

A mechanistic model of waterfall plunge pool erosion into bedrockJoel S. Scheingross^{1†*} and Michael P. Lamb¹¹ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA[†] Now at Helmholtz Centre Potsdam, German Research Center for Geosciences (GFZ), Telegrafenberg, 14473
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Additional MATLAB codes to calculate plunge-pool erosion attached separately

- `example_pool_erosion.m`: Example script to run plunge-pool erosion codes
- `pool_erosion_simple_fct.m`: Main script to calculate plunge-pool erosion
- `pool_erosion_fct_public.m`: Sub-script embedded within the plunge-pool erosion code
- `Qsc_pool_public.m`: Sub-script embedded within the plunge-pool erosion code
- `c_from_Qs_fct.m`: Sub-script embedded within the plunge-pool erosion code
- `readme.txt`: Additional information and disclaimer for codes

Introduction: This supporting information contains two tables and MATLAB codes. Table S1 contains data for natural waterfall plunge pools surveyed by *Scheingross and Lamb* [2016], including data from the Fox Creek reference site, which we use to estimate maximum possible plunge-pool radii and to evaluate assumptions that particles can detach from fluid flow to impact exposed bedrock in plunge pools. Table S2 contains parameters used in the *Scheingross et al.* [2017] plunge-pool erosion experiments which we use to calculate model predictions of plunge pool erosion. The MATLAB codes can be used to calculate plunge-pool vertical and lateral erosion following the theory developed here.

Table S1. Compilation of natural plunge pools (attached)

Table S2. Summary of parameters for waterfall plunge-pool erosion experiments (attached)

References

- Scheingross, J. S., and M. P. Lamb (2016), Sediment transport through waterfall plunge pools, *J. Geophys. Res. Earth Surf.*, 121.
- Scheingross, J. S., D. Y. Lo, and M. P. Lamb (2017), Self-formed waterfall plunge pools in homogeneous rock, *Geophysical Research Letters*, 44(1), 200-208, doi:10.1002/2016GL071730.

