Waterfall height sets the mechanism and rate of upstream retreat

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Abstract

Waterfalls are among the fastest eroding parts of river networks, but predicting natural waterfall retreat rates is difficult due to multiple processes which can drive waterfall erosion. We lack data on how waterfall height influences the mechanism and rate of upstream waterfall retreat. We address this knowledge gap with experiments testing the influence of drop height on waterfall retreat. Our experiments show that shorter waterfalls retreat up to five times faster than taller waterfalls, when bedrock strength, sediment supply, and water discharge are constant. This retreat rate difference is due to a change in the erosion mechanism. Short waterfalls retreat by the formation of several small, rapidly eroding bedrock steps (i.e., cyclic steps), whereas tall waterfalls tend to form large bedrock plunge pools where lateral plunge pool erosion allows headwall undercutting and subsequent waterfall retreat. Because waterfall height can be partially set by the waterfall formation mechanism, our results highlight that the rate of

waterfall retreat and subsequent landscape evolution can be modulated by the processes that form waterfalls.

Introduction

External forcing of river base level via sea level change or tectonic processes can cause the formation of steepened channel profiles, or knickzones, which are often composed of multiple waterfalls (Cook et al., 2013; Howard et al. 1994). As waterfalls and knickzones erode, they retreat upstream, thereby transmitting base level perturbations to the upstream catchment (Whipple and Tucker, 1999; Whittaker, 2011). This upstream propagation influences both the river and adjacent hillslopes; for example, retreating waterfalls steepen adjacent hillslopes, increasing landslides, and impacting subsequent river erosion (Gallen et al.,2011; Shobe et al., 2016; Baynes et al, 2022). Predicting how landscapes respond to base level perturbations, and inferring past base level perturbations from topography, requires understanding the mechanism and rate of waterfall retreat. Water discharge (Baynes et al., 2018, Bishop et al., 2005), sediment flux (Baynes et al., 2022, Jansen et al., 2011) and bedrock strength (Hayakawa and Matsukura, 2003, Raming and Whipple, 2022; Grimaud et al., 2016) are well known to influence waterfall retreat, but there has been comparatively less study of how waterfall height influences retreat rate (Hayakawa and Matsukura, 2003, Lamb et al., 2007).

We propose that the mechanism and rate of waterfall retreat varies with waterfall height, even when bedrock strength, flow discharge, and sediment flux are constant.

Excluding cases where waterfalls form on locally resistant beds (e.g., Holland and Pickup, 1976; Chilton and Spotila, 2022), the initial height of a waterfall is likely set by its formation mechanism. For example, glacial erosion and subsequent ice retreat can sculpt waterfalls ~10^1 – 10^2 m tall (e.g., Yosemite Falls, USA), whereas self-formed waterfalls tend to be tens of cm to meters tall, with waterfall height only a few multiples of river flow depth (Scheingross et al., 2019; Groh and Scheingross, 2021). Changes in rock uplift rate, fault displacement and sea level tend to produce knickzones (e.g., Wobus et al., 2006; Yanites et al., 2010; Crosby and Whipple, 2006). In cases, this forcing also creates individual waterfalls (e.g., DiBiase et al., 2015; Malatesta and Lamb, 2017; Mackey al., 2014), the initial height of which we expect should be limited by the magnitude of the external perturbation. If waterfall retreat rate is linked to waterfall height, this means that the process creating waterfalls may modulate the rate at which that perturbation is translated upstream.

