Electronic Supplementary Information

for the manuscript

Membrane-based methods of virus concentration from water: A review of process parameters and their effects on virus recovery

Original version submitted to the Environmental Science: Water Research and Technology journal

by

Hang Shi, Elodie V. Pasco, Volodymyr V. Tarabara*

Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA

June 24, 2017

* Corresponding author: tarabara@msu.edu; Phone: (517) 432-1755; Fax: (517) 355-0250

Table S1. Norovirus recovery by VIRADEL as a function of water matrix and VIRADEL process parameters.

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
1	HNoV (GI)	ground I	none	1.1×10^7 GC/L	20	glass wool (+) / none	3% BE 0.5 M Gly pH 9.5[Δ]	not reported	PEG precipitation	45	1
2		ground II								33	
3	HNoV (GII)	tap		1.3×10^3 GC/L						30	
4		ground I		$(1.9 \text{ to } 50)\times10^6$ GC/L						16	
5		ground II			10 to 20					32	
6	HNoV (GII)	tap	5 mM $MgCl_2$	4×10^5 GC/L	2	cellulose esters(-) / none	0.5 mM H_2SO_4 → 1 mM NaOH[±]	not reported	centrifugal UF	3 ± 1	2
7		sea		1.8×10^5 GC/L						1 ± 1	
8		river		3.3×10^6 GC/L						18 ± 9	
9		bottled		2.2×10^6 GC/L						17 ± 7	
10		tap	25 mM $MgCl_2$	4×10^5 GC/L						2 ± 3	
11		sea		1.3×10^6 GC/L						5 ± 7	
12		river		1.4×10^6 GC/L						9 ± 1	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
13		bottled		4.6×10^6 GC/L						23 ± 17	
14		tap	50 mM $MgCl_2$	3.5×10^5 GC/L						2 ± 2	
15		sea		1.6×10^6 GC/L						6	
16		bottled		4.1×10^5 GC/L						6 ± 5	
17		river		3.5×10^5 GC/L						4 ± 3	
18	HNoV	tap	none	1.2×10^6 GC/L	10 or 100	NanoCeram (+) / none	1.5% BE 0.05 M Gly pH 9.0[Δ]	not reported	Celite adsorption-elution	4 ± 1	3
19						1MDS (+) / none				1 ± 1	
20		river				NanoCeram (+) / none				12 ± 16	
21						1MDS (+) / none				0 ± 2	
22	HNoV (GII)	DI	none	$(2.9 \text{ to } 6.2)\times10^5$ GC/L	0.5	1MDS (+) / none	3% BE pH 9	77 to 107	not performed	same as primary recovery	4
23		tap		$(2.2 \text{ to } 5.8)\times10^5$ GC/L				14 to 46			
24		river		$(7.9 \text{ to } 13)\times10^5$ GC/L	0.25			13 to 24			
25		DI		$(6.5 \text{ to } 57)\times10^5$ GC/L	0.5	cellulose esters (-) / AlCl	0.5 mM H_2SO_4 → 1 mM	54 to 154			

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
26		bottled		$(3.8 \text{ to } 6.7)\times10^5$ GC/L				25 to 95			
27		tap		$(5.8 \text{ to } 6.2)\times10^5$ GC/L				36 to 63			
28		river		$(1.7 \text{ to } 11)\times10^5$ GC/L	0.25			24 to 45			
29		DI	25 mM $MgCl_2$	$(5.3 \text{ to } 19)\times10^6$ GC/L	0.5	cellulose esters (-) / none		172 to 200			
30		bottled		$(4.3 \text{ to } 4.5)\times10^5$ GC/L				138 to195			
31		tap		7.9×10^5 to 6.0×10^7 GC/L				55 to 104			
32		river		$(2.7 \text{ to } 5.5)\times10^5$ GC/L	0.25			11 to 18			
33		pond		$(4.5 \text{ to } 6.9)\times10^5$ GC/L				38 to 39			
34	HNoV (GII)	DI + tap	pH 3.5	1.2×10^3 GC/L	10	glass wool (+) / none	3% BE 0.05 M Gly pH 9.5	not reported	3% BE flocculation	0 to 19	5
35			none							<1	
36				2.4×10^2 GC/L	50					<1	
37						MK (+) / none	1% BE 0.25 M Gly pH 9.5			<1	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
38	HNoV (GII)	sea	none	8.8×10^4 GC/L	40	NanoCeram (+) / none	3% BE 0.1 M Gly pH 9.5[Δ]	<0.1	not performed	same as primary recovery	6
39							3% BE 0.1 M Gly pH 9.5[†]	111 ± 28			
40							3% BE 0.1 M Gly 0.01% TW 80 pH 9.5[†]	88 ± 24			
41							3% BE 0.1 M Gly 0.1% TW 80 pH 9.5[†]	119 ± 26			
42	HNoV (GII)	DI	none	9.7×10^4 GC/L	10	NanoCeram (+) / none	1.5% BE pH 9.8	not reported	1.5% BE, 0.1% $FeCl_3$, flocculation	42 ± 8	7
43		tap								29 ± 15	
44		river								18 ± 3	
45	HNoV (GII)	DI	none	1.0×10^5 GC/L	1	1MDS (+) / none	1.5% BE, 0.05 M Gly, pH 9.5[Δ]	61 ± 11	not performed	same as primary recovery	8
46							1.5% BE, 0.05 M Gly, 0.01% TW 80 pH 9.5[Δ]	68 ± 40			

