Surface Water Hydrology
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Lecture 03
Hydrological System Concept

In this lecture, we are discussing about the module one, where we are mostly focusing on the introduction to different hydrological processes. And, in the last class, we have seen the general hydrological cycle which is basically the backbone of this entire analysis part that we are going to learn gradually. Today, in this particular lecture, we will discuss about one very important concept that is called the hydrological system concept.

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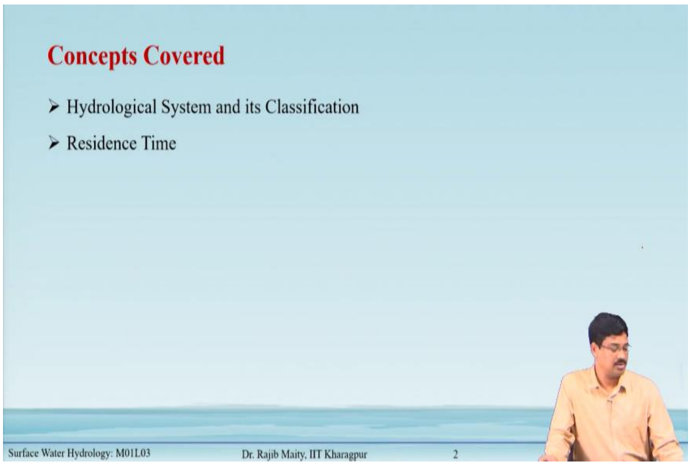

Concepts Covered

- Hydrological System and its Classification
- Residence Time

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We will cover two things – one is that hydrological system and its classification, and also another term that is called the residence time, in the context of hydrological cycle.

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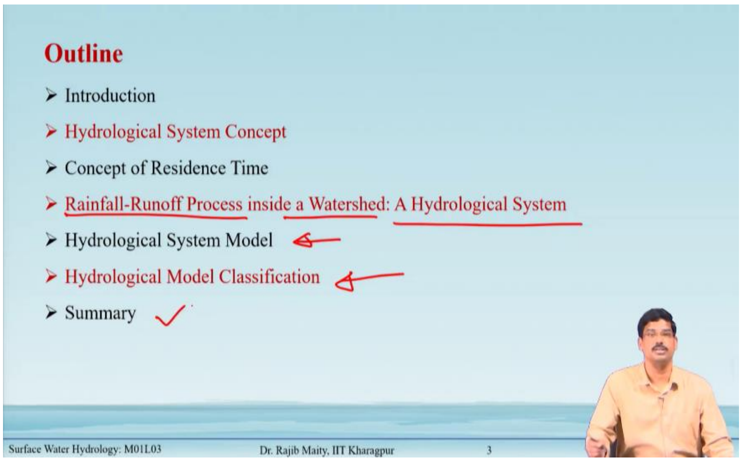

Outline

- Introduction
- Hydrological System Concept
- Concept of Residence Time
- Rainfall-Runoff Process inside a Watershed: A Hydrological System
- Hydrological System Model
- Hydrological Model Classification
- Summary

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The outline of this lecture goes like this: first we will give some basic introduction, then comes the hydrological system concept, then concept of residence time. We will take one example of the watershed, in which the rainfall-runoff process, one of the very basic and important process in the hydrological cycle, will be considered to discuss the system concept, i.e., hydrological system concept.

And then, in general, we will discuss what does that hydrological system model means and how it is useful for different components in the hydrologic cycle. And, we will also briefly touch upon the classification of different models that we use in different hydrological processes before going to the summary.

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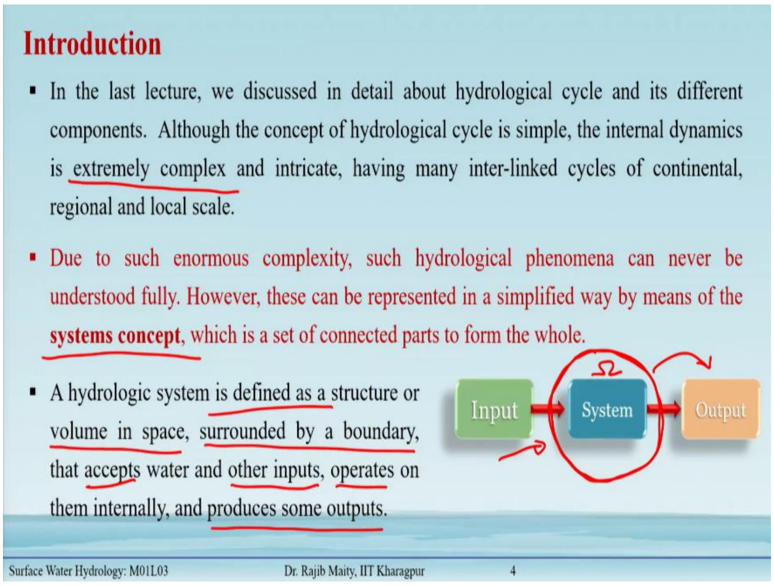

Introduction

- In the last lecture, we discussed in detail about hydrological cycle and its different components. Although the concept of hydrological cycle is simple, the internal dynamics is extremely complex and intricate, having many inter-linked cycles of continental, regional and local scale.
- Due to such enormous complexity, such hydrological phenomena can never be understood fully. However, these can be represented in a simplified way by means of the **systems concept**, which is a set of connected parts to form the whole.
- A hydrologic system is defined as a structure or volume in space, surrounded by a boundary, that accepts water and other inputs, operates on them internally, and produces some outputs.

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Introduction

In the last lecture, we discussed in detail about hydrological cycle and its different components. Although the concept of hydrological cycle is simple, the internal dynamics is extremely complex and intricate, having many inter-linked cycles of continental, regional and local scale.

Due to such enormous complexity, such hydrological phenomena can never be understood fully. However, these can be represented in a simplified way by means of the systems concept, which is a set of connected parts to form the whole.