We expect that waterfall retreat rate should scale inversely with waterfall height because taller waterfalls require erosion and transport of larger volumes of rock for the same amount of horizontal retreat relative to shorter waterfalls (Hayakawa and Matsukura, 2003). Even though particles falling from taller waterfalls have higher impact energy, this extra kinetic energy of impact is generally not large enough to overcome the requirement of eroding more mass. For example, for waterfalls retreating via headwall undercutting (Figs. 1a-c), upstream retreat is more likely to be set by the rate and energy of lateral particle impacts in the plunge pool, rather than vertical impacts from particles falling from the top of the waterfall (Gilbert, 1896, Haviv et al., 2010). The erosive power of lateral particle impacts is more sensitive to plunge pool width and depth than to waterfall height (Scheingross and Lamb, 2017), suggesting that increasing waterfall height may slow retreat for this specific mechanism, due to the need to erode larger rock volumes for the same horizontal retreat length. For waterfalls that retreat by the formation of small, vertically incising bedrock steps (i.e., cyclic steps) formed above the waterfall lip (Lamb et al., 2007, Yamaguchi et al. 2017, Scheingross et al., 2019) (Figs.1d-f), the retreat rate should be set by the spacing and vertical incision rate of these cyclic steps (Lamb et al., 2007, Yamaguchi et al. 2017). Cyclic step spacing, and thus waterfall retreat rate, is likely set by the flow conditions upstream of the waterfall and independent of waterfall height (Izumi et al., 2017; Haviv et al., 2006). Thus, under the same flow condition, shorter waterfalls should retreat faster than taller waterfalls due to the need to erode less total bedrock.

Determining how waterfall height sets the mechanism and rate of upstream retreat is essential to predicting how perturbations in climate and tectonics influence the evolution of steep landscapes. Addressing this knowledge gap is difficult in the field because variation in lithology, sediment and water supply, base level history and more complicate isolating individual variables. Here, we show results from a controlled laboratory experiment isolating the influence of waterfall height on waterfall retreat mechanism and rate.

Experimental Setup

Our experiment uses a 3 m long, 0.05 m wide rectangular channel tilted to 2% slope with a weak concrete bed as a bedrock simulant (e.g., Yamagchi et al. 2017; Mishra et al. 2017; Inoue and Nelson, 2020) (Supplementary Information). Like natural rivers, the concrete erodes via particle-impact abrasion, and cannot be eroded by water alone. We modeled the initial waterfall morphology after Oiran-buchi (Fig. 1e) and installed a 45° sloping waterfall two meters upstream of the flume outlet. We conducted three experiments with constant concrete strength, flow discharge (0.19 l/s), sediment supply (50 g/min of 1.4 mm diameter sand), and run time (15 hr), but different initial waterfall heights, H_{wf}: 5 cm (Run 1), 10 cm (Run 2), and 20 cm (Run 3). Holding the waterfall face slope constant at 45º resulted in initial waterfall lengths of ~7 cm (Run 1), ~14 cm (Run 2), and ~28 cm (Run 3) (Fig. 2). All experiments began with fully turbulent and supercritical flow, producing dynamic similarity for flow hydraulics (Supplementary Information).

Sediment was primarily transported as bedload, but was partially suspended in plunge pools. Concrete erosion produced silt -sized particles that were transported as wash load, and did not contribute to bedrock erosion. Waterfall retreat caused the development of tortuous inner channels (Figs. 3 and S1), making it difficult to measure the evolving topography. After each experiment, we made a mold of the eroded channel and used a 3D scanner to measure topographic change (Supplementary Information).

Results

In Run 1 (H_{wf} = 5 cm), bedload abrasion caused a small step to form ~5 – 10 cm upstream from the initial waterfall lip (Fig. 3a), which vertically drilled to the downstream base level (Fig. 3b) and coalesced with the initial waterfall. This process repeated six times (Figs. 3c, d), causing net upstream waterfall retreat and forming an incised, meandering channel with a sinuosity (the ratio of channel length to valley length) of 1.54 (Fig. 2a, Table S1), similar to previous findings (Dente et al., 2021, Inoue et al., 2021). This observation of upstream retreat driven by successive, drilling pools is consistent with retreat via cyclic step erosion (Lamb et al., 2007, Yamaguchi et al. 2017, Scheingross et al., 2019).

