Downstream Impacts of the Rio Coca Regressive Erosion

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Introduction

During fall 2019 subsurface flow developed a piping pathway beneath the 144-m tall San Rafael Waterfall on the Rio Coca, Ecuador. This process formed a sinkhole that captured the river discharge nearly instantaneously on 2 February 2020 (Reyes *et al.* 2021). Flow under the lava dam dropped the river grade, and eventually led to the collapse of the relatively thin lava structure that formed the waterfall (Barrera, 2021a). As of February 2023, regressive erosion in response to the base-level fall has progressed more than 12 km upstream, creating a valley that is up to 100 m deep and a kilometer wide (Figure 1 and Figure 2) and has eroded over 410 million tons of sediment (Barrera 2021a,b). The regressive erosion is threatening the Coca Coda Sinclair hydroelectric diversion structure, which is another 6 km upstream of the present erosion front. Erosion is also threatening residential areas and infrastructure (e.g. roads, bridges, pipelines) through valley widening.

These time-sensitive threats upstream of the former waterfall have received most of the attention and analysis (see Barrera, 2022b in this volume). However, 410 million tons of eroded sediment are transporting downstream at various rates, depending on particle size. One of the largest recorded sediment pulses in the Anthropocene is advancing downstream, where bed aggradation and excess sediment transport also threaten Ecuador's most important hydroelectric powerplant. The outlet structure for this powerplant is 45 kilometers downstream of the collapsed waterfall. Powerplant operations will have to shut down operations periodically if river-bed aggradation causes rivers stages to increase between 2 and 6 meters of deposition and the plat will become inoperable if the river stage increases more than 6m.

Figure 1. Looking upstream at the canyon formed by of the regressive erosion about 4 km upstream of the former lava dam site (Feb 2023) and some of the affected infrastructure and towns.

Figure 2. Looking upstream a the canyon formed by of the regressive erosion about 11 km upstream of the former lava dam site (Feb 2023).

Setting

The San Rafael waterfall was the tallest waterfall in Ecuador, situated about 20 km upstream of a reach of the Rio Coca which bends eastward about 130º. This large directional bend in the river alignment (Figure 3) makes it an attractive site for hydropower owing to the substantial head loss over a relatively short longitudinal distance for a diversion tunnel. La Corporación Eléctrica del Ecuador (CELEC), the Ecuadorian energy agency, manages the Coca Coda Sinclair project on this river that diverts water about 20 km upstream of the collapsed lava dam, (Figure 3) to an outlet 65 km downstream of the former dam site. This diverted water drops about 600 m (which the river naturally loses over 65 km) in less than 20 km, creating a more localized head differential for power generation.

Sediment Failure Modes

The collapse of the San Rafael waterfall threatens this hydroelectric project in two directions with two distinct processes. The lava dam collapse introduces two major failure modes for the Coca Coda Sinclair hydroelectric project.

Coca Coda Sinclair Failure Modes on The Rio Coca

Upstream	Downstream
Regressive Erosion	Progressive Deposition
Threatens to undercut the intake	Threatens to bury the outlet

Other papers in this conference, (Barrera, 2023b) and most of the investigation surrounding this event, focus on the "acute" failure mode, and the regressive erosion upstream (Figure 2). But the downstream deposition presents a "chronic" failure mode that could take longer to unfold and have longer-term effects (Gibson et al, 2021). In addition to the powerplant impacts, the downstream sediment pulse may impact infrastructure and ecosystems downstream.

In February 2023 an interagency team from the United States coordinated with CELEC to assess the downstream processes and timelines and review the mitigation alternatives. This reach is mostly inaccessible, and very few data are available to quantify these processes. Therefore, US Government science agencies gathered sediment subject matter experts from three agencies (USACE, USGS, and USBR) to form an Expert Elicitation team00. This team developed a conceptual model of the sediment processes and responded to a set of actionable management questions based on limited observations, inference from available imagery, and analogy to other large sediment pulse events (e.g. dam removals and management of the sediment pulse downstream of Mount Saint Helens). This paper summarizes the team's conclusions about transport processes and inferences about potential downstream impacts (Interagency Report, in review 2023).