However, to overcome these things, we generally simplify or we generally conceptualize different processes in the framework of a system concept, which is a set of connected parts and that form the whole. Now, a hydrologic system can be defined as a structure or volume in space that is surrounded by a boundary that accepts the water and other inputs, operates on them internally and then produce some output.

There are some inputs, not only in the form of the rainfall, there are some other meteorological forcing parameters also. We can consider all these as inputs. There are some operations that occur, and we can represent through some mathematical model or some conceptual model. There are different types of models. Those categories we will discuss at the end of this lecture itself.

And finally, it produces some outputs. Now, when we talk about conceptualizing one system, the system concept has to be considered, and we have to remember that entire hydrologic cycle is very, very difficult to consider within a particular system.

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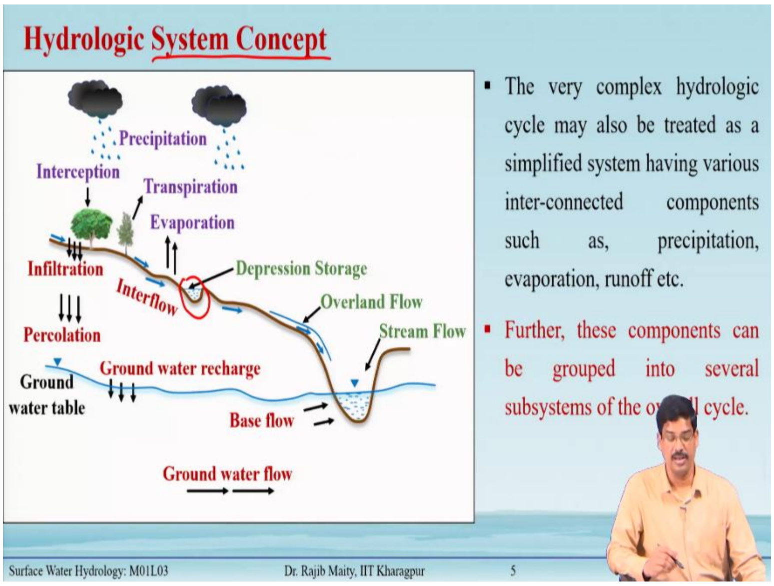

Hydrologic System Concept

- The very complex hydrologic cycle may also be treated as a simplified system having various inter-connected components such as, precipitation, evaporation, runoff etc.
- Further, these components can be grouped into several subsystems of the o l cycle.

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Hydrologic System Concept

The very complex hydrologic cycle may also be treated as a simplified system having various inter-connected components such as, precipitation, evaporation, runoff etc. Further, these components can be grouped into several subsystems of the overall cycle.

For example, in this schematic diagram (Fig.1) which is showing the different processes of hydrological cycle, if I just want to case a for example, small lake and want to see that water balance of it, I need not to go to the cloud physics or how the condensation takes place, how the precipitation occurs, how different processes on ground surface occur. So, what we can do, we can form a boundary, we can analyse what are the different fluxes that is occurring through that boundary and what are the processes within that boundary that is causing the change within the system itself.