Run 3 (H_{wf} = 20 cm) demonstrated a different retreat mechanism. Here, erosion was focused at the waterfall base with no bedrock steps forming upstream of the lip (Fig. 3g). Vertical sediment impacts formed a deep plunge pool (Fig. 3e), with lateral impacts from suspended sediment undercutting the waterfall face (Fig. 3f). As the pool enlarged, sediment deposited at the pool floor, preventing further vertical erosion, but allowing continued lateral erosion, analogous to past findings (Scheingross and Lamb, 2017; Scheingross et al., 2017). Lateral erosion of the waterfall face caused net upstream retreat, analogous to retreat via headwall undercutting, despite the lack of caprock collapse. Unlike Run 1, the channel upstream of the Run 3 waterfall was relatively straight (sinuosity of 1.03).

Run 2 (H_{wf} = 10 cm) exhibited mixed behavior with the waterfall retreating via both undercutting of the initial waterfall face and temporally intermittent formation of upstream bedrock steps with plunge pools. Run 2 plunge pools were intermediate in size and sinuosity (1.19) relative to Runs 1 and 3.

In all runs, waterfall retreat distance decreased with increasing waterfall height, from 48 cm in Run 1 to 9 cm in Run 3 (Fig. 4, Table S1). Undercutting of the waterfall face for taller waterfalls caused waterfall faces to steepen from the initial 45º cut to 56º and 62º in Runs 2 and 3, respectively. Despite faster retreat rates for shorter waterfalls, shorter waterfalls eroded less total volume relative to taller waterfalls. The total bedrock erosion volume, V_{tot}, more than doubled with waterfall height from 1,410 cm^3 in Run 1 to 2,570 cm^3 in Run 2, and 3,110 cm^3 for Run 3 (Table S1).

To assess the erosional efficiency between experiments, we defined an erosional efficiency metric by normalizing the total erosion volume by the initial waterfall height, $E_{norm} = V_{tot} / H_{wf}$. For Runs 1 and 3, E_{norm} is 281 cm^2 and 155cm^2, respectively, indicating that shorter waterfalls have efficient erosion per unit drop height (Table S1). This analysis suggests that, for the same magnitude of base level perturbation, creation of multiple, short waterfalls should result in more erosion than a single, large waterfall.

Discussion

Our results match field data showing that shorter waterfalls retreat faster than taller waterfalls (Hayakawa and Matsukura, 2003). Unlike previous explanations invoking the need to erode larger rock volumes for tall waterfalls (Hayakawa and Matsukura, 2003), we suggest the difference in retreat rates is driven by changes in the erosion mechanism and waterfall face slope angle. Face steepening for tall waterfalls should reduce retreat rate, because steeper faces receive fewer particle impacts for the same sediment flux. We attribute the high retreat rate in Run 1 due to the maintenance of a relatively low-angle waterfall face (45º) combined with cyclic step drilling which allowed distributed erosion upstream of the waterfall. Furthermore, concentration of erosion in a narrow, inner channel upstream of the waterfall in Run 1 allowed for relatively fast retreat because the same horizontal retreat distance required less erosion volume. In contrast, a steeper waterfall face (62°) and plunge pool undercutting in Run 3 limited erosion of the waterfall face and upstream channel. However, the steeper waterfall face in Run 3 allowed particles to fall the full distance from the waterfall lip to the plunge pool floor. Particles that fall from higher distances impact the pool floor with higher energy and produce more erosion per impact relative to particles falling shorter distances (e.g., Scheingross et al., 2017), perhaps resulting in larger total erosion volumes for the experiments with taller waterfalls.

Our results highlight a more fundamental question. Why does the erosion mechanism change as a function of waterfall height? Bedrock cyclic steps tend to form in steep channels due to the need for high Froude number flows (Izumi et al., 2017). Field observation (Groh and Scheingross, 2021) show that waterfalls with cyclic steps form at slopes >3%, coinciding with the onset of Froude supercritical flow. We test if the steps formed in Run 1 are cyclic steps by comparing the experimentally-observed step wavelength to theoretical predictions (Izumi et al., 2017). In Run 1, six steps formed upstream of the initial waterfall over a 48 cm straight-line distance (Fig. 4); however, the tortuous channel was ~74 cm in length, resulting in a 12.3 cm step wavelength. For the Froude number (1.7) and bed slope (0.02) upstream of the initials steps in Run 1, theory (Izumi et al., 2017) predicts cyclic steps should form with a 13 cm wavelength (Supplementary Information), roughly matching our experimental observations, and suggesting these features are indeed cyclic steps.

