**Course Name: Watershed Hydrology**

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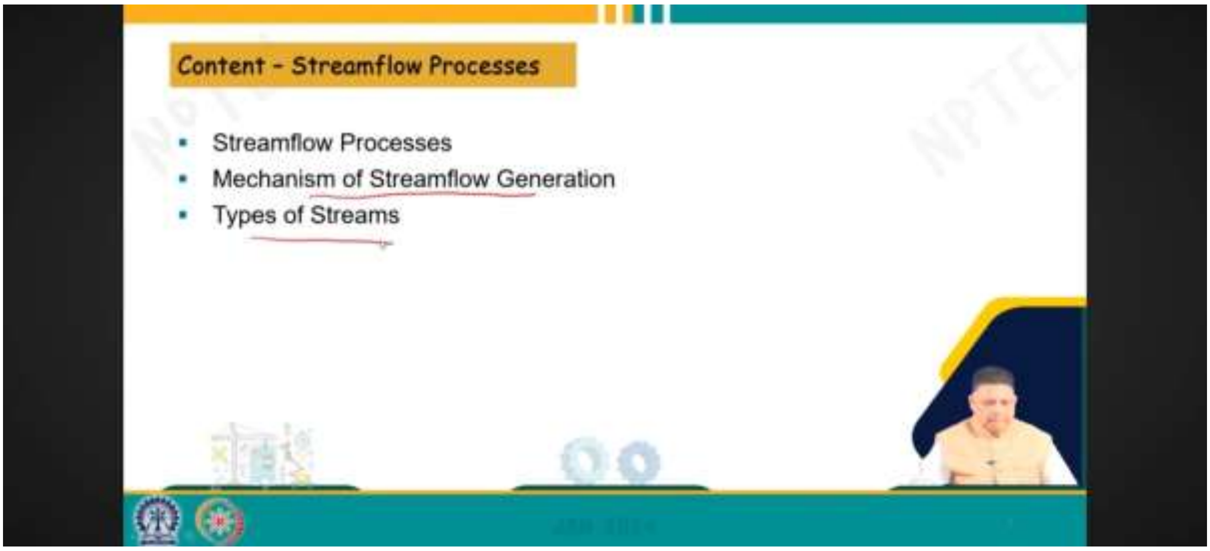
**Week: 03**

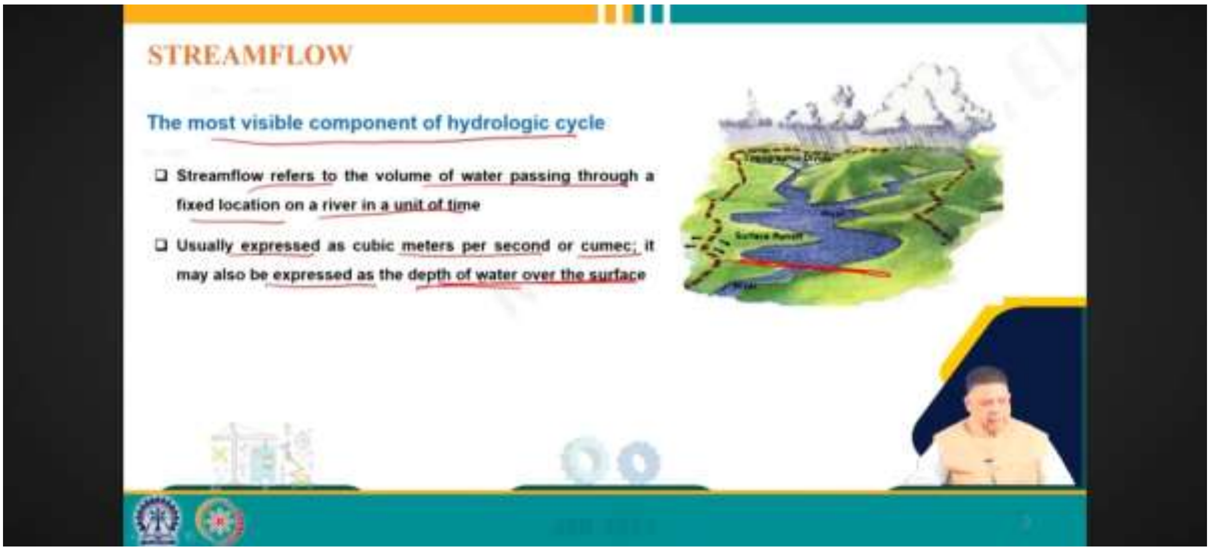
**Lecture 11: Streamflow Processes**

Hello friends, welcome back to the online certification course on watershed hydrology. I am Rajendra Singh, a professor in the Department of Agriculture and Food Engineering at the Indian Institute of Technology Kharagpur. Today, we are commencing Module 3 with Lecture 1 on stream flow processes.

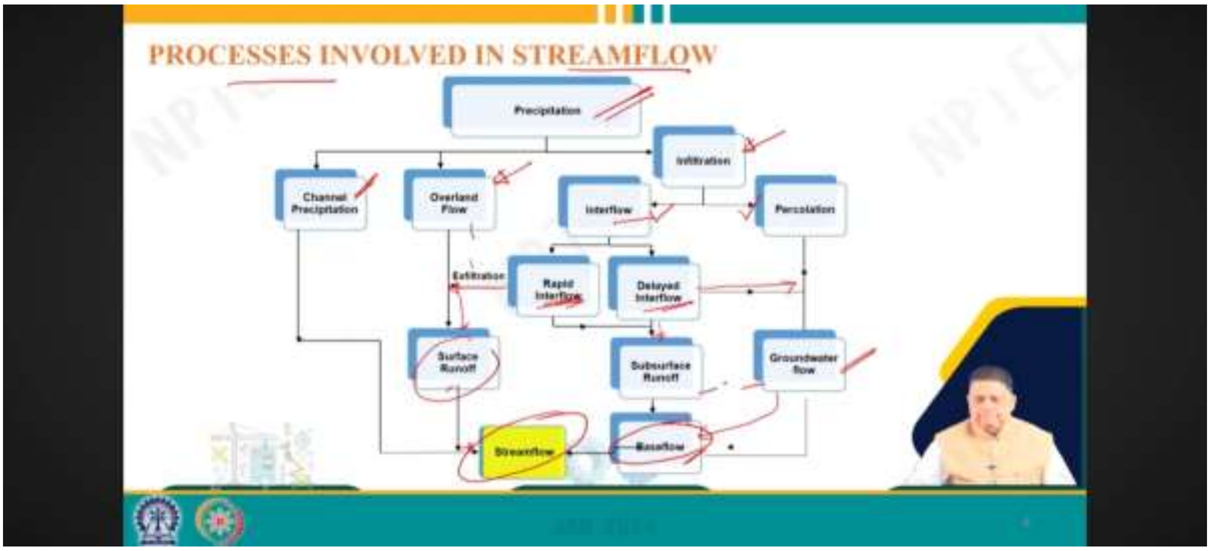

In this lecture, we will introduce stream flow processes, discuss the mechanism of stream flow generation, and explore the types of streams.



