Supplementary Information

Review of Quantitative Microbial Risk Assessments for Potable Water Reuse

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Table S1. Summary of studies focused on QMRA for potable reuse (listed in alphabetical order by first author; abbreviations summarized in main text).

Study	Target Pathogen	Reuse Type	QMRA Type	Risk Type	Ingestion Volume & Frequency	GC:IU Ratio; NoV Aggregation	Credited or Actual LRV	Failure Incorporation	Treatment Train	Sensitivity Analysis	Dose-Response	Buffer Storage Time & Decay
Amoueyan et al. (2017)[1]	*Crypto*	DFR, IPR, and DPR	Bottom up	10^{-4} P_{inf} and 10^{-6} DALYs	2 L/d, once daily*	None	Observed treatment performance LRVs	Failure probabilities associated with individual treatment processes and compound failures (‘domino effects’)	A) DFR: SW-coagulation/flocculation/sedimentation-filtration-disinfection B) IPR: UF-O_3-BAC-O_3-environmental buffer C) DPR: UF-O_3-BAC-UV-ESB	Considered different WW loadings of *Crypto*, treatment process failures, reservoir storage time, recycled water contribution, SW temperature, and dose response parameters	Exponential	Decay incorporated over 270-day baseline storage time
Amoueyan et al. (2019)[2]	*Crypto*, NoV, AdV and *Salmonella*	DFR, IPR, and DPR	Bottom up	10^{-4} P_{inf} and 10^{-6} DALYs	2 L/d, once daily*	AdV = 700:1 $TCID_{50}$/gc; NoV mean aggregate size = 1,106 gc	Observed treatment performance LRVs	Failure probabilities associated with individual treatment processes and compound failures (‘domino effects’)	A) DFR: SW augmentation-DWTP with Cl_2 B) MF-RO-UV-GW replenishment-Cl_2 C) UF-O_3-BAC-O_3-SW augmentation-DWTP with Cl_2 D) MF-RO-UV- SW augmentation-DWTP with Cl_2 E) MF-RO-UV- SW blending-DWTP with Cl_2 F) UF-O_3-BAC-UV-ESB+Cl_2 G) MF-RO-UV-ESB+Cl_2	Considered increasing concentrations of raw sewage pathogen concentrations (outbreak conditions), storage time and temperature in the environmental buffer, recycled water contributions, treatment process failures, and dose-response model for *Crypto* risk, aggregated/ disaggregated NoV dose-response	*Crypto:* exponential & Fractional Poisson, AdV: exponential, NoV: Fractional Poisson, *Salmonella:* Beta Poisson	GW: decay incorporated over 60-day storage time; SW: decay incorporated over 270-day storage time
Amoueyan et al. (2020)[3]	NoV	DFR and DPR	Bottom up	10^{-4} P_{inf}	2 L/d, once daily*	None; NoV mean aggregate size = 1,106 gc	Two different scenarios: observed treatment performance & credited LRVs	Failure probabilities associated with individual treatment processes and compound failures (‘domino effects’)	A) DFR: SW augmentation-DWTP B) DPR: MF-RO-UV-ESB+Cl_2 C) DPR: UF-O_3-BAC-UV-ESB+Cl_2	Considered differing storage/travel times (0, 15, and 30 days)	Fractional Poisson	Decay incorporated over 270-day baseline storage time
Asano et al. (1992)[4]	Enteric virus (Echovirus 12, Poliovirus 1, and Poliovirus 3)	DFR/IPR	Bottom up	Did not compare to benchmark	2 L/d, once daily*	None	Directly used tertiary effluent concentrations, or secondary effluent concentrations with LRV = 5 for tertiary treatment	No treatment failure modeled, but did model highest concentration in tertiary treatment with no LRV	Full treatment = Secondary treatment, coagulation, flocculation, clarification, filtration, disinfection Alternative TT1 = direct filtration (coagulation, flocculation, filtration, disinfection) Alternative TT2 = contact filtration (coagulation, filtration, disinfection)	Modeled different enteric virus concentrations (secondary or tertiary effluent concentrations)	Beta-distributed model; had different infectivities for echovirus 12, poliovirus 1, and poliovirus 3	Decay incorporated over 6-month storage time

