Reversible immobilization and irreversible removal of viruses in soils or mixtures of soil materials; an open data set enriched with a short review of main trends

Vincent Tesson, Pierre Renault

Reversible immobilization and irreversible removal of viruses in soils or mixtures of soil materials; an open data set enriched with a short review of main trends

Tesson V., Renault P. ✉

INRA, UMR 1114 EMMAH, CS 40509, 84914 Avignon Cedex 9, France

✉ Pierre Renault

pierre.renault@inra.fr

I. Introduction

Human enteric viruses brought to the soil by contaminated irrigation water can reach and contaminate plant or groundwater while remaining fully infective for weeks, and then cause waterborne and foodborne diseases. However, virus immobilization or inactivation within the soil may delay or prevent their transfer. In order to better assess those processes and the resulting sanitary hazards, models have been published. In this paper, we collected data from about 27 papers dealing simultaneously with reversible immobilization of viruses within the soil or in (mixtures of) soil material(s) (clay, sand ...) and irreversible virus removal, without always being able to distinguish between virus destruction and irreversible immobilization.

II. Reversible virus immobilisation

Some models distinguish kinetic reversible immobilization of free viruses in soil solution, from their kinetic remobilization:

$$\Phi_a = k_{a-r} \times \rho_b \times C_i \quad (1a)$$

$$\Phi_d = k_{d-r} \times \rho_b \times S_r \quad (1b)$$

where Φ_a and Φ_d are the adsorption and desorption fluxes of viruses per volume of bulk soil, respectively (mol day^{-1} ml^{-1}), ρ_b the bulk density of aggregates (g ml^{-1}), C_i the concentration of free viruses in soil solution (virus ml^{-1}), S_r the concentration of reversibly adsorbed viruses (virus g^{-1}), k_{a-r} the coefficient for reversible adsorption on soil solids (ml g^{-1} day^{-1}), and k_{d-r} the coefficient for desorption of reversibly adsorbed viruses (day^{-1}).

For high k_{a-r} and k_{d-r} values and for a constant k_{a-r}-to-k_{d-r} ratio, C_i and S_r satisfy the following equilibrium:

$$\frac{S_r}{C_i} = \frac{k_{a-r}}{k_{d-r}} = k_D \quad (2)$$

where k_D is the partition coefficient (ml g^{-1}). The adsorbed virus concentration S_r is then proportional to the concentration of free viruses suspended in water C_i. Equation (2) may be expressed in decimal logarithms:

$$log(S_r) = log(k_D) + log(C_i) \quad (3)$$

Because this assumption is not valid when adsorption sites differ from each other and/or adsorption cannot exceed a maximum, other mathematical formalisms have been proposed.

Freundlich isotherm corresponds to the following relationship between C_i and S_r:

$$S_r = k_F \times C_i^{\frac{1}{n_F}} \quad (4)$$

where n_F is a parameter that indirectly describes the deviation from the proportional model involving k_D partition coefficient, and k_F a proportionality parameter. Equation (4) is often expressed in decimal logarithms:

$$log(S_r) = log(k_F) + \frac{1}{n_F} \times log(C_i) \quad (5)$$

As in the k_D partition model, there is no maximum adsorption limit in the Freundlich isotherm model.

Langmuir isotherm corresponds to the following relationship between C_i and S_r:

$$S_r = S_{max-r} \times \left(\frac{C_i}{\beta + C_i}\right) \quad (6)$$

where S_{max-r} is the maximal concentration of reversibly adsorbed viruses (virus g^{-1}), and β the concentration of free viruses in soil solution (virus ml^{-1}) that leads to half of the reversible adsorption sites occupied. Equation (6) may be expressed in decimal logarithms:

$$log(S_r) = log(S_{max-r}) + log\left(\frac{C_i}{\beta + C_i}\right) \quad (7)$$

Main features of the models and the corresponding parameter values are reported in Tables 1 and 2. In Figure 1, adsorbed virus concentrations S_r are represented as a function of free virus concentrations C_i in soil solution. In Figure 2, the estimated S_r values for C_i=10^4 virus ml^{-1} are represented as a function of soil clay content.

