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Mass balance controls on sediment scour and bedrock erosion in waterfall plunge pools

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ABSTRACT

Waterfall plunge pools experience cycles of sediment aggradation and scour that modulate bedrock erosion, habitat availability, and hazard potential. We calculate sediment flux divergence to evaluate the conditions under which pools deposit and scour sediment by comparing the sediment transport capacities of waterfall plunge pools (Q_{sc_pool}) and their adjacent river reaches (Q_{sc_river}). Results show that pools fill with sediment at low river discharge because the waterfall jet is not strong enough to transport the supplied sediment load out of the pool. As discharge increases, the waterfall jet strengthens, allowing pools to transport sediment at greater rates than in adjacent river reaches. This causes sediment scour from pools and bar building at the downstream pool boundary. While pools may be partially emptied of sediment at modest discharge, floods with recurrence intervals >10 yr are typically required for pools to scour to bedrock. These results allow new constraints on paleodischarge estimates made from sediment deposited in plunge pool bars and suggest that bedrock erosion at waterfalls with plunge pools occurs during larger floods than in river reaches lacking waterfalls.

INTRODUCTION

Sediment fill and scour cycles in waterfall plunge pools can erode bedrock (e.g., Scheingross and Lamb, 2017), modify habitat (e.g., Magoulick and Kobza, 2003), and form deposits that preserve paleoclimate information (e.g., Nott and Price, 1994). For example, plunge pool erosion can drive waterfall retreat (Gilbert, 1890) but requires that pools scour to their bedrock floors because deposited sediment armors the bed, preventing incision (Lamb et al., 2007; Scheingross and Lamb, 2017). Deep pools are refuge for fish (e.g., Nielsen et al., 1994), and when pools fill with sediment, this habitat is lost and the pools instead create a hazard because sediment fills can liquefy by plunging jets, forming debris flows (e.g., Griffiths et al., 2004). Bars formed at the downstream boundary of plunge pools can be long lived and are used in paleodischarge and paleoclimate estimates (e.g., Carling and Grodek, 1994; Nott et al., 1996).

Most previous plunge pool studies have focused on sediment motion thresholds and the controls of plunge pool depth under clear water flow (zero sediment supply), as occurs below dams (e.g., Mason and Arumugam, 1985; Stein et al., 1993; Pagliara et al., 2006). Such a theory cannot explain sediment fill and evacuation in natural pools where sediment is supplied from upstream. Instead, mass balance dictates that pools fill when the upstream sediment supply exceeds the ability of the pool to transport that sediment, and pools scour when the sediment supply is less than the pool transport capacity. Plunge pool sediment transport capacity theory has only recently been developed (Scheingross and Lamb, 2016), and the relative transport capacities of plunge pools and rivers have not been compared.

Sediment deposited below waterfalls suggests that plunge pools respond to different transport thresholds than their adjacent river reaches (Carling, 1995). Waterfall plunge pools typically have bars at their downstream boundary that are coarser than the adjacent riverbed material, yet the pools are commonly filled with finer sediment than the adjacent riverbed (Fig. 1; Fig. S1 in the Supplemental Material[1]) (e.g., Carling, 1989, 1995). The juxtaposition of fine-grained pool deposits and coarse-grained bars, neither of which match the riverbed material, suggests that plunge pools likely experience sediment transport at different times than adjacent river reaches. Different thresholds for bedrock erosion in pools relative to rivers can create spatially variable erosion rates along rivers, which can alter knickpoint response to climatic and tectonic perturbations (DiBiase et al., 2015; Scheingross et al., 2020).

We coupled plunge pool and river sediment transport theory to predict when plunge pools transition from sediment aggradation to scour. We built on the previously developed plunge pool sediment transport capacity theory (Scheingross and Lamb, 2016) by using it to model fill and scour cycles in plunge pools, and by comparing the results to field data.

THEORY AND METHODS

By mass balance, plunge pools aggrade when the volumetric sediment flux (L^3/T, where L and T represent units of length and time, respectively) into the pool (Q_{s_river}) exceeds the flux out (Q_{s_pool}) (Fig. 2A). We hypothesize this occurs at low water discharge because the waterfall jet diffuses within the pool, limiting sediment export from the pool (Scheingross and Lamb, 2016). In contrast, during high discharge, the falling jet impinges on the pool floor, allowing sediment transport in the pool to exceed that of the adjacent channel reaches and resulting in sediment scour and potentially bedrock erosion (Fig. 2A) (e.g., Keller, 1971; Lisle, 1979). Furthermore, when Q_{s_pool} exceeds the river transport capacity downstream, bars form at the pool boundary to achieve mass balance.

