Experimental investigation of viruses and clay particles cotransport in unsaturated porous media

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Abstract

Suspended clay particles in groundwater can play a significant role as carriers of viruses, because, depending on the physicochemical conditions, clay particles may facilitate or hinder the mobility of viruses. This study examines the effects of clay colloids on the transport of viruses in variably saturated porous media. All cotransport experiments were conducted in partially saturated columns packed with glass beads, using bacteriophages MS2 and ΦX174 as model viruses, and kaolinite (KGa-1b) and montmorillonite (STx-1b) as model clay colloids. The various experimental collision efficiencies were determined using the classical colloid filtration theory. The experimental data indicated that the mass recovery of viruses and clay colloids decreased as the water saturation decreased. Temporal moments of the various breakthrough concentrations collected, suggested that the presence of clays significantly influenced virus transport and irreversible deposition onto glass beads. The mass recovery of both viruses, based on total effluent virus concentrations, was shown to reduce in the presence of suspended clay particles.

Materials and methods

Bacteriophages

MS2: an F-specific single-stranded RNA phage with effective particle diameter ranging from 24 to 26 nm

ΦX174: a somatic single-stranded DNA phage with effective particle diameter ranging from 25 to 27 nm

For the separation of viruses adsorbed onto clay particles from suspended viruses in the liquid phase, centrifugation was used as described in Syngouna and Chrysikopoulos (2013).

Clays

Kaolinite (KGa-1b): a well-crystallized kaolin from Washington County, Georgia

Montmorillonite (STx-1b): a Ca-rich montmorillonite, white, from Gonzales County, Texas

The <2 μm clay colloidal fraction was separated by sedimentation and then was purified (Rong et al., 2008)

Electrokinetic measurements

The zeta potentials were determined to be -40.4±3.7 mV for MS2, -31.78±1.25 mV for ΦX174, -26.03±2.77 mV for KGa-1b, and -20.5±0.8 mV for STx-1b (Chrysikopoulos and Syngouna, 2012).

Experimental Set Up

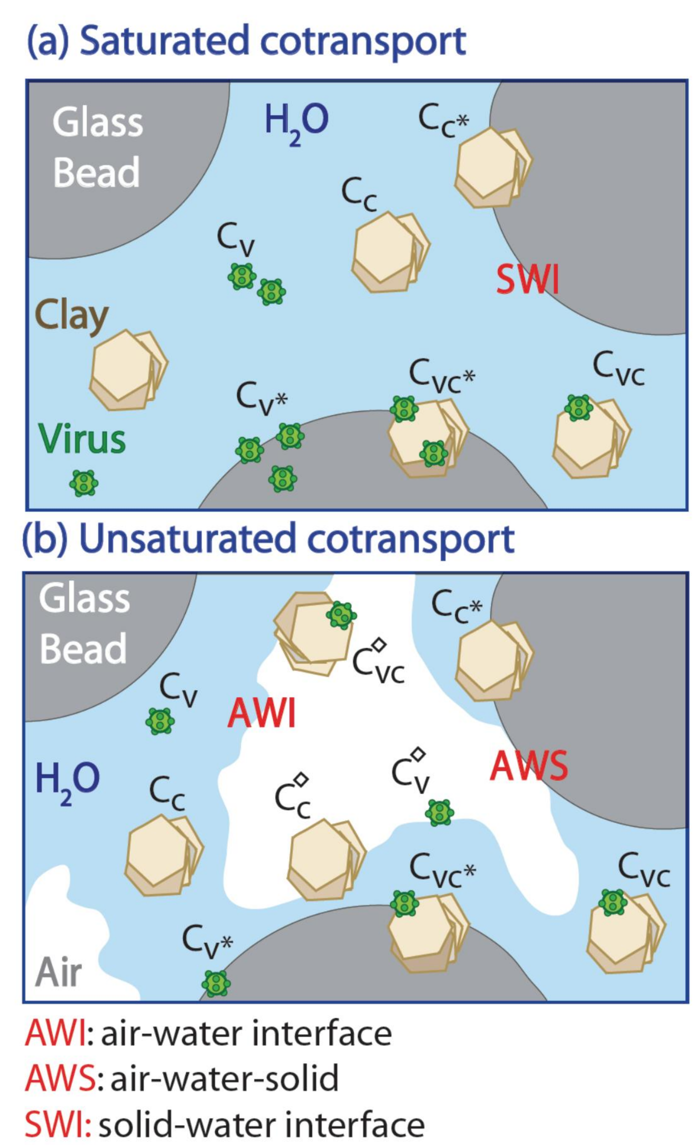
- Plexiglass column
  - Length 15.2 cm
  - Internal diameter 2.6 cm
- Uniformly wet-packed
- Glass beads 2mm
- Flow rate of Q=1.5 mL/min
- pH 7.0±0.2
- Saturation level: 81-100%
- Water potential: constant

