Analytical Model for Leakage Detection in CO_2 Sequestration in Deep Saline Aquifers: Application to ex Situ and in Situ CO_2 Sequestration Processes

Ahmadi, M.A., & Chen, Z., 2019.
***ACS Omega, 4*, 21381 - 21394.**

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Date : 2023/05/26

OUT LINE

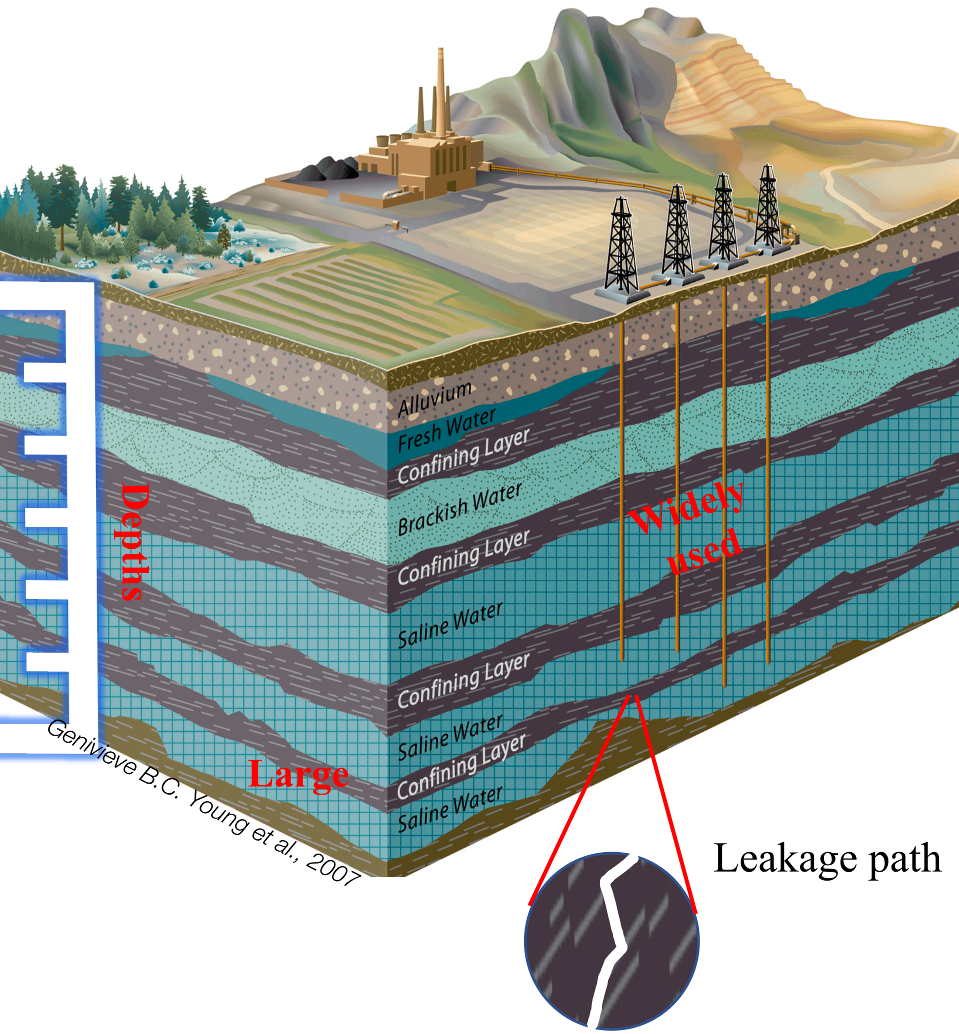
1. INTRODUCTION

2. METHODOLOGY

3. RESULTS AND DISCUSSION

4. CONCLUSIONS

What are CO_2 SEQUESTRATION & DEEP SALINE AQUIFER?



CO_2 SEQUESTRATION

- Carbon capture and storage **(CCS)**
- **Capturing** carbon dioxide emissions
- **Reduce** GHGs and **mitigate** the impacts of climate change

*The USGS is conducting assessments on two major types of carbon sequestration: **geologic** and biologic.

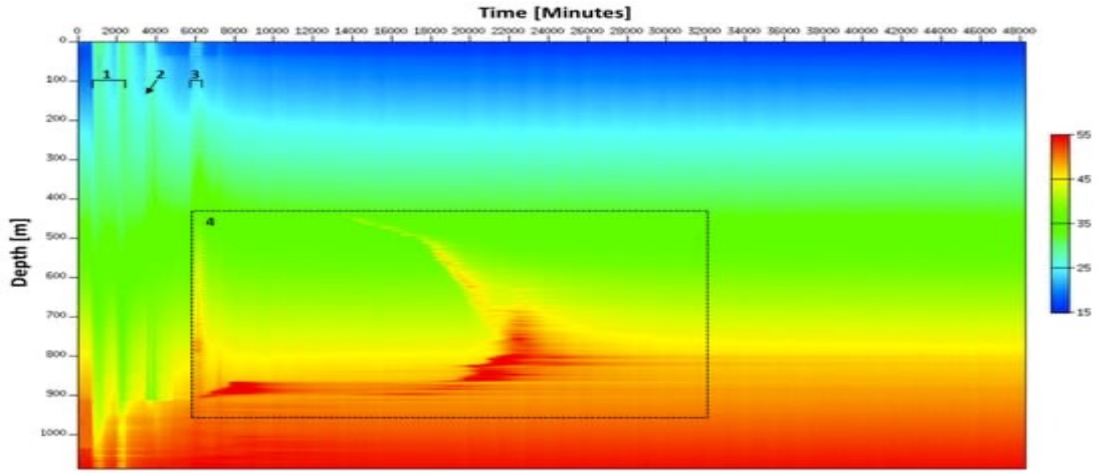
DEEP SALINE AQUIFER

Deep saline aquifers is one of the **main candidates** to cut anthropogenic CO_2 emissions.

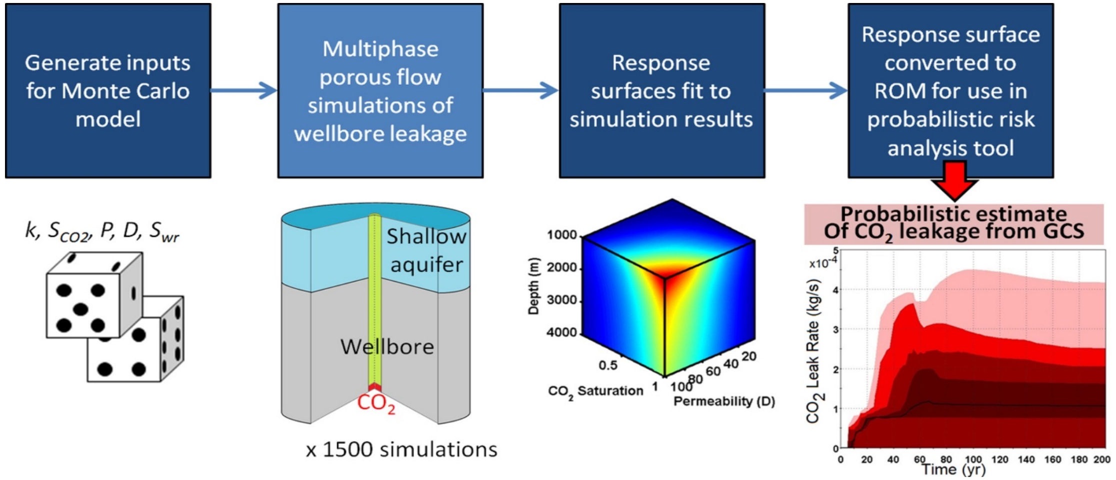
! Nevertheless, saline aquifers mostly **do not** have competent sealing cap rocks.

LITERATURE REVIEW

Different methods can be employed for detecting CO_2 leakage during the sequestration process:



Mao et al. (2017) and Zhang et al. (2018) used **the temperature distribution.**



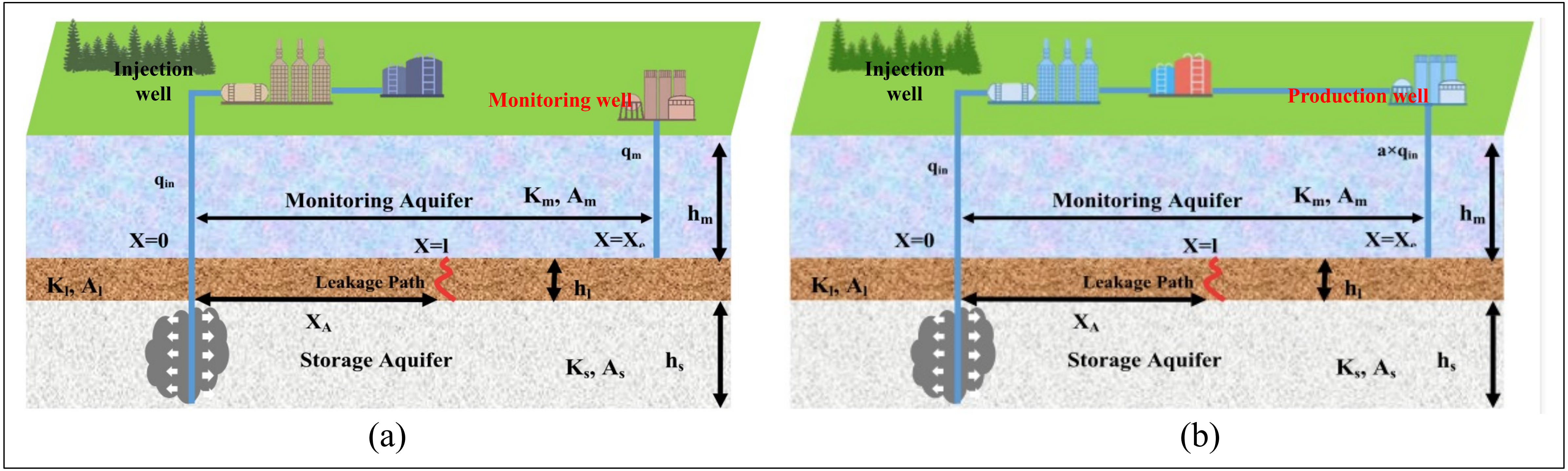
Jordan et al. (2015) used **a response surface method (RSM).**

In this work:

Pressure monitoring → **Detect and characterize leakage** ← **The rapid propagation of pressure**

Court (2012); Jung (2013); Nogues (2011); Sun (2012),…

MODEL DESCRIPTION



Schematic of the problem considered in this study **(a) In situ sequestration** and **(b) Ex situ sequestration**.

