**Groundwater Hydrology and Management**
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**Lecture 27**
**Groundwater recharge and discharge**

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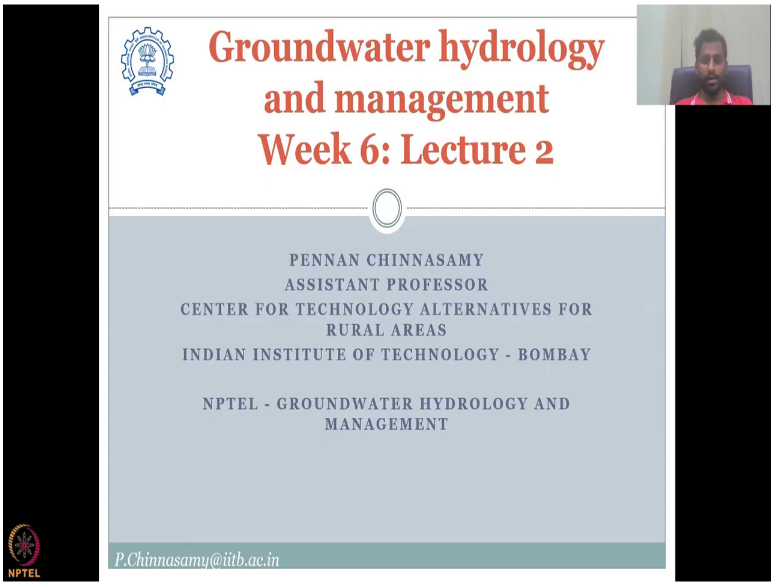


Hello, everyone, welcome to Groundwater Hydrology and Management. This is NPTEL course, week 6, lecture 2. In the previous weeks we looked at the importance of groundwater, and most importantly, the key parameters for groundwater. In this week, we are looking at why groundwater level would fluctuate.

And in particular, we are looking at groundwater recharge and discharge. The last class, we looked at the key functions or processes that influence groundwater levels, let us move on and look at groundwater recharge in this particular lecture.

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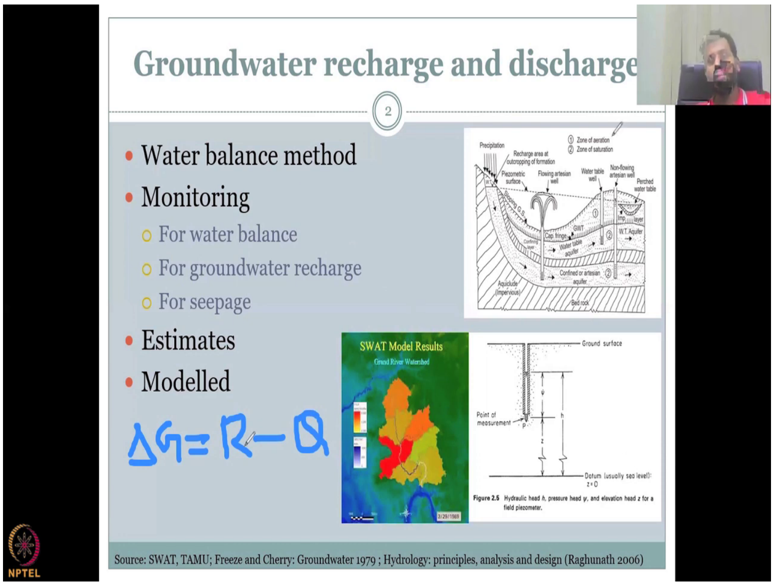