Cotransport Experiments

- C_c : Suspended clay particles
- $C_{Total\text{-}v}$: Total viruses
- C_v: Suspended viruses
- C_{vc}: Viruses attached onto C_c
- C_{c^*} : Clays attached onto glass beads
- C_{v^*} : Viruses attached onto glass beads
- C_{vc^*}: Viruses attached onto C_c*
- $C_{v^\diamond}$: Viruses captured in AWI
- $C_{c^\diamond}$: Clay colloids captured in AWI
- $C_{vc^\diamond}$: Viruses attached onto $C_c^\diamond$

In the column effluent:

$$C_{Total\text{-}v} = C_v + C_{vc}$$



Colloid Filtration Theory

Experimental attachment efficiency (Kretzschmar et al., 1999):

$$\alpha_{exp} = -\frac{2}{3}\frac{d_c}{L(1-\theta_m)\eta_0}\ln\left[\frac{C_{ss}}{C_0}\right]$$

where:

- θ_m [-] is the moisture content
- d_c [L] is the mean collector diameter
- C_0 [M/L^3] is the influent colloid concentration
- C_{ss} [M/L^3] is the effluent colloid concentration (steady state conditions)
- η_0 is the single-collector contact efficiency (Tufenkjii and Elimelech, 2004)

Results and discussion

Transport experiments

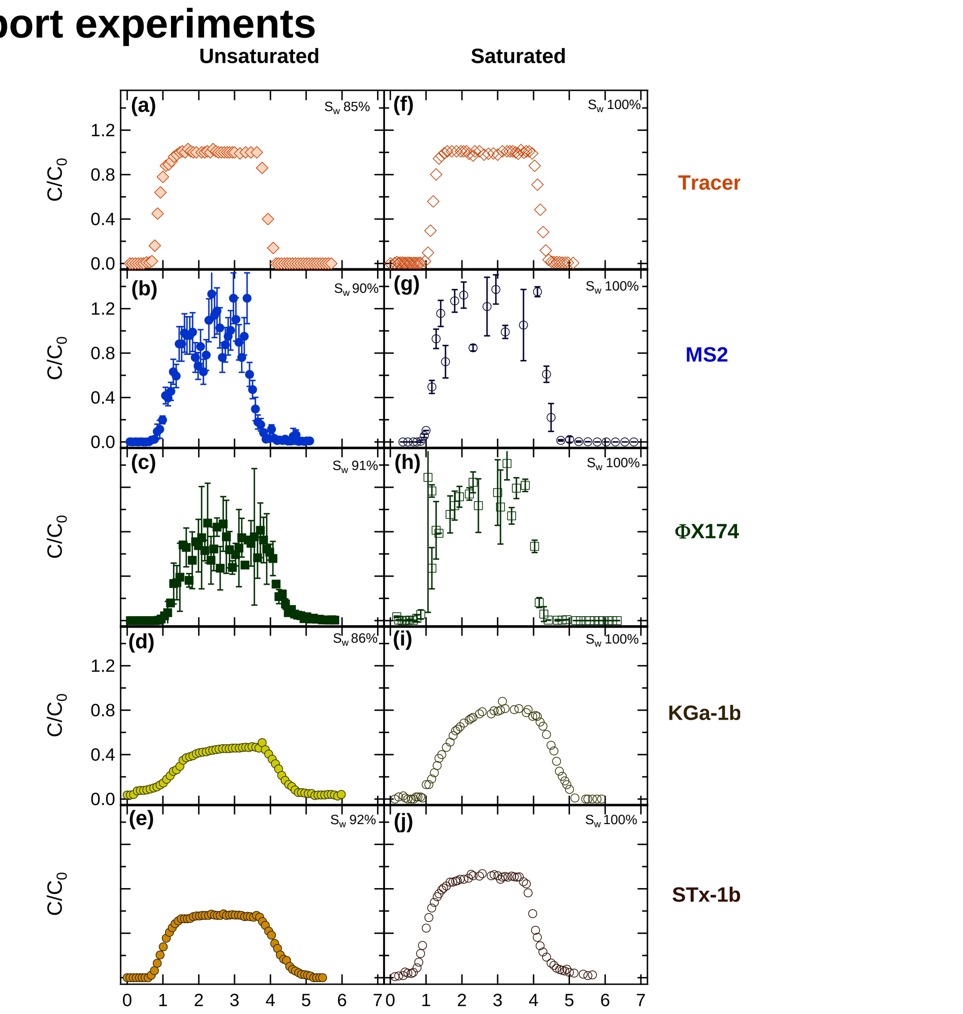


Figure 1. Experimental data of tracer, viruses (MS2, ΦX174) and clays (KGa-1b, STx-1b) breakthrough in unsaturated (a,b,c,d,e) and saturated (f,g,h,i,j) columns packed with glass beads.

