

**Environmental Remediation of Contaminated Sites**  
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**Lecture - 20**  
**Remediation of Contaminated GW**

Hello everyone, again welcome back to the latest lecture session. So in the last session, we were looking at designing the relevant PRB, designing the PRB meaning we are trying to get the or estimate the thickness of the PRB required so that the relevant concentration of the compound, let us say will be decreased to the relevant regulatory standards or such or whatever design value you want to look at let say.

So in that context obviously we need to understand let us say how the concentration or the compound is going to be affected within that reactor right. So in that context we had to look at material balance or mass balance. So thus we in the previous class or session, we looked at the relevant material balance equation and we looked at 2 kinds of equation. One, the fundamental mass balance equation right and the other one an applicable to a macroscopic systems.

So typically when we say macroscopic systems we applied that equation when the concentration of the compound throughout that particular reactor or the volume or controlled volume is the same, but let us say ground water let us say and you take a control volume let us say you typically obviously notice that the concentration changes with distance. So in that context we also looked at the fundamental material balance equation. So what were the 2 equations that we had?

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$$\rightarrow \underbrace{V \frac{dc}{dt}}_{\text{Acc.}} = \underbrace{Q_i c_i}_{\text{mass in}} - \underbrace{Q_o c_o}_{\text{mass out}} + V (r_f - r_L)$$

$$\rightarrow \frac{dc}{dt} + \underbrace{u \frac{dc}{dx}}_{\text{diffusion}} = D \frac{d^2c}{dx^2} + r_f - r_L$$

$$\frac{dc}{dx} = \frac{c_2 - c_1}{x_2 - x_1}$$

→ S.S

$$u \frac{dc}{dx} = r_f - r_L \Rightarrow \frac{dc}{dx} = \frac{r_f - r_L}{u}$$



So far the macroscopic scale we had something like  $Vdc/dt$ . This was giving me an idea about the accumulation of the compound is  $=Q$  in  $C$  in. So mass coming in this will give me an idea about mass coming in per time obviously and  $Q$  out  $C$  out. This will give me an idea about mass going out + volume\* rate of formation -rate of loss as in, you know, reactions leading to formation of that particular material and loss of that particular material.

And this is our particular case for the macroscopic systems. And obviously we also looked at the case for a microscopic systems and that was  $= +udC/dx$ . So in that context we considered that the concentration was changing only along a particular value not value pardon me a particular direction or along the  $x$  direction in this particular case. So again what is this giving me an idea about and if we will just tried to relate that to this equation out here.

So  $udC/dx$  right if I tried to understand that in terms of  $\Delta c / \Delta x$  what is that going to be  $= c_2 - c_1 / x_2 - x_1$  right in a way again it is coming it is similar not in a way it is similar to what you have out here. If you take these terms out to the left hand side right. Again this is giving me an idea about the mass going out- the mass coming in. Again let me finish this equation it is going to  $=$  the diffusion relevant term diffusion coefficient into the second derivative here + rate of formation-rate of loss.

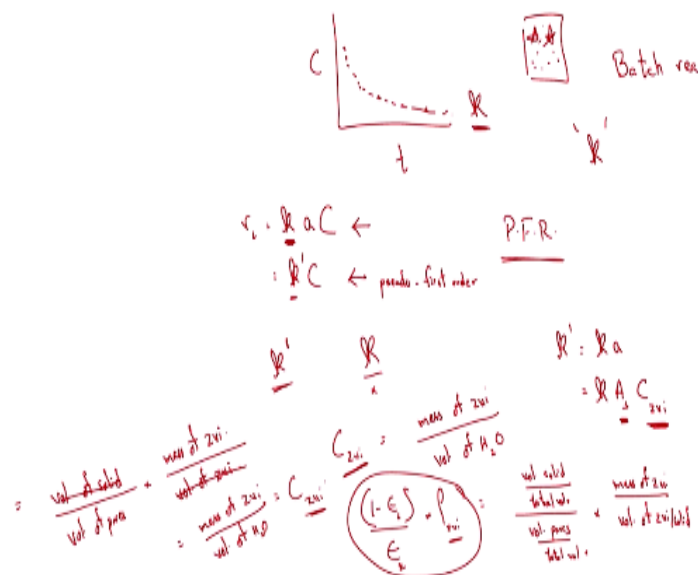
So this was the case when we considered that the velocity of flow of that particular fluid was constant and the flow was only in one direction let us say and also we assume that diffusion or dispersion is also relevant only in one direction. Obviously if it is relevant in the other direction we will have the  $Y$  and  $Z$  terms. Again this obviously is the fundamental mass

balance equation slightly tweaked to be able to apply that to the relevant groundwater though right.