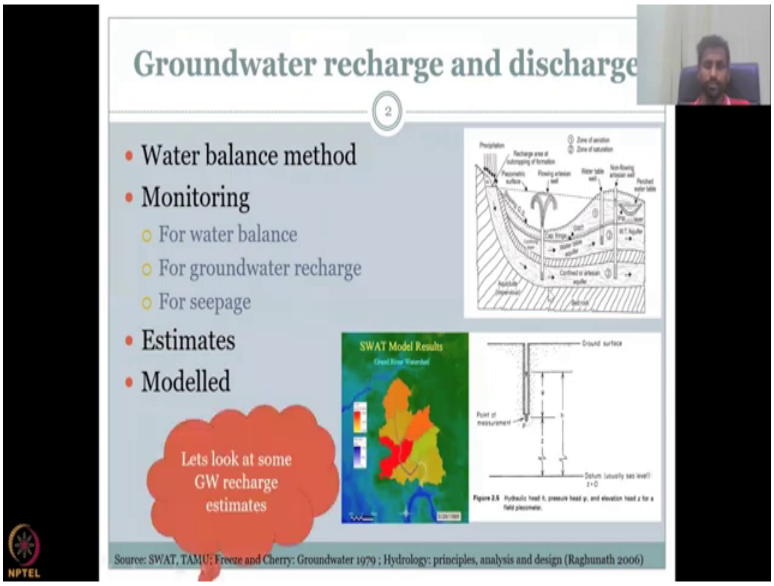


So, groundwater recharge can happen through multiple processes. However, it is important to distinguish between groundwater recharge and discharge, what we saw in the previous class is that one in the Hydrological Cycle that one process can lead to recharge and also discharge in the same process. The flow of water from the high aquifers into the rivers and lakes is an example yes, it is discharging but on the way it is recharging.

So, for that, we are going to look at what are the common methods in which these are assessed. We looked at the processes now look at how they are assessed, it could be different for recharge and discharge, but there are some processes or some methods that can capture both for example, the water balance method here you put in parameters for your water balance, and then you can estimate where the recharge is happening and discharge is happening or both are happening simultaneously.

So, in which there is a lot of monitoring needed and our understanding of your properties of the soil, the material and water rainfall hydro climate etc. Water balance method can also be done like back of the envelope calculation people do you have a surface runoff coefficient and then you have rainfall, we say that, whatever is not runoff is going into the ground and into the ground means it is groundwater recharge.

So, there are some simplified models, but we will look into very specific models and methods that are used for recharge and discharge in the coming lectures. The other method is monitoring method. There is a lot of sensors that can capture the parameters to assess the fluctuations in the water level. For example, more monitors or meters and sensors that can help in the water balance method which we explained using this hydrological cycle.

You have multiple components and you can put values for each components based on the recordings of these meters and sensors. Then you have groundwater recharge monitoring, specifically for groundwater recharge monitoring, which is done by wells and the well level recorder or meters you use to record the wealth levels. For seepage, there is a different method for example, your water coming, you can put a meter inside and then calculate the groundwater recharge or fluctuation or discharge using water meter.

On the other hand, the water can go and get into the ocean and rivers and lakes which is called seepage. And that seepage can be estimated using a seepage flux meter, which is a meter placed on the banks of the rivers and oceans and seas to monitor how much water is coming up. It may be easier for estimates in the oceans because there is a density difference in the water. However, it could be more difficult in the rivers and freshwater bodies.

So, monitoring can help in establishing the water balance components of specifically only the groundwater wells or the seepage. The third point is estimates there are lots and lots of estimates that are made. And these estimates as I said are based on the back of the envelope calculations, very simplified calculations, which are coming because of a prior understanding of the system. Let us take this example right your change in groundwater is nothing but Del G change in ground water level is equal to precipitation minus rainfall minus run off.

As I tell them the parameter variable differs, you can put rainfall as R or P, etc. etc. But it is also how you define it is very important. So, in this equation and defining in us, Del G, which is your difference in groundwater levels, which is the fluctuation is nothing but your rainfall, the water coming onto my land minus the runoff.

So, if I extract the runoff, if I subtract the runoff volume, whatever volume remains is going in the ground, remember, there is no Et there is no evapotranspiration, there is no other losses, because I am taking a very specific case study, where I do not have all these, let us take a barren land for example, in that barren land, there is no plants, there is no evaporation also happening is just going in it because there is no sunlight for example, the rainfall only happens in the night and in the night there is runoff happening and most of the water will go down the remaining water and recharge the ground water.

These are the estimates that you can put with even a R which is your rainfall, which you need data or every month you have statistical model to predict the data, But Q can be most probably they do estimates if you know for example, it is a cement road, if you know for example, it is a forest you know that 80 percent of the water will come off, the remaining 20 percent will go in.

So, those kinds of percentages are estimates based on previous field work from different locations. Then you have models like this model you have here, which is the SWAT model, very complex hydrological models, which if you give all the parameters ranging from the top water, meter models, water balance data, etc., etc., you feed it into these models, and the models give you the output of groundwater recharge or discharge based on your calculations and based on your estimates of these parameters.

So, for example, if you have all these parameters in the model, the model will spit out a groundwater recharge value and groundwater discharge value. It also is based on the climate, the land, the land use, which is your trees, plants, etc. growing and your slope of the land, how the land is tilted and stuff. Let us look at some of these estimates, especially the recharge estimates. So, now we are going to shift gears in just looking the recharge volumes for India and also only India.