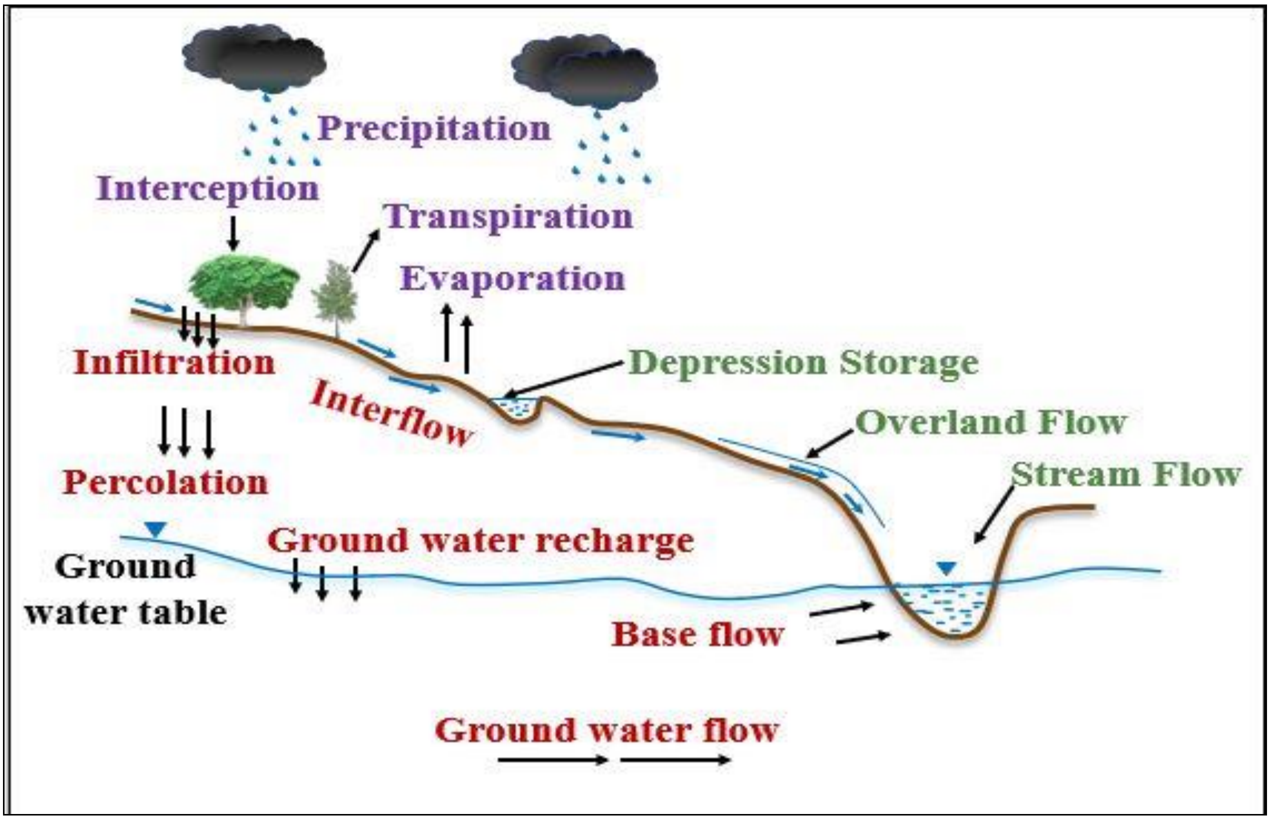

Fig.1 Different process of Hydrological cycle

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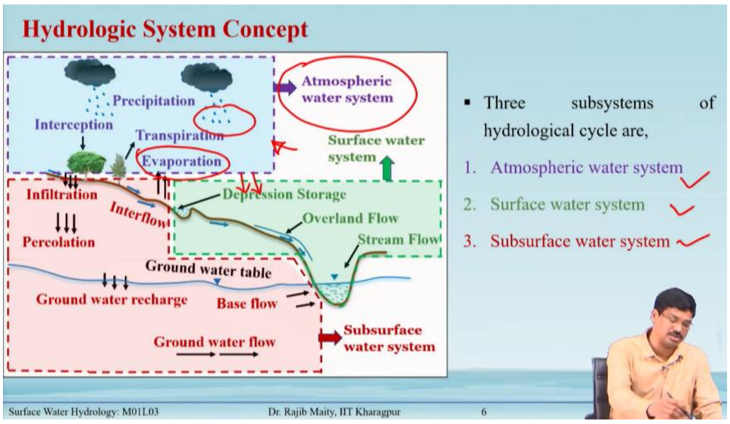

Hydrologic System Concept

- Three subsystems of hydrological cycle are,
  1. Atmospheric water system
  2. Surface water system
  3. Subsurface water system

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Now, coming to the overall hydrological cycle, suppose that we want to first of all considering three major components. They are

- Atmospheric water system,
- Surface water system,
- Subsurface water system

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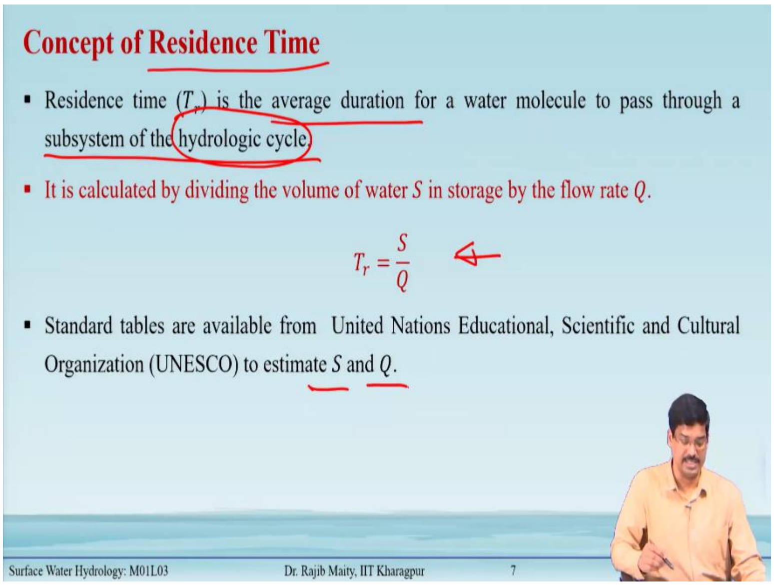

Concept of Residence Time

- Residence time (T_r) is the average duration for a water molecule to pass through a subsystem of the hydrologic cycle.
- It is calculated by dividing the volume of water S in storage by the flow rate Q.

$$T_r = \frac{S}{Q}$$

- Standard tables are available from United Nations Educational, Scientific and Cultural Organization (UNESCO) to estimate S and Q.

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Concept of Residence Time

Another term that is called the residence time. It is the average duration for water parcel that pass through a subsystem of the hydrologic cycle. So, we are discussing the residence time in the context of hydrological processes.

Now, the general expression of residence time is same, i.e., the residence time is equals to the total volume in storage divided by the flow rate from that system which is shown in equation (1).

$$T_r = \frac{S}{Q} \tag{1}$$

Now, in the hydrologic cycle, there are different components, and volume of those components, considering the entire earth, is available from the United Nations Educational Scientific and Cultural Organization (UNESCO). We can have an estimate of S (volume in storage) and Q (flow rate).

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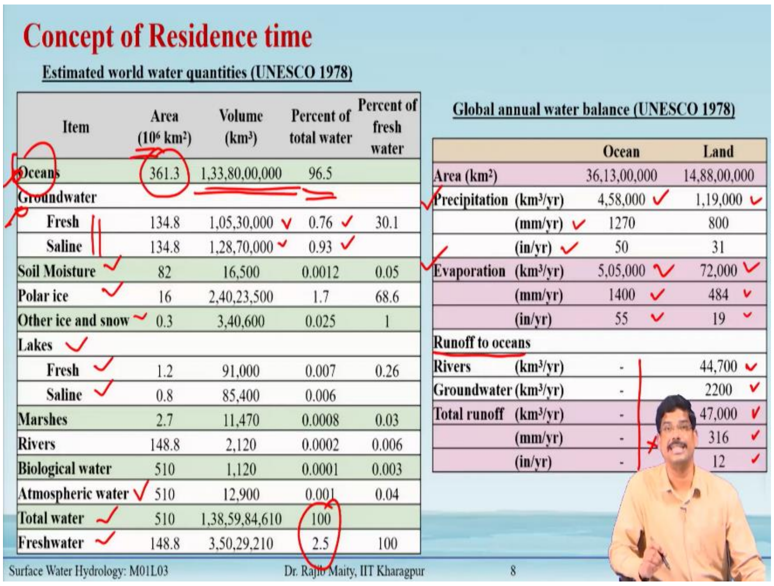