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
47						NanoCeram (+) / none	1.5% BE, 0.05 M Gly, pH 9.5[Δ]	27 ± 13			
48							1.5% BE, 0.05 M Gly, 0.01% TW 80 pH 9.5[Δ]	86 ± 26			
49	HNoV (GII)	lake	pH 6.5 to 7.0	$(4.6\pm8.1)\times10^3$ GC/L	10	Glasswool (+) / none	3% BE 0.5 M Gly pH 9.5	not reported	PEG precipitation	2	9
50	HNoV (GI)	irrigation	5 mM $AlCl_3$ pH 3.5	5×10^4 GC/L	10	Filterite (-) / none	10% TPB, 0.05 M Gly, pH 10	not reported	PEG precipitation	42 ± 7	10
51				5×10^5 GC/L						26 ± 5	
52				5×10^6 GC/L						43 ± 1	
53				5×10^4 GC/L					organic flocculation	14 ± 1	
54				5×10^5 GC/L						13 ± 0	
55				5×10^6 GC/L						16 ± 1	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
56	HNoV (GII)			5×10^4 GC/L					PEG precipitation	38 ± 1	
57				5×10^5 GC/L						22 ± 7	
58				5×10^6 GC/L						38 ± 1	
59				5×10^4 GC/L					organic flocculation	15 ± 1	
60				5×10^5 GC/L						15 ± 0	
61				5×10^6 GC/L						16 ± 1	
62	MNoV	ground	none	5×10^5 PFU/L	10	NanoCeram (+) / none	1.5% BE, 0.05 M Gly, pH 9[Δ]	not reported	1.5% BE flocculation ⇨ centrifugal UF	30	11
63		surface								6	
64		DI		100 PFU/L						< 1	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
65				30 PFU/L						2 to 16	
66	MNoV (S7)	DI	none	2.6×10^7 GC/L	5	cellulose ester (-) /$AlCl_3$	0.5 mM H_2SO_4 → 1 mM NaOH	45	not performed	same as primary recovery	12
67		tap		2.2×10^7 GC/L				31			
68	HNoV (GI)	bore hole	5mM $MgCl_2$ pH 3.5	10^6 GC/L	5	cellulose esters (-) / none	0.5 mM H_2SO_4 → Tr alk buffer[Δ]	not reported	PEG precipitation	16 to 30	13
69		rain			5					11 to 15	
70		open well			2					4 to 5	
71		river			5					6 to 10	
72		food processing			1					4 to 12	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration[C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
73	HNoV (GII)	bore hole		10^7 GC/L	5					23 to 32	
74		rain			5					17 to 25	
75		open well			2					10 to 11	
76		river			5					13 to 15	
77		food processing			1					14 to 24	

Notes for Table S1:

[A] HNoV (GI): human norovirus genogroup I; HNoV (GII): human norovirus genogroup II; MNoV: murine norovirus.

[B] DI: deionized water; DI+tap: mixture of equal volumes of DI water and tap water.

[C] GC/L: genome copies per liter; PFU/L: plaque forming units per liter.

[D] (+): electropositive filter; (-): electronegative filter.

[E] Filter pretreatment, if any.

[F] BE: beef extract; Gly: glycine; TW 80: Tween 80; TPB: tryptose phosphate broth; Tr alk buffer: 0.05 M KH_2PO_4, 1 M NaCl, 0.1% (v/v) Triton X-100, pH 9.2. The arrow (→) indicates sequential application of eluents. In most studies, the elution was performed by filtering the eluent. Additional features of the elution protocol include:

[Δ] Filters were soaked in the eluent prior to elution. See each study for specific contact time.

[†] Eluent is recirculated.

[⏚] Filter was placed feed side down in a Petri dish containing NaOH and shaken for 10 min.

[G] Recoveries were rounded to the nearest integer.

[H] The arrow (⇨) indicates the sequence of secondary concentration steps.

Table S2. Norovirus recovery by crossflow ultrafiltration as a function of water matrix and ultrafiltration process parameters.

Exp. #	Virus[A]	Water type[B]	Sample amendment[C]	Virus concentration[D]	Sample volume, L	Filter / MWCO[E] /Treatment[F]	Eluent[G]	Primary recovery[8], %	Secondary concentration	Total recovery[H], %	Ref.
1	HNoV (GII)	DI + tap	none	1.2×10^3 GC/L	10	Infilco Degremont filter / (NA) / 0.1% BSA	1 mM NaOH[±]	not reported	centrifugal UF	<1	5
2	MNoV-1	DI	none	2×10^8 GC/L	5	PS / 15 - 20 kDa / none	none	5 ± 6	not performed	same as primary recovery	14
3						PS / 15 - 20 kDa / 3% BE		63 ± 30			
4		DI + 0.05 M Gly 0.14 M NaCl				PS / 15 - 20 kDa / none		6 ± 5			
5						PS / 15 - 20 kDa / 3% BE		53 ± 74			
6	MNoV-1	tap	0.01% NaPP	"High seeding level"	100	CTA / 70 kDa / 0.1% NaPP	0.01% NaPP 0.1% TW 80 0.001% antifoam A[†]	not reported	centrifugal UF	42	15
7		surface		10 to 100 PFU/L						74	

