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Review of Regressive Channel Erosion and Grade Control Options on the Rio Coca, Ecuador

by Chris Haring, Tom Darby, David May, and Paul Boyd

PURPOSE: The US Army Corps of Engineers (USACE) is assisting the Ecuadorian state-run Corporación Eléctrica del Ecuador (CELEC) in addressing a water resource issue involving regressive channel erosion on the Rio Coca. Reconnaissance of the site was completed the week of 21 February 2022; parts of the river system were viewed to determine if improvements could be made to the current grade control structure (GCS) mitigation plan for reducing channel erosion and stabilizing the river system downstream of the Coca Coda Sinclair (CCS) Dam.

The Rio Coca is a tributary to the Amazon River system in South America. It originates on the east side of the Andes Mountains and generally flows from southwest to northeast through the project area and then turns and flows east into the Amazon basin (Figure 1).* The Rio Coca valley is a current example of how damaging regressive erosion can be to a fluvial system (Figure 2).

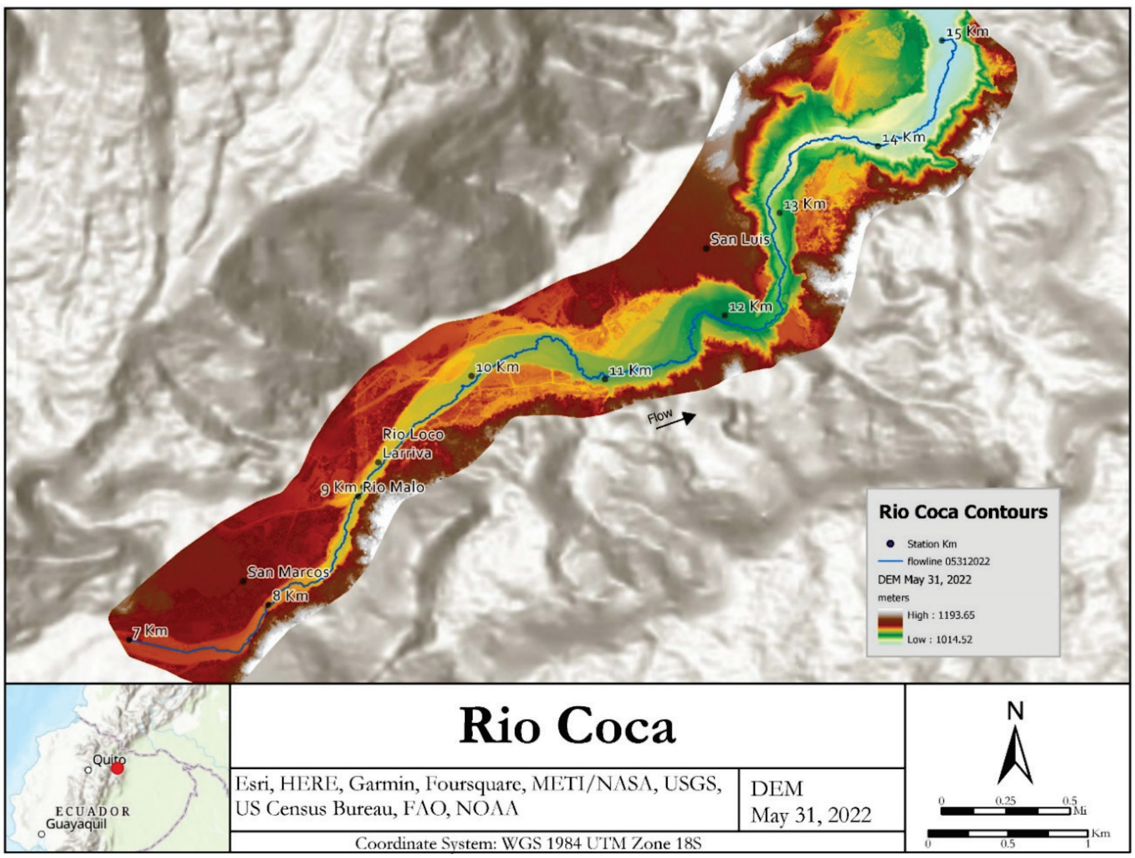

Figure 1. Rio Coca Valley, Coca Coda Sinclair (CCS) Dam (*lower left*) to San Rafael waterfall (*upper right*).

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Figure 2. Regressive erosion on the Rio Coca at an overlook on C. Teniente Hugo Ortiz, approximately 500 m northwest of San Luis, Ecuador.

INTRODUCTION: The Rio Coca naturally flowed over the San Rafael waterfall before being rerouted by a geotechnical-piping-failure event in early February 2020. The erosion of foundation materials and the subsequent collapse of the waterfall is causing regressive channel erosion to migrate upstream in a series of knickpoints or knick zones as the channel attempts to reestablish a stable quasi-equilibrium channel slope, dimension, and pattern through easily erodible valley materials. The regressive erosion is causing extensive damage to infrastructure (i.e., roads, bridges, and pipelines) and the environment through channel and valley widening (Figure 3).

Figure 3. Regressive erosion on the Rio Coca at a tributary bridge on C. Teniente Hugo Ortiz, approximately 550 m northwest of San Luis, Ecuador.

GEOMORPHOLOGY: The San Rafael Waterfall failed in early February 2020 due to a piping failure underneath the existing structure. As the foundation failed, materials and subsequent flow removed the lower rock sill and caused a large drop in the invert elevation of the river. The baselevel drop in river elevation was approximately 150 m. Since the time of the waterfall failure, the Rio Coca has experienced an extreme regressive erosion as the system attempts to rebalance local baselevel slope change with excessive transport capacity. The previous waterfall location allowed for energy dissipation over a stable 150 m drop. Now the slope energy is being released on a variety of less competent materials upstream in previously buried lakebed and lacustrine deposits.

When watershed changes occur at different spatial scales, they affect the natural balance of the fluvial system by increasing or decreasing runoff and sediment supplies. E.W. Lane's (1955) stream balance equation provides perhaps the best illustration of these relationships in simple terms (Figure 4). When one of the four variables is altered, a counter reaction occurs to rebalance the equation. Fluvial systems can take years, decades, or longer to rebalance variables, while the temporal scale of rebalancing variables is unknown (Schumm 1977). There is typically a rapid progression of channel slope adjustment when sediment transport increases. As the Rio Coca establishes a new equilibrium channel slope and balances sediment transport, the channel is deepening and widening, eroding from one valley wall to the other (Figure 2 and Figure 3) as less competent, easily erodible material is encountered.

