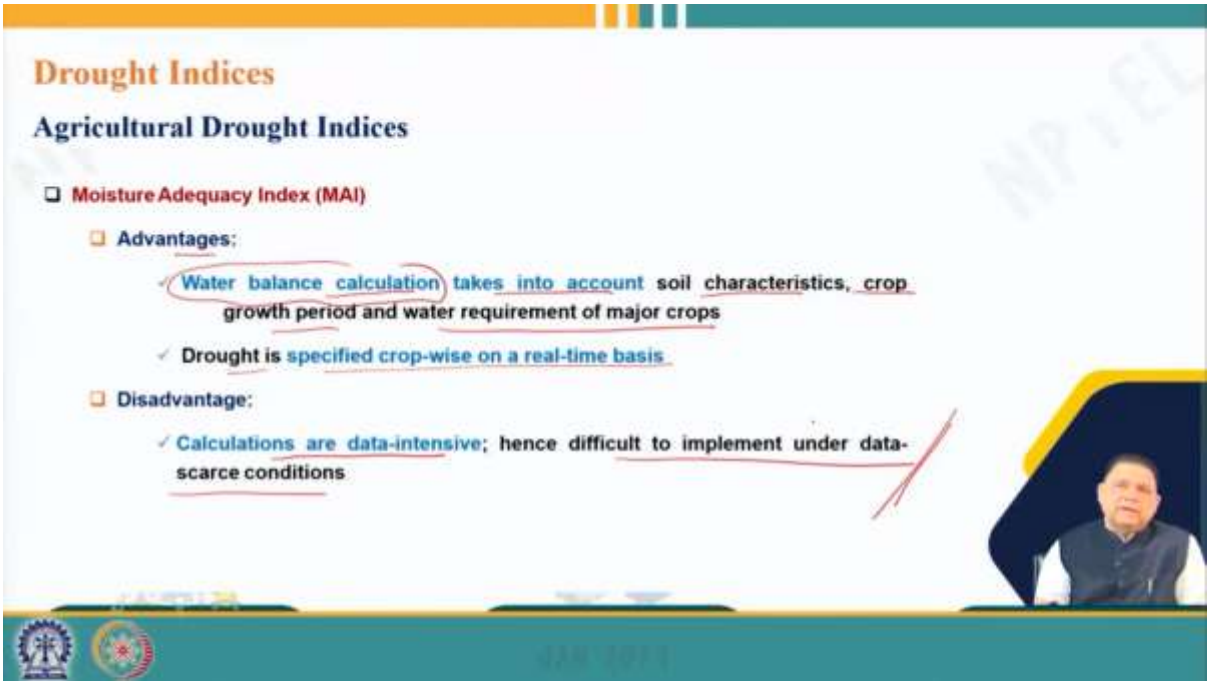
where ET_A is the actual evapotranspiration, ET_A, which we earlier saw that if you have lysimeter data, you can get the ET_A value, and ET_0 is the potential evapotranspiration, ET_0, as you said that we have different hydrometallurgical equations available for calculating ET_0 for a given place. For a large area, a soil water balance approach is used to calculateET_A. So, if you do not have lysimeter data, then you can also use a water balance approach also to estimate any hydrological variable for that matter.

And based on the MAI percent values, the drought classes are also identified: if MAI is between 76 and 100, then there is no drought; 51 to 75 is mild drought; 26 to 50 is moderate drought, and 0 to 25 is severe drought. So, based on MAI calculation, you can find out what kind of drought class you are dealing with in a particular given area.