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Bailey et al. (2020)[5]	*Salmonella* spp., AdV, *Crypto*, and *Giardia*	DPR with SW blending (20% DPR)	Bottom up	10^{-4} P_{inf}	2 L/d, once daily*	*Salmon.* = 1.54:1, AdV = 2.60:1, *Crypto* = 4:1, *Giardia* = 7.69:1	Credited LRV for DW treatment and observed LRVs for worst case reduction scenario	No failure, but included a worst case log_{10} reduction scenario for DW treatment based on real-world data	Used EPA, WHO, and observed log_{10} reductions for DWTP	Rank order correlation in uncertainty (parameter most often associated with high-risk scenarios is microbial concentration—led to most uncertainty)	AdV, *Crypto*, and *Giardia*: Exponential; *Salmonella*: Beta-Poisson	Decay incorporated over 5-day storage time
Barker et al. (2013)[6]	NoV, *Giardia*, and *Campy*	DPR	Top down	10^{-6} DALYs	Lognormal distribution (standard μ = 3 L/d, σ = 1 L/d, truncated at 2 and 6 L/d), once daily*	None	Top down, LRVs calculated based on risk thresholds (6.9/8.0/7.4 for municipal sewage, 12.1/10.4/12.3 for Davis Station outbreak)	Not performed	Top down, NA	Spearman rank correlation coefficient for each stochastic parameter. Pathogen concentration has largest impact.	NoV: Full Beta-Poisson, *Giardia:* exponential *Campy:* Full Beta-Poisson	No decay and no storage time consideration
Chaudhry et al. (2017)[7]	NoV, *Crypto*, and *Salmonella*	DFR and DPR	Bottom up	10^{-4} P_{inf}	Lognormal distribution (log-normal μ=-0.63 L/d, σ=0.989 L/d), once daily	None; NoV mean aggregate size = 1,106 gc	Observed treatment performance LRVs	Not performed	1) DFR: WW-impacted SW with coagulation, flocculation, sedimentation, media filtration, Cl_2; For DPR, raw WW with 2) sedimentation, activated sludge, MF-RO-UV AOP-Cl_2 C) Sedimentation, activated sludge, O_3-BAC-MF-RO-UV AOP-Cl_2 D) Sedimentation, membrane bioreactor, RO-UV AOP-Cl_2 E) Sedimentation, activated sludge, O_3-BAC-MF-NF-UV AOP-BAC-Cl_2	Included different blending ratios for DFR and DPR; modeled aggregated and disaggregated NoV dose-response; used Spearman rank correlation coefficients for DPR treatment trains.	*Crypto*: exponential; *Salmonella*: Beta-Poisson; NoV: Fractional Poisson, both aggregated and disaggregated	No decay and no storage time consideration
Church et al. (2015)[8]	NoV, *Salmonella* spp. (non-*typhi*), and *E. coli* O157:H7	DPR	Top down with pathogen conc. endpoint rather than LRVs	Maximum tolerable cases of illness set to 1 in 50,000 exposures	3 L/d, once daily*	None	Top down, NA	Not performed	Top down, NA	Not performed	NoV: hypergeometric based on best-fit parameters for 8fIIa & 8fIIb inocula; *Salmonella* spp.: approximate Beta-Poisson; *E. coli* O157:H7: approximate Beta-Poisson	No decay and no storage time consideration, but *E. coli* decay in the presence of surfactants was characterized separately