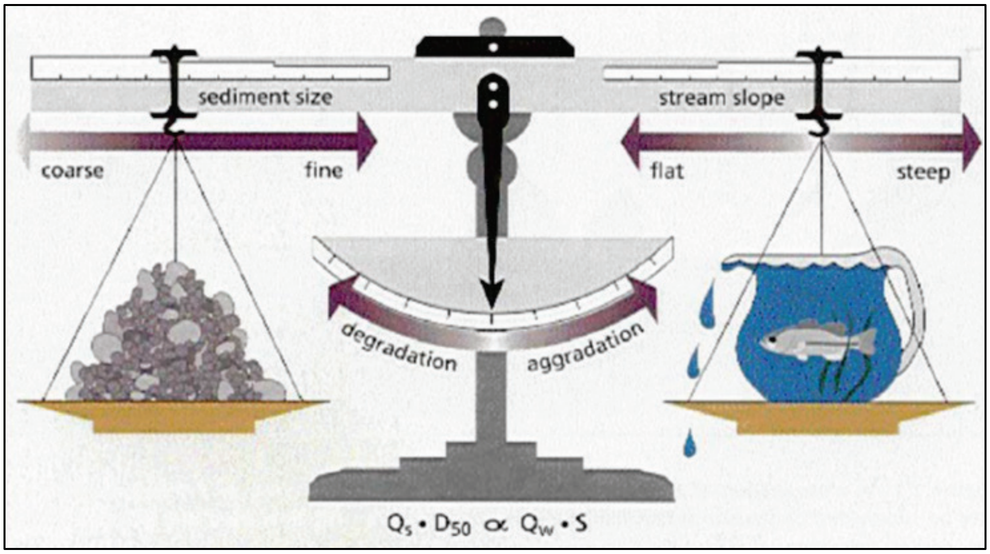

Figure 4. Stream balance equation (Lane 1955), where sediment discharge (Q_s) and median grainsize (D_{50}) of bottom sediment balance with water discharge (Q_w) and channel slope (S). Image reproduced from NRCS (2007, 13-8).

Before the waterfall failed, channel conditions were dominated by finer alluvial material deposits (i.e., lacustrine deposits) in the lower valley that is upstream of the waterfall. Larger colluvial materials were deposited from valley wall contributions, debris flows, and tributary discharge events. There are likely reworked alluvial fan deposits throughout the valley that are also contributing to the size ranges of channel material. As the Rio Coca degrades and adjusts channel slope, it will sort the larger materials from the alluvial and colluvial deposits and re-armor the channel margins, providing dissipation of flow energy. Before the waterfall failure, the river channel was likely a threshold channel between approximately kilometer marker (Km) 7 and 17. Threshold channel conditions occurred where the river sorted out larger materials with cascade and pool locations located at Km 7.8 (Walking Bridge), 12 (San Luis Bridge knick zone) and 14 (downstream of San Luis). More alluvial channel conditions likely dominated upstream and downstream of the threshold channel conditions, where local channel slope decreased and floodplain access was readily available.

The Rio Coca's longitudinal profile has changed drastically since the waterfall-failure event in February of 2020 (Figure 5 and Figure 6). Figure 5 illustrates the Rio Coca cross-section locations. To further assess the spatial and temporal changes to the channel and valley profile (Figure 6), FluvialGeomorph (FG; Haring et al. 2020; Haring and Biedenharn 2021) was used to plot lidar provided by CELEC. The purple profile illustrates the with-waterfall slope prior to the failure event in early February 2020. The red profile shows the effects of the regressive erosion, with the baselevel lowering by more than 114.3 m (375 ft) at San Rafael and by approximately 3.1–4.6 m (i.e., 10–15 ft) upstream, close to the mouth of the Rio Malo.

Spatial and temporal changes to cross-sectional channel locations provide detailed information on geomorphic channel adjustments. Figure 7 through Figure 10 illustrate channel deepening and widening, which increase from the downstream cross-section (XS) 1 to the upstream XS 90. The FG analysis matches well with general field observations that identified wholesale valley widening and deepening (XS 1) upstream of the failed waterfall. The regressive erosion decreased in the San Luis area (XS 60) because large bed material is present, resulting in less channel deepening and widening upstream (XS 60 and 75) at the mouth of the Rio Malo.