44%, 28%, 36% and 4% of the publications mentioned in this paper employed the kinetic model, the k_D partition model, Freundlich isotherm and/or Langmuir isotherm, respectively; three of the publications compared two of these models (Table 1). For a fixed concentration of free viruses in soil solution (e.g. 10^4 virus ml^{-1}), deviation between minimum and maximum concentration of reversibly adsorbed viruses is about 6 log_{10} (see Figures 1 and 2). Most Freundlich isotherms use a n_F value very close to 1, making these isotherms *de facto* close to the k_D partition model. Due to the various forces involved in virus adsorption, it is difficult to highlight obvious relationships between variables.

Table 1: Main features of reversible immobilization models retained in published papers.

References	Reversible adsorption				Irreversible adsorption	
	Kinetic approach	K_D partition coefficient	Freundlich isotherm	Langmuir isotherm	From soil solution	From reversibly adsorbed pool
Burge & Enkiri (1978)			●			●
LaBelle & Gerba (1979)			●		●	
Vilker & Burge (1980)				●	●	
Moore et al. (1981)			●			●
Tim & Mostaghimi (1991) with experimental results from Lance & Gerba (1984)	●	●				●
Yates & Ouyang (1992) with experimental results from Grosser (1985); Ungs *et al.* (1985); Grondin (1987); Yates *et al.* (1988); Bales *et al.* (1989); Ouyang (1990)		●			●	
Grant et al. (1993)	●			●		●
Powelson & Gerba (1994)		●	●		●	
Dowd et al. (1998)	●	●			●	
Thompson et al. (1998)			●			●
Sim & Chrysikopoulos (1999) with experimental results from Hurst et al. (1980)		●			●	
Gantzer et al. (2001)			●		●	
Schijven & Šimůnek (2002) with experimental results from Schijven *et al.* (1999, 2000)	●				●	
Flynn et al. (2004)	●				●	
Torkzaban et al. (2006)		●			●	
Cheng et al. (2007)		●			●	
Zhao et al. (2008)			●		●	
Zhuang & Jin (2008)		●			●	
Anders & Chrysikopoulos (2009)		●			●	
Cao et al. (2010)	●					●
Syngouna & Chrysikopoulos 2010)		●			●	
Chrysikopoulos & Syngouna (2012)			●		●	
Sadeghi et al. (2013)	●					●
Chrysikopoulos & Aravantinou (2014)			●		●	
Mayotte et al. (2017)	●					●
Sasidharan et al. (2017)		●			●	
Our upcoming study			●			●

Table 2: Parameter values used in published reversible immobilization models.

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	S_r	β
Chrysikopoulos & Aravantinou (2014)	Quartz sand	Φ174	3-8				1.55	1.15		
							2.57	1.10		
							1.15	1.05		
							0.14	0.97		
							0.52	1.09		
							0.79	1.18		
							0.3	1.08		
							0.52	1.16		
							0.63	1.06		
		MS2	3-8				2.06	1.18		
							3.54	1.41		
							3.55	1.16		
							1.54	1.04		
							2.22	1.18		
							8.51	1.18		
							0.57	1.16		
							2.12	1.33		
							3.08	1.27		
Chrysikopoulos & Syngouna (2012)	Kaolinite	Φ174	3-9				2260	1.00		
		MS2	3-9				758	0.89		
	Montmorillonite	Φ174	3-9				271	1.08		
		MS2	3-9				4340	0.94		
Thompson *et al.* (1998)	Loamy sand	Φ174	2-7				2.89	1.09		
							1.01	1.16		
		MS2	2-7				0.076	0.99		
	Sandy loam	Φ174	2-7				6.52	1.02		
							10.99	1.06		
		MS2	2-7				0.437	1.01		
	Sand	Φ174	2-7				0.44	0.99		
LaBelle & Gerba (1979)	Sediments	Echo 1	4-5				$10^{4.77}$	1.24		
		PV1	4-5				$10^{5.42}$	3.45		

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	S_r	β
Cao *et al.* (2010)	Sandy soil	MS2	2.5		0.06	6000				
					0.06	$10^{12.78}$				
					1.20	12.00				
					16.14	46.38				
					22.56	56.64				
					16.62	54.24				
					15.24	28.80				
					0.06	6000				
					0.06	$10^{12.78}$				
					3.48	43.62				
					4.62	13.26				
					5.76	32.76				
					6.18	52.32				
					7.32	24.06				
Zhao *et al.* (2008)	Loam	MS2	2-7				0.228	0.96		
							1.016	0.97		
Sasidharan *et al.* (2017)	Quartz sand	Φ174	6.7		0.02	0.04				
					0.07	0.02				
					0.07	0.06				
					0.07	0.02				
		PRD1	6.7		0.16	0.06				
					0.02	0.03				
					0.38	0.10				
					0.33	0.09				
Dowd *et al.* (1998)	Aquifer sand	MS2	9.3		19.08	3.96				
		PRD1	10.5		19.44	4.32				
		Qβ	4.8		24.48	1.44				
		ϕ 174	6.3		10.44	5.40				
		PM2	7.2		8.64	0.72				

