Geometric and Soil Property Control on the Performance of Vadose Zone Well Injection

Cuiting Qi[1], Hongbin Zhan[1]

[1]Department of Geology and Geophysics, Texas A&M University, College Station, TX 77843-3115, USA.

Abstract

As growing populations require more water and greater storage capacity is needed to save water in times of surplus for use in times of shortage, managed aquifer recharge (MAR) is expected to become increasingly important. Vadose-zone well (VZW) injection is an efficient way to implement MAR in semiarid and arid regions. This study establishes a numerical model by COMSOL Multiphysics to simulate VZW injection in an unconfined aquifer and investigates the geometric and soil property control on the performance of VZW injection.

Approach

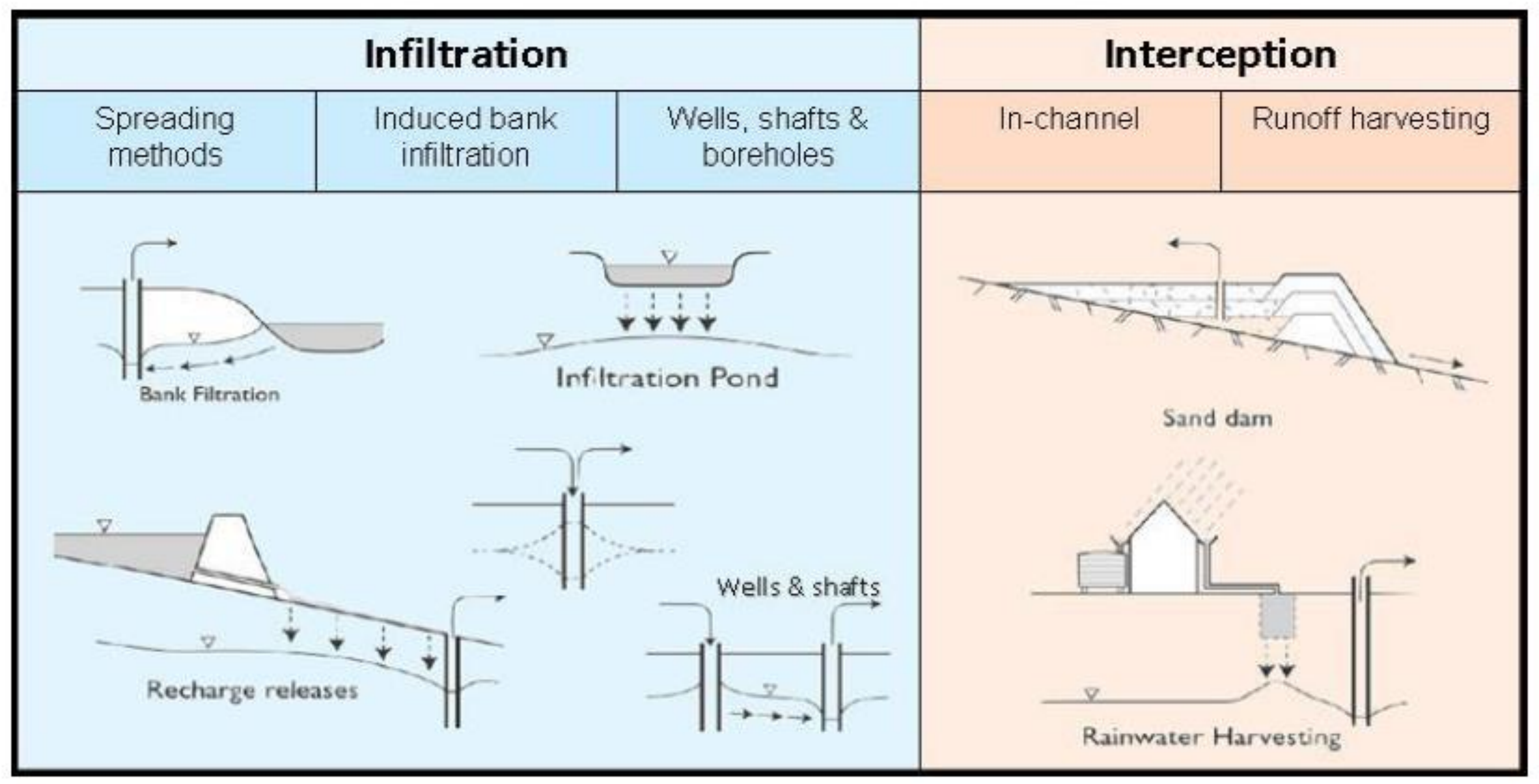

Figure: Schematic of types of MAR (Faneca Sanchez et al., 2015)