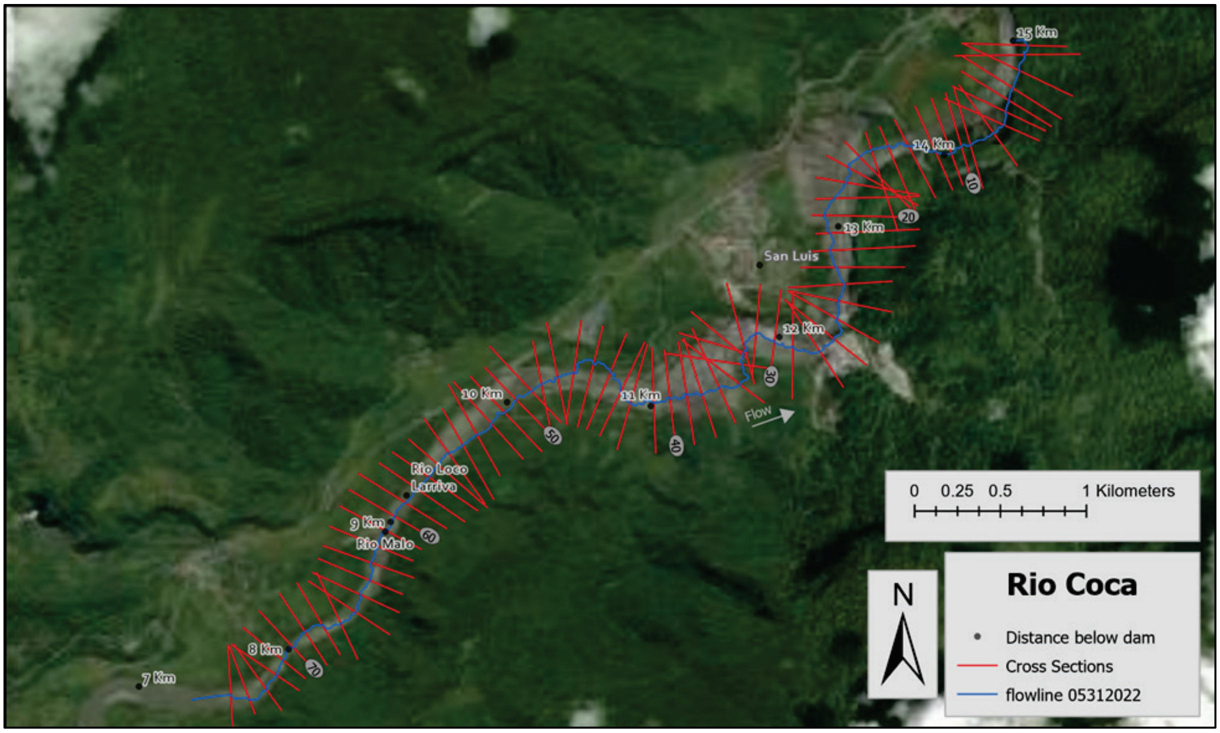

Figure 5. Rio Coca FluvialGeomorph (FG) cross-section locations starting downstream at the San Rafael waterfall (*upper right*) and progressing upstream to the Rio Malo (*lower left*) confluence.

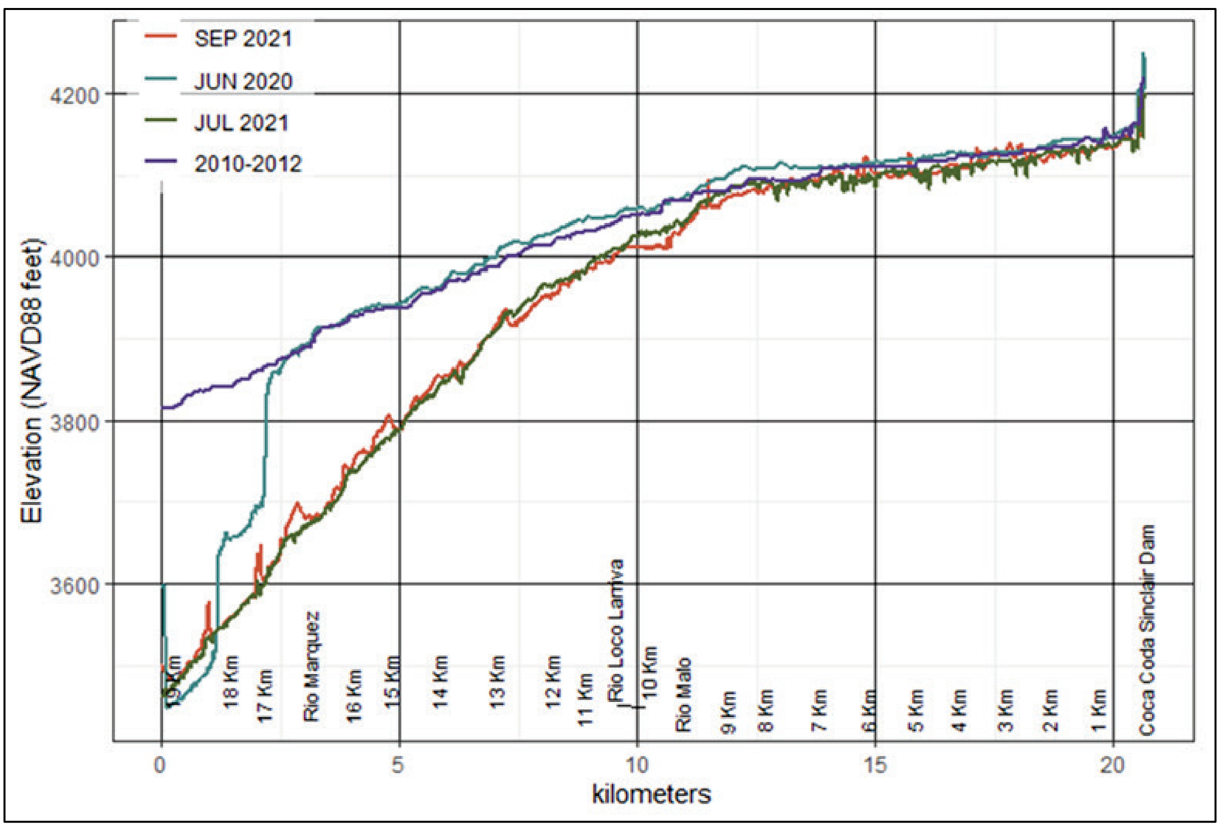

Figure 6. Plots of multiple Rio Coca longitudinal profiles based on lidar. (The oldest profile is *purple*, and the newest profile is *red*.)

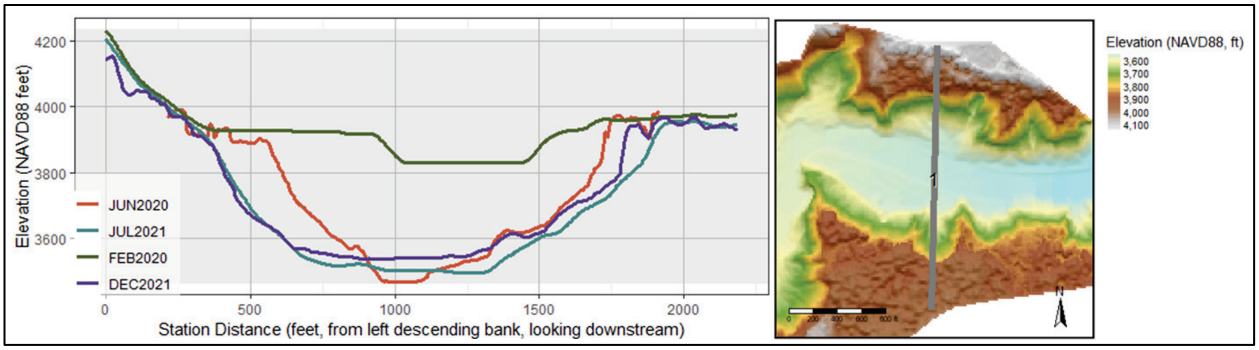

Figure 7. Rio Coca lidar for cross-section (XS) 1, illustrating temporal and spatial channel degradation at the San Rafael Waterfall.