Study	Target Pathogen	Reuse Type	QMRA Type	Risk Type	Ingestion Volume & Frequency	GC:IU Ratio; NoV Aggregation	Credited or Actual LRV	Failure Incorporation	Treatment Train	Sensitivity Analysis	Dose-Response	Buffer Storage Time & Decay
Gerrity et al. (2022)[9]	Hypothet. enteric virus (SARS-CoV-2 conc. and NoV dose-response function)	General potable reuse	Bottom up	Relative risks determined by dividing the percentile-sorted risk for each scenario by the baseline scenario. Daily, per ingestion, and annual	2 L/d, 8 ingestion events per day	None	Hypothetical train achieving LRV = 12 for virus (consistent with CA GW reuse)	Not performed	Hypothetical train achieving LRV = 12	Not performed	Hypergeometric for NoV	No decay and no storage time consideration
Gerrity et al. (2023)[10]	*Giardia*, *Crypto*, NoV, EnV, and AdV	DPR	Top down	2.7×10^{-7} daily risk benchmark, 10^{-4} P_{inf} benchmark	2.5 L/d, once daily	Baseline, GC:IU ratio and culture adjustments were considered; EnV, NoV, and AdV molecular GC: IU = 200:1	Top down, LRVs were calculated based on risk threshold; Suggested LRTs of 18/15/15 (13/10/10 without failure)	Off-specification conditions were considered for three scenarios of different durations, frequencies, and ingestion events.	Top down, NA	Performed sensitivity analysis on off-specification frequencies, failure duration, and ingestion frequency.	EnV: Beta-Poisson, NoV: hypergeometric, AdV: exact Beta-Poisson , *Giardia:* exponential, *Crypto:* Beta-Poisson	Top down, no decay, and no storage time
Jones et al. (2023)[11]	*Crypto*, *Giardia*, *Campy*, EnV, and AdV	IPR**	Bottom up	10^{-4} P_{inf} and 10^{-6} DALYs	Lognormal distribution (standard μ=1.948 L/d, σ=0.827 L/d) 1, 8, and 96 ingestion events per day	None	Credited LRV	Failure scenarios = No failure, real failure (literature), and total failure	MF-RO-UV AOP-ESB	Analyzed scenarios with different failure, consumption, and use of an ESB	*Crypto*, *Campy* and enterovirus: Beta-Poisson (used rotavirus DR model for enterovirus); adenovirus and *Giardia*: exponential	No decay and no storage time consideration
Kimbell et al. (2024)[12]	AdV, enteric viruses, *Crypto*, *Giardia*	IPR**	Bottom up	2.7×10^{-7} daily risk, 10^{-4} P_{inf}	2.5 L/d, 96 ingestion events per day	None	Credit LRV	3-log reduction in treatment for 24 h 9% of simulated days; 6-log reduction in treatment for 24 h 1% of simulated days	A) BNR-MBR-RO-UV AOP-Cl_2-O_3 B) BNR-MF/UF-CF-RO-UV AOP-Cl_2-O_3	Compared different LRVs and failure incorporations	Enteric virus: Beta-poisson, AdV: exponential, *Giardia:* exponential, *Crypto:* exponential	No decay and no storage time consideration
Kobayashi et al. (2015)[13]	*Crypto*, *Campy*, rotavirus	DFR	Bottom up	10^{-6} DALYs	0.75 L/d, once daily*	None	Observed treatment performance LRVs	Not performed	Used WWTP effluent concentration data, had a scenario with and without an additional advanced water treatment plant. A) DWTP: includes dissolved air floatation, rapid sand filtration, and Cl_2 B) Advanced Water Treatment prior to	Not performed	*Crypto*, *Campy* and rotavirus: Beta-Poisson	Incorporated decay with the travel times