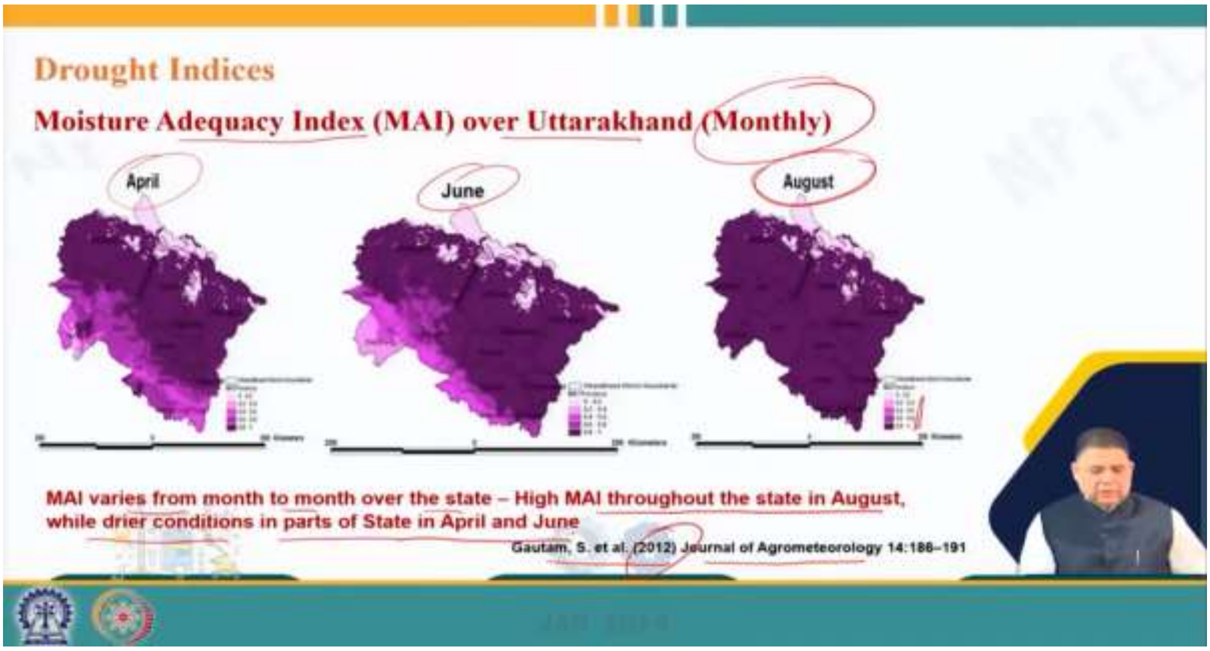


So, let us take an example here, and it is on MAI. So, find the MAI, that is, the moisture adequacy index, using the following information. So, again, for different months, January to June, 6 months AET and PET values are given to us, that is, monthly values are provided to us.

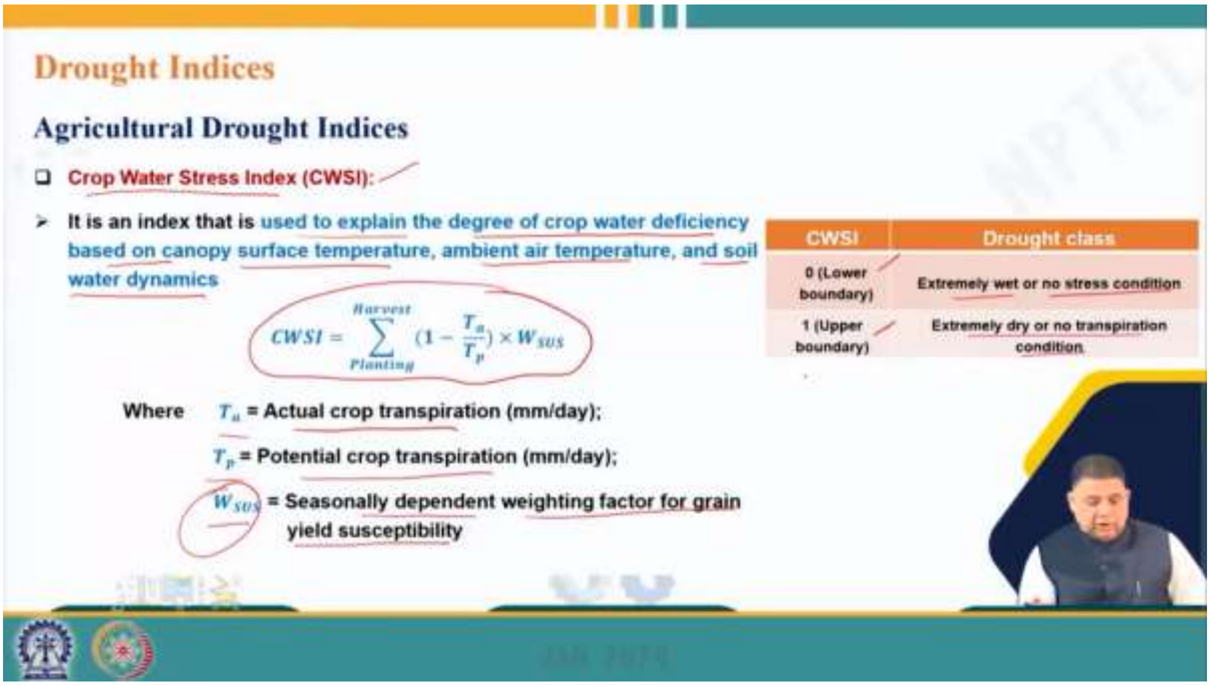
So, using the monthly AET, which is AET, and ET0, which is PET, MAI can be calculated for different months using this relationship. So, we have calculated that and tabulated here. So, because simple calculation, so there is no need to show it is 1 by 1 by 2 into 100, simply for January. So, that is why you get a value of 55. So, very simple calculation, and then of course, once you calculate the values of MAI, then your drought class can be identified, and here all values of MAI calculated fall under this category, that is, 51 to 75, and that is why you can say it is a mild drought situation in the area for over this 6-month period as per the data. So, this information can be used further for other purposes.