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	$S_{r\ max}$	β
Burge & Enkiri (1978)	Clay loam	Φ174	2-7				72.5	1.06		
	Silt loam	Φ174	2-7				4.61	1.09		
							161	1.10		
							45.7	0.81		
Moore *et al.* (1981)	Ottawa sand	PV	8-9				0.631	0.83		
Vilker & Burge (1980)	Kranzburg soil	Φ 174	4.2-7.2						$10^{8.32}$	$10^{10.30}$
			7.1-10.5						$10^{8.28}$	$10^{10.98}$
Powelson & Gerba (1994)	Sandy alluvium	PV	3-6	160.0						
		MS2	3-6	3.70						
		PRD1	3-6	16.00						
Schijven & Šimůnek (2002) with experimental results from Schijven *et al.* (1999, 2000)	Dune sand	MS2	7.9		0.17	$10^{-4.44}$				
					0.13	$10^{-4.18}$				
					0.12	$10^{-3.97}$				
					0.08	$10^{-4.12}$				
					0.05	$10^{-4.66}$				
					0.03	$10^{-3.90}$				
		PRD1	7		0.17	$10^{-4.49}$				
					0.13	$10^{-4.34}$				
					0.09	$10^{-4.12}$				
					0.06	$10^{-3.98}$				
					0.05	$10^{-4.06}$				
					0.03	$10^{-3.85}$				
Sim & Chrysikopoulos (1999) with experimental results from Hurst *et al.* (1980)	Loamy sand	PV1	4	0.087						

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	S_r	β
Syngouna & Chrysikopoulos 2010)	Kaolinite	Φ174	3-9	16.00						
				36.00						
				21.00						
				24.00						
	Montmorillonite	MS2	3-9	78.00						
				68.00						
				19.00						
				21.00						
Tim & Mostaghimi (1991) with experimental results from Lance & Gerba (1984)	Loamy sand	PV1	4	1200						
Cheng *et al.* (2007)	Sand	MS2	6-9		0.91	0.06				
					0.29	0.01				
					0.35	0.003				
					0.64	0.01				
					0.53	0.01				
Mayotte *et al.* (2017)	River sand	MS2	8.04-8.34		0.46	0.14				
					0.24	0.21				
					2.08	$10^{-5.08}$				
					0.72	0.13				

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	S_r	β
Flynn *et al.* (2004)	Fresh kappelen sands	H 40/1	2.6		$10^{4.06}$	-				
	Quartz sands	H 40/1	2.6		7290	-				
	Granitic sands	H 40/1	2.6		1800	-				
	Quartz-calcite mixture	H 40/1	2.6		3480	-				
	Reused kappelen sands	H 40/1	2.6		1080	-				
	Washed kappelen sands	H 40/1	2.6		$10^{4.41}$	-				
	Acid-digested sands	H 40/1	2.6		960	-				
Sadeghi *et al.* (2013)	Quartz sand	PRD1	4.5-5.2		0.19	0.026				
					0.086	0				
					0.21	0.014				
					1.20	$10^{-2.85}$				
					0.59	$10^{-4.57}$				
					1.10	$10^{-3.43}$				
					0.74	$10^{-3.04}$				
					2.10	$10^{-2.44}$				
Gantzer *et al.* (2001)	Cultivated soil	Coli-phages	1.3-2.9				4.34	0.80		
		F-RNA phages	0.6-2.6				40.74	1.11		