Exp. #	Virus[A]	Water type[B]	Sample amendment[C]	Virus concentration[D]	Sample volume, L	Filter / MWCO[E] /Treatment[F]	Eluent[G]	Primary recovery[8], %	Secondary concentration	Total recovery[H], %	Ref.
8	HNoV (GII)	lake	none	$(4.6\pm8.1)\times10^3$ GC/L	10	REXEED-25S (29 kDa) / none	0.01% TW 80†	not reported	PEG precipitation	2	[9]

Notes for Table S2:

[A] HNoV (GII): human norovirus genogroup II; MNoV-1: murine norovirus-1

[B] DI: deionized water; DI+tap: mixture of equal volume of DI and tap; Gly: glycine

[C] NaPP: sodium polyphosphate

[D] GC/L: genome copy per liter; PFU/L: plaque forming unit per liter

[E] PS: polysulfone; CTA: cellulose triacetate. The value in parentheses is the molecular weight cutoff (MWCO) of the membrane filter; NA: not available; kDa: kilodalton

[F] Filter pretreatment, if any; BSA: bovine serum albumin; BE: beef extract; NaPP: sodium polyphosphate

[G] TW 80: Tween 80, NaPP: sodium polyphosphate. Additional features of the elution protocol:

± shaking 30 min

† crossflow

[H] Recoveries were rounded to nearest integer

Table S3. Adenovirus recovery by VIRADEL as a function of water matrix and VIRADEL process parameters.

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration [C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
1	HAdV 41	tap	none	8.5 to 1700 GC/L	10 to 1500	glass wool (+) / none	3% BE 0.5 M Gly pH 9.5[Δ]	not reported	PEG precipitation	28	1
2		ground I		(8 to 16)×10^2 GC/L	20					22	
3		ground II								8	
4	HAdV 2	DI+tap	pH 3.5	2.6×10^6 GC/L	10	glass wool (+) / none	3% BE 0.05 M Gly pH 9.5	not reported	3% BE flocculation	2 to 7	5
5			none							~1	
6				5.3×10^5 GC/L	50					1 to 2	
7						MK (+) / none	1% BE 0.25 M Gly pH 9.5			0.01 to 0.02	
8	HAdV 41	sea	none	1.6×10^7 GC/L	40	NanoCeram (+) / none	3% BE 0.1 M Gly pH 9.5[Δ]	1	not performed	same as primary recovery	6
9							3% BE 0.1 M Gly pH 9.5[†]	5 ± 3			
10							3% BE 0.1 M Gly 0.1% TW 80 pH 9.5[†]	1 ± 0			

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration [C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
11							3% BE 0.1 M Gly 0.01% TW 80 pH 9.5†	1 ± 1			
12				4.5×10^5 GC/L			soy-based eluent pH 7.0†	0.2 ± 0.1			
13							soy-based eluent 0.01% TW 80 pH 7.0†	1 ± 1			
14				2.5×10^7 GC/L			3% BE 0.1 M Gly pH 9.5†	3 ± 2			
15		surface						2 ± 1			
16		treated-surface						1 ± 1			
17	HAdV 5	sea	none	10^3 PFU/L	1	nanoalumina fiber (+) / none	3% BE pH 6.0Δ	not reported	centrifugal UF	82 ± 11	16
18				10^2 PFU/L						37 ± 5	
19		RO treated sea		10^3 PFU/L						91 ± 12	
20				10^2 PFU/L						64 ± 8	
21		sewage effluent		10^3 PFU/L						86 ± 8	

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration [C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
22				10^2 PFU/L						44 ± 6	
23		sea	pH 3.5							66 ±10	
24		RO treated sea	5 mM $AlCl_3$, pH 3.5	10^3 PFU/L		cellulose esters (-) / none	0.5 mM H_2SO_4 → 1 mM NaOH[⊥]			90 ± 8	
25		sewage effluent			0.2					60 ± 8	
26	HAdV 41	source water	pH 3.5	2.5×10^6 GC/L	1	cellulose esters (-) / none	1.5% BE 0.75% glycerol pH 9.0[⊥]	55 ± 19	evaporation or centrifugal UF	not reported	17
27			pH 4.5					<5		not reported	
28	HAdV 2	tap	none	5×10^6 $TCID_{50}$/L	20	NanoCeram (+) / none	1.0% NaPP PB 0.05M Gly pH 9.3[⊥]	39 ± 13	centrifugal UF	14 ± 4	18
29	HAdV 41	DI	none	10^2 IU/L	10	NanoCeram (+) / none	1.5% BE pH 9.8	not reported	1.5% BE, 0.1% $FeCl_3$, flocculation	19 ± 2	7
30		tap								21 ± 3	
31		river								19 ± 3	
32	HAdV 41	lake	pH 6.5 to 7.0	$(5.9\pm3.4)\times10^4$ GC/L	10	glass wool (+) / none	3% BE 0.5 M Gly pH 9.5	not reported	PEG precipitation	5	9

