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Scenario Analysis of the Impact on Drinking Water Intakes from Bromide in the Discharge of Treated Oil and Gas Wastewater

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Supplemental Data

Initial Mixing in the Allegheny River

Initial mixing distances for the Allegheny River are given in Table S8 according to the method developed by Yotsukura and Cobb (1972), using the coefficients developed for differing injection points developed by Kilpatrick and Wilson (1989). When the injection is made at the edge, the initially skewed concentration distribution at the injection point requires greater distances than from Franklin to Kittaning (127 km) to achieve optimum lateral mixing. If the injection is made in the channel, either at the centerline or from multiple points, the optimum distance is reduced greatly.

Table S1. Characteristics of the Monocacy River used in the semi-analytical model simulations.

Location	***Distance from Downstream End (km)***	***Annual Discharge (m^3/s)***	***Discharge (m^3/s)***	***Drainage Area (km^2)***	***Slope (m/m)***	***Width (m)***	***Average Depth (m)***
Injection Point	34.3	--	--	--	--	--	--
Section 1	24.0	19.7	14.3	1586	0.0006	37.2	0.8
Section 2	16.0	20.5	15.1	1650	0.0006	50.0	1.0
Section 3	7.5	22.6	15.1	1819	0.0005	50.6	0.8
Section 4	0	26.2	18.5	2115	0.0003	51.2	0.6

Table S2. Monocacy River tracer data and semi-analytical model results.

Result Type	***Peak Arrival Time (hr)***				***Peak Concentration (mg/L)***			
	Measurement Section				***Measurement Section***			
	1	***2***	***3***	***4***	***1***	***2***	***3***	***4***
Tracer	7.2	13.6	19.6	25.8	0.1841	.01187	.00901	0.00606
	% difference with tracer value							
Semi-Analytical	3.3	-0.8	0.9	-1.1	19.9	23.2	29.1	44.6

Table S3. Steady-state simulation parameters for the creek and river scenarios. Effluent types are defined in Table 2 of main text.

Scenario	*River Discharge*	*Effluent Type*	*Effluent Discharge*
Creek	Low Flow Month	Produced-C	Permitted Level
		Produced-ME	Permitted Level
		Produced-ME	0.50 x Permitted Level
		Produced-ME	0.33 x Permitted Level
		Produced-ME	0.25 x Permitted Level
		Mixed/Flowback	Permitted Level
		Lower Flowback	Permitted Level
		Lower Bromide	Permitted Level
	High Flow Month	Produced-C	Permitted Level
		Produced-ME	Permitted Level
		Produced-ME	0.50 x Permitted Level
		Produced-ME	0.33 x Permitted Level
		Produced-ME	0.25 x Permitted Level
		Mixed/Flowback	Permitted Level
		Lower Flowback	Permitted Level
		Lower Bromide	Permitted Level
River	Low Flow Month	Produced-C	Permitted Level
		Produced-ME	Permitted Level
		Produced-ME	0.50 x Permitted Level
		Produced-ME	0.33 x Permitted Level
		Produced-ME	0.25 x Permitted Level
		Mixed/Flowback	Permitted Level
		Lower Flowback	Permitted Level
		Lower Bromide	Permitted Level
	High Flow Month	Produced-C	Permitted Level
		Produced-ME	Permitted Level
		Produced-ME	0.50 x Permitted Level
		Produced-ME	0.33 x Permitted Level
		Produced-ME	0.25 x Permitted Level
		Mixed/Flowback	Permitted Level
		Lower Flowback	Permitted Level
		Lower Bromide	Permitted Level

Table S4. Transient simulation parameters for produced water in the Allegheny River using effluents at the 5th and 95th percentiles of the bromide produced water frequency distribution. Effluent types are defined in Table 2 of main text.

Active discharge period	*River Flow*	*Effluent Concentration*	*Effluent Type*
4-, 8-, 12-, and 24- hour; 5 days/week	Low Flow Month	95% Concentration Percentile	Produced-ME Mixed/Flowback Lower Flowback
		5% Concentration Percentile	Produced-ME Mixed/Flowback Lower Flowback
	High Flow Month	95% Concentration Percentile	Produced-ME Mixed/Flowback Lower Flowback
		5% Concentration Percentile	Produced-ME Mixed/Flowback Lower Flowback

Table S5. Effluent characteristics for transient release scenarios.

Release Duration (hour)	*Effluent Discharge (MGD)*	*Effluent Type*	*Released Mass (Kg)*	
			5^{th}	*95^{th}*
4	0.3	Produced-ME	220	601
		Mixed/Flowback	68.9	189
		Lower Flowback	12.9	57.4
8	0.3	Produced-ME	441	1200
		Mixed/Flowback	138	379
		Lower Flowback	25.7	115
12	0.3	Produced-ME	661	1800
		Mixed/Flowback	207	568
		Lower Flowback	38.6	172
24	0.3	Produced-ME	1320	3600
		Mixed/Flowback	413	1140
		Lower Flowback	77	344

Table S6. Average bromide concentrations and bromide concentration reduction factors for continuous (24 hour) and pulse releases of Produced-ME water at downstream gaged locations in the Allegheny River.

Pulse Duration (hrs per work day)	*Average Bromide Concentration at Downstream Location*			*Average Bromide Concentration Reduction Factor[(a)]*		
	Parker, PA 65.98 (km)	*Rimer, PA 103.4 (km)*	*Kittanning, PA 126.5 (km)*	*Parker, PA 65.98 (km)*	*Rimer, PA 103.4 (km)*	*Kittanning, PA 126.5 (km)*
			Low Flow, 95TH percentile release concentration			
24	$3.18x10^{-1}$	$2.74x10^{-1}$	$2.43x10^{-1}$	1.00	1.00	1.00
12	$1.71x10^{-1}$	$1.47x10^{-1}$	$1.30x10^{-1}$	0.54	0.54	0.54
8	$1.16x10^{-1}$	$1.01x10^{-1}$	$8.97x10^{-2}$	0.36	0.37	0.37
4	$5.82x10^{-2}$	$5.09x10^{-2}$	$4.60x10^{-2}$	0.18	0.19	0.19
			High Flow, 95TH percentile release concentration			
24	$5.19x10^{-2}$	$3.65x10^{-2}$	$3.13x10^{-2}$	1.00	1.00	1.00
12	$2.68x10^{-2}$	$2.06x10^{-2}$	$1.69x10^{-2}$	0.52	0.56	0.54
8	$1.76x10^{-2}$	$1.51x10^{-2}$	$1.16x10^{-2}$	0.34	0.41	0.37
4	$8.64x10^{-3}$	$8.70x10^{-3}$	$6.10x10^{-3}$	0.17	0.24	0.19
			Low Flow, 5TH percentile release concentration			
24	$1.17x10^{-1}$	$1.00x10^{-1}$	$8.94x10^{-2}$	1.00	1.00	1.00
12	$6.30x10^{-2}$	$5.42x10^{-2}$	$4.84x10^{-2}$	0.54	0.54	0.54
8	$4.23x10^{-2}$	$3.68x10^{-2}$	$3.29x10^{-2}$	0.36	0.37	0.37
4	$2.14x10^{-2}$	$1.87x10^{-2}$	$1.70x10^{-2}$	0.18	0.19	0.19
			High Flow, 5TH percentile release concentration			
24	$1.90x10^{-2}$	$1.35x10^{-2}$	$1.16x10^{-2}$	1.00	1.00	1.00
12	$9.82x10^{-3}$	$7.56x10^{-3}$	$6.26x10^{-3}$	0.52	0.56	0.54
8	$6.45x10^{-3}$	$5.54x10^{-3}$	$4.30x10^{-3}$	0.34	0.41	0.37
4	$3.15x10^{-3}$	$3.20x10^{-3}$	$2.22x10^{-3}$	0.17	0.24	0.19

[(a)]The Average Bromide Concentration Reduction factor is the ratio of the average bromide concentration in the reduced pulse-duration to that of average bromide concentration in the 24-hour simulation.

Table S7. Discharge, average parameters and the estimated lateral mixing coefficient and initial mixing distance from the method developed by Yotsukura and Cobb (1972) and Kilpatrick and Wilson (1989). The transverse mixing coefficient is estimated in units of ft^2/s from $\boldsymbol{K_z = 1.13\, d^{1.5} s^{0.5}}$ where d is the average depth in feet and s is the slope of the water surface, which is approximated by the channel bed slope in the table.

