Supporting Information for "A unifying model for hyporheic oxygen mass transfer under a wide range of near-bed hydrodynamic conditions"

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SI1: Numerical model verification for result independence

The model using SA-IDDES was validated and compared against Smagorinsky LES model in OpenFOAM by simulating five-layer low-Re case in Manes et al. (2009). Three different mesh resolutions, DES1 with 4.8 million cells, DES1p33 with 12.1 million cells (1.33x finer than DES1) and LES2 with 40.5 million cells (2x finer than DES1), were performed in the domain of $L \times W = 30D \times 15D$ in the depth of $H_w = 1.67D$ and $H_b = 5D$. The boundary conditions are periodic in both streamwise (L) and spanwise (W) directions, non-slip at the bottom of porous media and at spheres, and symmetric at the top of water surface in vertical direction (H). The results were compared with PIV experiment of Manes et al. (2009) and LES simulation of Lian et al. (2021). Figures 1a-d show agreement among experiment, DES and LES models with different mesh resolutions.

In addition to DES/LES and mesh resolutions, we performed detailed analysis to establish result independence considering domain size and integration time. Four different domain sizes, $L \times W$=$18D \times 9D$ (2.5 million cells), $36D \times 18D$ (10.1 million cells), $72D\times36D$ (40.5 million cells), and $90D\times36D$ (50.6 million cells) in the depth of $H_w = 13.38D$ and $H_b = 4.46D$ with the same mesh resolution, were tested to ensure the modeling domain is large enough to apply periodic boundary conditions. The statistics for turbulence quantities become consistent when the domain is larger than $36D\times18D$ (Figures 1e-g), which is considered as the most cost-effective size and this simulation domain is selected in the current study.

Double-averaging method is used to study the turbulence statistics while using periodic boundary conditions. To ensure the simulation time is sufficiently long to construct the representative vertical profile, the analysis of integration time is performed to determine appropriate simulation flow cycles. Two simulation time, 167 and 234 flow cycles, were performed and they both show good convergence in Figures 1h-j. Therefore, running the simulation for at least 200 flow cycles is considered reliable for turbulence statistics while using periodic boundary conditions and double-averaging method.

SI2: Numerical setup and parameter selection for all simulation cases

Table 1 summarizes all cases that have been examined in the present study, aiming to expand the existing dataset for high Reynolds number and bed roughness.

SI3: Collection of D_{eff}/D_m dataset for model foundation

Table 3 integrates field and flume data from earlier studies (O'Connor & Harvey, 2008; Grant et al., 2012; Voermans et al., 2018) along with our numerical results. The dataset combines 93 field and flume samples and 17 simulations in current study.