Exp. #	Virus[A]	Water type[B]	Sample amendment	Virus concentration [C]	Sample volume, L	Filter (+/-)[D] /Treatment[E]	Eluent[F]	Primary recovery[G], %	Secondary concentration[H]	Total recovery[G], %	Ref.
33			none			NanoCeram (+) / none	1.5% BE 0.05 M Gly pH 9		Celite adsorption-elution ⇨ PEG precipitation	0.02	
34	HAdV 40	tap	none	10^7 to10^8 GC/L	0.1	1MSD (+) / none	1.5% BE 0.05 M Gly pH 7.5	not reported	Celite adsorption-elution	24 ± 8	19
35							1.5% BE 0.05 M Gly pH 10			52 ± 22	
36			pH 5							14 ± 7	
37	HAdV 41		none				1.5% BE 0.05 M Gly pH 7.5			9 ± 3	
38							1.5% BE 0.05 M Gly pH 10			64 ± 4	
39			pH 5							13 ± 4	
40	HAdV 7	sea	25 mM $AlCl_3$	10^5 PFU/L	1	cellulose esters (-) / none	0.5 mM H_2SO_4 → 1 mM NaOH, stirring[#] 30 min	79 ± 5	not performed	same as primary recovery	20
41							0.5 mM H_2SO_4 → 1 mM NaOH, shaking[⊥] 30 min	54			
42							0.5 mM H_2SO_4 → 1 mM NaOH, stirring[#] 45 min	52			

Notes for Table S3:

[A] HAdV: human adenovirus.

[B] DI: deionized water; DI+tap: mixture of equal volumes of DI water and tap water; source water: water collected from Water and Sewer Authority.

[C] GC/L: genome copies per liter; PFU: plaque forming unit per liter; $TCID_{50}$/L: 50% tissue culture infective dose per liter; IU/L: infectious unit per liter.

[D] (+): electropositive filter; (-): electronegative filter.

[E] Filter pretreatment, if any.

[F] BE: beef extract; Gly: glycine; TW 80: Tween 80; PB: phosphate buffer (3.8 mM Na_2HPO_4, 6.5 mM KH_2PO_4); The arrow (→) indicates sequential application of eluents.

In most studies, the elution was performed by filtering the eluent. Additional features of the elution protocol:

[Δ] Filters were soaked in eluent first prior to filtration of eluent. See each study for specific contact time.

[†] Eluent is recirculated.

[⩲] Filter was placed into a tube containing NaOH and vortexed. See each study for specific vortex times.

[⌙] Filter was immersed in the eluent. Filtration housing unit was inverted 10 times followed by 15 min of hold time. The procedure was performed 3 times prior to elution.

[#] Filter was soaked in the flask containing NaOH and stirred with a magnetic bar.

[G] Recoveries were rounded to the nearest integer (except when recoveries are below 1%).

[H] The arrow (⇨) indicates the sequence of secondary concentration steps.

Table S4. Adenovirus recovery by crossflow ultrafiltration as a function of water matrix and ultrafiltration process parameters.

Exp. #	Virus[A]	Water type[B]	Sample amendment[C]	Virus concentration, GC/L[D]	Sample volume, L	Filter (+/-)[E] / MWCO / Treatment[F]	Eluent[G]	Primary recovery[H], %	Secondary concentration	Total recovery[H], %	Ref.
1	HAdV 2	DI + tap	none	2.6×10^{6}	10	Infilco Degremont filter / NA / 0.1% BSA	1 mM NaOH[±]	not reported	centrifugal UF	3 to 6	5
2	HAdV 41	lake	none	$(5.9 \pm 3.4)\times10^{4}$	10	REXEED-25S / 29 kD / none	0.01% TW 80[†]	not reported	PEG precipitation	1	9
3	HAdV 5	cell culture	none	$>10^{12}$	0.45	PES / 750 kDa / none	none	~75	not performed	same as primary recovery	21
4	HAdV 41	tap	0.01% NaPP	$(2.5 \pm 0.5)\times10^{3}$	100	REXEED-25S / 30 kDa / none	0.01%NaPP 0.01% TW 80 0.001% antifoam A[†]	69 ± 12	Celite adsorption-elution	68 ± 14	22
5		river		$(2.6 \pm 0.3)\times10^{3}$	50			56 ± 8		30 ± 19	
6	HAdV 40	DI	none	~10^{9}	1	PES / 30 kDa) / 5% CS	0.01% NaPP 0.01% TW 80[†]	pre: 54 ± 6 post: 99 ± 8	not performed	same as primary recovery	23
7		tap						pre: 38 ± 9 post: ~90			
8		DI				PES (30 kDa) / PEM		pre: 75 ± 10 post:100 ± 7			
9		tap						pre: 41 ± 10			

Exp. #	Virus[A]	Water type[B]	Sample amendment [C]	Virus concentration, GC/L[D]	Sample volume, L	Filter (+/-)[E] / MWCO / Treatment[F]	Eluent[G]	Primary recovery[H], %	Secondary concentra-tion	Total recovery[H], %	Ref.
								post: ~ 90			
10		lake I				PES / 30 kDa / 5% CS		pre: ~40 post: 61 ± 3			
11		lake II						pre: ~20 post: 35 ± 10			
12		lake II					0.01% NaPP 0.01% TW 80 0.01% EDTA†	pre: ~20 post: ~84			
13		lake I				PES / 30 kDa / PEM	0.01% NaPP 0.01% TW 80†	pre: ~40 post: 62 ± 2			
14		lake II						pre: ~20 post: 42 ± 2			
15		lake II					0.01% NaPP 0.01% TW 80 0.01% EDTA†	pre: ~20 post: ~84			