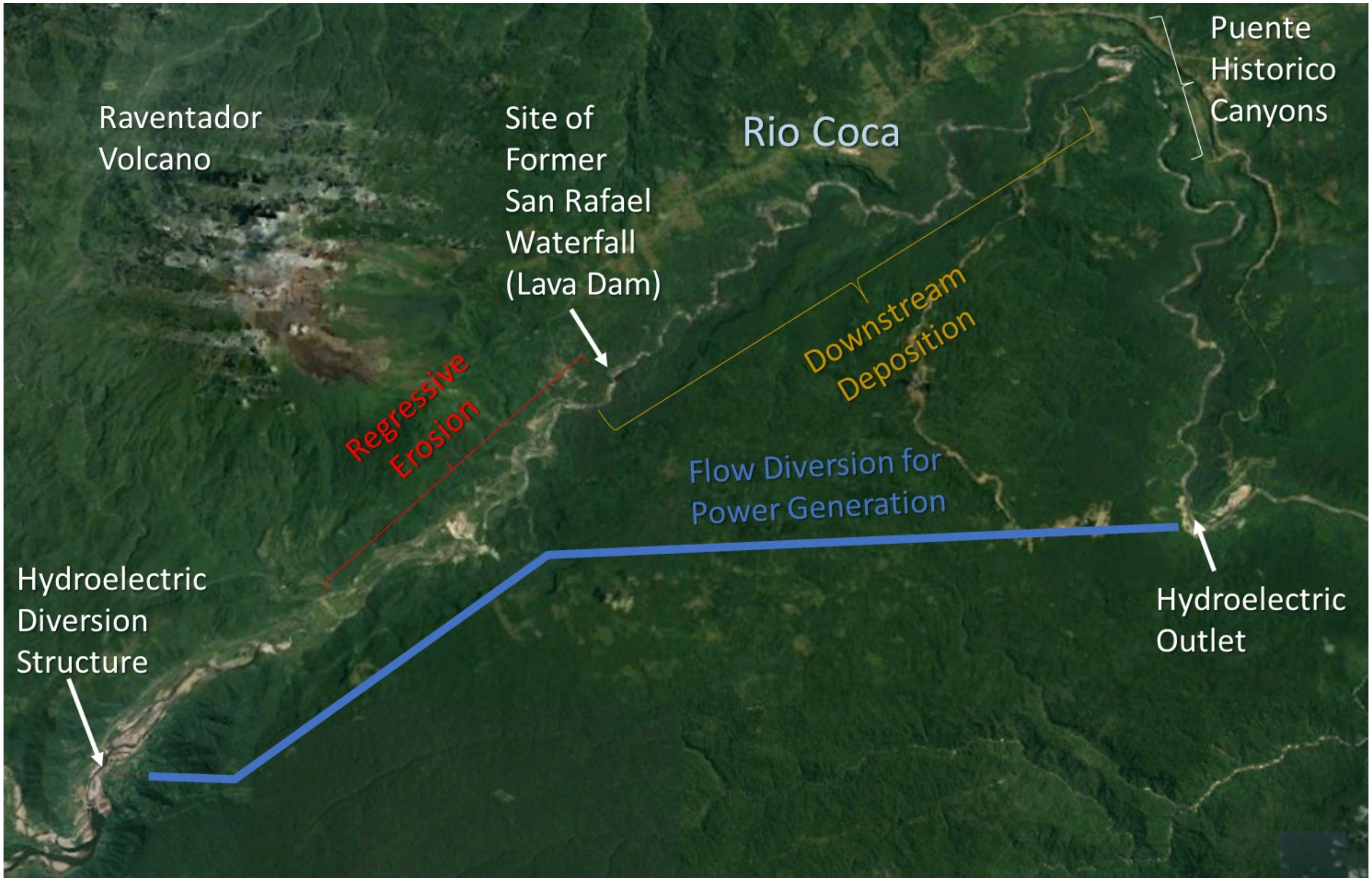

Figure 3. Map of the footprint of the hydroelectric infrastructure on the Rio Coca and the effects of the waterfall collapse.

Downstream Transport Processes

The downstream pulse has at least two distinct transport processes that will affect downstream infrastructure and ecosystems on two different time scales. First, it appears that the steep (~0.01 or 1%), confined, reach of the Rio Coca, that extends about 50km downstream of the former lava dam location, transports all the silt and clay, and most of the sand grain classes as wash load. It is likely that a substantial fraction of this material already transported past the hydroelectric outlet, potentially to the confluence with the Rio Napo, more than 100 km downstream of the former lava dam site. The coarser grain classes are advancing gradually downstream in a bed load pulse.