Table S1. Compilation of natural plunge pools^a

River	r_{pool} (m)	h_{pool} (m)	H_{drop} (m)	D (m)	Q_{2yr} (m ³ /s)	$b_{lat}(\delta)$ (m)	$h_{pool} /$ $b_{lat}(\delta)$	$l_{e fold} /$ $b_{lat}(r_{pool})$	$r_{max} /$ r_{crit}	$r_{pool} /$ r_{crit}	UTM Easting	UTM Northing	Pool floor
Colby Canyon	2.3	0.9	2.5	0.15	1.03	0.09	9.8	2.6	0.06	0.15	395326	3792758	sed
Colby Canyon	0.9	0.65	2	0.15	0.64	0.06	11.3	7.1	0.07	0.06	395467	3792855	sed
Colby Canyon	1.9	0.4	0.6	0.15	0.64	0.06	6.9	3.2	0.13	0.24	395467	3792855	sed
Colby Canyon	1.8	0.5	1.2	0.15	0.64	0.06	8.7	3.3	0.09	0.17	395463	3792879	sed
Colby Canyon	1.5	1	3.2	0.15	0.63	0.06	17.6	4.0	0.06	0.09	395568	3792957	sed
Colby Canyon	2.3	1	1.9	0.15	0.63	0.06	17.6	2.6	0.07	0.17	395568	3792957	sed
Little Santa Anita	1.0	0.1	8.5	0.1	1.43	0.13	0.8	4.0	0.18	0.03	403678	3782944	sed
Little Santa Anita	2.9	0.5	4	0.1	1.43	0.13	3.9	1.4	0.19	0.14	403681	3782993	?
Little Santa Anita	0.7	0.3	3.5	0.1	1.44	0.13	2.3	5.8	0.18	0.03	403700	3782879	br
Little Santa Anita	2.0	1.5	8	0.1	1.45	0.13	11.5	2.0	0.19	0.07	403707	3782848	?
Little Santa Anita	0.8	1.5	5.5	0.1	1.45	0.13	11.5	5.3	0.19	0.03	403704	3782825	?
Little Santa Anita	1.3	1.5	1.25	0.1	1.45	0.13	11.5	3.2	0.08	0.10	403704	3782825	?
Little Santa Anita	0.6	0.24	1	0.1	1.46	0.13	1.8	7.0	0.09	0.05	403707	3782759	br
Little Santa Anita	0.7	0.1	4	0.1	1.46	0.13	0.8	6.2	0.19	0.03	403707	3782759	sed
Little Santa Anita	1.9	2	5.2	0.1	1.46	0.13	15.2	2.1	0.20	0.08	403719	3782712	?
Little Santa Anita	1.0	0.3	4.5	0.1	1.46	0.13	2.3	4.1	0.20	0.04	403675	3782679	sed
Little Santa Anita	1.5	1.5	0.75	0.1	1.46	0.13	11.4	2.7	0.11	0.17	403675	3782679	?
Little Santa Anita	2.1	0.1	1.5	0.1	1.48	0.13	0.7	1.9	0.08	0.16	403693	3782583	sed
Little Santa Anita	2.0	0.1	4.5	0.1	1.49	0.13	0.7	2.0	0.19	0.09	403699	3782457	sed
Little Santa Anita	2.0	2	2.7	0.1	1.50	0.14	14.8	2.0	0.19	0.11	403722	3782369	?
Little Santa Anita	1.5	1	3	0.1	1.51	0.14	7.4	2.7	0.18	0.08	403870	3782433	?
Little Santa Anita	2.3	4	4.7	0.1	1.52	0.14	29.3	1.8	0.18	0.09	403910	3782489	?
Rubio Canyon	1.9	0.25	23	0.1	0.88	0.08	3.1	2.1	0.12	0.03	397227	3785825	sed
Rubio Canyon	1.6	0.2	6.5	0.1	0.88	0.08	2.5	2.6	0.13	0.05	397226	3785809	sed
Rubio Canyon	1.5	0.1	4.6	0.1	0.89	0.08	1.3	2.7	0.14	0.06	397223	3787590	sed
Rubio Canyon	2.3	0.1	6.2	0.1	0.89	0.08	1.3	1.8	0.13	0.08	397178	3785777	sed
Rubio Canyon	2.0	0.1	7.5	0.1	0.89	0.08	1.3	2.0	0.13	0.06	397172	3785769	sed
Rubio Canyon	1.4	0.1	8.5	0.1	0.89	0.08	1.2	3.0	0.13	0.04	397152	3785725	sed
Daisy Canyon	0.8	0.3	1.5	0.11	0.29	0.03	11.4	5.5	0.08	0.06	395633	3792897	sed
Daisy Canyon	1.3	0.65	2.3	0.11	0.29	0.03	24.6	3.3	0.07	0.09	395615	3792880	sed

Table S1. Compilation of natural plunge pools (continued)