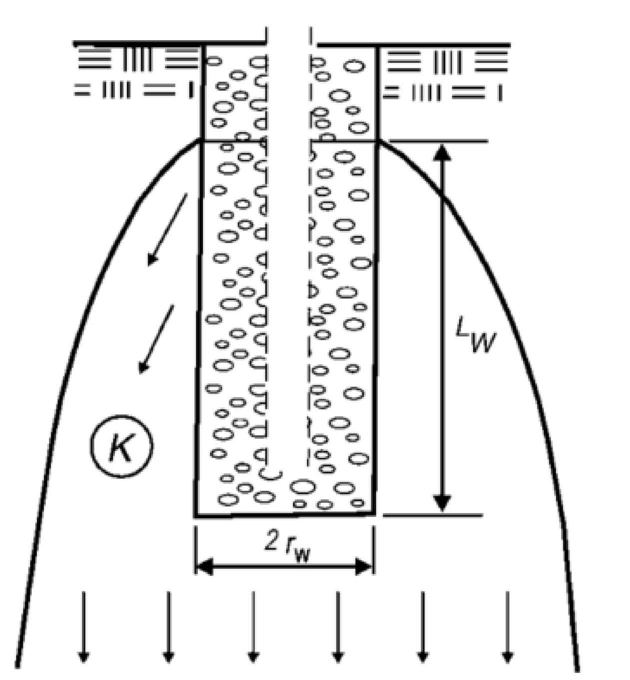

Figure: Section of VZW with sand or gravel fill and perforated supply pipe (Bouwer, 2002)