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[1]Supplemental Material. Methods, Tables S1 and S2 (data), and Figures S1–S4. Please visit https://doi.org/10.1130/GEOL.S.14524266 to access the supplemental material, and contact editing@geosociety.org with any questions.

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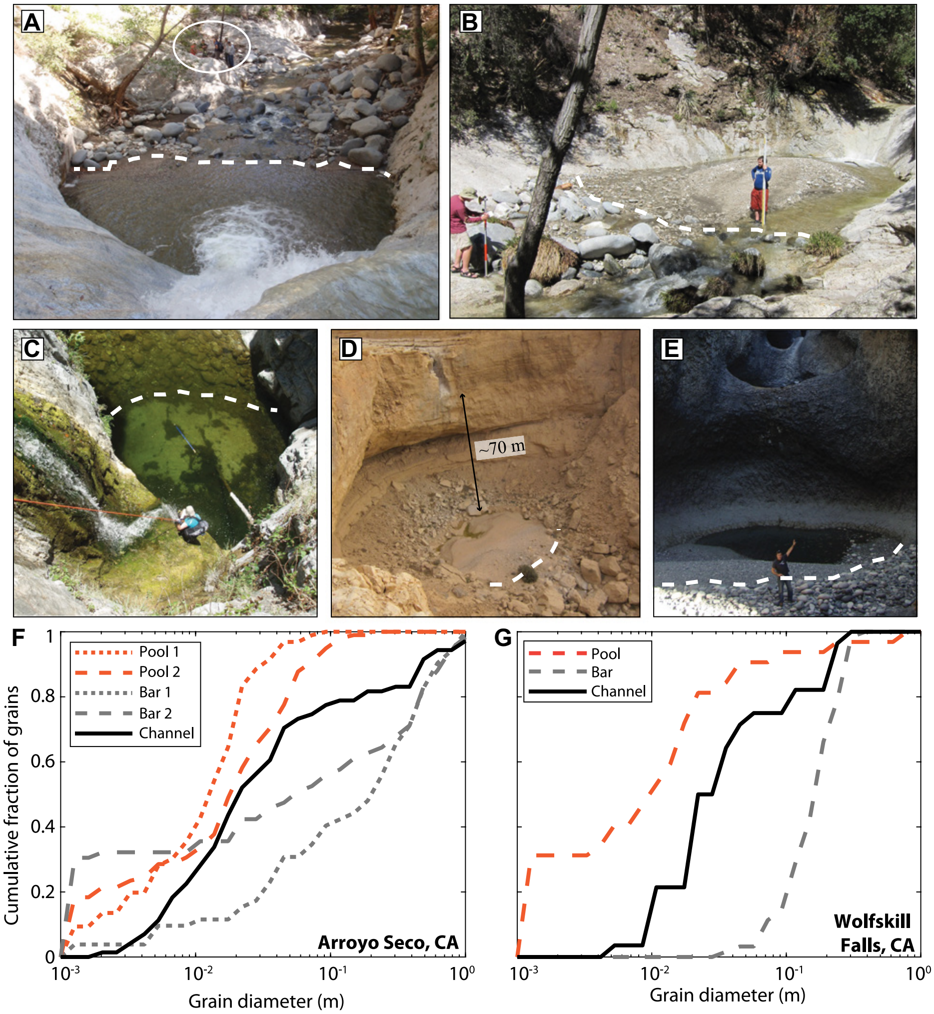

Figure 1. (A–E) Plunge pools with fine-grained fills and coarse-grained bars in the San Gabriel Mountains, California, USA (A–C), Nahal Heimar, Israel (D), and Siete Tazas, Chile (E). White dashed lines indicates the boundary between relatively fine sediment deposited in the plunge pool and coarse sediment deposited in the bar immediately downstream of the plunge pool. Note the presence of people (circled) in A for scale. (F,G) Grain-size distribution for pools in the San Gabriel Mountains (Table S2 [see footnote 1]). CA—California. Photos in C and D were provided by B. Pelletier and G. Vergara Muñoz, respectively.