But again we simplified this further and for our PRB case what did we come up with? We also looked at steady state. So when we look at steady state here at this particular term is 0 obviously. So we have  $u dC/dx = \text{rate of formation} - \text{rate of loss}$  assuming that there is no or the diffusion term is a negligible inside the PRB right. So we are now trying to get that what is happening inside the PRB.

So my control volume is the PRB right my control volume is the PRB and relevant compound is the component of interest here right so and this again transforms to  $dc/d\theta$ ,  $\theta$  is the (( )) (04:31) in this case called rate of formation- rate of loss. So one aspect is how do I get at this particular rate of loss. So in that context we talked about conducting experiments in the lab right? So you have a relatively similar reactive media. You will put the compound and measure the change in concentration with time.

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And then you will get to graph something like this. I have concentration here and time here batch reactor. I have relevant media and relevant compound. So I am going to write the concentration or have samples at different times and I will measure the concentration at those times. And then I can fit the model by regression and get the relevant K value right. So I can use this K value then for my particular PRB case, right?

So this is applying the mass balance for the batch reactor and then I will get the  $k$  value and then I will apply that in my plug flow reactor right. So one aspect that needs to be kept in mind is that we have our rate of loss is  $= \text{rate constant} \times \text{surface area per volume}$  right area of Zerovalent iron per volume of water times the concentration of compound right. So here I am using the  $K$  that are measuring in the lab, but typically what  $K$  am I measuring?

I am measuring the pseudo first order rate constant it is not the true rate constant I am measuring as in because I am going to put in a lot of Zerovalent iron let us say or a stoichiometric excess of Zerovalent iron. Typically, I can express this equation as  $k_{\text{dash}} \times C$ . So this as you see is not a second order as we see here, but it is a pseudo first order right. It is a pseudo first order. So typically in the lab we end up measuring  $k_{\text{dash}}$  and not the actual rate constant.

So when you are trying to use the same  $k_{\text{dash}}$  for the actual case of PRB in the ground. What issues should you be keeping in mind as in we know that  $k_{\text{dash}} = \text{rate constant} \times a$  and you know that  $a = \text{specific surface area} \times \text{concentration of Zerovalent iron}$ . So if you do not use the same kind of Zerovalent iron or the reactive media in your batch experiment in the lab and in the actual case that you are trying to estimate here then obviously there will be issues.

So you need to keep that in the mind. So if you use different kinds the surface area per what do we say mass of Zerovalent iron will be different or as in let us say simple example. Let us say because it is relatively cheap let us say I get some particular bigger size particle for my particular lab experiment, but in the actual PRB let us say I use relatively smaller size particles. So in that constant  $a$  case  $(( ))$  (07:20) is going to be different because the surface of Zerovalent iron available per mass of Zerovalent iron going to be different.

And so you cannot directly use that  $k_{\text{dash}}$  from the lab in the actual field or for the actual field designed you will need to be able to adjust that right same case with the concentration of Zerovalent iron whether it is the same or not in the lab and the actual condition. So that is something you should keep in mind because we are actually estimating  $k_{\text{dash}}$  and not  $k$ . So in that context obviously how can I calculate concentration of Zerovalent iron. So what is that equal to that the mass of Zerovalent iron per volume of water let us say.

I want to be able to calculate this. So how do I get this? If you look at this, we have  $1 - \text{porosity}$  times  $\text{porosity} \times \text{the density of that Zerovalent iron}$ . Let us say and what are the, how does this transform into what is porosity. Volume of pores/total volume and thus what does  $1 - \text{porosity}$  give you an idea about volume of solid/ total volume. Volume of solid obviously meaning that will be the volume of Zerovalent iron.

So density of Zerovalent iron what is that about? Mass of Zerovalent iron/volume of Zerovalent iron or the solid and what is that going to be=. Let me just write that out here that is going to be=I am going to cancel out the total volume here right. So it is going to be called to volume of solid by volume of pores  $\times$  mass of Zerovalent iron/volume of the solid which is Zerovalent iron right.