Then, coming to advantages, say water balance calculation takes into account soil characteristics, crop growth period, and water requirements of major crops, that means, so while calculating AET, you take care of all these features, and drought is specified crop-wise on a real-time basis. So, of course, very actually your transmission is there. So, actual crop growth is taking place. So, you are taking that into account. However, a disadvantage is the calculations are data-intensive and difficult to implement under data-scarce conditions. So, because it depends on ETA. So, ETA estimation either you have to use lysimeter experiments which is a very resource-intensive or you have to, even if you have to use water balance, then you have to have different kinds of data available. So, it is a bit tedious from that perspective. So, if data is scarce, conditions probably MAI or, in fact, any other method which uses ETA cannot probably be used. So, that is agricultural drought indices.



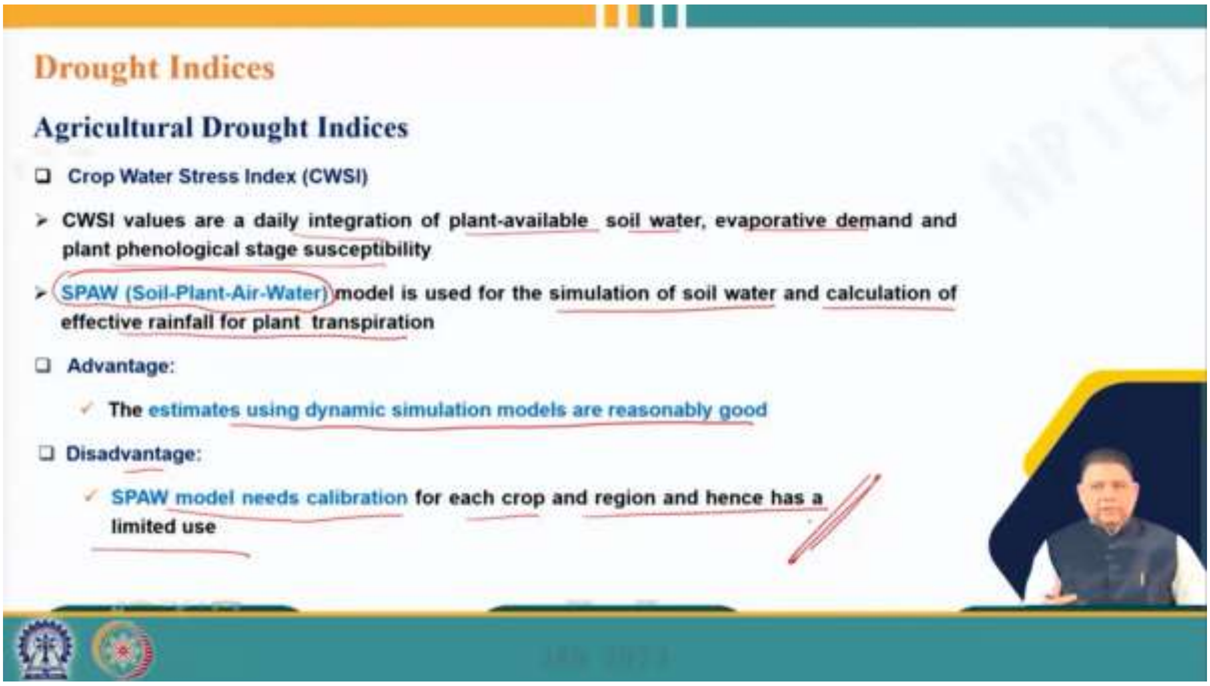
And this is a typical picture showing MAI or moisture adequacy index for Uttarakhand. This is a monthly value. So, you see April, June, and August months MAI here. And if you look at the scale, this shows that the dark brown colour is highest. So, you can see that as you move to August when the monsoon sets in India, you find that MAI is healthy. So, MAI varies from month to month over the state, high MAI throughout the state in August