Legend:

X: The distances
K: Permeability
A: The area of formation
h: Thickness
q: Rate

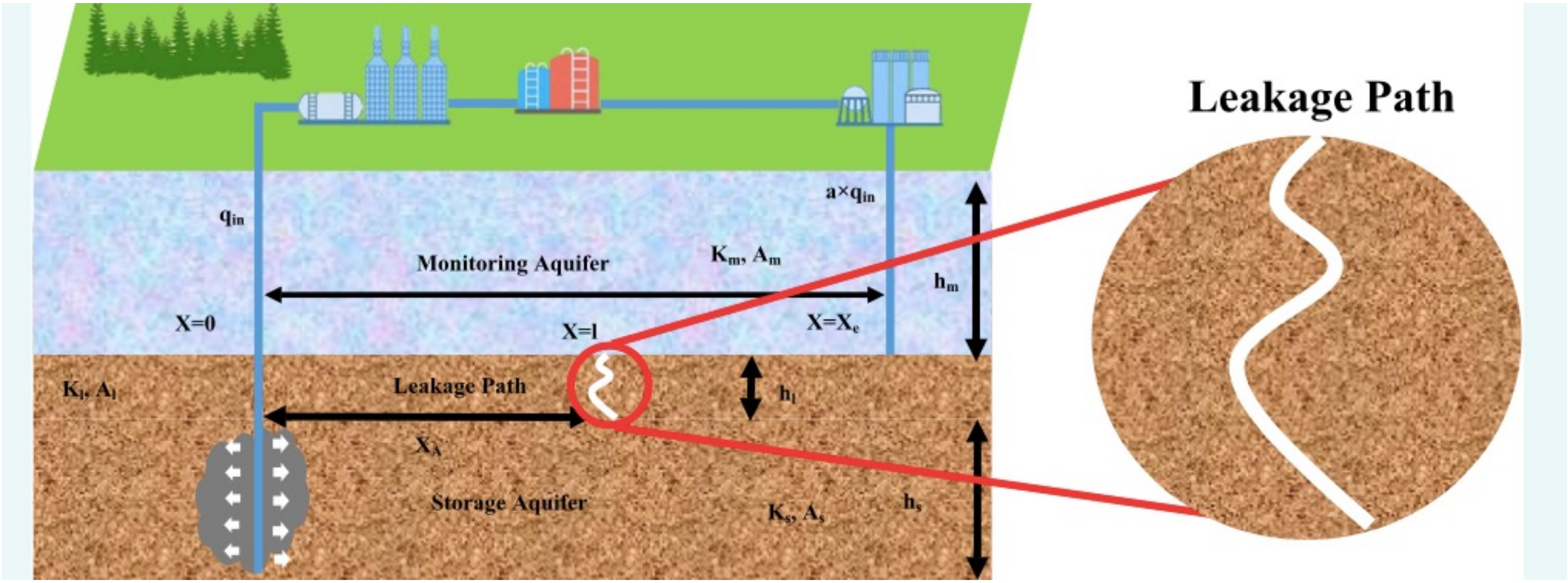
a: the ratio of production to the injection rate
m: monitoring well/aquifer
s: Storage aquifer
Subscript "A": Storage aquifer
l: leakage path

MODEL COMPARISON

	In Situ Sequestration	Ex Situ Sequestration
Process	CO_2 directly injected	CO_2 converted to CO_3^{2-} and then injected
Leakage Detection	Critical due to lack of competent sealing cap rocks	Still important but less critical due to carbonate formation
Efficiency	Higher efficiency due to direct injection	Lower efficiency due to additional conversion process

Objectives

Determining **dimensionless leakage rates** and **dimensionless pressure responses** due to leakage in both **in situ and ex situ** CO_2 sequestration processes.



GOVERNING EQUATION

Pressure Response of **the Monitoring Aquifer**

$$\frac{\partial^2 P_m}{\partial x^2} = \frac{1}{\eta_m} \times \frac{\partial P_m}{\partial t}$$

The initial and boundary conditions:

$P_m(X, t) = P_{mi} t = 0$

$P_m(X, t) = P_{mi} X \longrightarrow +\infty$

Where:
P_m: pressure in the mornitoring aquifer
η_D: diffusivity coefficient of the monitoring aquifer

Pressure Response of **the Storage Aquifer**

$$\frac{\partial^2 P_s}{\partial x^2} = \frac{1}{\eta_s} \frac{\partial P_s}{\partial t}$$

The initial and boundary conditions:

$P_{Ds}(X, t) = P_{si} t = 0$

$P_s(X, t) = P_{si} X \longrightarrow +\infty$

Where
P_s: pressure of the storage aquifer
η_D: diffusivity coefficient of the monitoring aquifer

Leakage rate equation

$$q_l(t) = \frac{K_m A_m}{\mu B} \times \frac{dP_m}{dx} \; at\, X = X_A$$

Where:
q_l: leakage rate
K_m : Permeability of monitoring aquifer
B: formation volume factor

GOVERNING EQUATION WITH DIMENSIONLESS VARIABLES

Pressure Response of **the Monitoring Aquifer**

$$\frac{\partial^2 P_{Dm}}{\partial x_D{}^2} = \frac{1}{\eta_D} \times \frac{\partial P_{Dm}}{\partial t_D}$$

The initial and boundary conditions:

$P_{Dm}(X_D, t_D) = 0 \; t_D = 0$

$P_m(X_D, t_D) = 0 \; X_D \longrightarrow +\infty$

Leakage rate equation:

$$q_{lD}(t_D) = \frac{K_m A_m}{\mu B} \times \frac{dP_{Dm}}{dx_D} \text{ at } X = X_A$$

Pressure Response of **the Storage Aquifer**

$$\frac{\partial^2 P_{Ds}}{\partial x_D{}^2} = \frac{\partial P_{Ds}}{\partial t_D}$$

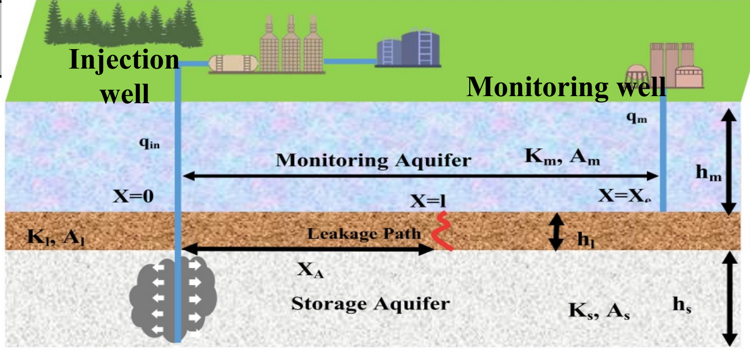
The initial and boundary conditions:

$P_s(X_D, t_D) = 0 t_D = 0$

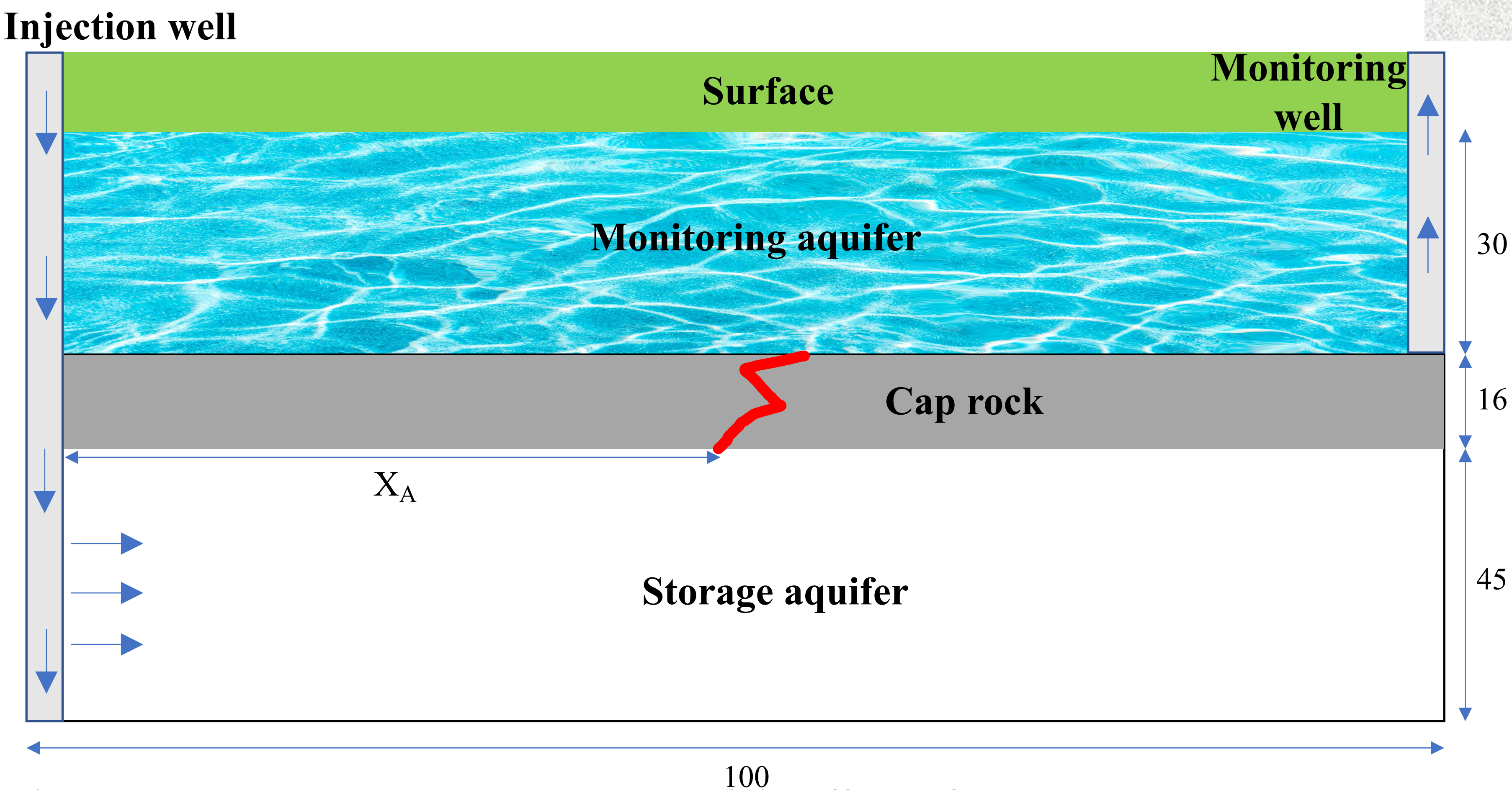
$P_s(X_D, t_D) = 0 X_D \longrightarrow +\infty$

$X_D = X/X_e$
$t_D = \frac{\eta_s t}{X_e{}^2}$
$T_D = \frac{K_m A_m}{K_s A_s}$
$P_{Dm} = \frac{K_s A_s}{q \mu B X_e}(P_{mi} - P_m)$
$P_{Ds} = \frac{K_s A_s}{q \mu B X_e}(P_{si} - P_s)$
$X_{AD} = X_A/X_e$
$\eta_D = \frac{\eta_m}{\eta_s}$
$q_{lD}(t_D) = \frac{q_l(t)}{q}$
$q_{inD}(t_D) = \frac{q_{in}(t)}{q}$
$q_{proD}(t_D) = \frac{q_{prod}(t)}{q}$

Table 1. Dimensionless Variables used for Driving the Dimensionless Form of Governing Equations.



In Situ CO_2 Sequestration Problem



- Analyze **pressure responses**, **leakage rate**, and the effects of **important parameters** on storage and monitoring aquifers.
- Two cases are examined with a sensitivity analysis of leakage path location and diffusivity. Details are presented in each case.

Synthetic Case 1

The analytical solutions are applied in which the dimensionless storage aquifer pressure response at the monitoring well and the dimensionless leakage rate are calculated.

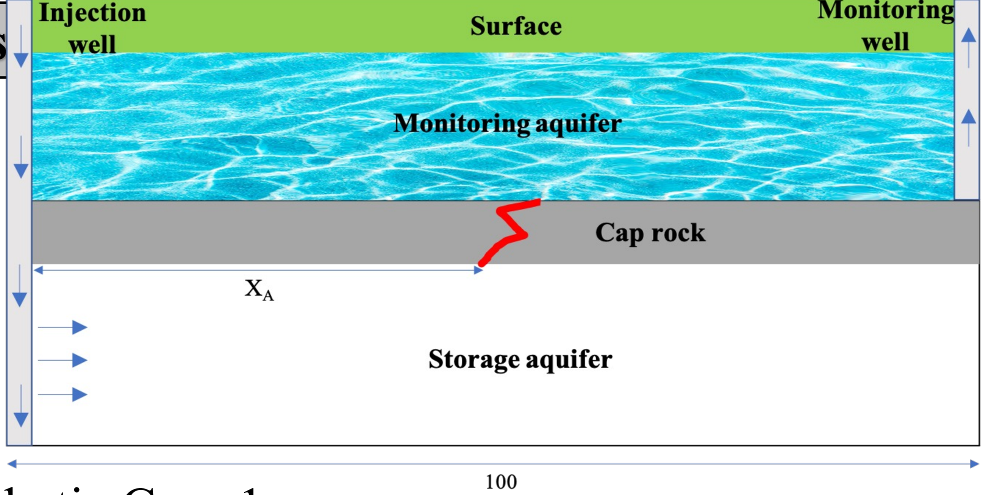


Table 2. Properties of the Storage and Monitoring Aquifers in the Synthetic Case 1.

