Modelling and projection of the morphological evolution of the Coca River after the collapse of the San Rafael waterfall

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Abstract

Between February 2nd and 11th, 2020, the natural collapse of the San Rafael waterfall located in the course of the Coca River in Ecuador occurred. The waterfall was located approximately 23 km downstream from the intake and 48 km upstream from the outflow of the Coca Codo Sinclair hydroelectric plant (CCS), respectively. The 150 m high waterfall was made up of a lava flow that stem from the Reventador volcano. The petrified lava wall acted as a natural dam that retained fluvial sediments and material produced by volcanic activity. As a result of its collapse, the discontinuity of the river profile was totally exposed to the constant action of the water. This discontinuity triggered a process of adaptation towards a new morphological equilibrium along a stretch of more than 70 km. The search for a new equilibrium is reflected in the gradual reduction of the discontinuity in the river profile, and in the new slope that it assumes. This implies the regressive erosion and headcut migration upstream, and the sedimentation of the eroded material downstream of the site of the former waterfall. The rate of the headcut migration upstream, as well as the rate of sedimentation downstream, are rapid. Consequently, the potential occurrence of two failure modes of the CCS plant is foreseen within the considered period of its operational life. On the one hand, the advance of the headcut implies the degradation of the bed around the intake facilities, and on the other hand, the progressive sedimentation threatens to prevent the discharge of the turbinated flow. So far the morphological changes involve the erosion of 277 hm^3 of sediment, and therefore, the need for mitigation and erosion control actions are urgent.

The detailed projection of the evolution of the erosion process is crucial for the conception and definition of potential interventions. In that regard, the projection of the morphological evolution is based on the implementation of a global hydromorphological model of the entire stretch of the river that is subject to the processes of regressive erosion and progressive sedimentation. This global model is conceived from a holistic perspective of the problem, for which the fundamental equations that describe the morphodynamic cycle are used, as well as the record of a sequence of topographic and geologic surveys of the river section under analysis. The idea is to project the temporal evolution of the longitudinal river profile that can be affected by the processes of regressive erosion and progressive sedimentation.

This paper summarizes the implementation of the model and describes the scenarios and projections analyzed with the aim to estimate the magnitude of the implications related to the river bed degradation around the intake facilities of the CCS hydropower plant.

Introduction

Background

Between February 2 and 11, 2020, a natural collapse occurred at San Rafael waterfall, located on the course of the Coca River in Ecuador. The waterfall was located approximately 23 km downstream of the intake and 48 km upstream of the outlet of the Coca Codo Sinclair (CCS) hydroelectric power plant, respectively. The 150 m high waterfall was formed by a lava flow from the Reventador volcano. The petrified lava wall acted as a natural dam that retained fluvial sediments and volcanoclastic material. As a result of its collapse, the discontinuity of the river profile was fully exposed to the constant action of the water stream. This discontinuity triggered a process of adaptation towards a new morphological equilibrium along a stretch of over 70 km. The search for a new equilibrium is reflected in the gradual reduction of the discontinuity in the river profile, and in the new slope that it assumes. This implies the regressive erosion and headcut migration upstream, and the sedimentation of the eroded material downstream of the site of the former waterfall. The rate of the headcut migration upstream, as well as the rate of sedimentation downstream, are rapid. Consequently, the potential occurrence of two failure modes of the CCS plant is foreseen within the considered period of its operational life. On the one hand, the advance of the headcut implies the degradation of the bed around the intake facilities, and on the other hand, the progressive sedimentation threatens to prevent the discharge of the turbinated flow. So far the morphological changes involve the erosion of 277 hm^3 of sediment, and therefore, the need for mitigation and erosion control actions are urgent.

The detailed projection of the headcut migration process is crucial for the conception and definition of possible interventions. In this sense, the projection of the morphological evolution is based on the implementation of a global hydromorphological model of the entire stretch of the river that is subject to the processes of regressive erosion and progressive sedimentation. This global model is conceived from a holistic perspective of the problem, for which the fundamental equations that describe the morphodynamic cycle are used, as well as the record of a sequence of topographic, sedimentological, and geological surveys of the river stretch under analysis. The idea is to project the temporal evolution of the river longitudinal profile that can be affected by the processes of regressive erosion and progressive sedimentation.