Date	Discharge (m3/s)	Mean velocity (m/s)	Width (m)	Mean depth (m)	Slope (m/m)	Transverse mixing coefficient (m^2/s)	Initial mixing distance (km)			
							Injection point location and coefficient K from Kilpatrick and Wilson (1989)			
							x10dge (0.4)	Centerline (0.1)	Two (a) (0.025)	Three (b) (0.011)
					Franklin, PA					
8/13/2013	80.1	0.406	206	0.963	0.000566	0.014	490	120	31	13
6/10/2014	286	0.792	168	2.16	0.000566	0.047	190	47	12	5
4/18/2013	725	1.37	184	2.86	0.000566	0.072	260	65	16	7
3/15/2011	1540	1.71	239	3.75	0.000566	0.11	360	91	23	10
					Parker, PA					
7/16/2012	90.3	0.418	230	0.936	0.000511	0.013	690	170	43	19
10/21/2014	294	0.954	238	1.3	0.000511	0.021	1030	260	65	28
5/5/2011	946	1.45	256	2.55	0.000511	0.057	660	170	41	18
					Kittanning, PA					
8/9/2012	107	0.144	251	2.94	0.000767	0.087	42	10	3	1
5/21/2014	1130	0.99	258	4.43	0.000767	0.16	160	40	10	5
3/11/2011	3270	1.74	284	6.63	0.000767	0.3	190	47	12	5

(a) The injection is made at the center of each half of flow
(b) The injection is made at the center of each third of flow

Table S8. Summary of peak concentration, average concentration and peak-to-average concentration ratios at Kittanning for the 5-day sequence of pulse releases of the 95th-percentile Produced-ME water effluent discharge in the Allegheny River.

Duration	*Minimum*	*Percentiles*					*Maximum*
		5th	*25th*	*50th*	*75th*	*95th*	
				Peak Concentration (mg/L) Low Flow			
4 hr	7.72×10^{-3}	3.35×10^{-2}	6.54×10^{-2}	1.02×10^{-1}	1.49×10^{-1}	2.40×10^{-1}	5.39×10^{-1}
8 hr	1.42×10^{-2}	5.25×10^{-2}	1.15×10^{-1}	1.78×10^{-1}	2.60×10^{-1}	4.12×10^{-1}	8.14×10^{-1}
12 hr	1.03×10^{-2}	6.18×10^{-2}	1.57×10^{-1}	2.35×10^{-1}	3.32×10^{-1}	5.48×10^{-1}	9.11×10^{-1}
				Average Concentration (mg/L), Low Flow			
4 hr	1.86×10^{-3}	1.12×10^{-2}	3.13×10^{-2}	4.60×10^{-2}	6.48×10^{-2}	1.15×10^{-1}	1.55×10^{-1}
8 hr	5.56×10^{-3}	2.14×10^{-2}	6.07×10^{-2}	8.97×10^{-2}	1.26×10^{-1}	2.23×10^{-1}	3.12×10^{-1}
12 hr	5.65×10^{-3}	3.15×10^{-2}	8.87×10^{-2}	1.30×10^{-1}	1.85×10^{-1}	3.23×10^{-1}	4.42×10^{-1}
				Peak to Average Concentration Ratio, Low Flow			
4 hr	4.15	3.00	2.09	2.21	2.29	2.09	3.47
8 hr	2.55	2.45	1.89	1.98	2.06	1.85	2.61
12 hr	1.82	1.96	1.77	1.80	1.80	1.70	2.06
				Peak Concentration (mg/L) High Flow			
4 hr	1.40×10^{-5}	7.58×10^{-3}	1.43×10^{-2}	1.95×10^{-2}	2.68×10^{-2}	3.76×10^{-2}	8.53×10^{-2}
8 hr	4.32×10^{-5}	8.85×10^{-3}	2.05×10^{-2}	2.89×10^{-2}	3.97×10^{-2}	5.74×10^{-2}	1.22×10^{-1}
12 hr	6.44×10^{-6}	9.39×10^{-3}	2.22×10^{-2}	3.31×10^{-2}	4.56×10^{-2}	6.72×10^{-2}	1.41×10^{-1}
				Average Concentration (mg/L), High Flow			
4 hr	3.74×10^{-6}	1.90×10^{-3}	4.22×10^{-3}	6.10×10^{-3}	8.79×10^{-3}	1.25×10^{-2}	2.47×10^{-2}
8 hr	1.75×10^{-5}	3.36×10^{-3}	8.02×10^{-3}	1.16×10^{-2}	1.66×10^{-2}	2.33×10^{-2}	4.92×10^{-2}
12 hr	4.30×10^{-6}	5.01×10^{-3}	1.15×10^{-2}	1.69×10^{-2}	2.41×10^{-2}	3.33×10^{-2}	7.08×10^{-2}
				Peak to Average Concentration Ratio, High Flow			
4 hr	3.74	3.99	3.39	3.20	3.05	3.00	3.46
8 hr	2.46	2.63	2.56	2.49	2.40	2.46	2.47
12 hr	1.50	1.87	1.93	1.95	1.89	2.02	2.00

Table S9. Summary of peak concentration, average concentration and peak-to-average concentration ratios at Kittanning for the 5-day sequence of pulse releases of the 5th-percentile Produced-ME water effluent discharge in the Allegheny River.

Duration	*Minimum*	*Percentiles*					*Maximum*
		5th	*25th*	*50th*	*75th*	*95th*	
				Peak Concentration (mg/L) Low Flow			
4hr	4.69×10^{-3}	1.21×10^{-2}	2.40×10^{-2}	3.73×10^{-2}	5.43×10^{-2}	8.89×10^{-2}	1.98×10^{-1}
8hr	5.73×10^{-3}	1.95×10^{-2}	4.25×10^{-2}	6.51×10^{-2}	9.53×10^{-2}	1.52×10^{-1}	3.05×10^{-1}
12 hr	3.77×10^{-3}	2.25×10^{-2}	5.76×10^{-2}	8.65×10^{-2}	1.22×10^{-1}	1.99×10^{-1}	3.47×10^{-1}
				Average Concentration (mg/L), Low Flow			
4hr	1.29×10^{-3}	4.07×10^{-3}	1.15×10^{-2}	1.70×10^{-2}	2.40×10^{-2}	4.21×10^{-2}	6.45×10^{-2}
8hr	2.25×10^{-3}	7.93×10^{-3}	2.25×10^{-2}	3.29×10^{-2}	4.66×10^{-2}	8.22×10^{-2}	1.16×10^{-1}
12 hr	2.07×10^{-3}	1.15×10^{-2}	3.26×10^{-2}	4.84×10^{-2}	6.81×10^{-2}	1.18×10^{-1}	1.69×10^{-1}
				Peak to Average Concentration (mg/L) High Flow			
4hr	3.65	2.98	2.10	2.20	2.27	2.11	3.07
8hr	2.55	2.46	1.88	1.98	2.05	1.85	2.63
12 hr	1.82	1.96	1.77	1.79	1.79	1.68	2.06
				Peak Concentration (mg/L) High Flow			
4hr	4.20×10^{-5}	2.83×10^{-3}	5.18×10^{-3}	7.12×10^{-3}	9.82×10^{-3}	1.36×10^{-2}	3.24×10^{-2}
8hr	1.19×10^{-5}	3.40×10^{-3}	7.53×10^{-3}	1.07×10^{-2}	1.47×10^{-2}	2.11×10^{-2}	4.68×10^{-2}
12 hr	3.43×10^{-5}	3.31×10^{-3}	8.13×10^{-3}	1.22×10^{-2}	1.67×10^{-2}	2.46×10^{-2}	5.27×10^{-2}
				Average Concentration (mg/L), High Flow			
4hr	1.12×10^{-5}	7.00×10^{-4}	1.54×10^{-3}	2.22×10^{-3}	3.23×10^{-3}	4.57×10^{-3}	9.32×10^{-3}
8hr	5.60×10^{-6}	1.29×10^{-3}	2.93×10^{-3}	4.30×10^{-3}	6.09×10^{-3}	8.55×10^{-3}	1.87×10^{-2}
12 hr	1.95×10^{-5}	1.76×10^{-3}	4.23×10^{-3}	6.26×10^{-3}	8.78×10^{-3}	1.23×10^{-2}	2.62×10^{-2}
				Peak to Average Concentration Ratio, High Flow			
4hr	3.73	4.04	3.36	3.20	3.04	2.98	3.47
8hr	2.13	2.64	2.57	2.49	2.41	2.47	2.50
12 hr	1.76	1.88	1.92	1.96	1.90	2.01	2.01

Table S10. Summary of peak concentration, average concentration and peak-to-average concentration ratios at Kittanning for the 5-day sequence of pulse releases of the 95th-percentile Lower Flowback effluent discharge in the Allegheny River.