Concept of Residence time

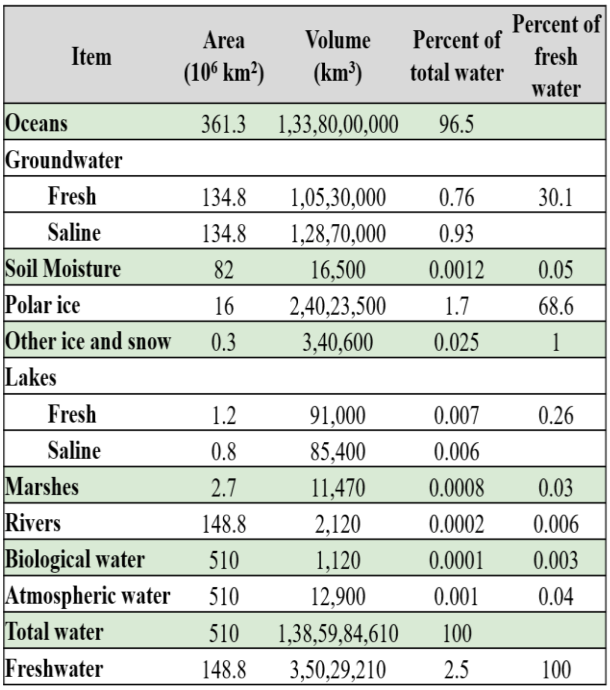
Estimated world water quantities (UNESCO 1978)

Item	Area (10^6 km^2)	Volume (km^3)	Percent of total water	Percent of fresh water
Oceans	361.3	1,33,80,00,000	96.5	
Groundwater				
Fresh	134.8	1,05,30,000	0.76	30.1
Saline	134.8	1,28,70,000	0.93	
Soil Moisture	82	16,500	0.0012	0.05
Polar ice	16	2,40,23,500	1.7	68.6
Other ice and snow	0.3	3,40,600	0.025	1
Lakes				
Fresh	1.2	91,000	0.007	0.26
Saline	0.8	85,400	0.006	
Marshes	2.7	11,470	0.0008	0.03
Rivers	148.8	2,120	0.0002	0.006
Biological water	510	1,120	0.0001	0.003
Atmospheric water	510	12,900	0.001	0.04
Total water	510	1,38,59,84,610	100	
Freshwater	148.8	3,50,29,210	2.5	100

Global annual water balance (UNESCO 1978)

		Ocean	Land
Area (km^2)		36,13,00,000	14,88,00,000
Precipitation	(km^3/yr)	4,58,000	1,19,000
	(mm/yr)	1270	800
	(in/yr)	50	31
Evaporation	(km^3/yr)	5,05,000	72,000
	(mm/yr)	1400	484
	(in/yr)	55	19
Runoff to oceans			
Rivers	(km^3/yr)	-	44,700
Groundwater	(km^3/yr)	-	2200
Total runoff	(km^3/yr)	-	47,000
	(mm/yr)	-	316
	(in/yr)	-	12

Estimated world water quantities (UNESCO 1978)



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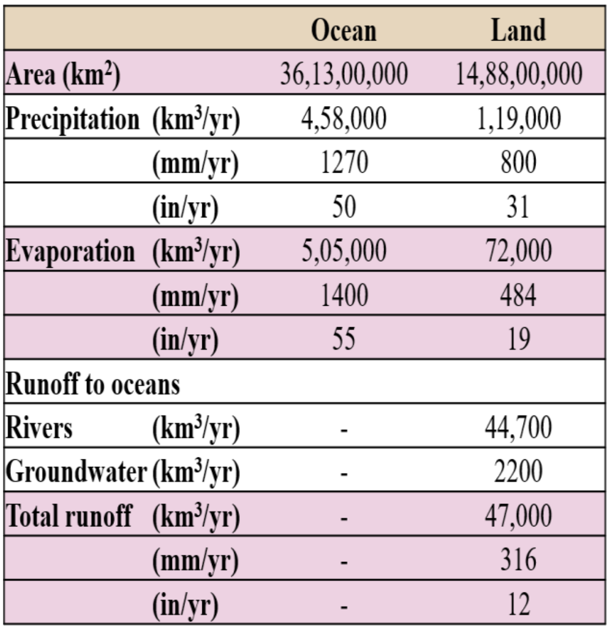

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So, just as an example, if I take the part of the ocean, then the area, the surface area I mean, is 361 multiplied by 10^6 kilometres squares. So, this is approximately the total volume. The percentage of the total water of this earth, as you know already, we have discussed earlier, is 96.5 % in the oceans itself.

Similarly, there are other storage components, for example, groundwater. Again, the groundwater is divided into two parts – one is fresh and the other one is saline. So, their areal coverage and total volume for these two parts, the percentage that it shares with respect to the entire earth, etc. are shown here. Similarly, details of soil moisture, polar ice, other ice, and snow are shown. Under the category of lakes, there are two types – one is fresh other one is saline. Then come marshes, river, biological water, atmospheric water. By atmospheric water what we mean is water in the atmosphere in the form of water vapor. How much is available there – total water, and within that, how much is the freshwater percent. These two terms are already discussed in the previous lecture.

Now, if we take this as, one of the components, and there are different fluxes, for example, the precipitation that occurs over the ocean. So, this much kilometre cube per year (approximate assessment) falls on the land. And, there are other units also. These are in the depth unit, i.e., millimetre per year or inch per year. These are the different estimates given here.

