B.Tech Project

APPLICATION OF LOW-SALINITY WATER FLOODING IN SANDSTONE CORES

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Acknowledgement

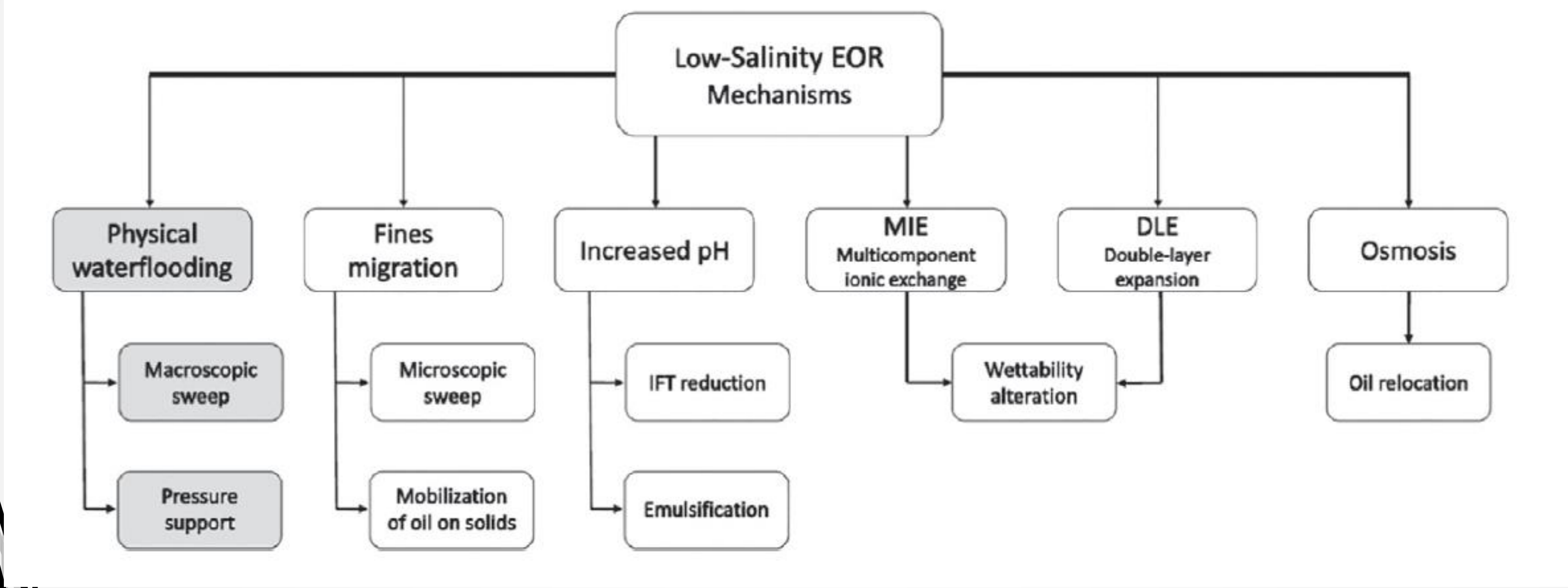
I would like to express my sincere gratitude to our guide Dr. Tushar Sharma for providing his invaluable guidance, comments and suggestions throughout the course of the project.

Onepetro research articles were also a big help for preparation of our research project

What we have learned so far In BTP 1?

- Concept of mobility ratio
- Conventional Water Flooding
- Factors affecting LSWF
- -Summary of laboratory experimental observation on low-salinity waterflooding.
- Concept of wettability

Our current approach



BTP-2 Report

- All the data that was taken for analysis has been referenced from the research articles mentioned on the bottom of the page.
- All the visualizations and analysis was done in Google Colab IDE, and python was used as the programming language.
- Used libraries were Matplotlib, seaborn for visualization and numpy, pandas for general operations

Variation of Remaining Oil Saturation with Injected Pore Volume

Composite core id	Core plug	Length [cm]	Diameter [cm]	K_{abs} [mD]	PV [ml]	Φ [fraction]	S_{wi} [fraction PV]
1		8.047	3.806*	164*	25.6	0.28*	0.294*
	1a	4.102	3.827	171	13.1	0.28	0.287
	1b	3.945	3.785	157	12.5	0.28	0.301
2		7.747	3.827*	92*	24.1	0.27*	0.322*
	2a	3.917	3.852	106	12.3	0.27	0.326
	2b	3.830	3.802	77	11.8	0.27	0.318

Step	Composite core 1		Composite core 2	
	Brine	Average remaining oil saturation [fraction PV]	Brine*	Average oil remaining saturation [fraction PV]
1	FW	0.245	LSW2	0.190
2	SW	0.235	LSW2	0.180
3	LSW1	0.219	LSW2	0.175
4	LSW2	0.216	LSW2	0.175