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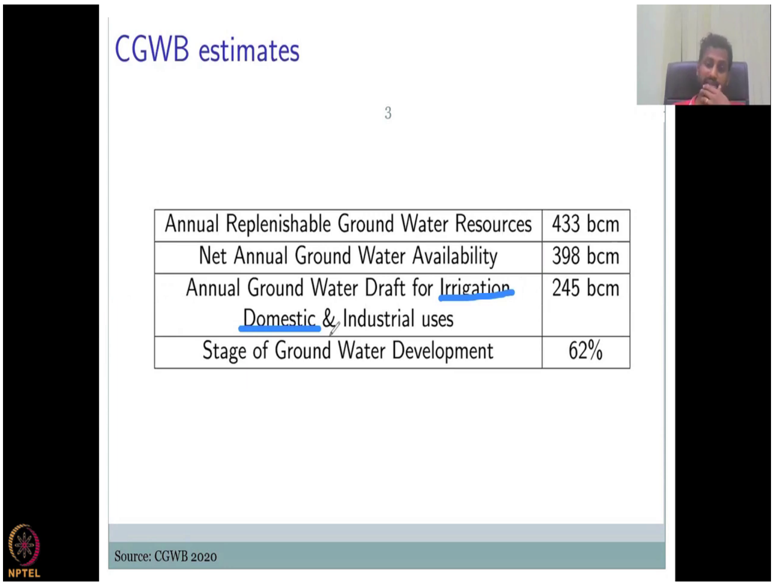


The first is our own Central Groundwater Board, where it says Annual Replenishable Groundwater Resources are 433 billion cubic meters, the net annual groundwater availability is 398 billion cubic meters and your annual groundwater draft for irrigation domestic and industrial uses 245 billion cubic meters.

So, this 433 is based on annual data of how much water can be used to the recharge. The net groundwater availability is the water that is remaining to be used, because not all 433 can be consumed, a part of it is going to be held in the soil and the rocks and other materials it is not going to be taken out, which is here it is approximately 35 billion cubic meters. It is a big amount, but it still take about pan India this this data is for Pan India.

So, I will say that this is data for whole of India CGWB estimate. And then you have your Annual groundwater draft for irrigation, domestic and industrial use. Basically, these are 3 different uses and if you understand what is a draft or pumping or use for irrigation because of the crop type, crop area, you know, how much water is required for irrigation, domestic you know how many people are there through populations senses.

And from the census data you can estimate what is the number of households and each household how much water they get for estimating domestic water use. Then you have your industrial use. Industrial use is a trickiest here because it is closed let us take a bottling company for example, where they make fruit juices, drinks, soda etc.

It is a big industry which takes a lot of water, we do not know how much water they use, they have pay per use system and or lease system they will say, 100 years I will pay this much money or 10 years, 30 years and the pumps efficiency only data, you cannot estimate it just by power supply and all because they can keep fine tuning the efficiency of these pumps.

So, what happens is the industry uses still a big estimate, well irrigation is also all kind of monitored and measured, because you know, satellites can take pictures of crop types and domestic use, you can take it from sensors, which is a survey based data. So, all this data is available industry is kind of really tight, but you still you can manage you can estimate as CGWB has done and it is saying 245 billion cubic meters, this is kind of an outdated number now, this 265 billion cubic meters.

So, what is the stage of groundwater development now, you know, the draft you know, the recharge, which is around 433 million cubic meters recharging after which 398 can only be used and out of the 390 only 245 is used 62 percent. So, 62 percent is nothing but the percentage of 245 in the 43 almost around 50 plus rate. So, it is 62 percentage, which means that it is still safe India safe in ground water for us as per the CGWB estimate it may or may not be the same by other estimates. Let us look at some other estimates.

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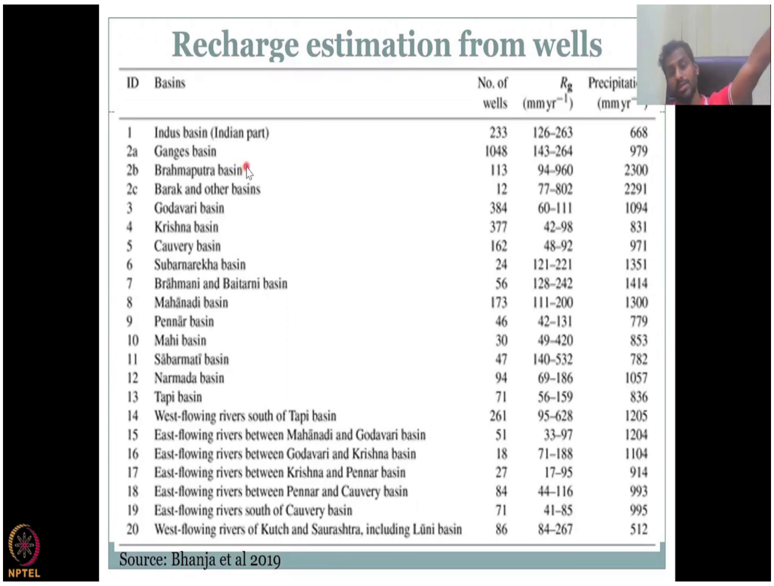