On the other hand, the evaporation that takes place from the ocean surface and land surface in depth unit and in volumetric unit. These are the depth unit, in millimetre or inch. Next comes the runoff to the ocean. Similarly, the runoff to the oceans can come from the river. It can come from the groundwater also. The total runoff to the from these sources is also mentioned here. Of course, the ocean components are not there because we are talking about the run off to the ocean. So, all are coming from the land.

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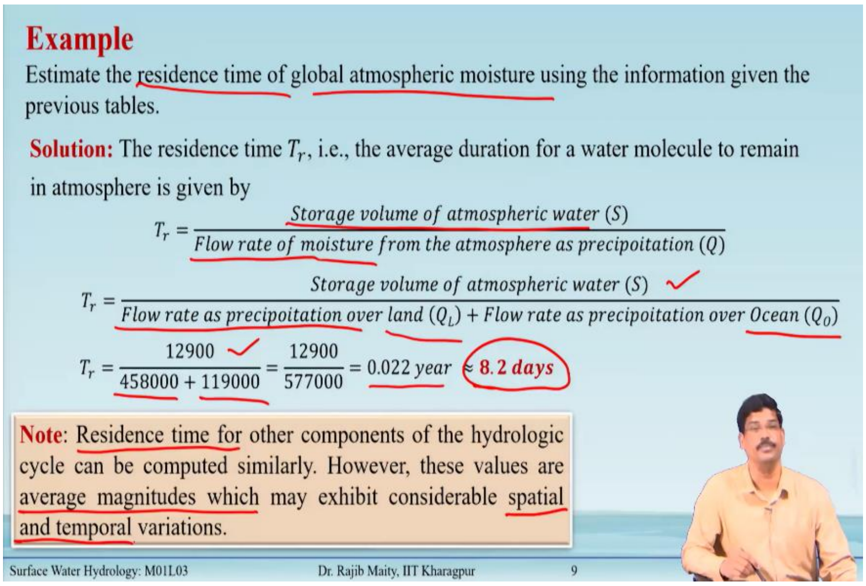

Example

Estimate the residence time of global atmospheric moisture using the information given the previous tables.

Solution: The residence time T_r, i.e., the average duration for a water molecule to remain in atmosphere is given by

$$T_r = \frac{Storage\ volume\ of\ atmospheric\ water\ (S)}{Flow\ rate\ of\ moisture\ from\ the\ atmosphere\ as\ precipoitation\ (Q)}$$

$$T_r = \frac{Storage\ volume\ of\ atmospheric\ water\ (S)}{Flow\ rate\ as\ precipoitation\ over\ land\ (Q_L) + Flow\ rate\ as\ precipoitation\ over\ Ocean\ (Q_O)}$$

$$T_r = \frac{12900}{458000 + 119000} = \frac{12900}{577000} = 0.022\ year \approx 8.2\ days$$

Note: Residence time for other components of the hydrologic cycle can be computed similarly. However, these values are average magnitudes which may exhibit considerable spatial and temporal variations.

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Now, considering this, i.e., if we know one particular system, and how longer, on an average, water stays there, if we just take as an example,

Estimate the residence time of the global atmospheric moisture using the given values information in the previous table.

Solution: The residence time T_r, i.e., the average duration for a water molecule to remain in the atmosphere is given by

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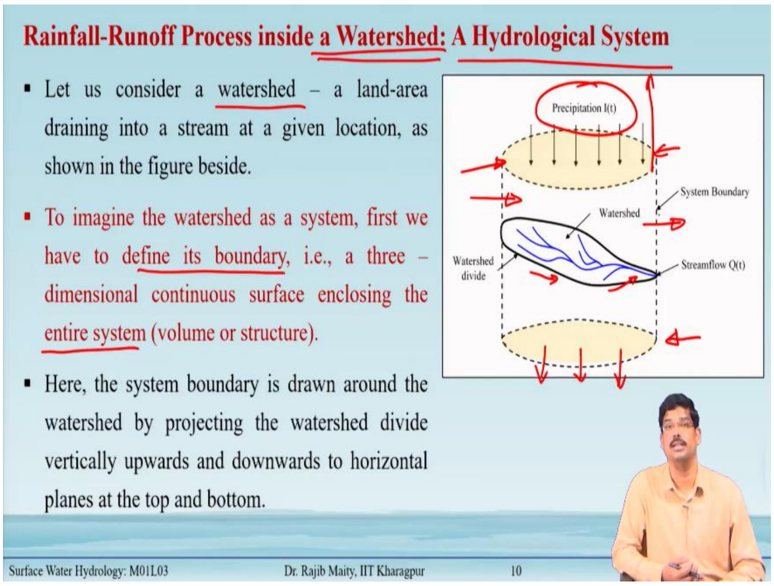

Rainfall-Runoff Process inside a Watershed: A Hydrological System

- Let us consider a watershed – a land-area draining into a stream at a given location, as shown in the figure beside.
- To imagine the watershed as a system, first we have to define its boundary, i.e., a three – dimensional continuous surface enclosing the entire system (volume or structure).
- Here, the system boundary is drawn around the watershed by projecting the watershed divide vertically upwards and downwards to horizontal planes at the top and bottom.

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Rainfall-Runoff Process inside a Watershed: A Hydrological System

Now, we will take it to take the concept as a more generalized form and the more specific with respect to one watershed and that we are frequently utilized in the surface water hydrology. So, let us consider a watershed – a land-area draining into a stream at a given location, as shown in the Fig. 2.