To explore this hypothesis, we modeled pool aggradation-scour cycles with an Exner equation:

$$\frac{d\eta}{dt} = -\frac{1}{(1-p)} \frac{Q_{s\_pool} - Q_{s\_river}}{A_{pool}}, \qquad (1)$$

where η is the elevation of the sediment bed in the pool, t is time, A_{pool} is the pool plan-view area, and $p = 0.35$ is sediment porosity. For simplicity, our model uses a single characteristic particle size for grain-size mixtures (e.g., median size), which is typical in sediment transport studies (e.g., Buffington and Montgomery, 1997). We do not expect that size-selective transport, which can be accounted for by explicit modeling of grain-size mixtures (e.g., Parker, 1990; Wilcock and Crowe, 2003), changes our primary findings (see the Supplemental Material). Bedrock rivers commonly evolve to transport the imposed sediment supply at transport capacity (Finnegan et al., 2007; Phillips and Jerolmack, 2016; Pfeiffer et al., 2017); therefore, we assumed transport-limited conditions, and set Q_{s_pool} and Q_{s_river} equal to the plunge pool (Q_{sc_pool}) and river (Q_{sc_river}) volumetric sediment transport capacity, respectively. The transition between sediment aggradation and scour in plunge pools (i.e., $d\eta/dt = 0$) occurs when $Q_{s\_pool} = Q_{s\_river}$.

We calculated plunge pool sediment transport capacity following Scheingross and Lamb (2016). This model evaluates Q_{sc_pool} using the waterfall height, plunge pool geometry, sediment size, and the flow hydraulics and geometry of the adjacent river reach (see the Supplemental Material). Because the critical Shields stress for incipient motion in plunge pools, τ_{*c_pool}, is not well defined, we allowed it to vary from 0.03 to 0.06. We calculated the total river sediment transport capacity (the sum of the bedload and suspended load capacities), Q_{sc_river}, following Lamb et al. (2008a) (see the Supplemental Material). We set river channel critical Shields stress to $\tau_{*c\_river} = 0.15S^{0.25}$, where S is bed slope (Lamb et al., 2008b), and assumed steady, uniform flow (see the Supplemental Material).

We solved for the discharge at which $d\eta/dt = 0$ numerically by calculating Q_{sc_river} and Q_{sc_pool} across a range of discharges and found the discharge at which $Q_{sc\_river} = Q_{sc\_pool}$ (see the Supplemental Material). We evaluated our theory using a reference site, Middle Switzer Falls, California, USA (Table S1 in the Supplemental Material), which is part of a database of 75 waterfalls surveyed by Scheingross and Lamb (2016). Middle Switzer Falls has characteristic values of a 3-m-tall waterfall, 4 m pool radius, 3.5% channel slope above and below the waterfall, 5 m channel width, and median river particle size of 2.1 cm (Scheingross and Lamb, 2016). We estimated that the bedrock pool depth was equal to the pool radius (4 m) (see the Supplemental Material).

RESULTS

Relationship between Sediment Transport Capacity and Water Discharge

Results show that Q_{sc_river} and Q_{sc_pool} increase with water discharge, Q_w, but differ in the threshold discharge for initial motion (Fig. 2). Rivers transport sediment when $\tau_* > \tau_{*c\_river}$, while sediment transport out of plunge pools requires a discharge that both moves sediment ($\tau_* > \tau_{*c\_pool}$) and suspends particles over the pool walls (Scheingross and Lamb, 2016). For deep pools, sediment export from the pool typically requires larger water discharges than needed for transport in adjacent river reaches (Fig. 2B). These different transport thresholds cause deep pools to aggrade at low water discharge when sediment is transported in rivers but cannot be evacuated from pools (Fig. 2B).

Increasing water discharge increases the river sediment transport capacity (Fig. 2). However, above the threshold for sediment transport out of pools, Q_{sc_pool} increases with discharge at a faster rate than Q_{sc_river} because the jet impinges with greater shear stress on the pool floor and because sediment suspension is driven by the upward return flow exiting the plunge pool (Fig. 2B). The return flow is faster for greater water discharges, as larger discharges produce wider waterfall jets, thereby forcing the return flow to pass through a smaller cross-sectional area. This combination results in a transition in pools from net aggradation ($Q_{sc\_river} > Q_{sc\_pool}$) at low flows to net degradation ($Q_{sc\_river} < Q_{sc\_pool}$) at high flows, with the water discharge at the transition point denoted as Q_{w_scour} (Fig. 2). For the scour regime ($Q_w > Q_{w\_scour}$), sediment transport out of the pool exceeds the capacity of the downstream river reach. This convergence of transport forces bar formation at the downstream pool boundary (e.g., Fig. 1), even though the discharge is far above the threshold for incipient sediment motion (Fig. 2).