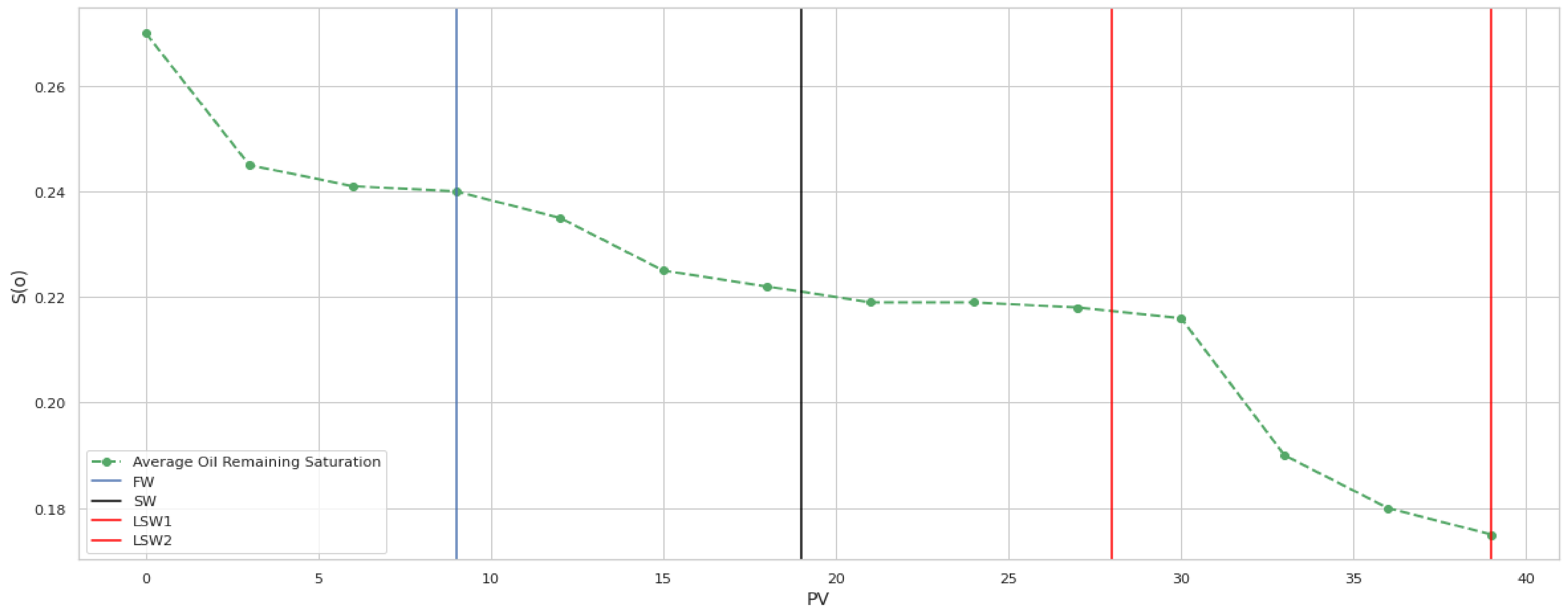
About experiment

- 2 types of core were taken
- Shut-in time after each step was 1 week
- Done for 4 different types of fluids(varying salinity)
- Graph of So(Avg. remaining oil saturation) v/s Pore volume injected

Observation: It was observed that remaining oil saturation decreases with decreasing salinity as shown in the graph on next page.

http://www.onepetro.org/doi/10.2118/154142-MS

```
plt.figure(figsize = (20,8))
plt.plot(df1.PV, df1.Avg_So, 'go--', linewidth=2, markersize=6, label='Average Oil Remaining Saturation')
plt.axvline(x=9, label='FW')
plt.axvline(x=19, label='SW', color="black")
plt.axvline(x=28, label='LSW1', color='red')
plt.axvline(x=39, label='LSW2', color='red')
plt.xlabel("PV",fontsize=14)
plt.ylabel("S(o)", fontsize=14)
plt.legend()
plt.grid(True)
```



Core Flood Experiment

- The requirements of this process are the presence of negatively charged surface on the rock, polar components on oil phase and divalent cations in the injection brine. MIE takes places during LSWF by removing organometallic complexes and polar compound from the clay surface and substituting them with noncomplex cations.

- Experimentally, it was concluded that the injection of low-salinity water into a sandstone reservoir in which mineral structure are not present will not result in incremental oil recovery. LSWF has no positive effect on acidized or fired sandstone which was due to the absence of polar compounds that did not promote the interaction of clay minerals to release oil particles.

Test No.	Core No.	∅ (%)	PV (cm^3)	K (mD)	S_{wi} [a] (%)	S_{wi} salinity (ppm)	Inj. brine salinity 1st, 2nd, and 3rd steps (ppm) ⇒		
1	1	19.78	10.95	2.76	17.49	30 710	30 710	3990	2760
2	2	16.64	9.14	0.79	9.92	20 470	20 470	2670	1780
3	3	17.04	9.52	0.99	10.44	53 320	53 320	6930	4890
4	2	16.64	9.14	0.79	9.92	53 320	20 470	2670	1780
5	1	19.78	10.95	2.76	17.49	20 470	20 470	2670	1780

[a] S_{wi}: irreducible water saturation.