Duration	*Minimum*	*Percentiles*					*Maximum*
		5th	*25th*	*50th*	*75th*	*95th*	
				Peak Concentration (mg/L) Low Flow			
4 hr	1.23×10^{-3}	3.17×10^{-3}	6.28×10^{-3}	9.67×10^{-3}	1.42×10^{-2}	2.30×10^{-2}	5.15×10^{-2}
8 hr	8.61×10^{-4}	5.05×10^{-3}	1.10×10^{-2}	1.70×10^{-2}	2.49×10^{-2}	3.93×10^{-2}	7.98×10^{-2}
12 hr	1.32×10^{-3}	5.93×10^{-3}	1.50×10^{-2}	2.26×10^{-2}	3.17×10^{-2}	5.22×10^{-2}	8.69×10^{-2}
				Average Concentration (mg/L), Low Flow			
4 hr	3.06×10^{-4}	1.06×10^{-3}	3.03×10^{-3}	4.45×10^{-3}	6.28×10^{-3}	1.11×10^{-2}	1.51×10^{-2}
8 hr	3.38×10^{-4}	2.09×10^{-3}	5.90×10^{-3}	8.65×10^{-3}	1.22×10^{-2}	2.14×10^{-2}	3.08×10^{-2}
12 hr	7.26×10^{-4}	3.02×10^{-3}	8.57×10^{-3}	1.27×10^{-2}	1.77×10^{-2}	3.11×10^{-2}	4.26×10^{-2}
				Peak to Average Concentration (mg/L) High Flow			
4 hr	4.04	2.99	2.08	2.17	2.26	2.07	3.40
8 hr	2.55	2.41	1.86	1.96	2.04	1.84	2.60
12 hr	1.82	1.97	1.75	1.78	1.80	1.68	2.04
				Peak Concentration (mg/L) High Flow			
4 hr	1.39×10^{-6}	7.32×10^{-4}	1.35×10^{-3}	1.87×10^{-3}	2.57×10^{-3}	3.55×10^{-3}	8.42×10^{-3}
8 hr	5.61×10^{-6}	8.68×10^{-4}	1.97×10^{-3}	2.79×10^{-3}	3.81×10^{-3}	5.54×10^{-3}	1.18×10^{-2}
12 hr	6.59×10^{-6}	8.37×10^{-4}	2.12×10^{-3}	3.18×10^{-3}	4.37×10^{-3}	6.42×10^{-3}	1.32×10^{-2}
				Average Concentration (mg/L), High Flow			
4 hr	1.24×10^{-6}	1.84×10^{-4}	4.02×10^{-4}	5.85×10^{-4}	8.41×10^{-4}	1.19×10^{-3}	2.43×10^{-3}
8 hr	3.20×10^{-6}	3.27×10^{-4}	7.67×10^{-4}	1.13×10^{-3}	1.60×10^{-3}	2.26×10^{-3}	4.69×10^{-3}
12 hr	4.40×10^{-6}	4.48×10^{-4}	1.10×10^{-3}	1.64×10^{-3}	2.30×10^{-3}	3.24×10^{-3}	6.71×10^{-3}
				Peak to Average Concentration Ratio, High Flow			
4 hr	1.12	3.97	3.36	3.20	3.06	2.98	3.46
8 hr	1.75	2.66	2.57	2.47	2.38	2.45	2.51
12 hr	1.50	1.87	1.91	1.94	1.90	1.98	1.96

Table S11. Summary of peak concentration, average concentration and peak-to-average concentration ratios at Kittanning for the 5-day sequence of pulse releases of the 5th-percentile Lower Flowback effluent discharge in the Allegheny River.

Duration	Minimum	Percentiles					Maximum
		5th	25th	50th	75th	95th	
				Peak Concentration (mg/L) Low Flow			
4 hr	2.70×10^{-4}	7.10×10^{-4}	1.41×10^{-3}	2.19×10^{-3}	3.21×10^{-3}	5.15×10^{-3}	1.08×10^{-2}
8 hr	2.78×10^{-4}	1.12×10^{-3}	2.50×10^{-3}	3.79×10^{-3}	5.51×10^{-3}	8.92×10^{-3}	1.79×10^{-2}
12 hr	4.39×10^{-4}	1.32×10^{-3}	3.33×10^{-3}	5.03×10^{-3}	7.10×10^{-3}	1.19×10^{-2}	1.98×10^{-2}
				Average Concentration (mg/L), Low Flow			
4 hr	6.75×10^{-5}	2.42×10^{-4}	6.91×10^{-4}	1.01×10^{-3}	1.42×10^{-3}	2.50×10^{-3}	3.38×10^{-3}
8 hr	1.09×10^{-4}	4.66×10^{-4}	1.34×10^{-3}	1.96×10^{-3}	2.76×10^{-3}	4.87×10^{-3}	6.85×10^{-3}
12 hr	2.41×10^{-4}	6.81×10^{-4}	1.93×10^{-3}	2.86×10^{-3}	4.02×10^{-3}	7.08×10^{-3}	9.77×10^{-3}
				Peak to Average Concentration (mg/L) High Flow			
4 hr	4.00	2.93	2.03	2.18	2.27	2.06	3.19
8 hr	2.54	2.40	1.87	1.94	2.00	1.83	2.61
12 hr	1.82	1.94	1.72	1.76	1.77	1.68	2.03
				Peak Concentration (mg/L) High Flow			
4 hr	2.86×10^{-6}	1.66×10^{-4}	3.03×10^{-4}	4.22×10^{-4}	5.81×10^{-4}	8.10×10^{-4}	1.86×10^{-3}
8 hr	3.56×10^{-6}	1.93×10^{-4}	4.39×10^{-4}	6.25×10^{-4}	8.50×10^{-4}	1.22×10^{-3}	2.80×10^{-3}
12 hr	1.03×10^{-6}	1.92×10^{-4}	4.76×10^{-4}	7.13×10^{-4}	9.75×10^{-4}	1.44×10^{-3}	3.02×10^{-3}
				Average Concentration (mg/L), High Flow			
4 hr	1.49×10^{-6}	4.22×10^{-5}	9.13×10^{-5}	1.33×10^{-4}	1.93×10^{-4}	2.69×10^{-4}	5.42×10^{-4}
8 hr	1.97×10^{-6}	7.36×10^{-5}	1.72×10^{-4}	2.55×10^{-4}	3.65×10^{-4}	5.11×10^{-4}	1.07×10^{-3}
12 hr	1.03×10^{-6}	4.94×10^{-5}	1.26×10^{-4}	2.00×10^{-4}	3.08×10^{-4}	4.40×10^{-4}	8.96×10^{-4}
				Peak to Average Concentration Ratio, High Flow			
4 hr	1.92	3.93	3.32	3.17	3.01	3.01	3.44
8 hr	1.80	2.62	2.55	2.45	2.33	2.40	2.61
12 hr	1.00	3.89	3.78	3.57	3.16	3.28	3.37