So here 2 aspects obviously what do we understand from volume of pores right. So in a PRB obviously the pores are filled with water so it is the volume of water. Volume of pores in this context would mean volume of water. So canceling these 2 terms the Zerovalent iron and the solid are the same in this context. So again obviously porosity refers to be the porosity of the Zerovalent iron right.

So I ended up with mass of Zerovalent iron per volume of pores which is nothing but volume of water in the PRB. So that is the concentration of Zerovalent iron right. So what do we how can we calculate that?  $1 - \text{porosity of Zerovalent iron} / \text{Zerovalent iron} \times \text{density of Zerovalent iron}$  gives you an idea about the concentration of the Zerovalent iron. So that is one aspect again that you need to keep in mind.

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$R'$   
 $\Rightarrow$   $\square$   
 Thickness of PRB.  
 $\frac{dC}{d\theta} = -r_L$   
 $\frac{C_\theta}{C_0} = e^{-R'\theta}$   
 $C_0, C_\theta, R', \theta \leftarrow$   
 $\theta = \frac{V}{Q}$   
 $Q = u_{avg} \cdot A$   
 $Q = E_{avg} \cdot A$   
 $\theta = E_{avg} \cdot A \cdot T$   
 Thickness of PRB: \_\_\_\_\_

So what do I have now? I have the rate constant or let us say pseudo first order rate constant yes and I can now get the relevant design done. So  $dc/d\theta = -\text{rate of loss here}$ . So again what is that going to be or how can I transform that into now. So if I integrate and so on a so forth  $C_t/C_0 = e$  to the power  $-k\theta$ .  $K$  here is the pseudo first order rate constant right Obviously rate of loss is  $k\theta$  time  $C$  right? it is not  $C$  here,  $C$  at  $\theta$  time  $C_0 = e$  to the power  $-k\theta$ .

So plugging in the relevant what do we say values here  $dc/d\theta = -kC$   $dC/dC$  pardon me  $dc/C = -k\theta$  times  $d\theta$  and again integrating that. This is what I end up with right. So what am I trying to calculate here? The whole point is I am trying to calculate the thickness right thickness of PRB. So how will I and you know so I have one particular equation from relevant mass balance here.

See when it enters the system is  $C_0$   $C$  when it leaves the system is  $C_\theta = e$  to the power  $-k\theta$ . So I can measure the concentration coming in which is I have  $C_0$  I know the concentration that I want when this compound leaves the system  $C_\theta$  and I already have  $k$  right. So what is it that I am trying to calculate? I'm trying to calculate  $\theta$  here. So I am trying to calculate  $\theta$  here.

So from this particular equation I can get  $\theta$  here right and what is  $\theta$  giving me an idea about the Hydraulic retention time or in this context, how much time is it relevant compound pending inside the PRB right. So that is what it is giving me an idea about and as we know

$\theta$  = volume of that particular system by the flow through that particular system. So what is the volume of that particular system?

It is going to be = to the porosity of that particular PRB times the cross sectional area of the PRB times thickness. Thickness let us say I will use the term okay I will write a  $t$  it  $t$  for thickness. So this is the volume of the PRB times porosity of the PRB is the volume of water obviously/divided by the flow of that particular water through that particular PRB right. So from here as you can see what do I have? I already have porosity I already have Hydraulic retention time. I calculated that out here. I have the cross-sectional area of the PRB right.

What is the length and height of the PRB equal to; it is going to be dependent upon the size distribution of the relevant plume right. So the plume is let us say a 100 meter wide and 2 meter thick not thick let us say height let us say. So relevant dimensions of the relevant PRB so from that I can get the cross sectional area and I know the flow rate let us say now what can calculate. I can calculate the thickness of PRB so that I can calculate here right.

So that is something I have and in this context one minor aspect though how can I get  $Q$  though? So for example, if I have Darcy's velocity  $u$  Darcy's velocity let us say and what is that going to be how do I get  $Q$  from Darcy's velocity into the cross-sectional area though right. So \*the cross section area, but if have the seepage velocity. Seepage velocity as in how is this different from the Darcy's velocity.