	Brine								
Ion content (mol lit^{-1})	FW1	FW2	FW3	LS1	LS2	LS3	LS4	LS5	LS6
Na^+	0.710	0.409	0.273	0.092	0.065	0.053	0.037	0.035	0.024
Mg^{2+}	0.081	0.047	0.031	0.010	0.007	0.006	0.004	0.004	0.003
Ca^{2+}	0.015	0.008	0.006	0.002	0.001	0.001	0.0007	0.0007	0.0005
K^+	0.015	0.008	0.006	0.002	0.001	0.001	0.0008	0.0007	0.0005
Cl^-	0.827	0.476	0.318	0.107	0.076	0.062	0.043	0.041	0.027
SO_4^{2-}	0.043	0.025	0.016	0.005	0.004	0.003	0.002	0.002	0.001
HCO_3^-	0.007	0.004	0.003	0.001	0.0006	0.0005	0.0004	0.0003	0.0002
TDS[a], g l^{-1}	53.32	30.71	20.47	6.93	4.89	3.99	2.76	2.67	1.78
Ionic strength (mol l^{-1})	1.053	0.606	0.404	0.137	0.097	0.079	0.054	0.053	0.035
pH@SC[b]	7.33	8.31	8.01	7.5	7.44	7.17	7	7.57	7.32

[a] TDS: total dissolved solids,
[b] SC: standard condition.

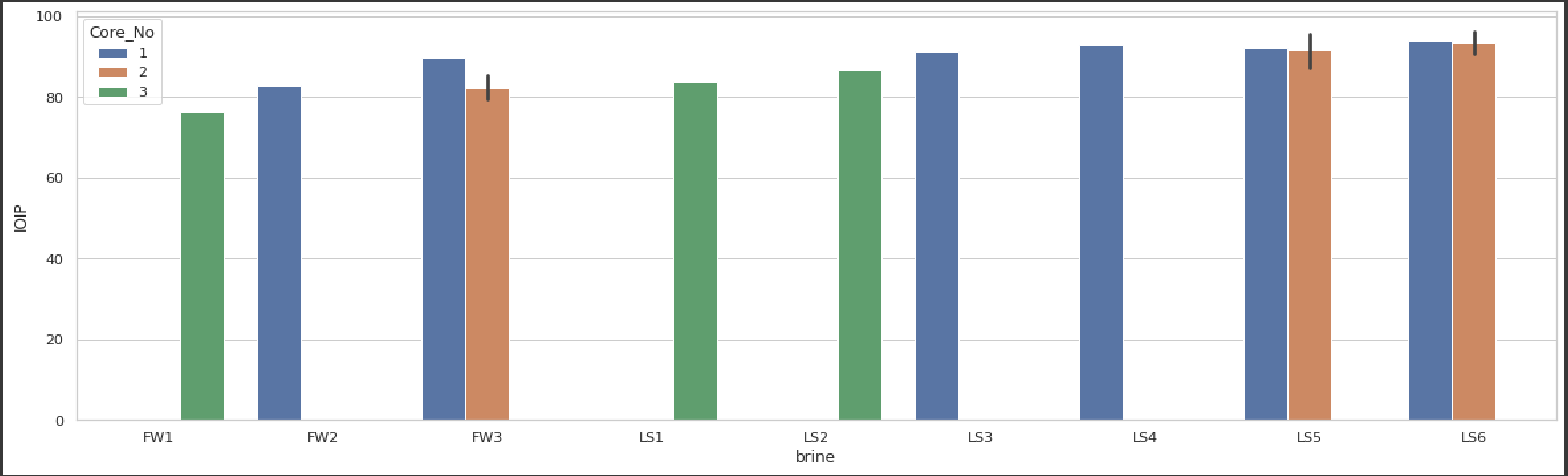
https://doi.org/10.1088/1742-2140/aaae84

```python
df2 = pd.read_excel("/content/drive/MyDrive/Project Requirements/Datasets/BTP/Book2.xlsx")
df2.head()
```

	Core_No	brine	IOIP
0	1	FW2	83.06
1	1	FW3	89.60
2	1	LS5	92.28
3	1	LS6	94.21
4	1	LS6	94.21

```python
import seaborn as sns
sns.set_theme(style="whitegrid")

plt.figure(figsize = (20,6))
ax = sns.barplot(x=df2.brine, y=df2.IOIP, hue=df2.Core_No, data=df2, estimator=np.mean, order=["FW1", "FW2", "FW3", "LS1", "LS2", "LS3", "LS4", "LS5", "LS6"])
```