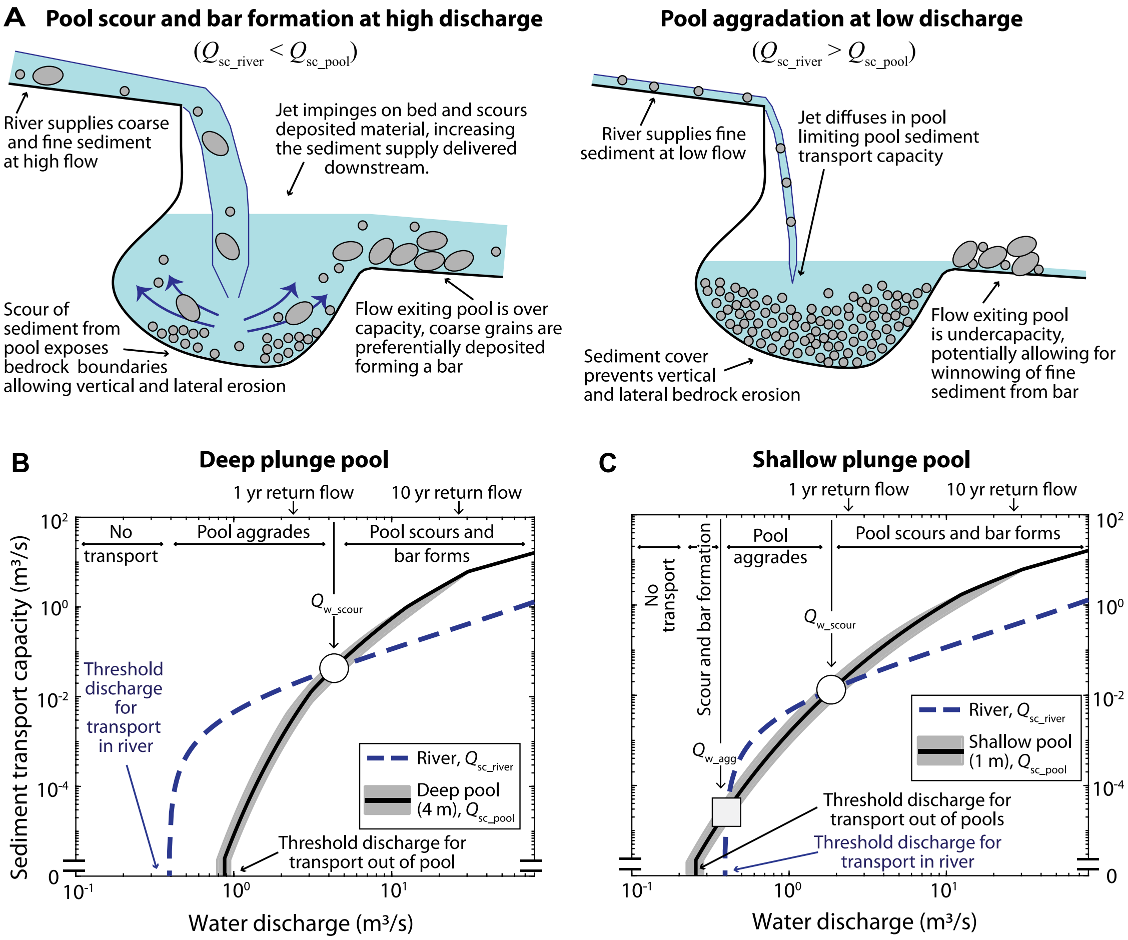

Figure 2. (A) Schematic of pool scour and aggradation. (B,C) Plunge pool and river sediment-transport capacity for deep and shallow pool. Gray shading shows variability in the sediment transport capacities of waterfall plunge pools (Q_{sc_pool}) for $0.03 < \tau_{*c\_pool}$ (critical Shields stress for incipient motion in plunge pools) < 0.06. Circles show the transition from plunge-pool sediment aggradation to sediment scour at high discharge (Q_{w_scour}); square shows transition aggradation to scour at low discharge (Q_{w_agg}).