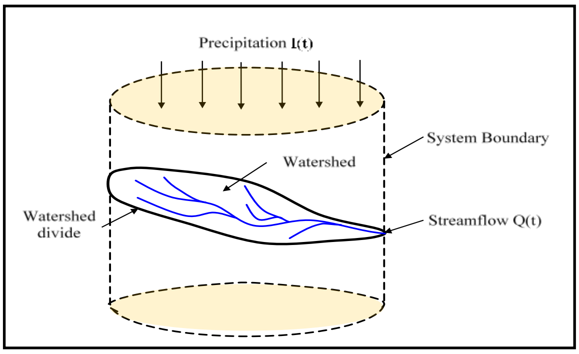

Fig.2 The watershed as a hydrological system

Now, imagine this watershed as a system. First, we have to define its boundary as I have just now told in the previous slides. So, we have to define a boundary that is a three-dimensional continuous surface enclosing the entire system (volume or structure). Here, the system boundary is drawn around the watershed by projecting the watershed divide vertically upwards and downwards to horizontal planes at the top and bottom.

The reason for taking this example is that for many of us this rainfall runoff process the watershed thing is already known to you so, I am just trying to explain in the hydrological system concepts so that for the other cases also, for a lake, for even the entire domain of the groundwater system, for a domain of the surface water system or a domain of the atmospheric region or the other regional analysis these things can be extended, but this one I am just explaining with respect to the watershed only.

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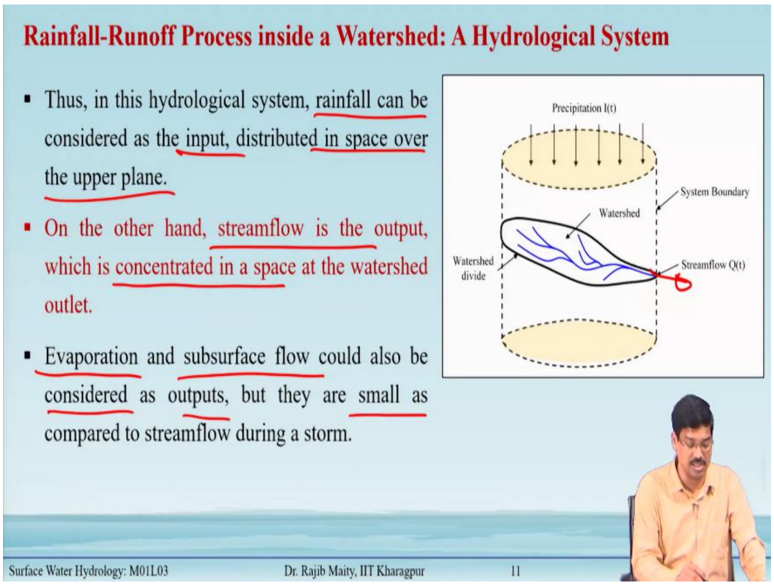

Rainfall-Runoff Process inside a Watershed: A Hydrological System

- Thus, in this hydrological system, rainfall can be considered as the input, distributed in space over the upper plane.
- On the other hand, streamflow is the output, which is concentrated in a space at the watershed outlet.
- Evaporation and subsurface flow could also be considered as outputs, but they are small as compared to streamflow during a storm.

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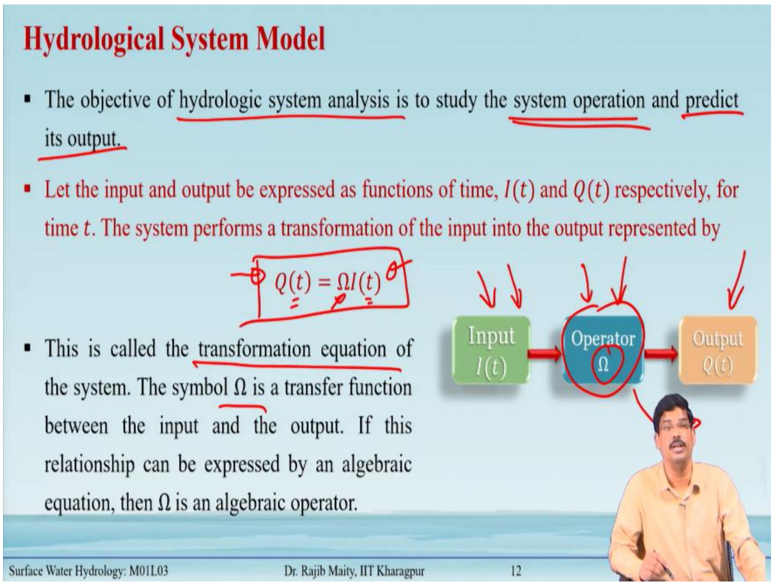

Hydrological System Model

- The objective of hydrologic system analysis is to study the system operation and predict its output.
- Let the input and output be expressed as functions of time, $I(t)$ and $Q(t)$ respectively, for time t. The system performs a transformation of the input into the output represented by

$$Q(t) = \Omega I(t)$$

- This is called the transformation equation of the system. The symbol Ω is a transfer function between the input and the output. If this relationship can be expressed by an algebraic equation, then Ω is an algebraic operator.

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Hydrological System Model

The objective of this hydrologic system analysis is to study the system operation. The system operation means this is the operator that I am talking about in terms of some conceptualization or the mathematical conceptualization and to predict the output. Let the input and output be expressed as functions of time, I(t) and Q(t)respectively, for time t. The system performs a transformation of the input into the output represented by the equation (2)

$$Q(t) = \Omega I(t) \tag{2}$$

This is the output maybe it is we are talking about the form of a discharge and this is the input I(t) and this omega is the operator that is occurring on the inputs by the system.

This t in the bracket is basically time-dependent. So, this is called the transformation equation of the system and the symbol Ω, it is a transfer function between the input and the output. If this relationship can be expressed as an algebraic equation or any mathematical form, then that becomes an operator is known to us which helps to go for the further analysis.