Variation of Relative Permeability with Water Saturation

- Wyllie-Gardner Correlation

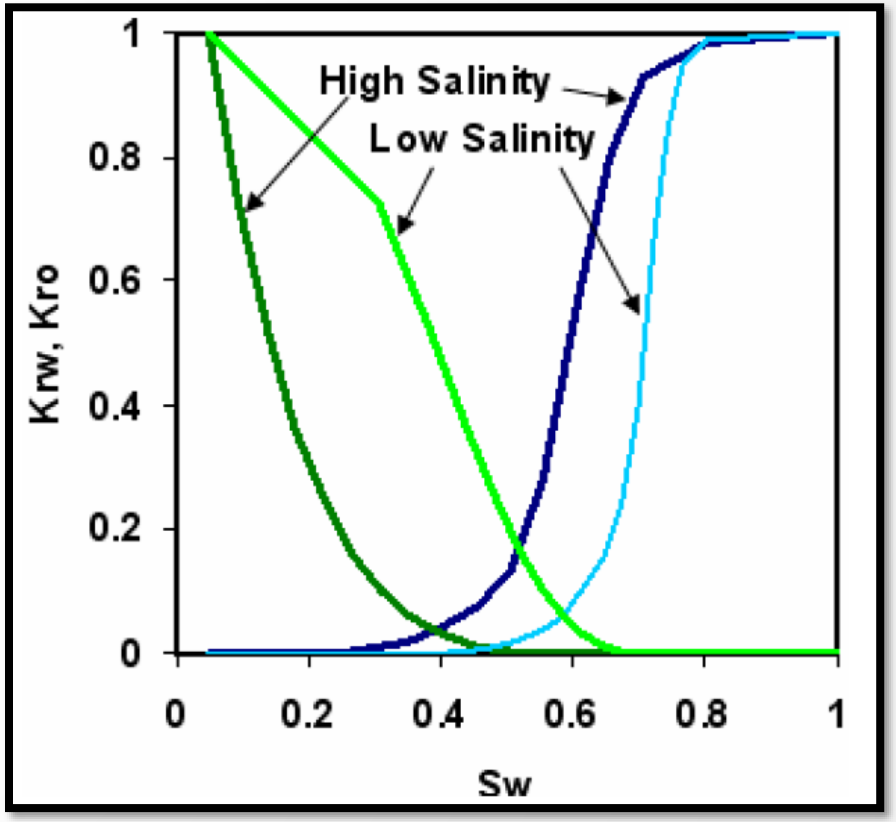
$$Krw = (S_o^{*})^{4}$$

$$Kro = \frac{(1 - S_o^{*})^2}{(1 - S_w^{*2})}$$

- Determination of Fractional Flow

$$fw = \frac{q_w}{q_t} = \frac{q_w}{q_w + q_o}$$

$$fw = \frac{1}{1 + \frac{Kro\,\mu_w}{Krw\,\mu_o}}$$



http://www.onepetro.org/doi/10.2118/102239-MS

Dr. Ir. Ratnayu Sitaresmi, 2016, The Study of the Effect of Water Saturation (Sw) on Fractional Flow and Water Cut to Determine Sw Cutoff, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 05, Issue 07 (July 2016),

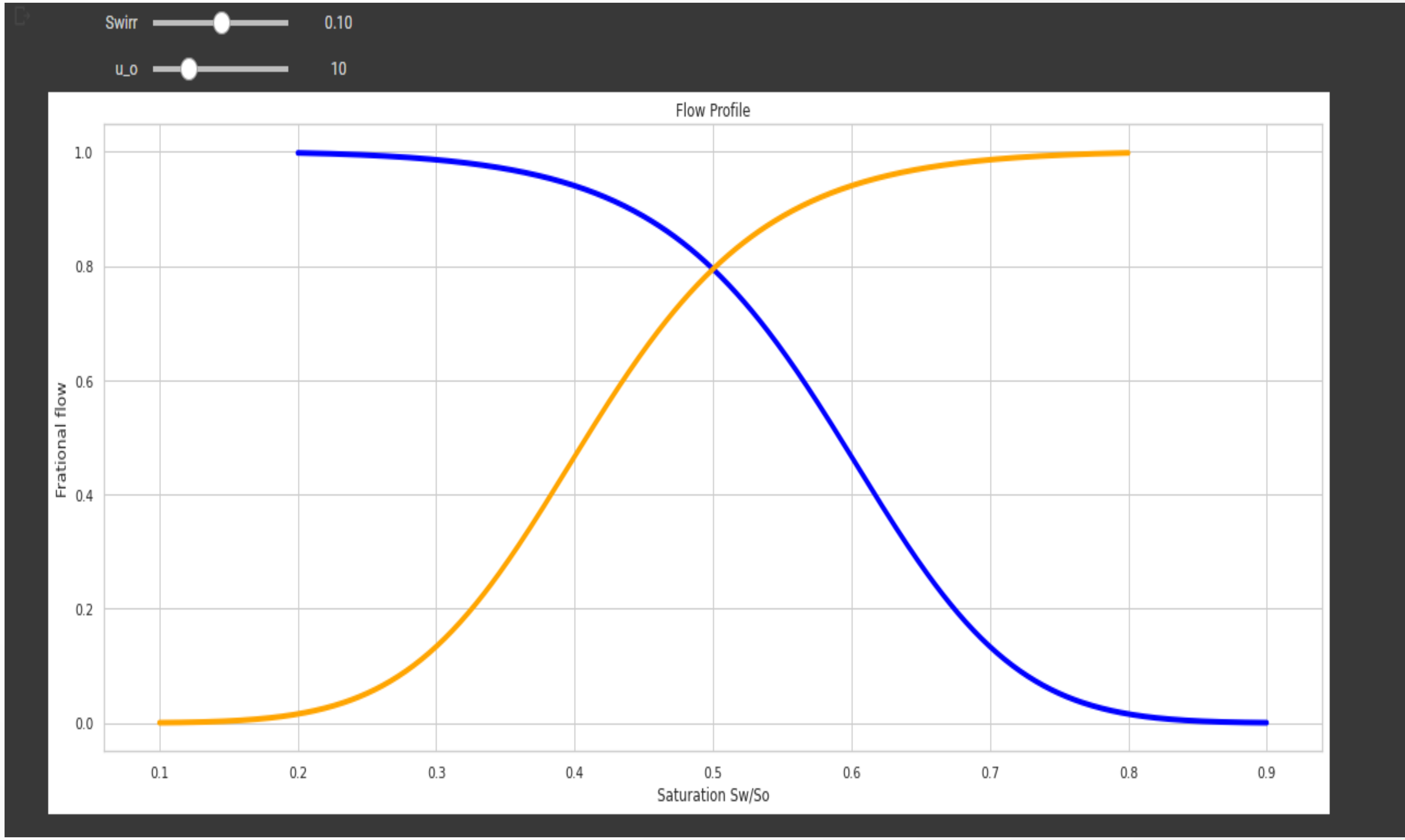
Interactive graph b/w Fractional Flow and Saturation

```
def var3(Swirr, u_o):
    u_w = 1
    Sw = np.linspace(0.2,0.9,500)
    So = 1-Sw
    So_ = So/(1-Swirr)
    Sw_ = (Sw-Swirr)/(1-Swirr)
    #Wyllie - Gardner Correlations
    Krw = (So_)**4
    Kro = ((1-So_)**2)/(1-(Sw_**2))
    ##
    Fw = 1/(1+((Kro*u_w)/(Krw*u_o)))
    plt.figure(figsize = (20,5))
    plt.plot(Sw, Fw, linewidth=4, color='blue')
    plt.plot(So, Fw, linewidth=4, color='orange')

    plt.xlabel('Saturation Sw/So')
    plt.ylabel('Frational flow')

    plt.title('Flow Profile')
    plt.grid(True)
    return Sw,Fw
```

```
x = interactive(var3, Swirr = (0,0.2), u_o = (0,40) )
display(x)
```