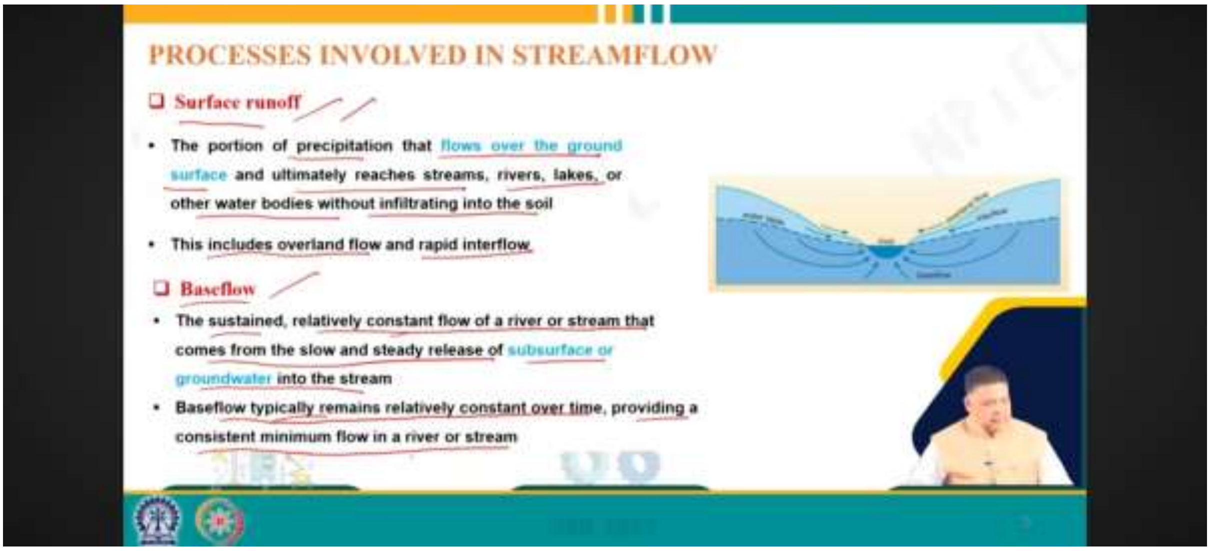
Stream flow is the most visible component of the hydrological cycle, meaning it is a process that you can observe with your naked eyes. Stream flow refers to the volume of water passing through a fixed location on a river within a unit of time. So, it could be a river, stream, or watercourse. Therefore, at any given point, if you measure the volume of water passing through that particular location or cross-section over a period of time, that constitutes stream flow. Stream flow is typically expressed in cubic meters per second or cumec , which is short for cubic meters per second. It may also be expressed as the depth of water over the surface. This means that if you know the basin area or catchment area, you can divide the volume by the catchment area to determine the stream flow depth. So, whatever we obtain in terms of depth units is also referred to as stream flow.



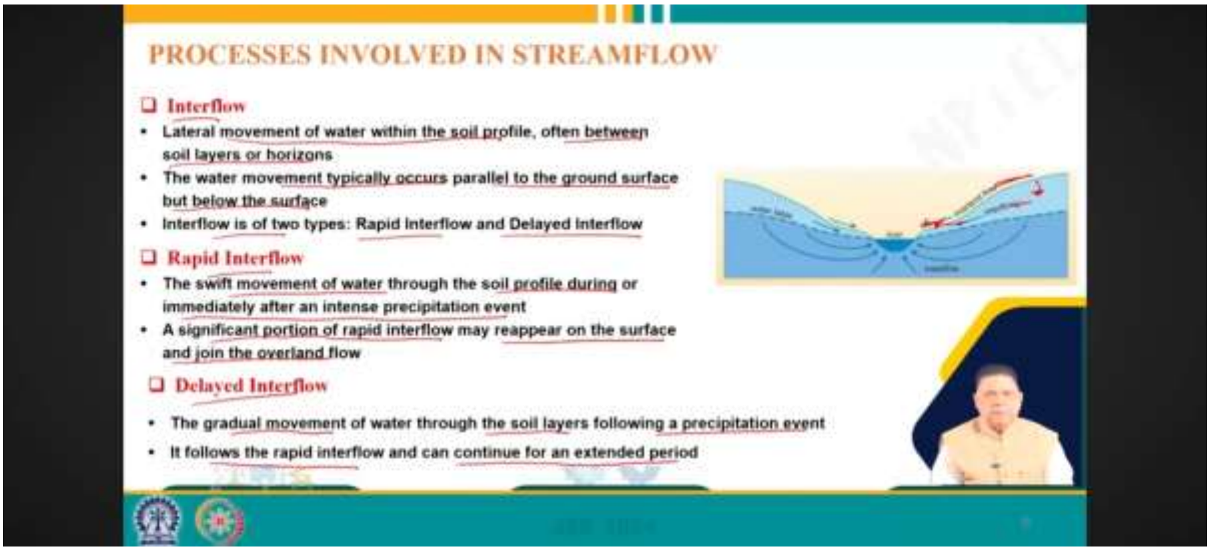

If we examine the processes involved in stream flow, it all starts with precipitation. When precipitation occurs, a part of it falls directly on the channel, stream, or river. This is known as channel precipitation. Additionally, when precipitation water comes into contact with the soil surface, infiltration begins. After the infiltration process is satisfied, overland flow occurs. If some of the infiltration becomes interflow, and the remainder may interflow, meaning it flows close to the surface of the soil parallel to the surface, and then the remainder, due to gravity, percolates down and joins the groundwater. This interflow has two components: rapid interflow or delayed interflow. Rapid interflow may reappear on the soil surface in the form of exfiltration, which is the reverse of infiltration. Then, the combination of overland flow and exfiltration forms surface runoff, a significant component of stream flow, along with channel precipitation. On the other hand, we have delayed interflow. So, a part of that joins percolation and enters the groundwater, but a component of both rapid and delayed interflow forms surface runoff, which is another form of runoff. Therefore, we have surface runoff, subsurface runoff, and groundwater flow. Subsurface runoff and groundwater combine to form base flow. Overland flow or surface runoff, plus base flow, combined together form the stream flow. Thus, stream flow has two major components: surface flow and base flow, which originate from precipitation in the hydrological cycle.