Plunge pool sediment transport capacity is highly sensitive to pool depth. For shallow pools (e.g., pools with alluvial fills), the threshold for transport out of the pool can correspond to a lower water discharge than the threshold for fluvial transport, resulting in a second regime of pool scour at low flows (Fig. 2C). This low-flow scour regime occurs because, for shallow pools, sediment is more easily suspended up and over the pool lip and because the jet experiences less drag before reaching the pool floor, resulting in higher stresses on the pool floor. This scour is transient, causing pools to deepen to the point where $Q_{sc\_river} = Q_{sc\_pool}$, and is common when pools fill with sand following wildfire (Fig. S2). We denote the discharge at the transition between the low-flow scour and pool aggradation regimes as Q_{w_agg}.

Influence of Varying Grain Size and Channel, Waterfall, and Pool Geometry

Changes in grain size and geometry of the channel, waterfall, and pool all can influence sediment transport capacity, thereby changing the magnitude of Q_{w_agg} and Q_{w_scour}. We solved for Q_{sc_pool} and Q_{sc_river} by systematically varying pool depth and radius, channel slope, grain diameter, and waterfall height while holding all other parameters constant (Fig. 3).

Channel slope exerts a large influence on river sediment transport but has negligible influence on plunge pool sediment transport (Fig. 3A). Therefore, plunge pools downstream of low-gradient channels can scour sediment at lower discharges because there is reduced sediment supply from upstream. As channel slope increases with all else held constant, rivers transport more sediment while the pool transport capacity stays approximately constant, requiring larger water discharges for pools to scour (Fig. 3A).

Increasing grain size decreases Q_{sc_river} and Q_{sc_pool} because larger grains require greater shear stresses (and thus greater discharges) for transport. This effect limits plunge pools more than rivers because increased settling velocities for large grains make them difficult to suspend out of deep pools. This results in plunge pools transitioning from scour to aggradation to no transport as grain size increases under constant water discharge (Fig. 3B). If water discharge and the transported grain size covary, as is common in nature, pools may maintain a state of scour or aggradation.

Variations in waterfall height and pool geometry influence Q_{sc_pool} but not Q_{sc_river}. Increasing waterfall height increases the jet velocity and thereby increases Q_{sc_pool}. This allows pools below taller waterfalls to transition from aggradation to scour at lower discharges than pools below shorter waterfalls (Fig. 3C). Deeper and wider pools have a lower sediment transport capacity because shear stress at the pool floor decreases with depth and it is more difficult to transport sediment over the pool walls as pools grow in depth and radius. This causes the transition from pool aggradation to scour to increase as pools deepen and widen, with all else held constant (Figs. 3D and 3E). At very shallow pool depths, pools can scour at low flows when transport in the river becomes negligible (Fig. 3D).

Relative Frequency of Plunge Pool Bedrock Erosion versus River Sediment Transport

To find the return period of floods capable of exposing and eroding the pool bedrock floor, we analyzed a preexisting database of 75 waterfalls (Scheingross and Lamb, 2016) and historical water discharge records (see the Supplemental Material). We calculated the conditions under which $Q_w > Q_{w\_scour}$ using a pool depth equal to the depth to bedrock. To account for potential sediment supply limitations, we varied the ratio Q_{s_river}/Q_{sc_river} from 0.1 to 1. While the onset of sediment motion in river channels occurred for floods with return periods <10 yr in 97% of the field examples analyzed, bedrock erosion in pools required larger floods with longer return periods (only 36%–53% of the surveyed pools, depending on Q_{s_river}/Q_{sc_river}, are predicted to erode in floods with return periods <10 yr) (Fig. 4; Fig. S3).

