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*Supplement of*

## **Use of column experiments to investigate the fate of organic micropollutants – a review**

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**Table S1: Saturated / flowthrough column experiments**

Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concentra- tions	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Alidina et al. (2014)	saturated flow through	atenolol, caffeine, diclofenac, gemfibrozil, primidone, trimethoprim	glass	4 x 100 (in se- ries)	5	natural soil	sieved, wet (satu- rated)	0.32	1.44 m/d (as "loading rate")	n/a	n/a	peristal- tic pump	synthetic wastewater with different ratios of different organic carbon sources	300 - 500 ng/L	n/a	sampling ports
Alotaibi et al. (2015)	saturated flow through	5-methylbenzotriazole, benzotriazole	stainless steel	200	14.5	natural sediment	wet (satu- rated) under flushing nitro- gen gas	0.402 (bromide tracer test)	2.86 cm/d (bromide tracer test)	n/a	n/a	gear pump	treated waste wa- ter	200 ng/L per com- pound	Origin v61 (CDE)	sampling ports
Banzhaf et al. (2012)	saturated flow through	carbamazepine, diclofenac, ibuprofen, sulfamethoxazole	stainless steel	35	13.6	natural sediment	dry, com- paction by a stamp	0.42 (to- tal) 0.41 (ef- fective from tracer ex- periment)	14 mL/h / 6.3 - 6.5 cm/d	quartz filter sand / gravel	n/a	peristal- tic pump	natural surface water	165 - 295 µg/L	CXTFIT (Toride et al., 1995)	flowthrough cells (physi- co-chemical parameters), fraction col- lector
Baumgarten et al. (2011)	saturated flow through	sulfamethoxazole	n/a	200	15.5	artificial sediment (filter sand/tech- nical quartz sand), 0.7 - 1.2 mm grain size	n/a	0.4 ("void- age")	0.13 m/d ( $v_i$ )	n/a	n/a	n/a	natural surface water (aerobic & anaerobic)	0.25 - 4.15 µg/L	n/a	sampling ports (online: pH, O <sub>2</sub> ; of- fline: 0.2 L samples), 0.2 L sam- ples at the in- fluent & efflu- ent
Bertelkamp et al. (2012)	saturated flow through	acetaminophen, atrazine, caffeine, carbamazepine, gemfibrozil, ibuprofen, hydrochlorothiazide, Ketoprofen, lincomycin, phenytoin, propranolol, metoprolol, trimethoprim, sulfamethoxazole	PVC (transpar- ent)	100	3.6	artificial sediment (filter sand/tech- nical quartz sand), 1.4 - 2 mm	n/a	0.31 - 0.4	2.4 - 3.2 m/d (pore velocity, NaCl Tracer)	n/a	dark pol- yethylene , Mar- prene® pump tubing	peristal- tic pump	natural surface water with sodium acetate or sodium azide, tap water spiked with OMPs	200 ng/L per sub- stance	n/a	bottles

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			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Bertelkamp et al. (2014)	saturated flow through	acetaminophen, atrazine, caffeine, carbamazepine, gemfibrozil, ibuprofen, hydrochlorothiazide, ketoprofen, lincomycin, phenytoin, propranolol, metoprolol, trimethoprim, sulfamethoxazole	PVC (transparent)	100	3.6	artificial sediment (filter sand/technical quartz sand), 1.4 - 2 mm	compaction by tapping in 4 - 5 cm increments	0.31 - 0.42	2.4 - 3.2 m/d	perforated PVC plates	dark polyethylene, Marprene® pump tubing	peristaltic pump	natural surface water with sodium acetate or sodium azide, demineralized water	200 ng/L per substance	CXTFIT (Toride et al., 1995)	bottles
Burke et al. (2013)	saturated flow through	1-acetyl-1-methyl-2-dimethyl-oxamoyl-2-phenylhydrazide, 1-acetyl-1-methyl-2-phenylhydrazide, acetaminopyrine, atenolol, diazepam, formylaminoantipyrine, meprobamate, metoprolol, N-methylphenacetine, oxazepam, p-TSA, phenacetine, phenazone, phenylethylmalonamide, primidone, propranolol, propylphenazone, pyriithylidone, sotalol, tolyltriazone,	stainless steel	30	10	natural sediment	wet (saturated), compaction by vibration	0.45	0.147 m/d	stainless steel mesh	PTFE	n/a	tap water	0.8 µg/L each compound	Phreeqc-2 (Parkhurst and Appelo, 1999)	fraction collector
Burke et al. (2014)	saturated flow through	acesulfame, acetaminopyrine, benzotriazole, carbamazepine, diclofenac, formylaminoantipyrine, iopromide, metoprolol, phenazone, tolyltriazone,	aluminum	120	8	natural sediment	undisturbed core	0.3	1.38 m/d (pore water velocity)	n/a	n/a	peristaltic pump	natural surface water	0.07 – 0.72 µg/L	PEST, removal rates (Doherty, 2005)	sampling ports, by hand

Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concentra- tions	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Burke et al. (2016)	saturated flow through	atenolol, propranolol, metoprolol, sotalol, iopromide, phenazone, propyphenazone, FAA, AAA, AMPH, AMDOPH, diazepam, oxazepam, primidone, PEMA, carbamazepine, trimethoprim, benzotriazole, tolyltriazole, acesulfame	stainless steel	30	10	natural sediment	wet (satu- rated), com- paction by vi- bration	0.4	0.16 m/d (pore water velocity)	stain- less steel mesh	n/a	peristal- tic pump	natural water	1 µg/L	n/a	manual
Casas and Bester (2015)	saturated flow through	diclofenac, iohexol, iomeprol, iopromide, propiconazole, propranolol, tebuconazole	glass	50 (filled up to 29)	2.5	artificial sediment (filter sand/tech- nical quartz sand)	n/a	0.36 (from bro- mide tracer test)	0.025 -0.2 mL/min	glass-fi- ber filter (1.2 µm)	n/a	piston pump	treated waste wa- ter	0.022 - 20.8 µg/L	n/a	on-line (HPLC-UV) & off-line (HPLC- MS/MS)
Chen et al. (2011)	saturated flow through	ciprofloxacin, sulfamethoxazole	acrylic cylinder	10	2.5	artificial sediment (filter sand / technical quartz sand)	wet, stirring and tapping	0.42	0.2 cm/min	n/a	n/a	peristal- tic pump	deionized water with 0.1 mM KBr, pH 9.5 (NaOH)	200 µg/L sulfa- methoxa- zole, 50 µg/L ciprofloxac- in	1D- CDE coupled with re- action terms	fraction col- lector
D'Alessio et al. (2015)	saturated flow through	17-β estradiol, caffeine, carbamazepine, estrone, gemfibrozil, phenazone	stainless steel	14.5	4.75	artificial sediment (filter sand / technical quartz sand)	n/a	0.41	0.2 mL/min	fine stain- less steel wire cloth	n/a	peristal- tic pump	natural surface water (aerobic & anaerobic)	50 µg/L	n/a	n/a

Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concentrations	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Estrella et al. (1993)	saturated	2,4-dichlorophenoxyacetic acid (2,4-D)	n/a ("chromatography column" →probably glass)	5	2.5	natural soil	n/a	n/a	4.7-6.2 cm/h	n/a	n/a	n/a	artificial (ground)water (CaCl <sub>2</sub> )	100 mg/L	CDE, incl. first order degrada- tion (Van Genuch- ten and Wagen et, 1989)	fraction col- lector
Greenhagen et al. (2014)	saturated flow through	acetaminophen, caffeine, methamphetamine	PVC	30	30	natural soil, artifi- cial sedi- ment (filter sand / technical quartz sand)	undis- turbed (soil); n/a for sand	0.28 (un- dis- turbed)	600 mL/d	quartz filter sand / gravel, alumi- num screen	black Tygon, PVC pump tubing, Vinyl, brass (com- pression fittings), Polysul- fone (tees)	peristal- tic pump	natural groundwa- ter	1000 mg/L ac- etamino- phen, 250 mg/L caf- feine, 100 mg/L metham- pheta- mine	CDE, incl. first order degrada- tion (Van Genuch- ten and Wagen et, 1989)	manual
Gruenheid et al. (2008)	saturated flow through	iopromide, sulfamethoxazole, naphthalenedisulfonic acid (each isomer)	plexiglas	50	14	artificial sediment (filter sand / technical quartz sand)	n/a	n/a	8.3 cm/d (pore water velocity)	quartz filter sand / gravel	n/a	peristal- tic pump	natural surface water	10 µg/L iopromide , 2.5 µg/L sulfa- methoxa- zole, 2.5 µg/L each iso- mer of naphtha- lenedisul- fonic acid	n/a	n/a
Hebig et al. (submitted)	saturated flow through	caffeine, carbamazepine, gemfibrozil, ibuprofen, naproxen, sulfamethoxazole	acrylic glass	41.0 – 41.2	7.6	one natu- ral sedi- ment, two artificial sands (or- ganic car- bon en- riched sand, iron coated sand)	dry, layers of 1 – 2 cm, tamper- ing	0.27 – 0.33	9.0 – 9.7 cm/d (pore water velocity from tracer test)	tech- nical quartz sand (2 cm top and bot- tom); two gauzes	Teflon	peristal- tic pump	synthetic ground- water	1 µg/L of each com- pound	CXTFIT (Toride et al., 1999)	sampling by hand (bot- tles)

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			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Jia et al. (2007)	saturated flow through	benzotriazole	plastipak tube	12	2.6	natural soil, artifi- cial sedi- ment (zerovalent iron Fe(0))	n/a	0.37 (soil) 0.41 / 0.44 (Fe(0))	different flow rates (from 20 to 27.1 mL/h)	glass wool	tygon	peristal- tic pump	distilled water	10 mg/L	PHREE QC-2 (Parkhu- rst and Appelo, 1999)	flow-through bottles
Ke et al. (2012)	saturated flow through	17 $\alpha$ -ethynylestradiol, 17 $\beta$ -estradiol, bisphenol A, ibuprofen, naproxen	n/a	8x 100 (series connec- tion)	10	natural sediment	n/a	0.44	22.7 cm/d	n/a	Teflon (PTFE), stainless steel	n/a	treated waste wa- ter	~ 100 $\mu$ g/L	n/a	glass syringe & three-way valves
Lorphensri et al. (2007)	saturated flow through	17 $\alpha$ -ethynylestradiol, acetaminophen, nalidixic acid	glass (borosili- cat)	15	2.5	artificial sediment (alumina Al <sub>2</sub> O <sub>3</sub> , sil- ica gel) and aquifer sand	n/a	0.38 - 0.52	10.5 - 18.8 cm/h	HDPE (20 $\mu$ m porous bed support)	n/a	peristal- tic pump	artificial (ground)water (CaCl <sub>2</sub> )	10 mg/L	CXT- FIT, CDE (Toride et al., 1995), UFBTC( Universi- ty of Florida, 1989)	fraction col- lector, inline- UV spectro- photometer
Massmann et al. (2008)	<i>down- ward</i> sat- urated flow- through	phenazone-type phar- maceuticals and metab- olites: 1-acetyl-1-methyl-2-di- methyloxamoyl-2-phe- nylhydrazide, 1-acetyl-1-methyl-2-phe- nylhydrazide, 1,5-dimethyl-1,2-dehy- dro-3-pyrazolone, 4-acetylaminopyrin, 4-formylaminopyrin, 4-(2-methylethyl)-1,5-di- methyl-1,2-dehydro-3- pyrazole, dimethylaminophena- zone, phenazone, propyphenazone,	n/a	n/a	n/a	undis- turbed core of sediments from the Lake Wannsee bed	undis- turbed	n/a	6*10 <sup>-6</sup> m/s = 0.52 m/d (pore veloc- ity)	n/a	n/a	pulsating pump at the bot- tom of the col- umn	natural surface (lake) water	0.03 - 0.53 $\mu$ g/L (median Lake Wannsee)	n/a	redox-condi- tions: oxygen minisensors in the sedi- ment
Mersmann et al. (2002)	saturated flow through	carbamazepine, clofibrac acid, diclofenac, ibuprofen, propyphenazone	stainless steel	35	13.59	natural sediment	n/a	0.27 - 0.36	0.33 - 0.36 m/d (mean pore veloc- ity)	n/a	Teflon, glass, polyeth- ylene, stainless steel	peristal- tic pump	natural groundwa- ter	10 $\mu$ g/L each com- pound	n/a	flowthrough cells, fraction collector

Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input con- centra- tions	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Müller et al. (2013)	saturated flow through	carbamazepine, primidone, sulfamethoxazole	n/a	35	13.5	natural sediment (un- and heat pre-treated)	n/a	0.35	1.20 - 1.56 cm/h (pore velocity)	n/a	n/a	peristaltic pump	natural surface water (ozonated and not-ozonated)	0.73 - 0.8 µg/L primidone, 0.80 µg/L carbamazepine, 0.87 - 0.90 µg/L sulfamethoxazole	CXT-FIT, CDE (Toride et al., 1999)	flowthrough cells, fraction collector
Patterson et al. (2010)	saturated flow through	17α-ethynylestradiol, 17β-estradiol, bisphenol A, carbamazepine, iodipamide, iohexol, N-nitrosomorpholine, N-nitrosodimethylamine oxazepam	stainless steel	200	14.5	anaerobic natural sediment	n/a	0.42 (bromide tracer test)	0.052 m/d	stainless steel mesh and grate	n/a	peristaltic pump	treated waste water	130 – 700 µg/L	fitting using Origin® v7 (Microcal Software Inc., 1995)	hypodermic syringe
Patterson et al. (2011)	saturated flow through	17α-ethynylestradiol, 17β-estradiol, bisphenol A, carbamazepine, iodipamide, iohexol, N-nitrosomorpholine, N-nitrosodimethylamine oxazepam	stainless steel	200	14.5	aerobic natural sediment	wet (saturated)	0.46 (bromide tracer test)	0.047 m/d	stainless steel mesh and grate, silicone polymer mat	n/a	peristaltic pump	treated waste water	130 – 700 µg/L	fitting to CDE using Origin® v7 (Microcal Software Inc., 1995)	hypodermic syringe
Preuss et al. (2001)	(probably) saturated <i>upward</i> and <i>downward</i> flow through (various experiments)	bezafibrat, diclofenac, carbamazepine, gemfibrozil, clofibrac acid	glass	80	20	natural sediment	n/a	n/a	5 cm/h (Darcy velocity)	n/a	n/a	n/a	natural groundwater (aerobic & anaerobic), natural surface water	100 µg/L each compound	n/a	n/a

Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concentrations	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Rauch-Williams et al. (2010)	saturated flow through	carbamazepine, diclofenac sodium, gemfibrozil, ibuprofen, ketoprofen, naproxen, phenacetine, primidone, propyphenazone, tris(2-chloroethyl)phosphate	plexi-glass	4x 100 (in series connection)	15	natural sediment	n/a	n/a	0.065 m/d (loading rate)	n/a	n/a	n/a	treated waste water	23-1,503 ng/L	CXT-FIT, CDE (Toride et al., 1995)	n/a
Schaffer et al. (2012b)	saturated flow through	atenolol, metoprolol	stainless steel	25	3.4	natural sediment	n/a	0.29 - 0.38 (chloride tracer test)	0.62 - 0.75 m/d (Darcy velocity) 1.91 - 2.43 m/d (pore velocity)	n/a	n/a	piston pump	tap water	1 – 30,000 µg/L atenolol 500 µg/L metoprolol	CXT-FIT, CDE (Toride et al., 1995)	fraction collector
Schaffer et al. (2012a)	saturated flow through	atenolol, carbamazepine, cetirizine, diazepam, naproxen, phenobarbital, primidone, trimethoprim	stainless steel	25	3.4	natural sediment	n/a	0.34 (chloride tracer test)	1.28 m/d (Darcy velocity), 3.77 m/d (pore velocity)	n/a	n/a	n/a	natural surface water	500 µg/L	fitting to CDE	n/a
Scheytt et al. (1998)	saturated flow through	clofibrac acid	stainless steel (personal communication)	30	9	natural sediment	n/a	0.34	0.26 m/d (Darcy velocity)	n/a	n/a	peristaltic pump	natural groundwater (anaerobic)	0.7 µg/L	n/a	flowthrough cells, fraction collector
Scheytt et al. (2004)	saturated flow through	clofibrac acid, diclofenac, propyphenazone	stainless steel	35	13.6	natural sediment	dry	0.32	0.30 m/d (dominant linear velocity)	glass (?) globes and gauze net	n/a	n/a	natural groundwater	10 µg/L	graphical analysis of BTCs	flowthrough cells, fraction collector



Citation	Condi- tions	Compounds	Column			Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concentra- tions	Model- ling	Sampling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			Tubes	Pump	Fluids			
Simon et al. (2000)	saturated flow through	p-cyanonitrobenzene	glass	62	5	natural sediment	wet (satu- rated)	0.47 (tracer test)	2.5 mL/min (=16.25 cm/h) in the tracer test; 0.5 mL/min during the experiment	n/a	n/a	Rabbit- HP, Rainin Instru- ment Co. Inc (mobile phase), syringe pump (injection of com- pound)	ultrapure water (air-saturated)	25 µM	CDE model	fraction col- lector (tracer)  syringe (compound)
Srivastava et al. (2009)	saturated flow through	ornetoprim, sulfadimethoxine	glass	10 and 4	5	natural soil, artifi- cial sedi- ments (fil- ter sand / technical quartz sand)	dry	n/a	0.27 - 0.48 cm/min (pore water velocity)	cheese- cloth, paper filter, Teflon end cap	polypro- pylene, silicone	peristal- tic pump	artificial (ground)water (CaCl <sub>2</sub> )	100 µg/L	CXT- FIT, CDE (Toride et al., 1999)	fraction col- lector
Strauss et al. (2011)	saturated flow through	sulfadimethoxine, sulfa- methazine, sulfamethoxazole	stainless steel	30	5.2	natural soil	dry, com- paction by tap- ping with rubber ham- mer	0.38 - 0.40 (po- rosity as water content)	3.99 - 4.15 cm/h (Darcy ve- locity)	perfo- rated stain- less steel plates, glass fi- ber filter	Teflon (PTFE), pharmed	peristal- tic pump	artificial (ground)water (CaCl <sub>2</sub> ), liquid ma- nure	500 µg/L	HY- DRUS- 1D, CDE (Šimůn ek and Van Genuch- ten, 2008)	fraction col- lector
Teijón et al. (2014)	saturated flow through	naproxen	stainless steel, the internal wall was covered with Tef- lon	10	1.6	natural sediment	dry, com- paction by vi- bration	0.27	0.19 - 0.7 cm/min (pore water velocity)	n/a	PTFE, stainless steel	peristal- tic pump	artificial (ground)water (CaCl <sub>2</sub> )	10 µg/L	HY- DRUS- 1D, CDE (Šimůn ek and Van Genuch- ten, 2008)	fraction col- lector

Citation	Condi- tions	Compounds	Column		Sediment			Velocities / flowrates	Filter layers	Infrastructure / used materials			Input concen- trations	Model- ling	Sampling methods	
			material	length [cm]	diameter [cm]	type	instal- lation			porosity	Tubes	Pump				Fluids
Teijón et al. (2014)	saturated flow through	naproxen	stainless steel, the internal wall was covered with Tef- lon	5	2	natural sediment	dry, com- paction by vi- bration	0.25	0.08 cm/min	n/a	PTFE, stainless steel	peristal- tic pump	artificial (ground)water (CaCl <sub>2</sub> )	10 µg/L	HY- DRUS- 1D, CDE (Šimůn ek and Van Genuch- ten, 2008)	fraction col- lector