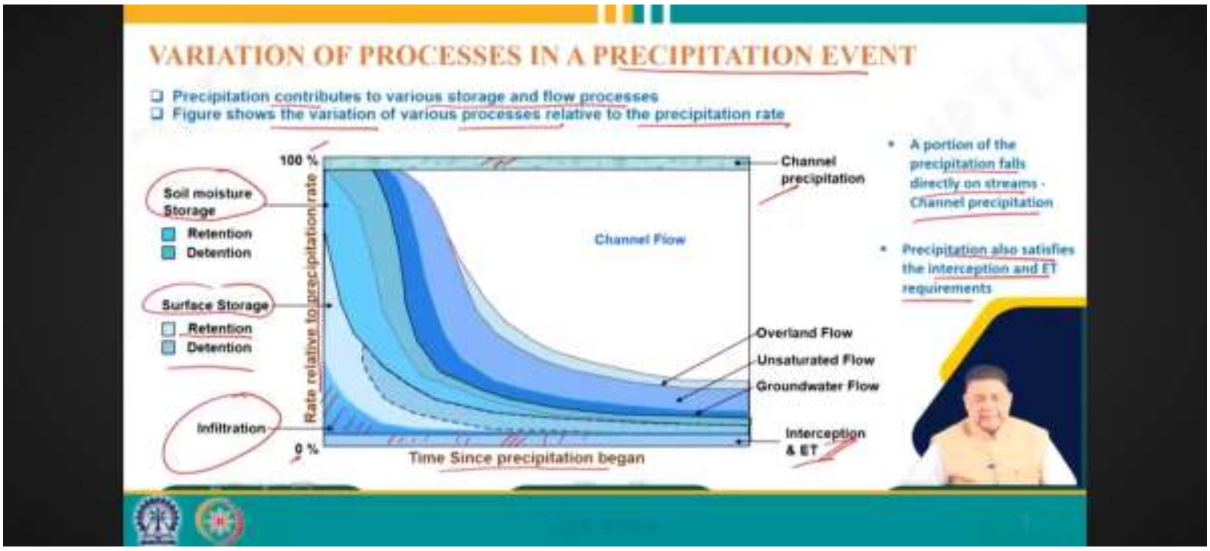

Now, let's discuss the processes one by one. Surface runoff is the portion of precipitation that flows over the ground surface and ultimately reaches streams, rivers, lakes, or other water bodies without infiltrating into the soil. This is quite obvious because when precipitation reaches the earth's surface, the first thing it does is satisfy the infiltration capacity of the soil. As we discussed in the previous lecture, the soil's infiltration capacity must be satisfied first before overland flow occurs. So, surface runoff includes overland flow and rapid interflow, as we just discussed. Then, there is base flow, which is the sustained, relatively constant flow of water in a stream that comes from the slow and steady release of subsurface or groundwater into the stream. This constitutes base flow. As we saw in the previous slide, there are two major components: surface runoff and base flow, which together form stream flow. As we've seen, by definition, surface runoff is a rapid flow overland that follows a precipitation event. On the other hand, we have a sustained, relatively constant flow contribution to rivers or streams, which comes from the slow and steady release of subsurface or groundwater flow. Base flow typically remains relatively constant over time, providing a consistent minimum flow in the river or stream. So, base flow is primarily the reason why perennial rivers have flow throughout the year, because surface runoff or overland flow only occurs when precipitation happens. However, during the dry season or non-monsoon season, it's the base flow that sustains the flow in a perennial river in the form of base flow.



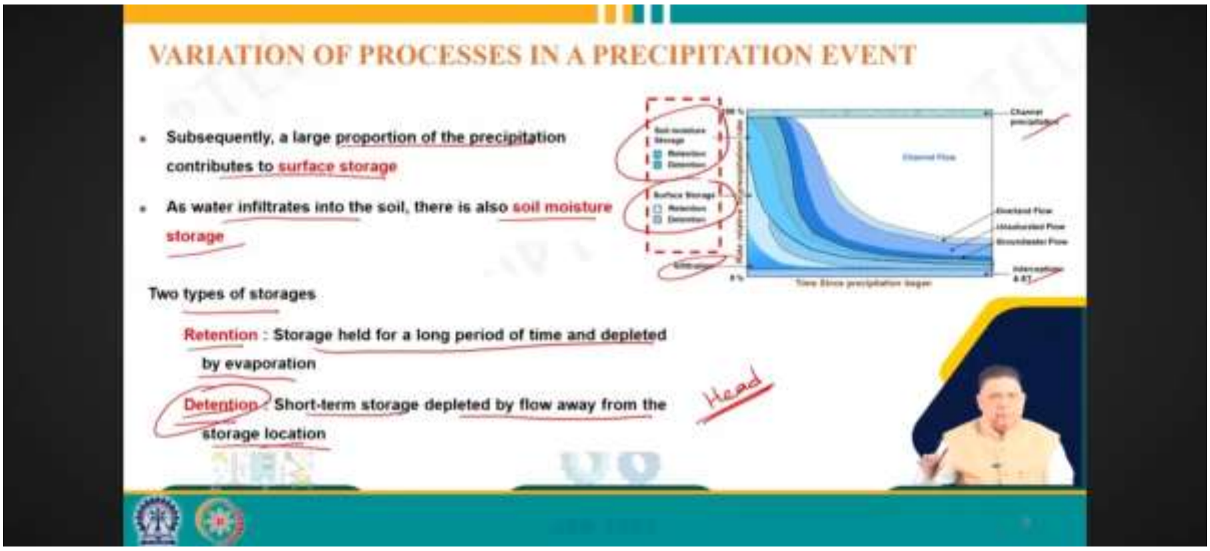

Then, of course, we also discussed interflow, which is the lateral movement of water within the soil profile, often between soil layers or regions. The movement of water typically occurs parallel to the ground surface but below the surface. So, here you can see that overland flow is occurring on the surface, and just below the overland or ground surface, we have a flow taking place, which is interflow, and it could be of two types: rapid interflow and delayed interflow. Rapid interflow is a swift movement of water through the soil profile during or immediately after an intense precipitation event. Obviously, the entire interflow process starts only after a precipitation event when infiltration has taken place, and infiltrated water starts moving swiftly; then, it is called rapid interflow. A significant portion of this rapid interflow may reappear on the surface and join the overland flow. So, if the soil profile permits, this water may come to the surface and join the overland flow, and that is the rapid interflow. Then there is delayed interflow, which is a gradual movement of water through the soil layers following a precipitation event. It follows the rapid interflow and continues for an extended period. So, rapid interflow is pretty quick; the water surface, the interflow starts moving parallel to the surface, and then, if the soil profile permits, it reappears on the ground surface, whereas delayed interflow moves slowly and joins the groundwater, and it continues for a longer period, which involves a very slow release of water.



Now, let's consider the variation of processes in a precipitation event. Of course, we know that precipitation contributes to various storages and flow processes, and this figure shows the variation of various processes relative to precipitation rate. On this scale, you have 0 to 100, representing the rate related to precipitation rate, and the x-axis represents the time since the precipitation began. If you look at the figure on the top and at the bottom, there are two straight-line portions. One of them represents channel precipitation, and the other represents interception and evapotranspiration. So, a portion of precipitation falls directly on streams, which is referred to as channel precipitation. Whatever precipitation occurs directly on the surface of the stream, river, or watercourse is channel precipitation, where precipitation also satisfies the interception and evapotranspiration requirements. That's why a percentage of precipitation is considered in the form of interception and evapotranspiration. Of course, beyond that, the first requirement, the first abstraction which precipitation satisfies, is infiltration. So, it is continuous, but a large portion of water goes into surface storage first and then soil moisture storage. So, here you can observe surface storage and soil moisture storage, and in both cases, the storage has two components: retention and detention, which we will define in the next slides.