The reason for the lack of cyclic step formation in Runs 2 and 3 is less clear. We speculate that the difference in behavior is due to the increase in the Froude number associated with flow acceleration over the waterfall lip. The larger drop height in Runs 2 and 3 led to more distinct free-fall jets relative to Run 1, suggesting both the Froude number at the lip, and acceleration of the flow towards the step were greater in Runs 2 and 3 than in Run 1. This is consistent with the idea that flow upstream of waterfalls with free-falling jets can accelerate under supercritical flow (Haviv et al., 2006). As the Froude number increases, cyclic steps form more readily, but the step wavelength decreases (for example, a Froude number doubling can cause a >90% step wavelength decreases, see Fig. 9c in Izumi et al. (2017)). In Runs 2 and 3, we propose that the Froude number at the lip had become excessively large, causing the step wavelength to become so small that it was impossible to form new, distinct steps separated from the pre-existing waterfall lip. This process of forming a new cyclic step on top of the pre-existing waterfall lip should steepen the waterfall, consistent with our observations of steepening waterfall faces in Runs 2 and 3. This interpretation highlights that the experimental results may be sensitive to our choice of an initial 45° waterfall face, and further experiments exploring the role of waterfall face slope are a target for future work.

Our experimental results match field observations of tall waterfalls that are both undercut and have a single drop, whereas short waterfalls frequently occur in series without undercutting (Fig. 1). To compare between the experimental and field scales we use the ratio of waterfall height to upstream flow depth, H_{wf} / h_{river}. In Run 1 (cyclic-step-driven retreat) $H_{wf} / h_{river} \approx 6$, consistent with the $\sim 3 < H_{wf} / h_{river} < 6$ observed experimentally for self-formed waterfalls (Scheingross and Lamb, 2019). These experimental values of H_{wf} / h_{river} roughly match that of waterfalls retreating via cyclic step erosion in Fig. 1e and 1f which have H_{wf} / h_{river} values of ~1.9 – 4.4 and ~3.0 – 7.5, respectively (Supplementary Information). In contrast, in Run 3 (undercutting-driven retreat) $H_{wf} / h_{river} \approx 25$, roughly matching undercut waterfalls such as Unokonotaki (Fig. 1b) and Niagara Falls (Fig. 1c) which have H_{wf} / h_{river} values of 13.3 – 18.5 and 8.7 –

30.5, respectively. These results suggest that when the height to depth ratio becomes large, cyclic-step-driven retreat is less likely to occur.

Conclusions

Our experiments show that waterfalls with small drop height to flow depth ratios tend to develop cyclic steps with rapid upstream retreat; whereas waterfalls that are tall relative to flow depth lack cyclic step development and instead retreat slowly via plunge pool undercutting. While we performed only three experiments (with no replicates), our experimental results are consistent with existing theory and field observations that give us confidence that the experiments capture the fundamental aspects of waterfall retreat in homogenous rock. Our findings imply that waterfall retreat rate, and perhaps subsequent landscape evolution rates, can be modulated by the processes that form waterfalls (which set waterfall height) and changes in water discharge (which set flow depth). Improving our understand of the height of waterfalls formed by changes in climate and tectonics, lithologic heterogeneity, and autogenic processes is a key next step in predicting rates of landscape evolution.

Acknowledgments

We thank three anonymous reviewers for thoughtful feedback. This work was supported by JSPS KAKENHI Grant Number 22H01602. JSS acknowledges U.S. NSF support (grant EAR-1946342) and E. Groh and S. Rothman for field assistance.