Notes for Table S4:

[A] HAdV : human adenovirus

[B] DI: deionized water; DI+tap: mixture of equal volume of DI and tap;

[C] NaPP: sodium polyphosphate

[D] GC/L: genome copy per liter

[E] PES: polyethersulfone; The value in parentheses is the molecular weight cutoff (MWCO) of the membrane filter; NA: not available; kDa: kilodalton

[F] Filter pretreatment, if any; BSA: bovine serum albumin; CS: calf serum; PEM: polyelectrolyte multilayer

[G] TW 80: Tween 80, NaPP: sodium polyphosphate; EDTA: Ethylenediaminetetraacetic acid. Additional features of the elution protocol:

[⊥] shaking for 30 min

[†] crossflow

[H] Recoveries were rounded to the nearest integer; pre: pre-elution recovery; post: post-elution recovery

Table S5. Primary recovery of bacteriophage MS2 by VIRADEL as a function of water matrix and VIRADEL process parameters.

Exp. #	Water type[A]	Sample amendment	Virus concentration, PFU/L[B]	Sample volume, L	Filter (+/-)[C] /Treatment[D]	Eluent[E]	Primary recovery[F],	Ref.
1	tap	pH 3.5	not reported	10	filterite (-) / none	5% BE 0.1% TW 80 pH 7	67±11	24
2		0.1 M $MnCl_2$, pH 3.5	not reported				79±14	
3	tap	pH 6.5 to 7	10^6	1	1-MDS (+) / none	1.5% BE 0.05M Gly pH 8[Δ]	31 ± 12	25
4						1.5% BE 0.05M Gly pH 9[Δ]	24 ± 5	
5						1.5% BE 0.05 M Gly 0.01% TW 80 pH 8[Δ]	31 ± 4	
6						1.5% BE 0.05 M Gly 0.01% TW 80 0.1% NaPP pH 8[Ŧ]	92 ± 10	
7						1.5% BE 0.05 M Gly 0.01% TW 80 0.1% NaPP pH 8[Δ]	89 ± 10	

Exp. #	Water type[A]	Sample amendment	Virus concentration, PFU/L[B]	Sample volume, L	Filter (+/-)[C] /Treatment[D]	Eluent[E]	Primary recovery[F],	Ref.
8			10^3				44 ± 9	
9			5×10^4	20		1.5% BE 0.05 M Gly 0.01% TW 80 0.1% NaPP pH 8▼	32 ± 13	
10	sea[G]	none	(1.5 to 4.6)×10^5	0.1	cellulose ester (-) / none	1.5% BE pH 9*	35	26
11						0.5 mM H_2SO_4 → 1.5% BE pH 9*	20	
12						1mM NaOH*	16	
13						0.5 mM H_2SO_4 → 1.5% BE pH 9	9	
14						1mM NaOH	6	
15						0.5mM H_2SO_4 → 1mM NaOH	2	
16	DI	none	5×10^4	20	NanoCeram (+) / none	1.5% BE 0.05M Gly 0.01% TW 80 pH 9.5Δ	65 ± 23	27

Exp. #	Water type[A]	Sample amendment	Virus concentration, PFU/L[B]	Sample volume, L	Filter (+/-)[C] /Treatment[D]	Eluent[E]	Primary recovery[F],	Ref.
17					1-MDS (+) / none		30 ± 10	
18	sea				NanoCeram (+) / none		63 ± 13	
19		0.1M $MgCl_2$			nitrocellulose ester(-) / none	0.5mM H_2SO_4 → 1mM NaOH	15 ± 5	
20	tap	none	~5×10^2	20	NanoCeram (+) / none	1.0% NaPP PB 0.05 M Gly pH 9.3 [L]	86 ± 9	18
21			~5×10^6				57 ± 3	
22						1.0% NaPP PB 0.05 M Gly pH 7.5 [L]	26 ± 4	
23						3% BE pH 9.3 [L]	34 ± 18	
24						0.05 M Gly pH 9.3 [L]	0.4 ± 0.5	
25						3% BE 0.05 M Gly pH 9.3 [L]	12 ± 1	
26						PB 0.05 M Gly pH 9.3 [L]	26 ± 5	

Exp. #	Water type[A]	Sample amendment	Virus concentration, PFU/L[B]	Sample volume, L	Filter (+/-)[C] /Treatment[D]	Eluent[E]	Primary recovery[F],	Ref.
27						PB 0.05 M Gly pH 7.5 [L]	24 ± 7	
28						PB 0.05 M Gly 0.3% TW 80 pH 9.3 [L]	37 ± 2	
29						0.1% NaPP PB 0.05 M Gly pH 9.3 [L]	40 ± 7	
30						0.6 M NaI PB 0.05 M Gly pH 9.3 [L]	3 ± 2	
31	river+DI	0.05 M $MgCl_2$	10^7	0.1	cellulose ester (-) / none	3% BE 0.5 M NaCl pH 9 [⊥]	52 ± 6	28
32		0.05 M $MgCl_2$ pH 3.5				0.5 mM H_2SO_4 →0.05 M KH_2PO_4 0.1 M NaCl 0.1% TritonX-100 pH 9.2 [⊥]	16 ± 3	
33		none			Zeta Plus 60S (+) / none	2.9% TPB 6%Gly pH 9 [⊥]	1 ± 0	