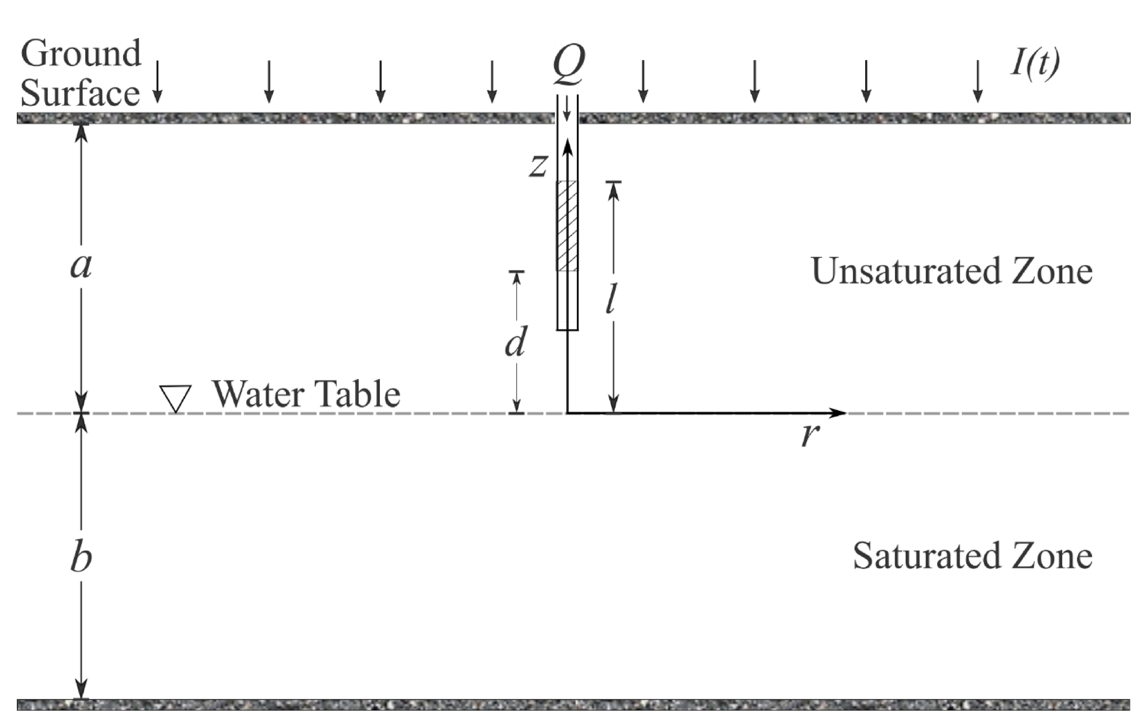

Figure: Schematic diagrams of unsaturated-saturated flow induced by the VZW injection and ground surface infiltration

- In the unsaturated zone:

$$K_r \frac{1}{r}\frac{\partial}{\partial r}\left(k(\psi) r \frac{\partial u}{\partial r}\right) + K_z \frac{\partial}{\partial z}\left(k(\psi)\frac{\partial u}{\partial z}\right) = C_0(\psi)\frac{\partial u}{\partial t}, \qquad 0 \le z \le a$$

$$\mathrm{u(r,z,0)} = 0$$

$$K_z k(\psi)\frac{\partial u}{\partial z}(\mathrm{r,z,t})\Big|_{z=a} = I(t)$$

$$\lim_{\mathrm{r}\to\infty} \mathrm{u(r,z,t)} = 0$$

$$\lim_{\mathrm{r}\to 0} \mathrm{r}\frac{\partial \mathrm{u(r,z,t)}}{\partial \mathrm{r}} = -\frac{Q\Theta(z)}{2\pi K_r(l-d)} \qquad (0 \le z \le a)$$

- In the saturated zone:

$$K_r \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial s}{\partial r}\right) + K_z\frac{\partial^2 s}{\partial z^2} = S_s\frac{\partial s}{\partial t}, \qquad -b \le z \le 0$$

$$\mathrm{s(r,z,0)} = 0$$

$$\frac{\partial s}{\partial z}(\mathrm{r,z,t})\Big|_{z=-b} = 0$$

$$\lim_{\mathrm{r}\to\infty} \mathrm{s(r,z,t)} = 0$$

$$\lim_{\mathrm{r}\to 0} \mathrm{r}\frac{\partial \mathrm{s(r,z,t)}}{\partial \mathrm{r}} = 0, \qquad -b \le z \le 0$$

- The van Genuchten (1980) – Mualem (1976) constitutive model:

$$\theta = \begin{cases} \theta_r + S_e(\theta_s - \theta_r) & \psi < 0 \\ \theta_s & \psi \ge 0 \end{cases}$$

$$C = \begin{cases} \frac{\alpha m}{1-m}(\theta_s - \theta_r) S_e^{\frac{1}{m}}(1 - S_e^{\frac{1}{m}})^m & \psi < 0 \\ 0 & \psi \ge 0 \end{cases}$$

$$S_e = \begin{cases} \frac{1}{[1 + |\alpha\psi|^n]^m} & \psi < 0 \\ 1 & \psi \ge 0 \end{cases}$$

$$\mathrm{k} = \begin{cases} {S_e}^l[1 - (1 - S_e^{\frac{1}{m}})^m]^2 & \psi < 0 \\ 0 & \psi \ge 0 \end{cases}$$