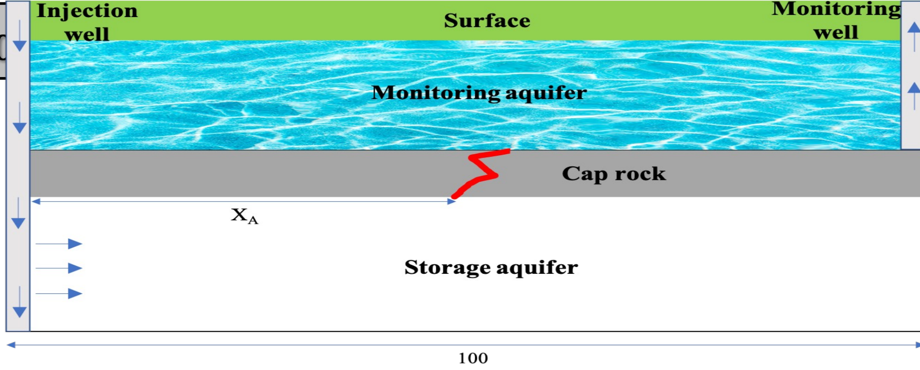
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
h_m	30	X_e	100	K_m	$2*10^{-13}$	η_m	2.67
h_l	16	T_D	0.026667	K_l	$2.5*10^{-15}$	η_s	5
h_s	45	μ	0.0005	K_s	$5*10^{-13}$	η_D	0.533
q	0.02	ϕ_m	0.15	c_s	$1*10^{-9}$		
X_A	50	Φ_s	0.2	c_m	$1*10^{-9}$		
X_B	50	B_w	1	A_s	4500		
X_{AD}	0.5	A_m	3000	A_l	1600		

Legend:

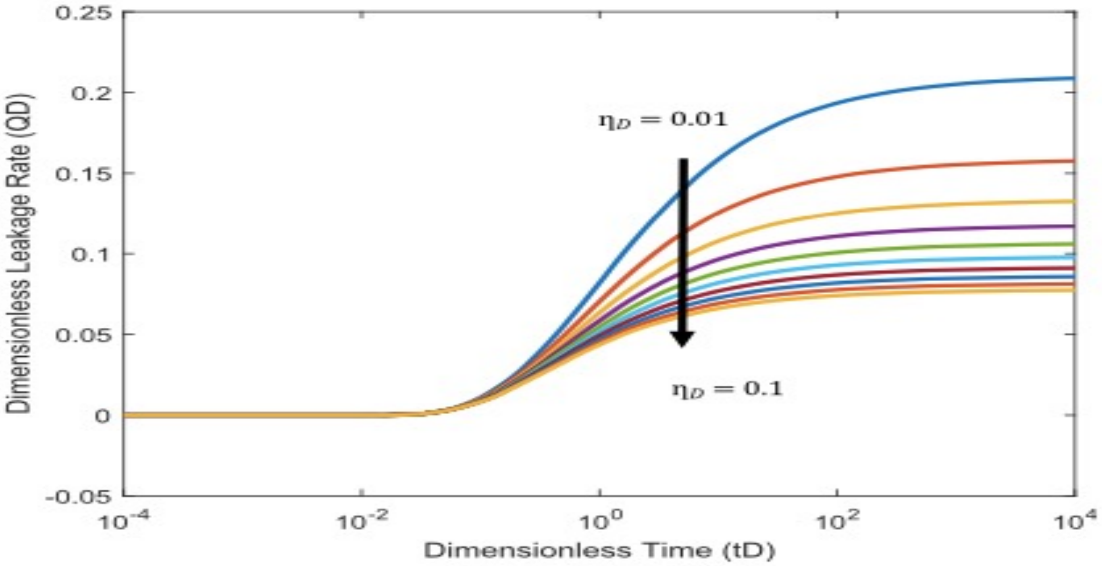
η_D : The dimensionless **diffusivity** coefficient

X_{AD}: Dimensionless **distance** between **leakage path** and **injection well**

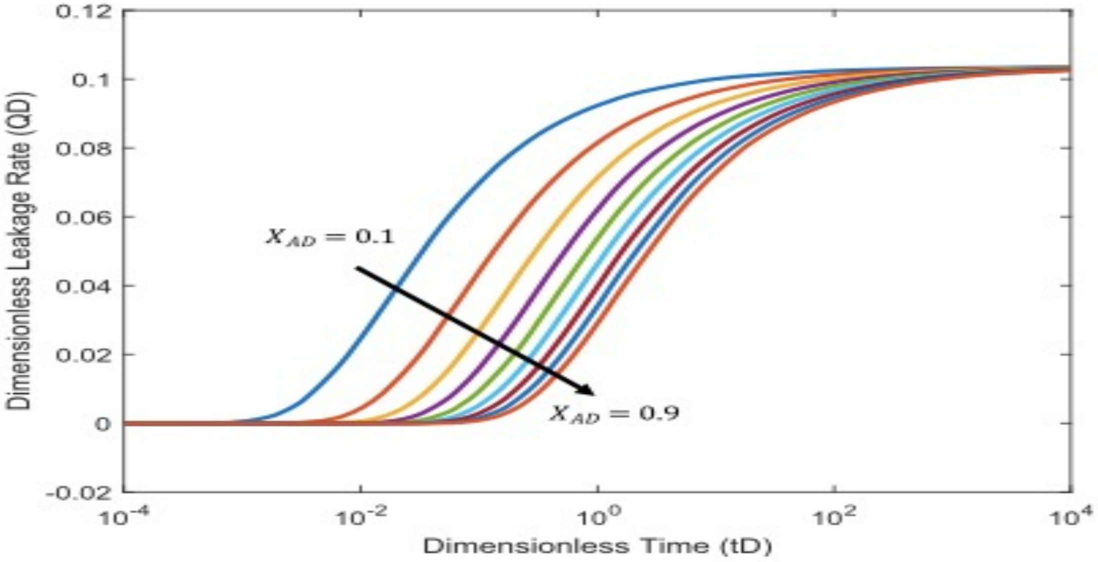
t_D : Dimensionless **time for leakage detection**



Dimensionless leakage rate (Q_D)



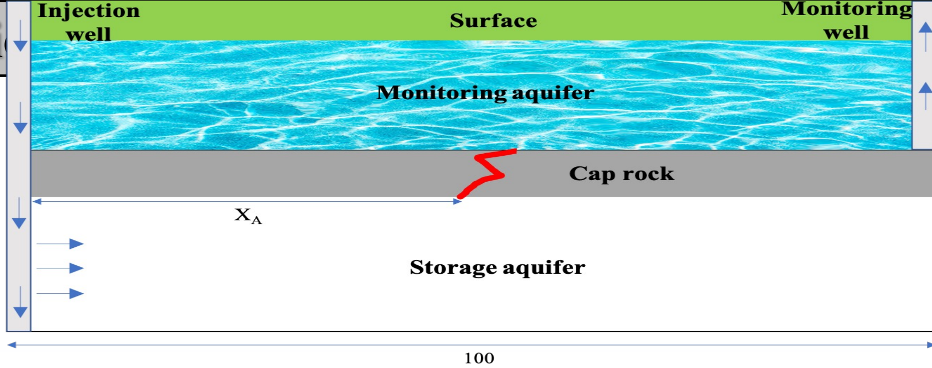
Different dimensionless **diffusivity coeffcients (η_D)** [0.01:0.01:0.1] when $X_{AD} = 0.5$



Different dimensionless **distance between leakage path and injection well (X_{AD})** [0.1:0.1:0.9] when $\eta_D = 0.533$

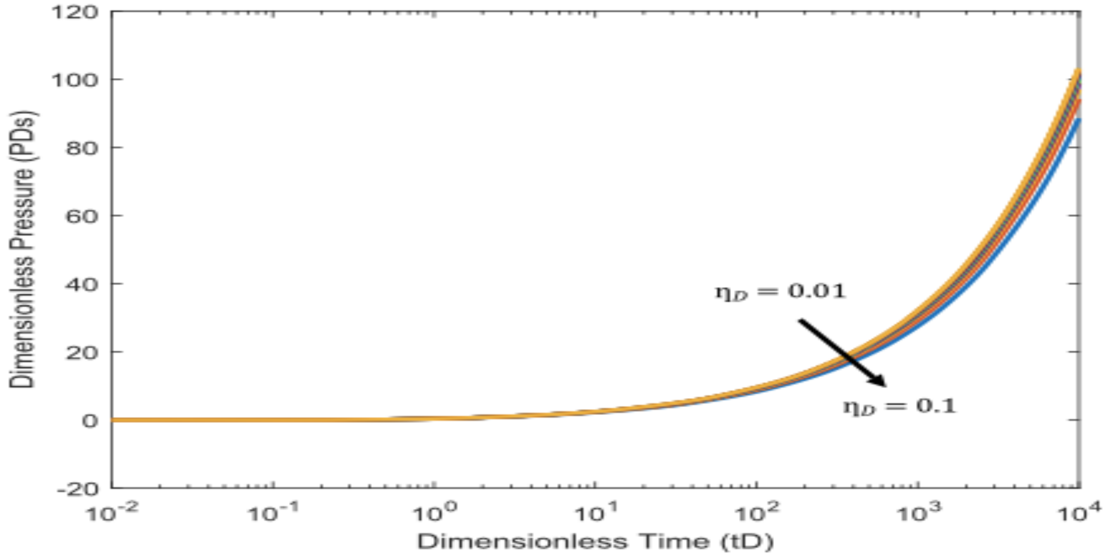
The lower the values of the dimensionless diffusivity coefficient (η_D), the higher the dimensionless leakage rate.

Increasing the X_{AD} results in delaying the leakage time.