Cotransport experiments

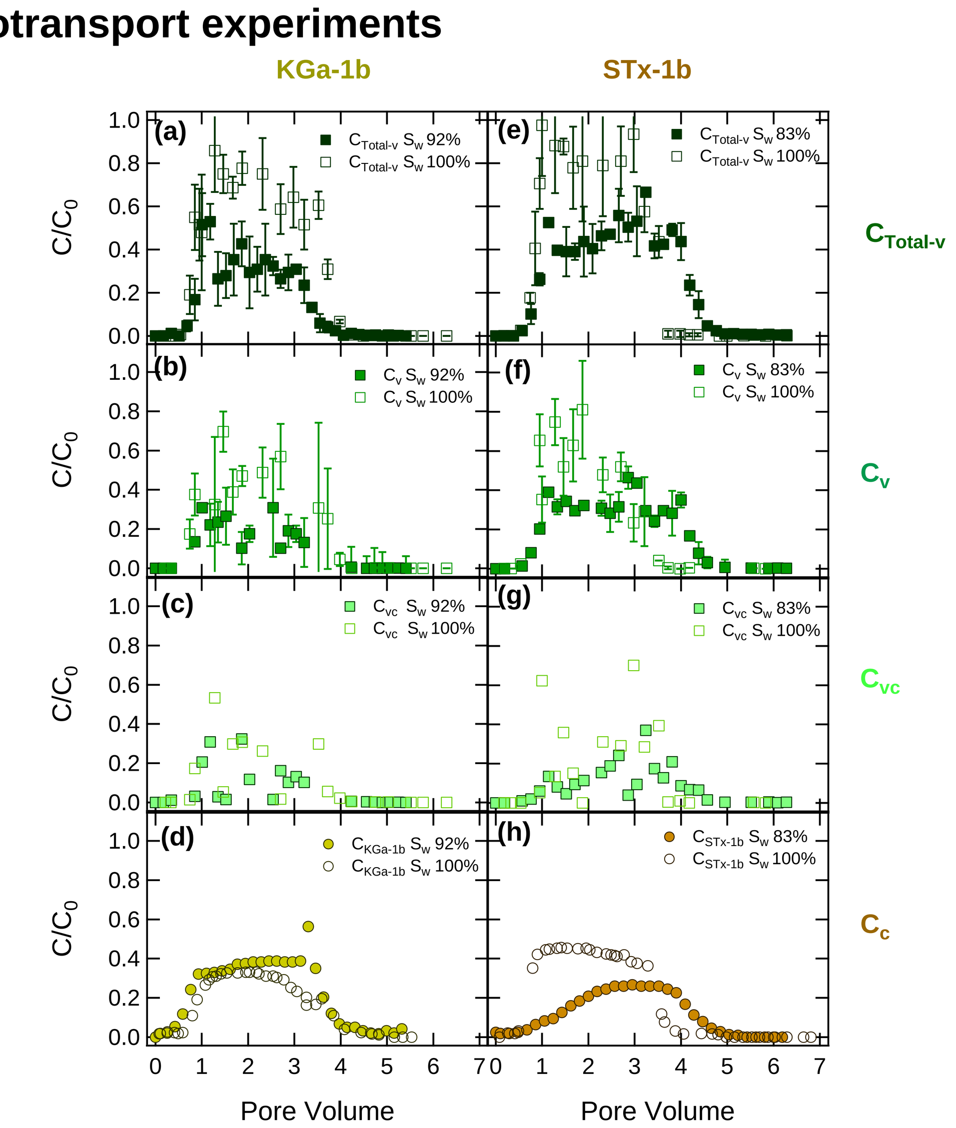


Figure 2. Experimental data for the cotransport of (a,b,c,d) ΦX174-KGa-1b and (e,f,g,h) ΦX174-STx-1b in both saturated (open symbols) and unsaturated (filled symbols) columns packed with glass beads.