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									discharge: strainer-μF-chemical dosing-RO-pH adjustment-recarbonation-Cl_2-dechlorination, then the same DWTP			
Lim et al. (2017)[14]	*Crypto* and NoV	DFR	Bottom up	10^{-4} P_{inf} and 10^{-6} DALYs	2 L/d, once daily*	None	Credited LRV = 3 for *Crypto* and LRV = 4 for NoV in DWTP	Not performed	TT for DWTP not specified, used LRVs of 3 for Crypto and 4 for NoV	Three different retention times (270, 15, and 360 days) and three dilutions rates (15%, 30%, 45%)	*Crypto*: fractional Poisson; NoV non-aggregated: exact Beta-Poisson (hypergeometric)	Decay incorporated over 270, 315, and 360-day storage time
MacNevin and Zornes (2020)[15]	*Crypto* and *Giardia*	DPR	Iterative Bottom up to get LRV min	10^{-4} P_{inf}	2 L/d, once daily*	None	Started at LRV = 4 then increased by 0.5 until the simulated risk was less than 1 in 10,000	Not performed	Chose the LRVs	Not performed	Exponential	No decay and no storage time consideration
Page et al. (2010a)[16]	Rotavirus, *Crypto*, and *Campy*	IPR	Bottom up	10^{-6} DALYs	2 L/d, once daily*	None	LRVs from Australian guidelines for water recycling + capped LRV for aquifer	Not performed	Stormwater-wetland--aquifer- post treatment (UV, Cl_2)	A factor sensitivity was calculated for each barrier in the treatment train (wetland, aquifer, UV and Cl_2) to determine relative value of aquifer	Rotavirus: Beta-Poisson; *Campy*: Beta-Poisson; *Crypto*: exponential	Decay incorporated over 241±58 day (lognormal distribution) storage time
Page et al. (2010b)[17]	Rotavirus, *Crypto*, and *Campy*	IPR	Bottom up	10^{-6} DALYs	Not reported	None	Used pathogen decay information to calculate the time for a 1-log_{10} reduction in pathogen numbers	Not performed	Stormwater-wetland--aquifer- post treatment (UV, Cl_2)	Not performed	Rotavirus: Beta-Poisson, *Crypto*: Beta-Poisson, *Campy*: not specified	Decay incorporated over a 240 day residence time
Page et al. (2010c)[18]	Rotavirus, *Crypto*, and *Campy*	IPR	Bottom up	10^{-6} DALYs	Not reported	None	Actual LRVs for aquifer and engineered treatment	Not performed	A) Primary Treatment – aquifer – post-treatment (Cl_2) B) Secondary treated (activated sludge) WW + stormwater – wetland – aquifer – post-treatment (water softening, Cl_2) C) Tertiary Treated WW (RO) – aquifer – post-treatment (aeration, rapid sand filtration, UV) D) Stormwater – wetland – aquifer – post-treatment (UV, Cl_2)	A sensitivity analysis was performed for each barrier in the treatment train for each case study site.	Rotavirus: Beta-Poisson, *Crypto*: Beta-Poisson, *Campy*: not specified	Decay incorporated for each case study storage time (20-730 days)
Page et al. (2015a)[19]	AdV, *Crypto*, and *Campy*	General reuse	Top down	10^{-6} DALYs	2 L/d, once daily	AdV = 100:1	NA, top down, found LRT = 5.8 for	Not performed	NA, top down	Not performed	Dose equivalent to 10^{-6} DALYs used for each	No decay and no storage time consideration