Bed Load Pulse Progression

The bed-material load pulse includes a fraction of the estimated 410 million tons eroded so far, because it does not include the clay, silt, and sand grain classes that transport as wash load in this system. This bed-material pulse includes substantial cobble and boulder fractions supplied by the poorly sorted volcaniclastic avalanche and debris flow deposits from volcanic mass-wasting processes upstream of the former dam site.

Figure 4 includes river bed profiles collected prior to the lava dam collapse and 20 months after the collapse. As of September 2021, the center of mass of the bed material pulse advanced approximately three kilometers downstream, where the new bed elevations were more than 20 m above the original grade. This sediment pulse tapered downstream for about 20 km. Figures 5 and 6 includes images of the deposition 7 km downstream of the lava dam site (close to the inflection point in Figure 4), about 15 months after the initial lava dam failure.

The regressive erosion supplied enough sediment that the deposition zone extends upstream of the former lava dam location. The post-collapse surveys from Figure 4 measured more than 40 m of deposition at, and upstream of, the former lava dam location. The phases of deposition and erosion in this dynamic reach of the system likely follow Schumm's (1977) complex response model, responding to supply pulses from episodic erosion, and a series of head-cutting and widening events along the river and tributaries. Discrete observations of reach behavior may represent temporary or transient responses to recent, complex response episodes.

However, the sediment delivery from the regressive erosion has decreased. The river is beginning incise into these initial around the lava dam location as the supply decreases relative to the locally over-steepened slope, which initially formed by the peak sediment load from the highest-gradient erosion through the highly erodible volcaniclastic avalanche material that composed most of the eroding material in the first 10-km upstream of the waterfall site.

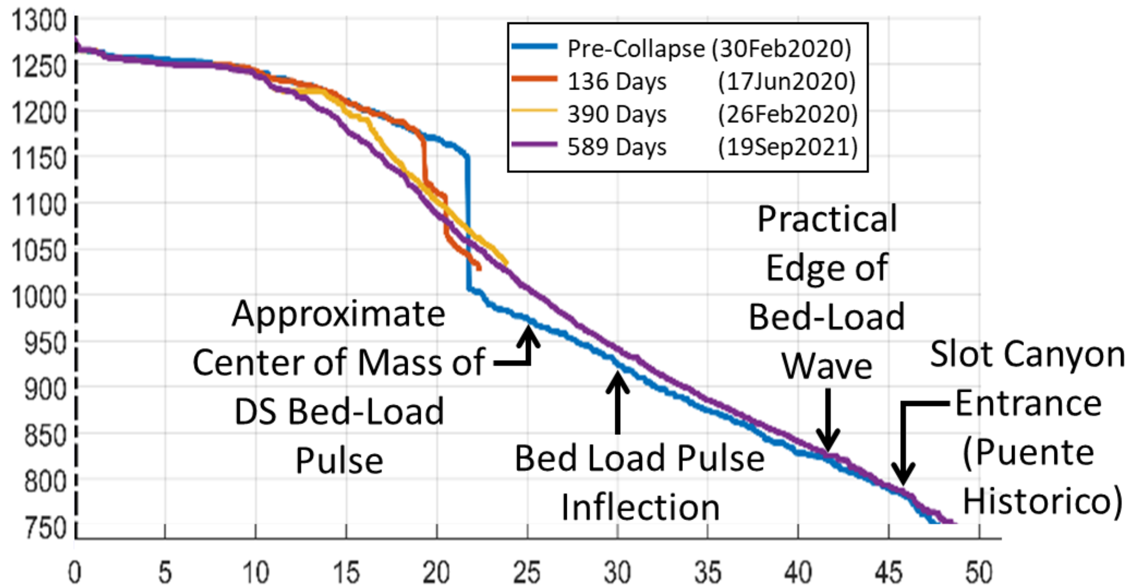

Figure 4. Bed profiles collected at three intervals after piping failure undermined the lava dam, including a downstream profile collected 20 months after the event. Three different measures of bedload progression are labeled on this profile with the location of the slot canons (Puente Historico). Modified from Barrara (2023a).