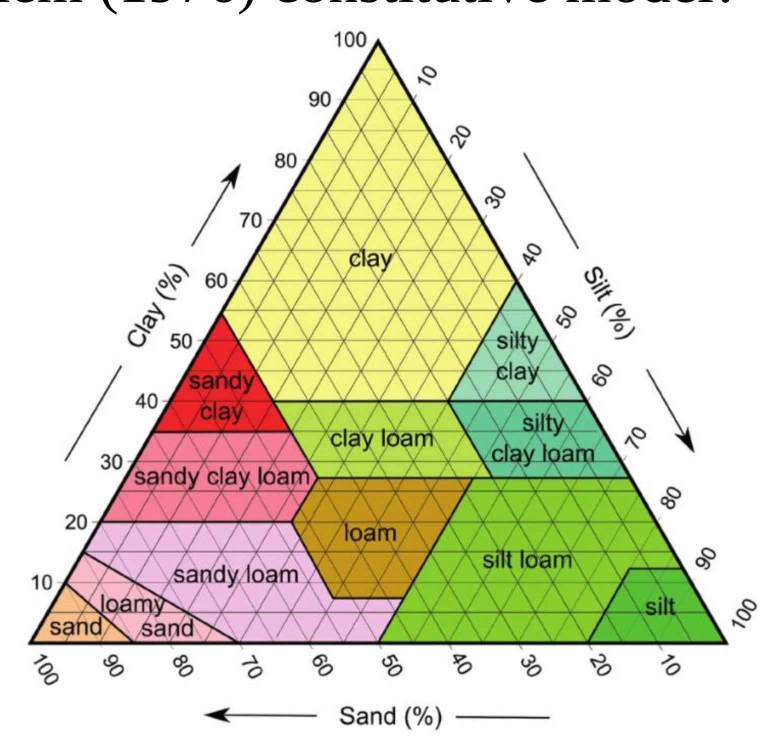

Figure: Soil texture triangle

Soil Texture (USDA)	θ_r (m^3/m^3)	θ_s (m^3/m^3)	α (cm^{-1})	n (–)	K_s (cm/d)	l (–)
Clay Loam	0.095	0.41	0.019	1.31	6.24	0.5
Loam	0.078	0.43	0.036	1.56	24.96	0.5
Loamy Sand	0.057	0.41	0.124	2.28	350.2	0.5

Table: Hydraulic properties of the selected soils (Carsel, 1988)