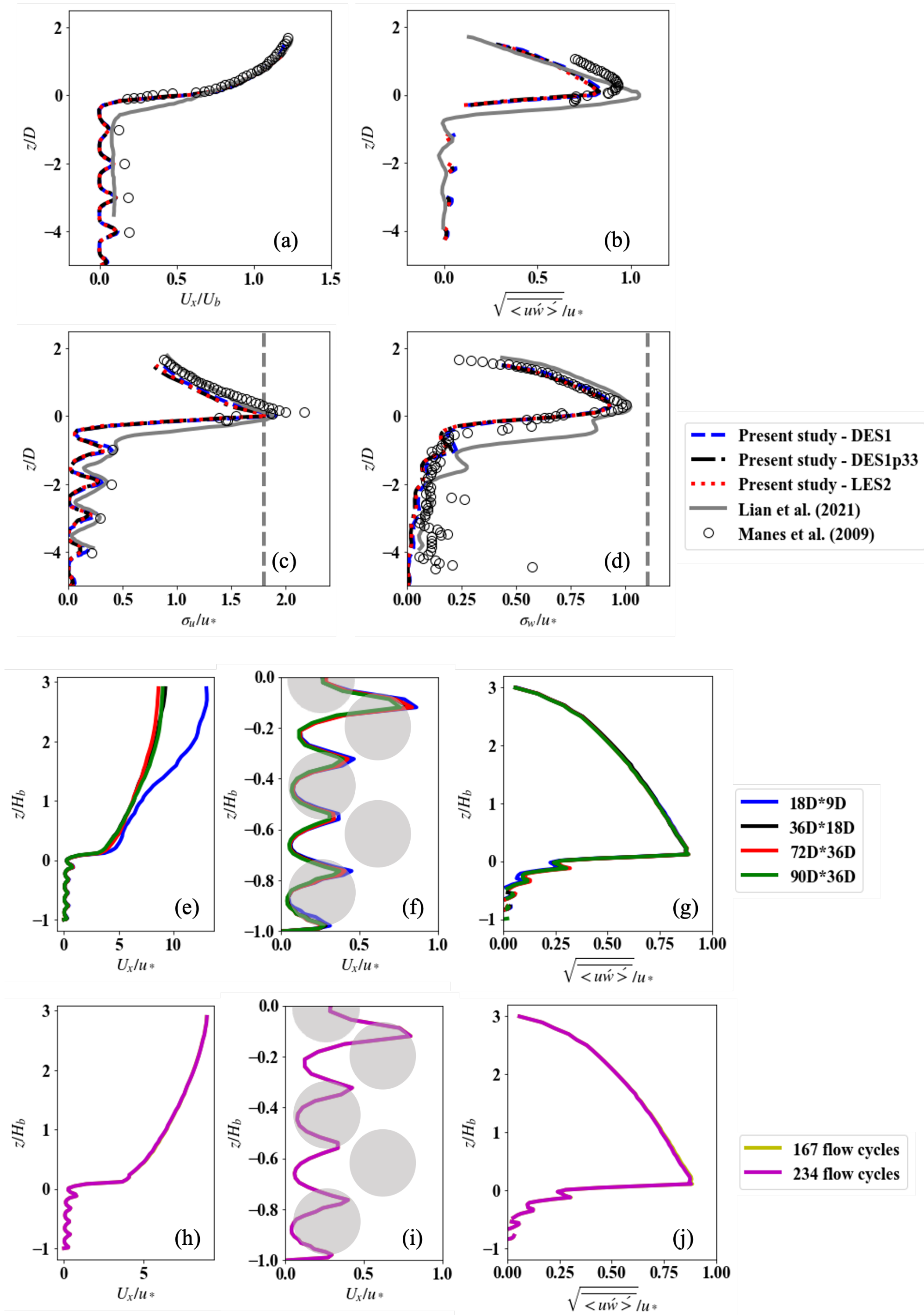

Figure 1. (a), (b), (c) and (d) Model validation of DES/LES and mesh resolutions for U_x/U_b, $\sqrt{<\overline{u'w'}>}/u_*$, σ_u/u_* and σ_w/u_*. (e), (f) and (g) justification of domain size for U_x/u_* and $\sqrt{<\overline{u'w'}>}/u_*$. (h), (i) and (j) justification of integration time.

Table 1. Parameter selection of total 14 simulations.

Case name (Symbol)	Bed type	ϕ	H_w (m)	H_b (m)	U_b (m/s)	u_* (m/s)	K (m^2)	Re_*	Re_k
Base case	impermeable	N/A	0.134	N/A	1	0.093	N/A	2326.84	N/A
●	hyporheic	0.6	0.134	0.045	1	0.168	7.5×10^{-7}	4208.44	145.79
Low Re	impermeable	N/A	0.134	N/A	0.1	0.008	N/A	192.06	N/A
●	hyporheic	0.6	0.134	0.045	0.1	0.013	7.5×10^{-7}	319.60	11.07
Moderate Re	impermeable	N/A	0.134	N/A	0.5	0.045	N/A	1119.01	N/A
●	hyporheic	0.6	0.134	0.045	0.5	0.074	7.5×10^{-7}	1839.88	63.74
High Re	impermeable	N/A	0.134	N/A	10	1.036	N/A	25896.83	N/A
●	hyporheic	0.6	0.134	0.045	10	2.006	7.5×10^{-7}	50137.81	1736.83
Compact	impermeable	N/A	0.107	N/A	1	0.099	N/A	2485.13	N/A
▲	hyporheic	0.4	0.107	0.036	1	0.131	9.877×10^{-8}	3276.29	41.19
Shallow	impermeable	N/A	0.045	N/A	1	0.123	N/A	3063.98	N/A
■	hyporheic	0.6	0.045	0.045	1	0.345	7.5×10^{-7}	8624.99	298.78
Deep	impermeable	N/A	0.312	N/A	1	0.069	N/A	1724.24	N/A
■	hyporheic	0.6	0.312	0.045	1	0.097	7.5×10^{-7}	2425.96	84.04

* Particle diameter (D) is 0.01 m and roughness height ($k_s = 2.5D$) is 0.025 m (Engelund, 1970; Garcia, 2008) for all cases.

** Permeability (K) is computed by the KozenyCarman model : $K = \frac{\phi^3 d^2}{180(1-\phi)^2}$ (p. 166 in Bear (1972).

*** All cases are simulated as incompressible and isothermal with $\nu = 1 \times 10^{-6}$ m^2/s at 20 °C.

Table 2: Collection of parameters in previously published dataset and current study.

Source, Tracer	Exp.	Bed form	U (m/s)	u_* (m/s)	k_s (m)	K (m^2)	ν (m^2/s)	H_w (m)	H_b (m)	ϕ
Richardson and Parr (1988), Fluorescein	a6	Plane	0.0366	0.0033	0.00948	7.14E-09	1.53E-06	0.013	0.0254	0.38
	d1	Plane	0.0762	0.00552	0.00314	7.91E-10	9.78E-07	0.00635	0.0254	0.4
	d1r	Plane	0.0792	0.00752	0.00314	7.91E-10	9.77E-07	0.00635	0.0254	0.4
	d2	Plane	0.0366	0.00271	0.00314	7.91E-10	1.06E-06	0.013	0.0254	0.4
	d3	Plane	0.152	0.0108	0.00314	7.91E-10	1.07E-06	0.013	0.0254	0.4
	b1	Plane	0.226	0.0129	0.00154	1.58E-10	1.09E-06	0.0135	0.0254	0.38
	b2	Plane	0.155	0.00936	0.00154	1.58E-10	1.05E-06	0.0127	0.0254	0.38
	b2r	Plane	0.152	0.0112	0.00154	1.58E-10	1.16E-06	0.0124	0.0254	0.38
	b5	Plane	0.0792	0.00524	0.00154	1.58E-10	1.01E-06	0.0066	0.0254	0.38
	b5r	Plane	0.0762	0.00808	0.00154	1.58E-10	1.12E-06	0.0066	0.0254	0.38
	b6	Plane	0.0366	0.00268	0.00154	1.58E-10	1.09E-06	0.0127	0.0254	0.38
	b7	Plane	0.152	0.00885	0.00154	1.58E-10	1.09E-06	0.0188	0.0254	0.38
	b8	Plane	0.0701	0.00443	0.00154	1.58E-10	1.09E-06	0.0188	0.0254	0.38
	b8r	Plane	0.0762	0.00602	0.00154	1.58E-10	1.26E-06	0.0193	0.0254	0.38
	e1	Plane	0.0792	0.00524	0.000888	5.43E-11	9.69E-07	0.0066	0.0254	0.37
	e1r	Plane	0.0762	0.00762	0.000888	5.43E-11	9.49E-07	0.0066	0.0254	0.37
	e2	Plane	0.155	0.00869	0.000888	5.43E-11	1.04E-06	0.0127	0.0254	0.37
	e2r	Plane	0.152	0.0116	0.000888	5.43E-11	1.01E-06	0.0124	0.0254	0.37
	e3	Plane	0.0366	0.00265	0.000888	5.43E-11	1.04E-06	0.013	0.0254	0.37
	e4	Plane	0.229	0.0117	0.000888	5.43E-11	1.02E-06	0.013	0.0254	0.37
	c1	Plane	0.152	0.0104	0.00033	1.7E-11	1.36E-06	0.0127	0.0254	0.36
	c1r	Plane	0.152	N/A	0.00033	1.7E-11	1.03E-06	0.0127	0.0254	0.36
	c2	Plane	0.0762	0.00703	0.00033	1.7E-11	1.34E-06	0.0066	0.0254	0.36
	c2r	Plane	0.0732	0.01	0.00033	1.7E-11	1.36E-06	0.00686	0.0254	0.36
	c3	Plane	0.0366	0.00361	0.00033	1.7E-11	1.44E-06	0.013	0.0254	0.36
Elliot and Brooks (1977), NaCl	8	Bed form	0.132	0.0159	0.00946	1.12E-10	1.00E-06	0.0645	0.13	0.33
	9	Bed form	0.132	0.0244	0.0289	1.12E-10	1.00E-06	0.0645	0.135	0.33
	10	Bed form	0.087	0.0154	0.0154	1.12E-10	1.00E-06	0.031	0.126	0.33
	12	Bed form	0.132	0.0195	0.0154	1.12E-10	1.00E-06	0.0648	0.125	0.33