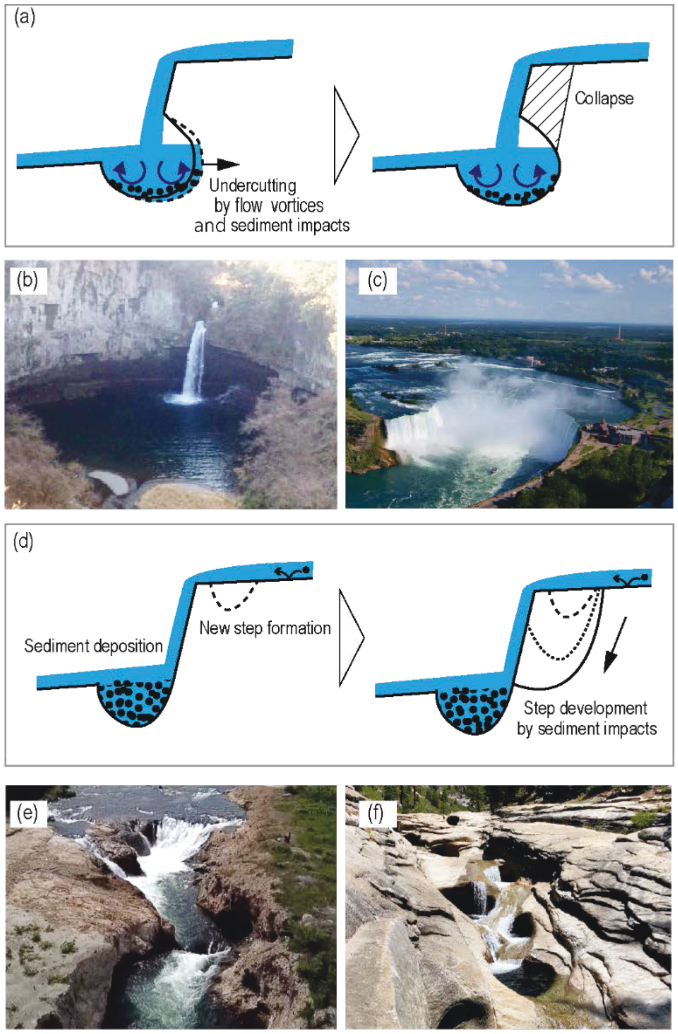

Figure 1. (a) Schematic of waterfall retreat via plunge pool undercutting. (b) Unokonotaki (Kumamoto, Japan) and (c) Niagara Falls (USA / Canada) both retreat via headwall undercutting and caprock collapse. (d) Schematic of retreat via the development of new, vertically drilling cyclic steps. (e) Oiran-buchi (Hokkaido, Japan) and (f) South Fork Silver Creek (California, USA) show retreat likely driven by the creation of new cyclic steps upstream of the original waterfall.