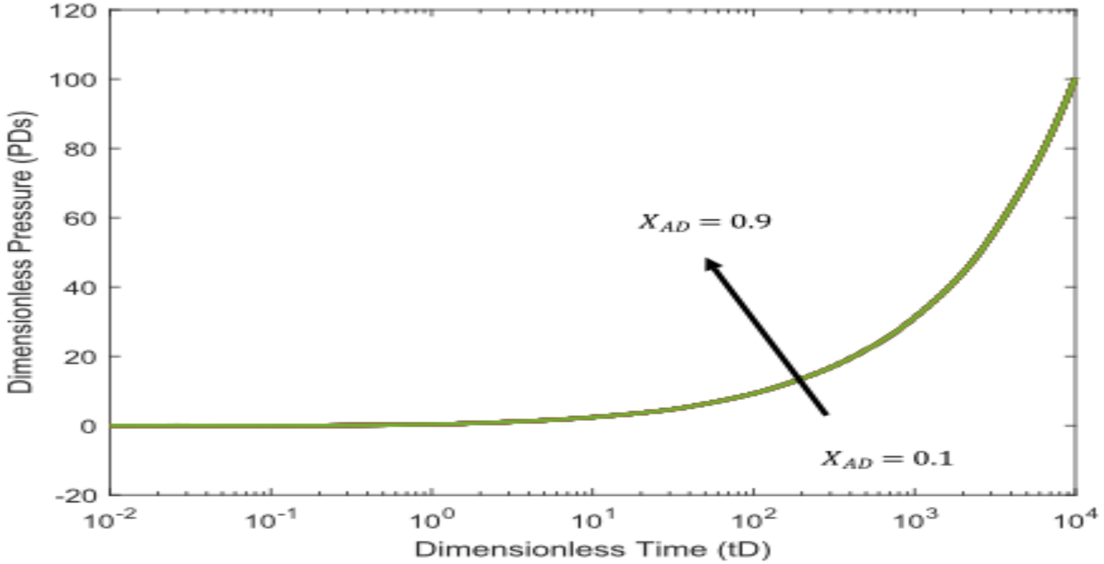


Dimensionless pressure (P_{Ds})

At the location of monitoring well in the storage aquifer



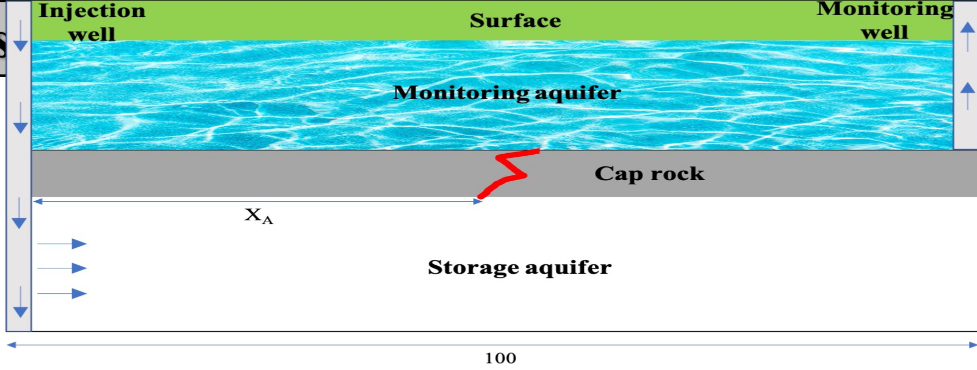
The different dimensionless **diffusivity coeffcients (η_D)** [0.01:0.01:0.1] when $X_{AD} = 0.5$



The different dimensionless **distance** between the leakage path and injection well (X_{AD}) [0.1:0.1:0.9] when $\eta_D = 0.533$.

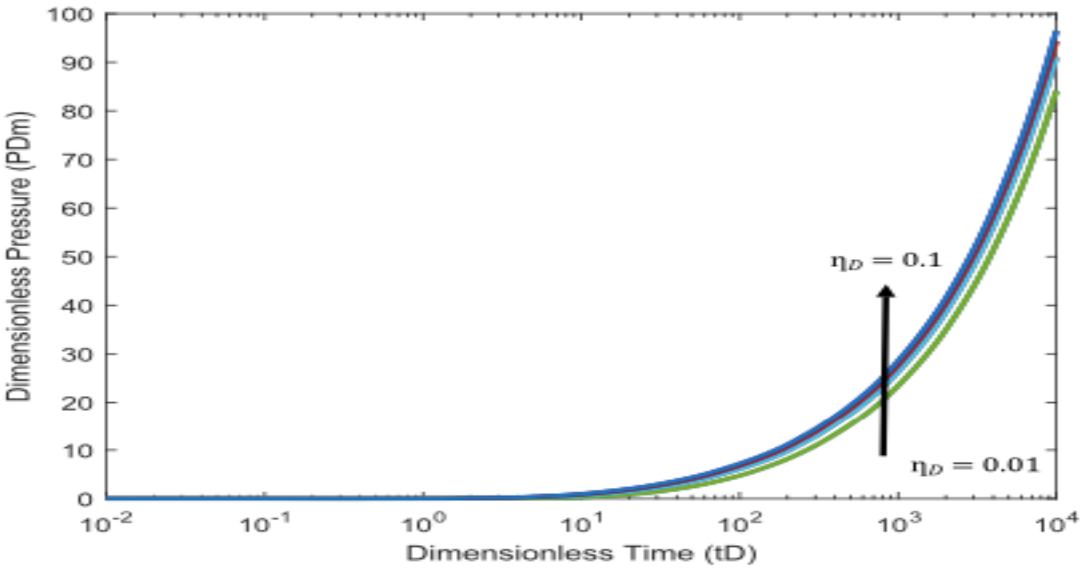
Increasing the η_D decreases the P_{Ds} at the late time.

Increasing the X_{AD} results in no considerable change in the P_{Ds}.



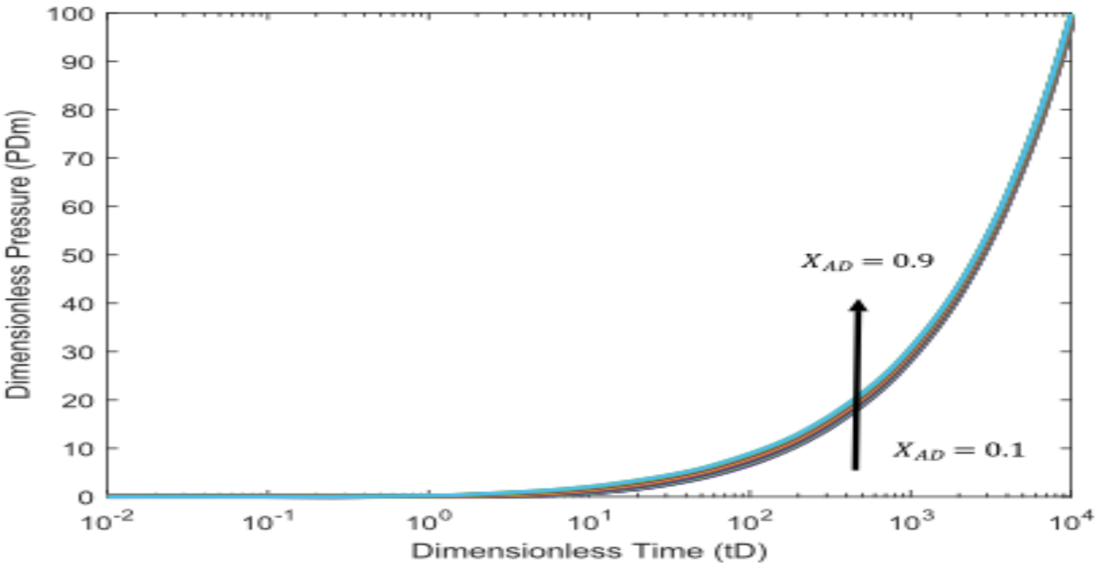
Dimensionless pressure (P_{Dm})

At the monitoring well



The different dimensionless **diffusivity coefficients (η_D)** [0.01:0.01:0.1] when $X_{AD} = 0.5$

Increasing the η_D increases the P_{Dm}.



The different dimensionless **distance between the leakage path and injection well (X_{AD})** [0.1:0.1:0.9] when $\eta_D = 0.533$.

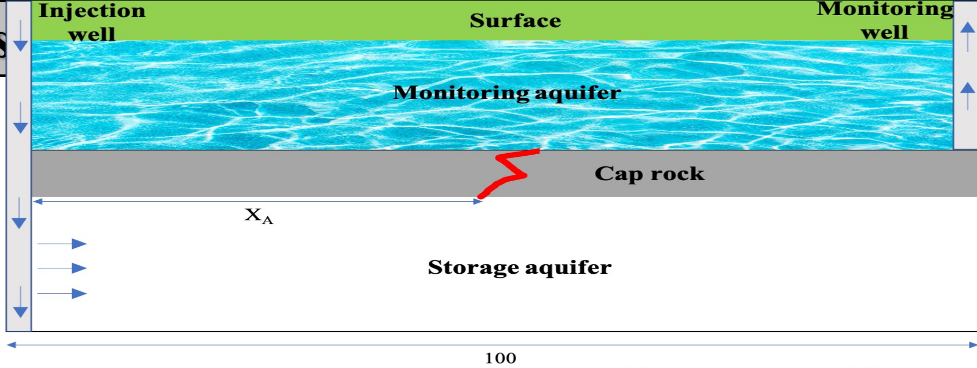
At the late time, increasing the X_{AD} increases slightly the P_{Dm}.

Synthetic Case 2

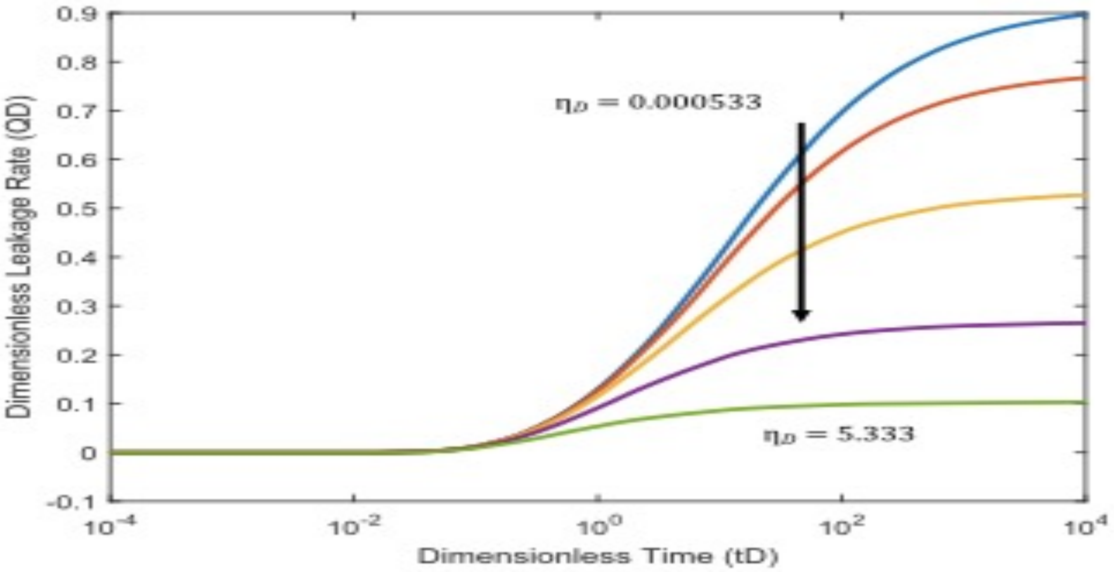
As clearly seen, the k_m and η_D in this case, is 10 times that in the previous case. This is because we will determine the effect of the parameters in both cases on the matter whether the η_D is large or small.