	14	Bed form	0.086	0.0129	0.0154	1.12E-10	1.00E-06	0.0648	0.22	0.33
	15	Bed form	0.087	0.0143	0.0289	1.12E-10	1.00E-06	0.0648	0.22	0.33
	16	Bed form	0.107	0.0171	0.0197	1.12E-10	1.00E-06	0.0648	0.22	0.33
	17	Bed form	0.087	0.014	0.0129	8.05E-12	1.00E-06	0.0645	0.225	0.3
Packman et al. (2000), LiCl	7	Bed form	0.152	0.0158	0.0121	1.53E-10	1.00E-06	0.127	0.119	0.33
	13	Bed form	0.144	0.0155	0.0118	1.53E-10	1.00E-06	0.09	0.1	0.33
	15	Bed form	0.126	0.0152	0.015	1.53E-10	1.00E-06	0.079	0.097	0.33
Marion et al. (2002), NaCl	S1	Plane	0.25	0.0172	0.00338	5.04E-10	1.30E-06	0.109	0.4	0.38
	S2	Ripples	0.24	0.0173	0.0054	5.04E-10	1.30E-06	0.11	0.4	0.38
	S3	Dunes/Ripples	0.28	0.0182	0.00849	5.04E-10	1.30E-06	0.118	0.4	0.38
	S4	Dunes	0.22	0.0176	0.0236	5.04E-10	1.30E-06	0.123	0.4	0.38
	S5	Dunes	0.22	0.0177	0.018	5.04E-10	1.30E-06	0.121	0.4	0.38
Packman and McCay (2003), NaCl	1	Dunes	0.233	0.0171	0.0166	1.83E-10	1.00E-06	0.087	0.099	0.38
	2a	Dunes	0.237	0.0153	0.0172	1.83E-10	1.00E-06	0.118	0.099	0.38
	2b	Dunes	0.237	0.0153	0.0172	6.8E-11	1.00E-06	0.118	0.099	0.29
	3a	Dunes	0.236	0.017	0.0159	1.83E-10	1.00E-06	0.086	0.103	0.38
	3b	Dunes	0.236	0.017	0.0159	6.8E-11	1.00E-06	0.086	0.103	0.29
Rehg et al. (2005), NaCl	1	Natural bed	0.154	0.0066	0.0132	1.82E-10	1.00E-06	0.109	0.105	0.36
	2	Natural bed	0.164	0.0146	0.0158	1.82E-10	1.00E-06	0.104	0.0986	0.36
Tonina and Buffington (2007), Fluorescein	1	Pool-riffle	0.282	0.0511	0.116	5.1E-09	1.00E-06	0.065	0.18	0.34
	2	Pool-riffle	0.384	0.0549	0.116	5.1E-09	1.00E-06	0.075	0.18	0.34
	3	Pool-riffle	0.369	0.0429	0.116	5.1E-09	1.00E-06	0.104	0.18	0.34
	4	Pool-riffle	0.308	0.0475	0.094	5.1E-09	1.00E-06	0.056	0.18	0.34
	5	Pool-riffle	0.413	0.0507	0.094	5.1E-09	1.00E-06	0.064	0.18	0.34
	6	Pool-riffle	0.421	0.0392	0.094	5.1E-09	1.00E-06	0.087	0.18	0.34
	7	Pool-riffle	0.365	0.0421	0.0792	5.1E-09	1.00E-06	0.044	0.18	0.34
	8	Pool-riffle	0.46	0.0462	0.0792	5.1E-09	1.00E-06	0.053	0.18	0.34
	9	Pool-riffle	0.425	0.039	0.0792	5.1E-09	1.00E-06	0.086	0.18	0.34
	10	Pool-riffle	0.367	0.0396	0.064	5.1E-09	1.00E-06	0.039	0.18	0.34
	11	Pool-riffle	0.452	0.0457	0.064	5.1E-09	1.00E-06	0.052	0.18	0.34
	12	Pool-riffle	0.442	0.0381	0.064	5.1E-09	1.00E-06	0.082	0.18	0.34
Nagaoka and Ohgaki (1990), NaCl	1	Plane	0.428	0.043	0.245	2.31E-07	1.00E-06	0.0675	0.236	0.24
	2	Plane	0.28	0.0407	0.245	2.31E-07	1.00E-06	0.0675	0.236	0.24