n/a = not applicable

**Table S2: Unsaturated / leaching column experiments**

Citation	Condi-tions	Compounds	Column			Sediment			Veloci-ties / flowrates	Filter lay-ers	Infrastructure / used materials			Input concentrations	Modelling	Sam-pling methods
			material	length [cm]	diameter [cm]	type	instal-lation	porosity			tubes	pump	fluids			
Aga et al. (2003)	leaching	tetracycline	irrigation pipes with metal screen and porous tin cover	ap-prox. 152	approx. 20	natural soil	undis-turbed	n/a	n/a	n/a	n/a	n/a	distilled water	n/a	n/a	n/a
Cabrera-Lafaurie et al. (2015)	leaching	caffeine, carbamazepine, clofibric acid, salicylic acid	glass	30	0.8	artificial sedi-ment (inor-ganic-organic pillared clays modified with transition metals)	n/a	n/a	2 and 7.5 mL/min	n/a	n/a	by gravity	distilled & deion-ized water	14 mg/L	fitted to ana-lytical	n/a
Cordy et al. (2004)	leaching (satu-rated)	131 organic waste water compounds and patho-gens, e.g. antibiotics, steroids, reproductive hormones	stainless steel	240	32.5	natural soil	hand packed	0.38	16.5 to 4.5 cm/d	sand layer at the bot-tom	n/a	n/a	treated waste water	26 µg/L (total concentration of all com-pounds)	n/a	by hand
De Wilde et al. (2009)	leaching (unsatu-rated)	bentazone, isoproturon, linuron, metalaxyl	glass	15	10	artificial soil	com-paction by a weight on top of the column	n/a	1.74 cm/d (Darcy flux)	glass filter	PTFE	peristaltic pump	artificial (ground)water (CaCl <sub>2</sub> )	10 mg/L each com-pound	HYDRUS-1D, CDE (Simunek et al., 2005)	fraction collector
Dusek et al. (2015)	Leaching (satu-rated)	atrazine, imazaquin, sulfometuron methyl, S-metolachlor, imidacloprid	n/a	20	15	natural soil	undis-turbed	n/a	15 cm/d	glass wool	n/a	high pres-sure liquid chroma-tography pump	artificial water (CaCl <sub>2</sub> )	5-10 mg/L	S1D (Vogel et al., 2007)	fraction collector
Estrella et al. (1993)	leaching	2,4-dichlorophenoxyace-tic acid (2,4-D)	glass	30.5	5	natural soil	n/a	n/a	0.7 cm/h	porous stainless steel plate at the bot-tom of the glass col-umn	n/a	vacuum chamber	artificial (ground)water (CaCl <sub>2</sub> )	100 mg/L	numerical solution of the CDE, incl. first order degrada-tion (Van Genuchten and Wagenet, 1989)	fraction collector

Citation	Condi-tions	Compounds	Column			Sediment			Veloci-ties / flowrates	Filter lay-ers	Infrastructure / used materials			Input concen-trations	Modelling	Sam-pling methods
			material	length [cm]	diameter [cm]	type	instal-lation	porosity			tubes	pump	fluids			
Fan et al. (2011)	leaching	sulfamethazine	glass	15	8.4	natural soil (garden soil), artificial sedi-ment (filter sand / tech-nical quartz sand)	dry, wetted from the bottom	0.37 - 0.67 (volumet-ric water content)	19.8 - 39.5 cm/h	stainless steel mesh, cheese-cloth	Teflon (PTFE)	n/a	artificial (ground)water (CaCl <sub>2</sub> )	8 µg/L	CXTFIT, CDE (Toride et al., 1995), libSRES (Ji and Xu, 2006)	fraction collector
Kamra et al. (2001)	leaching (unsatu-rated)	atrazine, isoproturon	n/a	10	5.7	natural soil	undis-turbed	n/a	0.8 cm/d (Darcy flux) 1.92 - 2.48 cm/d (pore wa-ter veloc-ity)	porous glass plate with nylon mem-brane	n/a	vacuum pump	artificial rain	n/a	CXTFIT, CDE (Toride et al., 1995), time moment analysis (Jury and Sposito, 1985)	fraction collector
Kay et al. (2005)	leaching (unsatu-rated)	oxytetracycline, sulphachloropyridazine, tylosin	n/a	30	5	natural soil, partly pig farm slurry on top	undis-turbed & dis-turbed (air dried & sieved)	n/a	45000 L/ha	nylon mesh	HDPE funnel	n/a	artificial (ground)water (CaCl <sub>2</sub> )	18.85 - 25.58 mg/L	n/a	amber glass bot-tles
Lopez-Blanco et al. (2005)	leaching (unsatu-rated)	α-endosulfan	PVC	80	1.5	natural sedi-ment, natural soil	n/a	0.49	1.14 cm/h	washed quartz sand, 0.25 - 0.5 mm	PTFE, fluoro-elasto-mer	peristaltic pump	artificial (ground)water (KCl)	100 mg/L	CXTFIT, CDE (Toride et al., 1999), CHAIN (Van Genuchten, 1985)	n/a
Maeng et al. (2011)	n/a (prob-ably leaching)	bezafibrate, caffeine, carbamazepine, clofibric acid, gemfibrozil, diclofenac, fenoprofen, ibuprofen, ketoprofen, naproxen, paracetamol, pentoxifylline, phenacetine	n/a ("XK50/30; Amer-sham Pharma-cia Bio-tech, Swe-den")	30	5	artificial sedi-ment (filter sand / tech-nical quartz sand)	n/a	n/a	0.64 m/d (hydraulic loading rate)	n/a	n/a	n/a	surface water, tap water, treated waste water, deminer-alized water	1.2 - 8.1 µg/L	n/a	n/a
Murillo-Torres et al. (2012)	leaching (unsatu-rated)	4-nonylphenol, di-2-ethyl(hexyl)phthalate	n/a	15	3	natural soil	moist	na	0.013 mL/s	n/a	n/a	peristaltic pump	artificial (ground)water (CaCl <sub>2</sub> )	n/a	temporal mo-ments (Pang et al., 2003)	by gravity in pre-cleaned glass flask

Citation	Condi- tions	Compounds	Column			Sediment			Veloci- ties / flowrates	Filter lay- ers	Infrastructure / used materials			Input concen- trations	Modelling	Sam- pling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			tubes	pump	fluids			
Nkedi-Kizza et al. (1987)	leaching (satu- rated)	atrazine, diuron	glass (HPLC- column)	30	2.5	natural soil (Eustis soil)	air-dry	0.33 - 0.41 (as water content)	5.18 - 6.44 cm/h	n/a	HPLC fittings	HPLC pump	aqueous solu- tions from 0.01 N CaCl <sub>2</sub> & vari- ous methanol- water mixtures	30 mg/L diuron 20 mg/L atrazine	leaching re- tardation fac- tors by graphical analysis of column BTCs	flow- through variable- wave- length UV detector, assaying radioac- tivity with liquid scintilla- tion tech- niques
Oppel et al. (2004)	Leaching according to OECD (2003) guideline (unsatu- rated)	carbamazepine, clofibric acid, diazepam, ibuprofen, ivermectin, iopromide and its deriva- tives, 5-amino-2,4,6-triiodo- isophthalic acid, desmethoxyacetyl- iopromide, (N-2,3-dihydroxypropyl)- 5-amino-2,4,6-triiodo- isophthalic acid amide	glass	30	n/a	natural soil	air-dry, com- paction by vi- bration	n/a	393 mL drop wise within 48 h	n/a	n/a	n/a	artificial rain (0.01 mol/L CaCl <sub>2</sub> )	as aque- ous solu- tions or dis- solved in organic solvent: 100 mg/kg soil (dry weight)	n/a	n/a
Rodriguez- Cruz et al. (2007)	leaching (saturated flow re- gime)	atrazine, linuron, metalaxyl	glass	20	3	natural soil, partly ex & in situ modified with cationic surfactant oc- tadecyltrime- thylammoni- umbromde	dry	n/a	drainage rate of 1 mL/min	n/a	n/a	peristaltic pump	n/a	1000 µg/L in metha- nol (1 mL of solution applied at the top of the soil and leached by appli- cation of 500 mL of water)	n/a	fraction collector