Table 3. Properties of the Storage and Monitoring Aquifers in the Synthetic Case 2

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
h_m	30	X_e	100	K_m	$2*10^{-12}$	η_m	26.67
h_l	16	TD	0.026667	K_l	$2.5*10^{-15}$	η_s	5
h_s	45	μ	0.0005	K_s	$5*10^{-13}$	η_D	5.333
q	0.02	ϕ_m	0.15	c_s	$1*10^{-9}$		
X_A	50	Φ_s	0.2	c_m	$1*10^{-9}$		
X_B	50	B_w	1	A_s	4500		
X_{AD}	0.5	A_m	3000	A_l	1600		

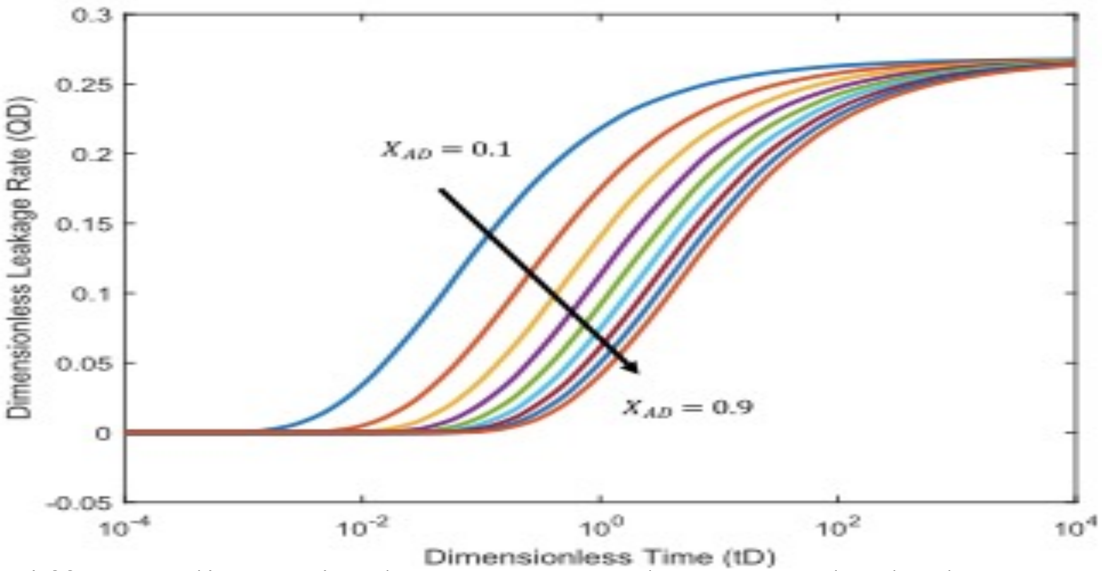


Dimensionless leakage rate (Q_D)



The different dimensionless **diffusivity** coefficients (η_D) [0.000533 0.00533 0.0533 0.5333 5.333] when $X_{AD} = 0.5$

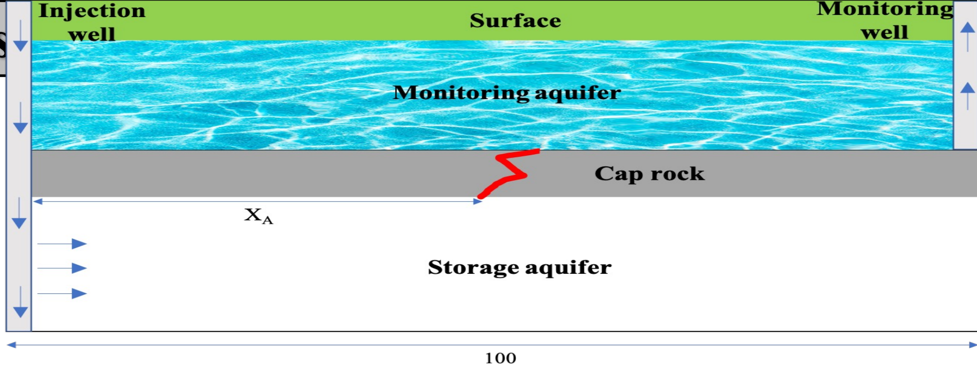
The permeability of monitoring and storage aquifers inversely affected the dimensionless leakage rate.



Different dimensionless **distance** between the leakage path and injection well (X_{AD}) [0.1:0.1:0.9] when $\eta_D = 5.33$.

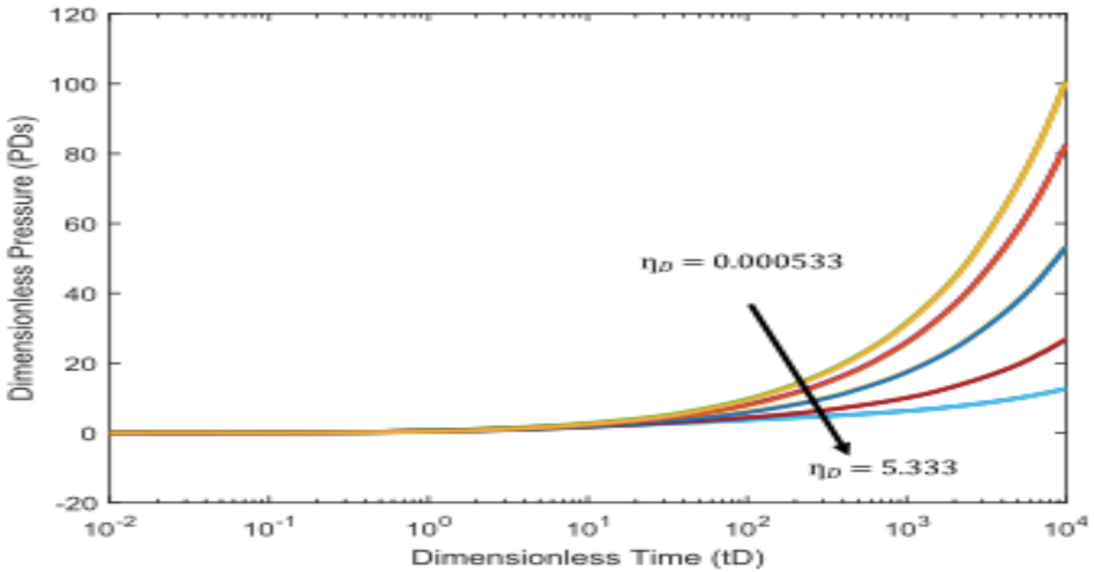
Increasing the X_{AD} results in delaying the leakage.

Comparing with synthetic case 1 when $\eta_D = 0.533$, we can results that the **delay period** when $\boldsymbol{\eta_D = 5.33}$ **is greater than**.



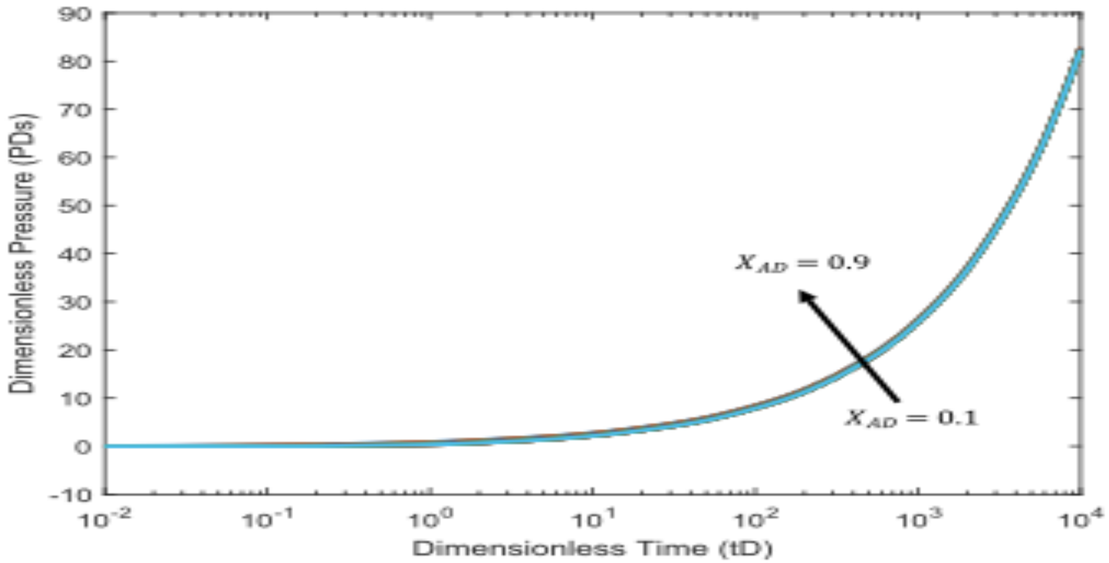
Dimensionless pressure (P_{Ds})

At the location of monitoring well in the storage aquifer



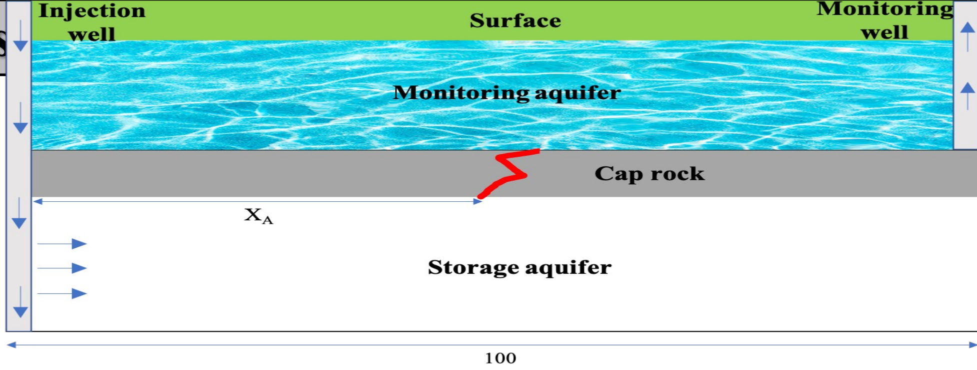
The different dimensionless **diffusivity coefficients (η_D)** [0.000533 0.00533 0.0533 0.5333 5.333] when $X_{AD} = 0.5$

Increasing the η_D affacts the dimensionless pressure (P_{Ds}) noticeably in the storage aquifer at the late time.



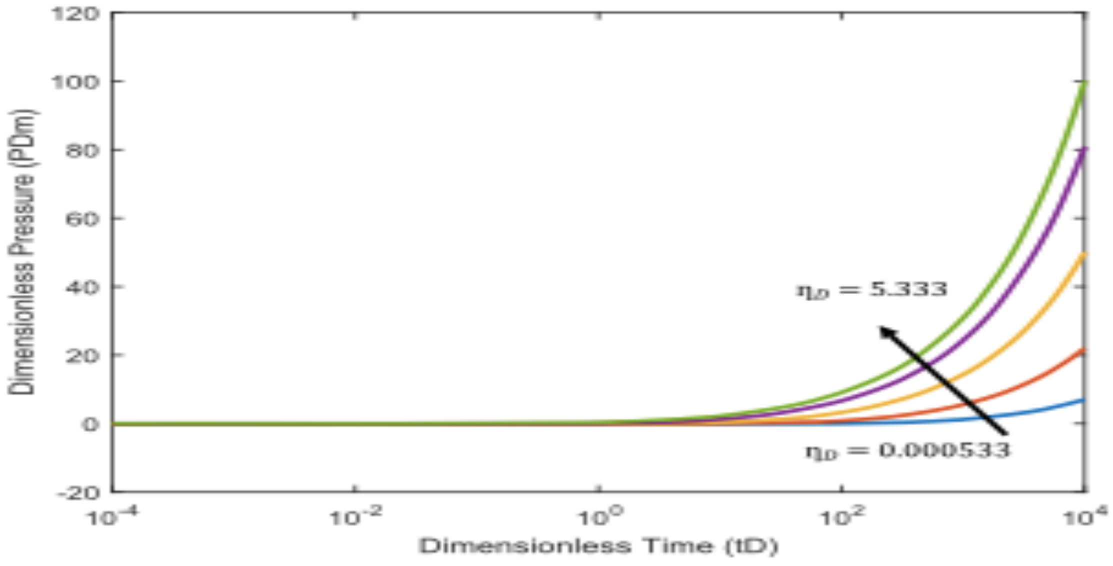
The different dimensionless **distance** between the leakage path and injection well **(X_{AD})** [0.1:0.1:0.9] when $\eta_D = 5.33$

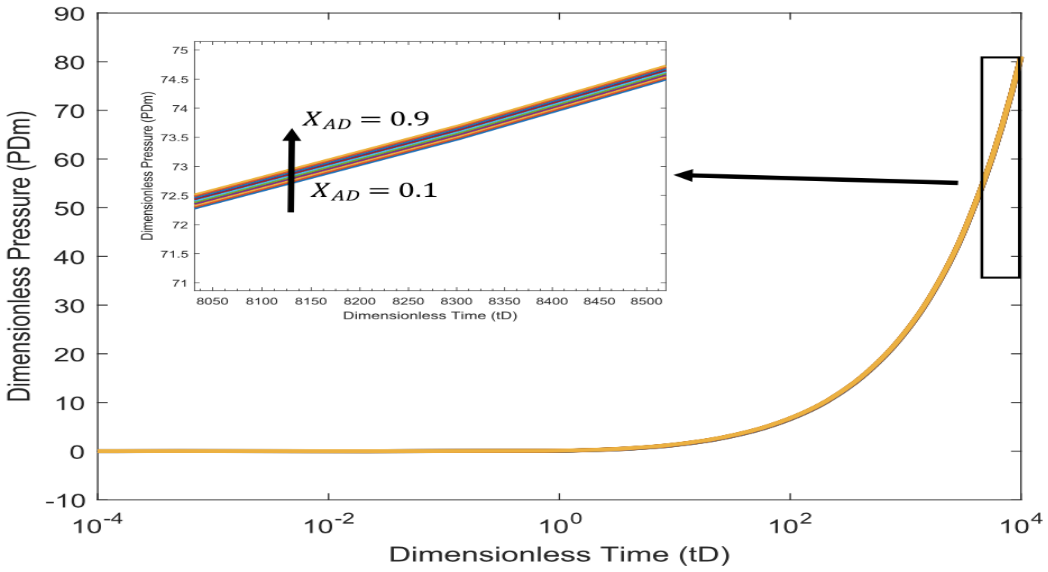
Increasing the X_{AD} results in no considerable change in the P_{Ds}.