The Rio Coca also includes narrow bedrock canyons in this downstream-deposition reach that complicate predictions of the downstream fate and timeline of this sediment pulse. About 25 kilometers downstream of the former lava dam site, not far downstream of the downstream edge of the bed material load pulse, the river transitions into a reach of narrow, bedrock, slot canyons (location indicated in Figures 1 and 4). The entrance to these slot canyons is a substantial flow constriction (Figure 8).

Figure 7. Photograph of the river bed taken at the same location as the areal photograph in the previous figure (the bedrock "island" is visible in both (Feb, 2023). This reach still has the valley-wall-to-valley-wall deposition from the initial sediment pulse but has recently begun to incise into those deposits.

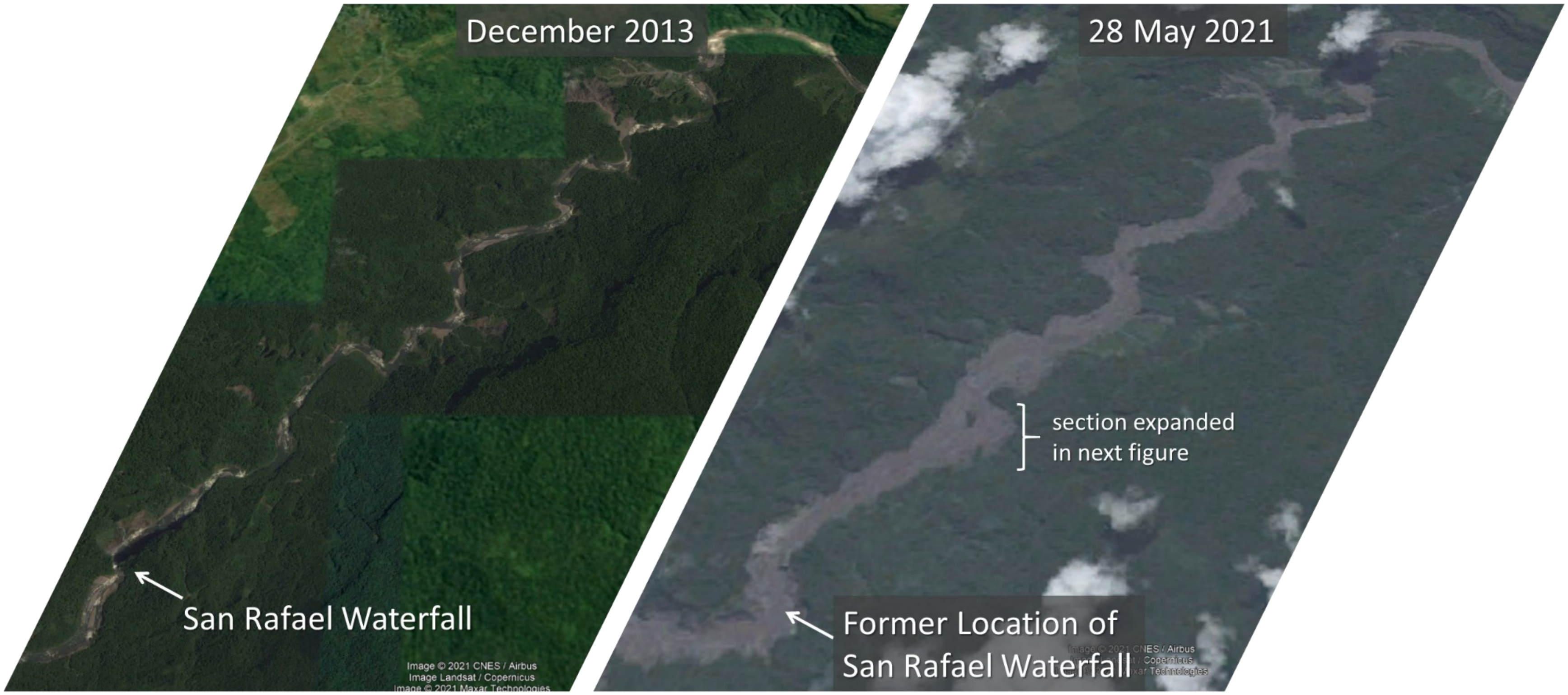

Figure 5. Approximately seven kilometers downstream of the San Rafael waterfall site before (2013) and after (May 2021) the collapse. The image on the right provides some insight on the scale of deposition downstream of the dam and the center of mass of the downstream sediment that must transport past the outlet structure. (May 2021, photographs from the Unclassified Digital Globe database which USACE requested access to for this project). The next figure zooms in on the indicated section from the post-collapse image.