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							rotavirus, 4.8 for *Crypto*, and 5.3 for *Campy* to meet health targets				pathogen: rotavirus (used for AdV) = $2.5x10^{-3}$ n/year; *Crypto*= $1.6x10^{-2}$ n/year; *Campy* =$3.8x10^{-2}$ n/year.	
Page et al. (2015b)[20]	AdV, *Crypto*, *Campy*	IPR	Top down with comparison to treatment train	10^{-6} DALYs	2 L/d, once daily*	None	LRVs from attachment and decay rates	Not performed	A) Storage Transfer and Recovery (ASTR, uses separate recharge and recovery wells) B) Aquifer Storage and Recovery (ASR, uses one well for recharge and recovery)	Not performed	Dose equivalent to 10^{-6} DALYs used for each pathogen: rotavirus (used for AdV) = $2.5x10^{-3}$ n/year; *Crypto*= $1.6x10^{-2}$ n/year; *Campy* =$3.8x10^{-2}$ n/year.	Decay incorporated over 250-days storage time for ASTR and 25-days for ASR
Page et al. (2016)[21]	Rotavirus, *Crypto*, and *Campy*	IPR	Top down with comparison to treatment train	10^{-6} DALYs	2 L/d, once daily	None	LRVs from Australian drinking water guidelines	None	A) Stormwater catchment-pretreatment-aquifer-final treatment (UV, Cl_2) B) Stormwater catchment-pretreatment-reservoir-final treatment (coagulation and dual media filtration, UV, Cl_2) C) Stormwater catchment-pretreatment-aquifer-reservoir-final treatment (coagulation and dual media filtration, Cl_2) D) Stormwater catchment-pretreatment-aquifer-intermediate treatment-reservoir-final treatment (coagulation and dual media filtration, Cl_2)	None	Dose equivalent to 10^{-6} DALYs used for each pathogen: rotavirus (used for AdV) = $2.5x10^{-3}$ n/year; *Crypto*= $1.6x10^{-2}$ n/year; *Campy* =$3.8x10^{-2}$ n/year.	Decay incorporated over 250-days storage time in aquifer
Pecson et al. (2017)[22]	EnV and *Crypto*	DPR	Bottom up	10^{-4} and 10^{-3} P_{inf} and 10^{-6} DALYs	Lognormal distribution with median of 1.8 L/d, ingested over 96 15-min intervals	None	Observed LRV = 14.1 (+6 for free Cl_2) for EnV, 16.0 for *Crypto*	Each process was modeled with one failure per year lasting 15 min, 1 h, 8 h, or 24 h	O_3-BAC-MF/UF-RO-UV AOP	Sensitivity analysis on volume of water consumed and impact of different *Crypto* dose-response functions	Dose-response for enterovirus used rotavirus model using a Beta-Poisson; Crypto: Beta-Poisson	No decay and no storage time consideration
Pecson et al. (2023)[23]	*Giardia*, *Crypto*, NoV, and EnV	DPR	Top down	2.7×10^{-7} daily risk, 10^{-4} P_{inf}	2 L/d, 96 ingestion events per day	EnV = 1:1 to 10,000:1; AdV = 1:1 to 100,000:1; NoV mean aggregate size = 1,106 gc	NA, top down, suggested LRTs of 17/14/14 (13/10/10 without failure)	Suggested a 4-log redundancy to protect against failures	Top down, NA	Used two different NoV dose-response functions	NoV (GI): hypergeometric; NoV (GI and GII.4) Fractional Poisson; *Giardia*: exponential; *Crypto*: Beta-Poisson;	Top down, no decay and no storage time

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											rotavirus: approximate Beta-Poisson (used it with the enterovirus occurrence data)	
Remy et al. (2019)[24]	Rotavirus, *Campy jejuni*, *Crypto parvum*, *Giardia intestinalis*	IPR**	Bottom up	10^{-6} DALYs	Triangular distribution from 1-2 L/d, once daily	None	Credited (DWT, WWT) and observed (tertiary treatment) LRVs used	Not performed	A) WWTP-Filter-EDR-µGAC-UV-DWTP B) WWTP-UF-RO with 5% bypass-DWTP	Not performed	*Giardia:* exponential *Campy:* Beta-Poisson *Crypto:* exponential Rotavirus*:* Beta-Poisson	No decay and no storage time consideration
Seis et al. (2020)[25]	NoV	IPR	Top down	10^{-4} P_{inf}	1 L/d, once daily*	None	Hypothetical train achieving LRV = 12-16	Not performed	Hypothetical train achieving LRV = 12-16	Not performed	Hypergeometric (disaggregated)	Top down, no decay, and no storage time
Soller et al. (2017a)[26]	NoV, AdV, *Crypto* spp., *Giardia lamblia*, *Campy jejuni*, and *Salmonella enterica*	DPR	Bottom up	10^{-4} P_{inf}	2.5 L/d, once daily*	None	Observed LRVs from literature	Not performed	A) MF-RO-UV-ESB+Cl_2 B) O_3-BAF-MF-RO-UV C) O_3-BAF-UF-UV-ESB+Cl_2 D) O_3-BAF-UF-UV-ESB+Cl_2-conventional DWTP (coagulation/flocculation/ sedimentation-filtration-Cl_2	Used two UV doses (12 and 800 mJ/cm^2) and two dose-response models for NoV and *Crypto*	AdV: exponential; *Campy*: hypergeometric; *Crypto*: exponential and Fractional Poisson; *Giardia*: exponential; NoV: hypergeometric and Fractional Poisson; *Salmonella*: Beta-Poisson	No decay and no storage time consideration
Soller et al. (2018)[27]	NoV, AdV, *Crypto*, *Giardia lamblia*, *Campy* spp., and *Salmonella enterica*	DPR	Bottom up and top down	10^{-4} P_{inf}	2.5 L/d, once daily*	None	Credited LRVs and calculated LRVs necessary for 10^{-4} P_{inf} for 95% (14/11/11) and 100% scenario compliance (15/11/11)	Not performed	A) MF-RO-UV-ESB+Cl_2; B) O_3-BAF-UF-UV-ESB+Cl_2	Used different NoV concentrations in raw wastewater; used different dose-response models for AdV, NoV, and *Crypto*; two UV doses (12 and 800 mJ/cm^2)	AdV: exponential and hypergeometric; *Campy*: hypergeometric; *Crypto*: exponential and Fractional Poisson and exponential with immunity; *Giardia*: exponential; NoV: hypergeometric and Fractional Poisson and weighted model;	No decay and no storage time consideration