while dry conditions in parts of the state in April and June, which is quite expected because typically, in the month of June or end of June, rainfall sets in northern India. So, that is why the monsoon sets up and that is why August is pretty healthy, but dry conditions are seen before that, and this has been referred from a published paper in the Journal of Agrometeorology in 2012. This data is just to show you how MAI analysis could be done on a larger scale also.



Then we come to CWSI, crop water stress index, CWSI, which is an index used to explain the degree of crop water deficiency based on canopy structure temperature, ambient temperature, air temperature, and soil water dynamics. So, a little bit complicated,

$$CWSI = \sum_{Planting}^{Harvest} (1 - \frac{T_a}{T_p}) \times W_{SUS}$$

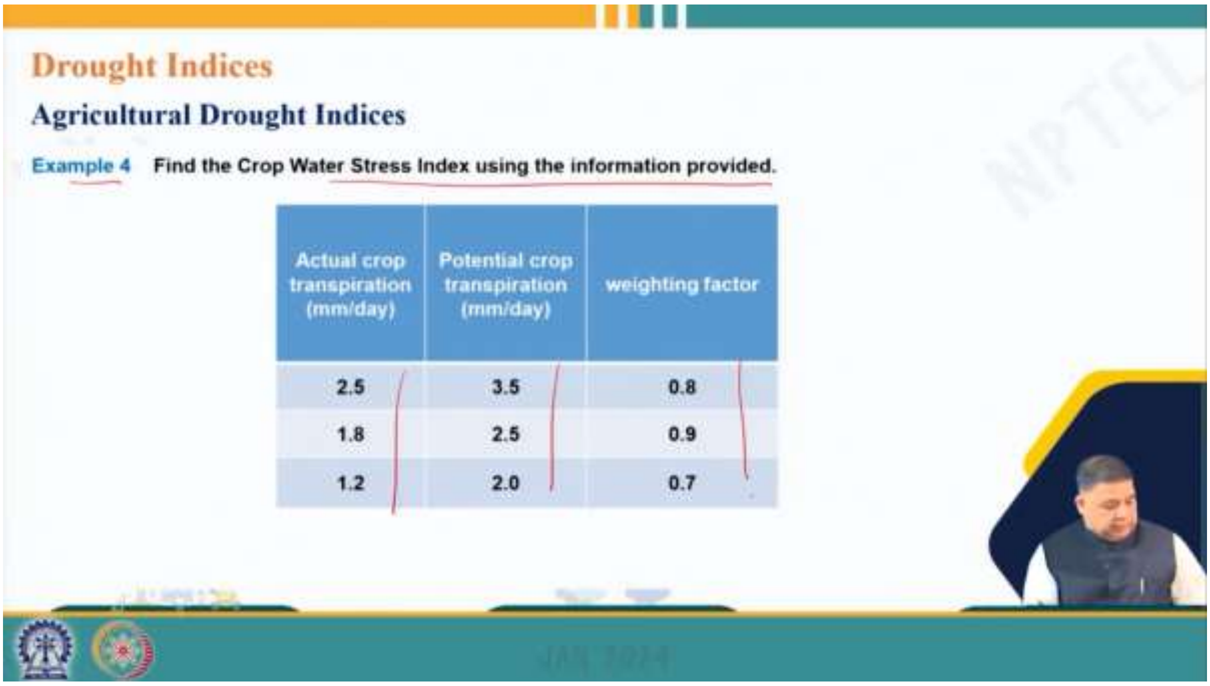
but it uses temperature data basically. T_a is the actual crop transpiration, T_p is the potential crop transpiration, and W_{SUS} is a seasonally dependent weighing factor for grain yield susceptibility. So, this is a typical data you have to obtain, and if CWSI value is 0, then it is an extreme wet or no stress condition, that means, no drought, and if it is closer to 1, then extremely dry or no transpiration condition. So, that means, that shows the extreme drought condition. So, a 0 value is okay, and that is when stress is lower, and 1, which is closer to 1, then shows that extremely extreme drought conditions here.