You can think of Darcy's velocity as in this is in the context of groundwater obviously. So let us say the average velocity of that particular fluid for that particular cross sectional area let us say. So this is the side view and the ground water is flowing through this particular system and this is my cross section area or let me draw the other side view and the groundwater is going in this direction towards the screen okay or into the screen let us say it is going into this.

So if this is the cross sectional area that is what I am talking about here the area of this particular system, cross section area times Darcy's velocity will give the flow of groundwater right, but if I do not have the Darcy's velocity but the seepage velocity. What is seepage velocity about? So here in groundwater you have soil and then the pores right. Where is the groundwater flowing through, through these pores right?

So the velocity of that particular ground water through these pores is called the seepage velocity. So if you obviously think about it the seepage velocity is going to be higher than the Darcy's velocity. So when you are writing it down or trying to calculate  $Q$ , you need to try to understand, do you have the Darcy's velocity or the seepage velocity. Let us say if this is the seepage velocity and times cross sectional area then I will end up with a higher value obviously right.

So I need to multiply that by the porosity of that particular aquifer. Keep in mind this is not the ground, PRB, but for the aquifer. So why did we look at that again how do I get  $Q$  the flow of the groundwater right. How can I get that? I can get that by multiplying the Darcy's velocity into the area relevant area or if I have the seepage velocity, I need to obviously look at it with respect to or try to modify it with respect to the porosity of the Aquifer right.

So these are aspects that you need to keep in mind. So obviously from this context we come up with the thickness of the PRB. So obviously if it is funnel and gate still the relevant calculations are still the same because we are just considering volume by  $Q$  the volume changes are the cross sectional area changes right. So with that I guess I will move on to the relevant aspect with respect to the case study right.

So until now we have looked at the relevant technical aspects. So let us look at a and a bit more detail where this PRB was applied at least initially anyway, you know, now it is relatively more widely used for most purposes out there. So the case study we are going to look at was one of the initial case studies done onsite actual site conditions. So they obviously conducted some laboratory experiments to get the data, choose 3 different kinds of reactive media right and they put in 3 PRBs in the ground water.

And this ground water was contaminated with uranium right say radioactive and other heavy metals too, but mostly they were concerned with the removal of uranium from the contaminated groundwater right and then they looked at the relevant efficiency of removal and then other parameters and I believe they monitored it for a year or 2 years so that they could use this particular case study to be able to judge let us say whether PRB is worthwhile for what do we say a wide scale or full scale and placement or such or usage pardon me.

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## Reference

Field Demonstration Of Permeable Reactive Barriers To Remove Dissolved Uranium From Groundwater, Fry Canyon, Utah

September 1997 through September 1998 Interim Report-EPA and USGS

So let us look at that case. So here the reference that I am going to look at here is, you know, all the data that I am going to present are figures are not what I developed there from this particular document available in the public domain. It is the field demonstration of PRB to remove dissolved uranium from groundwater and it was an Utah and it was run from September 1997 to 1998.

It was developed by EPA and USGS right Utah in the US okay. So I think I have that particular, you know, document here.

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The image shows the front cover of a report. At the top, it says 'United States Environmental Protection Agency' and 'Air and Radiation (6608J) Emergency and Remedial Response'. To the right, it says 'EPA 402-C-00-001 November 2000 www.epa.gov'. Below this, the EPA and USGS logos are displayed. The main title is 'Field Demonstration Of Permeable Reactive Barriers To Remove Dissolved Uranium From Groundwater, Fry Canyon, Utah'. Below the title, it says 'September 1997 through September 1998 Interim Report'. In the bottom left corner, there is a button that says 'MORE VIDEOS'.

So this is the relevant document that you can get. Let us say if you know, from the relevant internet, it is in the public domain again. So we are going to discuss the aspects you know that are presented in this particular document here for our case study now right. So let us go

back to where we are here okay. So this is the difference here. Again some background so looks like uranium let us say contamination can occur due to multiple what do we say sources.