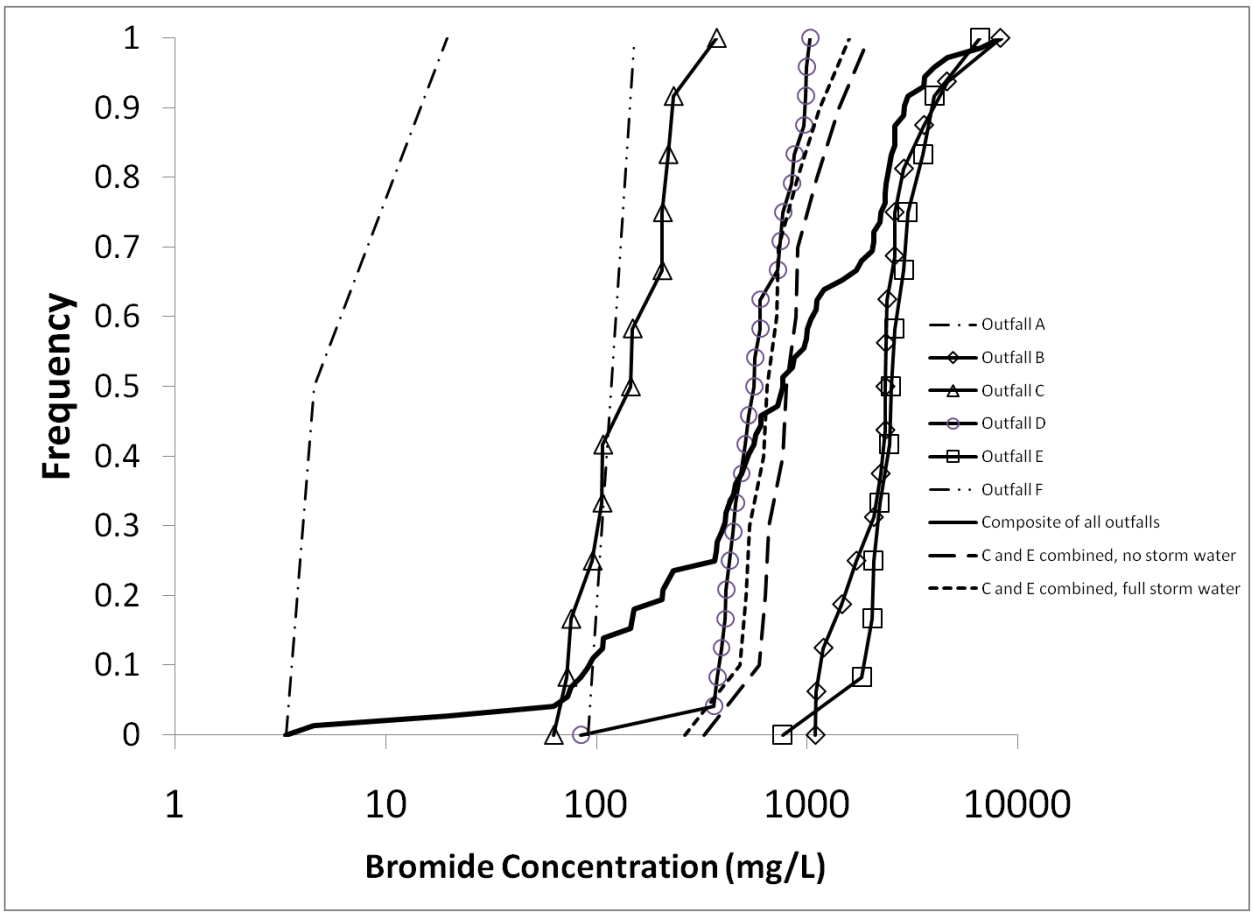

Figure S1. Frequency of bromide from outfalls with NPDES-reported data with non-Marcellus shale data collected after 9/2011 included. The composite frequency distribution from all plants is shown as a solid line without symbols. Outfalls A (dot-dash) and F (dot-dot-dash) had limited data on plant operation and were not used in scenarios. Outfalls C (triangles) and outfall E (squares) discharged treated flowback and produced water, respectively. These two were monitored separately but were combined at the point of discharge, with either no storm water (short dash) or with a design maximum of 59.1 m3/s (long dash). Outfall D (circles) discharged similar concentrations to the combined flowback and produced water of C & E. Outfall B (diamonds) discharged similarly to the treated produced water from outfall E.

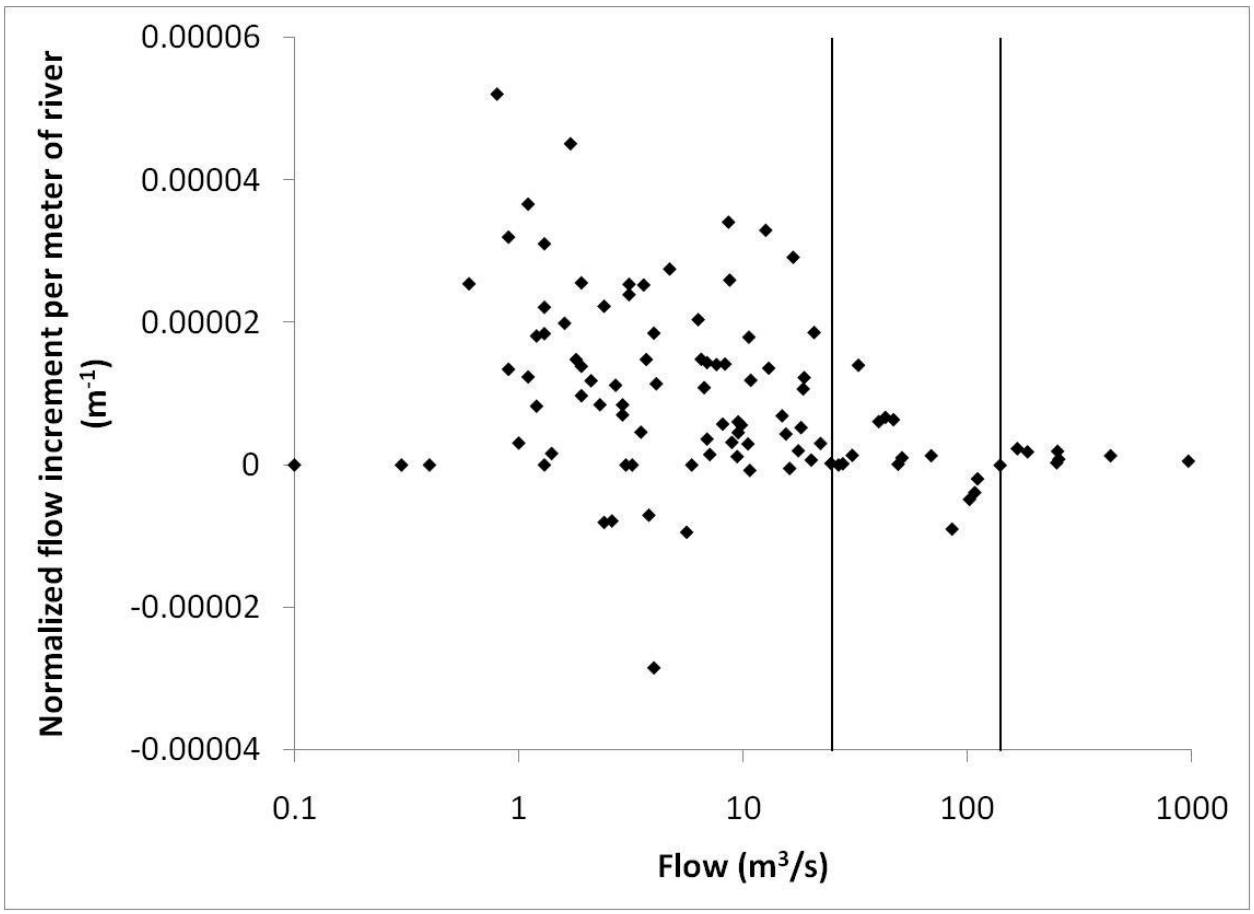

Figure S2. Normalized flow increment per meter of river as a function of flow rate. Approximate break points for Monte Carlo simulation increments are indicated for flows of 25 m^3/s and 140 m^3/s.

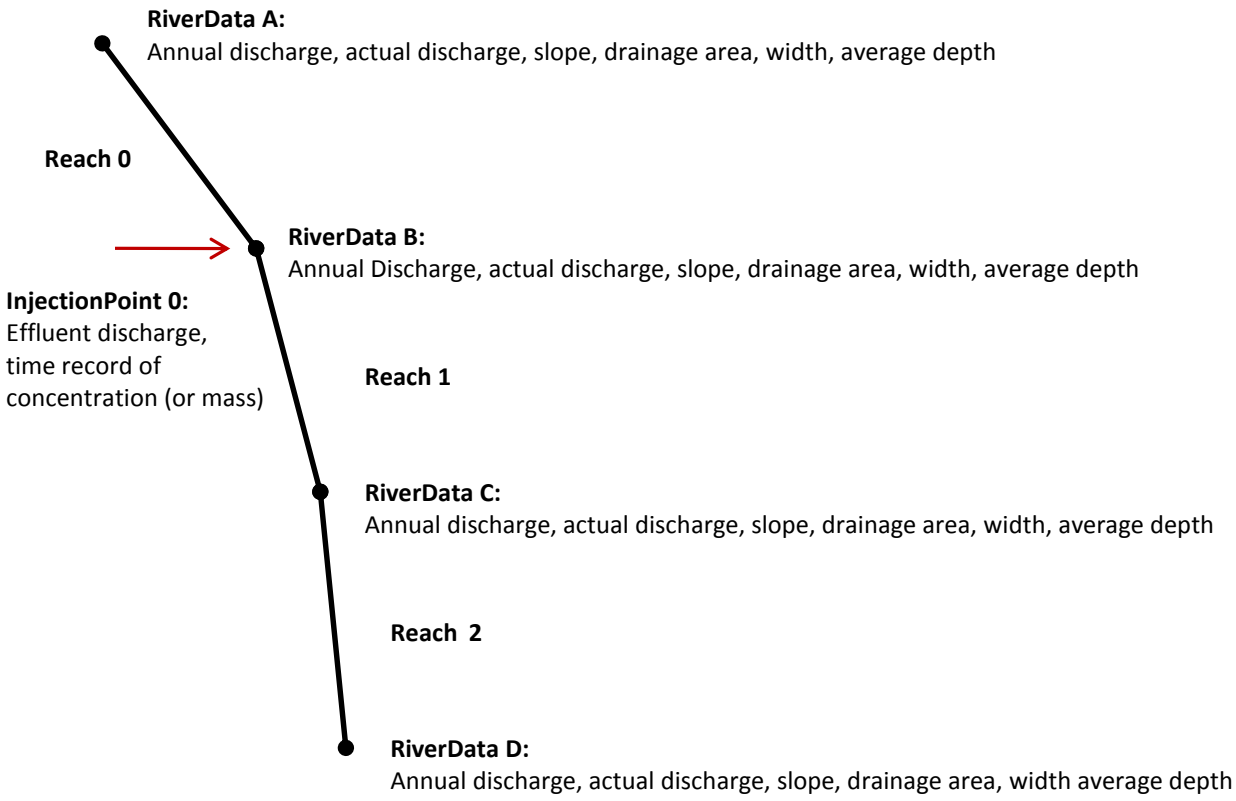

Figure S3. Data relationships in the empirical and numerical models. River reaches are constructed from contributing upstream and downstream reaches. River properties are contained in RiverData objects, which are assigned to upstream and downstream ends of reaches. Injection points are always located at the downstream end of a reach.