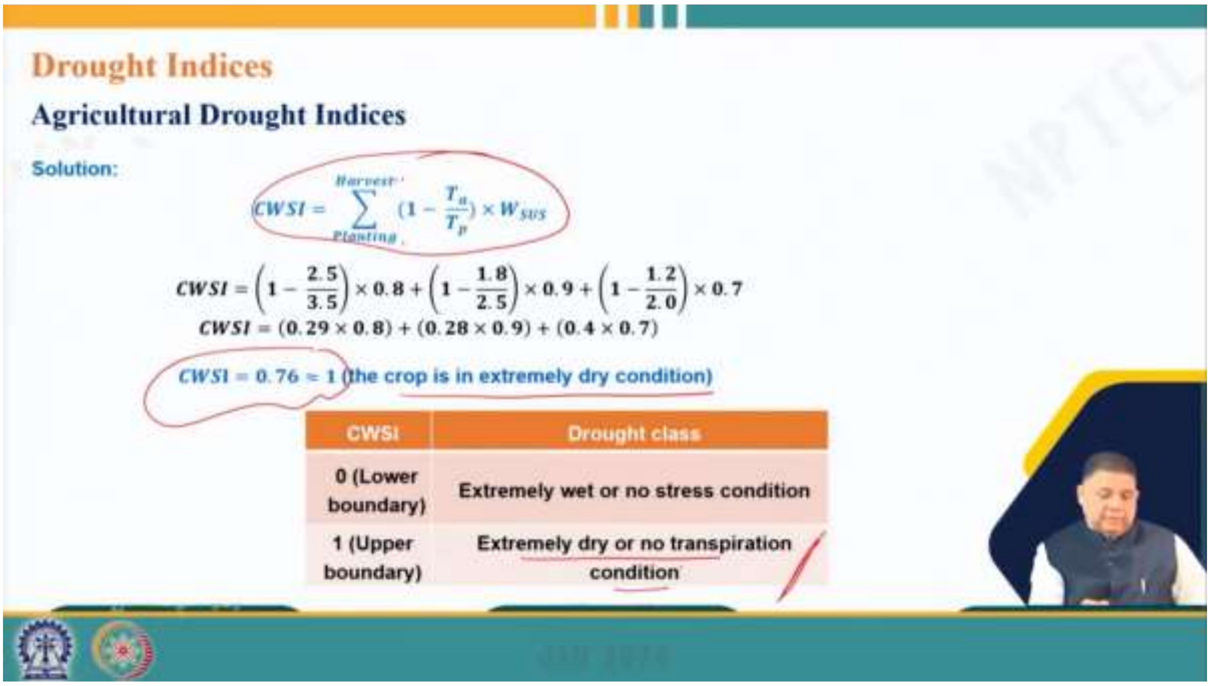
And CWSI values are daily integration of plant available soil water, evaporative demand, and plant phenological stress susceptibility, and typically a model called SPAW, which is a soil plant air water model, is used for simulation of soil water and calculation of effective rainfall for plant transpiration, and basically CWSI can be estimated using SPAW.