This study outlines the model implementation, scenarios, and projections evaluated to estimate the potential riverbed degradation magnitude near the CCS hydroelectric power plant intake. The objective is to assess the temporal evolution of the river's longitudinal profile over a period of time ranging from annual to decadal scales.

Potential reach of the regressive erosion

The constant and permanent activity of the Reventador volcano defines some of the important morphological development processes in the area. The San Rafael waterfall was formed by a lava flow that caused the closure and subsequent damming of the old river channel. The damming of the riverbed became entirely filled with sediment transported by the Coca River and materials from volcanic activity, such as avalanches and pyroclastic flows. This resulted in the San Rafael waterfall, a 150 m drop in elevation that marked a discontinuity in the river longitudinal profile.

The upper graph in Figure 1 shows the delimitation and morphology of the Coca River catchment up to the CCS power plant outflow site. The same image shows a classification of the main river network based on the progressive downstream increment of the tributaries. In other words, the graph shows the increasing importance of watercourses as they flow towards the outflow point of the catchment. On the other hand, the lower graph presents the longitudinal profile starting from the discharge point located at the CCS outlet up to the heads of each of the tributaries shown on the plan view. This provides a complete characterization of the river network in the basin.

The river network profile allows for a preliminary evaluation of the potential regressive erosion reach upstream of the waterfall. By adjusting the upstream profile trend from the discontinuity at km 43 (former San Rafael waterfall), the new equilibrium profile can be inferred. As a result, it can be observed that the erosion is capable of reaching the confluence the Bombón and Quijos rivers (20 km upstream of the CCS intake). Furthermore, the equilibrium profile indicates that the magnitude of the bed level degradation around the CCS intake site, could add up to 50 m approximately. This supports the need to devise erosion control and mitigation measured to protect the existing hydropower infrastructure.