Figure 6. Imagery from one river bend (location indicated in previous figure) about one kilometer downstream of the former site of the San Rafael lava dam before and after the collapse (from Gibson *et al*, 2021).

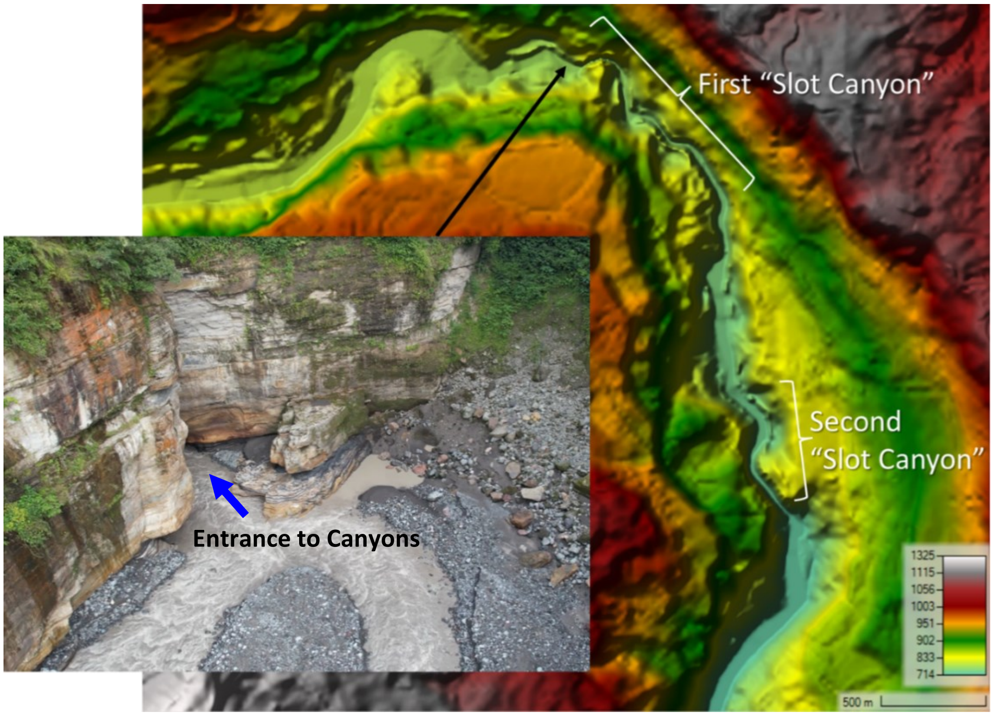

Figure 8. Topography of the slot-canyon reach downstream of the bed load pulse and the flow constriction at the entrance to these features.

Hydraulic modeling confirms a substantial backwater (and slower flow velocities) upstream of narrow bedrock canyons (Figure 9). Sediment transport capacity of the bed-material load grain classes has in inverse relationship with flow through these backwaters. At higher flows, backwater effects extend farther upstream, decreasing transport capacity. This feature will trap bed material. The backwater "reservoir" upstream of the slot canyons only represents about 4 million m^3, which is a small fraction of the bed material pulse. However, it could affect, and possible attenuate, the arrival of the cobble-boulder pulse.