Dimensionless pressure (P_{Dm})

At the monitoring well





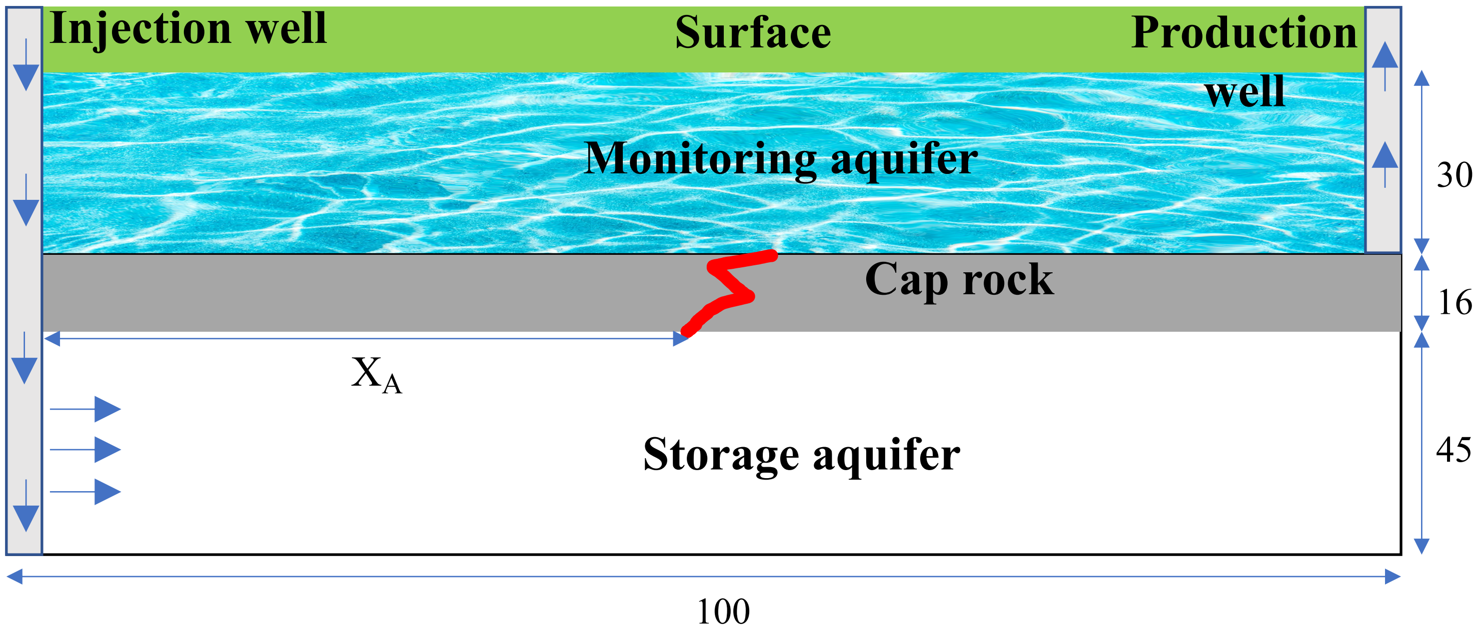
The different dimensionless **diffusivity coeffcients** ($\boldsymbol{\eta_D}$) [0.000533 0.00533 0.0533 0.5333 5.333] when X_{AD} = 0.5

The different dimensionless **distance** between the leakage path and injection well **(X_{AD})** [0.1:0.1:0.9] when η_D = 5.33.

Increasing the η_D increases the P_{Dm} at the monitoring well considerably at the late time.

At the late time, increasing the X_{AD} results in a very small change in the P_{Dm} at the monitoring well.

Ex situ sequestration Problem



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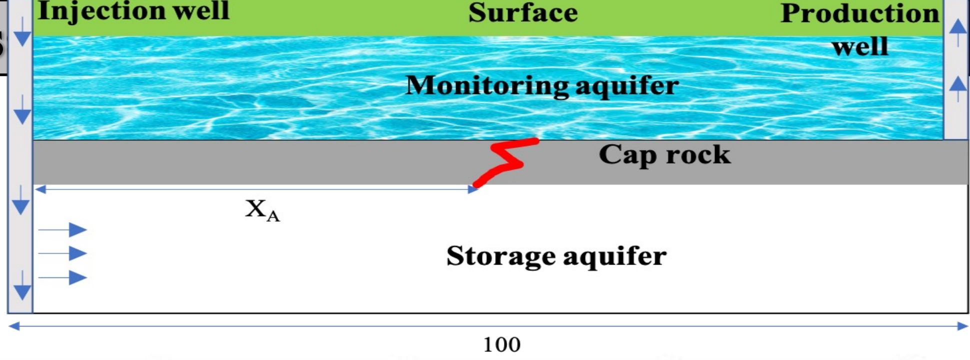
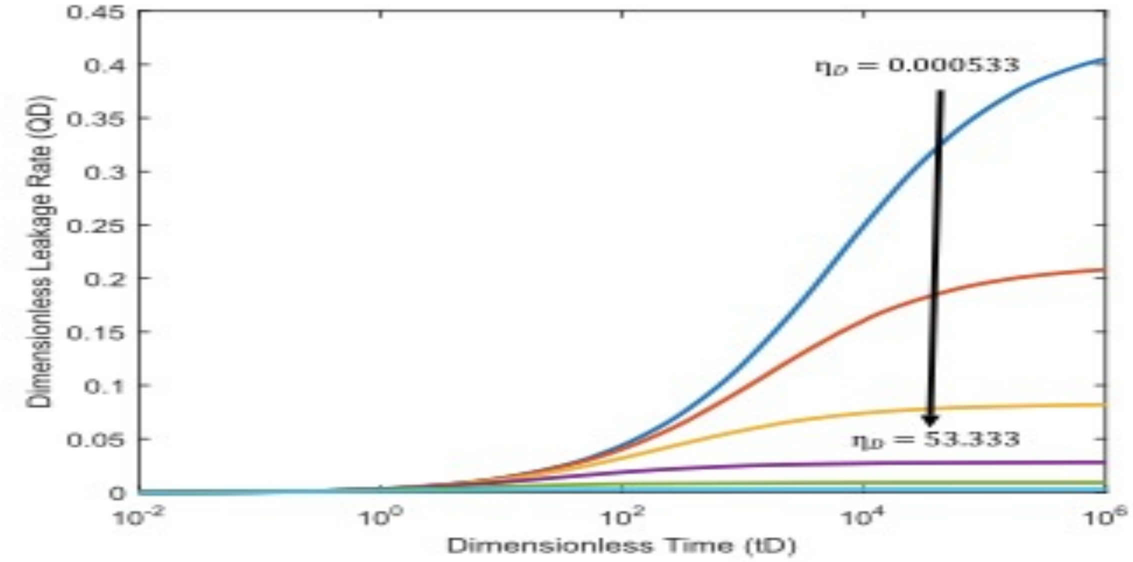
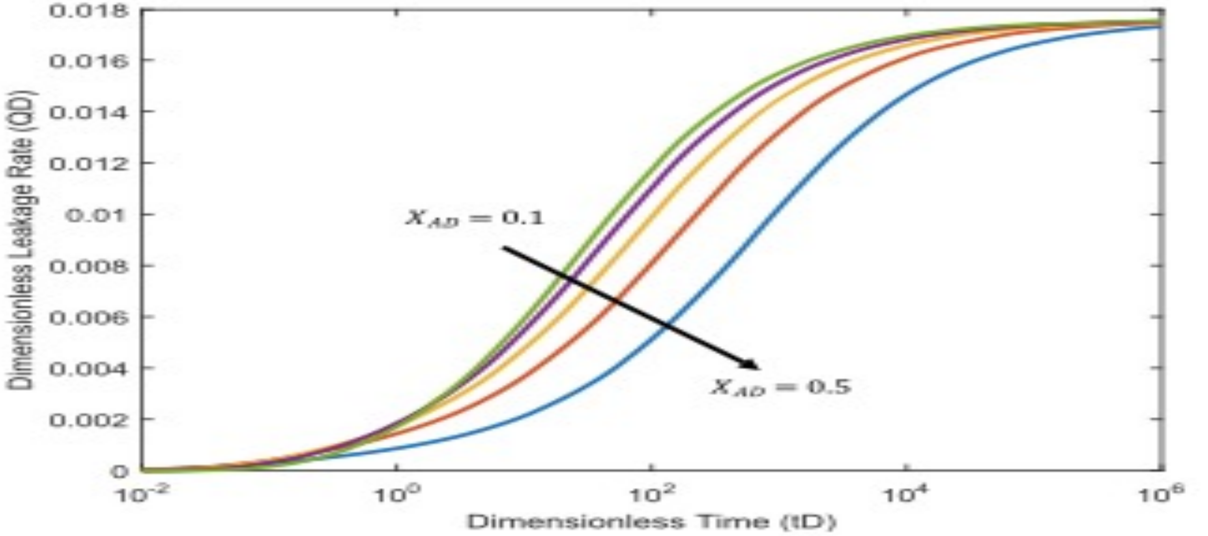
q	0.2	ϕ_m	0.15	c_s	$1*10^{-9}$		
X_A	50	Φ_s	0.2	c_m	$1*10^{-9}$		
X_B	50	B_w	1	A_s	4500		
X_{AD}	0.5	A_m	3000	A_l	1600		



Dimensionless leakage rate (Q_D)



(a) The different dimensionless **diffusivity coefficients** (**η_D**) [0.000533 0.00533 0.0533 0.5333 5.333 53.333] when $X_{AD} = 0.5$

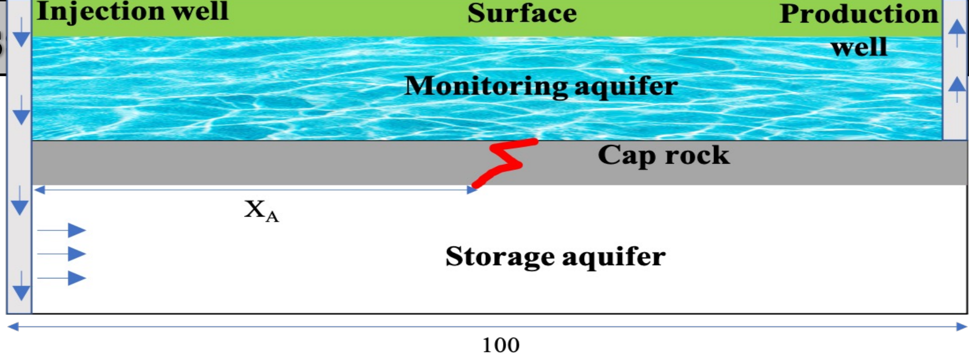


(b) The different dimensionless **distance** between the leakage path and injection well **(X_{AD})** [0.1:0.1:0.5] when $\eta_D = 0.533$.