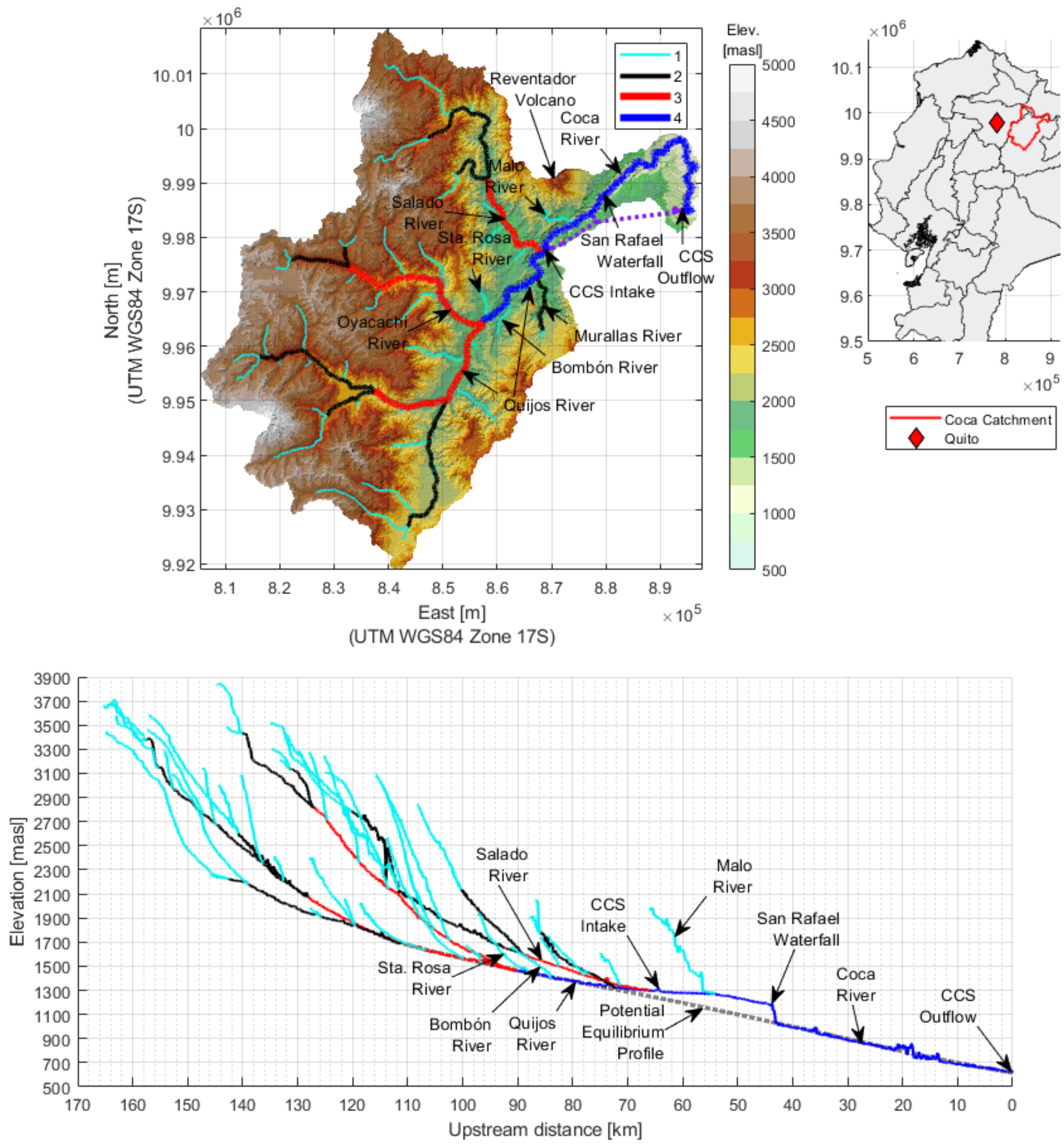

Figure 1. Main river network of the Coca River catchment.

Failure modes of the CCS hydropower plant arising from the regressive erosion process

The regressive erosion of the Coca River following the collapse of the San Rafael waterfall is analogous to the processes derived from the removal of large dams. In these cases, the sedimented material upstream of the dam, which occupies a certain volume of the reservoir, once the structure is removed, begins to be eroded by the river and transported downstream. In that sense, the implications of regressive erosion affect the CCS power plant in two different failure modes that involve both, the intake and outflow infrastructure as follows:

- The progression of the channel bed degradation poses a threat to the integrity of the power plant intake complex. The thickness of the alluvial bed, where the intake is located, is considerable before competent materials such as bedrock can be found. Then, it is possible that the ongoing headcut migration and degradation process results in an equilibrium profile that is located below the current intake facilities.
- The continuous sedimentation experienced downstream of the former San Rafael Falls site threatens the power plant outlet works. The sudden release of material into the river system involves the progressive transport of this anomalous pulse of sediments downstream. Depending on the amount of material eroded, the downstream channel may experience a general rise in levels that could results in the permanent change of the longitudinal slope. The change may be such that the bed levels in the plant's outflow site could rise up to the maximum defined threshold for safe hydropower generation. This would imply that the plant cannot operate due to the inability to discharge the turbined water back into the river.

These failure modes are equally significant as the plant's operability can be compromised by the occurrence of any of them.

Characterization of the Coca River longitudinal profile

Reference longitudinal axis and observed profile evolution

To investigate the temporal changes in the longitudinal profile of the river, a reference axis was established by tracing the thalweg of the river. Figure 2 illustrates the reference axis, which originates from the CCS plant intake point at km 0+000 and extends up to the plant outflow zone at km 71+000 (the former San Rafael waterfall located at km 23+500). All monitoring activities that incorporate different aspects of topography, geology, and geotechnics are aligned with this reference axis