References	Soil type	Virus species	Conc. range or punctual value ($\log_{10}$ virus ml^{-1})[a]	K_d (ml g^{-1})	Kinetic approach		Freundlich isotherm		Langmuir isotherm	
					k_{att} (h^{-1})	k_{det} (h^{-1})	K_F	n_F	S_r	β
Torkzaban *et al.* (2006)	Quartz sand	MS2	6		6.00	2820				
					7.80	1800				
					6.00	1200				
					30.00	1320				
					48.00	1500				
					222	1.80				
					306	0.60				
					384	0.60				
		Φ 174	6		25.80	1500				
					49.20	420.00				
					492	84.00				
					780	90.00				
					900	102				
Anders & Chrysikopoulos (2009)	Monterey sand	MS2	5.74	33.72						
				380.9						
				136.7						
		PRD1	5.74	36.17						
				311.9						
				40.75						
Zhuang et al 2008	Goethite-sand mixture	ϕ 174	8.7	0.319						
				0.138						
				0.093						
				0.197						
		MS2	8.7	0.045						
				0.306						
				0.013						
				0.588						
Our upcoming study	Calcaric phaeozem	MNV	3-6				127.6	1.60		

[a] Virus concentration in our study are expressed in genomic copies per ml (GC ml^{-1})

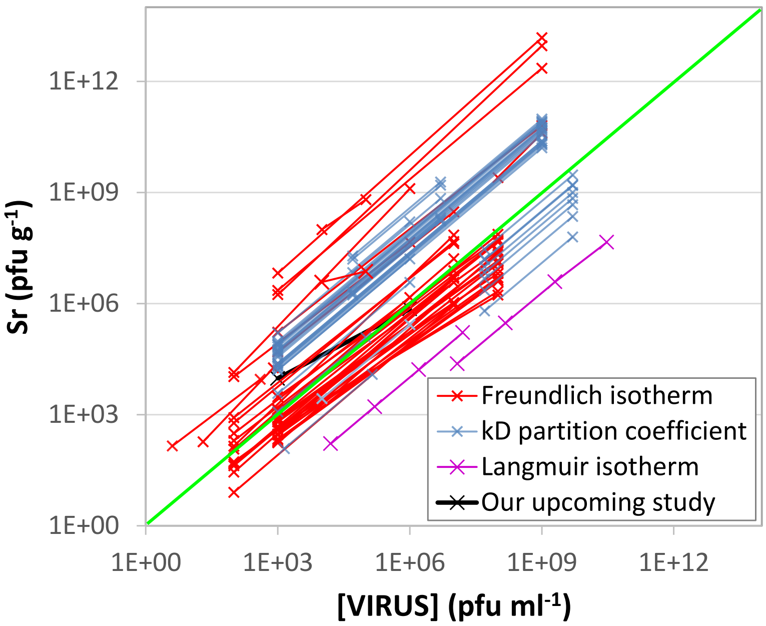

Figure 1: Published relationships between adsorbed virus concentrations S_r and free virus concentrations C_i in soil solution. Curves were plotted either in the given range of virus concentrations C_i, or when a unique C_i was experimented (especially for k_D partition models), between one tenth and ten times this value.

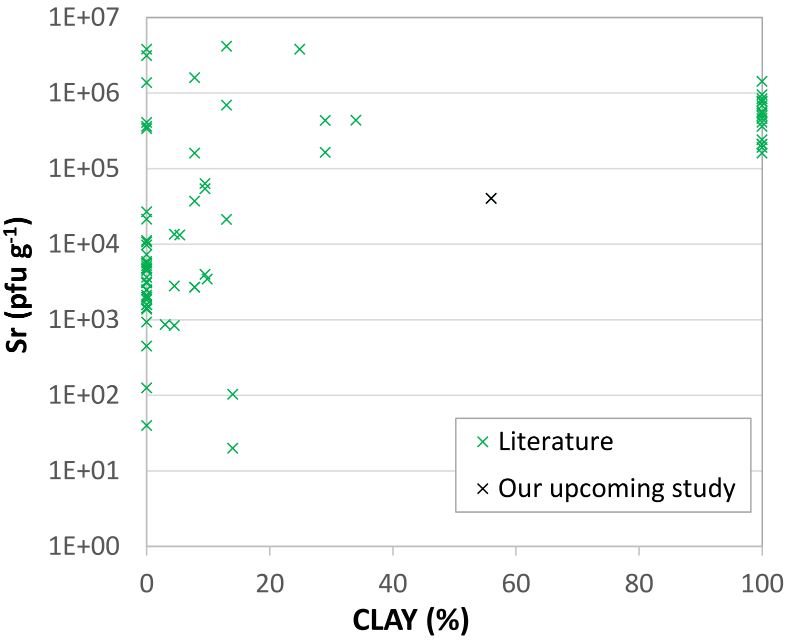

Figure 2: Relationships between reversibly adsorbed virus concentrations S_r for free virus concentrations C_i =10^4 virus ml^{-1}, and soil clay contents (%) that were reported or estimated from the soil textural triangle. (Red circle accounts for iron oxide supplemented sands).