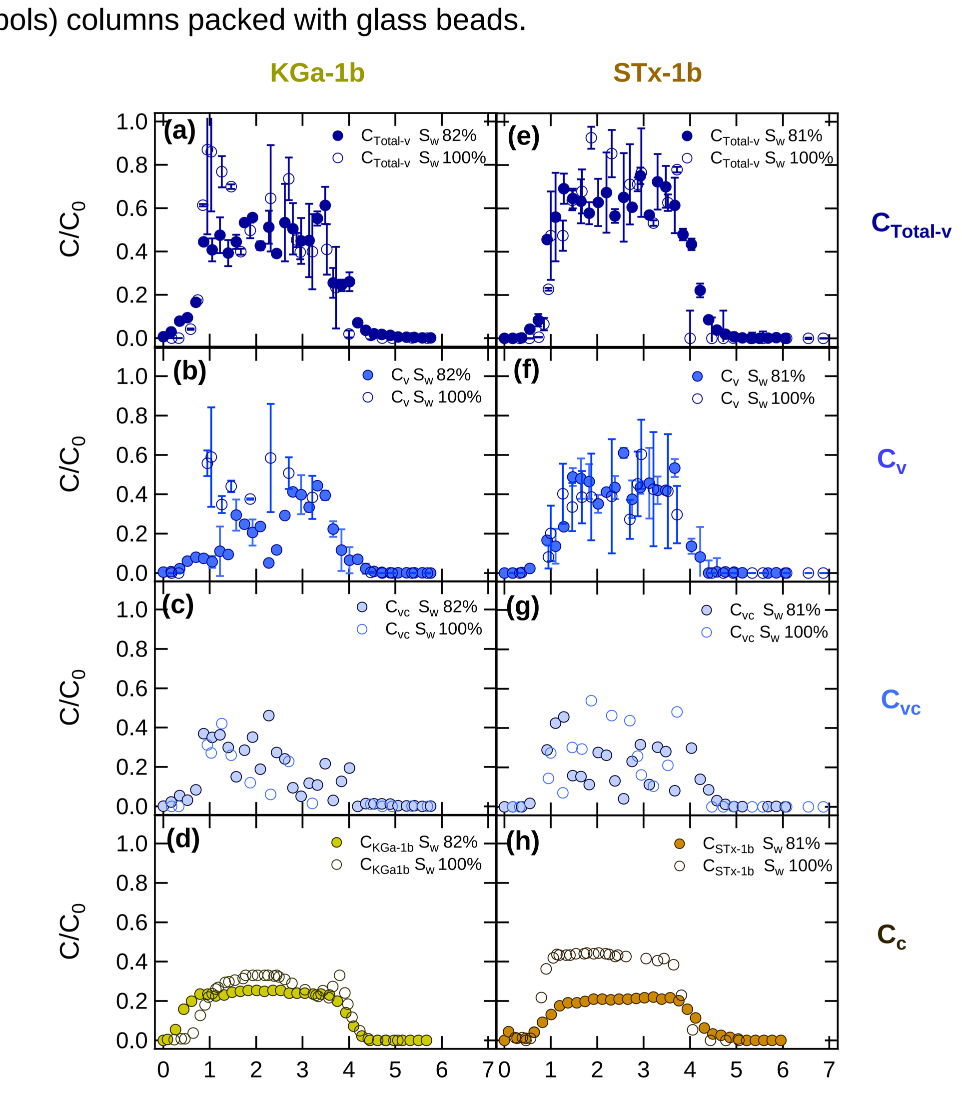


Figure 3. Experimental data for the cotransport of (a,b,c,d) MS2-KGa-1b and (e,f,g,h) MS2-STx-1b in both saturated (open symbols) and unsaturated (filled symbols) columns packed with glass beads.

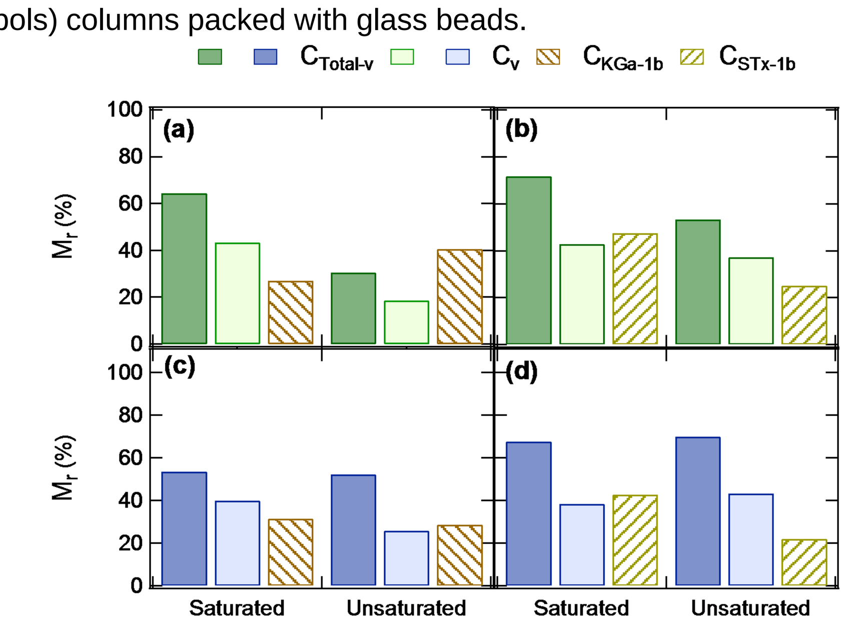


Figure 4. Calculated M_r values based on $C_{Total\text{-}v}$ (solid columns), C_v (filled columns), and C_c (cross-shaded columns) for cotransport of: (a) ΦX174 with KGa-1b, (b) MS2 with KGa-1b, (c) ΦX174 with STx-1b, and (d) MS2 with STx-1b under saturated and unsaturated experimental conditions.

Table 1. Experimental conditions and estimated parameters for the cotransport experiments