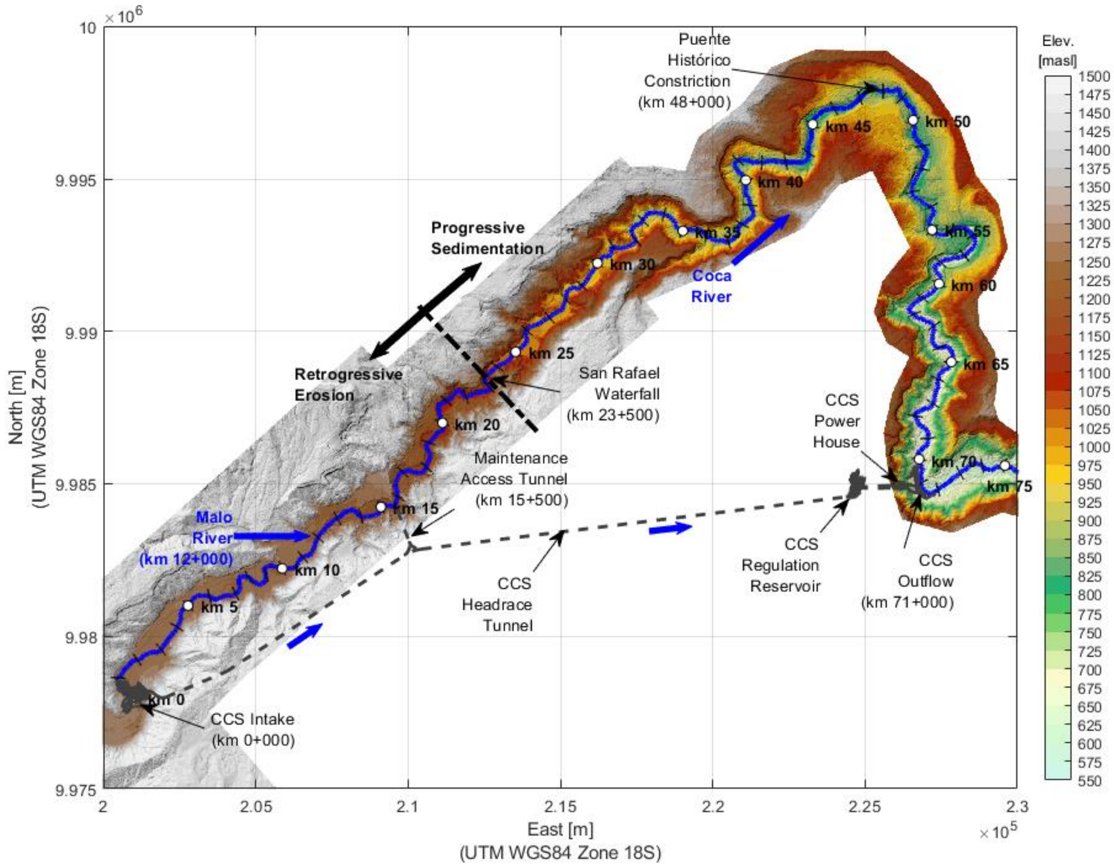

Figure 2. Reference axis defined starting at the CCS intake site (km 0+000) up to the outflow site (km 71+000).

Geological model

Figure 3 depicts the disposition of the geological units that comprise the initial longitudinal profile (prior to the collapse of the San Rafael waterfall). A total of six geological units are identified.