Increasing η_D decreases the dimensionless leakage rate.

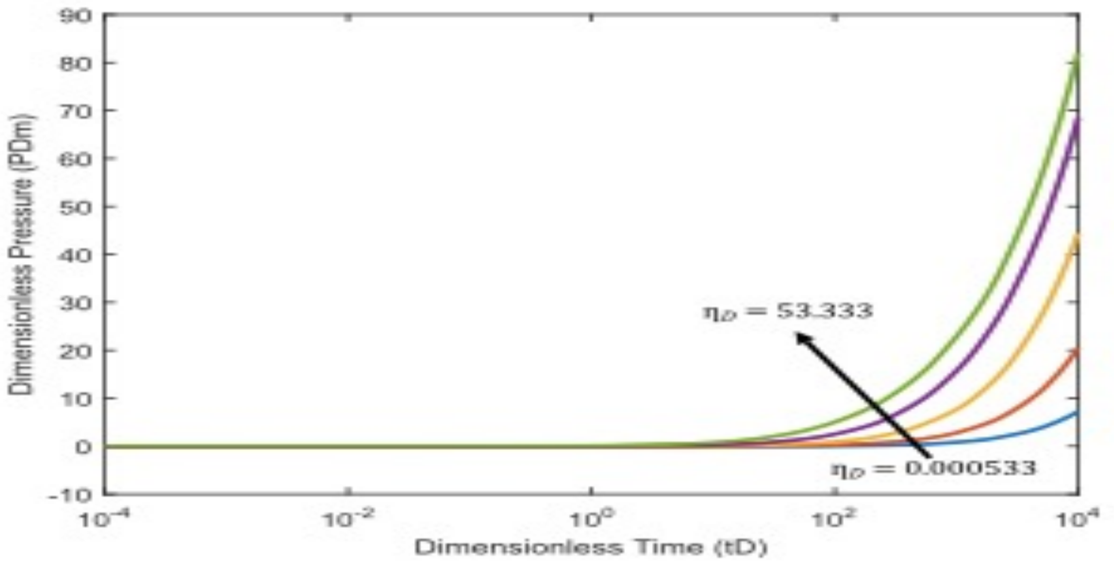
Increasing X_{AD} results in delaying the leakage; the ultimate leakage rates in all leakage locations are the same.

The result reveals that the ultimate leakage rate is independent of the leakage location.

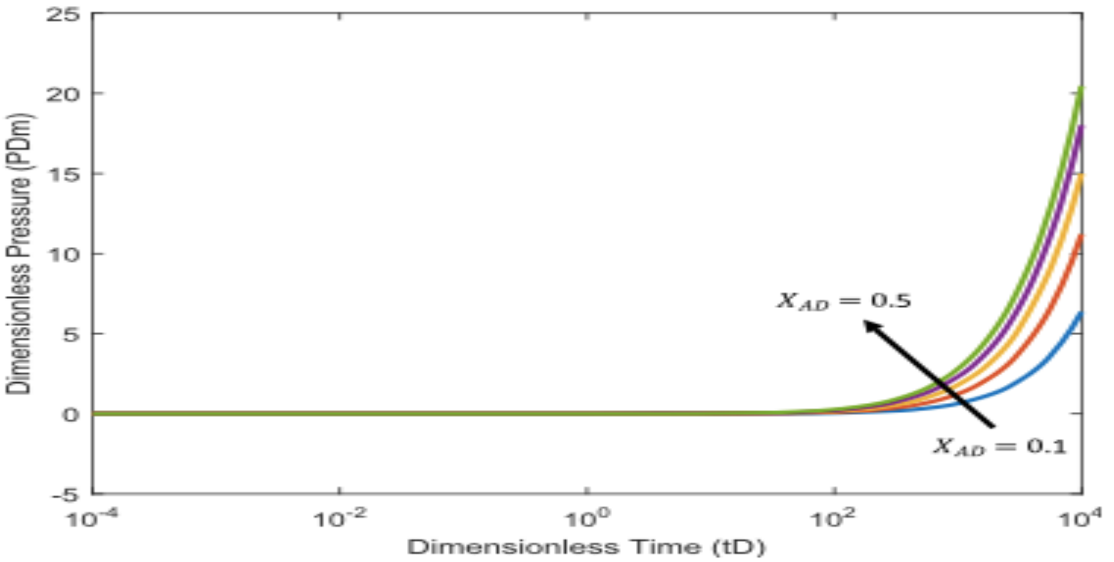


Dimensionless pressure (P_{proD})

At the production well



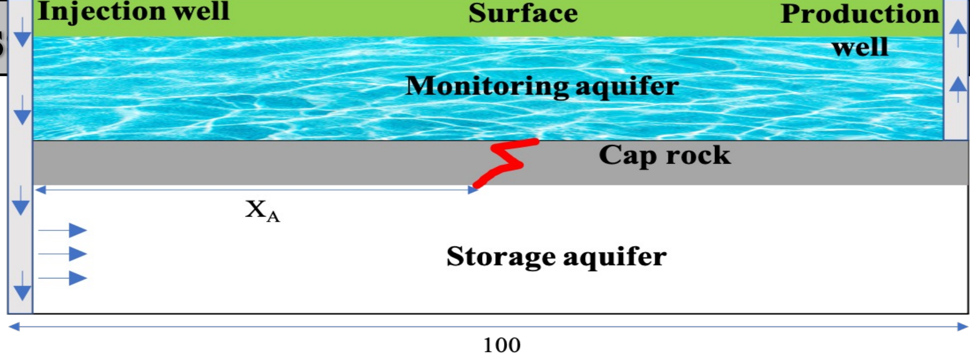
(a) The different dimensionless **diffusivity coefficients (η_D)** [0.000533 0.00533 0.0533 0.5333 5.333 53.333] when $X_{AD} = 0.5$



(b) The different dimensionless **distance** between the leakage path and injection well **(X_{AD})** [0.1:0.1:0.5] when $\eta_D = 0.533$.

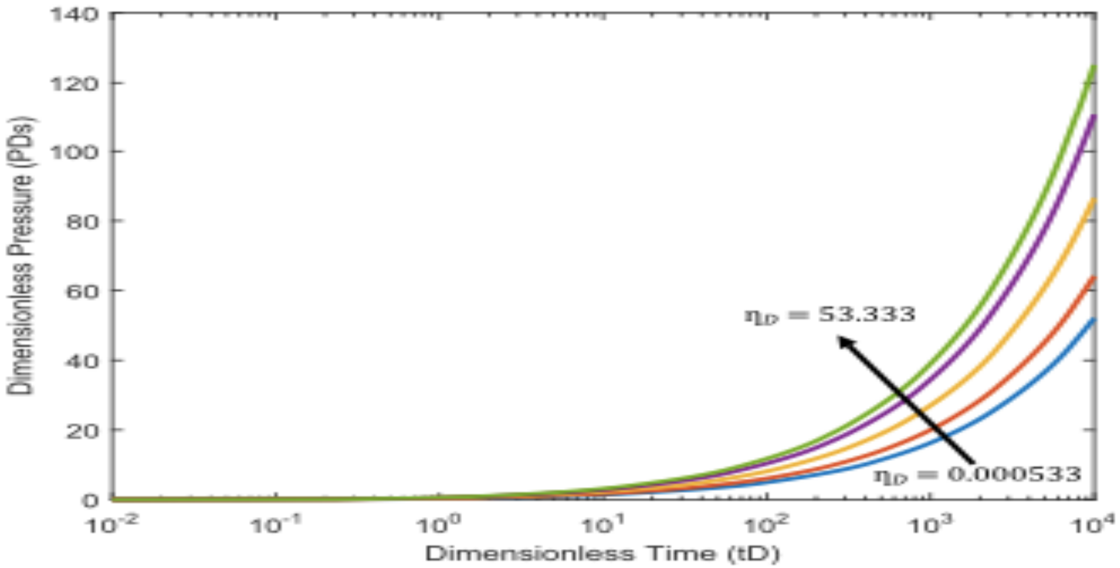
Increasing the η_D increases the P_{Dm} at the late time.

Increasing the X_{AD} from 0.1 to 0.5 increases the P_{Dm} at the late time.



Dimensionless pressure (P_{proD})

At the location of production well



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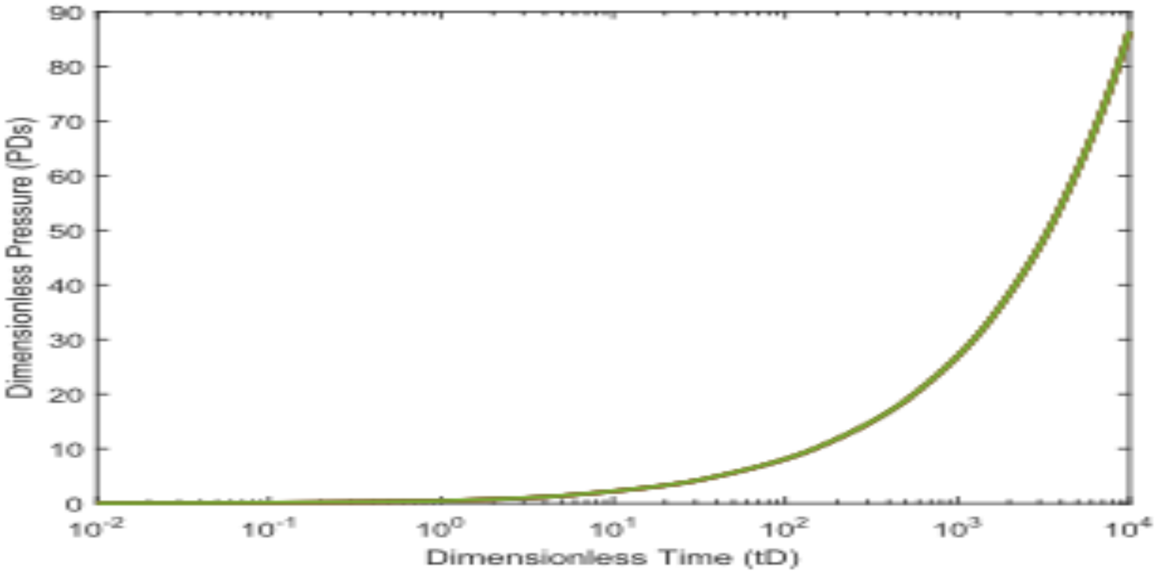


(b) The different dimensionless **distance** between the leakage path and injection well **(X_{AD})** [0.1:0.1:0.5] when $\eta_D = 0.533$

Increasing the η_D increases the P_{Ds} at the late time.