III. Irreversible virus removal

Among the 27 papers dealing with reversible virus adsorption, irreversible virus removal could be neglected over periods not exceeding the duration of reversible virus adsorption experiments in 4 papers (Dowd *et al.*, 1998; Cao *et al.*, 2010; Syngouna & Chrysikopoulos, 2010; Sasidharan *et al.*, 2017). In addition, results were not clear enough in five other papers (Burge & Enkiri, 1978; Chrysikopoulos & Syngouna, 2012; Chrysikopoulos & Aravantinou, 2014), and the estimated inactivation coefficients were probably biased due inappropriate partition coefficient k_D for reversible adsorption in another paper (Yates & Ouyang, 1992). Lastly, inactivation resulted mainly from the triple phase (air-liquid-solid (tube wall)) boundary in a last paper (Thompson *et al.*, 1998). Therefore, the following analysis focuses on the other 17 publications.

When irreversible virus removal was taken into account, it was described by first order kinetics. For irreversible removal from the soil solution, this may be written:

$$\frac{\partial C_i}{\partial t} = -\lambda \times C_i \quad (8)$$

where λ is a kinetic coefficient (day^{-1}). This equation leads to:

$$C_i(t) = C_i(t=0) \times e^{-\lambda t} = C_i(t=0) \times 10^{-\frac{\lambda}{Ln(10)}t} \quad (9)$$

For irreversible removal from the viruses reversibly adsorbed on the soil, equation (8) could be transposed as:

$$\frac{\partial S_r}{\partial t} = -\lambda \times S_r \quad (10)$$

When the quantity of reversibly adsorbed viruses can be described by the k_D partition model, the irreversible removal of reversibly adsorbed viruses leads to simultaneous change of virus concentration in soil solution according to equation (8) with the same rate coefficient λ.

When the quantity of reversibly adsorbed viruses can be described by Freundlich isotherms, the irreversible removal of reversibly adsorbed viruses leads to the simultaneous change of virus concentration in soil solution according to the following equation:

$$\frac{\partial C_i}{\partial t} = -\lambda \times n_F \times C_i \quad (11)$$

The coefficient rates of the published first order rates models of virus irreversible removals are reported in Table 3, as well as the durations of the corresponding experiments and/or simulations. In addition, coefficient rate values are reported as a function of the iron oxides of the corresponding soil or soil material(s) in Figure 3.

85 non-zero inactivation rate coefficients were reported in Table 3. They varied between 0.001 and 864 day^{-1}. No significant relationships were noted between coefficient rate values and other values that could affect it, e.g. with the soil clay content (Figure 3), probably because it depends on the simultaneous validation of different condition.

Table 3: Daily removal coefficient rates (λ) reported in literature.