## Recharge estimation from wells

| ID | Basins | No. of wells | $R_g$ (mm yr$^{-1}$) | Precipitati (mm yr |
|---|---|---|---|---|
| 1 | Indus basin (Indian part) | 233 | 126–263 | 668 |
| 2a | Ganges basin | 1048 | 143–264 | 979 |
| 2b | Brahmaputra basin | 113 | 94–960 | 2300 |
| 2c | Barak and other basins | 12 | 77–802 | 2291 |
| 3 | Godavari basin | 384 | 60–111 | 1094 |
| 4 | Krishna basin | 377 | 42–98 | 831 |
| 5 | Cauvery basin | 162 | 48–92 | 971 |
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| 7 | Brāhmani and Baitarni basin | 56 | 128–242 | 1414 |
| 8 | Mahānadi basin | 173 | 111–200 | 1300 |
| 9 | Pennār basin | 46 | 42–131 | 779 |
| 10 | Mahi basin | 30 | 49–420 | 853 |
| 11 | Sābarmatī basin | 47 | 140–532 | 782 |
| 12 | Narmada basin | 94 | 69–186 | 1057 |
| 13 | Tapi basin | 71 | 56–159 | 836 |
| 14 | West-flowing rivers south of Tapi basin | 261 | 95–628 | 1205 |
| 15 | East-flowing rivers between Mahānadi and Godavari basin | 51 | 33–97 | 1204 |
| 16 | East-flowing rivers between Godavari and Krishna basin | 18 | 71–188 | 1104 |
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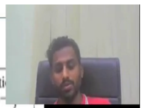
| 20 | West-flowing rivers of Kutch and Saurashtra, including Lūni basin | 86 | 84–267 | 512 |

Source: Bhanja et al 2019

# Recharge estimation from wells



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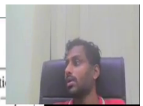

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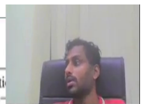

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Source: Bhanja et al 2019

This is the estimate done by your team in Bhanja et al 2019, where they use explicitly lot of wells groundwater well data and they measure the recharge happening and also the precipitation happening per year. So, millimeters is a thickness not a volume, but a thickness of recharge and thickness of rainfall happening in a year.

And note that they only do it for India. And because of the data they have and there are multiple trans boundary rivers also here like the Indus, Ganges and Brahmaputra could be multiple trans boundary Ganges goes from Tibet, China, Nepal and India. Indus can be Pakistan and India apart. So, there are differences Brahmaputra, Bangladesh, etc. So, here only the India part is spoken. And what you could see is the number of wells help in estimating the recharge for sure.

And there is differences in groundwater recharge. There the differences is led by the groundwater parameters, which we saw earlier in the class of the importance, which is basically your aquifer type, the soil material, the rock material present in that basin, which allows the groundwater to flow, the ease of warm water to flow and recharge, not only that, the area should have a good rainfall, you might have the best darn water aquifer.

But if you do not have rainfall, water does not go in. So, water is important. And after water, the water from rainfall the rainfall should go into the aquifer. So, the availability and readiness of the aquifer to recharge is also important. And in that aspect, you could see that the recharge ranges from 143 to 264, Barak and other basins are 94 to 960. Whereas I am sorry, the Brahmaputra River 94 to 960 Barak is 77 to 802 so, mostly your alluvial aquifers, which are given in this first couple of things.

Most of these basins I am saying were alluvial aquifers are more, you can see a very healthy groundwater recharge, compared to the other regions. Actually, all of them are basins all of them have a river and stuff so you will see some part of alluvial in it. But what is the major discussion in this slide is that you have multiple wells that can give you accurate data for estimating recharge and recharge is not the same across India this is the driving factor, it could be a 960 in the Brahmaputra whereas, it is only 131 in the Pennar basin in the south.