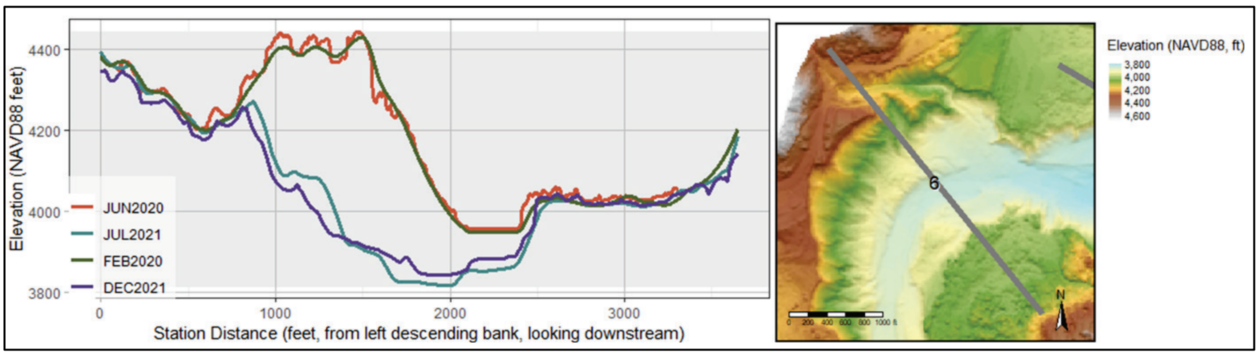

Figure 8. Rio Coca lidar for XS 60 at San Luis.

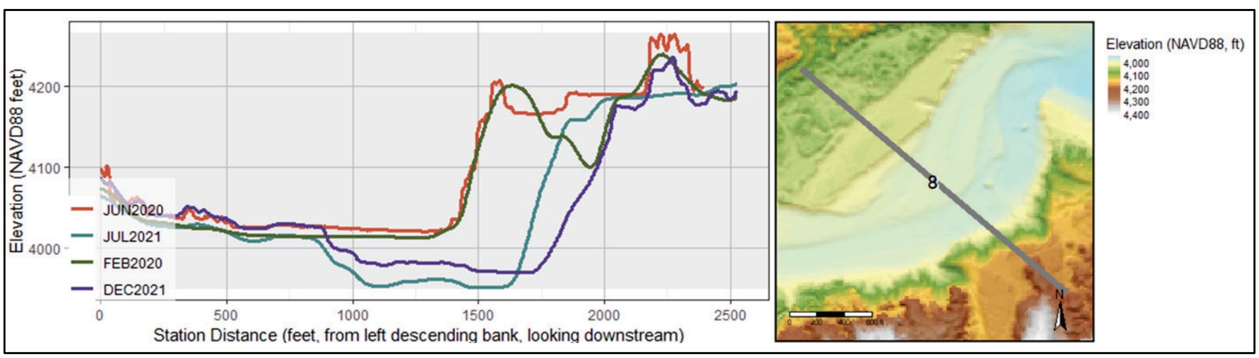

Figure 9. Rio Coca lidar for XS 75 (close to the location of the grade control structure [GCS]).

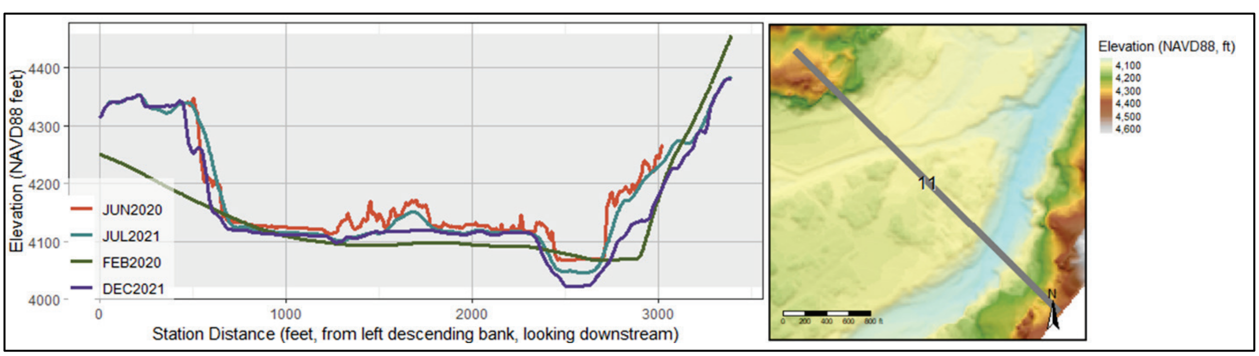

Figure 10. Rio Coca lidar for XS 90, approximately 550 m downstream of the Rio Malo confluence.

Geologic and surficial mapping is currently being updated to provide more localized details for the Rio Coca valley from San Rafael to the CCS Dam (Figure 11). The mapping units generally consist of avalanche deposits (between Km 12 and Km 19), fluvio-lake character deposits (between Km 0+0 and Km 12), and deposits of gap volcanic underlying the deposits of avalanche to the fluvio-lacustrine (between Km 5.6 and 16.8; CELEC 2021). Figure 11 illustrates the general geological profile. There have been some additional updates to the geologic mapping, especially in the area upstream and downstream of the Rio Malo tributary confluence (approximate stations Km 7–12). The newer mapping and field observations monitoring the progress of the regressive erosion front have located important resistive materials present in the form of surface outcrops acting as hard points. The main hard point locations are at Km 7.8 (Walking Bridge), 12 (San Luis Bridge knick zone) and 14 (downstream of San Luis). All three hard points are located where the Rio Coca encounters the right valley wall. The hard points are areas where consistent fluvial erosion has weathered valley wall materials (i.e., bedrock) from the adjacent and underlying strata and provided larger, concentrated, erosion-resistant bed materials (Figure 12).

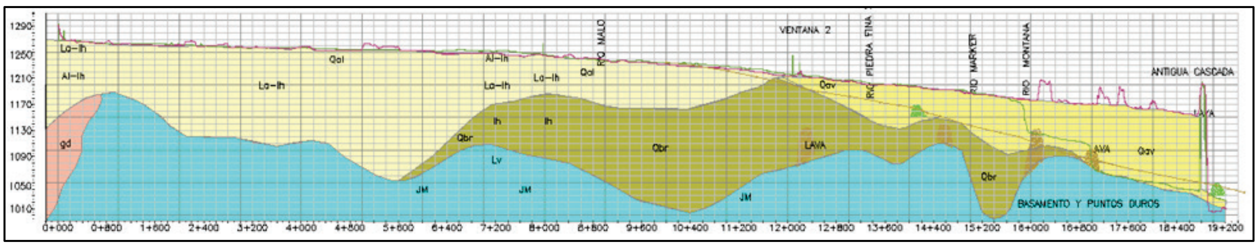

Figure 11. Rio Coca geologic profile from CCS Dam (*0+00 m*) to the San Rafael Waterfall (*19+200 m*). Image adapted from CELEC (2021).