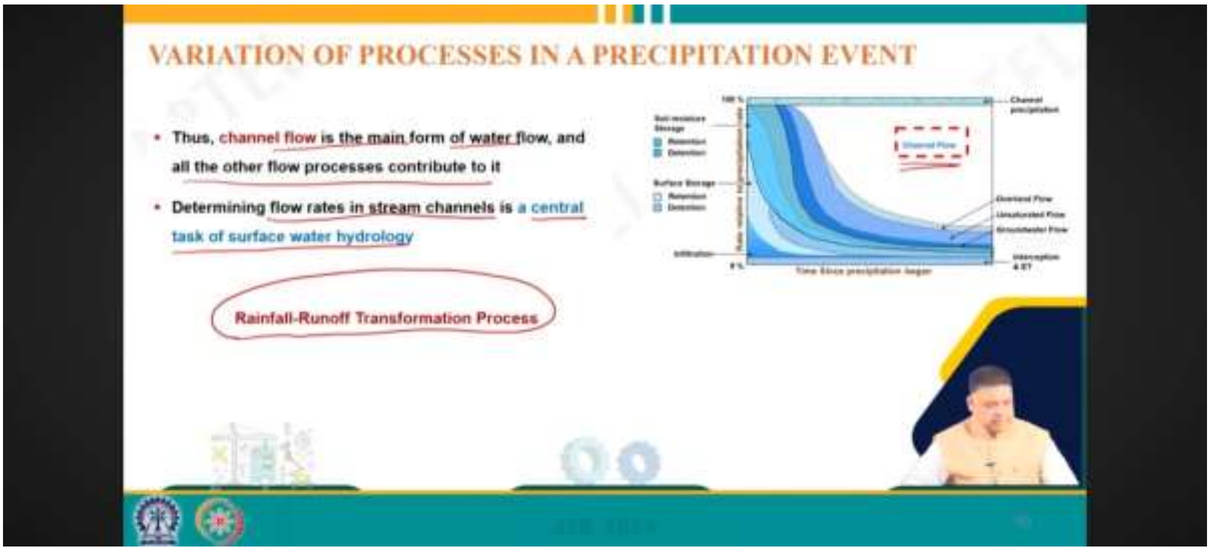



A large portion of the precipitation contributes to surface storage. Just now, we saw that after channel precipitation, after interception and evapotranspiration, and after infiltration, the next thing that occurs is surface storage. If this water infiltrates the soil, there is also soil moisture storage. So, there is surface storage here and soil moisture storage here. You can see the components here as percentages of the total rainfall. Now, any storage could be of two types: retention and detention. These terms are quite common, so it's important to know the difference between them. Retention is the storage held for a long period of time and depleted by evaporation. It mostly occurs on the surface, such as overland flow. As we discussed, when overland flow starts, if there are potholes on the ground, a part of the overland flow will be trapped there and retained, eventually getting evaporated or infiltrated. It does not become a part of the overland flows. The next type is detention, which is a short-term storage depleted by flow away from the storage location. Essentially, detention is the storage required to build the head for flow to start taking place. So, basically, it is a short-term storage depleted by flow away from the storage location. When the head is built and if inflow stops, then obviously, it will slowly deplete in the form of overland flow.

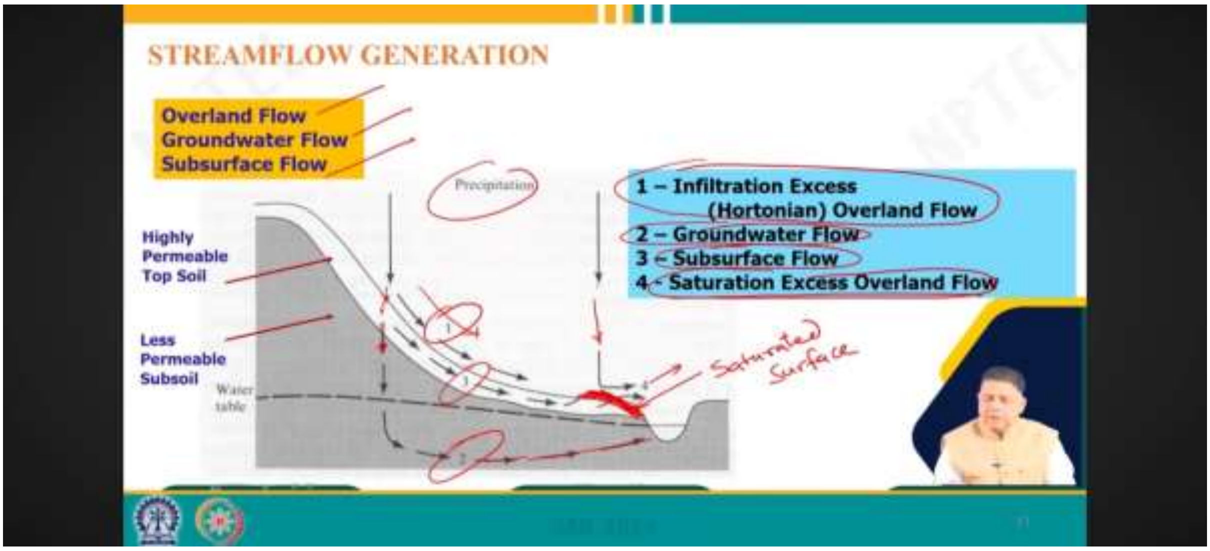



As detention storages begin filling, flow away from them occurs in the following form. When sufficient head has been generated in the detention, there will be overland flow across the land surface, as you can see here. There are three different flow processes: overland flow, unsaturated flow, and groundwater flow. Overland flow occurs across the land surface, unsaturated flow happens through the unsaturated soil near the land surface, very close to the ground surface, and groundwater flow occurs through saturated aquifers deeper down. All these three contribute to channel flow. So, ultimately, all the flow processes contribute to channel flow.


Thus, channel flow is the main form of water flow, and all other processes contribute to it, just as we saw. Determining flow rates in stream channels is a central task of surface water hydrology. Basically, what this means is that how precipitation occurring on a basin or watershed gets converted into channel flow is what we study in hydrology; that is the central focus of study. In other terms, we can also say that the central task of surface water hydrology is studying the rainfall-runoff transformation process. This means understanding how rainfall gets converted or transformed into runoff, which, of course, we measure in the form of channel flow, and that is the central task of hydrology.

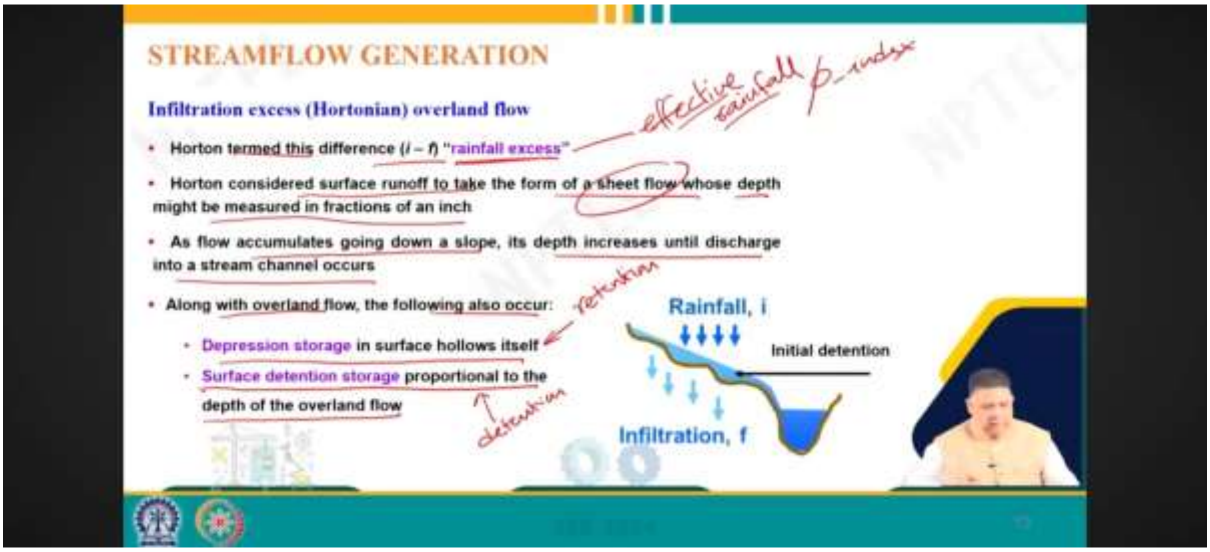



Now, stream flow generation, if we look back, involves three forms: overland flow, groundwater flow, and subsurface flow. Once precipitation starts, water reaches the ground surface. Of course, the first thing that occurs is infiltration. Then, water will start moving on the surface, which is referred to as overland flow. We already mentioned this, but it is typically called infiltration excess overland flow. This is a part of precipitation that exceeds the infiltration requirement or infiltration capacity of the soil, and it flows in the form of overland flow. This is also known as Hortonian overland flow, named after Horton, who coined the term. Then, of course, infiltration occurs. As we have seen, a part of it percolates down into the ground, joining the water table. This water table flows and contributes to stream flow, as we have seen in the form of base flow. This second type of flow is groundwater flow. Then, of course, we have also seen that once infiltration takes place, in highly permeable topsoil, flow starts occurring parallel to the ground surface, referred to as subsurface flow. We also saw that similar to interflow, the fourth type of flow is saturation excess overland flow. This occurs near the foothills, where groundwater reaches the surface, or a part of the subsurface flow or interflow reappears on the surface, saturating the ground surface. When the ground surface is saturated, any precipitation that falls directly onto it is converted into overland flow, known as saturation excess overland flow. So, to recap, there are two types of overland flow: infiltration excess or Hortonian overland flow, which occurs when precipitation satisfies infiltration and water starts flowing on the surface, and saturation excess overland flow, which occurs when the soil becomes saturated from the bottom, and any precipitation falling directly onto this saturated part is converted into overland flow.