Study	Target Pathogen	Reuse Type	QMRA Type	Risk Type	Ingestion Volume & Frequency	GC:IU Ratio; NoV Aggregation	Credited or Actual LRV	Failure Incorporation	Treatment Train	Sensitivity Analysis	Dose-Response	Buffer Storage Time & Decay
											Salmonella: Beta-Poisson	
Soller et al. (2019)[28]	NoV, *Crypto*, and *Giardia*	DFR IPR and DPR	Bottom up	10^{-4} P_{inf}	2.5 L/d, once daily*	None	Observed LRVs from literature	Not performed	A) (for IPR—all were used for DPR): MF-RO-UV-ESB+Cl_2; B) O_3-BAF-MF-RO-UV; C) O_3-BAF-UF-UV-ESB+Cl_2 D) O_3-BAF-UF-UV-ESB+Cl_2-conventional DWTP (flocculation/ sedimentation-filtration-Cl_2)	DPR TTs compared two UV doses (12 and 800 mJ/cm^2), two dose-response models for NoV, different retention times and recycled water contributions for IPR and DFR.	*Crypto*: exponential with immunity; *Giardia*: exponential; NoV: weighted model based on hypergeometric and Fractional Poisson with aggregation models	DFR: Decay incorporated over 2, 15, 30, 90, 180, and 360-day storage time. IPR: Decay incorporated over 30, 90, 180, and 360-day storage time
Tanaka et al. (1998)[29]	Enteric virus	DFR/IPR	Bottom up	10^{-4} P_{inf}	2 L/d, once daily*	None	LRVs from a previous study for different trains	Not performed	A) Secondary treatment, coagulation, flocculation, sedimentation, filtration, disinfection with high Cl_2 (LRV = 5.2) B) direct Cl_2 of secondary effluent (LRV = 3.9) C) Secondary treatment, coagulation, filtration, disinfection with low Cl_2 (LRV = 4.7) D) unchlorinated second. effluent (LRV = 0)	Used virus concentrations from different California treatment facilities, two different decay rate constants, and compared four different treatment trains	Used two dose-response models: Single-hit exponential model and beta-distributed probability model	Decay incorporated over 6-month storage time
Zhiteneva et al. (2021)[30]	NoV, *Campy* and *Crypto*	IPR	Bottom up	10^{-6} DALYs	Lognormal distribution (log-normal μ= 0.65 L/d, σ= 0.53 L/d), once daily*	None	Observed treatment performance and credited LRVs	In the Bayesian network, the failure of each treatment step (LRV = 0) was assessed with selector nodes; created a model where the performance of one LRV node was correlated by 0.5 to other LRV nodes	Biological treatment, rapid sand filtration, sand biofilter, GAC, UV, GW recharge, DW treatment	Sensitivity analysis to see which parameters exerted the most influence on the final risk; also did a high pathogen loading event, a performance failure of the sand biofilter, managed aquifer recharge failure, experimental NoV removal, and the effect of the common factor	*Campy*: Approximate Beta-Poisson and exact Beta-Poisson; *Crypto*: exponential and Fractional Poisson NoV: approximate Beta-Poisson and Fractional Poisson	Decay incorporated between 50 and 120-day storage time

* Not reported, assuming one ingestion event per day
** Authors reported study as IPR, but neglect the environmental buffer, so the risk simulation was identical to DPR

References

1 E. Amoueyan, S. Ahmad, J. N. S. Eisenberg, B. Pecson and D. Gerrity, Quantifying pathogen risks associated with potable reuse: A risk assessment case study for Cryptosporidium, *Water Research*, 2017, **119**, 252–266.