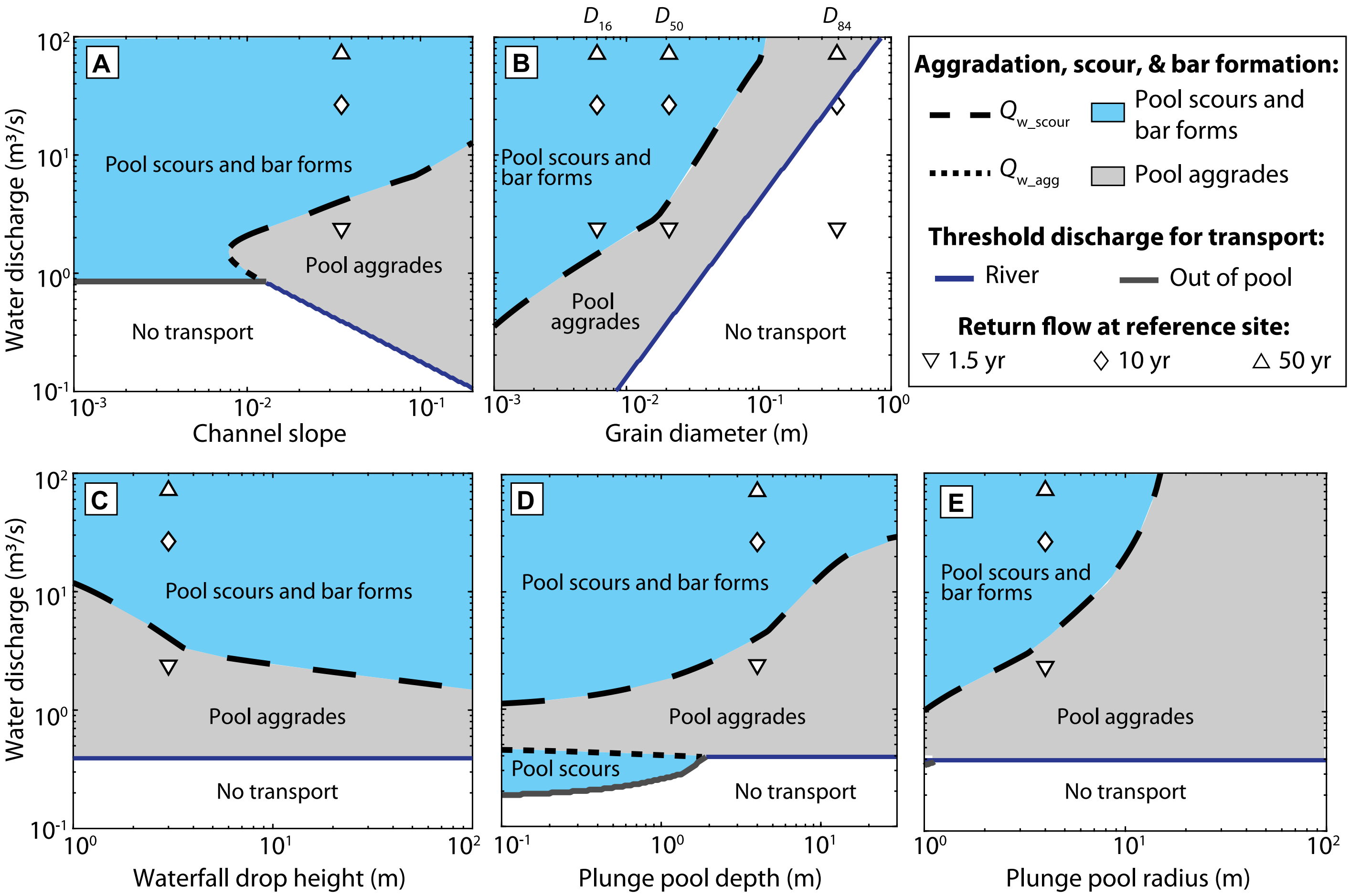

Figure 3. Phase space of pool scour and aggradation as function of channel slope (A), grain diameter (B), waterfall height (C), pool depth (D), and pool radius (E). Q_{w_scour} and Q_{w_agg} indicate the transition between plunge pool sediment scour and sediment aggradation regimes for high and low discharges, respectively. Calculations use Middle Switzer Falls reference site (California, USA) values and critical Shields stress for incipient motion in plunge pools (τ_{*c_pool}) = 0.045. D_{16}, D_{50}, and D_{84} represent grain diameters for which 16%, 50%, and 84% of the grain size distribution is finer, respectively.

DISCUSSION

Our theory provides a quantitative framework for modeling cycles of plunge pool sediment fill, scour, and bar formation, with implications for habitat, reconstructing past discharges, and landscape evolution. Isolating mechanistic controls on pool alluviation allows prediction of aquatic habitat availability associated with deep pools. For example, our work shows pools are more likely to fill after disturbances like wildfire and landsliding that can cause upland rivers to shift from supply- to transport-limited regimes, thereby increasing the sediment flux into pools. Similarly, prolonged low-flow periods may allow pools to remain within the aggradation regime for extended periods, causing pool aggradation and habitat loss during dry periods when ecosystems may already be stressed (Magoulick and Kobza, 2003) (Fig. 3).