References	Soil type	Virus species	λ (day^{-1})	Experiment duration (h)
Zhao et al. (2008)	Ferriudic cambosols	MS2	0.032	1320
		MS2	0.015	1320
		MS2	0.015	1320
		MS2	0.011	1320
	Ustandic primosols	MS2	0.008	1320
		MS2	0.006	1320
		MS2	0.01	1320
		MS2	0.007	1320
Gantzer et al. (2001)	Cultivated soil	Coliphages	0.131	240
		Coliphages	0.017	240
		Coliphages	0.049	240
		F-RNA	0.067	240
		F-RNA	0.075	240
		F-RNA	0.136	240
LaBelle & Gerba (1979)	Sediment	PV1	864.0	0.5
		Cox B4	864.0	0.5
		Echo 1	864.0	0.5
		Echo 7	864.0	0.5
		Rotavirus	864.0	0.5
Powelson & Gerba (1994)	Sandy alluvium	MS2	0.079	72
		PRD1	0.167	72
		PV1	0.719	72
Sim & Chrysikopoulos (1999) with experimental results from Hurst et al. (1980)	Loamy sand	PV1	0.0	1800
Tim & Mostaghimi (1991) with experimental results from Lance & Gerba (1984)	Loamy sand	PV1	2.22	96
Anders & Chrysikopoulos (2009)	Monterey sand	MS2	0.026	2
		MS2	0.066	2
		PRD1	0.001	2
		PRD1	0.002	2
Schijven & Šimůnek (2002) with experimental results from Schijven *et al.* (1999, 2000)	Dune sand	MS2	0.017	960
		MS2	0.071	960
		MS2	0.024	960
		MS2	0.049	960
		MS2	0.053	960
	Dune sand (Well 1-6)	MS2	0.013	2880
	Dune sand (Well 1)	MS2	0.037	2880
	Dune sand (Well 2-6)	MS2	0.040	2880
	Dune sand (Well 1-6)	PRD1	0.052	2880
	Dune sand (Well 1)	PRD1	0.031	2880
	Dune sand (Well 2-6)	PRD1	0.029	2880
Cheng et al. (2007)	Vinton soil	MS2	2.88	50
		MS2	5.76	50
		MS2	6.34	50
Mayotte et al. (2017)	River sand (new)	MS2	0.190	1440
	River sand (new)	MS2	0.083	1440
	River sand (used)	MS2	0.065	1440
	River sand (used)	MS2	0.083	1440
	River sand (new)	MS2	0.013	1440
	River sand (used)	MS2	112.6	1440
Vilker & Burge (1980)	Kranzburg soil	Φ 174	0.620	48

References	Soil type	Virus species	λ (day^{-1})	Experiment length (h)
Dowd *et al.* (1998)	Aquifer sand	MS2	0.02	4
		PRD1	0.03	
		Qβ	0.08	
		ϕ 174	0.42	
		PM2	0.58	
Flynn et al. (2004)	Fresh kappelen sands	H40/1	118.82	3
	Quartz sands	H40/1	11.26	3
	Granitic sands	H40/1	10.01	3
	Quartz-calcite mixture	H40/1	265.16	3
	Reused kappelen sands	H40/1	75.98	3
	Washed kappelen sands	H40/1	18.76	3
	Acid-digested kappelen sands	H40/1	36.27	3
Sadeghi et al. (2013)	Quartz sand	PRD1	0.07	30
		PRD1	0.07	30
		PRD1	0.53	30
Torkzaban et al. (2006)	Sand	MS2	0.02	6
		ϕ 174	0.01	6
Powelson et al. (1993)	Sandy alluvium	MS2	2.40	6
		MS2	2.71	6
		MS2	3.86	6
		MS2	1.35	6
		MS2	2.40	6
		PRD1	6.77	6
		PRD1	10.42	6
		PRD1	3.65	6
		PRD1	5.94	6
		PRD1	6.15	6
		PRD1	8.55	6
Zhuang & Jin (2008)	Goethite-coated sand	ϕ 174	4.59	1320
		ϕ 174	13.55	1320
		ϕ 174	1.25	1320
		ϕ 174	5.73	1320
		MS2	0.21	1320
		MS2	8.13	1320
		MS2	3.13	1320
		MS2	4.69	1320
Our upcoming study	Calcaric phaeozem	MNV	0.38	7