River	r_{pool} (m)	h_{pool} (m)	H_{drop} (m)	D (m)	Q_{2yr} (m ³ /s)	$b_{lat}(\delta)$ (m)	$h_{pool} /$ $b_{lat}(\delta)$	$l_{e fold} /$ $b_{lat}(r_{pool})$	$r_{max} /$ r_{crit}	$r_{pool} /$ r_{crit}	UTM Easting	UTM Northing	Pool floor
Daisy Canyon	1.0	0.5	1.1	0.11	0.30	0.03	18.7	4.6	0.09	0.09	395604	3792828	sed
Daisy Canyon	1.0	0.1	1.5	0.11	0.31	0.03	3.5	4.4	0.08	0.08	395581	3792807	sed
Daisy Canyon	1.0	0.1	4	0.11	0.33	0.03	3.3	4.4	0.07	0.05	395508	3792735	sed
Arroyo Seco	7.3	0.5	12	0.21	4.73	0.43	1.2	1.2	0.19	0.20	393659	3791349	sed
Arroyo Seco	4.0	3	3	0.21	4.81	0.43	6.9	2.1	0.06	0.22	393855	3791207	?
Arroyo Seco	4.4	2	5	0.21	4.81	0.43	4.6	1.9	0.04	0.19	393855	3791207	?
Arroyo Seco	3.0	0.3	1.21	0.21	4.90	0.44	0.7	2.8	0.10	0.29	394148	3790733	sed
Arroyo Seco	3.0	0.5	1.45	0.21	4.90	0.44	1.1	2.8	0.07	0.22	394085	3790816	sed
Arroyo Seco	3.0	0.3	2.18	0.21	4.89	0.44	0.7	2.8	0.06	0.19	394042	3790846	sed
Arroyo Seco	3.0	3	2.32	0.21	4.89	0.44	6.8	2.8	0.06	0.19	394048	3790853	?
Arroyo Seco	3.0	0.1	1.23	0.21	4.88	0.44	0.2	2.8	0.09	0.28	394066	3790866	sed
Fall Creek	1.9	2	10.5	0.025	0.26	0.02	83.9	0.5	0.20	0.06	392877	3796770	?
Fall Creek	3.7	0.7	12	0.025	0.26	0.02	29.4	0.3	0.20	0.12	392885	3796758	sed
Fall Creek	3.9	0.55	7	0.025	0.26	0.02	23.1	0.3	0.23	0.16	392890	3796746	sed
Fall Creek	3.9	0.5	23	0.025	0.26	0.02	21.0	0.3	0.16	0.09	392895	3796728	sed
Classic Canyon	1.5	0.4	1.5	0.05	0.07	0.01	67.1	1.3	0.09	0.13	392893	3796323	sed
Classic Canyon	2.3	0.8	6.5	0.05	0.07	0.01	127.9	0.9	0.07	0.10	392684	3796459	sed
Classic Canyon	2.3	0.5	9	0.05	0.07	0.01	80.0	0.9	0.07	0.08	392675	3796474	sed
Classic Canyon	1.4	1.3	2	0.05	0.07	0.01	207.9	1.5	0.07	0.10	392675	3796474	br
Classic Canyon	1.6	0.3	2	0.05	0.07	0.01	48.0	1.2	0.07	0.12	392675	3796474	sed
Fox Creek	2.3	1	3	0.03	7.27	0.65	1.5	0.5	0.94	0.10	391431	3797425	br
Fox Creek	3.5	0.75	13	0.03	7.27	0.65	1.1	0.3	0.83	0.09	391467	3797391	sed
Fox Creek	3.5	1	3.5	0.03	7.27	0.65	1.5	0.3	1.00	0.16	391482	3797388	sed
Fox Creek	3.4	0.85	7.5	0.03	7.27	0.65	1.3	0.4	0.89	0.11	391495	3797399	sed
Fox Creek	2.8	0.7	3.5	0.03	7.27	0.65	1.1	0.4	1.07	0.13	391501	3797420	sed
Fox Creek	2.0	0.5	27	0.03	7.27	0.65	0.8	0.6	0.71	0.04	391565	3797461	sed
Fox Creek	3.0	2	6	0.03	7.27	0.65	3.1	0.4	0.95	0.11	391582	3797472	?
Fox Creek	3.5	0.7	3.5	0.03	7.27	0.65	1.1	0.3	1.07	0.16	391611	3797487	sed
Fox Creek ^b	3.5	0.5	16	0.03	7.86	0.71	0.7	0.3	0.81	0.08	391524	3796514	sed
Millard Canyon	2.9	0.3	17	0.05	2.00	0.18	1.7	0.7	0.30	0.07	394833	3787038	sed

Table S1. Compilation of natural plunge pools (continued)