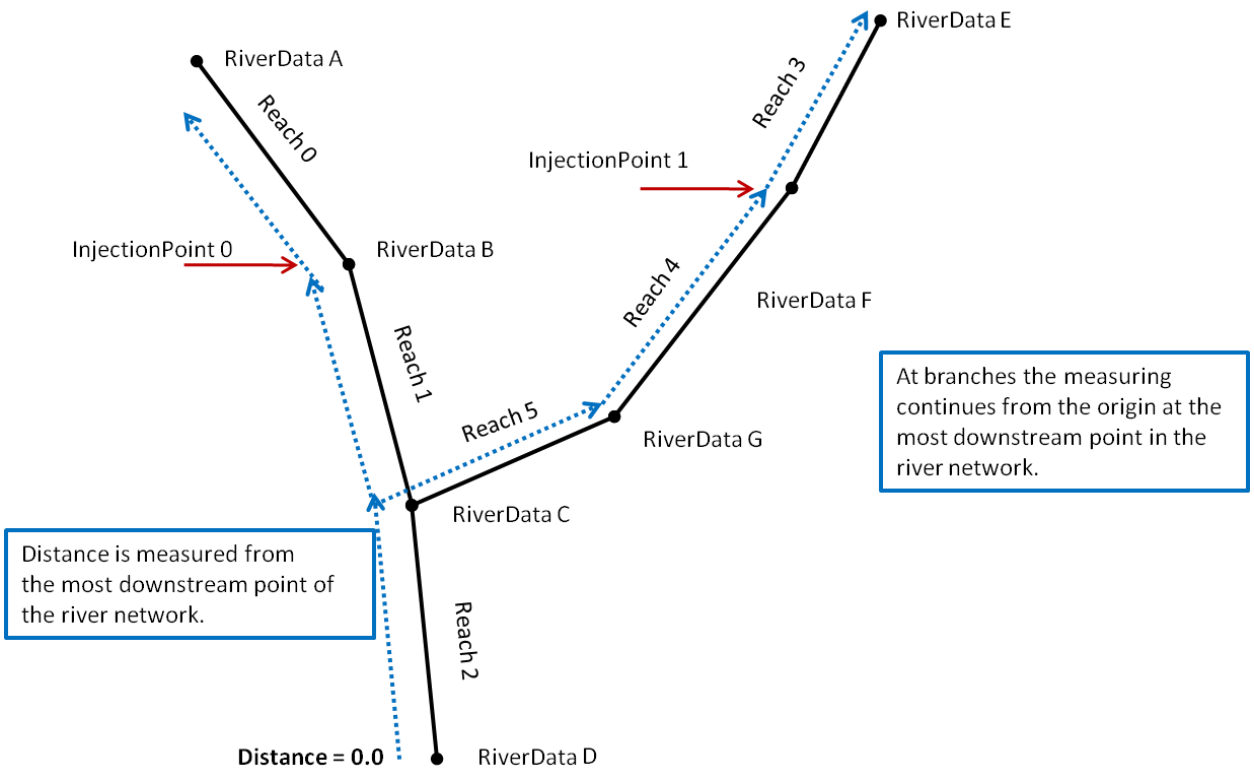

Figure S4. All distances in the models are measured from the most downstream point in the network. Measurement of distance along branches continues using the most downstream point of the entire network as the origin.

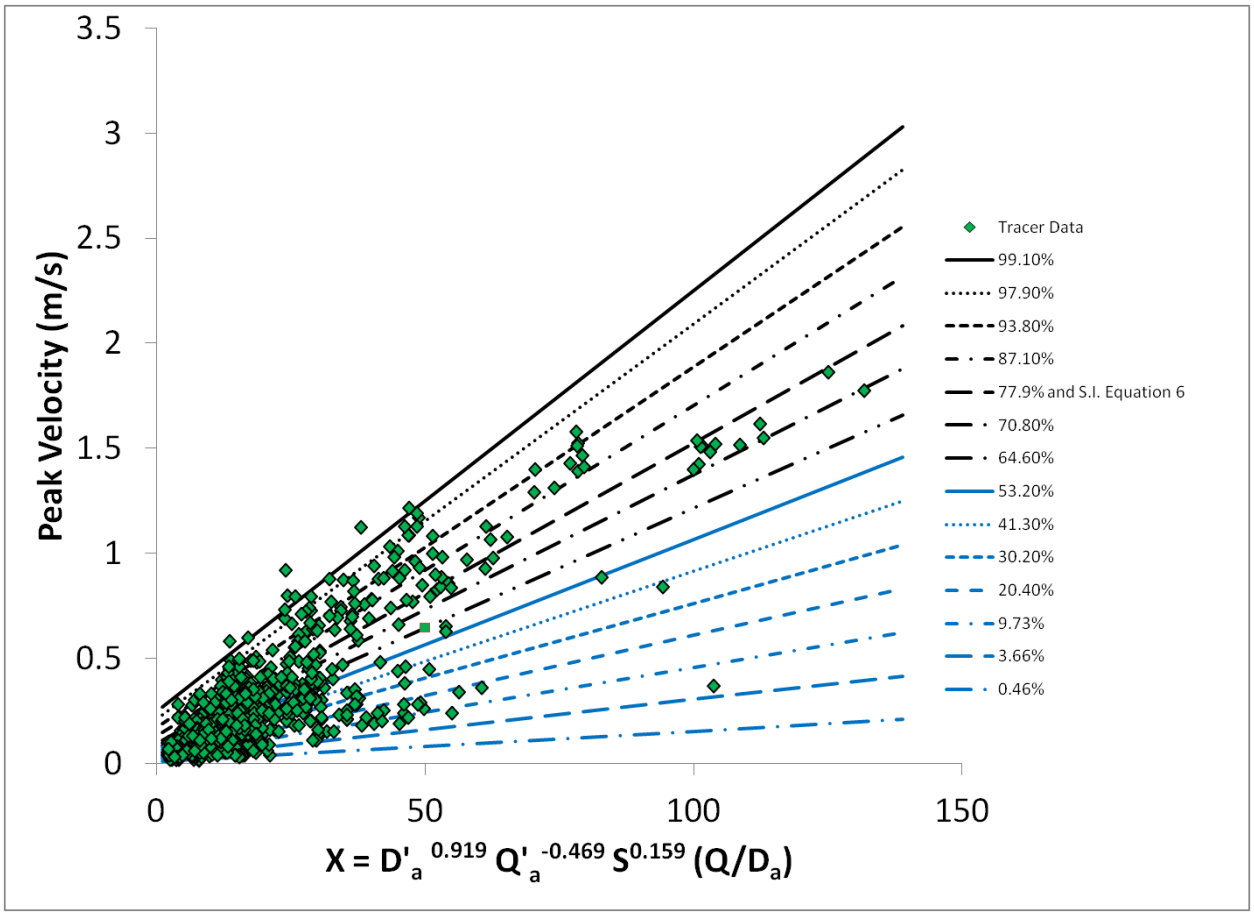

Figure S5. Peak velocity from Jobson (1996) data analysis. The lines drawn on the figure indicate Jobson's bounding (Jobson equation 13) and best fit (equation 12) regression lines, along with a set of regression lines constructed to provide a cumulative frequency distribution. The percentages give the cumulative percent of the data points lying below the line.

