FRAMES Overview

The Framework for Aquatic Modeling in the Earth System (FrAMES) was designed for coupled simulations of hydrology and biogeochemistry. FrAMES uses the Water Transport Model for flow propagation through the Simulated Topological Network (STN). We used the STN representing the river network of the study domain of a geographic resolution of 45 arc seconds (approximately 1.5 km resolution). Daily gridded precipitation and air temperature data were acquired from NASA's Global Modeling and Assimilation Office (Modern Era- Retrospective Analysis for Research and Applications, or MERRA).

The cross-sectional channel shape of a stream is governed by at-a-site and downstream hydraulic geometry [1]. Hydraulic geometry that influence residence time and exchange with sediments, and hence removal, were estimated based on empirical functions of width, depth and velocity vs. discharge. Simulated discharge to calculate river channel dimensions with downstream and at-a-site power law relationships [2]. Hydraulic dimensions change with discharge both at-a-site, and in the downstream direction [3]. In the downstream direction, mean annual channel width (W_a, m), depth (D_a, m), and velocity (V_a, m s^{-1}) in river stream reach i were calculated from the relationship with mean annual discharge (Q_a) developed by Stewart et al. (2011) [4]:

$$W_a = 9.56Q_a^{0.65} \quad \text{(S1)}$$

$$D_a = 0.45Q_a^{0.17} \quad \text{(S2)}$$

$$V_a = 0.23Q_a^{0.18} \quad \text{(S3)}$$

Instantaneous channel width, depth, and velocity in stream reach *i* (w_i, d_i, *and* v_i,) at each time step are based on the at-a-site power relationship with instantaneous discharge (q_i, m^3s^{-1}):

$$w_i = a_i q_i^{\,x} \quad \text{(S4)}$$

$$d_i = b_i q_i^{\,y} \quad \text{(S5)}$$

$$v_i = c_i q_i^{\,z} \quad \text{(S6)}$$

where $a_i = W_a/Q_a^x$, $b_i = D_a/Q_a^y$, and $ci = V_a/Q_a^z$. The values for *x*, *y*, *and z* are 0.1, 0.4, and 0.5 [5], respectively, and are typical for rivers worldwide [1,6].

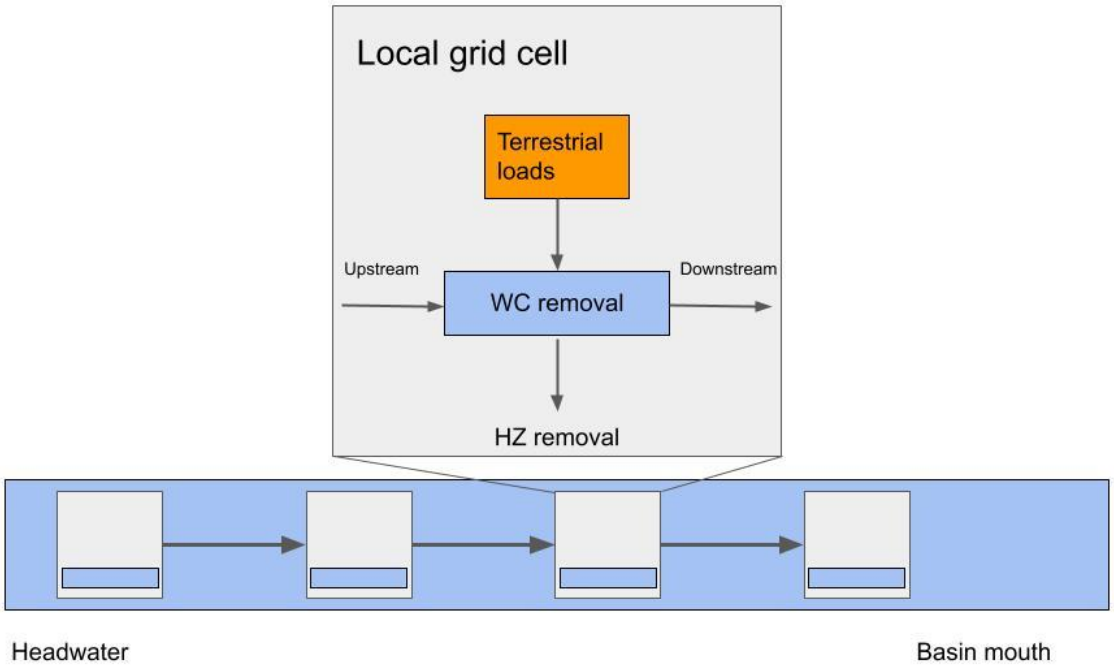

Figure S1. The conceptual model of the *E. coli* fate and transport in the FrAMES model.