And this is where I say it is also based on the rainfall which is 2300 in the Brahmaputra compared to 779 almost arid semi-arid condition in the south of India, Pennar. And you also have the aquifer type the geology which is allowing recharge or not. So, recharge is a good combination of your rainfall availability your physical processes the aquifer properties that allow the recharge and the availability of water inside the aquifer if the water is already there, recharge will not happen.

So, this study beautifully quantifies across India through wells, not the recharge rates and also compares them with the rainfall rate and most importantly, they establish the range. So, the range could. Why is there a range of difference for example, you have a Brahmaputra let us say this is the Brahmaputra, Ganges looks something like this. So, you have 143 to 264. Why is there a range difference because the rainfall also varies even though they give only one rainfall here, we erase some of it.

So, then you have multiple wells in different locations the rainfall is not the same, but then Let us say on average, this is the rainfall, but there is very, very important change in the groundwater recharge because of the location aquifer type and the slope and the rainfall also differs along the Ganges it is not the same, so this study is very important to quantify the differences one can expect because of the placement of the basin in a particular aquifer system or a geology type, and also the rainfall.

All of this is driven by your well record. So, different estimates are there. This is the another confusing part, this may not agree with the CGWBs estimate. The differences can occur because of the well type, maybe they are using more deep wells to establish the aquifer recharge conditions, and also the region in the previous slide.

We just saw 245, 433 as a recharge annual. But where is it placed? Where is that 433 billion cubic meters happening? We do not know. It is a combination, but which regions have more which regions have less we do not know this gives a good picture of where in data it happens more. So, as I said, more recharge is happening in the Brahmaputra compared to the other regions, and then the Pennar in the South have very, very less recharge.

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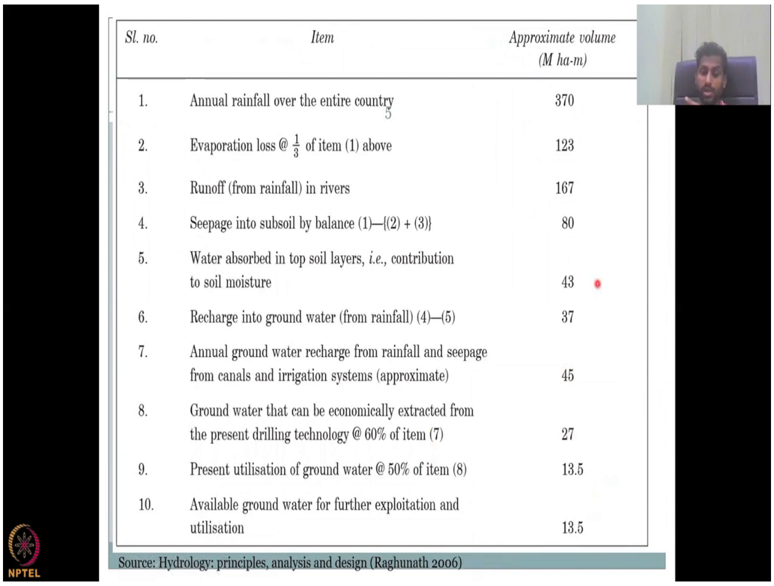
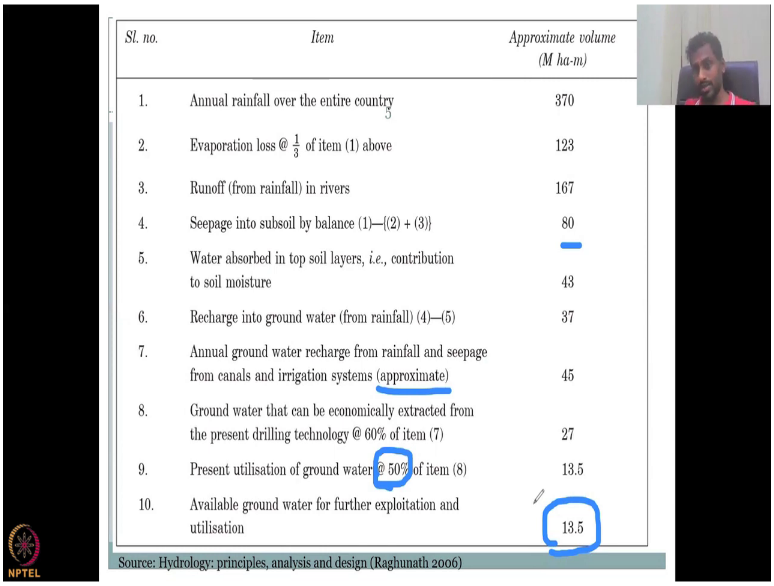