Exp. #	Water type[A]	Sample amendment	Virus concentration, PFU/L[B]	Sample volume, L	Filter (+/-)[C] /Treatment[D]	Eluent[E]	Primary recovery[F],	Ref.
34						PB 1% NaPP 0.05 M Gly pH 9.3$^{\pm}$	2 ± 0	
35		pH 5.5 to 6				0.05 M arginine 1% BE	0.04 ± 0.05	

Notes on Table S5:

[A] DI: deionized water; river+DI: river water diluted with sterile water

[B] PFU/L: plaque forming units per liter

[C] (+): electropositive filter; (-): electronegative filter

[D] Filter pretreatment, if any

[E] BE: beef extract; TW 80: Tween 80; Gly: glycine; NaPP: sodium polyphosphate; PB: phosphate buffer (3.8 mM Na_2HPO_4, 6.5 mM KH_2PO_4); TPB: tryptose phosphate buffer; The arrow (→) indicates sequential application of eluents. In most studies, elution was performed by filtering the eluent, but the elution protocol could include additional features. These features are marked as follows:

[Δ] Filters were soaked in eluent first prior to filtration of eluent. See each study for specific contact time

[T] Eluent heated to 37 C

▼ Eluent was pumped in the direction opposite to that of the water sample flow, then filter was soaked for 10 min in the eluent prior to eluent collection

* Sample prefiltered through PVDF membrane and drop-by-drop elution was performed

[L] Filter was immersed in the eluent. Filtration housing unit was inverted 10 times followed by 15 min hold time. Such procedure was performed 3 times prior to filtering the eluent

[⊥] Filter was placed feed side down in a Petri dish containing eluent

[F] Recoveries were rounded to the nearest integer (except for recoveries < 1%)

[G] This work was performed with an indigenous coliphage (and not MS2 specifically). The study is included in the Table as illustrative of the effect of the eluent on coliphage recovery.

Table S6. Primary recovery of bacteriophage MS2 by crossflow ultrafiltration as a function of water matrix and ultrafiltration process parameters.

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
1	tap	none	~10^5	10	PS (15 to 20 kDa)/ none	none	44 ± 30	[29]
2					PS (15 to 20 kDa) / 5% FBS (overnight)		51 ± 19	
3					PS (15 to 20 kDa) / 5% FBS (1 hour)		50 ± 14	
4		0.1% NaPP			PS (15 to 20 kDa) / 5% FBS (overnight)		108 ± 16	
5					PS (15 to 20 kDa) / 5% FBS (1 hour)		71 ± 11	
6					PS (15 to 20 kDa) / 5% CS	0.1% NaPP‡	pre: 84 ± 13 post: 89 ± 15	
7					PS (15 to 20 kDa) / 0.1% NaPP		pre: 71 ± 25 post: 82 ± 25	

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
8		0.01% NaPP			PS (15 to 20 kDa) / 0.01% NaPP	0.01% NaPP‡	pre: 86 ± 20 post: 96 ± 21	
9		0.01% TW 80					pre: 105 ± 23 post:106 ± 23	
10		0.002% TW 80					pre: 70 post: 73	
11		none			PS (15 to 20 kDa) / none	tap‡	34±28	
12		0.01% NaPP			PS (15 to 20 kDa) / 0.01% NaPP	0.01% NaPP‡	59 ± 10	
13						0.01% NaPP 0.01% TW 80 0.01% TW 20 0.001% antifoam A‡	65 ± 35	
14						0.01% NaPP 0.5% to 1% Tween 80 0.001% antifoam A‡	91 ± 33	
15	tap	0.01% NaPP	720 ± 240	100	PS (30 kDa) / 5% CS	0.01% NaPP 0.01% TW 80 0.001% antifoam Y-30†	120 ± 22	[30]

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
16	tap	none	~10^4	100	PS (30 kDa) / 0.1% NaPP	0.01% NaPP 0.5% TW 80 0.001% antifoam A‡	52 ± 34	31*
17		0.01% NaPP					84 ± 12	
18						0.01% NaPP 0.1% TW 80 0.001% antifoam A‡	94 ± 11	
19						0.01% NaPP 0.1% TW 80 0.001% antifoam A†	53 ± 13	
20	tap	none	10^4	100	PS & CTA (20 to 70 kDa) /0.5% CS	0.001% TW 80‡	64 ± 48	32
21	river	none	5×10^4	20	PES (30 kDa) / none	1%BE, 0.4% Gly pH 9.5†	73 to 84	33
22						MilliQ water (1#)† → 1%BE 0.4% Gly pH 9.5 (2#)†	42 to 64	
23	DI	none	2×10^9	5	PS (15 to 20 kDa) / none	none	30 ± 7	14