The advantages of CWSI are that the estimates using dynamic simulation models are reasonably good, but the disadvantage is that SPAW model needs calibration for each crop and region, hence has limited use. So, unless you calibrate the model for a given region for different crops, you cannot really use it for estimating CWSI.

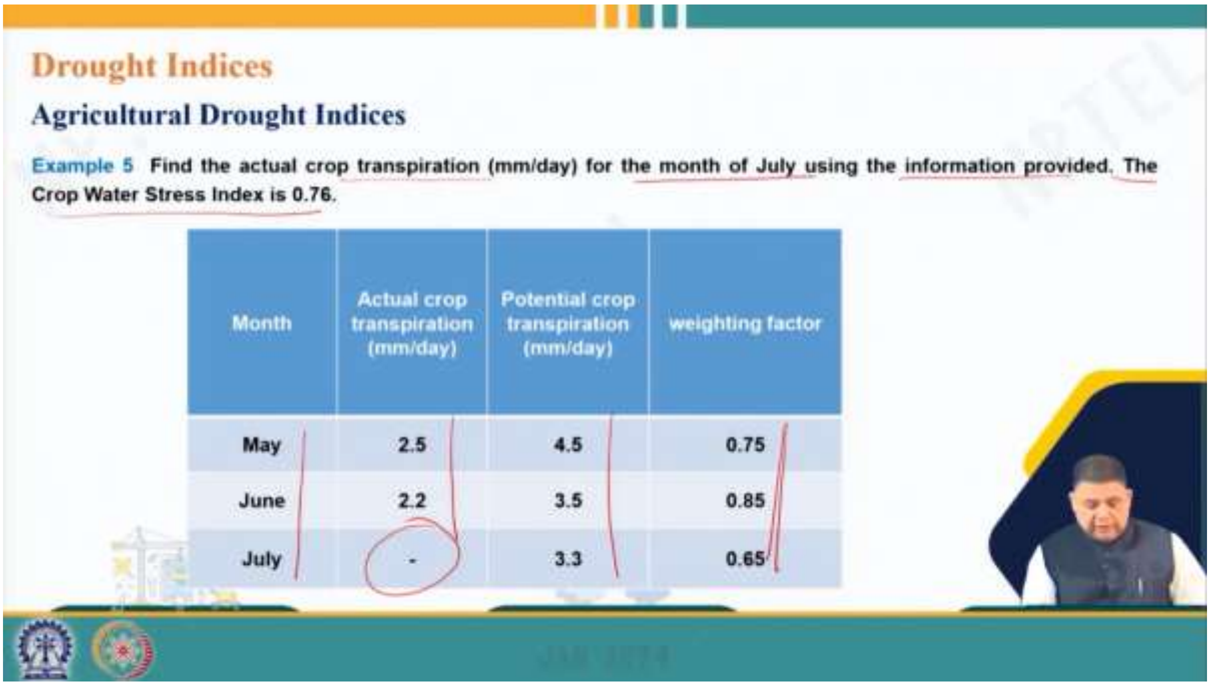
And this is typically, again, as for other indices, I have also tried to show crop water stress index, this one is for Marath water region in India, and as you can see, 0 to 1, these are the values, and you see 2015 and 2020, and of course, CWSI shows that 2015 was a dry year compared to 2020, and this has been taken from again the Journal of Agro-hydrology published in 2024, a very recent paper.