River	r_{pool} (m)	h_{pool} (m)	H_{drop} (m)	D (m)	Q_{2yr} (m ³ /s)	$b_{lat}(\delta)$ (m)	$h_{pool} /$ $b_{lat}(\delta)$	$l_{e_fold} /$ $b_{lat}(r_{pool})$	$r_{max} /$ r_{crit}	$r_{pool} /$ r_{crit}	UTM Easting	UTM Northing	Pool floor
Wolfskill Canyon	5.0	1.2	9	0.17	0.55	0.05	24.5	1.4	0.07	0.17	430738	3781897	sed
Dry Meadow Ck	6.2	3.9	2.66	0.1	3.66	0.33	11.8	0.6	0.06	0.38	366139	3984275	?
Dry Meadow Ck	4.8	2	3.74	0.1	3.66	0.33	6.1	0.8	0.32	0.25	366143	3984266	?
Dry Meadow Ck	9.2	5	5.34	0.1	3.66	0.33	15.2	0.4	0.34	0.40	366146	3984250	sed
Dry Meadow Ck	5.9	4.62	3.89	0.1	3.66	0.33	14.0	0.7	0.32	0.30	366155	3984237	sed
Dry Meadow Ck	4.9	2.21	1.24	0.1	3.66	0.33	6.7	0.8	0.09	0.44	366159	3984225	br
Dry Meadow Ck	7.4	2.53	2.85	0.1	3.66	0.33	7.7	0.5	0.20	0.44	366166	3984219	?
Dry Meadow Ck	4.5	2.55	2.36	0.1	3.66	0.33	7.7	0.9	0.07	0.29	366175	3984206	sed
Dry Meadow Ck	4.4	1.35	11	0.1	3.66	0.33	4.1	0.9	0.32	0.13	366191	3984207	?
Dry Meadow Ck	6.4	3.57	13.99	0.1	3.66	0.33	10.8	0.6	0.32	0.17	366246	3984191	?
Kapaa Stream	4.0	3	6	0.15	111.73	10.06	0.3	1.5	1.40	0.15	464537	2444738	?
SF Wailua River	40.0	10	49	0.1	412.33	37.11	0.3	0.1	2.34	0.46	460951	2436662	?
Huleia Stream	22.3	7.5	5.6	0.2	177.76	16.00	0.5	0.4	1.22	0.81	456876	2427414	?
Kaulaula Valley	3.7	0.2	39	0.3	2.31	0.21	1.0	3.3	0.08	0.05	425986	2442220	?
Hanakapiai Stream	22.0	4.7	120	0.3	27.19	2.45	1.9	0.5	0.11	0.08	438743	2453474	?

^a Data for natural plunge pools compiled by *Scheingross and Lamb* [2016]. Pool depth (h_{pool}) refers to the vertical distance from the downstream plunge-pool lip to the pool floor (i.e., $h_{pool} = z_{lip} - z_{sed}$) which was typically sediment but for some pools the bedrock floor was exposed (as indicated in the "pool floor" column where "sed" and "br" indicate a sediment versus bedrock floor, respectively, and "?" indicates no distinction was made). Waterfalls were surveyed at low flow when pools were often partially filled with sediment, and pool depths should be greater when the bedrock floor is exposed and vertical erosion occurs. The radial jet half width at $b_{lat}(\delta)$ was calculated with Eq. (29), and we interpret the generally large values of $h_{pool}/b_{lat}(\delta)$ to suggest our assumption that falling grains impact the pool floor without significant deflection from radial jets likely holds in natural pools. Similarly, $l_{e_fold}/b_{lat}(r_{pool})$ represents the ability of particles within the radial wall jet to detach from the flow and impact the pool wall, and was calculated assuming a drag coefficient of 1, where l_{e_fold} is an e-folding length scale for particles slowing due to drag. r_{max}/r_{crit} is the ratio of maximum plunge-pool radius (r_{max} , set by the sediment transport capacity of the pool) relative to the critical radius needed for caprock failure via undercutting (r_{crit}). Additional variables: D - estimated median grain size in the river reach adjacent to the plunge pool, r_{pool} - field-measured plunge-pool radius, H_{drop} - field-measured waterfall drop height, Q_{2yr} - two-year recurrence interval water discharge.

^b This waterfall occurs downstream of the Fox Creek knickzone and was not included in the Fox Creek reference site calculations.

Table S2. Summary of parameters for waterfall plunge-pool erosion experiments^a

Experiment ID	Water discharge (l/s)	Waterfall drop height (m)	Grain diameter (mm)	Sediment flux (g/s)	Flow depth at brink (cm)	Upstream flume slope (deg)	Downstream flume slope (deg)	Total run time (hr)
Exp1	0.58	0.42	2.4	9	1.3	2	10	113
Exp2	0.58	0.53	7	9 - 45	1.3	2	14.5	51

^a All experiments used a commercially available, closed-cell polyurethane foam bedrock simulant (<http://www.precisionboard.com>), with 0.32 MPa tensile strength. In both experiments the upstream flume is 9.6 cm wide, 2.06 m long, is tilted to ~2 degrees, and has a fixed bed of 2.4 mm sub-rounded quartz grains. The downstream flume is 24 cm wide and 80 cm long, and in which we fixed a polyurethane foam block (~18 cm wide by 27 cm long).