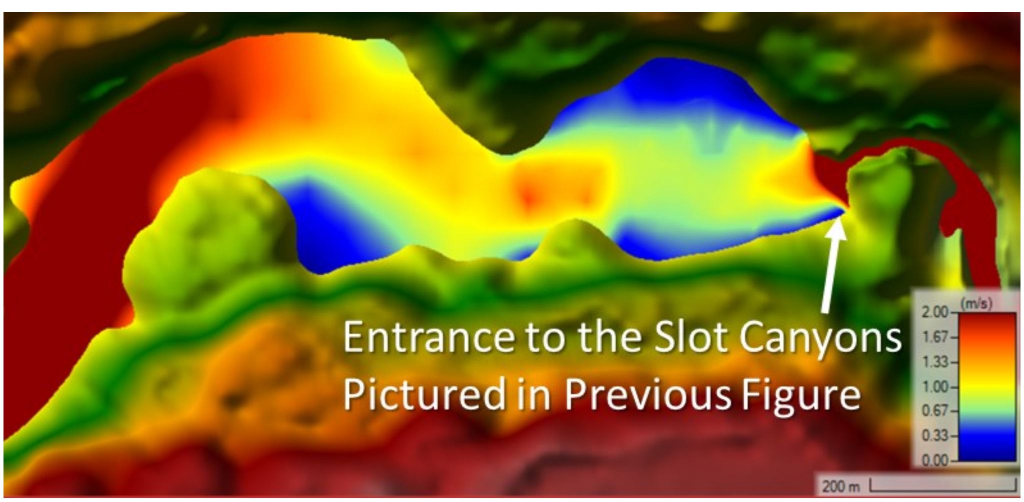

Figure 9. Velocity results from an HEC-RAS 2D model of the reach directly upstream of the slot canyons (4,000 m^3/s). Large flows form a backwater reservoir upstream of the bedrock constrictions which will slow the downstream progression of the bed material pulse.

Wash Load Effects

The sediment response from the 1980 Mount Saint Helens eruption provides a conceptual model and comparable process that helped interpret the fate and response of the finer grain sediments. In the first year after the Mount St. Helens eruption, a sand pulse transported to the Columbia River, more than 100 km downstream.

The reach of the Rio Coca downstream of the bedload pulse includes evidence of elevated sediment load. The river includes multi-thread, sheet-like flow paths separated by multiple sand-and-gravel bars that are reminiscent of reaches overloaded with sediment downstream of dam removals (East et al., 2015, 2018).

However, dredging activities at the power-plant outlet provide evidence that this specific location may be supply-limited. CELEC has dredged the channel twice at the powerplant outlet (45 km downstream of the former dam location and 25 km downstream of the edge of the bed material pulse) to help keep water stages at the outlet at operational levels. The river has not deposited in these dredged areas. Rather, the dredging has induced mild erosion and head cutting around the dredge locations rather than deposition. Slack water deposits in this reach include sand, suggesting that sand is actively transporting through this part of the system.

If the silt, clay, and some of the sand classes are transporting as wash load, much of that sediment has already transported past the hydroelectric outlet. The advancing bed load pulse will be a fraction of the 410+ million tons eroded (to date). However, it is also likely that a substantial sand flux is already affecting downstream reaches and communities.

In addition to increased turbidity, downstream impacts are likely where slope changes shift the coarser wash load grain classes to bed-material load. About 70 km downstream of the former lava dam site, the Rio Coca emerges from the confined channel into a lower gradient, anastomosing reach (Figure 10). This lower-gradient anastomosing reach (with slope 0.003, compared to the 0.009 throughout the reach from 0 to 70 km discussed above) already exhibits signs of aggradation. Coarser sand grain classes that transport through the steeper, confined reach, past the hydroelectric outlet, will transition to bed material load in this reach and deposit, potentially increasing the flood risk for communities along this reach.

Additionally, the backwater influence (Figure 10) of the Rio Napo extends through the largest city in the region (Coca). This backwater zone will decrease capacity again, and additional sand sizes will transition to bed-material load, potentially depositing through the urban reach and affecting flood risk.