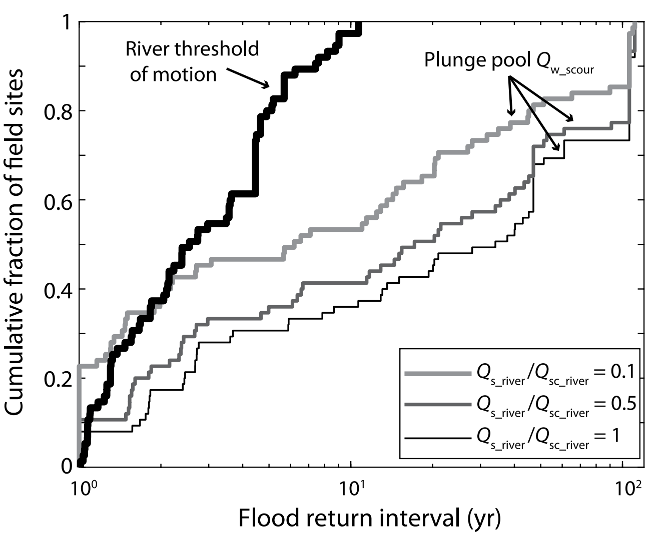

Figure 4. Comparison of flood return period for mobilizing sediment in river reaches ($\tau_* > \tau_{*c\_river}$; τ_*—Shields stress; τ_{*c_river}—critical Shields stress for incipient motion in the river channel) versus for scouring plunge pools to bedrock ($Q_w > Q_{w\_scour}$; Q_w—water discharge; Q_{w_scour}—water discharge at the transition point) for waterfalls surveyed by Scheingross and Lamb (2016). All calculations use τ_{*c_pool} = 0.045. Q_{s_river}—river sediment flux; Q_{sc_river}—river sediment transport capacity.

Our work shows previous methods to estimate paleodischarge using the threshold of motion to form pool bars (e.g., Carling and Grodek, 1994) may underestimate the minimum bar-forming discharge (Fig. 2). This is because bars form when the mass flux of sediment at the downstream end of the pool exceeds the river's transport capacity (i.e., $Q_w > Q_{w\_scour}$), and these conditions are typically above the threshold of sediment motion in the river (Fig. 2). For example, for the case shown in Figure 2B, using the threshold of motion results in an ~10× lower estimate of the minimum bar-forming discharge relative to using Q_{w_scour}. Therefore, estimates of Q_{w_scour} (via measuring the grain size of bar deposits, in addition to waterfall and river geometry) may improve paleodischarge estimates relative to using the threshold of motion.

The large water discharges needed for pool bedrock erosion are greater than that required for the onset of sediment transport in river reaches (the threshold commonly used to predict the onset of bedrock river incision; e.g., Tucker, 2004; Sklar and Dietrich, 2006; Scherler et al., 2017) (Fig. 4). While many waterfall erosion mechanisms exist, most mechanisms require erosion of exposed bedrock within the pool (e.g., Howard et al., 1994; Lamb et al., 2007; Scheingross et al., 2017) or transport of sediment away from the waterfall base (Gilbert, 1895; Lamb et al., 2006). Our results suggest that the threshold discharge for bedrock erosion is commonly greater for plunge pools than for adjacent river reaches (Fig. 4). These findings support the idea that waterfalls may erode at a different pace than river reaches (DiBiase et al., 2015), highlighting the likely importance of large, rare floods in knickpoint migration.

CONCLUSIONS

Our results show how mass-flux divergences—set by the difference between river and plunge pool sediment transport—control pool aggradation, scour, bar formation, and when waterfalls erode bedrock. At low water discharge, pools aggrade because the waterfall jet is too weak to penetrate the pool water and transport sediment at the rate it is supplied from upstream (Fig. 2). At high discharge, the waterfall jet impinges on the pool floor, and the high-velocity return flow within the pool causes Q_{sc_pool} to exceed Q_{sc_river}, sediment scour within the pool, and bar formation at the downstream pool margin (Fig. 2). The mass balance framework employed here explains observations of alluviated pools and downstream boulder bars (Fig. 1), provides a quantitative framework for predicting pool filling and constraining past discharges, and highlights waterfall erosion can occur during floods of different magnitude and frequency than bedrock erosion of lower-gradient river channels.

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