	3	Plane	0.211	0.027	0.245	2.31E-07	1.00E-06	0.0675	0.236	0.24
	4	Plane	0.167	0.0218	0.245	2.31E-07	1.00E-06	0.0675	0.236	0.24
	5	Plane	0.117	0.0153	0.245	2.31E-07	1.00E-06	0.07	0.236	0.24
	6	Plane	0.089	0.0115	0.245	2.31E-07	1.00E-06	0.0675	0.236	0.24
	10	Plane	0.302	0.0291	0.114	5.02E-08	1.00E-06	0.032	0.115	0.24
	11	Plane	0.203	0.0165	0.114	5.02E-08	1.00E-06	0.032	0.115	0.24
	12	Plane	0.112	0.0109	0.114	5.02E-08	1.00E-06	0.032	0.115	0.24
Ren and Packman (2004), NaCl	2	Bed form	0.13	0.00482	0.0131	1.82E-10	1.00E-06	0.079	0.0924	0.36
	3	Bed	0.144	0.00456	0.0114	1.82E-10	1.00E-06	0.0707	0.104	0.36
	4	Bed	0.141	0.00464	0.00905	1.82E-10	1.00E-06	0.073	0.102	0.36
	5	Bed	0.12	0.00505	0.00957	1.82E-10	1.00E-06	0.0865	0.114	0.36
	6	Bed	0.157	0.00515	0.00909	1.82E-10	1.00E-06	0.09	0.113	0.36
Lai et al. (1994), KCl	a6	Plane	0.154	0.00597	0.0207	1.86E-09	1.00E-06	0.0097	0.15	0.38
	a8	Plane	0.0741	0.00236	0.0207	1.86E-09	1.00E-06	0.0202	0.15	0.38
	a9	Plane	0.101	0.00342	0.0207	1.86E-09	1.00E-06	0.0199	0.15	0.38
	b1	Plane	0.0988	0.00338	0.0125	1.29E-09	1.00E-06	0.0051	0.15	0.38
	b4	Plane	0.0988	0.00359	0.0125	1.29E-09	1.00E-06	0.0101	0.15	0.38
	b7	Plane	0.0998	0.00347	0.0125	1.29E-09	1.00E-06	0.015	0.15	0.38
	c4	Plane	0.0998	0.00471	0.00701	6.1E-10	1.00E-06	0.005	0.15	0.37
	d4	Plane	0.101	0.00468	0.00354	2.31E-10	1.00E-06	0.0049	0.15	0.36
Packman et al. (2004), NaCl	1	Plane	0.361	0.0319	0.0526	1.53E-08	1.00E-06	0.114	0.19	0.38
	2	Plane	0.274	0.0275	0.0526	1.53E-08	1.00E-06	0.113	0.19	0.38
	3	Plane	0.179	0.0198	0.0526	1.53E-08	1.00E-06	0.114	0.19	0.38
	4	Plane	0.091	0.0106	0.0526	1.53E-08	1.00E-06	0.114	0.19	0.38
	5	Plane	0.179	0.0301	0.0526	1.53E-08	1.00E-06	0.201	0.19	0.38
	6	Plane	0.092	0.0167	0.0526	1.53E-08	1.00E-06	0.202	0.19	0.38
	7	Bed form	0.177	0.0279	0.0648	1.53E-08	1.00E-06	0.204	0.19	0.38
	8	Bed form	0.09	0.0276	0.0648	1.53E-08	1.00E-06	0.205	0.19	0.38
	9	Bed form	0.268	0.0283	0.0462	1.53E-08	1.00E-06	0.204	0.19	0.38
	10	Bed form	0.177	0.015	0.0462	1.53E-08	1.00E-06	0.203	0.19	0.38
	11	Bed form	0.091	0.0237	0.0462	1.53E-08	1.00E-06	0.204	0.19	0.38
Present study, numerical modeling	Base	Hyporheic	1.000	0.1683	0.025	7.5E-07	1.00E-06	0.134	0.045	0.6
	Low Re	Hyporheic	0.100	0.0128	0.025	7.5E-07	1.00E-06	0.134	0.045	0.6

Moderate Re	Hyporheic	0.500	0.0736	0.025	7.5E-07	1.00E-06	0.134	0.045	0.6
High Re	Hyporheic	10.000	2.0055	0.025	7.5E-07	1.00E-06	0.134	0.045	0.6
Compact	Hyporheic	1.000	0.1311	0.025	9.88E-08	1.00E-06	0.107	0.036	0.4
Shallow	Hyporheic	1.000	0.3450	0.025	7.5E-07	1.00E-06	0.045	0.045	0.6
Deep	Hyporheic	1.000	0.0970	0.025	7.5E-07	1.00E-06	0.312	0.045	0.6
Base	Impermeable	1.000	0.0931	0.025	N/A	1.00E-06	0.134	0.000	0.6
Low Re	Impermeable	0.100	0.0077	0.025	N/A	1.00E-06	0.134	0.000	0.6
Moderate Re	Impermeable	0.500	0.0448	0.025	N/A	1.00E-06	0.134	0.000	0.6
High Re	Impermeable	10.000	1.0359	0.025	N/A	1.00E-06	0.134	0.000	0.6
Compact	Impermeable	1.000	0.0994	0.025	N/A	1.00E-06	0.107	0.000	0.4
Shallow	Impermeable	1.000	0.1226	0.025	N/A	1.00E-06	0.045	0.000	0.6
Deep	Impermeable	1.000	0.0690	0.025	N/A	1.00E-06	0.312	0.000	0.6
BM-DES1	Hyporheic	0.252	0.0306	0.03	3.16E-07	1.00E-06	0.026	0.054	0.48
BM-DES1p33	Hyporheic	0.252	0.0294	0.03	3.16E-07	1.00E-06	0.026	0.054	0.48
BM-LES2	Hyporheic	0.254	0.0306	0.03	3.16E-07	1.00E-06	0.026	0.054	0.48

Table 3: Collection of Reynolds and Peclet numbers in previously published dataset and current study.