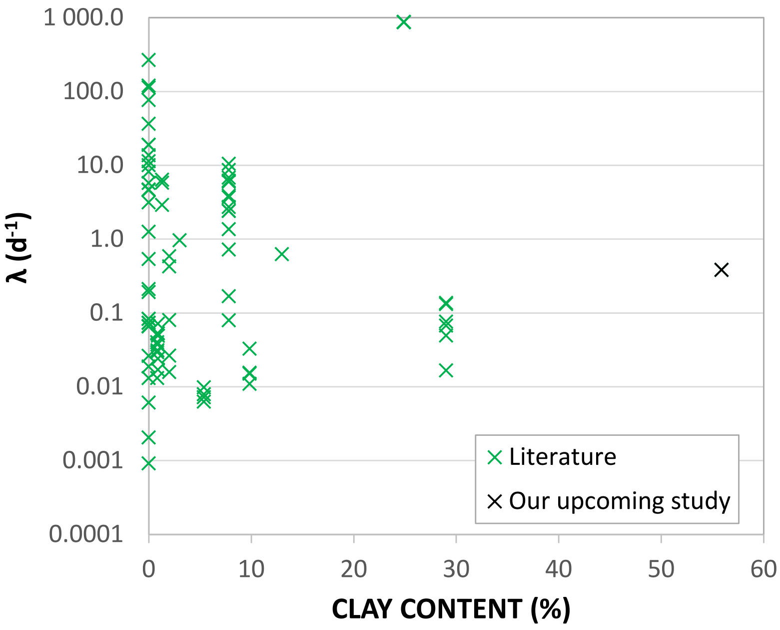

Figure 3: Daily removal rates as reported in literature

References

Anders, R. & Chrysikopoulos, C.V. 2009. Transport of Viruses Through Saturated and Unsaturated Columns Packed with Sand. *Transport in Porous Media*, **76**, 121–138.

Bales, R.C., Gerba, C.P., Grondin, G.H. & Jensen, S.L. 1989. Bacteriophage transport in sandy soil and fractured tuff. *Applied and Environmental Microbiology*, **55**, 2061–2067.

Burge, W.D. & Enkiri, N.K. 1978. Virus Adsorption by Five Soils. *Journal of Environmental Quality*, **7**, 73–76.

Cao, H., Tsai, F.T.-C. & Rusch, K.A. 2010. Salinity and Soluble Organic Matter on Virus Sorption in Sand and Soil Columns. *Ground Water*, **48**, 42–52.

Cheng, L., Chetochine, A.S., Pepper, I.L. & Brusseau, M.L. 2007. Influence of DOC on MS-2 Bacteriophage Transport in a Sandy Soil. *Water, Air, and Soil Pollution*, **178**, 315–322.

Chrysikopoulos, C.V. & Aravantinou, A.F. 2014. Virus attachment onto quartz sand: Role of grain size and temperature. *Journal of Environmental Chemical Engineering*, **2**, 796–801.

Chrysikopoulos, C.V. & Syngouna, V.I. 2012. Attachment of bacteriophages MS2 and ?X174 onto kaolinite and montmorillonite: Extended-DLVO interactions. *Colloids and Surfaces B: Biointerfaces*, **92**, 74–83.

Dowd, S.E., Pillai, S.D., Wang, S. & Corapcioglu, M.Y. 1998. Delineating the specific influence of virus isoelectric point and size on virus adsorption and transport through sandy soils. *Applied and Environmental Microbiology*, **64**, 405–410.

Flynn, R.M., Rossi, P. & Hunkeler, D. 2004. Investigation of virus attenuation mechanisms in a fluvioglacial sand using column experiments. *FEMS Microbiology Ecology*, **49**, 83–95.

Gantzer, C., Gillerman, L., Kuznetsov, M. & Oron, G. 2001. Adsorption and survival of faecal coliforms, somatic coliphages and F-specific RNA phages in soil irrigated with wastewater. *Water Science and Technology*, **43**, 117–124.

Grant, S.B., List, E.J. & Lidstrom, M.E. 1993. Kinetic analysis of virus adsorption and inactivation in batch experiments. *Water Resources Research*, **29**, 2067–2085.

Grondin, G.H. 1987. Transport of MS-2 and f2 bacteriophage through saturated Tanque Verde Wash soil.

Grosser, P.W. 1985. One-Dimensional Mathematical Model of Virus Transport. In: *Second International Conference on Groundwater Quality Research: Proceedings, National Center for Groundwater Research, Houston TX.(1985). p 105-107, 4 fig, 7 ref.*

Hurst, C.J., Gerba, C.P. & Cech, I. 1980. Effects of environmental variables and soil characteristics on virus survival in soil. *Applied and Environmental Microbiology*, **40**, 1067–1079.

LaBelle, R.L. & Gerba, C.P. 1979. Influence of pH, salinity, and organic matter on the adsorption of enteric viruses to estuarine sediment. *Applied and environmental microbiology*, **38**, 93–101.

Lance, J.C. & Gerba, C.P. 1984. Effect of ionic composition of suspending solution on virus adsorption by a soil column. *Applied and environmental microbiology*, **47**, 484–488.

Mayotte, J.-M., Hölting, L. & Bishop, K. 2017. Reduced removal of bacteriophage MS2 in during basin infiltration managed aquifer recharge as basin sand is exposed to infiltration water. *Hydrological Processes*, **31**, 1690–1701.