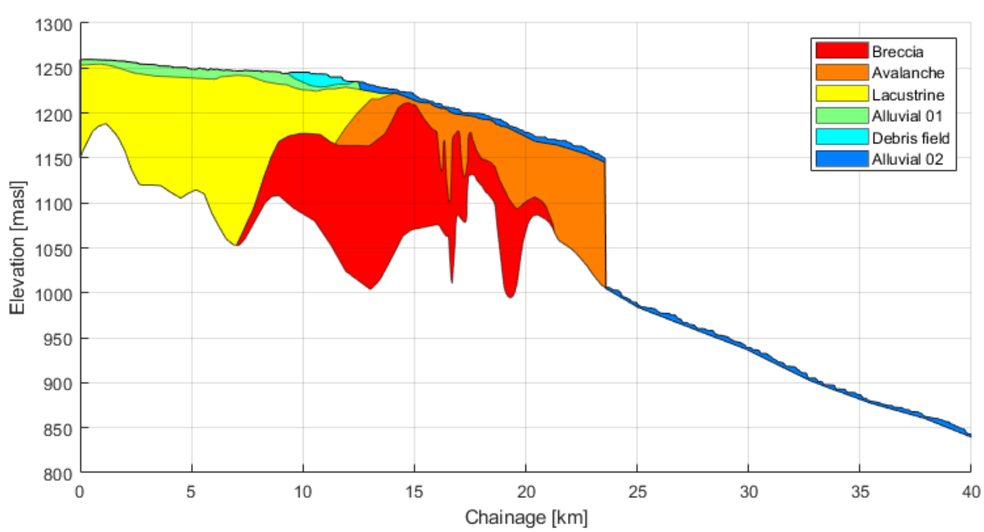

Figure 3. Disposition of the geological units along the river longitudinal profile.

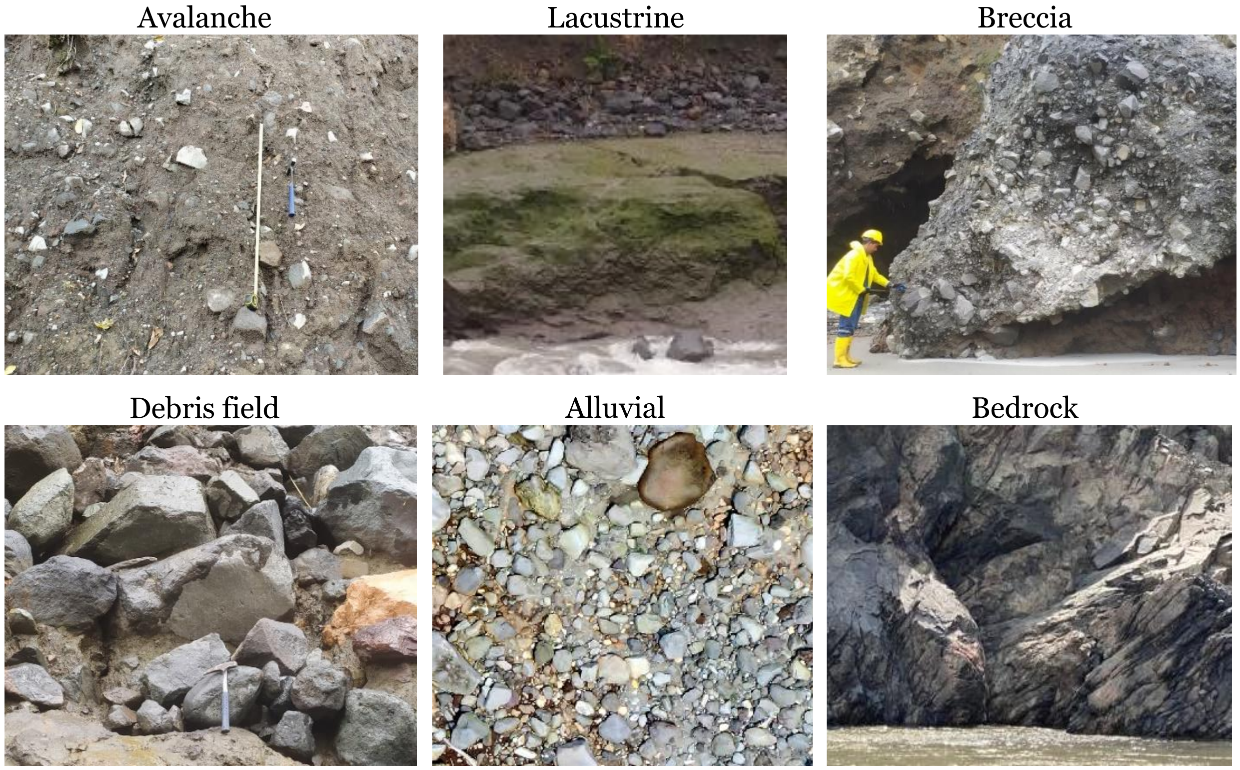

Figure 4. Geological units.