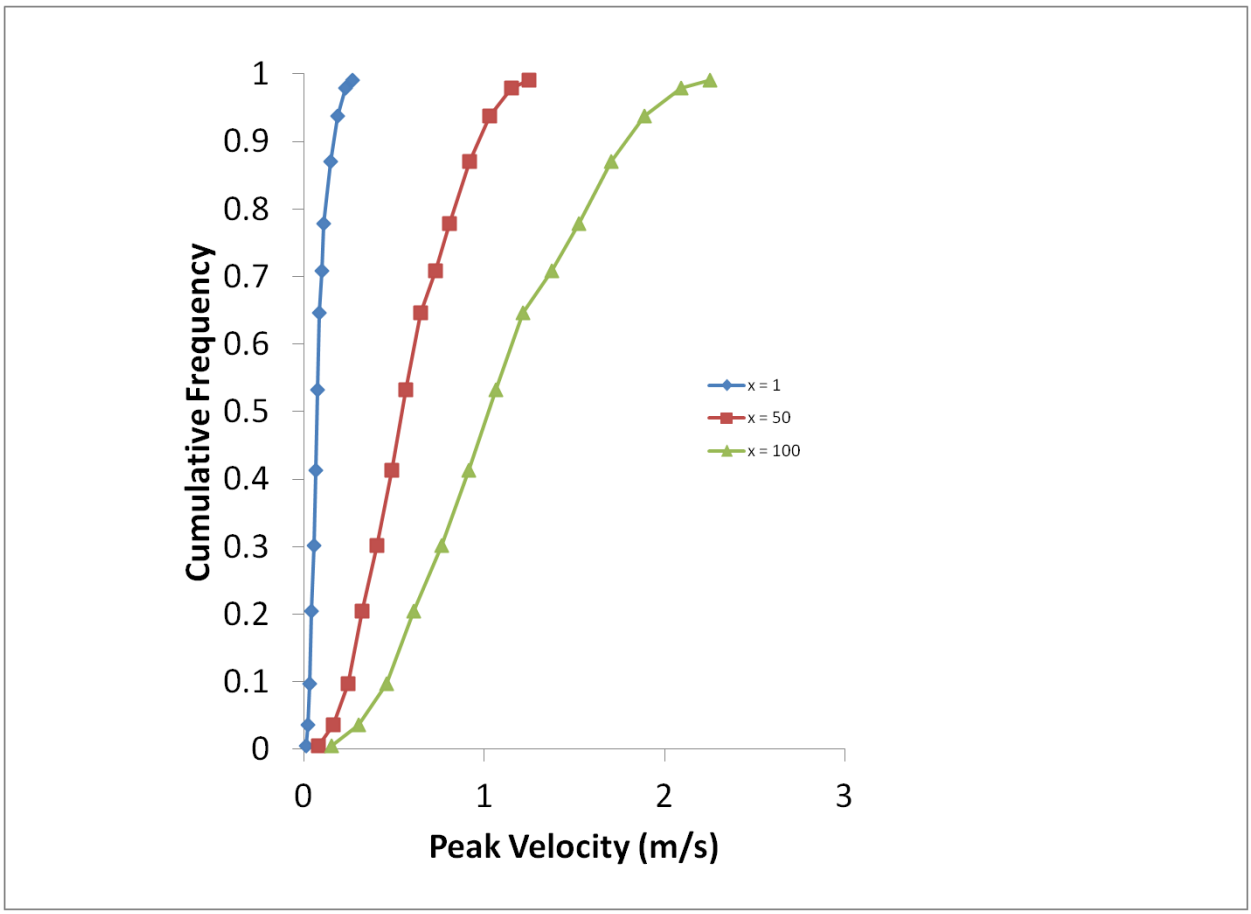

Figure S6. Cumulative frequency curves for peak velocity as parameterized by the quantity x, which is equal to $\mathbf{D_a'}^{0.919}\mathbf{Q_a'}^{-0.469}\mathbf{S}^{0.159}\frac{\mathbf{Q}}{\mathbf{D_a}}$.

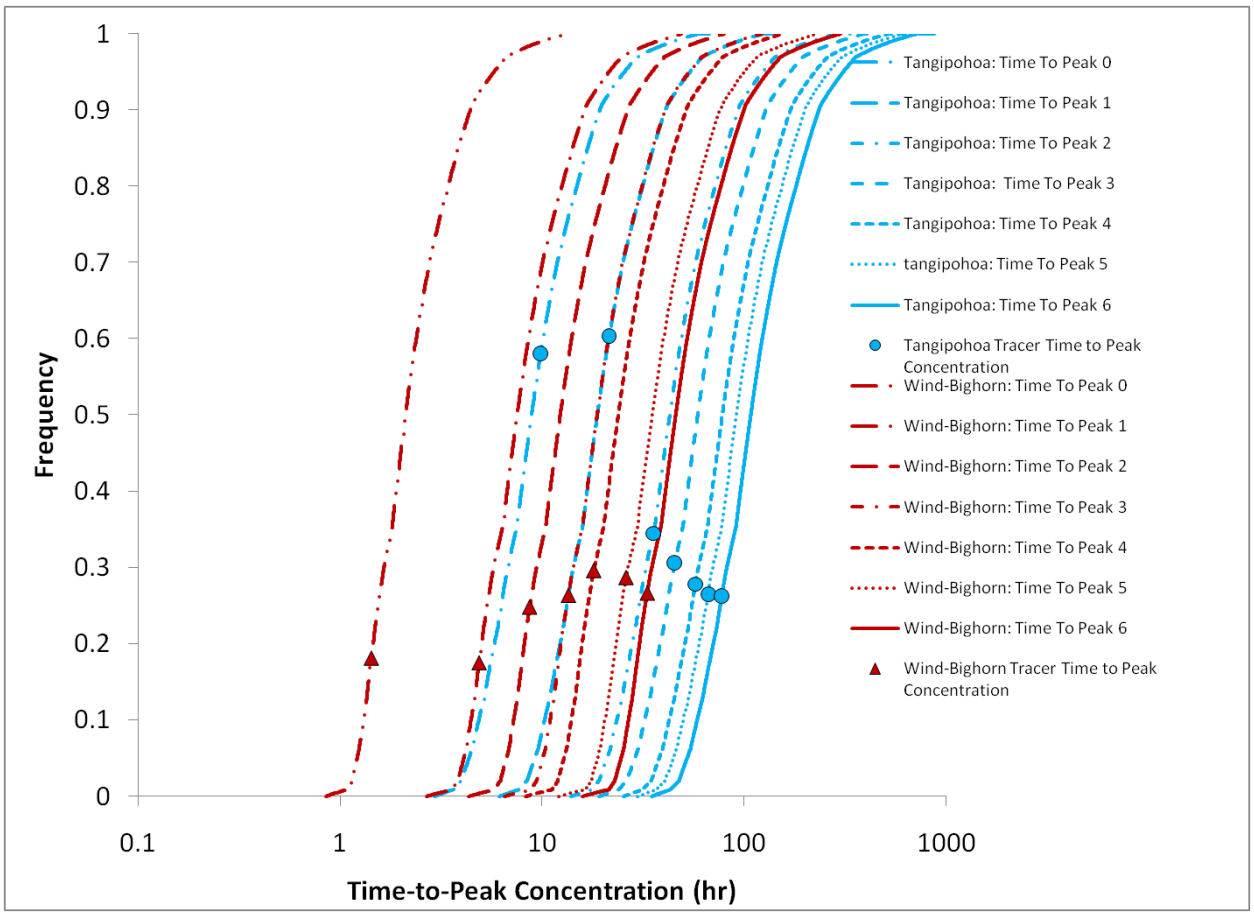

Figure S7. Peak arrival times for tracer experiments in the Tangipohoa River (circles) and the Wind-Bighorn River (triangles), plotted against the frequency distributions from the model.