Exp. .	Bed form	$D_m (m^2/s)$	$D_{eff} (m^2/s)$	$\frac{Deff}{D_m}$	$Re_{bulk} = \frac{U_b H_w}{\nu}$	$Re_{H_w} = \frac{u_* H_w}{\nu}$	$Re_{H_b} = \frac{u_* H_b}{\nu}$	$Pe_k = \frac{u_* \sqrt{K}}{D_m}$	$Re_k = \frac{u_* \sqrt{K}}{\nu}$	$Re_* = \frac{u_* k_s}{\nu}$
a6	Plane	4.75E-10	2.17E-08	45.60	310.00	27.90	54.80	586.04	0.18	20.40
d1	Plane	4.75E-10	1.83E-08	38.50	495.00	35.90	143.00	327.54	0.16	17.70
d1r	Plane	4.75E-10	5.43E-08	114.00	515.00	48.90	195.00	444.96	0.22	24.10
d2	Plane	4.75E-10	2.10E-09	4.42	445.00	33.00	64.70	160.38	0.07	7.99
d3	Plane	4.75E-10	3.93E-08	82.70	1850.00	131.00	256.00	639.00	0.28	31.70
b1	Plane	4.75E-10	4.80E-08	101.00	2800.00	159.00	301.00	341.21	0.15	18.20
b2	Plane	4.75E-10	1.81E-08	38.20	1880.00	113.00	226.00	248.64	0.11	13.70
b2r	Plane	4.75E-10	4.93E-08	104.00	1640.00	120.00	245.00	295.24	0.12	14.80
b5	Plane	4.75E-10	3.81E-09	8.01	520.00	34.40	132.00	138.86	0.07	8.00
b5r	Plane	4.75E-10	1.52E-08	32.10	450.00	47.70	184.00	213.38	0.09	11.10
b6	Plane	4.75E-10	1.22E-09	2.57	425.00	31.20	62.30	70.84	0.03	3.77
b7	Plane	4.75E-10	2.55E-08	53.70	2630.00	152.00	206.00	234.60	0.10	12.50
b8	Plane	4.75E-10	3.23E-09	6.79	1210.00	76.50	103.00	117.25	0.05	6.25
b8r	Plane	4.75E-10	5.75E-09	12.10	1170.00	92.50	122.00	159.53	0.06	7.36
e1	Plane	4.75E-10	9.13E-10	1.92	540.00	35.70	137.00	81.19	0.04	4.80
e1r	Plane	4.75E-10	4.44E-09	9.36	530.00	53.00	204.00	118.20	0.06	7.13
e2	Plane	4.75E-10	3.38E-09	7.12	1900.00	106.00	212.00	134.47	0.06	7.41
e2r	Plane	4.75E-10	1.22E-08	25.70	1870.00	142.00	289.00	179.55	0.08	10.10
e3	Plane	4.75E-10	4.30E-10	0.91	455.00	33.00	64.60	40.95	0.02	2.26
e4	Plane	4.75E-10	1.11E-08	23.30	2900.00	149.00	291.00	181.68	0.08	10.20
c1	Plane	4.75E-10	2.21E-09	4.65	1420.00	96.60	193.00	90.12	0.03	2.51
c1r	Plane	4.75E-10	2.56E-09	5.38	1880.00	N/A	N/A	N/A	N/A	N/A
c2	Plane	4.75E-10	5.21E-10	1.10	375.00	34.60	133.00	61.13	0.02	1.73
c2r	Plane	4.75E-10	1.12E-09	2.36	370.00	50.70	188.00	86.93	0.03	2.44
c3	Plane	4.75E-10	2.59E-10	0.55	330.00	32.60	63.90	31.41	0.01	0.83
8	Bed form	4.10E-10	2.20E-07	536.00	8510.00	1030.00	2070.00	409.92	0.17	151.00
9	Bed form	4.10E-10	1.95E-07	476.00	8510.00	1570.00	3290.00	629.52	0.26	705.00