Figure 12. Rio Coca; downstream channel at kilometer marker (Km) 7.8 (Walking Bridge).

GRADE CONTROL PLAN (EXISTING): A GCS plan was developed and partially implemented in 2021. The plan was to construct a series of four check dams around Km 12 (Figure 13). These are located at San Luis, in a pinch-point in the valley with a high alluvial terrace on the left bank and a resistant valley wall and bedrock on the right bank (Pedro Barrera, pers. comm., February 2022). The Rio Coca is entrenched in the right valley wall materials, and recent field reconnaissance indicated the river appears to be incised 3 m into the breccia materials in this location. At this location, channel degradation is propagating more slowly upstream because the river has encountered more resistant materials, thereby slowing down the regressive erosion process of widening and deepening. However, some of the knickpoints have propagated upstream in the form of knick zone expansion, and the channel has degraded 3 to 5 m upstream (Figure 10 and Figure 14). Once the Rio Coca encounters the less-erosion-resistant alluvial floodplain deposits, channel widening and deepening occurs relatively rapidly, depending on the frequency and magnitude of flow events.

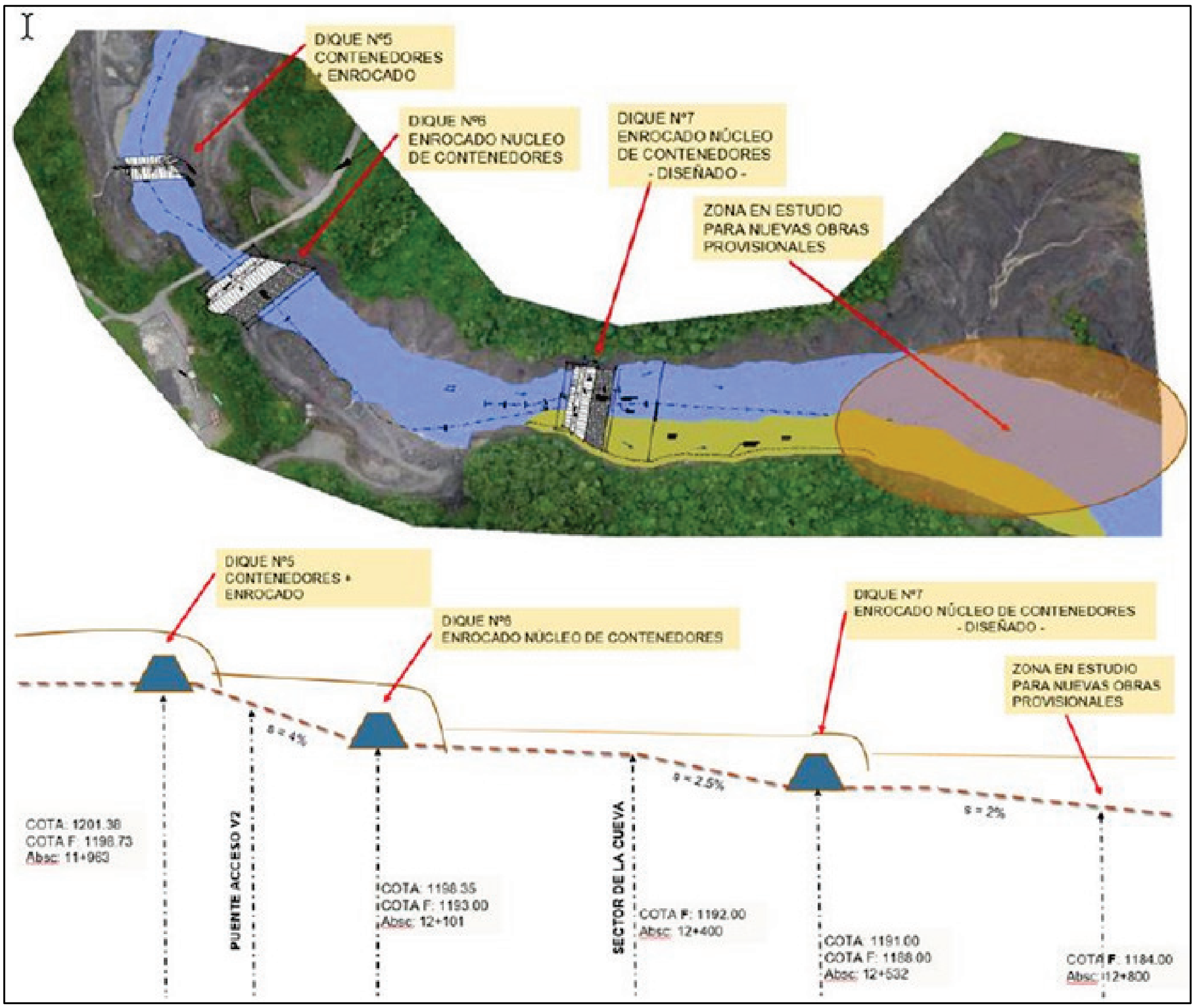

Figure 13. Rio Coca Km 12 location illustrating the existing GCS plan. Image reproduced with permission from CELEC (2021).

Figure 14. Channel degradation and instability progressing from the Rio Coca upstream into the tributary Rio Malo.

Two check dam structures (CDSs; Figure 13) were constructed in the pinch-point location (i.e., San Luis) to protect from extension of the knickpoint upstream and to protect an existing bridge. Both structures were compromised during a March 2021 flow event of 1600 m^3/s. The structures were constructed with a solid core and concrete-filled metal containers and were shaped upstream and downstream with large local channel materials. The materials used for construction had a median size of 1.2 m (Pedro Barrera, pers. comm., February 2022). Highly concentrated flow velocities in the pinch-point river section undoubtedly compromised the structure. A structure with a rigid core is typically able to adjust to minor winnowing of materials. However, loss of the structure may occur when excessive foundation scour occurs and the solid core cannot freely adjust; movement of the CDS may occur. The CDS is one form of GCS that is designed with a solid core and uses available onsite materials. There are many other types of GCSs that incorporate similar materials, such as well-graded riprap. The sizing of riprap depends on accurately measuring and predicting channel velocities and shear stresses so that materials can be sized appropriately. The advantage of large and well-graded riprap is that it has launching and relocking capabilities once the structure or revetment encounters the anticipated velocities and resulting scour. The construction of the CDSs was limited by the requirement to use only locally available rock (i.e., 1.2 m in size) and the limited gradation that was present; these likely caused the structures to be compromised. Flanking of the structure on either bank line, especially in a pinch-point-incised channel location, is also a concern because water depth and channel shear stress increase. These locations were not observed during the site visit.