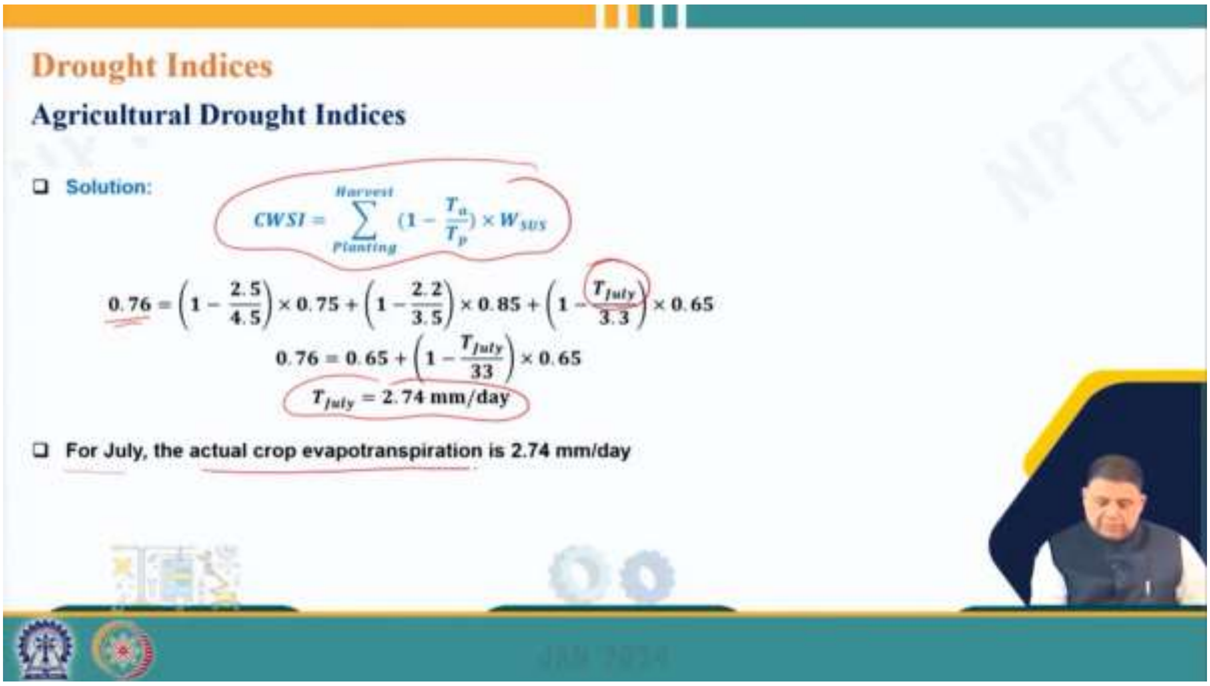
Then we go to example, find the crop water stress index using information provided. So, actual crop transpiration potential crop transpiration and weighing factors are provided to us,



And we know the equation. So, basically, we know the equation. So, for each period separately, we have to calculate because it is planting to harvest. So, the crop growth period is there. So, for each period, knowing the weighing factor, we have to calculate this, and finally, we get CWSI is 0.76, very close to 1. So, the crop is in an extremely dry condition as well. So, if it is close to 1 then extremely dry or no transpiration condition and it is nearer one. So, that is why it is a dry condition basically this data is showing.



Next example, example 5, find the actual crop transpiration for the month of July using the information provided. The crop water stress index is 0.76. So, here we have for different months, 3 months, actual crop transpiration and potential crop transpiration for all 3 months are given, but for July, we do not know the value, and the weighing factors are given here.



So, obviously, we know that this is the formula we have to use for getting the CWSI value which is given. So, of course, we have one known unknown here, T July is unknown here. So, putting the values here we can calculate and we get to T July is 2.74 millimetres per day, that means, for the July month for the given area, the actual crop transpiration is 2.74 millimetres per day. So, with this, we come to the end of this lecture. So, we saw some typical and popular indices which are used to signify agricultural drought over a year area and we also saw how to estimate them. Please feel free to give your feedback and also raise your questions or doubts; we shall be happy to answer on the forum. Thank you very much.