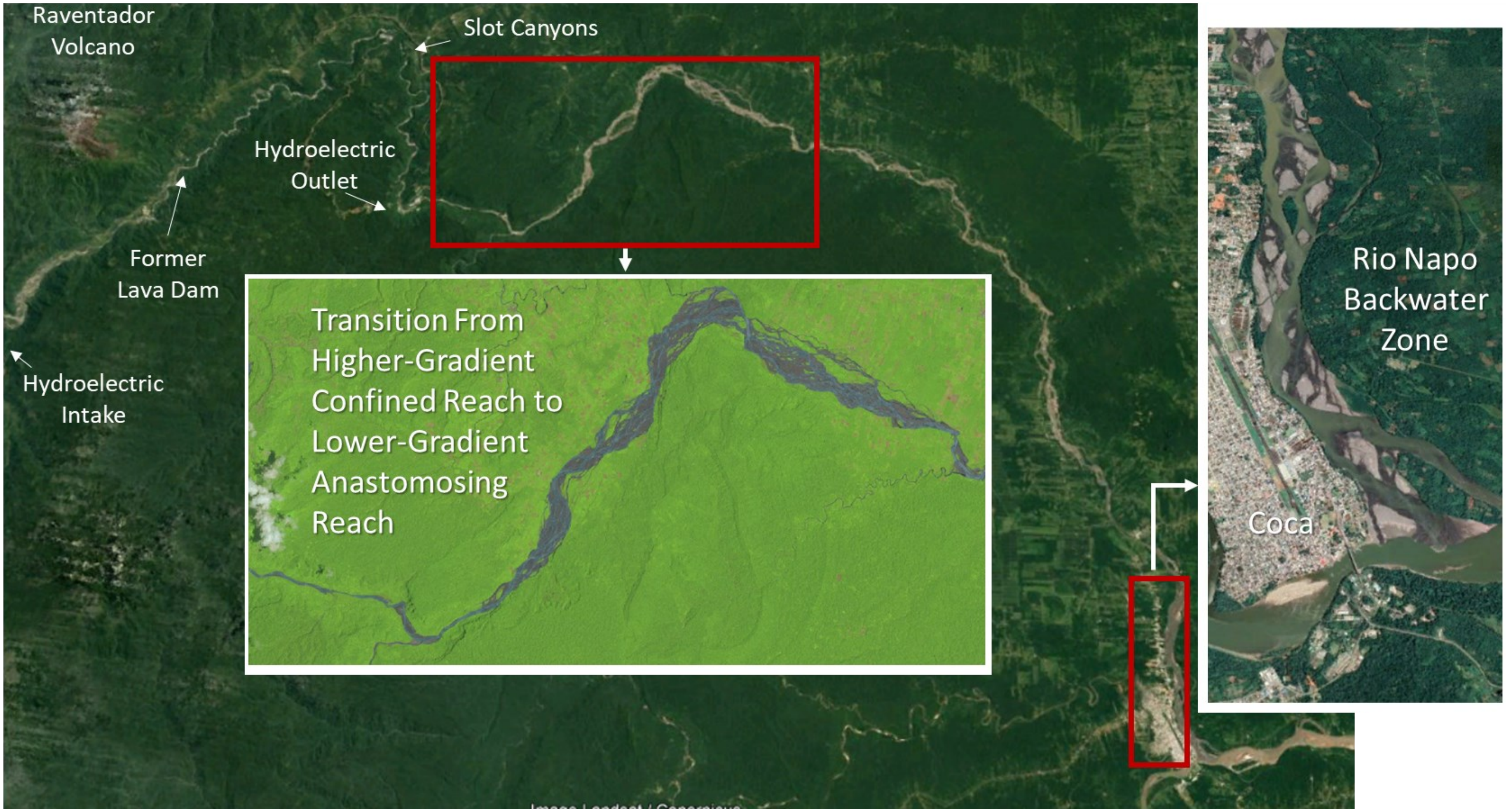

Figure 10. Downstream locations with sediment deposition potential. At capacity transitions, sand grain classes that transported as wash load in the confined, higher gradient reach can transition to bed material load and deposit, inducing flood risk. Inset image from Sentinel-2, background image from Google Earth.

Conclusions

The regressive erosion on the Río Coca has eroded more than 410 million tons of sediment and the study team estimates that it could erode at least another 200 to 350 million tons. That sediment will affect downstream turbidity, flood risk, and operations at the CCS outlet. These impacts will unfold on several time scales. The Río Coca's gradient transports fines and a fraction of the sand in wash load in the confined reach extending 50 km downstream of the former lava dam site. These impacts unfold downstream in near-real time, as these materials are eroded, and are likely to decrease over time. The front of the bed load pulse is approaching the slot canyons 20 km downstream of the lava dam site, but the center of mass of this pulse is still within 5 km of the that lava dam location. However, coarser wash load grain classes are likely to transition to bed material at friction slope transitions (i.e. the transition to the anastomosing reach about 50 km downstream of the former lava dam site and the Rio Napo backwater). This transition could lead to deposition and increased flood risk at these locations. This bed load pulse will take much longer to transport downstream, and will be attenuated by the backwater effect of the canyons. But because of its substantial cobble and boulder content, when it does arrive downstream, the deposition will persist relatively long-term.

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