Exp. No	Initial concentration C_{v0}, C_{c0}	θ_m (-)	S_w (-)	U (cm/min)	M_r (%) for $C_{Total-v}$ or C_c	M_r (%) for C_v	$M_{1(i)}/M_{1(t)}$ for $C_{Total-v}$	$M_{1(i)}/M_{1(t)}$ for C_v	$\alpha_{Total-v}$	α_v
Cotransport experiments										
ΦX174-KGa-1b										
1	2767 PFU/mL	-	1	0.74	64.55	43.41	0.82	0.83	0.080	0.152
	80.75 mg/L				27.2		0.87		0.648	
2	5100 PFU/mL	0.39	0.92	0.64	30.62	18.67	1.01	1.01	0.178	0.371
	75 mg/L				40.59		1.13		0.776	
ΦX174-STx-1b										
3	4817 PFU/mL	-	1	0.74	71.85	43	0.79	0.82	0.060	0.153
	122.21 mg/L				47.74		0.77		0.208	
4	7433 PFU/mL	0.37	0.83	0.72	53.52	37.32	1.11	1.08	0.183	0.288
	107 mg/L				25.11		1.18		0.597	
MS2-KGa-1b										
5	9767 PFU/mL	-	1	0.74	53.75	39.98	0.78	0.85	0.109	0.161
	76.98 mg/L				31.41		0.85		0.577	
6	21383 PFU/mL	0.37	0.83	0.72	52.22	25.79	1.08	1.20	0.172	0.360
	69 mg/L				28.64		1.01		0.930	0.172
MS2-STx-1b										
7	9500 PFU/mL	-	1	0.74	67.65	38.45	0.89	0.92	0.069	0.168
	92.56 mg/L				42.88		0.85		0.238	
8	11067 PFU/mL	0.35	0.81	0.7	69.98	43.42	1.09	1	0.091	0.213
	89 mg/L				22		1.12		0.612	

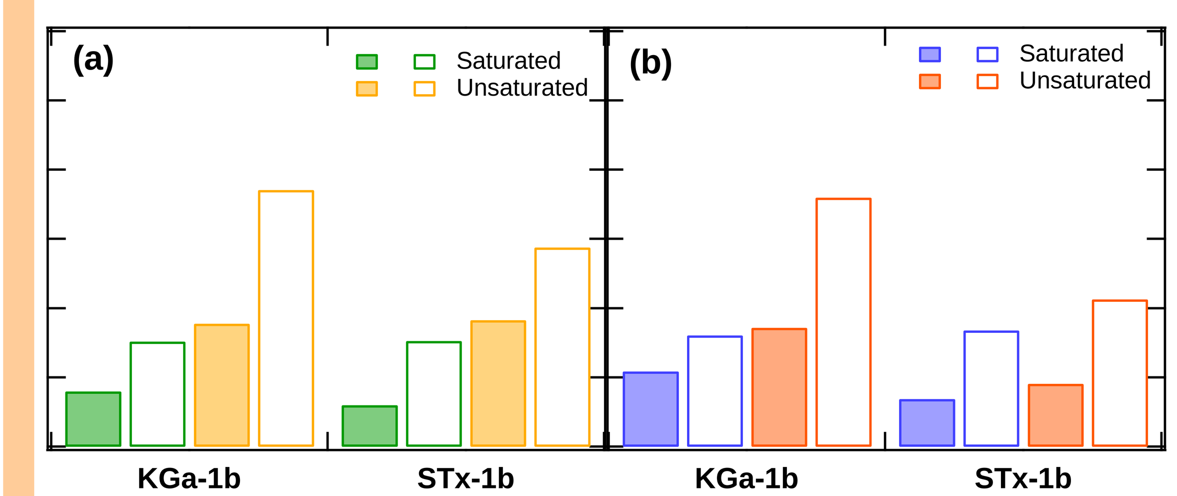


Figure 5. Experimental collision efficiencies $\alpha_{Total-v}$, based on $C_{Total-v}$ (filled columns) and α_v, based on C_v (open columns) in the effluent in both saturated and unsaturated conditions for: (a) ΦX174-clays (KGa-1b, STx-1b) and (b) MS2-clays (KGa-1b, STx-1b) cotransport experiments.

Conclusions

- The mass recovery of viruses and clay colloids decreased as the water saturation decreased.
- The mass recovery of both viruses was shown to reduce in the presence of suspended clay particles.
- Under saturated conditions, the transport of both $C_{Total\text{-}v}$ and C_v was retarded, compared to the conservative tracer while under unsaturated conditions the opposite was observed.
- Under unsaturated conditions both clay particles hindered the transport of both viruses.
- In the presence of STx-1b, the $C_{vc}=C_{Total\text{-}v}-C_v$ values of both viruses were higher than those in the presence of KGa-1b under both saturated and unsaturated conditions.
- In the presence of both KGa-1b and STx-1b, $\alpha_{Total-v}$ and α_v values increased with decreasing saturation level.

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