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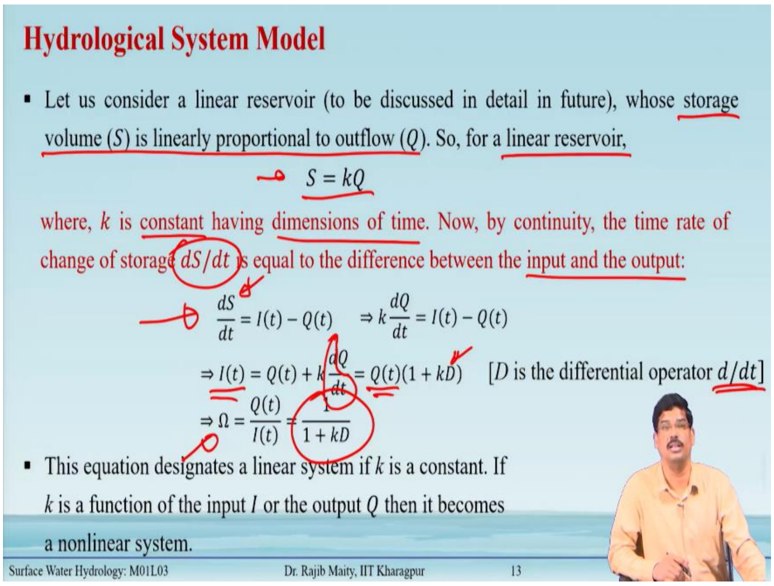

Hydrological System Model

- Let us consider a linear reservoir (to be discussed in detail in future), whose storage volume (S) is linearly proportional to outflow (Q). So, for a linear reservoir,

$$S = kQ$$

where, k is constant having dimensions of time. Now, by continuity, the time rate of change of storage dS/dt is equal to the difference between the input and the output:

$$\frac{dS}{dt} = I(t) - Q(t) \qquad \Rightarrow k\frac{dQ}{dt} = I(t) - Q(t)$$

$$\Rightarrow I(t) = Q(t) + k\frac{dQ}{dt} = Q(t)(1 + kD) \quad [D \text{ is the differential operator } d/dt]$$

$$\Rightarrow \Omega = \frac{Q(t)}{I(t)} = \frac{1}{1 + kD}$$

- This equation designates a linear system if k is a constant. If k is a function of the input I or the output Q then it becomes a nonlinear system.

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Let us consider a linear reservoir (to be discussed in detail in future), whose storage volume (S) is linearly proportional to outflow (Q). So, for a linear reservoir, mathematically expressed as the equation (3)

$$S= kQ \tag{3}$$

where, k is constant having dimensions of time. Now, by continuity, the time rate of change of storage ds/dt is equal to the difference between the input and the output:

$$\frac{dS}{dt} = I(t) - Q(t) \qquad \Rightarrow k\frac{dQ}{dt} = I(t) - Q(t)$$

$$\Rightarrow I(t) = Q(t) + k\frac{dQ}{dt} = Q(t)(1 + kD) \quad [D \text{ is the differential operator } d/dt]$$

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This equation designates a linear system if k is a constant. If k is a function of the input I or the output then it becomes a nonlinear system.

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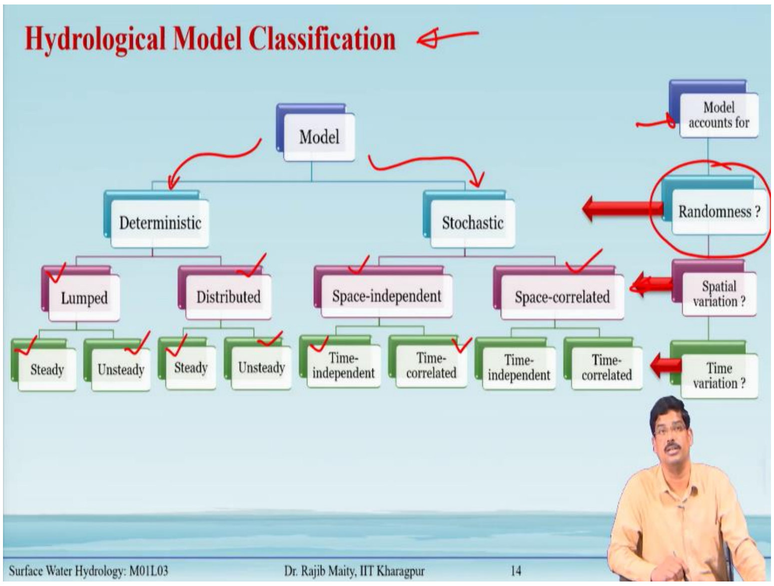
Hydrological Model Classification

Model
Deterministic
Stochastic
Lumped
Distributed
Space-independent
Space-correlated
Steady
Unsteady
Steady
Unsteady
Time-independent
Time-correlated
Time-independent
Time-correlated

Model accounts for
Randomness ?
Spatial variation ?
Time variation ?

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Hydrological model classification

Hydrological model classification means there is number of models that are available for different processes and all. But all s these models the three questions that you have to remember in this one so far as the classification is concerned. Another way more precisely to ask this question is that, can we proceed without considering randomness or randomness has to be considered? If our answer is yes, then we are in this branch that is wherein the stochastic branch. If we say no, this is the randomness we can we need not consider for this particular model, then we are going to a deterministic model.

Next question that we have to ask is there any special variation or not? If we say yes there is a spatial variation or we say no there is no spatial variation. So, if we say yes there is spatial variation, then models are distributed and if there is no spatial variation, we call that it is the lumped model.

Similarly, under the stochastic branch also, we can use the similar term lumped or distributed but just to differentiate we say that, if there is no spatial variation, we call it space independent, and if there is spatial variation and yes then it will call it as a space correlated. The third question is thought and the last person that comes is the time variation, whether the time variation is there or not. If we say yes, then under this deterministic branch, we say that it is unsteady. Unsteady means that time variation is there and steady means there is no time variation.

Similarly, under distributed also steady and unsteady. And space independent under this stochastic branch is also what we call time-independent or time-correlated. Time correlated means it has the time variation. Time independent means it has no time variation. Similarly, under this space correlated also.