| Sl. no. | Item | Approximate volume (M ha-m) |
|---|---|---|
| 1. | Annual rainfall over the entire country | 370 |
| 2. | Evaporation loss @ $\frac{1}{3}$ of item (1) above | 123 |
| 3. | Runoff (from rainfall) in rivers | 167 |
| 4. | Seepage into subsoil by balance (1)—{(2) + (3)} | 80 |
| 5. | Water absorbed in top soil layers, *i.e.*, contribution to soil moisture | 43 |
| 6. | Recharge into ground water (from rainfall) (4)—(5) | 37 |
| 7. | Annual ground water recharge from rainfall and seepage from canals and irrigation systems (approximate) | 45 |
| 8. | Ground water that can be economically extracted from the present drilling technology @ 60% of item (7) | 27 |
| 9. | Present utilisation of ground water @ 50% of item (8) | 13.5 |
| 10. | Available ground water for further exploitation and utilisation | 13.5 |

Source: Hydrology: principles, analysis and design (Raghunath 2006)

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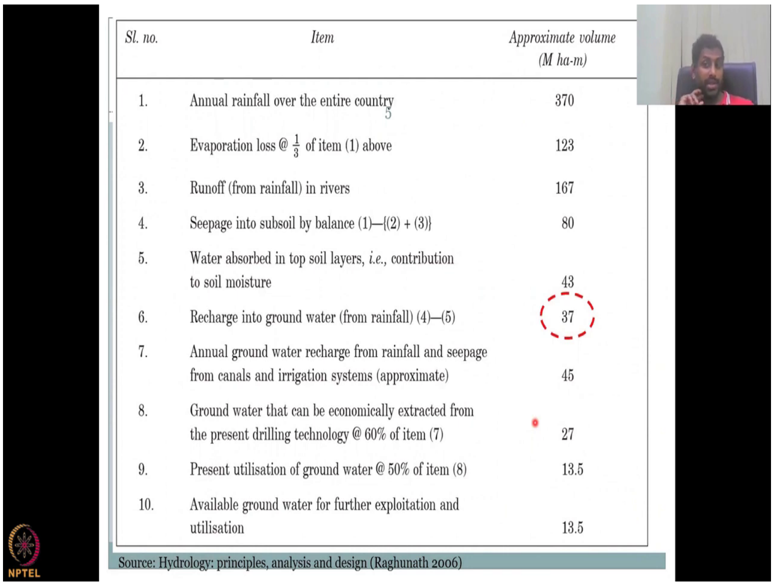


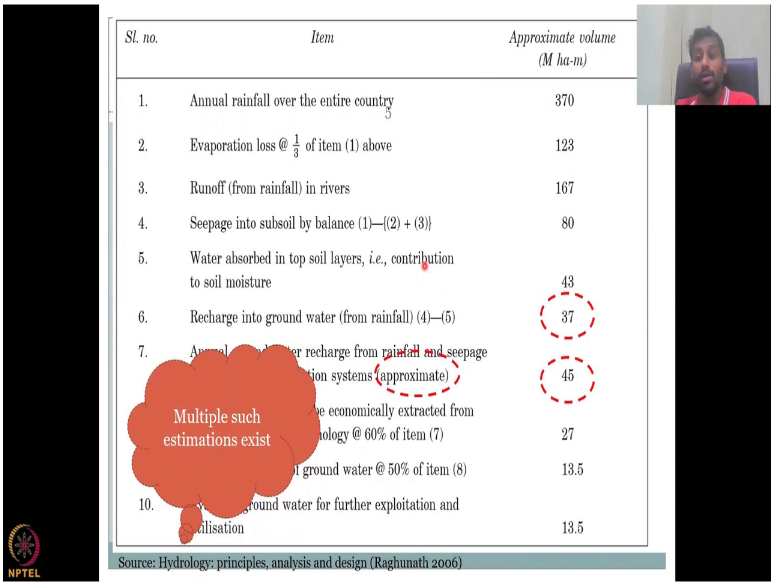


Let us come back to the book that we are using for the class, which is the hydrology principles and analysis designed by Raghunath, Professor Raghunath and what you see here is water is taken as rainfall and then an estimate. See, here is the estimate at one third. So, this estimate is given it is not or it may not be a calculated monitor.

Report sensibly acquired data it is one third based on literature review, so they say the rainfall is 370 million hectare meters, it is a volume, hectare meter is a volume, see how the units change? So, it is not readily comparable, the previous slide was millimeters per year in the previous slide, it was billion cubic meters per year. So, in the CGWBs slide, it was a volume the next slide the Bhanja et al paper, it is a thickness here it is a volume.