2 E. Amoueyan, S. Ahmad, J. N. S. Eisenberg and D. Gerrity, Equivalency of indirect and direct potable reuse paradigms based on a quantitative microbial risk assessment framework, *Microbial Risk Analysis*, 2019, **12**, 60–75.

3 E. Amoueyan, S. Ahmad, J. N. S. Eisenberg and D. Gerrity, A dynamic quantitative microbial risk assessment for norovirus in potable reuse systems, *Microbial Risk Analysis*, 2020, **14**, 100088.

4 T. Asano, L. Y. C. Leong, M. G. Rigby and R. H. Sakaji, Evaluation of the California Wastewater Reclamation Criteria Using Enteric Virus Monitoring Data, *Water Science and Technology*, 1992, **26**, 1513–1524.

5 E. S. Bailey, L. M. Casanova and M. D. Sobsey, Quantitative microbial risk assessment of North Carolina reclaimed water for potable reuse, *AWWA Water Science*, 2020, **2**, e1200.

6 S. F. Barker, M. Packer, P. J. Scales, S. Gray, I. Snape and A. J. Hamilton, Pathogen reduction requirements for direct potable reuse in Antarctica: evaluating human health risks in small communities, *Sci Total Environ*, 2013, **461–462**, 723–733.

7 R. M. Chaudhry, K. A. Hamilton, C. N. Haas and K. L. Nelson, Drivers of Microbial Risk for Direct Potable Reuse and de Facto Reuse Treatment Schemes: The Impacts of Source Water Quality and Blending, *International Journal of Environmental Research and Public Health*, 2017, **14**, 635.

8 J. Church, M. E. Verbyla, W. H. Lee, A. A. Randall, T. J. Amundsen and D. J. Zastrow, Dishwashing water recycling system and related water quality standards for military use, *Science of The Total Environment*, 2015, **529**, 275–284.

9 D. Gerrity, K. Papp and B. M. Pecson, Pathogen Peak "Averaging" in Potable Reuse Systems: Lessons Learned from Wastewater Surveillance of SARS-CoV-2, *ACS EST Water*, 2022, **2**, 1863–1870.

10 D. Gerrity, K. Crank, E. Steinle-Darling and B. M. Pecson, Establishing pathogen log reduction value targets for direct potable reuse in the United States, *AWWA Water Science*, 2023, **5**, e1353.

11 C. H. Jones, V. Wylie, H. Ford, J. Fawell, M. Holmer and K. Bell, A robust scenario analysis approach to water recycling quantitative microbial risk assessment, *Journal of Applied Microbiology*, 2023, **134**, lxad029.

12 L. K. Kimbell, F. Sabba, G. Hunter and L. Botero, Comparison of treatment trains for indirect potable reuse and use of quantitative microbial risk assessment (QMRA) to evaluate reliability of pathogen removal: Zoo Miami case study, *Journal of Water Process Engineering*, 2024, **65**, 105850.

13 Y. Kobayashi, G. M. Peters, N. J. Ashbolt, S. Heimersson, M. Svanström and S. J. Khan, Global and local health burden trade-off through the hybridisation of quantitative microbial risk assessment and life cycle assessment to aid water management, *Water Research*, 2015, **79**, 26–38.

14 K.-Y. Lim, Y. Wu and S. C. Jiang, Assessment of Cryptosporidium and norovirus risk associated with de facto wastewater reuse in Trinity River, Texas, *Microbial Risk Analysis*, 2017, **5**, 15–24.