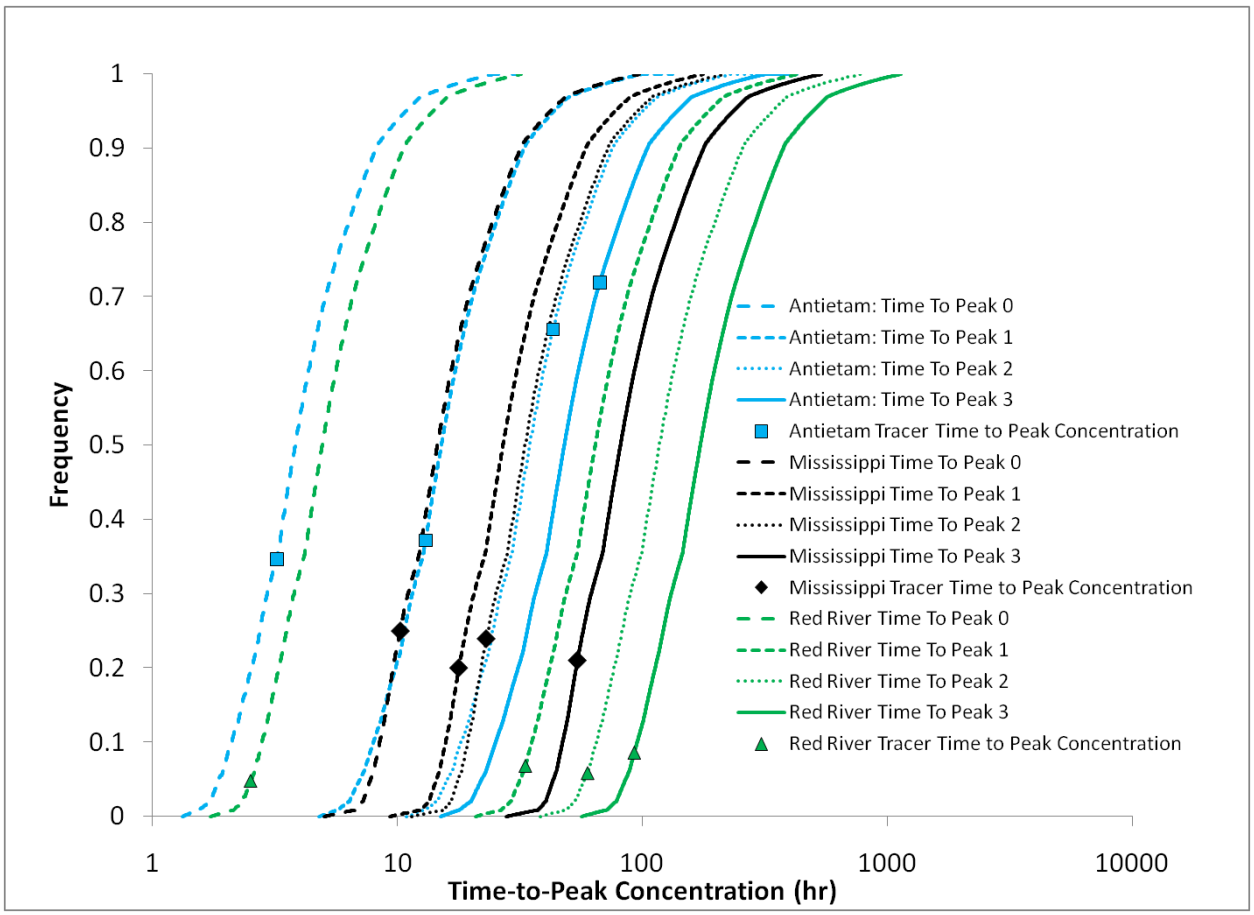

Figure S8. Peak arrival times for tracer experiments in Antietam Creek (squares), the Red River (triangles), and the Mississippi River (diamonds), plotted against the frequency distributions from the model.

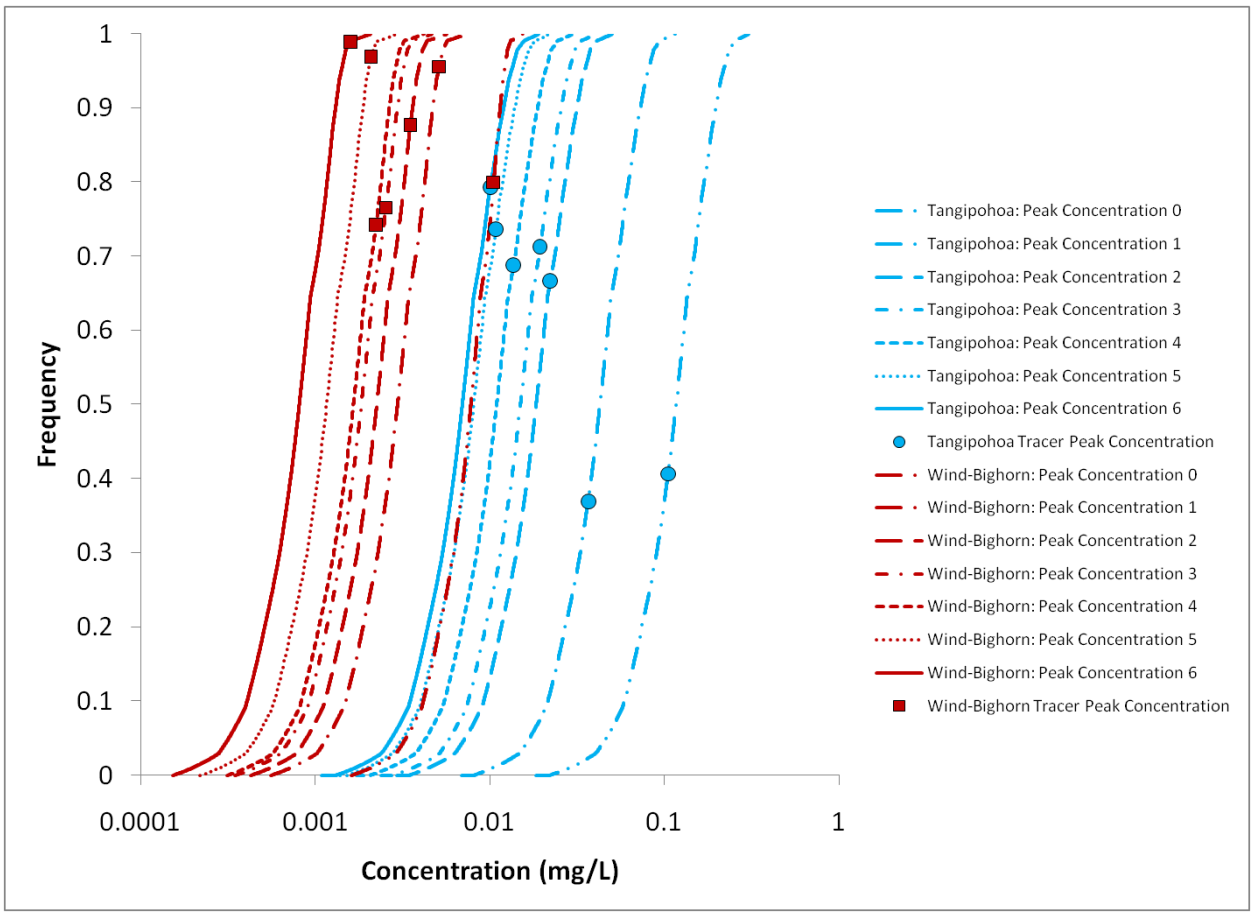

Figure S9. Peak concentrations for tracer experiments in the Tangipohoa River (circles) and the Wind-Bighorn River (triangles), plotted against the frequency distributions from the model.

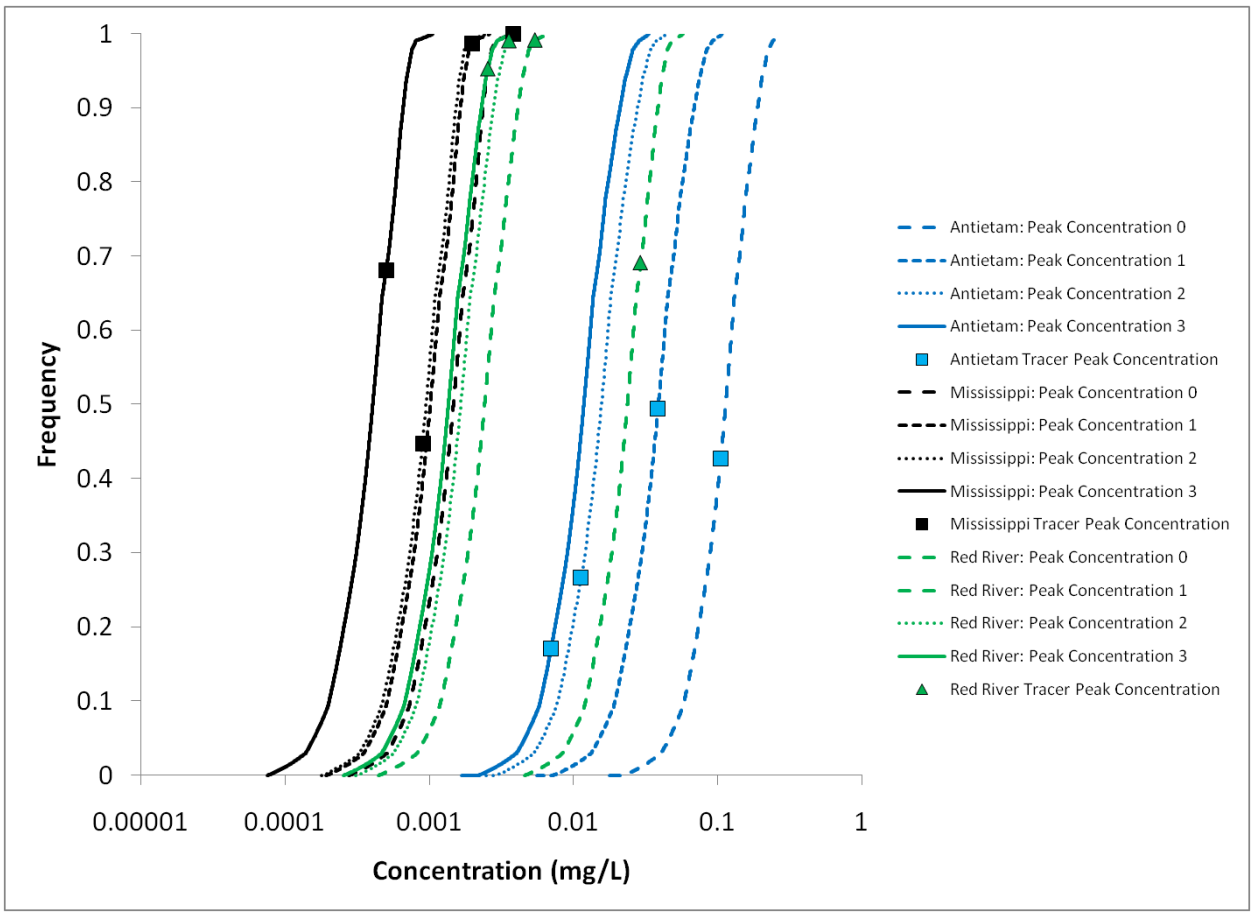

Figure S10. Peak concentrations for tracer experiments in Antietam Creek (squares), the Red River (triangles), and the Mississippi River (squares), plotted against the frequency distributions from the model.