10	Bed form	4.10E-10	3.29E-08	80.30	2700.00	477.00	1940.00	397.72	0.16	237.00
12	Bed form	4.10E-10	1.08E-07	264.00	8550.00	1270.00	2440.00	505.08	0.21	300.00
14	Bed form	4.10E-10	3.93E-08	95.90	5570.00	833.00	2830.00	331.84	0.14	198.00
15	Bed form	4.10E-10	1.03E-07	250.00	5640.00	924.00	3140.00	368.44	0.15	413.00
16	Bed form	4.10E-10	2.50E-07	610.00	6930.00	1110.00	3760.00	441.64	0.18	336.00
17	Bed form	4.10E-10	1.05E-08	25.60	5610.00	903.00	3150.00	96.87	0.04	180.00
7	Bed form	8.70E-10	1.54E-07	177.00	19300.00	2000.00	1880.00	224.25	0.20	191.00
13	Bed form	8.70E-10	1.28E-07	147.00	13000.00	1400.00	1550.00	220.80	0.19	184.00
15	Bed form	8.70E-10	1.33E-07	153.00	9950.00	1200.00	1480.00	217.35	0.19	229.00
S1	Plane	1.50E-09	1.16E-06	776.00	21000.00	1440.00	5290.00	257.50	0.30	44.60
S2	Ripples	1.50E-09	2.21E-06	1480.00	20200.00	1460.00	5320.00	258.37	0.30	71.80
S3	Dunes/Ripples	1.50E-09	2.61E-06	1740.00	25300.00	1640.00	5600.00	272.24	0.31	119.00
S4	Dunes	1.50E-09	4.06E-06	2710.00	20800.00	1670.00	5410.00	263.57	0.30	319.00
S5	Dunes	1.50E-09	6.78E-06	4520.00	20500.00	1650.00	5460.00	265.30	0.31	246.00
1	Dunes	1.50E-09	6.49E-07	433.00	20300.00	1490.00	1690.00	154.74	0.23	283.00
2a	Dunes	1.50E-09	2.50E-07	167.00	28000.00	1810.00	1510.00	138.07	0.21	263.00
2b	Dunes	1.50E-09	2.49E-07	166.00	28000.00	1810.00	1510.00	84.04	0.13	263.00
3a	Dunes	1.50E-09	1.25E-07	83.40	20300.00	1460.00	1750.00	153.41	0.23	270.00
3b	Dunes	1.50E-09	1.30E-07	86.40	20300.00	1460.00	1750.00	93.38	0.14	270.00
1	Natural bed	1.50E-09	6.12E-08	40.80	16700.00	717.00	696.00	59.36	0.09	87.30
2	Natural bed	1.50E-09	1.97E-07	131.00	17100.00	1520.00	1440.00	131.40	0.20	231.00
1	Pool-riffle	4.75E-10	5.10E-05	107000.00	18300.00	3320.00	9200.00	7701.50	3.65	5920.00
2	Pool-riffle	4.75E-10	3.64E-05	76600.00	28800.00	4120.00	9890.00	8271.20	3.92	6360.00
3	Pool-riffle	4.75E-10	4.09E-05	86200.00	38400.00	4460.00	7710.00	6456.60	3.06	4960.00
4	Pool-riffle	4.75E-10	4.61E-05	97100.00	17200.00	2660.00	8540.00	7152.90	3.39	4460.00
5	Pool-riffle	4.75E-10	1.38E-04	291000.00	26400.00	3250.00	9130.00	7638.20	3.62	4770.00
6	Pool-riffle	4.75E-10	6.62E-05	139000.00	36600.00	3410.00	7060.00	5908.00	2.80	3680.00
7	Pool-riffle	4.75E-10	7.23E-05	152000.00	16100.00	1850.00	7570.00	6330.00	3.00	3330.00
8	Pool-riffle	4.75E-10	5.30E-05	112000.00	24400.00	2450.00	8310.00	6963.00	3.30	3660.00
9	Pool-riffle	4.75E-10	3.90E-05	82200.00	36600.00	3350.00	7010.00	5865.80	2.78	3090.00
10	Pool-riffle	4.75E-10	3.69E-05	77600.00	14300.00	1540.00	7130.00	5971.30	2.83	2530.00
11	Pool-riffle	4.75E-10	3.50E-05	73800.00	23500.00	2380.00	8230.00	6878.60	3.26	2930.00

	12	Pool-riffle	4.75E-10	2.18E-05	45900.00	36200.00	3120.00	6850.00	5739.20	2.72	2440.00
	1	Plane	1.50E-09	6.46E-04	430000.00	28900.00	2900.00	10100.00	13806.90	20.70	10500.00
	2	Plane	1.50E-09	4.33E-04	289000.00	18900.00	2750.00	9610.00	13073.20	19.60	9960.00
	3	Plane	1.50E-09	1.55E-04	103000.00	14200.00	1820.00	6370.00	8671.00	13.00	6610.00
	4	Plane	1.50E-09	1.26E-04	83800.00	11300.00	1470.00	5140.00	7003.50	10.50	5340.00
	5	Plane	1.50E-09	9.09E-05	60600.00	8190.00	1070.00	3610.00	4909.12	7.36	3750.00
	6	Plane	1.50E-09	6.58E-05	43900.00	6010.00	776.00	2710.00	3688.51	5.53	2820.00
	10	Plane	1.50E-09	1.51E-04	100000.00	9660.00	931.00	3350.00	4348.84	6.52	3320.00
	11	Plane	1.50E-09	7.62E-05	50800.00	6500.00	528.00	1900.00	2467.90	3.70	1880.00
	12	Plane	1.50E-09	1.88E-05	12500.00	3580.00	349.00	1250.00	1627.48	2.44	1240.00
	2	Bed form	1.50E-09	2.44E-08	16.20	10300.00	381.00	446.00	43.36	0.07	63.00
	3	Bed	1.50E-09	5.94E-08	39.60	10200.00	322.00	473.00	41.02	0.06	52.10
	4	Bed	1.50E-09	3.72E-08	24.80	10300.00	338.00	475.00	41.69	0.06	41.90
	5	Bed	1.50E-09	8.30E-08	55.30	10300.00	436.00	574.00	45.42	0.07	48.30
	6	Bed	1.50E-09	1.52E-07	101.00	14100.00	463.00	583.00	46.29	0.07	46.80
	a6	Plane	1.50E-09	5.94E-07	396.00	1490.00	57.90	895.00	171.42	0.26	123.00
	a8	Plane	1.50E-09	2.14E-08	14.30	1500.00	47.60	353.00	68.03	0.10	48.70
	a9	Plane	1.50E-09	5.65E-08	37.70	2010.00	68.10	513.00	98.72	0.15	70.80
	b1	Plane	1.50E-09	1.71E-07	114.00	504.00	17.20	507.00	80.71	0.12	42.20
	b4	Plane	1.50E-09	4.46E-08	29.70	998.00	36.20	538.00	86.04	0.13	44.80
	b7	Plane	1.50E-09	2.20E-08	14.60	1500.00	52.10	521.00	83.38	0.13	43.40
	c4	Plane	1.50E-09	9.61E-08	64.10	499.00	23.50	706.00	77.37	0.12	33.00
	d4	Plane	1.50E-09	2.73E-08	18.20	495.00	22.90	702.00	47.49	0.07	16.60
	1	Plane	1.50E-09	1.58E-04	106000.00	41200.00	3640.00	6060.00	2627.98	3.94	1680.00
	2	Plane	1.50E-09	1.06E-04	70600.00	31000.00	3100.00	5220.00	2261.13	3.39	1450.00
	3	Plane	1.50E-09	4.60E-05	30700.00	20400.00	2260.00	3760.00	1634.15	2.45	1040.00
	4	Plane	1.50E-09	7.08E-06	4720.00	10400.00	1210.00	2010.00	873.77	1.31	557.00
	5	Plane	1.50E-09	1.22E-04	81500.00	36000.00	6050.00	5720.00	2481.24	3.72	1590.00
	6	Plane	1.50E-09	2.05E-05	13700.00	18600.00	3360.00	3160.00	1374.02	2.06	877.00
	7	Bed form	1.50E-09	1.83E-04	122000.00	36100.00	5700.00	5310.00	2301.15	3.45	1810.00
	8	Bed form	1.50E-09	4.85E-05	32300.00	18500.00	5670.00	5250.00	2281.14	3.42	1790.00
	9	Bed form	1.50E-09	2.73E-04	182000.00	54700.00	5770.00	5380.00	2334.50	3.50	1310.00
	10	Bed form	1.50E-09	1.83E-04	122000.00	35900.00	3050.00	2850.00	1233.95	1.85	693.00