Citation	Condi- tions	Compounds	Column			Sediment			Veloci- ties / flowrates	Filter lay- ers	Infrastructure / used materials			Input concen- trations	Modelling	Sam- pling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			tubes	pump	fluids			
Salem Attia et al. (2013)	leaching (saturated)	diclofenac, gemfibrozil, ibuprofen, naproxen	glass	25	1	artificial sedi- ment (mag- netic nano- particle coated zeo- lithe)	n/a	n/a	flow rate: 25 mL/min	glass wool	n/a	suction pump	influent from drinking water treatment plants	n/a	n/a	1 L am- ber glass bottles.
Salvia et al. (2014)	leaching (unsaturated)	androstenedione, carbamazepine, dicyclanil, erythromycin, fluvoxamine, gestodene, levonorgestrel, norethindrone, paracetamol, penicillin G potassium salt, progesterone, roxithromycin, sulphabenzamide, sulphadiazine, sulphadimethoxine, sulphadimidine, sulphameter, sulphamethoxazole, sulphanylamide, sulphathiazole, testosterone, trimethoprim, tylosin tartrate	PVC	30	10	natural soil	dry	n/a	40 mL of artificial rain every 2 days	glass beads	n/a	n/a	artificial rain ( CaCl <sub>2</sub> )	1 mg of each sub- stance	fitting of deg- radation curves to the exponential decay model	leachates were re- covered every 2 days in amber flasks
Schaffer et al. (2015)	leaching (varying hydraulic recharge conditions)	4-acetaminoantipyrine, 1H-benzotriazole, acesulfame, atenolol, atenolol acid, bezafibrate, carbamazepine, citalopram, clarithromycin, diclofenac, diazepam, fluoxetine, gemfibrozil, haloperidol, ibuprofen, irbesartan, isoproturon, losartan, mecoprop, metoprolol, naproxen,	stainless steel	150	35	artificial sedi- ment (mix from sieved sand and compost)	n/a	0.40 - 0.49	0.05 – 0.19 m/d	n/a	PTFE, stain- less steel	peristaltic pump	treated waste water	up to 6.5 µg/L	CXFTFIT, CDE (Toride et al., 1995) for tracer BTCs, PMWIN with MT3D (Chiang and Kinzelbach, 1998) for compound BTCs	glass sy- ringe

Citation	Condi- tions	Compounds	Column			Sediment			Veloci- ties / flowrates	Filter lay- ers	Infrastructure / used materials			Input concentra- tions	Modelling	Sam- pling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			tubes	pump	fluids			
Scheytt et al. (2006)	leaching (unsaturated)	phenazone, primidone, sulfamethoxazole, tamoxifen, tolyltriazone, valsartan, valsartan acid  carbamazepine, diclofenac, ibuprofen, propyphenazone	stainless steel	35	13.6	natural sediment	dry, compaction by plunger	n/a	0.71 – 0.88 m/d (av pore water velocities)	glass beads and teflon gauze net (personal communication)	n/a	by gravity	artificial (ground)water and simulated treated waste water	1 µg/L	CXTFIT, CDE (Toride et al., 1995)	flowthrough cells, fraction collector
Scheytt et al. (2007)	leaching (unsaturated)	clofibrac acid, diclofenac, ibuprofen, propyphenazone	stainless steel	35	13.6	natural sediment	dry, compaction by plunger	n/a	0.96 m/d (av pore water velocities)	glass beads and teflon gauze net (personal communication)	n/a	by gravity	artificial (ground)water - simulated treated waste water	1 µg/L	CXTFIT, CDE (Toride et al., 1995)	flowthrough cells, fraction collector
Siemens et al. (2010)	leaching	bezafibrate, clarithromycin, clindamycin, diclofenac, erythromycin, gemfibrozil, ibuprofen, metoprolol, naproxen, trimethoprim	PVC	10	8	natural soil	n/a	n/a	0.047 cm/h - 0.136 cm/h	moist quartz silt, porous glass suction plate	n/a	suction / vacuum pump	artificial (ground)water, equilibrated with CaCO <sub>3</sub> , unknown composition	20 - 2000 µg/L	CXTFIT, CDE (Toride et al., 1995), HYDRUS (Simunek et al., 1998), Gaussian 03 (Frisch et al., 2004)	aliquots of 0.07 L
Unold et al. (2009)	leaching, steady state flow, near saturation	sulfadiazin	stainless steel	10	8.5	natural soil	dry (slightly wetted before packing), compaction by pestle	n/a	0.24 - 0.26 cm/h (Darcy velocity) 0.49 - 0.64 cm/h (tracer pore velocity)	quartz filter sand / gravel, porous ceramic plate	n/a	peristaltic pump	artificial (ground)water (CaCl <sub>2</sub> )	0.57 mg/L	CXTFIT, CDE (Toride et al., 1999) HYDRUS (Simunek et al., 1998), PEST (Doherty, 2002)	fraction collector

Citation	Condi- tions	Compounds	Column			Sediment			Veloci- ties / flowrates	Filter lay- ers	Infrastructure / used materials			Input concen- trations	Modelling	Sam- pling methods
			material	length [cm]	diameter [cm]	type	instal- lation	porosity			tubes	pump	fluids			
Wu et al. (2010)	leaching (unsatu- rated)	carbamazepine, carbamazepine-10,11- epoxide, clindamycin, diltiazem, diphenhydramine, fluoxetine, norfluoxetine	PVC	40	4	natural soil, biosolids added	com- paction by vi- bration	n/a	200 mm over 48 h	glass wool, quartz fil- ter sand and (un- known) screening material	n/a	peristaltic pump	artificial rain (CaCl <sub>2</sub> )	100 ng/g (sub- stance / soil)	n/a	by glass funnels into 250- ml Erlen- meyer flasks wrapped with alu- minum foil to avoid pho- to-degrada- tion
Xu et al. (2010)	leaching (satu- rated)	ibuprofen, diclofenac-sodium, ketoprofen, naproxen,	stainless steel	12	1.5	natural soil	n/a	0.42 - 0.48 ( <i>calcu- lated us- ing pro- vided mass, bulk density and pore volume</i> )	n/a	aluminum plate with a stain- less steel needle	acrylic	by gravity	artificial (ground)water (CaCl <sub>2</sub> ), deionized water, DOC and poly- acrylamide amendment	about 2 mg/kg (sub- stance / soil)	n/a	manual
Yao et al. (2012)	leaching	sulfamethoxazole	acrylic cylinder	16.5	4	natural soil, artificial sedi- ment (biochar & sandy soil)	wet (satu- rated)	n/a	n/a	stainless steel mesh	n/a	n/a	artificial (ground)water, artificial re- claimed water	2 mg/L	n/a	manual