15 D. MacNevin and G. Zornes, Health risks from protozoa in potable reuse: Implications of Florida's data set, *AWWA Water Science*, 2020, **2**, e1199.
16 D. Page, P. Dillon, S. Toze and J. P. S. Sidhu, Characterising aquifer treatment for pathogens in managed aquifer recharge, *Water Science and Technology*, 2010, **62**, 2009–2015.
17 D. Page, P. Dillon, J. Vanderzalm, S. Toze, J. Sidhu, K. Barry, K. Levett, S. Kremer and R. Regel, Risk Assessment of Aquifer Storage Transfer and Recovery with Urban Stormwater for Producing Water of a Potable Quality, *Journal of Environmental Quality*, 2010, **39**, 2029–2039.
18 D. Page, P. Dillon, S. Toze, D. Bixio, B. Genthe, B. E. Jiménez Cisneros and T. Wintgens, Valuing the subsurface pathogen treatment barrier in water recycling via aquifers for drinking supplies, *Water Research*, 2010, **44**, 1841–1852.
19 D. W. Page, K. Barry, D. Gonzalez, A. Keegan and P. Dillon, Reference pathogen numbers in urban stormwater for drinking water risk assessment, *Journal of Water Reuse and Desalination*, 2015, **6**, 30–39.
20 D. Page, D. Gonzalez, S. Torkzaban, S. Toze, J. Sidhu, K. Miotliński, K. Barry and P. Dillon, Microbiological risks of recycling urban stormwater via aquifers for various uses in Adelaide, Australia, *Environ Earth Sci*, 2015, **73**, 7733–7737.
21 D. Page, D. Gonzalez, J. Sidhu, S. Toze, S. Torkzaban and P. Dillon, Assessment of treatment options of recycling urban stormwater recycling via aquifers to produce drinking water quality, *Urban Water Journal*, 2016, **13**, 657–662.
22 B. M. Pecson, S. C. Triolo, S. Olivieri, E. C. Chen, A. N. Pisarenko, C.-C. Yang, A. Olivieri, C. N. Haas, R. S. Trussell and R. R. Trussell, Reliability of pathogen control in direct potable reuse: Performance evaluation and QMRA of a full-scale 1 MGD advanced treatment train, *Water Research*, 2017, **122**, 258–268.
23 B. Pecson, A. Kaufmann, D. Gerrity, C. N. Haas, E. Seto, N. J. Ashbolt, T. Slifko, E. Darby and A. Olivieri, Science-based pathogen treatment requirements for direct potable reuse, *Environmental Science: Water Research & Technology*, 2023, **9**, 3377-3390, DOI:10.1039/D3EW00362K.
24 C. Remy, W. Seis, U. Miehe, J. Orsoni and J. Bortoli, Risk management and environmental benefits of a prospective system for indirect potable reuse of municipal wastewater in France, *Water Supply*, 2019, **19**, 1533–1540.
25 W. Seis, P. Rouault and G. Medema, Addressing and reducing parameter uncertainty in quantitative microbial risk assessment by incorporating external information via Bayesian hierarchical modeling, *Water Research*, 2020, **185**, 116202.
26 J. A. Soller, S. E. Eftim, I. Warren and S. P. Nappier, Evaluation of microbiological risks associated with direct potable reuse, *Microbial Risk Analysis*, 2017, **5**, 3–14.
27 J. A. Soller, S. E. Eftim and S. P. Nappier, Direct potable reuse microbial risk assessment methodology: Sensitivity analysis and application to State log credit allocations, *Water Research*, 2018, **128**, 286–292.
28 J. A. Soller, S. E. Eftim and S. P. Nappier, Comparison of Predicted Microbiological Human Health Risks Associated with de Facto, Indirect, and Direct Potable Water Reuse, *Environ Sci Technol*, 2019, **53**, 13382–13389.
29 H. Tanaka, T. Asano, E. D. Schroeder and G. Tchobanoglous, Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data, *Water Environment Research*, 1998, **70**, 39–51.

30 V. Zhiteneva, G. Carvajal, O. Shehata, U. Hübner and J. E. Drewes, Quantitative microbial risk assessment of a non-membrane based indirect potable water reuse system using Bayesian networks, *Sci Total Environ*, 2021, **780**, 146462.