A third CDS (Figure 15) was constructed upstream of the pinch-point at approximate station 9+550 (upstream of La Loma Camp). This structure was viewed during the site visit on 22 February 2022 and appeared to be functioning well (Figure 16). From design information, it appears that the structure was installed as a linear structure perpendicular to flow and did not have a solid core (CELEC 2021). The structure will be tested with the upcoming rainy season (Spring/Summer 2022).

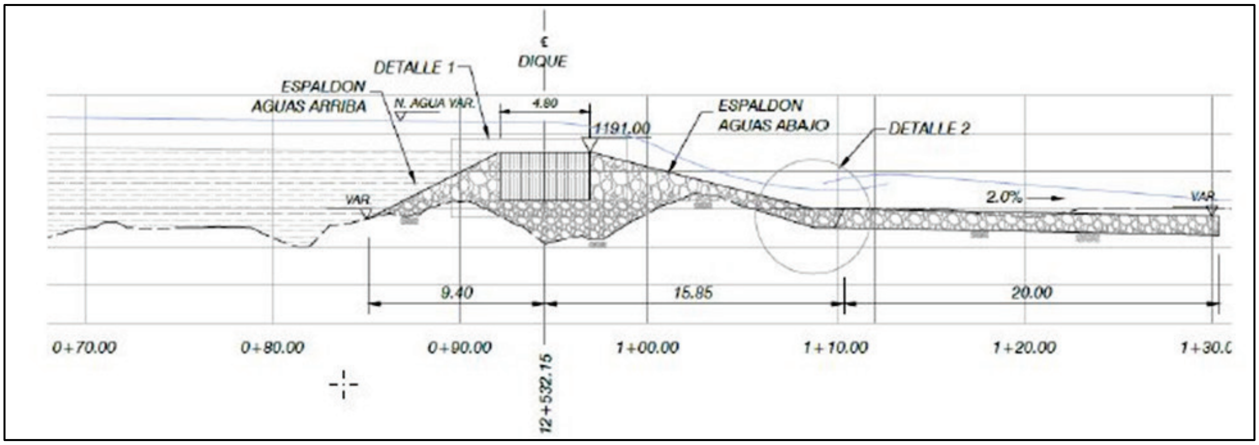

Figure 15. Rio Malo control dam structure (CDS) profile (*left* is upstream to *right* downstream). Image reproduced with permission from CELEC (2021).

Figure 16. Rio Coca CDS in foreground of photo (looking upstream, structure location in *red*).

It is not known why the two CDSs were compromised, but some enhancements to the designs will increase the likelihood of success. The extreme shear stress and velocities in the pinch-point likely produced sufficient energy to compromise the structures in some way, whether it was flanking, material removal movement (approximately 1–1.2 m sizing) around the solid core, or a combination of both. Possible enhancements to the structure designs are provided in the next section.

ENHANCEMENTS TO EXISTING GRADE CONTROL PLANS: As part of a comprehensive stabilization plan, which includes the existing stepped spillway at Km 1 and additional diversion dam-spillway structures at Km 8, the downstream grade control plan needs to be further developed to provide a system-wide approach to stabilizing the Rio Coca. The largest concentration of knickpoints is in the San Luis section of the Rio Coca. Downstream of this location, the valley has substantially deepened and widened (Figure 7 and Figure 8). Upstream of this location, there has been some degradation and migration of knickpoints (Figure 9 and Figure 10), but that propagation has mostly led to channel deepening with only moderate widening, especially immediately upstream of San Luis. This location is threatening the La Loma Camp as the high terrace is eroded.

Possible upgrades to structures are listed, with more descriptions and figures providing details on the enhancements.

1. A system-wide approach to grade control would start downstream of the existing knick zone at San Luis and work upstream to stabilize the channel slope (Figure 17). Based on the existing lidar profile surface, there is the potential to construct nine GCSs, ranging from 5 to 10 m in height, to stabilize the channel from Km 7.8 to 12.5. This would likely be extended downstream to the previous San Rafael Waterfall location if access to the river corridor can be established. A road is currently being constructed downstream of San Luis and could be used to provide access for construction of a series of structures below the existing knick zone. This would provide additional protection from continued degradation migrating from the downstream reaches. The exact height, width, and location of structures need to be field verified.