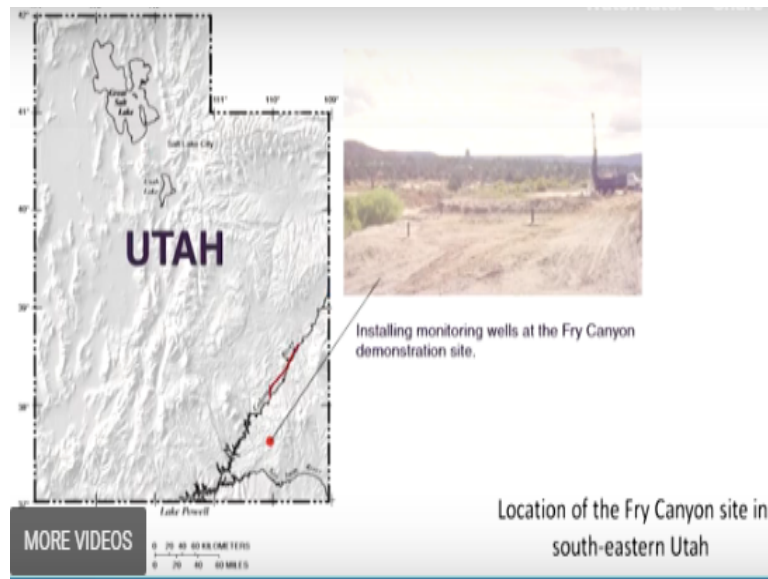
One source is obviously if I let us say have uranium a source and I am digging for uranium or uranium mine let us say. Obviously the relevant waste or such, or you know, the leachate let us say I can have the relevant uranium contamination or leading to uranium contamination, but looks like a, you know, there is another case that is relatively more, you know, the major source. Let us say for uranium contamination in ground water.

So let us say you have other metals or ores and you are processing these ores or trying to upgrade the relevant quality of this particular ore. You also have radium and this particular ores. So when you are processing them, let us say you are going to have contamination of the relevant side with uranium and that is the case here.

So it looks like in the 60s or 70s, 1960s or 1970s or 50s rather pardon me. They had what do we say over processing units are over up gradation units in this particular vicinity and Fry Canyon in Utah right and at that time they had what did we say obviously uranium tailings, let us say from pressingly relevant ores. And from those particular tailings, they now had contamination of the relevant groundwater and the soil with uranium among other heavy metals right.

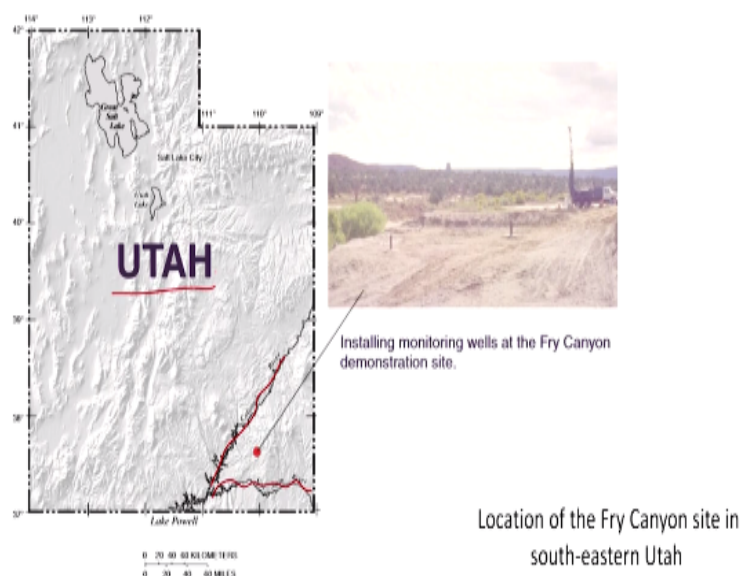
But they were primarily or they as we are going to look at were primarily concern with heavy metals now. So in that not heavy metals with uranium and then what did they do, they connect it some lab experiments, let us say on a huge number of what do we say types of reactive media then choose that 3 kinds of process, you know, seem to be better as in one with respect to adoption by bone char I believe right.

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And also precipitation or adsorption by amorphous ferric hydroxide and then the third one as in the case that we typically have looked at until now. First reduction and then precipitation onto Zerovalent iron. So 3 process they narrowed down their relevant options and then they choose conducted the relevant experiments choose one kind of material for each of these process put them in and went ahead for the analysis. So let us look at that now.