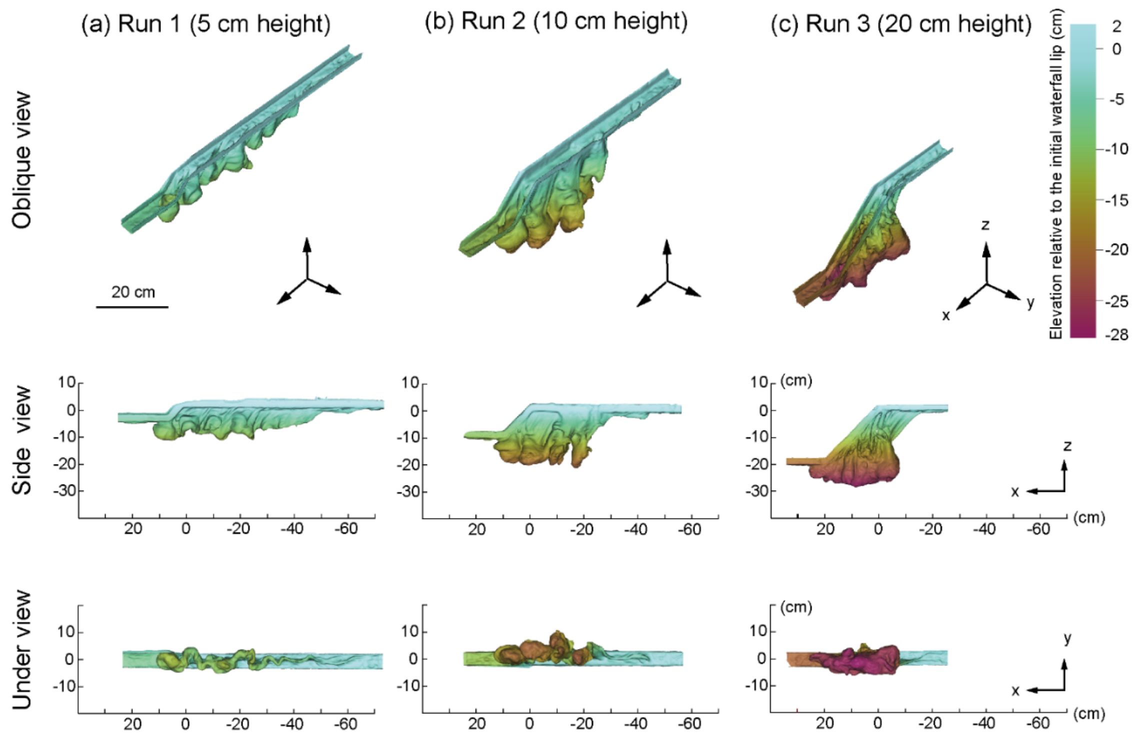

Figure 2. 3D scans of experimental waterfalls, (a) Run 1, (b) Run 2, (c) Run 3. The center of the initial waterfall lip lies at (x, y, z) = (0, 0, 0).

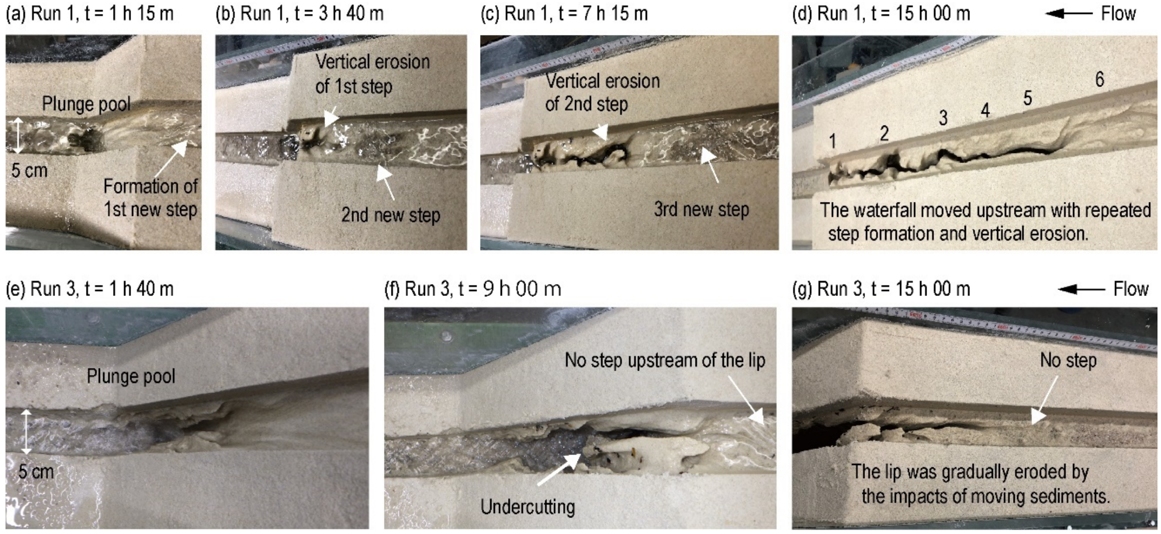

Figure 3. (a) - (d) Waterfall retreat via cyclic step erosion (Run 1), numbers 1 to 6 in (d) show location of steps formed during retreat. (e) - (g) Retreat via undercutting (Run 3).