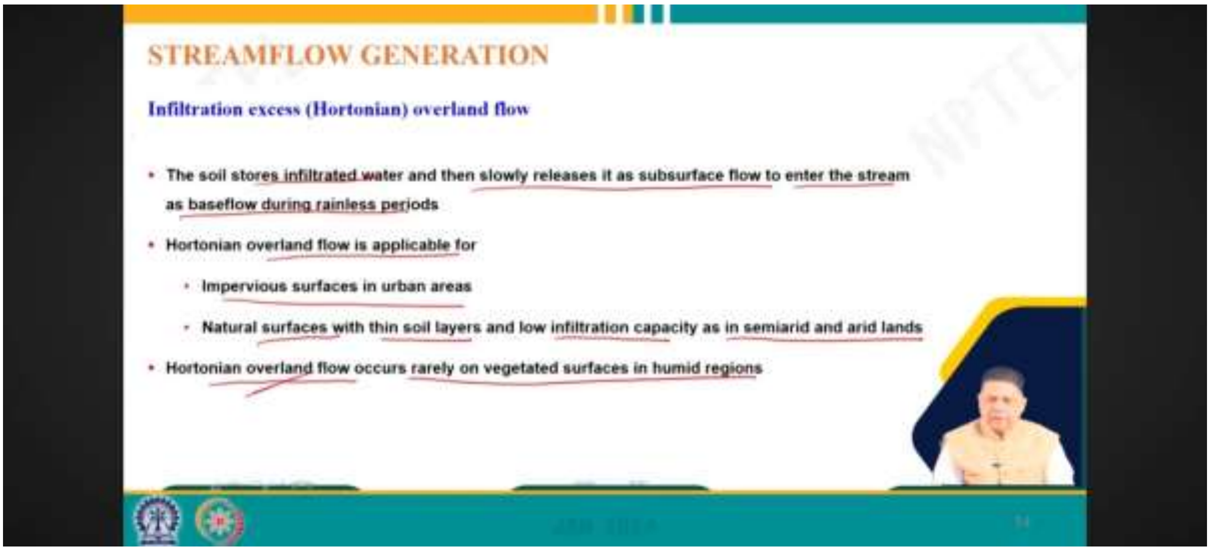



Now, regarding infiltration excess overland flow, it was Horton in 1933 who described this process, which is why it is also referred to as Hortonian overland flow. Horton described this overland flow as neglecting interception by vegetation; surface runoff is that part of rainfall which is not absorbed by soil through infiltration. So, as we said, the first requirement is to satisfy the infiltration capacity of the soil, and once that is done, whatever flow occurs is overland flow or surface runoff. If the soil has an infiltration capacity, F, expressed in inches depth absorbed per hour, then when the rain intensity, i, is less than F, all the rain is absorbed, and there is no surface runoff. That means, if i is less than F, where i is the rainfall intensity and F is the infiltration capacity, then everything is absorbed as infiltration, and there is no overland flow. As a first approximation, we can say that if I is greater than F, surface runoff will occur at the rate i - F, with I being the rainfall intensity after satisfying the initial requirement. So, it is important to neglect interception by vegetation. To a certain extent, we can also say that it is the difference between rainfall intensity and initial abstractions.

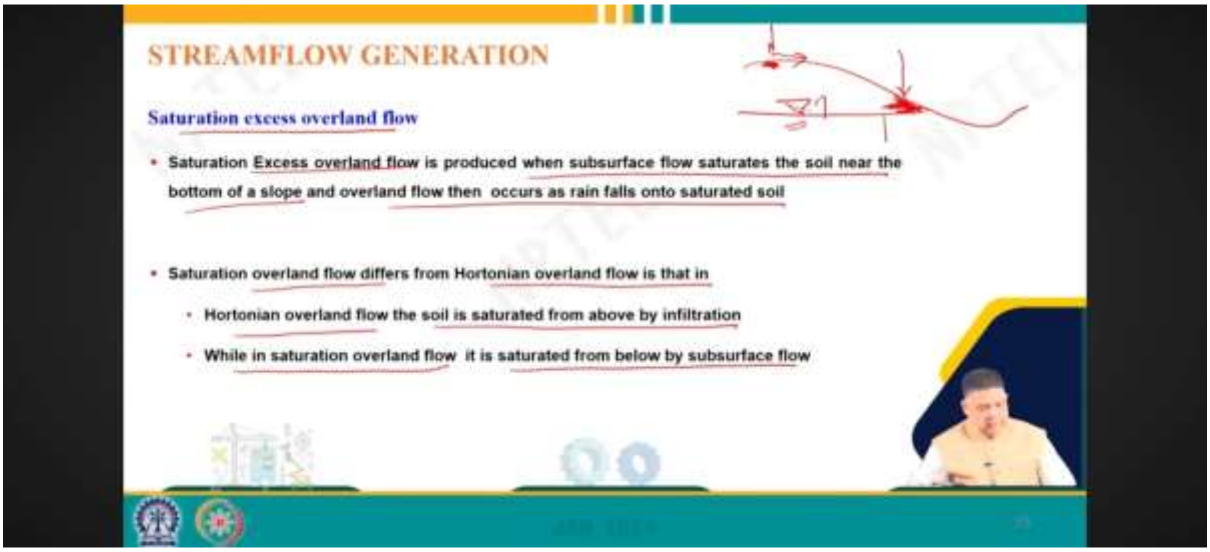

This difference, i - F, is termed rainfall excess or, as we discussed earlier, effective rainfall. So, either effective rainfall or rainfall excess, we remember discussing this concept previously. It's similar to that: from precipitation, if you subtract all the losses, including infiltration, then the remainder of rainfall intensity or rainfall is termed effective rainfall or rainfall excess. Horton considered surface runoff to take the form of sheet flow, whose depth might be measured in fractions of inches. So, basically, this overland flow or surface runoff occurs in the form of sheet flow, which is a very thin layer of water that starts flowing on the ground surface. As flow accumulates going down a slope, its depth increases until discharge into a stream channel occurs. So, obviously, if there is a sufficient slope, then as the overland flow starts, more and more flow will join. The thickness of the sheet, which initially started as a thin layer, will grow as the flow moves down, and finally, the discharge into the final stream will occur. Along with overland flow, the following also occur: depression storage in the surface hollows that we have discussed many times, surface detention, and depression storage and surface distillation proportional to the depth of overland flow. So, that means, as we just discussed, this is nothing but retention because water is retained in hollows, and this is detention because we said that a sufficient depth will be required for building the head for flow to take place from a particular location.