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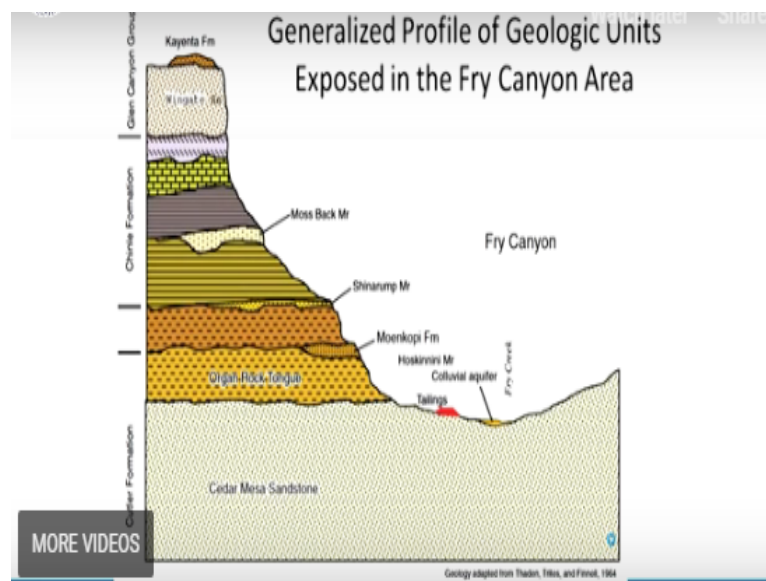
So what do we have here so I will say Utah it is near the Salt Lake. So I believe you have a particular rivers out here and I think in the vicinity of these particular surface water streams again just that it is in Utah I guess. So typically we are looking at the Fry Canyon site and the relevant site out here that is something that you can see here and you can see the installed monitoring wells and such.

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• Name of Site:	<u>Fry Canyon Site</u>
• Location Of Site:	Fry Canyon, UT
• Installation Year:	<u>1997</u>
• Containment:	<u>Uranium (U)</u>
• Construction Type:	<u>Funnel and Gate PRB</u>
• Design and Installation Cost:	<u>\$170K (estimated)</u>

Yes. So here Fry canyon site in Utah installation from 1997 and they looked at until 98 typically we are looking at uranium and the type that they looked at was not the continuous PRB, but the Funnel and Gate PRB right and the estimated cost was 1, 70,000 US dollars, but keep in mind that this is the estimated cost. Let us see what the actual cost turns out to be and what are the reasons I guess right.

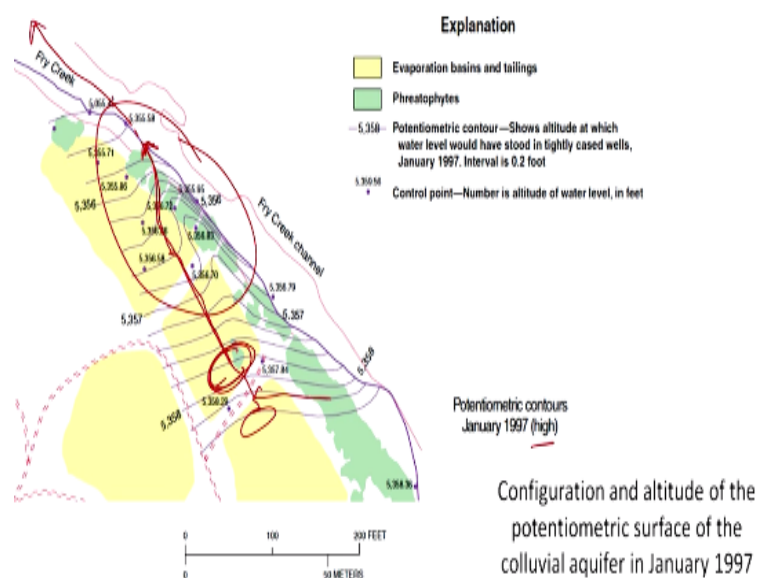
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So let us move on. So I believe I might have presented this earlier in my one of the two one of the slides or sessions right. So again they looked at the stratification and looked at the relevant geological units exposing the Fry Canyon area. So here you have the uranium tailings typically the source of your particular contamination. So 2 ways either you have runoff coming in contact and directly this is the Fry creek somewhere out here and relevant aquifer (()) (21:57) aquifer and keep in mind we have sandstone underneath here right.

So runoff from the tailings contaminated runoff reached the relevant aquifer or the Fry creek a small stream here or again percolation let us say and then contamination of the relevant (( )) (22:15). These are the relevant aspects, but typically they have a colluvial aquifer and then sandstone underneath and again keep in mind that there is a stream out here.