11	Bed form	1.50E-09	4.85E-05	32300.00	18600.00	4830.00	4500.00	1954.31	2.93	1090.00
Base	Hyporheic	2.00E-09	8.33E-04	416509.55	133791.00	22522.07	7507.36	72892.37	145.78	4208.44
Low Re	Hyporheic	2.00E-09	4.39E-05	21956.53	13379.10	1710.39	570.13	5535.67	11.07	319.60
Moderate Re	Hyporheic	2.00E-09	3.52E-04	176040.39	66895.50	9846.36	3282.12	31867.60	63.74	1839.88
High Re	Hyporheic	2.00E-09	9.88E-03	4941608.87	1337910.00	268319.53	89439.84	868412.42	1736.82	50137.81
Compact	Hyporheic	2.00E-09	8.87E-04	443437.23	106800.00	13996.32	4665.44	20592.78	41.19	3276.29
Shallow	Hyporheic	2.00E-09	1.52E-03	757797.07	44597.00	15385.95	15385.95	149389.23	298.78	8624.99
Deep	Hyporheic	2.00E-09	3.49E-04	174575.94	312179.00	30293.41	4327.63	42018.94	84.04	2425.96
Base	Impermeable	2.00E-09	3.07E-04	153536.98	133791.00	12452.40	N/A	N/A	N/A	2326.84
Low Re	Impermeable	2.00E-09	1.42E-05	7088.30	13379.10	1027.84	N/A	N/A	N/A	192.06
Moderate Re	Impermeable	2.00E-09	1.38E-04	68859.41	66895.50	5988.55	N/A	N/A	N/A	1119.01
High Re	Impermeable	2.00E-09	3.58E-03	1789636.17	1337910.00	138590.50	N/A	N/A	N/A	25896.83
Compact	Impermeable	2.00E-09	6.34E-04	317234.17	106800.00	10616.46	N/A	N/A	N/A	2485.13
Shallow	Impermeable	2.00E-09	2.68E-04	133751.71	44597.00	5465.77	N/A	N/A	N/A	3063.98
Deep	Impermeable	2.00E-09	1.58E-04	79122.89	312179.00	21530.87	N/A	N/A	N/A	1724.24
BM-DES1	Hyporheic	2.00E-09	7.60E-05	38003.00	6564.95	796.68	1654.64	8605.62	17.21	919.24
BM-DES1p33	Hyporheic	2.00E-09	6.83E-05	34171.33	6546.85	764.10	1586.97	8253.68	16.51	881.65
BM-LES2	Hyporheic	2.00E-09	7.23E-05	36142.85	6598.29	795.78	1652.77	8595.90	17.19	918.20

Table 4. Five best models of D_{eff}/D_m fitness in MLR analysis

Model	R^2	AIC	VIF
$\frac{D_{eff}}{D_m} = Re_k^{1.08} Re_{H_b}^{1.04}$	0.984	127	1.00
$\frac{D_{eff}}{D_m} = Re_*^{1.31} Re_k^{0.39}$	0.98	149	1.03
$\frac{D_{eff}}{D_m} = Re_{bulk}^{0.85} Re_k^{1.15}$	0.974	178	1.00
$\frac{D_{eff}}{D_m} = Re_k^{1.71} \phi^{-7.59}$	0.969	195	1.06
$\frac{D_{eff}}{D_m} = Re_{Hw}^{1.13} Re_k^{0.86}$	0.968	198	1.00

SI4: Five best models of D_{eff}/D_m fitness in MLR analysis

Table 4 summarizes the 5 models with best fitness to the training data of D_{eff}/D_m (Table 4).

SI5: Collection of $\tilde{K_L}$ dataset for model foundation

Table 5 integrates dataset reported by O'Connor et al. (2009), Han et al. (2018) and Voermans et al. (2018). The dataset that includes smooth to fully rough beds and low to high permeabilities for mass transfer coefficient (Steinberger & Hondzo, 1999; O'Connor & Hondzo, 2008; O'Connor et al., 2009; Nagaoka & Ohgaki, 1990; Elliott & Brooks, 1997; Marion et al., 2002; Packman et al., 2004; Tonina & Buffington, 2007; Voermans et al., 2017).