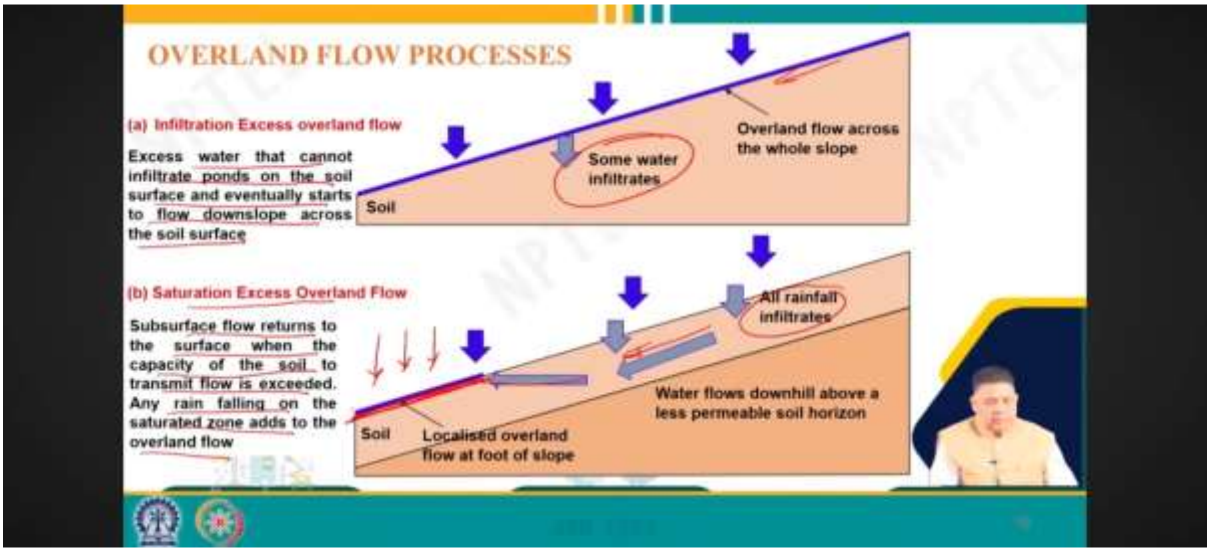

The soil stores infiltrated water and then slowly releases it as subsurface flow to enter the stream as base flow during the dry period. Hortonian overland flow is applicable for impervious surfaces in urban areas. That means, if it is a paved area, then obviously, whatever rainfall occurs on this paved area translates into overland flow automatically or surface runoff. Natural surfaces with thin soil layers and low infiltration capacity, especially in semi-arid regions, also experience this phenomenon. So, if the infiltration capacity is low, then excess rainfall will start moving in the form of overland flow. Hortonian overland flow occurs rarely on vegetated surfaces in humid regions for a simple reason: the infiltration capacity is high, and because of littering on the soil surface, a lot of water gets retained on the surface. That's why overland flow seldom occurs under such circumstances.



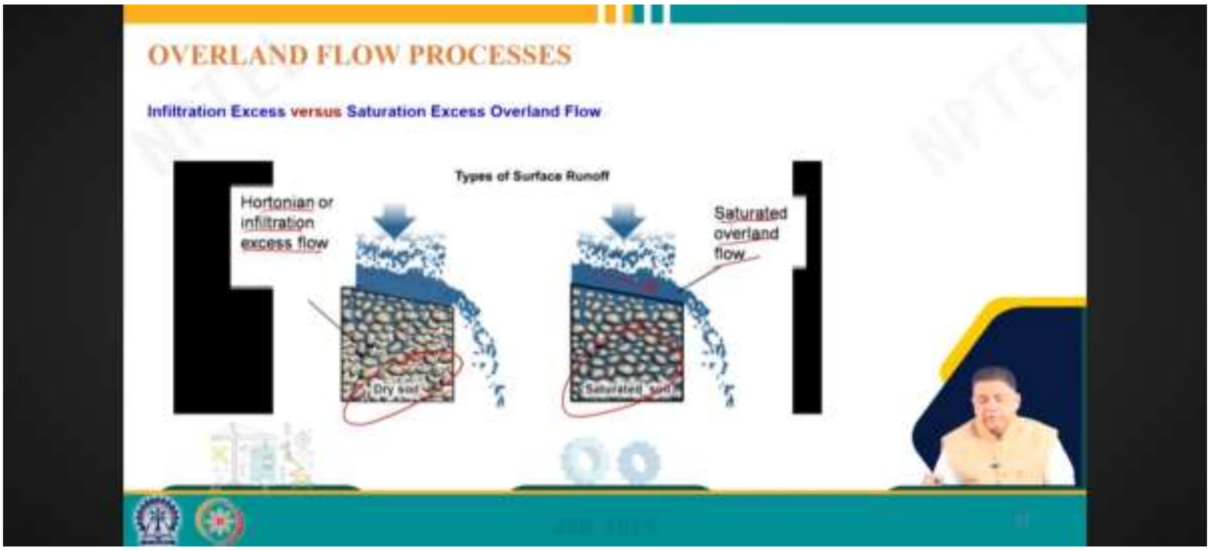

Then, we have saturation excess overland flow. Saturation excess overland flow is produced when subsurface flow saturates the soil near the bottom of a slope, and overland flow occurs as rain falls on the saturated surface. As we saw in the picture, if we have this kind of situation where the water table rises and saturates this portion, for instance, then any precipitation occurring on this surface will translate into saturation excess overland flow. Saturation excess overland flow differs from Hortonian overland flow in that in Hortonian overland flow, the soil is saturated from above by infiltration. That means, precipitation occurs, then infiltration occurs, and then it saturates the soil, and then flow starts taking place. While in saturation excess overland flow, it is saturated from below by subsurface flows. So, subsurface flows, due to groundwater table rise, saturate the surface from below, and then any precipitation occurring on the surface becomes overland flow.