Results

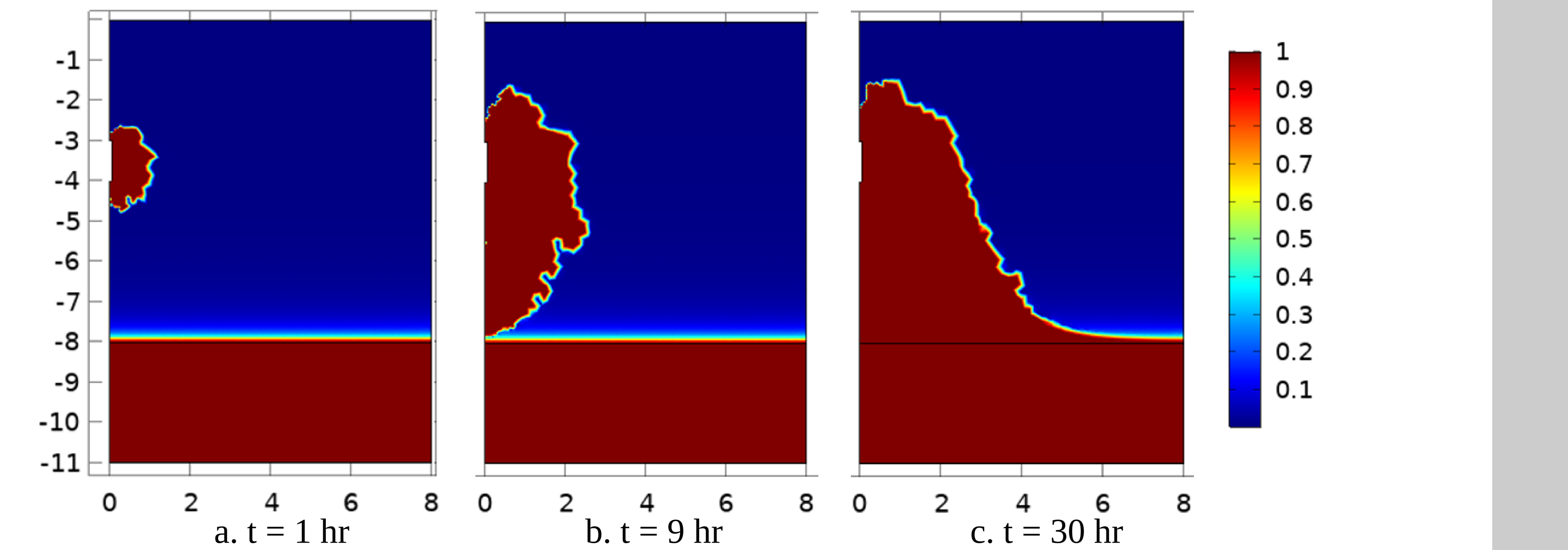

Figure: S_e change during VZW injection in loamy sand

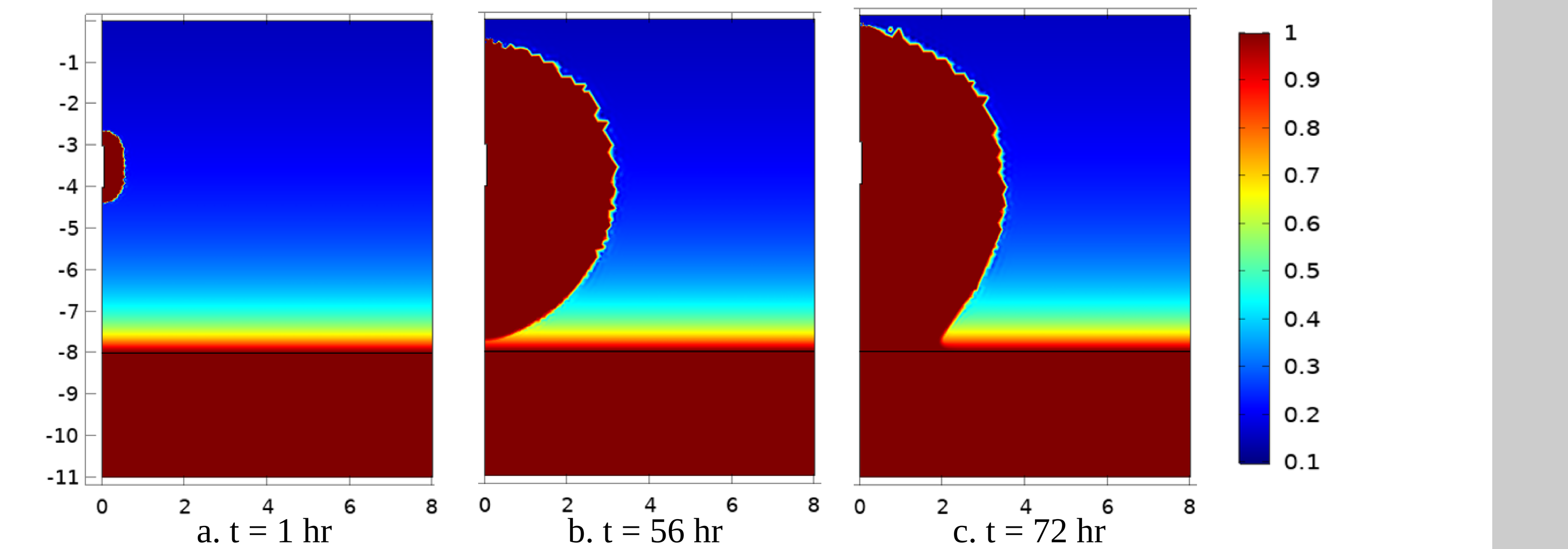

Figure: S_e change during VZW injection in loam

Conclusions

- The soil properties greatly affect the travel time of injection water during VZW injection. For less permeable soil, it takes much more time for injection water to move to the position of the original water table.
- The soil properties greatly affect the injection efficiency of VZW injection in the unconfined aquifer. For less permeable soil, more water is held in the unsaturated zone, reducing the volume of water which flows through the original interface between the unsaturated zone and the saturated zone.

Reference

- Bouwer, H., 2002. Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeology Journal, 10(1): 121-142.
- Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. Soil science society of America journal, 44(5): 892-898.