n/a = not applicable



## References

- Aga, D. S., Goldfish, R., and Kulshrestha, P.: Application of ELISA in determining the fate of tetracyclines in land-applied livestock wastes, *Analyst*, 128, 658-662, 10.1039/b301630g, 2003.
- Alidina, M., Li, D., Ouf, M., and Drewes, J. E.: Role of primary substrate composition and concentration on attenuation of trace organic chemicals in managed aquifer recharge systems, *J. Environ. Manag.*, 144, 58-66, 2014.
- Alotaibi, M. D., Patterson, B. M., McKinley, A. J., Reeder, A. Y., Furness, A. J., and Donn, M. J.: Fate of benzotriazole and 5-methylbenzotriazole in recycled water recharged into an anaerobic aquifer: Column studies, *Water Res.*, 70, 184-195, 10.1016/j.watres.2014.11.040, 2015.
- Banzhaf, S., Nödler, K., Licha, T., Krein, A., and Scheytt, T.: Redox-sensitivity and mobility of selected pharmaceutical compounds in a low flow column experiment, *Sci. Tot. Environ.*, 438, 113-121, 10.1016/j.scitotenv.2012.08.041 2012.
- Baumgarten, B., Jahrig, J., Reemtsma, T., and Jekel, M.: Long term laboratory column experiments to simulate bank filtration: Factors controlling removal of sulfamethoxazole, *Water Res.*, 45, 211-220, 10.1016/j.watres.2010.08.034, 2011.
- Bertelkamp, C., Reungoat, J., Botton, S., Cornelissen, E., Ghadiri, E., de Jonge, M., Singhal, N., van der Hoek, J. P., and Verliefe, A. R. D.: Transformation of organic micropollutants during river bank filtration: Laboratory versus field data, *Water Pract. Technol.*, 7, 10.2166/wpt.2012.081, 2012.
- Bertelkamp, C., Reungoat, J., Cornelissen, E. R., Singhal, N., Reynisson, J., Cabo, A. J., van der Hoek, J. P., and Verliefe, A. R. D.: Sorption and biodegradation of organic micropollutants during river bank filtration: A laboratory column study, *Water Res.*, 52, 231-241, 10.1016/j.watres.2013.10.068, 2014.
- Burke, V., Treumann, S., Duennbier, U., Greskowiak, J., and Massmann, G.: Sorption behavior of 20 wastewater originated micropollutants in groundwater - Column experiments with pharmaceutical residues and industrial agents, *J. Contam. Hydrol.*, 154, 29-41, 10.1016/j.jconhyd.2013.08.001, 2013.
- Burke, V., Greskowiak, J., Asmuß, T., Bremermann, R., Taute, T., and Massmann, G.: Temperature dependent redox zonation and attenuation of wastewater-derived organic micropollutants in the hyporheic zone, *Sci. Tot. Environ.*, 482, 53-61, 2014.
- Burke, V., Greskowiak, J., Grünenbaum, N., and Massmann, G.: Redox and temperature dependent attenuation of 20 organic micropollutants-a systematic column study, *Water Environ. Res.*, 2016.
- Cabrera-Lafaurie, W. A., Román, F. R., and Hernández-Maldonado, A. J.: Single and multi-component adsorption of salicylic acid, clofibric acid, carbamazepine and caffeine from water onto transition metal modified and partially calcined inorganic-organic pillared clay fixed beds, *J. Hazard. Mater.*, 282, 174-182, 2015.
- Casas, M. E., and Bester, K.: Can those organic micro-pollutants that are recalcitrant in activated sludge treatment be removed from wastewater by biofilm reactors (slow sand filters)?, *Sci. Tot. Environ.*, 506, 315-322, 2015.
- Chen, H., Gao, B., Li, H., and Ma, L. Q.: Effects of pH and ionic strength on sulfamethoxazole and ciprofloxacin transport in saturated porous media, *J. Contam. Hydrol.*, 126, 29-36, 2011.
- Chiang, W.-H., and Kinzelbach, W.: Processing Modflow, A simulation program for modelling groundwater flow and pollution. User manual, 1998.
- Cordy, G. E., Duran, N. L., Bouwer, H., Rice, R. C., Furlong, E. T., Zaugg, S. D., Meyer, M. T., Barber, L. B., and Kolpin, D. W.: Do pharmaceuticals, pathogens, and other organic waste water compounds persist when waste water is used for recharge?, *Ground Water Monit. Rem.*, 24, 58-69, 2004.
- D'Alessio, M., Yoneyama, B., and Ray, C.: Fate of selected pharmaceutically active compounds during simulated riverbank filtration, *Sci. Tot. Environ.*, 505, 615-622, 2015.
- De Wilde, T., Mertens, J., Simunek, J., Sniegowski, K., Ryckeboer, J., Jaeken, P., Springael, D., and Spanoghe, P.: Characterizing pesticide sorption and degradation in microscale biopurification systems using column displacement experiments, *Environ. Pollut.*, 157, 463-473, 10.1016/j.envpol.2008.09.008, 2009.
- Doherty, J.: PEST: Model-independent parameter estimation, Watermark Computing, Corinda, Australia, 2002.
- Doherty, J.: PEST: Model-independent parameter estimation, 5th edition, Watermark Computing, Corinda, Australia, 2005.