Avalanche deposits

The deposits consist of non-cohesive granular material, which is a mixture of loosely packed particles with varying sizes. The range of particle sizes includes sands with a characteristic diameter of D50 = 0.001 m, gravels with D50 = 0.05 m, and metric-sized boulders.

Lacustrine deposits

These deposits consist of a thick layer of cohesive fine-grained material capable of reaching depths of tens of meters (approximately 70 m) until bedrock can be found. A relatively thin alluvial material layer of approximately 5 meters in thickness covers these deposits near the CCS plant intake site. Erosive resistance of cohesive materials is determined by their critical shear stress and erosion rate. Therefore, in-situ jet test are currently being conducted to investigate the critical shear stress. Preliminary findings regarding lacustrine deposits indicate an average critical shear stress of 86 Pa.

Volcanic Breccia

Between km 7+000 and km 22+000, volcanic breccias underlie the avalanche and fluviolacustrine deposits. Volcanic breccia is characterized as a conglomerate where a fine material matrix is cemented and agglutinates coarse particles, typically with a size of D50 = 0.45 m.

Debris field

These materials originate from the recent volcanic activity of Reventador, and comprise a layer composed of coarse-grained rock material with a characteristic diameter that ranges from D50 = 0.87 m to D50 = 2.70 m. The debris flow extends throughout the entire river valley between km 6+100 and km 8+800, and exhibits a varying thickness ranging from 30 m to 10 m towards the margins and the channel, respectively.

Surficial alluvial layer

The presence of alluvial material is observed throughout the entire profile, with its most significant occurrence being a thin layer 5 m to 8 m thick between km 8+000 and km 12+000. Based on the grain size distribution of the alluvial deposits, a distinction is made between smaller alluvial deposits covering the first 10 km (from km 0+000 to km 10+000) and larger alluvial deposits from km 10 onwards. The smaller alluvial deposits, are characterized by a mean grain diameter of D50 = 0.209 m, whereas the larger alluvial deposits have a mean grain diameter of D50 = 0.551 m.

Bedrock

Throughout the entire profile, the lower limit of the deposits is recognized as the bedrock. This stratum is regarded as a non-erodible material.

Configuration of geological units based on material content

To provide a schematic representation of the geological units, it is possible to interpret each unit as a combination of sediment fractions found along the river profile in varying proportions. To this end, six fractions have been identified, they are differentiated by the presence of cohesive or non-cohesive materials as follows:

- Silt and clay: cohesive material that is mainly present in lacustrine deposits.
- Cementing matrix: Refers to the cohesive material that binds the coarse particles together and is mainly present in volcanic breccia deposits.
- Loose sand: Identifies non-cohesive, granular material with particles of a characteristic size of D50 = 2 mm.
- Gravel: Non-cohesive granular material with particles of a characteristic size of D50 = 200 mm.
- Coarse gravel: Non-cohesive granular material with particles of a characteristic size of D50 = 500 mm.
- Boulders: Non-cohesive granular material with particles of a characteristic size of D50 = 800 mm.

According to the field investigations, Table 1 shows the composition of the geological units based on the set of identified sediment fractions. The distribution of materials in their different proportions along the longitudinal profile is shown in Figure 9, which corresponds to the situation prior the waterfall's collapse.

Table 1. Geological units composition based on material content

Geological Units	MATERIAL					
	Silt and Clay	Cementing matrix	Sand (D = 2 mm)	Gravel (D50 = 200 mm)	Coarse Gravel (D50 = 500 mm)	Boulders (D50 =800 mm)
	Cohesive	Cohesive	Non-cohesive	Non-cohesive	Non-cohesive	Non-cohesive
Alluvial 01			20%	45%	35%	
Debris field			15%	35%	30%	20%
Alluvial 02			20%	35%	45%	
Lacustrine	90%		10%			
Avalanche			75%	15%	8%	2%
Volcanic Breccia		53%	25%	15%	5%	2%