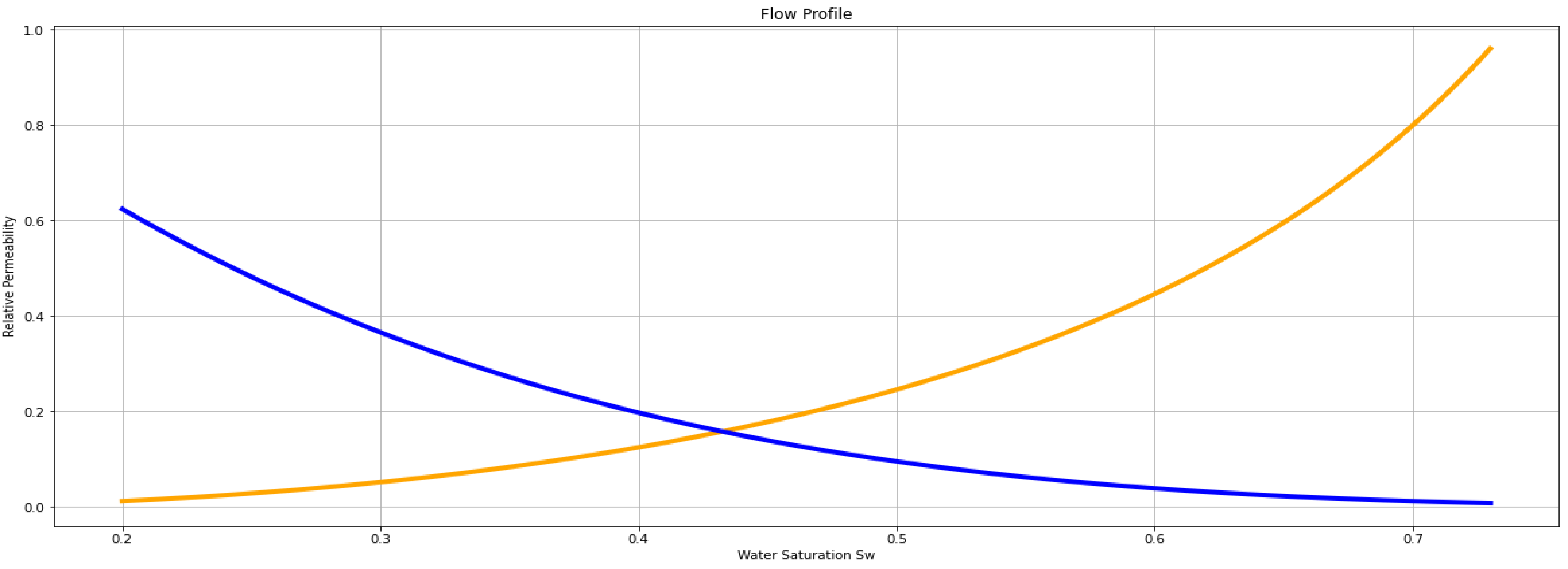
```
    plt.plot(Sw, Kro, linewidth=4, color='orange')
    plt.plot(Sw, Krw, linewidth=4, color='blue')


    plt.xlabel('Water Saturation Sw')
    plt.ylabel('Relative Permeability')

    plt.title('Flow Profile')
    plt.grid(True)
    return Sw,Kro

display(interactive(var4, Swirr = (0,0.2) ))
```