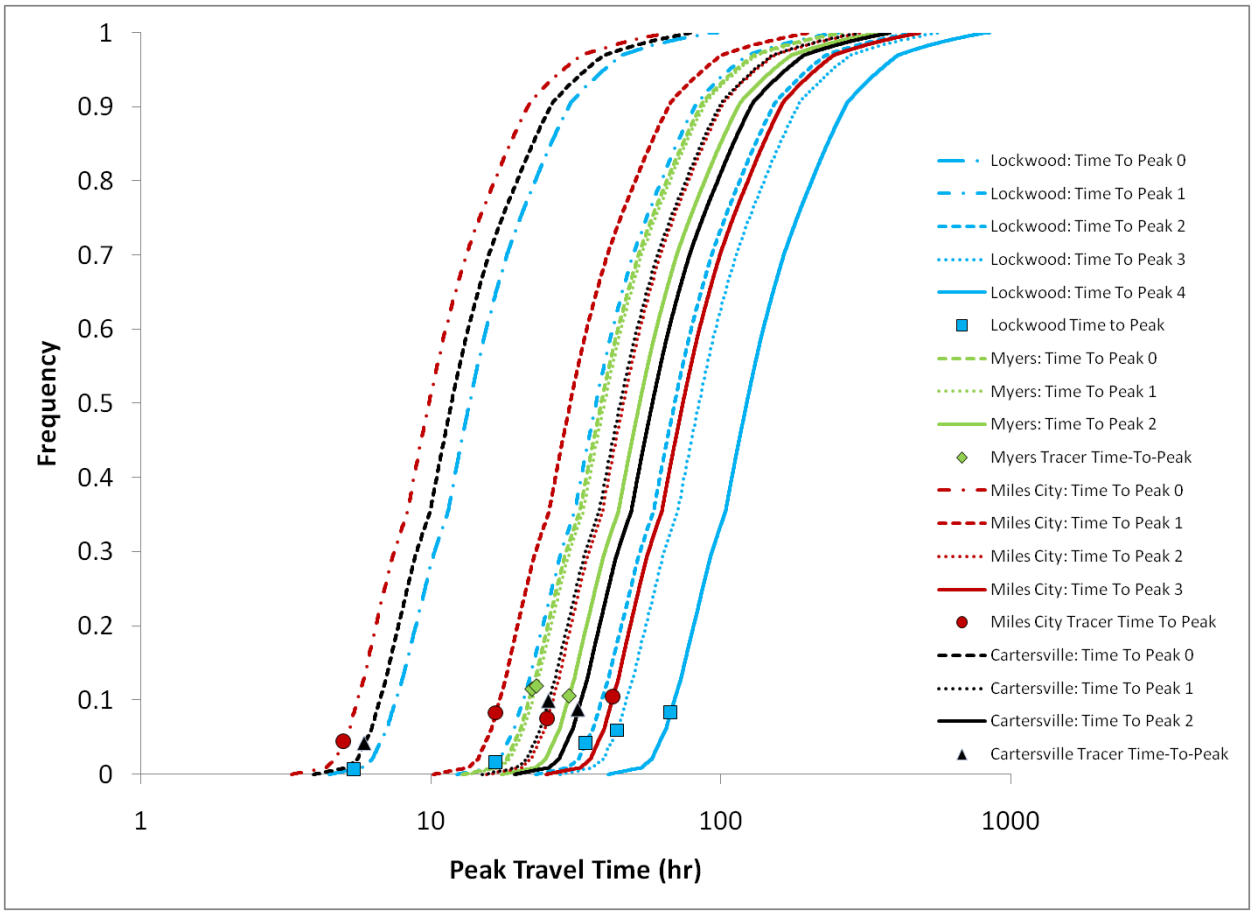

Figure S11. Yellowstone River tracer time-to-peak plotted against the model frequency distribution for releases at Lockwood Bridge (squares), Myers Bridge (diamonds), Miles City Bridge(circles), and Cartersville Dam (triangles).

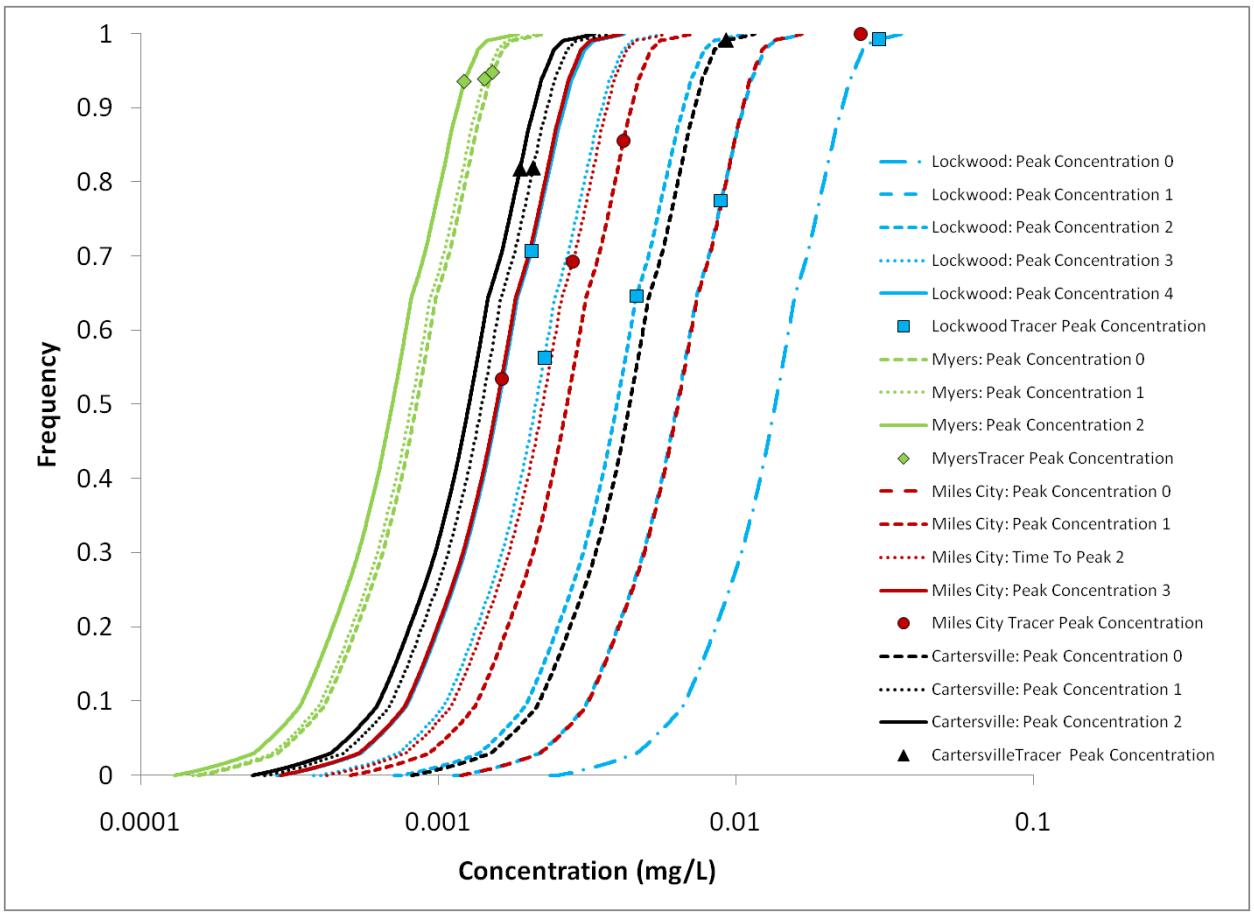

Figure S12. Yellowstone River tracer peak concentrations plotted against the model frequency distribution for releases at Lockwood Bridge (squares), Myers Bridge (diamonds), Miles City Bridge(circles), and Cartersville Dam (triangles).