Moore, R.S., Taylor, D.H., Sturman, L.S., Reddy, M.M. & Fuhs, G.W. 1981. Poliovirus adsorption by 34 minerals and soils. *Applied and Environmental Microbiology*, **42**, 963–975.

Ouyang, Y. 1990. *Dynamic mathematical model of oxygen and carbon dioxide exchange between soil and atmosphere*. (At: http://ir.library.oregonstate.edu/xmlui/handle/1957/37466. Accessed: 3/10/2017).

Powelson, D.K. & Gerba, C.P. 1994. Virus removal from sewage effluents during saturated and unsaturated flow through soil columns. *Water Research*, **28**, 2175–2181.

Powelson, D.K., Gerba, C.P. & Yahya, M.T. 1993. Virus transport and removal in wastewater during aquifer recharge. *Water Research*, **27**, 583–590.

Sadeghi, G., Schijven, J.F., Behrends, T., Hassanizadeh, S.M. & van Genuchten, M.T. 2013. Bacteriophage PRD1 batch experiments to study attachment, detachment and inactivation processes. *Journal of Contaminant Hydrology*, **152**, 12–17.

Sasidharan, S., Torkzaban, S., Bradford, S.A., Cook, P.G. & Gupta, V.V.S.R. 2017. Temperature dependency of virus and nanoparticle transport and retention in saturated porous media. *Journal of Contaminant Hydrology*, **196**, 10–20.

Schijven, J.F., Hoogenboezem, W., Hassanizadeh, M. & Peters, J.H. 1999. Modeling removal of bacteriophages MS2 and PRD1 by dune recharge at Castricum, Netherlands. *Water Resources Research*, **35**, 1101–1111.

Schijven, J.F., Medema, G., Vogelaar, A.J. & Hassanizadeh, S.M. 2000. Removal of microorganisms by deep well injection. *Journal of Contaminant Hydrology*, **44**, 301–327.

Schijven, J.F. & Šimůnek, J. 2002. Kinetic modeling of virus transport at the field scale. *Journal of Contaminant Hydrology*, **55**, 113–135.

Sim, Y. & Chrysikopoulos, C.V. 1999. Analytical models for virus adsorption and inactivation in unsaturated porous media. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **155**, 189–197.

Syngouna, V.I. & Chrysikopoulos, C.V. 2010. Interaction between Viruses and Clays in Static and Dynamic Batch Systems. *Environmental Science & Technology*, **44**, 4539–4544.

Thompson, S.S., Flury, M., Yates, M.V. & Jury, W.A. 1998. Role of the air-water-solid interface in bacteriophage sorption experiments. *Applied and environmental microbiology*, **64**, 304–309.

Tim, U.S. & Mostaghimi, S. 1991. Model for Predicting Virus Movement Through Soils. *Ground Water*, **29**, 251–259.

Torkzaban, S., Hassanizadeh, S.M., Schijven, J.F., Bruin, D., M, H.A., Husman, de R. & M, A. 2006. Virus Transport in Saturated and Unsaturated Sand Columns. *Vadose Zone Journal*, **5**, 877–885.

Ungs, M.J., Boersma, L., Akratanakul, S. & others. 1985. *Or-nature: the numerical analysis of transport of water and solutes through soil and plants: Volume 1: Theoretical Basis*. Corvallis, Or.: Agricultural Experiment Station, Oregon State University. (At: http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/5094/?sequence=1. Accessed: 3/10/2017).

Vilker, V.L. & Burge, W.D. 1980. Adsorption mass transfer model for virus transport in soils. *Water Research*, **14**, 783–790.

Yates, M.V. & Ouyang, Y. 1992. VIRTUS, a model of virus transport in unsaturated soils. *Applied and environmental microbiology*, **58**, 1609–1616.

Yates, M.V., Yates, S.R. & Gerba, C.P. 1988. Modeling microbial fate in the subsurface environment. *Critical Reviews in Environmental Science and Technology*, **17**, 307–344.

Zhao, B., Zhang, H., Zhang, J. & Jin, Y. 2008. Virus adsorption and inactivation in soil as influenced by autochthonous microorganisms and water content. *Soil Biology and Biochemistry*, **40**, 649–659.

Zhuang, J. & Jin, Y. 2008. Interactions between viruses and goethite during saturated flow: Effects of solution pH, carbonate, and phosphate. *Journal of Contaminant Hydrology*, **98**, 15–21.