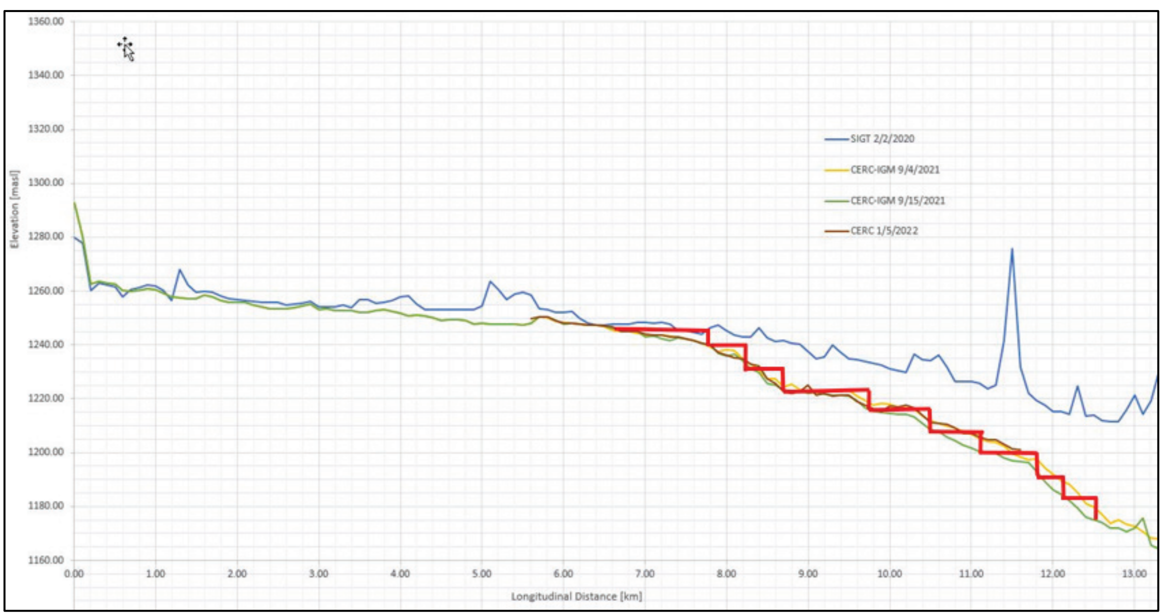

Figure 17. Longitudinal channel profiles based on separate lidar collection dates (2/2/2020 is *blue*, 9/4/2021 is *yellow*, 9/15/2021 is *green*, and 1/5/2022 is *brown*). Potential Rio Coca stabilization grade control plan (Km 7.8–12.5).

2. The hard-point locations at Km 7 (Walking Bridge), 12 (San Luis Bridge knick zone), and 14 (downstream of San Luis) should be used to continue the system-wide approach to stabilizing the Rio Coca. After the February 2022 trip, discussions at USACE (Figure 18) centered on possibly blasting and using local bedrock sources to stabilize the channel in these locations. This could possibly be extended to other locations where the harder bedrock materials are present.

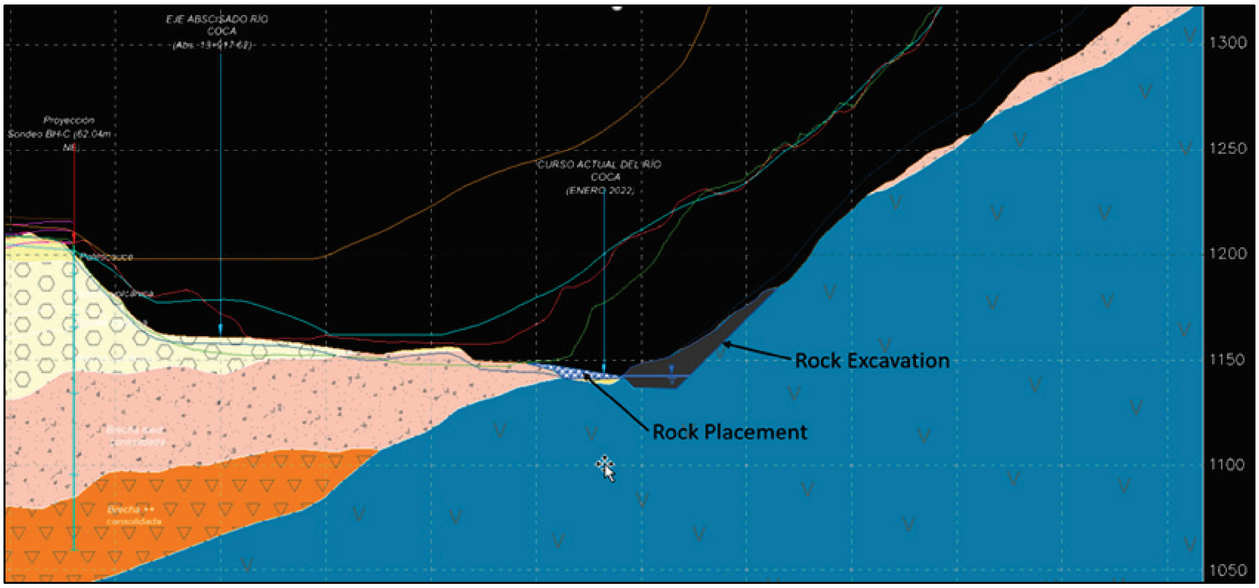

Figure 18. Rock excavation and placement to prevent further downcutting; example is at Km 14. Image adapted from CELEC (2021).

3. Using local materials with limited size and gradation to continue to construct the CDS would provide some local protection but would only slow down, rather than halt, the channel degradation. Some enhancements to the structure design would be to slightly V-shape the structure upstream, with a lower elevation at the center of the V. This would allow upstream flow to concentrate in the center of the channel and away from the potential of flanking at the bank lines. If using large boulder materials (i.e., well-graded material sizes based on velocity/shear stress calculations), the center could be built with an invert elevation notch, with increasing elevation in the direction of each bank line. This would provide some level of protection as the knickpoints migrate upstream, concentrating the degradation in the center of the channel and not around the sides where it will encounter less-resistant alluvial and terrace deposits. The V-shape could be modified to either side of the channel, depending on planform characteristics or promoting channel locations away from the alluvial terraces. Best practice would be to reinforce the center, where the velocities and shear stresses are high, with larger materials in the crest and the downstream plunge pool. The more rock placed on the backslope of the structure, the better as degradation progresses upstream to the structure apron. Mimicking natural cascades and falls at the structure locations would provide the greatest energy dissipation and a local stable slope. Examples of reestablishing high-gradient channel stability after flood events or for wildfire recovery are common in the Western United States (Figure 19). Concepts and designs from these stabilization projects could be applied on the Rio Coca.

Figure 19. The Boulder Creek, Colorado, stabilization project was completed using onsite large boulders and well-graded finer materials to reestablish cascades, falls, pools, and revegetation.

4. Keys or tiebacks into both bank lines should be extensive at each structure (Figure 20 and Figure 21). If there is a high terrace at the revetment location, the tieback can be lowered so that construction does not have to be completed to three-fourths of bank height. Each site will likely have different characteristics and should be assessed independently.