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
24					PS (15 to 20 kDa) / 3% BE		54 ± 24	
25	DI + 0.05 M Gly 0.14 M NaCl				PS (15 to 20 kDa) / none		34 ± 16	
26					PS (15 to 20 kDa) / 3% BE		33 ± 19	
27	DI+ 100 mM Tris-HCl				PS (15 to 20 kDa) / none		18 ± 10	
28					PS (15 to 20 kDa) / 3% BE		29 ± 7	
29	tap	0.01% NaPP	$(4.9\pm1.4)\times10^2$	100	REXEED-25S (30 kDa) / none	none	65 ± 5[a]	34
30			$(7.4\pm6.8)\times10^2$				99 ± 5[b]	
31	treated wastewater	none	630±340	10	PS (30 kDa) / 5% CS	none	84 ± 2	35
32					PS (30 kDa) / none		79 ± 18	
33					PS (65 kDa) / 5% CS		80 ± 6	

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
34					PS (65 kDa) / none		42 ± 12	
35					CTA (70 kDa) / 5% CS		87 ± 10	
36					CTA (70 kDa) / none		88 ± 15	
37					PS (30 kDa) / none	none	110 ± 18	
38					PS (30 kDa) / none	0.01% NaPP, 0.01% TW 80, 0.001% antifoam Y-30†	120 ± 20	
39					CTA (70 kDa) / none	none	80 ± 14	
40					CTA (70 kDa) / none	0.01% NaPP, 0.01% TW 80, 0.001% antifoam Y-30†	130 ± 10	
41	tap	none	9×10^3 to 2×10^7	10	PES (20 nm) / none	water†	31 ± 8	36
42	lake	none	$(4.6\pm3.1)\times10^4$	10	REXEED-25S (29 kDa) / none	0.01% TW 80†	68	9

Exp. #	Water type[A]	Sample amendment[B]	Virus concentration, PFU/L[C]	Sample volume, L	Filter (MWCO/size)[D] /Treatment[E]	Eluent[F]	Primary recovery[G],	Ref.
43	river	0.01% NaPP	$(1.2\pm0.5)\times10^2$	50	PS (30 kDa) / 5% CS	0.01% NaPP 0.01% TW 80 0.001% antifoam Y-30†	91 ± 38	37
44	lake I						65 ± 33	
45	lake II						53 ± 19	
46	ground I						85 ± 23	
47	ground II						77 ± 8	

Notes on Table S6:

A DI: deionized water; Gly: glycine

B NaPP: sodium polyphosphate; TW 80: Tween 80

C PFU/L: plaque forming units per liter

D PS: polysulfone; CTA: cellulose triacetate; PS & CTA: recovery averaged with polysulfone membrane and cellulose triacetate membrane; PES: polyethersulfone; The value in parentheses is the molecular weight cutoff (MWCO) or pore

size of the membrane filter

[E] Filter pretreatment, if any; FBS: fetal bovine serum; CS: calf serum; NaPP: sodium polyphosphate; BE: beef extract

[F] NaPP: sodium polyphosphate; TW 80: Tween 80; TW 20: Tween 20; BE: beef extract; Gly: glycine; The arrow (→) indicates sequential application of eluents. Additional features of the elution protocol are marked as follows:

[†] crossflow

[‡] backflush

[#] Number of rinses (1#: rinsed once; 2#: rinsed twice)

[G] Recoveries were rounded to the nearest integer; pre: pre-elution recovery; post: post-elution recovery

[a] recovery at a high filtration rate (2500 mL/min)

[b] recovery at a low filtration rate (1750 mL/min)

[*] In this paper, Polaczyk et al. performed secondary concentration as well and reported only one recovery value: “ultrafiltration recovery efficiency”. It is this value that is included herein

References

1. E. Lambertini, S. K. Spencer, P. D. Bertz, F. J. Loge, B. A. Kieke and M. A. Borchardt, *Appl. Environ. Microbiol.*, 2008, **74**, 2990-2996.

2. M. Victoria, F. Guimaraes, T. Fumian, F. Ferreira, C. Vieira, J. P. Leite and M. Miagostovich, *J. Virol. Methods*, 2009, **156**, 73-76.

3. M. R. Karim, E. R. Rhodes, N. Brinkman, L. Wymer and G. S. Fout, *Appl. Environ. Microbiol.*, 2009, **75**, 2393-2399.

4. E. Haramoto, H. Katayama, E. Utagawa and S. Ohgaki, *J. Virol. Methods*, 2009, **160**, 206-209.

5. N. Albinana-Gimenez, P. Clemente-Casares, B. Calgua, J. M. Huguet, S. Courtois and R. Girones, *J. Virol. Methods*, 2009, **158**, 104-109.

6. C. D. Gibbons, R. A. Rodriguez, L. Tallon and M. D. Sobsey, *J. Appl. Microbiol.*, 2010, **109**, 635-641.

7. X. L. Pang, B. E. Lee, K. Pabbaraju, S. Gabos, S. Craik, P. Payment and N. Neumann, *J. Virol. Methods*, 2012, **184**, 77-83.

8. H. Lee, M. Kim, S. Y. Paik, C. H. Lee, W. H. Jheong, J. Kim and G. Ko, *J. Water Health*, 2011, **9**, 27-36.

9. D. S. Francy, E. A. Stelzer, A. M. Brady, C. Huitger, R. N. Bushon, H. S. Ip, M. W. Ware, E. N. Villegas, V. Gallardo and H. D. Lindquist, *Appl. Environ. Microbiol.*, 2013, **79**, 1342-1352.