Swirr 0.10

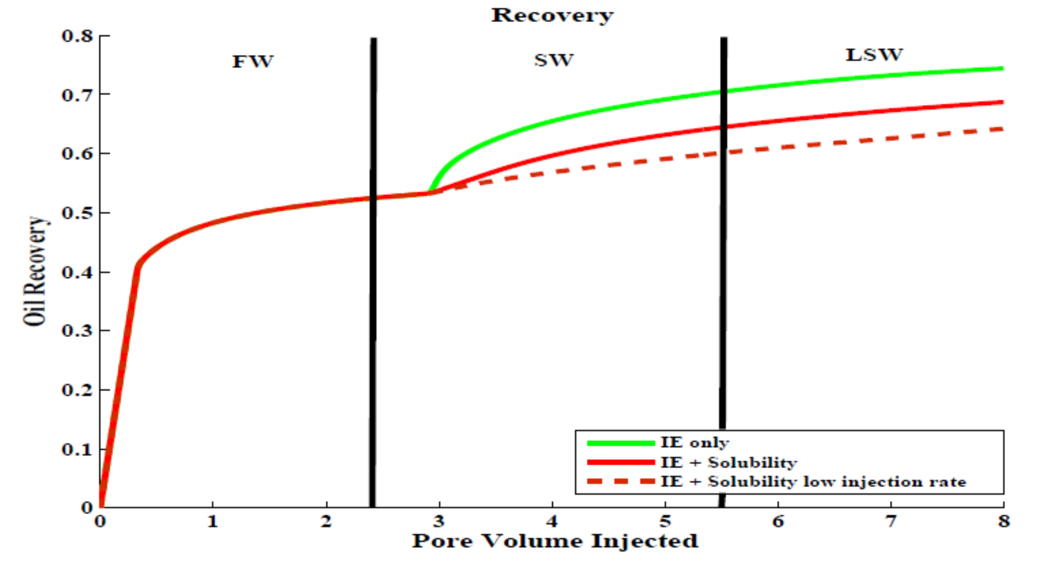


Ionic Exchange

- This is basically the alteration in the wettability of reservoir rock towards more water-wet due to the release of oil particles from the clay surfaces.

- Low-salinity water expands the double layer and eases the process of desorption of divalent ion on oil bearing to take place. Divalent cations such as Ca2+ and Mg2+ from the injected low-salinity brine control this process that results in ion exchange

Ions	FW [mol/l]	SW [mol/l]	LSW [mol/l]
Na^+	2.3663	0.7341	0.0654
Cl^-	2.4245	0.8807	0.0727
Ca^{2+}	0.0264	0.0166	0.0098
Mg^{2+}	0.0066	0.0938	0.0027
SO_4^{2-}	0.0039	0.0371	0.0009



Length of core (cm)	12.0
Mass of clay (Kg/Litre Core)	0.088
CEC (moles/Kg of clay)	0.013
Porosity	0.274
Absolute permeability (mD)	150.0
Oil viscosity (cP)	8.0
Injection velocity (cm/day)	42.0
Injection velocity (low) (cm/day)	4.2
Relative permeability	Synthetic