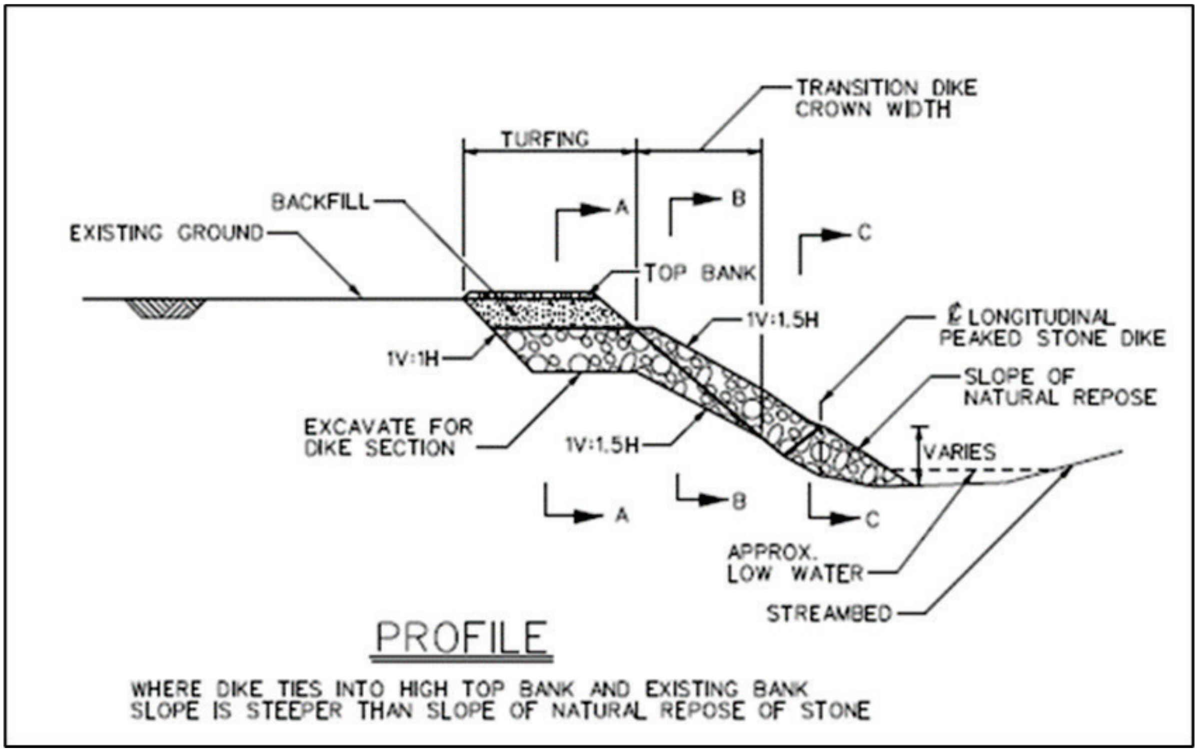

Figure 20. Example revetment key or tieback to prevent structure flanking.

Figure 21. Example revetment key on the Mississippi River. Images reproduced from USACE Vicksburg District (n.d.).

5. Construction of access roadways and staging areas with rock stockpiles and readily available equipment at the GCS sites would enhance the ability to monitor and mitigate issues that arise in fighting the channel degradational process. Locating local sources of rock materials (e.g., list entry

2) and having them stockpiled at strategic locations would be beneficial for working on stabilizing the river.

6. Bank erosion protection should be considered in areas that need stabilization. The meander bend upstream of the La Loma Camp is eroding rapidly into the high terrace on the left bank and is endangering the camp. Toe erosion protection set back from the edge of the existing channel could be applied at this location to smooth the meander transition as it approaches the downstream reach. However, grade control is needed downstream of any bank protection for it to be successful in this system. There was also a proposal to form a pilot channel on the inside right point bar for higher flow events to take pressure off the left bank terrace. This should be investigated further. However, neither bank protection nor pilot channel projects will be successful without some form of grade control downstream of this location to stabilize the energy slope and resolve the bed degradation.

7. Continue to consider and develop measures at the Lombardi structure location (Km 1) as part of the comprehensive stabilization plan. Revetments upstream and downstream require careful consideration (e.g., of potential flanking) as further analysis is completed on geomorphic modeling to assess new data and its influence on regressive erosion propagating up the valley.

8. Investigate the mouth of the Rio Malo and upstream alluvial materials present in the Rio Coca Valley to determine regressive erosion potential and additional need for stabilization to reduce the chance of the Rio Coca channel flanking the proposed or constructed tetrapod dam structure (Km 8).

9. Investigate and assess stabilization measures applicable to all Rio Malo tributary channels. Regressive erosion will continue in tributaries and further contribute to sediment delivery to the downstream Rio Coca reaches, especially the downstream CCS Dam outflow structure (Km 15).

RECOMMENDATIONS: The recommendations that follow can address the water resource issues involving regression channel erosion on the Rio Coca.

- A system-wide, comprehensive GCS plan for upstream and downstream regressive erosion treatment should be further evaluated. This includes providing a GCS at the Lombardi location (Km 1), structures at the permeable bridge (Km 7.8), enhancing the GCS design, and constructing more GCSs from Km 7.8 to Km 12.5 and possibly more structures downstream.

- Continue downstream monitoring for a possible stabilizing slope (downstream of Km 12.5), and expect continued degradation that requires monitoring all the way downstream to the old San Rafael Waterfall. Plan continued field reconnaissance for knick zone and downstream reach adjustments.

- Continue monitoring downstream sediment accumulation and channel fill below the old San Rafael Waterfall and outflow structure.

- Concentrate construction of structures below the existing knick zone (just downstream of La Loma Camp) and upstream to the Rio Malo confluence. This could also include bank protection upstream to protect the meander bend erosion into the La Loma Camp. There are likely other strategic bank protection locations that could be constructed once grade control has been implemented.

- As part of the comprehensive stabilization plan, consider some additional toe scour protection at the CCS Dam. This would include strengthening the downstream outlet apron with additional scour protection by coring in large rock (i.e., well-graded rock) to provide local protection. This would provide additional protection against some of the regressive erosion that may have already propagated upstream and has not made it to the downstream dam apron.

- Connect the CCS Dam structure with the stepped spillway at Km 1 in a single hydraulic system with bank stabilization and erosion protection measures. This design should be incorporated into the stepped spillway design to direct flow over the spillway and reduce the chance of flanking of the structure, primarily on the left bank.

These recommendations are just the beginning of a larger initiative to provide technical support to CELEC in providing stabilization alternatives for the Rio Coca Valley to limit the regressive erosion process. Additional site visits, geologic reports, geomorphic assessments, and more detailed modeling results will be forthcoming as the project progresses.

ADDITIONAL INFORMATION: This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared as part of Water Operations Technical Support (WOTS) and was written by Chris Haring (*christopher.p.haring@usace.army.mil*) of the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). The director of ERDC-CHL is Dr. Ty Wamsley. This CHETN should be cited as follows:

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