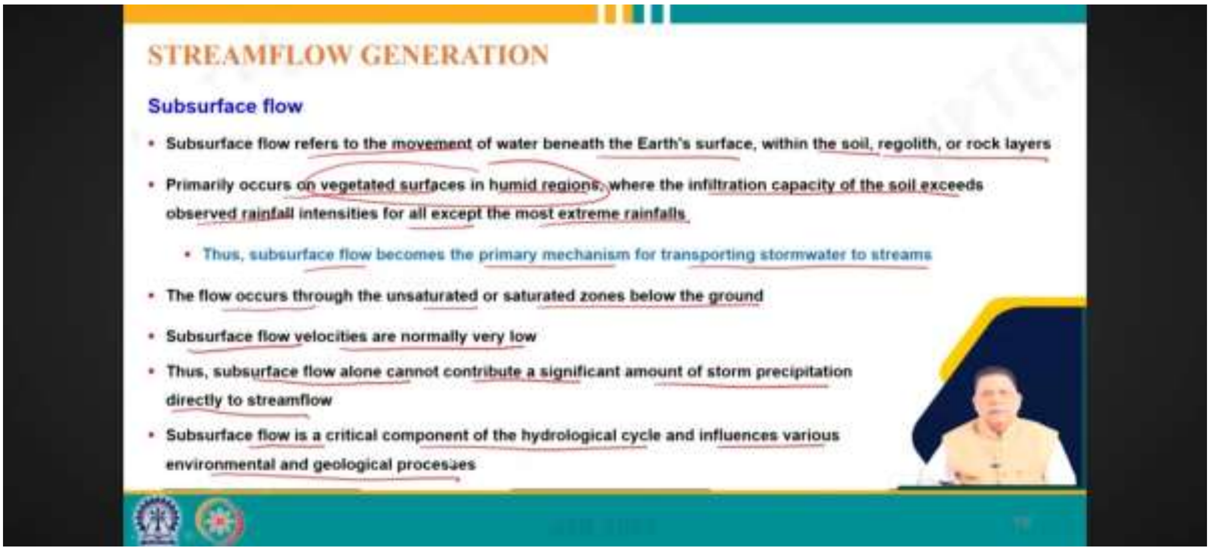

So, this is a pictorial view of the two types: first, infiltration excess overland flow. Excess water that cannot infiltrate ponds on the soil surface and eventually starts to flow down slope across the soil surface. Here, precipitation is occurring, and of course, some water infiltrates, and then as a thin layer, it starts moving on the soil surface. In the case of saturation excess overland flow shown here, subsurface flow returns to the surface when the capacity of the soil to transmit flow is exceeded. Any rain falling on the saturated zone adds to the overland flow. Here also, rainfall infiltration is taking place, but because of the soil characteristics, there is a flow parallel to the ground surface, and then this flow reappears, saturating this part of the land surface. So, if any precipitation occurs on this surface, it translates into the form of saturation excess overland flow.



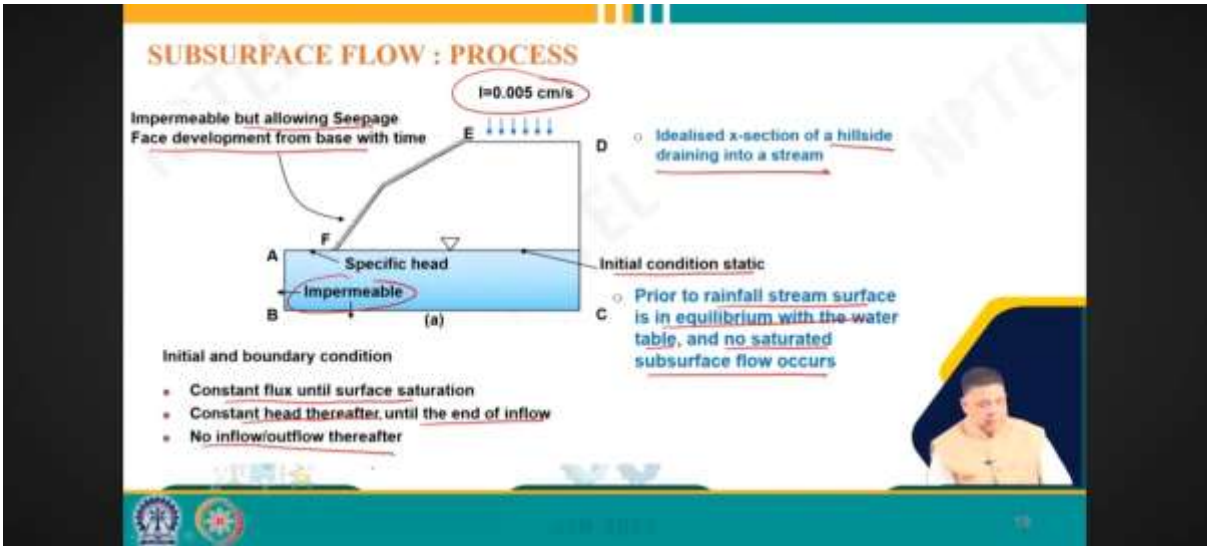

We can also understand this in a simpler way: if you look at these two soil columns, one is dry and the other is saturated. When precipitation occurs on a dry soil column, it first saturates the soil, and then overland flow starts, which is Hortonian or infiltration excess flow. On the other hand, if the soil column is already saturated, whatever precipitation occurs starts flowing in the form of overland flow. So, it is called saturation excess or saturated overland flow. So, these are the two different processes.



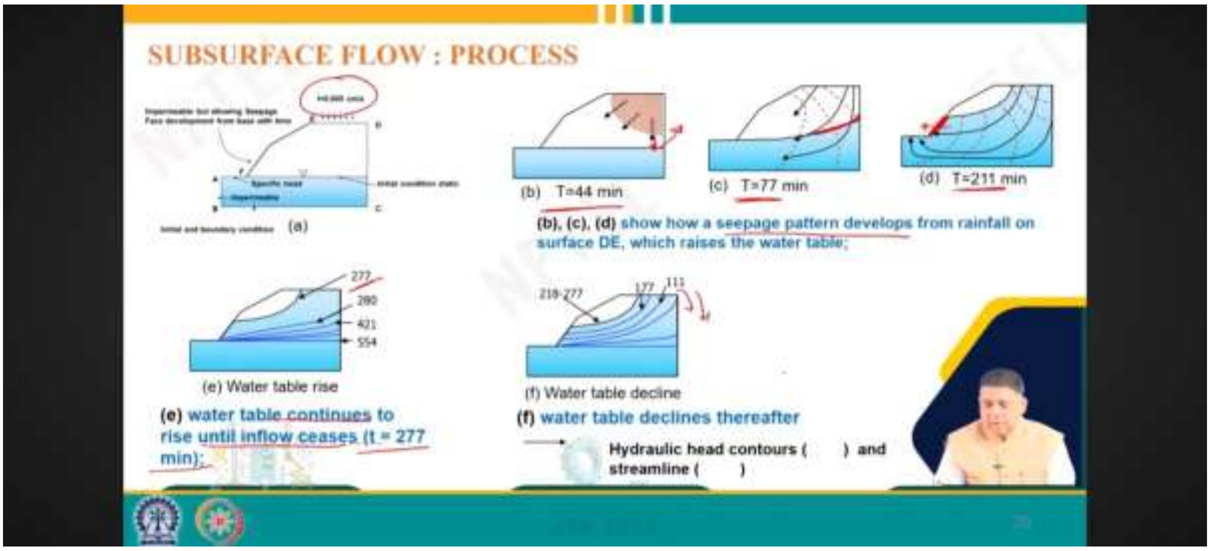

Now, we come to subsurface flow, and subsurface flow refers to the movement of water beneath the earth's surface within the soil or rock layers below the soil surface. This primarily occurs on vegetated surfaces in humid regions where the infiltration capacity of the soil exceeds the observed rainfall intensity for all except the most extreme rainfalls. That means, when the infiltration capacity of the soil is higher than the rainfall intensity, then of course, the entire water will be absorbed, and then the flow will start taking place. Subsurface flow becomes the primary mechanism for transporting stormwater to streams in such areas, like vegetated surfaces in humid regions. The flow occurs through the unsaturated or saturated zone below the ground surface. So, we have seen that a part of infiltrated water either flows as subsurface flow or percolates down and joins the groundwater, and then groundwater flow takes place. But typically, the surface and subsurface flow velocities are very slow, and thus, subsurface flow alone cannot contribute a significant amount of storm precipitation directly to stream flow. So, during the storm, it is the infiltration excess overland flow that carries most of the water to the streams. However, subsurface flow is a critical component of the hydrological cycle and influences various environmental and geological processes. As we have seen, base flow is very important and contributes to stream flow in a significant way.