Table 5: Collection of mass transfer coefficients in previously published dataset and current study

Source	Exp.	u_* (m/s)	D (m)	K (m^2)	Re_k	Re_*	$\tilde{K}_L$ (m/s)
O'Connor et al. (2009)	Thin-film theory	0.0797	0.00004	1.200E-11	0.276	7.974	4.001E-05
	(diffusive sublayer thickness)	0.1614	0.00004	1.200E-11	0.559	16.135	1.070E-04
		0.2013	0.00004	1.200E-11	0.697	20.130	7.979E-05
		0.2222	0.00004	1.200E-11	0.770	22.216	1.067E-04
		0.2295	0.00004	1.200E-11	0.795	22.949	2.865E-04
		0.3092	0.00004	1.200E-11	1.071	30.922	3.355E-04
		0.4383	0.00004	1.200E-11	1.518	43.830	4.247E-04
		0.3905	0.00004	1.200E-11	1.353	39.047	6.363E-04
		0.5279	0.00004	1.200E-11	1.829	52.792	1.476E-03
		0.5581	0.00004	1.200E-11	1.933	55.807	1.643E-03
		0.4580	0.00004	1.200E-11	1.587	45.800	1.216E-03
	Thin-film theory	0.0774	0.00004	1.200E-11	0.268	7.745	3.008E-04
	(Batchelor length)	0.1588	0.00004	1.200E-11	0.550	15.879	5.432E-04
		0.2006	0.00004	1.200E-11	0.695	20.059	5.474E-04
		0.2193	0.00004	1.200E-11	0.760	21.927	7.587E-04
		0.2306	0.00004	1.200E-11	0.799	23.062	7.901E-04
		0.3082	0.00004	1.200E-11	1.068	30.824	9.830E-04
		0.3880	0.00004	1.200E-11	1.344	38.801	1.010E-03
		0.4580	0.00004	1.200E-11	1.587	45.802	1.202E-03
		0.4368	0.00004	1.200E-11	1.513	43.685	1.382E-03
		0.5262	0.00004	1.200E-11	1.823	52.616	1.382E-03
		0.5584	0.00004	1.200E-11	1.934	55.836	1.449E-03
	Surface renewal theory	0.0813	0.00004	1.200E-11	0.282	8.133	2.468E-04
		0.1589	0.00004	1.200E-11	0.550	15.887	4.892E-04
		0.1987	0.00004	1.200E-11	0.688	19.872	5.250E-04
		0.2155	0.00004	1.200E-11	0.747	21.552	7.227E-04
		0.2269	0.00004	1.200E-11	0.786	22.687	7.586E-04
		0.3063	0.00004	1.200E-11	1.061	30.634	9.830E-04
		0.3860	0.00004	1.200E-11	1.337	38.600	1.077E-03

		0.4367	0.00004	1.200E-11	1.513	43.670	1.477E-03
		0.4577	0.00004	1.200E-11	1.586	45.775	1.382E-03
		0.5278	0.00004	1.200E-11	1.828	52.775	1.584E-03
		0.5561	0.00004	1.200E-11	1.926	55.612	1.670E-03
Han et al. (2018)	Nagaoka and Ohgaki (1990)	0.0109	0.019	1.420E-07	4.107	207.100	1.014E-03
(Rough-bed dataset)		0.0407	0.041	1.080E-06	42.297	1660.600	1.123E-02
	Elliott and Brooks (1997)	0.0131	0.00012	8.480E-12	0.038	6.100	1.009E-04
		0.0247	0.00046	1.180E-10	0.268	11.500	1.075E-03
	Marion et al. (2002)	0.0173	0.0008	5.000E-10	0.387	13.900	1.972E-04
		0.0183	0.0008	5.000E-10	0.409	14.700	1.157E-03
	Packman et al. (2004)	0.0166	0.0049	4.690E-11	0.114	82.000	6.640E-04
		0.0319	0.005	1.560E-10	0.398	160.000	4.785E-03
	Tonina and Buffington (2007)	0.0109	0.0046	5.010E-08	2.440	50.400	2.333E-04
		0.0283	0.0046	5.010E-08	6.334	131.500	2.346E-03
Voermans et al. (2017)	S4	0.0066	0.006	3.960E-08	0.970	73.220	3.674E-05
Voermans et al. (2018)	M8	0.0060	0.01	1.100E-07	1.480	111.850	2.435E-04
	M9	0.0069	0.01	1.100E-07	1.700	128.520	4.202E-04
	L12	0.0042	0.025	6.870E-07	2.560	193.060	1.564E-04
	L13	0.0064	0.025	6.870E-07	3.900	293.980	7.692E-04
	L14	0.0081	0.025	6.870E-07	4.970	374.540	1.280E-03
	L15	0.0103	0.025	6.870E-07	6.300	475.000	2.215E-03
Present study	Base-HF	0.1683	0.01	7.500E-07	145.785	4208.443	2.257E-01
	Low Re-HF	0.0128	0.01	7.500E-07	11.071	319.602	8.243E-03
	Moderate Re-HF	0.0736	0.01	7.500E-07	63.735	1839.877	9.538E-02
	High Re-HF	2.0055	0.01	7.500E-07	1736.825	50137.814	2.677E+00
	Compact-HF	0.1311	0.01	9.877E-08	41.186	3276.291	2.085E-01
	Shallow-HF	0.3450	0.01	7.500E-07	298.778	8624.991	3.541E-01
	Deep-HF	0.0970	0.01	7.500E-07	84.038	2425.964	7.657E-02
	Base-IF	0.0931	0.01	N/A	N/A	2326.839	8.319E-02
	Low Re-IF	0.0077	0.01	N/A	N/A	192.061	2.661E-03
	Moderate Re-IF	0.0448	0.01	N/A	N/A	1119.012	2.585E-02
	High Re-IF	1.0359	0.01	N/A	N/A	25896.828	9.697E-01
	Compact-IF	0.0994	0.01	N/A	N/A	2485.128	1.492E-01

	Shallow-IF	0.1226	0.01	N/A	N/A	3063.981	5.639E-02
	Deep-IF	0.0690	0.01	N/A	N/A	1724.241	3.470E-02

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