Table S1. Characteristics of study watersheds.

Watershed	Area (km^2)	Developed (%)	Forest (%)	Other (%)	Average summer daily runoff[a] (mm/d)	Skewness index
Winnicut R.	40	28	31	41	0.77	1.06
Oyster R.	44	18	55	27	0.71	0.77
Ipswich R.	403	36	35	29	0.78	1.09
Cocheco R.	456	10	65	25	0.93	0.72
Lamprey R.	551	14	61	24	0.66	0.89
Merrimack R.	11996	13	68	19	1.19	0.64
Penobscot R.	22691	2	67	30	1.65	0.56

[a] Based on USGS gauges between 2011 and 2015.

Table S2. Comparison of *E. coli* loading function.

Study	Independent variables	Dependent variable	R^2
Strauch et al. 2014 [7]	% forest cover and mean annual rainfall	Monthly log-transformed *E. coli* yield (*E. coli* *discharge, MPN s^{-1} km^{-2})	0.62
Islam et al. 2017 [8]	Water temperature and precipitation	log transformed monthly mean *E. coli*	0.46
Chen and Chang, 2014 [9]	Precipitation, TSS, and temperature	log transformed seasonal mean *E. coli*	0.27- 0.61

Table S3. A priori parameter values for the FrAMES-*Ecoli* module.

Parameter	Value	Unit	Reference
Water Column *E. coli* die-off rate (K_{20})	0.8	d^{-1}	Mancini (1978) [**Error! Reference source not found.**]
Hyporheic exchange coefficient (α_{HZ})	$9.5*10^{-6}$	s^{-1}	Briggs et al. (2010) [11]
Temperature adjustment factor (θ)	1.07	Dimensionless	Mancini (1978) [**Error! Reference source not found.**]
The proportional removal of *E. coli* in HZ (R_{HZ})	1	Dimensionless	Assumption of this study.

Table S4. Sensitivity analysis of parameter impacts to WC, HZ, and total *E. coli* removal by the Oyster R. network compared to the Base scenario as defined in Table S3 (α_{HZ}: exchange coefficient, A_{cross} (width*depth): cross-sectional

area, θ: temperature adjustment factor, R_{HZ}: the proportional removal of *E. coli* in the HZ, and K_{20}: die-off rate at 20 °C).

	WC (%)	**HZ (%)**	**Total (%)**
Base values	6	20	26
A_{cross} +25%	6	23	29
A_{cross} -25%	4	15	19
α_{HZ} +25%	4	23	27
α_{HZ} -25%	7	16	23
R_{HZ} -25%	7	16	23
K_{20} +25%	8	19	27
K_{20} -25%	5	20	25
θ=1.12	3	21	24
θ=1.02	16	17	33

Table S5. *E. coli* removal parameters included in previous studies.

Study	**Scale**	**Model(s)**	**Temperature**	**Predation**	**Nutrient**	**Solar radiation**
Cho et al. (2012) [12]	Watershed	Modified SWAT	Yes	No	No	Yes
Drummond et al. (2015) [13]	Stream reach	A numerical model developed by the study	Yes	No	No	No
Surbeck et al. (2010) [14]	Microcosm	Spearman's rank correlation	Yes	Yes	Yes	No
Iudicello & Chin (2015) [15]	Watershed	SWAT and HSPF	Yes	No	No	No
Niazi et al. (2015) [16]	Watershed	SWAT	Yes	No	No	No

Whitehead et al. (2016) [17]	Watershed	INCA Model	Yes	No	No	Yes
Kim et al. (2017) [18]	Watershed	Modified SWAT	Yes	No	No	No
Reder et al. (2015) [19]	Large watershed	WorldQual	Yes	No	No	Yes
Kondo et al. (2021) [20]	Watershed	SWAT	Yes	No	No	No
Sowah et al. (2020) [21]	Watershed	SWAT	Yes	No	No	No

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