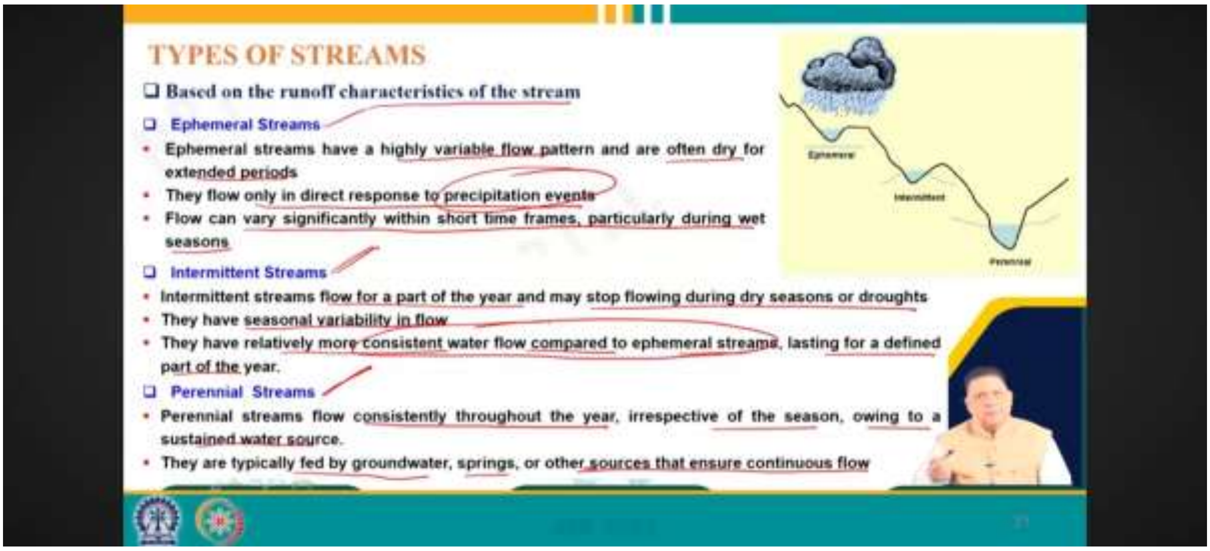

Now, this is just an idealized cross-section of a hillside draining into a stream. On this surface, there is a flux of 0.005 centimetre per second, and this side is impermeable, allowing seepage force developed from the base with time. The initial condition is static, meaning that prior to rainfall, the stream surface is reclaimed with the water table, and no saturated subsurface flow occurs. So, there is no saturation. This is the water table, and these are impermeable sites. Initial and boundary conditions are the constant flux until surface saturation, constant head thereafter until the end of the flow, and no inflow or outflow thereafter.



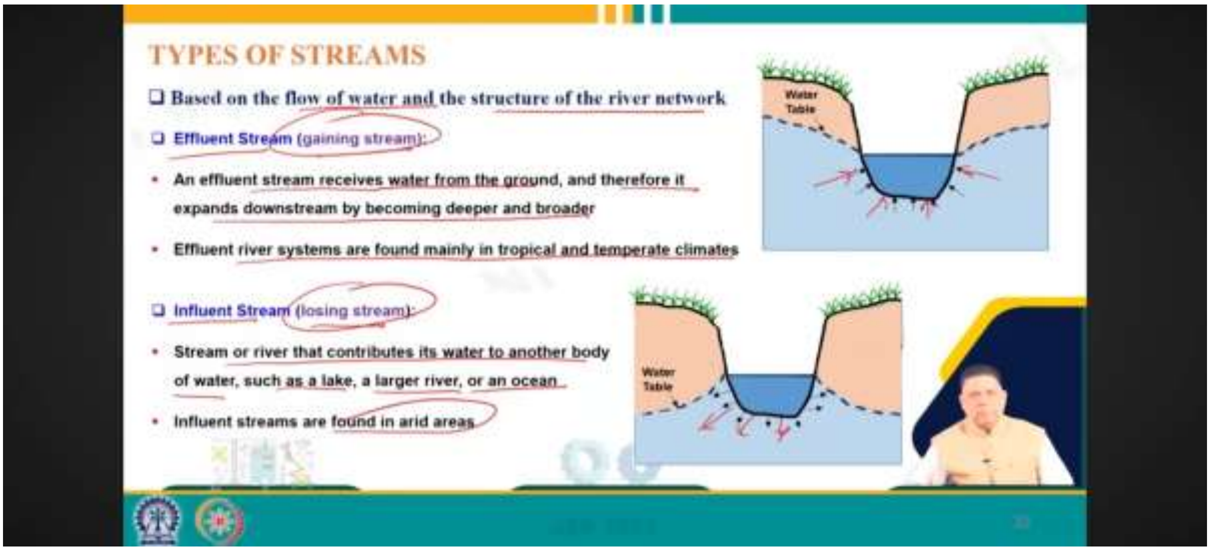

So, what happens here is initially the condition, but if this flux continues, then let's say at t equals 45 minutes, which is 45 minutes after this flow has started, you will see that a seepage pattern develops, as you can see, the seepage pattern is developing. And then, what happens after a certain period of time is that because of the distance, this part reaches the groundwater first, which is here, and this groundwater will start rising, and that is the case you can see here at t equals 75. Similarly, at 211, this will continue, and then, of course, as you can see here, a seepage phase will develop here, that means flow will start taking place, though it is impermeable, but a seepage flow takes place. So, obviously, at this point, this will continue until t equals 277, that water table continues to rise until inflow seizes at 277, and beyond 277, what happens is slowly, you see there is a groundwater decline, the water table declines, and finally, it reaches equilibrium. So, this is how the subsurface flow process takes place in idealized conditions.




Now, let's discuss the types of streams. Streams are categorized based on their runoff characteristics into ephemeral streams, intermittent streams, and perennial streams. The key difference lies in the flow-carrying period within a given year. Perennial streams carry water throughout the year, intermittent streams flow during the monsoon season or whenever there is rainfall, and ephemeral streams only carry flow during a storm or immediately after a storm. Ephemeral streams exhibit a highly variable flow pattern and are often dry for extended periods; they flow only in direct response to precipitation. Flow can vary significantly within short time frames, particularly during the wet season. So, when rainfall occurs, if the flow is significant enough to create a stream, it is classified as an ephemeral stream. So, we've discussed ephemeral streams, where intermittent streams flow for part of the year and may stop during dry seasons or droughts. They exhibit seasonal variability in flow but maintain a relatively consistent water flow compared to ephemeral streams, lasting for a defined part of the year. In the case of intermittent streams, water flow occurs over a season or so, following a precipitation event. On the other hand, perennial streams flow consistently throughout the year, irrespective of the season, owing to a sustained water source. They are typically fed by groundwater springs or other sources that ensure continuous flow. Examples of typical perennial streams in our country include the Ganges, which primarily receives its water from glacier melt. So, regarding Ganga and Yamuna, they receive water primarily from glacier melt, hence ensuring a continuous flow.




Streams can also be categorized based on the flow of water and the structure of the river network. They may be termed as effluent streams, influent streams, gaining streams, or losing streams. An effluent stream receives water from the ground, causing it to expand downstream by becoming deeper and broader. These river systems are mainly found in tropical and temperate climates. Here, the flow level is such that the groundwater table significantly contributes to it. So, that's why they're referred to as gaining streams. On the other hand, influent streams are those that contribute their water to another water body, such as a lake, larger river, or ocean. Their flow pattern indicates water loss, hence they're called losing streams, predominantly found in arid areas. We've explored stream flow processes and attempted to classify streams based on water flow patterns and river network structure.




With this, we conclude this lecture. Thank you very much. I look forward to receiving your feedback and addressing any questions you may have in the forum. Thank you once again.