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So let us move on and I think we looked at this particular graph. So obviously they need to understand site categorization that is what we need to do obviously and obviously they need to understand the ground water flow. So for that obviously they had various control points from which they developed the potential matrix contours right, they developed the potential matrix contours they develop the contours. As you can see 5358, 5357 so on and so forth.

So I can try to understand the ground water flow direction here, but obviously the case is that the ground water flow direction changes especially in this case because you have a stream running nearby where is that as you see there is a channel out here Fry creek channel so this is the channel out here right. This is the surface water stream that we are considered with. So depending upon the rainfall and amount of rainfall these contours can change because typically let us say in the dry season the aquifers.

Let us say the subsurface aquifers or aquifer let us say is going to or the ground water is going to flow from this aquifer to the surface water that is how the surface water is recharged, but during rainfall the case can be that you know the surface water acts as recharge for this

particular ground water here. Yes, so there are different aspects. So I think this was in October 1996 and let us try to understand 2 cases.

Once when we have low ground water level during the relatively dry season I guess right and this was July and you look at the profile here in this zone typically okay and we will move on to the case when we had relatively higher what do we see rainfall let us say during rainfall events and now you see that the contours have relatively changed yes. You can see the relevant different here.

So obviously depending upon where I am putting in my PRB right I need to be very much considerate of these changes in ground water flow direction why is that otherwise the groundwater flow or the flow lines can flow around the PRB so that is something I need to be considered and I think we did look at one of these relevant figures in one of the previous sessions as in the case was that initially the surface water was what do we say recharging the ground water.

Groundwater was flowing in this direction and then it was being contaminated somewhere out here I think contamination source was somewhere out here or here and then again the groundwater flow was reaching the aquifer. So what is the key here that these particular contaminate due to the ground water reaching the surface water stream can then be transported to a wider area right? So obviously we need to limit this particular aspect.

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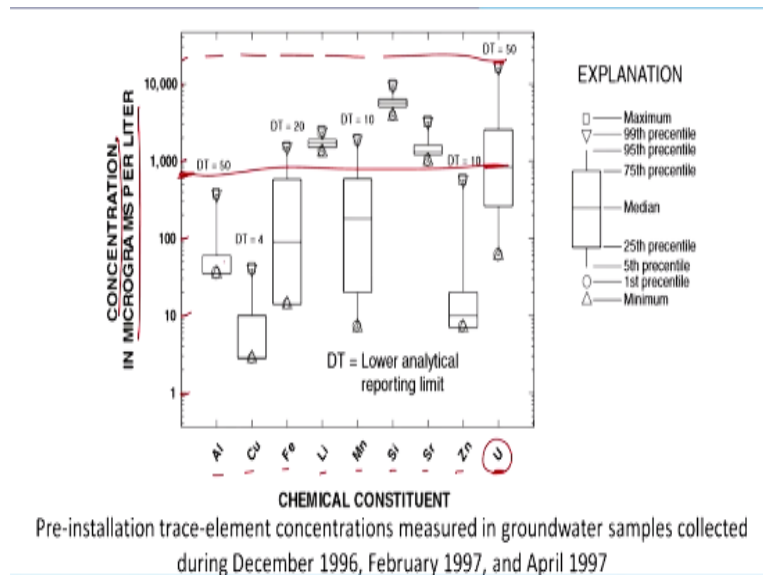
- U concentrations measured in groundwater at the Fry Canyon site prior to PRB installation were as high as 16,300 micrograms per liter ( $\mu\text{g/L}$ ) with a median concentration of 840  $\mu\text{g/L}$ .
  - Maximum Contaminant level (MCL) is 30 micrograms per liter ( $\mu\text{g/L}$ ) for Uranium in drinking water as per EPA.
-

And let us see what we have. So again the concentration seem to be as high as 16000 PPB, but typically the typically the average is 840 PPB and keep in mind that the limit is 30 PPB for uranium and drinking water as per their standards. So again 16,300 was the maximum but 840 PPB was the average. So keep in mind that again we talked about risk assessment right. So let us say if a person in the initial classes, we discussed risk assessment.

If you remember and in those classes, if you remember, we looked at calculating the risk based upon the exposure concentration. So as you see here if I took my particular mean or let us say median here, I guess not the mean median and 840 microgram per liter and that is used as a basis to calculate the risk assessment. The scenario would be much different from what let us say a person exposed to the maximum concentration would be right.