- Dusek, J., Dohnal, M., Snehota, M., Sobotkova, M., Ray, C., and Vogel, T.: Transport of bromide and pesticides through an undisturbed soil column: A modeling study with global optimization analysis, *J. Contam. Hydrol.*, 175-176, 1-16, 10.1016/j.jconhyd.2015.02.002, 2015.
- Estrella, M. R., Brusseau, M. L., Maier, R. S., Pepper, I. L., Wierenga, P. J., and Miller, R. M.: Biodegradation, sorption, and transport of 2,4-dichlorophenoxyacetic acid in saturated and unsaturated soils, *Appl. Environ. Microbiol.*, 59, 4266-4273, 1993.
- Fan, Z., Casey, F. X. M., Hakk, H., Larsen, G. L., and Khan, E.: Sorption, Fate, and Mobility of Sulfonamides in Soils, *Water Air Soil Pollut.*, 218, 49-61, 10.1007/s11270-010-0623-6, 2011.
- Frisch, M., Trucks, G., Schlegel, H., Scuseria, G., Robb, M., Cheeseman, J., Montgomery Jr, J., Vreven, T., Kudin, K., and Burant, J.: Gaussian 03, revision C. 02, Gaussian, Inc., Wallingford, CT, 2004.
- Greenhagen, A. M., Lenczewski, M. E., and Carroll, M.: Natural attenuation of pharmaceuticals and an illicit drug in a laboratory column experiment, *Chemosphere*, 115, 13-19, 2014.
- Gruenheid, S., Huebner, U., and Jekel, M.: Impact of temperature on biodegradation of bulk and trace organics during soil passage in an indirect reuse system, *Water Sci. Technol.*, 57, 987-994, 10.2166/wst.2008.207, 2008.
- Hebig, K. H., Groza, L. G., Sabourin, M. J., Scheytt, T. J., and Ptacek, C. J.: Transport behavior of the pharmaceutical compounds Carbamazepine, Sulfamethoxazole, Gemfibrozil, Ibuprofen, and Naproxen, and of the lifestyle drug Caffeine in saturated laboratory columns, *Sci. Tot. Environ.*, submitted.
- Ji, X., and Xu, Y.: libSRES: A C library for stochastic ranking evolution strategy for parameter estimation, *Bioinformatics*, 22, 124-126, 10.1093/bioinformatics/bti753, 2006.
- Jia, Y., Breedveld, G. D., and Aagaard, P.: Column studies on transport of deicing additive benzotriazole in a sandy aquifer and a zerovalent iron barrier, *Chemosphere*, 69, 1409-1418, 10.1016/j.chemosphere.2007.04.074, 2007.
- Jury, W. A., and Sposito, G.: Field calibration and validation of solute transport models for the unsaturated zone, *Soil Sci. Soc. Am. J.*, 49, 1331-1341, 1985.
- Kamra, S. K., Lennartz, B., Van Genuchten, M. T., and Widmoser, P.: Evaluating non-equilibrium solute transport in small soil columns, *J. Contam. Hydrol.*, 48, 189-212, 2001.
- Kay, P., Blackwell, P. A., and Boxall, A. B. A.: Column studies to investigate the fate of veterinary antibiotics in clay soils following slurry application to agricultural land, *Chemosphere*, 60, 497-507, 10.1016/j.chemosphere.2005.01.028, 2005.
- Ke, J., Gin, K. Y. H., Tan, L. H., and Reinhard, M.: Fate of endocrine-disrupting and pharmaceutically active substances in sand columns fed with secondary effluent, *Journal of Environmental Engineering (United States)*, 138, 1067-1076, 10.1061/(ASCE)EE.1943-7870.0000564, 2012.
- Lopez-Blanco, M. C., Cancho-Grande, B., Simal-Gandara, J., Lopez-Periago, E., and Arias-Estevez, M.: Transport of commercial endosulfan through a column of aggregated vineyard soil by a water flux simulating field conditions, *J. Agric. Food Chem.*, 53, 6738-6743, 10.1021/jf050545i, 2005.
- Lorphensri, O., Sabatini, D. A., Kibbey, T. C. G., Osathaphan, K., and Saiwan, C.: Sorption and transport of acetaminophen, 17 alpha-ethynyl estradiol, nalidixic acid with low organic content aquifer sand, *Water Res.*, 41, 2180-2188, 10.1016/j.watres.2007.01.057, 2007.
- Maeng, S. K., Sharma, S. K., Abel, C. D. T., Magic-Knezev, A., and Amy, G. L.: Role of biodegradation in the removal of pharmaceutically active compounds with different bulk organic matter characteristics through managed aquifer recharge: Batch and column studies, *Water Res.*, 45, 4722-4736, 10.1016/j.watres.2011.05.043, 2011.
- Massmann, G., Dünnebier, U., Heberer, T., and Taute, T.: Behaviour and redox sensitivity of pharmaceutical residues during bank filtration - Investigation of residues of phenazone-type analgesics, *Chemosphere*, 71, 1476-1485, 10.1016/j.chemosphere.2007.12.017, 2008.
- Mersmann, P., Scheytt, T., and Heberer, T.: Column experiments on the transport behavior of pharmaceutically active compounds in the saturated zone, *Acta Hydroch. Hydrob.*, 30, 275-284, 2002.
- Microcal Software Inc.: Origin Users's Manual, Microcal Software, Inc., Northampton, USA, 1995.
- Murillo-Torres, R., Durán-Álvarez, J. C., Prado, B., and Jiménez-Cisneros, B. E.: Sorption and mobility of two micropollutants in three agricultural soils: A comparative analysis of their behavior in batch and column experiments, *Geoderma*, 189-190, 462-468, 10.1016/j.geoderma.2012.05.019, 2012.

- Müller, B., Scheytt, T., and Grützmacher, G.: Transport of primidone, carbamazepine, and sulfamethoxazole in thermally treated sediments-laboratory column experiments, *J. Soils Sediments*, 13, 953-965, 10.1007/s11368-013-0671-9, 2013.
- Nkedi-Kizza, P., Rao, P. S. C., and Hornsby, A. G.: Influence of organic cosolvents on leaching of hydrophobic organic chemicals through soils, *Environ. Sci. Technol.*, 21, 1107-1111, 1987.
- Oppel, J., Broll, G., Löffler, D., Meller, M., Römbke, J., and Ternes, T.: Leaching behaviour of pharmaceuticals in soil-testing-systems: A part of an environmental risk assessment for groundwater protection, *Sci. Tot. Environ.*, 328, 265-273, 10.1016/j.scitotenv.2004.02.004, 2004.
- Pang, L., Goltz, M., and Close, M.: Application of the method of temporal moments to interpret solute transport with sorption and degradation, *J. Contam. Hydrol.*, 60, 123-134, 10.1016/S0169-7722(02)00061-X, 2003.
- Parkhurst, D. L., and Appelo, C.: User's guide to PHREEQC (Version 2): A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations, 1999.
- Patterson, B., Shackleton, M., Furness, A., Bekele, E., Pearce, J., Linge, K., Buseti, F., Spadek, T., and Toze, S.: Behaviour and fate of nine recycled water trace organics during managed aquifer recharge in an aerobic aquifer, *J. Contam. Hydrol.*, 122, 53-62, 2011.
- Patterson, B. M., Shackleton, M., Furness, A. J., Pearce, J., Descourvieres, C., Linge, K. L., Buseti, F., and Spadek, T.: Fate of nine recycled water trace organic contaminants and metal(loid)s during managed aquifer recharge into a anaerobic aquifer: Column studies, *Water Res.*, 44, 1471-1481, 10.1016/j.watres.2009.10.044, 2010.
- Preuss, G., Willme, U., and Zullei-Seibert, N.: Behaviour of some pharmaceuticals during artificial groundwater recharge - Elimination and effects on microbiology, *Acta Hydroch. Hydrob.*, 29, 269-277, 2001.
- Rauch-Williams, T., Hoppe-Jones, C., and Drewes, J. E.: The role of organic matter in the removal of emerging trace organic chemicals during managed aquifer recharge, *Water Res.*, 44, 449-460, 10.1016/j.watres.2009.08.027, 2010.
- Rodriguez-Cruz, M. S., Sanchez-Martin, M. J., Andrades, M. S., and Sanchez-Camazano, M.: Retention of pesticides in soil columns modified in situ and ex situ with a cationic surfactant, *Sci. Tot. Environ.*, 378, 104-108, 10.1016/j.scitotenv.2007.01.021, 2007.
- Salem Attia, T. M., Hu, X. L., and Yin, D. Q.: Synthesized magnetic nanoparticles coated zeolite for the adsorption of pharmaceutical compounds from aqueous solution using batch and column studies, *Chemosphere*, 93, 2076-2085, 10.1016/j.chemosphere.2013.07.046, 2013.
- Salvia, M. V., Experton, J., Geandel, C., Cren-Olivé, C., and Vulliet, E.: Fate of pharmaceutical compounds and steroid hormones in soil: Study of transfer and degradation in soil columns, *Environ. Sci. Pollut. Res.*, 21, 10525-10535, 10.1007/s11356-014-3038-x, 2014.
- Schaffer, M., Boxberger, N., Börnick, H., Licha, T., and Worch, E.: Sorption influenced transport of ionizable pharmaceuticals onto a natural sandy aquifer sediment at different pH, *Chemosphere*, 87, 513-520, 10.1016/j.chemosphere.2011.12.053, 2012a.
- Schaffer, M., Börnick, H., Nödler, K., Licha, T., and Worch, E.: Role of cation exchange processes on the sorption influenced transport of cationic  $\beta$ -blockers in aquifer sediments, *Water Res.*, 46, 5472-5482, 2012b.
- Schaffer, M., Kröger, K. F., Nödler, K., Ayora, C., Carrera, J., Hernández, M., and Licha, T.: Influence of a compost layer on the attenuation of 28 selected organic micropollutants under realistic soil aquifer treatment conditions: Insights from a large scale column experiment, *Water Res.*, 74, 110-212, 10.1016/j.watres.2015.02.010, 2015.
- Scheytt, T., Grams, S., and Fell, H.: Vorkommen und Verhalten eines Arzneimittels (Clofibrinsäure) im Grundwasser, *Grundwasser*, 2/98, 67-77, 1998.
- Scheytt, T., Mersmann, P., Leidig, M., Pekdeger, A., and Heberer, T.: Transport of pharmaceutically active compounds in saturated laboratory columns, *Ground Water*, 42, 767-773, 2004.
- Scheytt, T. J., Mersmann, P., and Heberer, T.: Mobility of pharmaceuticals carbamazepine, diclofenac, ibuprofen, and propyphenazone in miscible-displacement experiments, *J. Contam. Hydrol.*, 83, 53-69, 2006.
- Scheytt, T. J., Mersmann, P., Rejman-Rasinski, E., and These, A.: Tracing pharmaceuticals in the unsaturated zone, *J. Soils Sediments*, 7, 75-84, 10.1065/jss2006.12.200, 2007.