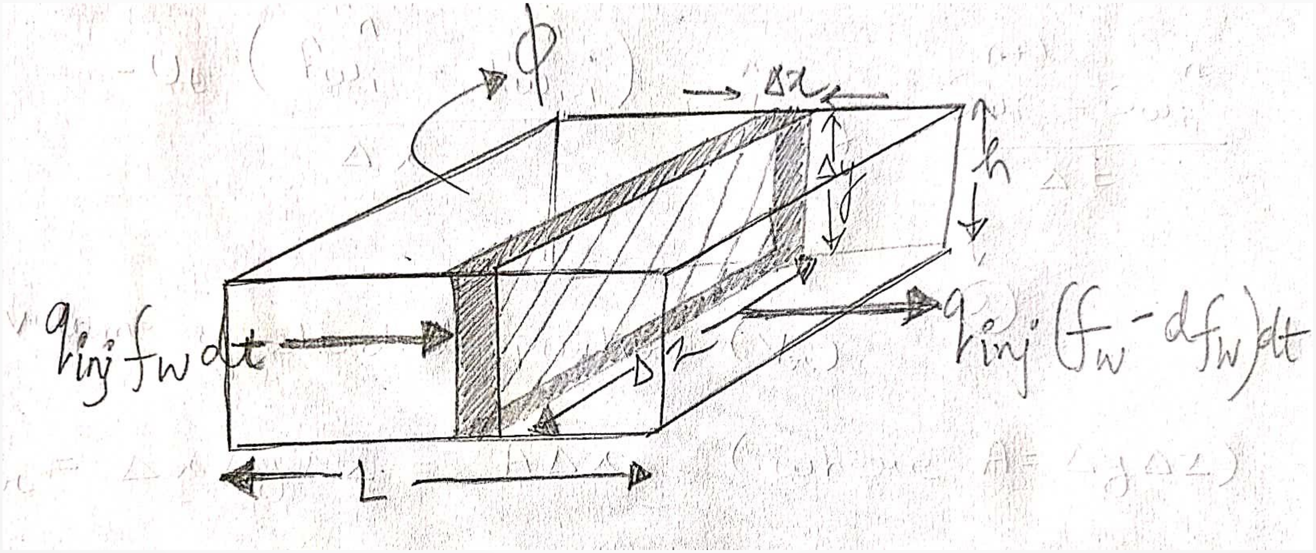
https://doi.org/10.2118/129724-MS

Numerical Analysis of Buckley-Leverett Theory

$$q_{inj} f_w \, dt - q_{inj} (f_w - df_w) \, dt = A \phi (dx)(dS_w)$$

$$q_{inj} \, df_w \, dt = A \phi (dx)(dS_w)$$

$$\frac{dx}{dt} = \frac{q_{inj}}{(\phi A)} \left(\frac{df_w}{dS_w} \right)$$



$$V_t = \frac{q_{inj}}{A}$$

$V_t \rightarrow$ Darcy velocity

$U_t \rightarrow$ Interstitial velocity

now, $-U_t \frac{\partial f_w}{\partial x} = \frac{\partial S_w}{\partial t} \rightarrow (1)$

Discretize the above equation (1)

$$-U_t \frac{\left(f_{w_i}^{n} - f_{w_{i-1}}^{n}\right)}{\Delta x} + \hat{q}_{inj} = \frac{S_{w_i}^{n+1} - S_{w_i}^{n}}{\Delta t} \quad (2)$$

now, volume of shaded portion (V_r)

$V_r = \Delta x \Delta y \Delta z = A \Delta x$ (where $A = \Delta y \Delta z$)

Also, $\hat{q}_{inj} = \frac{q_{inj}}{V_r}$

multiplying eq 2 by V_x

$$\Rightarrow -U_t A \left(f_{w_i}^{n} - f_{w_{i-1}}^{n} \right) + q_{inj} = A \frac{\Delta x}{\Delta t} \left(S_{w_i}^{n+1} - S_{w_i}^{n} \right)$$

now, $\because U_t = \dfrac{V_t}{\phi}$

$$\Rightarrow -\frac{V_t}{\phi} A \left(f_{w_i}^{n} - f_{w_{i-1}}^{n} \right) + q_{inj} = \frac{A \Delta x}{\Delta t} \left(S_{w_i}^{n+1} - S_{w_i}^{n} \right)$$

$$\Rightarrow \frac{q_{inj}}{\phi} \left(f_{w_i}^{n} - f_{w_{i-1}}^{n} \right) + q_{inj} = \frac{A \Delta x}{\Delta t} \left(S_{w_i}^{n+1} - S_{w_i}^{n} \right)$$

$$\Rightarrow \left(S_{w_i}^{n+1} - S_{w_i}^{n} \right) = \frac{-\Delta t}{A \Delta x} \frac{q_{inj}}{\phi} \left(f_{w_i}^{n} - f_{w_{i-1}}^{n} \right) + \frac{\Delta t \, q_{inj}}{A \Delta x}$$

$$\Rightarrow \boxed{S_{w_i}^{n+1} = -\frac{\Delta t}{A \Delta x} \frac{q_{inj}}{\phi} \left(f_{w_i}^{n} - f_{w_{i-1}}^{n} \right) + \frac{\Delta t \, q_{inj}}{A \Delta x} + S_{w_i}^{n}}$$

While deriving the Frontal Advance Equation, we take the water saturation to be constant but here we have derived the relation without keeping water saturation constant.

Corey's Relations

- From the general equation we arrived at an expression using Corey type equations which were used to calculate the oil and water relative permeabilities, and oil/water mobilities.