So, evaporation at one third, 123, runoff from rainfall in rivers is 167. As I said they just estimate how much runoff seepage into subsoil by balance. So, how much is seepage, seepage happening, you just subtract one which is your rainfall and then 123 and 167. So, if you know one quantity in your water balance, you can estimate the other components by a simple addition or subtraction, so here they have added 2 and 3 and subtracted excuse me to get that 80.

So, this is the groundwater recharge. See how the languages seepage is used here which is basically your recharge into the subsoil into the soil. Water observed in top soil contribution to the soil moisture, this is also an estimate, he has put forward 43 and 43 is from the 80. So, what is the recharge for the deeper aquifers.

So, recharge into groundwater from rainfall the net recharge going into the aquifers after the water is absorbed or in the soil moisture is only 37, so seepage is here, is just a infiltration water infiltrates part of the water stays in the soil which is 43 the remaining goes down as recharge which is 37. So, 43 plus 37 is 80, then your annual groundwater recharge from rainfall and seepage from other canal.

And approximate they have put it very clearly data entry, which is good if you do not have the data read some books and papers and put a number and say it is an estimate do not say it is actual value. So, these are actual rainfall is actual you cannot say that. You can say approximate.

Then groundwater that can economically extracted from the present drilling technology at 60 percent, so 60 percent is again a number they put that on 7 and then take 27 percent utilization of groundwater at 50 percent in the previous CGWB slide it was saying 62 percent. Here they using 50 percent maybe when they did the book in 2006 it was a CGWB estimate, ours was 2010 passed. So, there is some difference in the percentage, they so let us say 50 percent of 8, 50 percent of 27 is 13.5.

So, available groundwater for future exploitation which is the remaining 50 percent, 50 percent is utilized 50 percent is remaining. So, that is 13.5. So, you see here how water balance equation is set up in the mind and then they have written it down, identified which are the key parameters and throw it out the negligible parameters like Et capture, water capture in the canopy, those kinds of things through rainfall, et cetera.

They lift it out, we do not know, we do not want to and then they put estimates for each and every parameter one third, 50 percent, 60 percent and then arrive at recharge. So, this is another way of estimating groundwater recharge. So, this is 37 it could be also be done with the equation I gave you which is Del G is equal to just rainfall minus Q.

So, if I assume there is no evaporation, I say rainfall is happening 370 minus runoff 167 is recharged in my very simplistic case, it is approximate please read in between the lines is it an actual data it was an actual data that will give you the data source otherwise it is approximate and there are differences, they have identified only parameters that they want to be sure of the others they give it very blatantly it is an approximate.

So, driving home here is there are multiple methods for estimation of groundwater recharge, and it can be based on multiple physical or data intensive or modeling perspectives.

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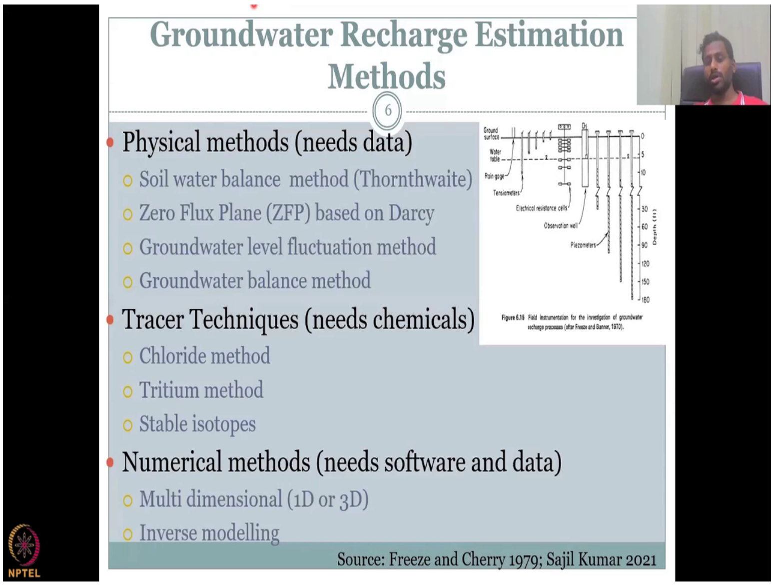


Let us look at some of them the very very important as per the recent review by Sachin Kumar in 2021. And also as defended by the Freeze and Cherries, groundwater book which is identified the most important groundwater recharge estimation methods. So, now estimates is a important like you saw that different estimates are there, not one method is important there are multiple methods depending on the data depending on the cost, depending on the time for the research project.