- Siemens, J., Huschek, G., Walshe, G., Siebe, C., Kasteel, R., Wulf, S., Clemens, J., and Kaupenjohann, M.: Transport of Pharmaceuticals in Columns of a Wastewater-Irrigated Mexican Clay Soil, *J. Environ. Qual.*, 39, 1201-1210, 10.2134/jeq2009.0105, 2010.
- Simon, R., Colón, D., Tebes-Stevens, C. L., and Weber, E. J.: Effect of redox zonation on the reductive transformation of p-cyanonitrobenzene in a laboratory sediment column, *Environ. Sci. Technol.*, 34, 3617-3622, 10.1021/es000960l, 2000.
- Simunek, J., Huang, K., and Van Genuchten, M. T.: The HYDRUS code for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, *US Salin. Lab. Res. Rep.*, 144, 1998.
- Simunek, J., Van Genuchten, M. T., and Sejna, M.: The HYDRUS-1D software package for simulating the movement of water, heat, and multiple solutes in variably saturated media, version 3.0, HYDRUS software series 1, Department of Environmental Sciences, University of California Riverside, Riverside Edition, 2005.
- Šimůnek, J., and Van Genuchten, M. T.: Modeling nonequilibrium flow and transport processes using HYDRUS, *Vadose Zone J.*, 7, 782-797, 10.2136/vzj2007.0074, 2008.
- Srivastava, P., Sanders, S. M., Dane, J. H., Feng, Y., Basile, J., and Barnett, M. O.: Fate and Transport of Sulfadimethoxine and Ormetoprim in Two Southeastern United States Soils, *Vadose Zone J.*, 8, 32-41, 10.2136/vzj2007.0186, 2009.
- Strauss, C., Harter, T., and Radke, M.: Effects of pH and Manure on Transport of Sulfonamide Antibiotics in Soil, *J. Environ. Qual.*, 40, 1652-1660, 10.2134/jeq2010.0535, 2011.
- Tejón, G., Candela, L., Šimůnek, J., Tamoh, K., and Valdes-Abellán, J.: Fate and Transport of Naproxen in a Sandy Aquifer Material: Saturated Column Studies and Model Evaluation, *Soil Sediment Contam.*, 23, 736-750, 10.1080/15320383.2014.869194, 2014.
- Toride, N., Leij, F. J., and van Genuchten, M. T.: The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments, Version 2.0, U.S. Salinity Laboratory, USDA, ARS, Riverside, California., 1995.
- Toride, N., Leij, F. J., and van Genuchten, M. T.: The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments, Version 2.1, U.S. Salinity Laboratory, USDA, ARS, Riverside, California., 1999.
- University of Florida: UFBTC, version 2-One dimensional subsurface transport model, finite difference technique, 1989.
- Unold, M., Kasteel, R., Groeneweg, J., and Vereecken, H.: Transport and transformation of sulfadiazine in soil columns packed with a silty loam and a loamy sand, *J. Contam. Hydrol.*, 103, 38-47, 10.1016/j.jconhyd.2008.09.002, 2009.
- Van Genuchten, M. T.: Convective-dispersive transport of solutes involved in sequential first-order decay reactions, *Computers and Geosciences*, 11, 129-147, 10.1016/0098-3004(85)90003-2, 1985.
- Van Genuchten, M. T., and Wagenet, R.: Two-site/two-region models for pesticide transport and degradation: Theoretical development and analytical solutions, *Soil Sci. Soc. Am. J.*, 53, 1303-1310, 1989.
- Vogel, T., Lichner, L., Dusek, J., and Cipakova, A.: Dual-continuum analysis of a cadmium tracer field experiment, *J. Contam. Hydrol.*, 92, 50-65, 10.1016/j.jconhyd.2007.01.001, 2007.
- Wu, C., Spongberg, A. L., Witter, J. D., Fang, M., Czajkowski, K. P., and Ames, A.: Dissipation and leaching potential of selected pharmaceutically active compounds in soils amended with biosolids, *Arch. Environ. Contam. Toxicol.*, 59, 343-351, 2010.
- Xu, J., Wu, L. S., Chen, W. P., and Chang, A. C.: Leaching potential of nonsteroidal anti-inflammatory drugs in soils, *Environ. Toxicol. Chem.*, 29, 800-807, 10.1002/etc.107, 2010.
- Yao, Y., Gao, B., Chen, H., Jiang, L., Inyang, M., Zimmerman, A. R., Cao, X., Yang, L., Xue, Y., and Li, H.: Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation, *J. Hazard. Mater.*, 209, 408-413, 10.1016/j.jhazmat.2012.01.046, 2012.