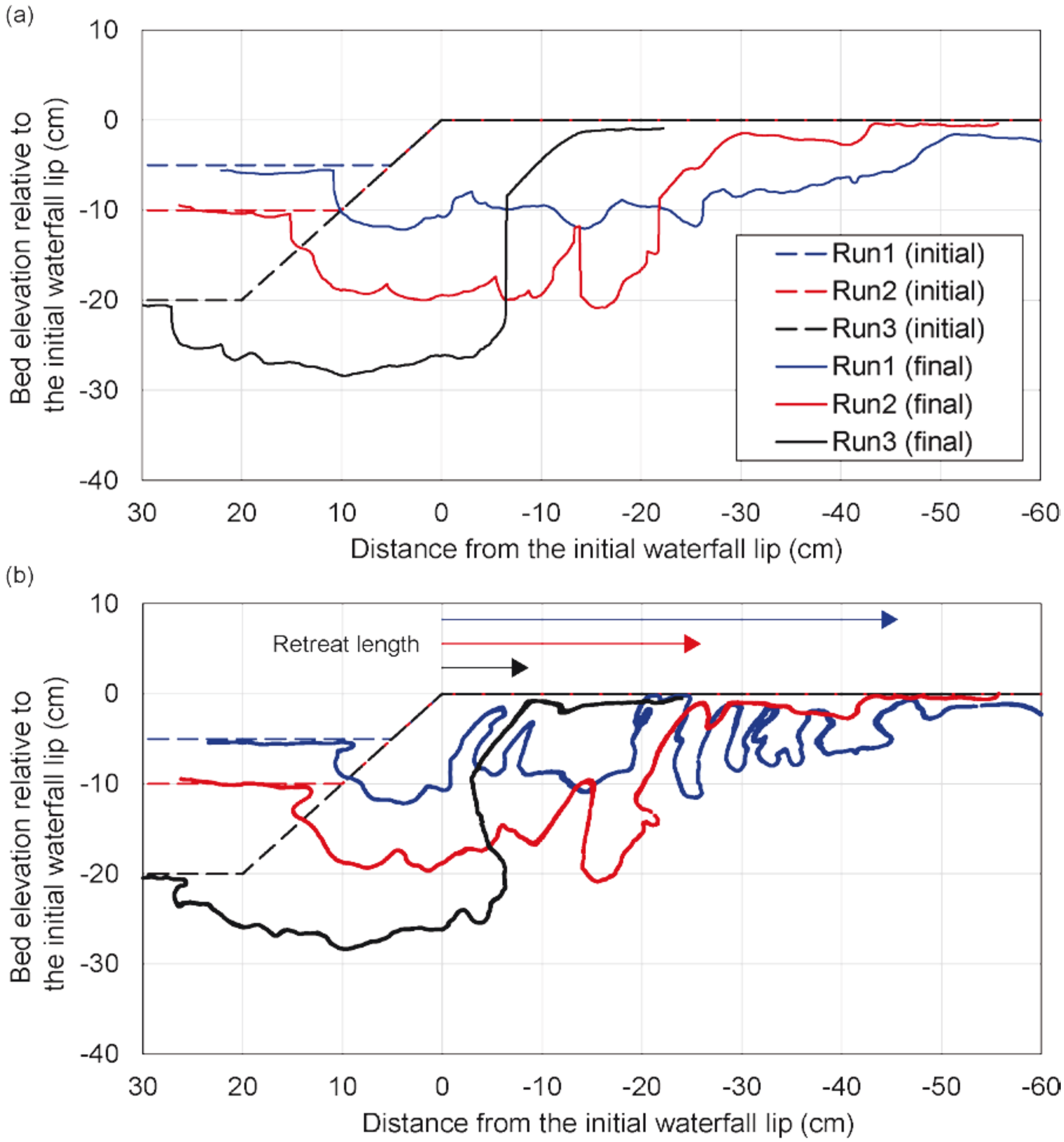

Figure 4. Longitudinal profiles showing (a) the channel thalweg (i.e., the lowest elevation measured at each cross-section) and (b) the elevation along the center line of the initial channel.

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