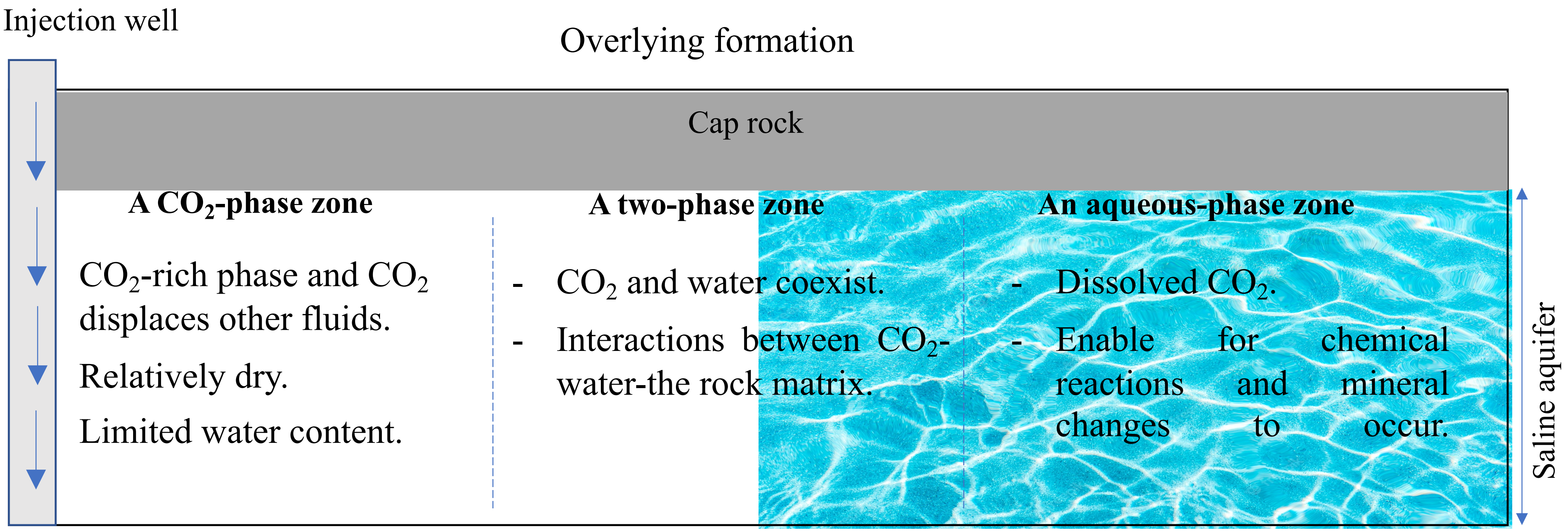
P_{Ds} at the production well is independent of leakage location.

- Analytical models are developed to determine the leakage rate and pressure response from the storage to monitoring aquifers for CO_2 sequestration.

-These models can be useful in detecting and characterizing potential leakage paths in the cap rock, helping to ensure the safety and integrity of CO_2 storage in deep saline aquifers

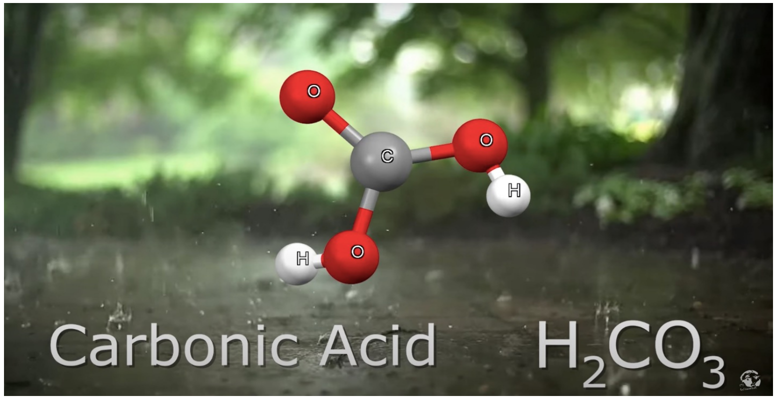
Thank you for your attention!

Three distinct zones form during CO_2 injection



Mineral carbonation

$CO_2 + H_2O \rightarrow H_2CO_3$



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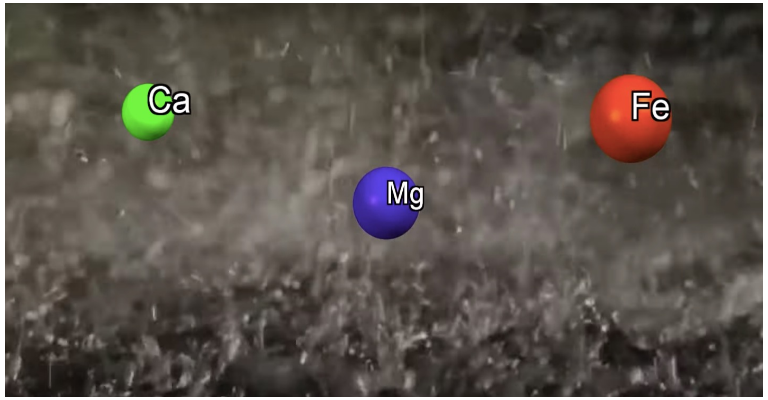
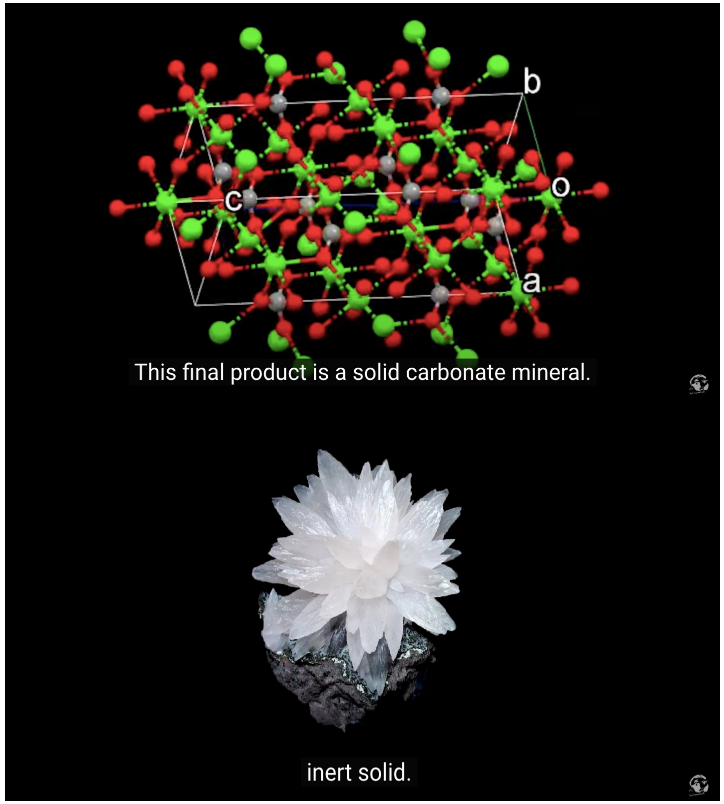
Minerals

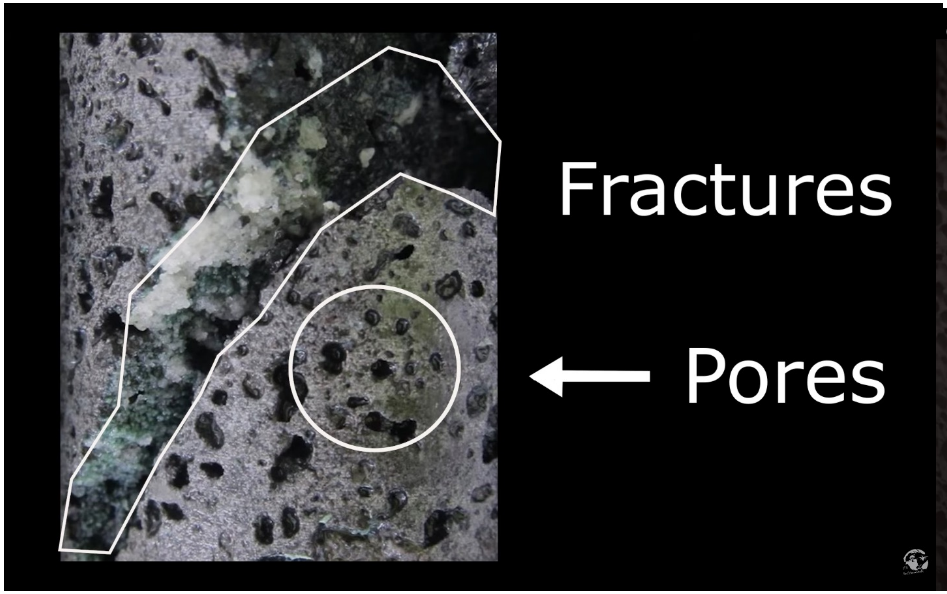


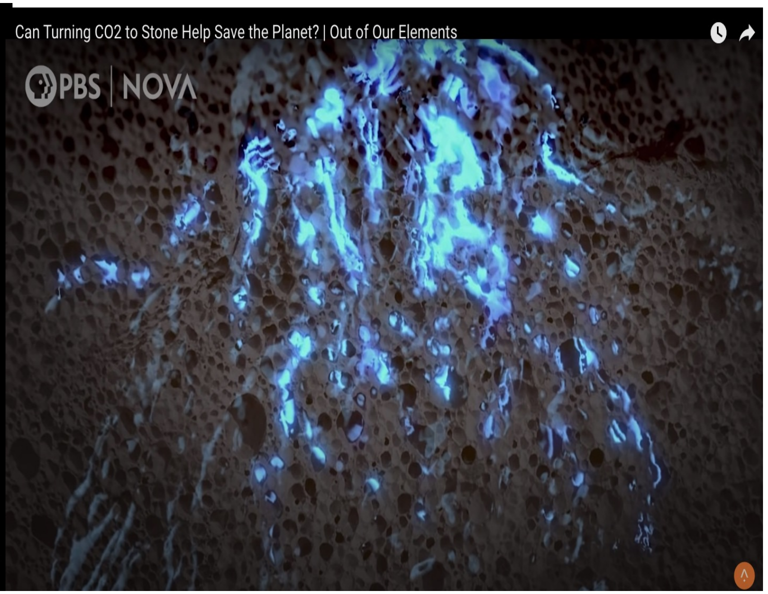
→

$CACO_3$, $MgCO_3$, $FeCO_3$



Immobilized within the solid carbonate matrix





Effect of Injection

$$P_s(X, t) = P_{si} \quad t = 0$$

$$P_s(X, t) = P_{si} \quad X \to +\infty$$

$$q_{in} = \frac{K_s A_s}{\mu B} \times \frac{dP_s}{dx} \quad X = 0$$

Dimentionless variables:

$$P_{Ds}(X_D, t_D) = 0 \quad t_D = 0$$

$$P_{Ds}(X_D, t_D) = 0 \quad X_D \to +\infty$$

$$q_{inD} = \frac{K_s A_s}{\mu B} \times \frac{dP_s}{dx} \quad X_D = 0$$

Effect of Leakage

$$P_s(X, t) = P_{si} \quad t = 0$$

$$P_s(X, t) = P_{si} \quad X \to +\infty$$

$$q_l(t) = \frac{K_s A_s}{\mu B} \times \frac{dP_s}{dx} \quad X = X_A$$

Dimentionless variables:

$$P_{DS}(X_D, t_D) = 0 \quad t_D = 0$$

$$P_{DS}(X_D, t_D) = 0 \quad X_D \to +\infty$$

$$q_{lD}(t_D) = \frac{K_s A_s}{\mu B} \times \frac{dP_{Ds}}{dx_D} \quad X_D = X_{AD}$$

Effect of Production

$$P_s(X, t) = P_{si} \quad t = 0$$

$$P_s(X, t) = P_{si} \quad X \to +\infty$$

$$q_{prod} = a\frac{K_s A_s}{\mu B} \times \frac{dP_s}{dx} \quad X = X_e$$

Dimentionless variables:

$$P_{Ds}(X_D, t_D) = 0 \quad t_D = 0$$

$$P_{Ds}(X_D, t_D) = 0 \quad X_D \to +\infty$$

$$q_{proD} = a\frac{K_s A_s}{\mu B} \times \frac{dP_s}{dx} \quad X_D = X_{eD}$$