- Interactive graph between fo v/s Kro with variable relative water permeability.

$$\lambda_o = \frac{k_{row}}{\mu_o}$$

$$\lambda_w = \frac{k_{rw}}{\mu_w}$$

$$f_w = \frac{\frac{k_{rw}}{u_w}}{\frac{k_{rw}}{u_w} + \frac{k_{row}}{u_o}}$$

Interactive graph b/w Oil Fractional Flow and Relative Oil Permeability (Using Corey relations)

```
[4]  from ipywidgets import interact, interactive
     from IPython.display import clear_output, display, HTML
```

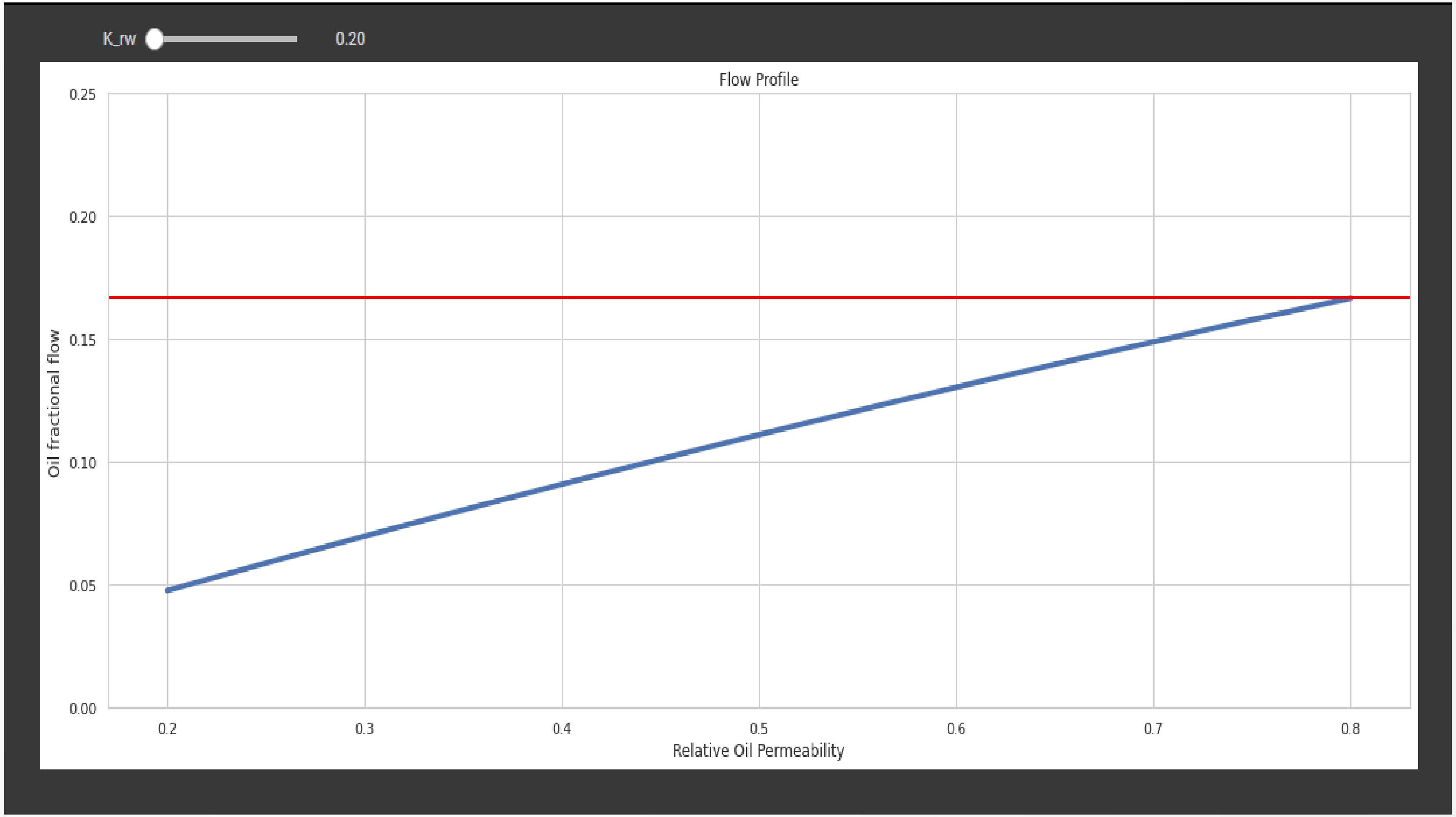
```
[5]  def var2(K_rw):
       Mu_w = 1
       Mu_o = 20
       K_ro = np.linspace(0.2,0.8,500)
       Lambda_o = K_ro/Mu_o
       Lambda_w = K_rw/Mu_w
       F_o = Lambda_o/(Lambda_o + Lambda_w)
       plt.figure(figsize = (20,8))
       plt.plot(K_ro, F_o, linewidth=4)

       y_max = F_o[np.where(K_ro == 0.8)]
       plt.axhline(y_max,linewidth=2,color='red')
       plt.ylim(0,0.25)

       plt.xlabel('Relative Oil Permeability')
       plt.ylabel('Oil fractional flow')

       plt.title('Flow Profile')
       plt.grid(True)
       return K_ro,F_o
```

```
[6]  w = interactive(var2, K_rw = (0.2,0.8) )
     display(w)
```



Conclusion

- **We have observed the effect of injection water salinity on relative permeability.**
- **We have related injection salinity with relative permeability but have not found an empirical correlation but we have found the correlation b/w Relative permeability and saturation using the equation derived from Buckley Leverett model which directly relates to oil recovered.**
- **From graphical analysis, we found out that after decrement of salinity values to a certain extent the oil recovery factor almost became constant. So further injection was not needed which saves time and cost.**

Thank you