10. W. M. El-Senousy, M. I. Costafreda, R. M. Pinto and A. Bosch, *Int. J. Food Microbiol.*, 2013, **167**, 74-79.

11. J. L. Cashdollar, N. E. Brinkman, S. M. Griffin, B. R. McMinn, E. R. Rhodes, E. A. Varughese, A. C. Grimm, S. U. Parshionikar, L. Wymer and G. S. Fout, *Appl. Environ. Microbiol.*, 2013, **79**, 215-223.

12. A. Hata, K. Matsumori, M. Kitajima and H. Katayama, *Food Environ. Virol.*, 2015, **7**, 7-13.

13. A. De Keuckelaere, L. Baert, A. Duarte, A. Stals and M. Uyttendaele, *J Virol. Methods*, 2013, **187**, 294-303.

14. H. Kim, H. Park and G. Ko, *J. Food Protect.*, 2009, **72**, 2547-2552.

15. K. E. Gibson and K. J. Schwab, *Appl. Environ. Microbiol.*, 2011, **77**, 385-391.

16. D. Li, H. C. Shi and S. C. Jiang, *J. Microbiol. Methods*, 2010, **81**, 33-38.

17. J. Wu, R. A. Rodriguez, J. R. Stewart and M. D. Sobsey, *J. Appl. Microbiol.*, 2011, **110**, 1332-1340.

18. L. A. Ikner, M. Soto-Beltran and K. R. Bright, *Appl. Environ. Microbiol.*, 2011, **77**, 3500-3506.

19. B. R. McMinn, *J. Virol. Methods*, 2013, **193**, 284-290.

20. S. Sun, Y. L. Shi, H. I. Tong, W. Kang, Z. Wang, E. Allmann and Y. A. Lu, *J. Virol. Methods*, 2016, **229**, 78-85.

21. P. Nestola, D. L. Martins, C. Peixoto, S. Roederstein, T. Schleuss, P. M. Alves, J. P. B. Mota and M. J. T. Carrondo, *PLOS ONE*, 2014, **9**.

22. E. R. Rhodes, E. M. Huff, D. W. Hamilton and J. L. Jones, *J. Virol. Methods*, 2016, **228**, 31-38.

23. H. Shi, I. Xagoraraki, K. N. Parent, M. L. Bruening and V. V. Tarabara, *Appl. Environ. Microbiol.*, 2016, **82**, 4982-4993.

24. T. M. Scott, J. Lukasik and S. R. Farrah, *Can. J. Microbiol.*, 2002, **48**, 305-310.

25. A. L. Polaczyk, J. M. Roberts and V. R. Hill, *J. Microbiol. Methods*, 2007, **68**, 260-266.

26. A. M. Abdelzaher, H. M. Solo-Gabriele, M. E. Wright and C. J. Palmer, *J. Environ. Qual.*, 2008, **37**, 1648-1655.

27. H. B. Bennett, H. D. O'Dell, G. Norton, G. Shin, F. C. Hsu and J. S. Meschke, *Water Sci. Technol.*, 2010, **61**, 317-322.

28. T. H. Jones, V. Muehlhauser and G. Thériault, *J. Virol. Methods*, 2014, **206**, 5-11.

29. V. R. Hill, A. L. Polaczyk, D. Hahn, J. Narayanan, T. L. Cromeans, J. M. Roberts and J. E. Amburgey, *Appl. Environ. Microbiol.*, 2005, **71**, 6878-6884.

30. V. R. Hill, A. M. Kahler, N. Jothikumar, T. B. Johnson, D. Hahn and T. L. Cromeans, *Appl. Environ. Microbiol.*, 2007, **73**, 4218-4225.

31. A. L. Polaczyk, J. Narayanan, T. L. Cromeans, D. Hahn, J. M. Roberts, J. E. Amburgey and V. R. Hill, *J. Microbiol. Methods*, 2008, **73**, 92-99.

32. P. M. Holowecky, R. R. James, D. P. Lorch, S. E. Straka and H. D. A. Lindquist, *J. Appl. Microbiol.*, 2009, **106**, 738-747.

33. S. Skraber, C. Gantzer, K. Helmi, L. Hoffmann and H. M. Cauchie, *Food Environ. Virol.*, 2009, **1**, 66-76.

34. E. R. Rhodes, D. W. Hamilton, M. J. See and L. Wymer, *J. Virol. Methods*, 2011, **176**, 38-45.

35. P. B. Liu, V. R. Hill, D. Hahn, T. B. Johnson, Y. Pan, N. Jothikumar and C. L. Moe, *J. Microbiol. Methods*, 2012, **88**, 155-161.

36. L. Pei, M. Rieger, S. Lengger, S. Ott, C. Zawadsky, N. M. Hartmann, H. C. Selinka, A. Tiehm, R. Niessner and M. Seidel, *Environ. Sci. Technol.*, 2012, **46**, 10073-10080.

37. A. M. Kahler, T. B. Johnson, D. Hahn, J. Narayanan, G. Derado and V. R. Hill, *Water*, 2015, **7**, 1202-1216.