As you can see that there are it can be steady lump deterministic, unsteady and lump deterministic model, steady distributed deterministic model, unsteady distributed deterministic model like this any branch you can follow and you can just classify that model.

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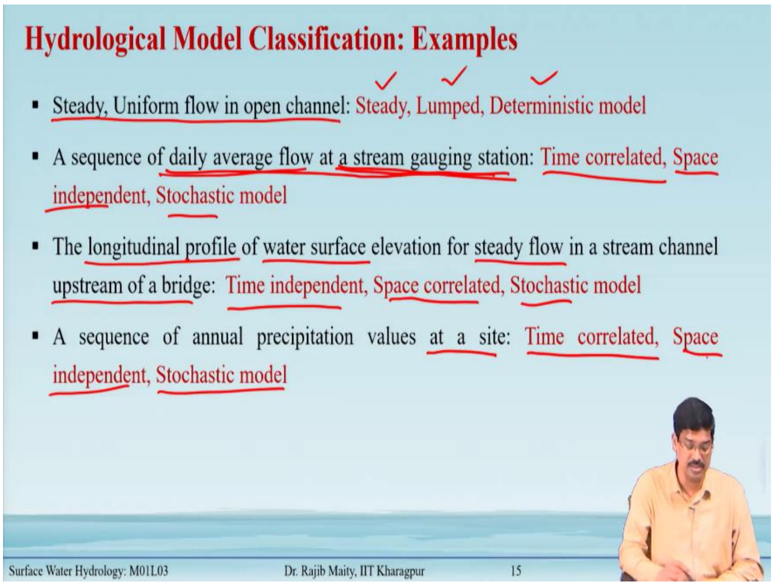

Hydrological Model Classification: Examples

- Steady, Uniform flow in open channel: Steady, Lumped, Deterministic model
- A sequence of daily average flow at a stream gauging station: Time correlated, Space independent, Stochastic model
- The longitudinal profile of water surface elevation for steady flow in a stream channel upstream of a bridge: Time independent, Space correlated, Stochastic model
- A sequence of annual precipitation values at a site: Time correlated, Space independent, Stochastic model

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Hydrological Model Classification: Examples

Let us see one or two examples then it will be even more clear. For example, , the steady uniform flow in an open channel., We know that is a manning's equation, it gives the fixed value for some fixed inputs. So, we are not considering the randomness in it. So, it is a deterministic model. , Here, we do not consider any special variation. We call it as a lumped. And we do not consider the time variation also. So, this is a steady lumped deterministic model.

Similarly, if we take a sequence of daily average flow at a stream gauging station, there should be the randomness we cannot say anything very precisely. So, it is a stochastic model.

The second question is that is there a variation in this one? So, let us see that in this way at a stream gauging station itself at this point we are just talking about. So, we are not saying any spatial variation out of it. So, that is why it is space-independent. Similarly, it is a daily average flow that means, from one day to another day, it will vary that is why it is time-correlated. So, it is time-correlated space independent stochastic model.

The third one is the longitudinal profile of water surface elevation of the steady flow in a stream channel upstream of a bridge. You know that backwater effect over a structure. So, it is a longitudinal profile of water surface and it goes as a steady flow means, there is no flood is approaching and all. So, there is some randomness.

In this case, there are some profiles we may get that may say that I get one deterministic profile, but there also can be some randomness, if we considered that one in some of the analyses, then it becomes a stochastic model. It varies over space, that is why it is space correlated. And whatever the profile that we get for a steady flow, that profile remains the same. That is why it is time-independent. So, that is why the model you can categorize as the time-independent space correlated stochastic model.

A sequence of annual precipitation values at a site, again at a site moment, we say that is space independent and it is a sequence of this annual precipitation. So, the randomness has to be considered, so, it is a stochastic model and it is annual precipitation which means, it will vary from one year to another year. So, it is time-correlated. So, the classification of the model will be the time-correlated space-independent stochastic model.

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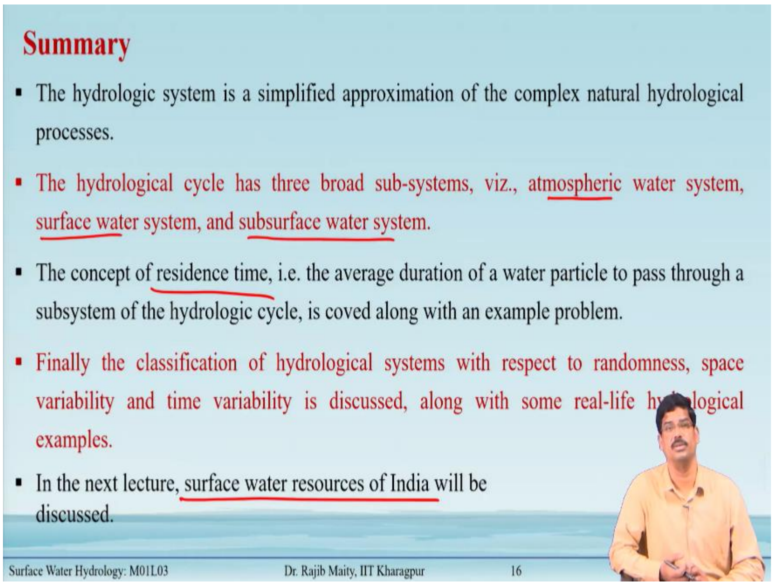

Summary

- The hydrologic system is a simplified approximation of the complex natural hydrological processes.
- The hydrological cycle has three broad sub-systems, viz., atmospheric water system, surface water system, and subsurface water system.
- The concept of residence time, i.e. the average duration of a water particle to pass through a subsystem of the hydrologic cycle, is coved along with an example problem.
- Finally the classification of hydrological systems with respect to randomness, space variability and time variability is discussed, along with some real-life hydrological examples.
- In the next lecture, surface water resources of India will be discussed.

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In summary, we learned the following points from this lecture:

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