Let us look at some Physical methods. This needs a lot of physical data, the soil water balance method by Thornthwaite is an example, where you construct a hydrological water balance only for the soil because you do not care about the evaporation you do not care about how much is left in the rainfall etc. You only care about how much water comes in and out of that what is the re-allocation to plants, animals etc. and how much water goes in.

So, this is a soil water balance method which is developed by Thornthwaite nothing else but a water balance which is focused on the soil water. So, the groundwater surface your water table in dashed lines and you have multiple instruments that can collect data different depths. For understanding ground recharge understand that the first set of tensio meters here will only look at infiltration, slow infiltration of water and then you have a rainfall gauge to look at how much rainfall is happening.

So, you have the input to the system. You are the first seepage infiltration into the system and then you start slowly monitoring your groundwater wells the soil electrical resistance is a device that is used to measure soil moisture, once a soil moisture is full 100 percent.

Then water goes down if soil moisture is 100 percent water still stays in the soil slowly recharging the soil motion not the groundwater, we are here looking at groundwater recharge, not soil moisture recharge, then we have observation wells which is your wells with a meter in it and all but Piezometers which are deep aquifer wells. So, these two are just wells, but the difference is the depth, you can see here how deep it is, it is a broken x axis sorry y axis.

So, it is not going in 10s and hundreds it goes in different units in depth in feet. Then you have Zero Flux Plane is that ZFP based on Darcy remember Darcy's is a saturated column and how water flows through this plane is determined by Darcy's flow. So, Darcy’s flow, if it is kept only in this soil profile gives you the groundwater recharge. After that you can use a Darcy's flow here to look at groundwater flow.

Remember your class notes then we use Darcy to estimate groundwater flow, but Darcy's principle can also be used as a recharge, all you are doing is shifting from the confined aquifer and unconfined aquifer into the zone where water is coming into the soil it is recharging and then comes out, which is recharge. Again recharge is also, is a flow it happens from top to bottom, it goes down in the soil profile.

So, there is a Groundwater level fluctuation method, which is one of the most important methods used worldwide, including USGS including CGWB, there always people use this ground water level fluctuation method for which there is a need of groundwater data. And then you have the Groundwater balance method which is another soil water balance type of water balance but only cared for the groundwater.

We have already seen these water balance equations in the previous class, all of these need extensive data that is the driving point. Then you have tracer techniques here comes the kind of an invasive way of testing ground water because you are now getting into contact with the water here you just measuring the water that said here you are putting something in the water to measure.

Please understand here it is need of not data alone, but need of chemicals, we are going to put a chloride you are going to put a chloride to see how the chloride signal travels or traces like environmentally friendly traces inks you can put it in to see how one would recharge happens. But then there are Tritium Method and Stable Isotope method which are water signature methods which are based on the chemical property of the water.

So, traces not only include the aches and bio biological or chemical traces that you add in the water, it can be also done by analyzing the water chemicals components for the isotopes that are present. In fact, the isotopes are very useful for understanding the age of the water.

Then finally, we have the numerical methods which are based on pure modeling. There are software's which actually ask you for a lot of data and then it is data heavy, but there are models which can also estimate for you, you just have to tell this is the type of soil, this is the rainfall, this is the crop I am growing, it automatically tells you the groundwater recharge.

And within the groundwater model, you have multiple dimensions there can be a 1D which is just looking at 1 dimensional moment of water, there can be a 3D, where Kx alone is not only there but 1 also we have Kc, Ky and Kx, so, 3 dimensions how groundwater moves, and the net groundwater flow is going to be modeled. Hydrolysis is a good one for 1D whereas MODFLOW is a very good model for 3d.

Then you have inverse modeling, which is also based on lot of data. So, here we have seen that establishing these connections on how recharge happens, like the physical establishments, you can have different estimates based on different methods. There is no one method that is being promoted across the world. It depends on your region. It depends on the data you have the time and the resources.

For example, for numerical methods, it is very important to have a very sophisticated computer otherwise the model will crash, for traces you need a good environmental tracer or clearance from the government to test this traces most importantly, the stable isotopes and tritium would need a radioactive lab it is not easy to do all these the physical matters are more easier you have to put data collecting monitoring sensors collect the data come back do the calculations by hand or by computer and then you estimate.

So, there is give and take in each method and what method is suitable for you, you could use it for the long run, so, we have looked at the different methods. We will look into one or two methods for this class and then we will jump into the discharge methods. With this I will see you in the next class. Thank you.