As a risk assessment calculated from median as you see will be widely different from the risk assessment or risk pose when I calculate the relevant risk assessment or risk pardon me again from this maximum concentration. So these are aspects obviously we need to keep in mind we are not going to go into that in detail now.

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So here we have concentration in PPB right and here we have different metals as I mentioned these are in ground water and this is where we have Uranium and we have other heavy metals too. So obviously the median is somewhere out here as we mentioned 840 or something like that this is the logarithmic scale as you can see and as you can see the maximum is around 16000 or so.

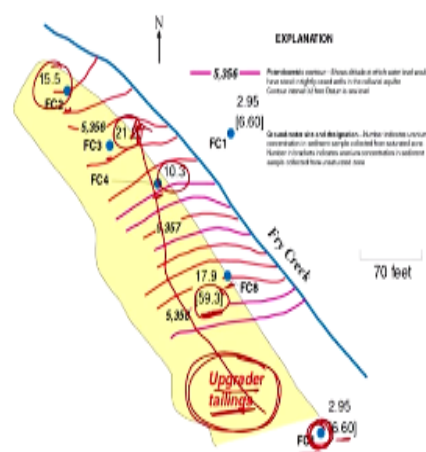
The maximum is around 16000 the median is around 840 or what was the value please 840 right and obviously you have other compounds some at relatively higher concentration than Uranium some much lower though right. Again just to the profile of they took the relevant samples from different samples and only then can they get this relevant picture as in maximum, median 75th and 25 percentile and so on, so that is what you see here.

Let us move on and also as you remember I guess one of the aspects where or one of the scenario where this PRB is much relevant or worthwhile or would add to the advantage let us say or is advantageous when compared to the other options is that you know you have absorption of the relevant contaminate to the soil. Let us say or when you have a non-aqueous phase liquid. Obviously you cannot have a non-aqueous phase liquid in this case, but you can certainly have uranium absorbed down to the relevant soil right.

So it desorb overtime just pumping out the water and treating that particular contaminated plume will not work right because the time required for pumping out the entire contaminant right will take time. Again why is that because once you pump out the contaminated water this particular uranium absorbed on to the soil will now again desorb into the ground water right.

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Total uranium concentrations in subsurface sediment samples



So as you can see here looks like here is the contaminated compound or source of contamination the upgraded tailing which have high uranium concentration. And here you have what do we have one particular sample location upstream of that particular source of contamination and other sampling zones downstream of that contamination. So obviously as



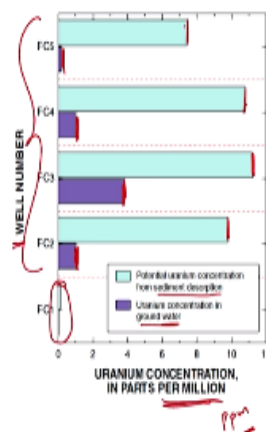
you see upstream or far upstream or (( )) (28:39) in the vicinity I guess it is relatively low but you see that the value is let us say near that particular or downstream of that particular.

So this is how let us say of the groundwater is flowing let us say yes you see that the values are relatively higher out here yes 21.2 and so on and again what are these values. These are not the values in the groundwater, but these are the values absorbed on to the soil and keep in mind that I believe these are PPM values not PPB let us just to look at that okay I have the relevant value later but I think these are PPM and not PPB.

For example, these are PPB parts per billion, but the concentration in the soil to my knowledge were PPM but let us look at that.

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## Uranium desorption results



Okay, I do have the graph here so well number and here you see that parts per million PPM right. What do we have here? Uranium concentration from sediment absorption and uranium concentration in ground water. So as you can see in each of these well especially the one downstream. This is the one upstream and these are the wells downstream of the contaminated site. You see that the concentration in groundwater are relatively much lower compared to the concentration absorbed on to the soil right.

So keep in mind that when you are trying to take out the contaminant you also need to take out the contaminate absorbed on to or you know both the phases. So the compound here is in the phase of or dissolved in groundwater or in the aqueous phase and also absorbed on to the soil right. So again these are aspects that we need to consider but again looks I am running

out of time. So we will continue this discussion in much detail in the next session and I guess, that is from me for today and thank you.