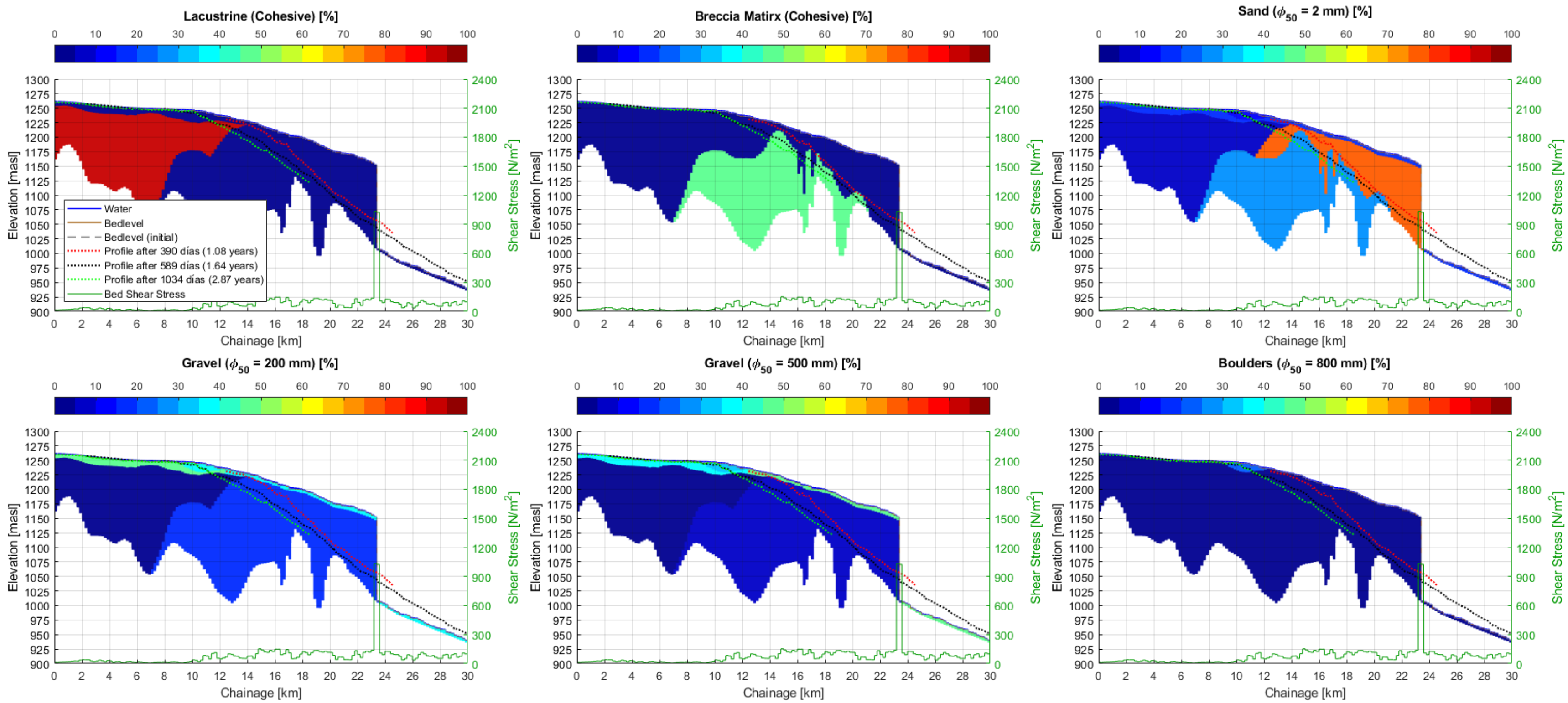

Figure 4. Distribution of sediment fractions along the river profile according to the geological model

Magnitude of the regressive erosion

The compilation of sequential topographic surveys carried out along the stretch of the Coca River between the intake and the outlet of the CCS plant is summarized in the longitudinal profiles shown in Figure 5. These profiles demonstrate the progression of river erosion. After 1034 days following the collapse of the waterfall, the headcut position has been identified at km 10+000. In addition, the lower graph presents the mean channel width over the entire river stretch.

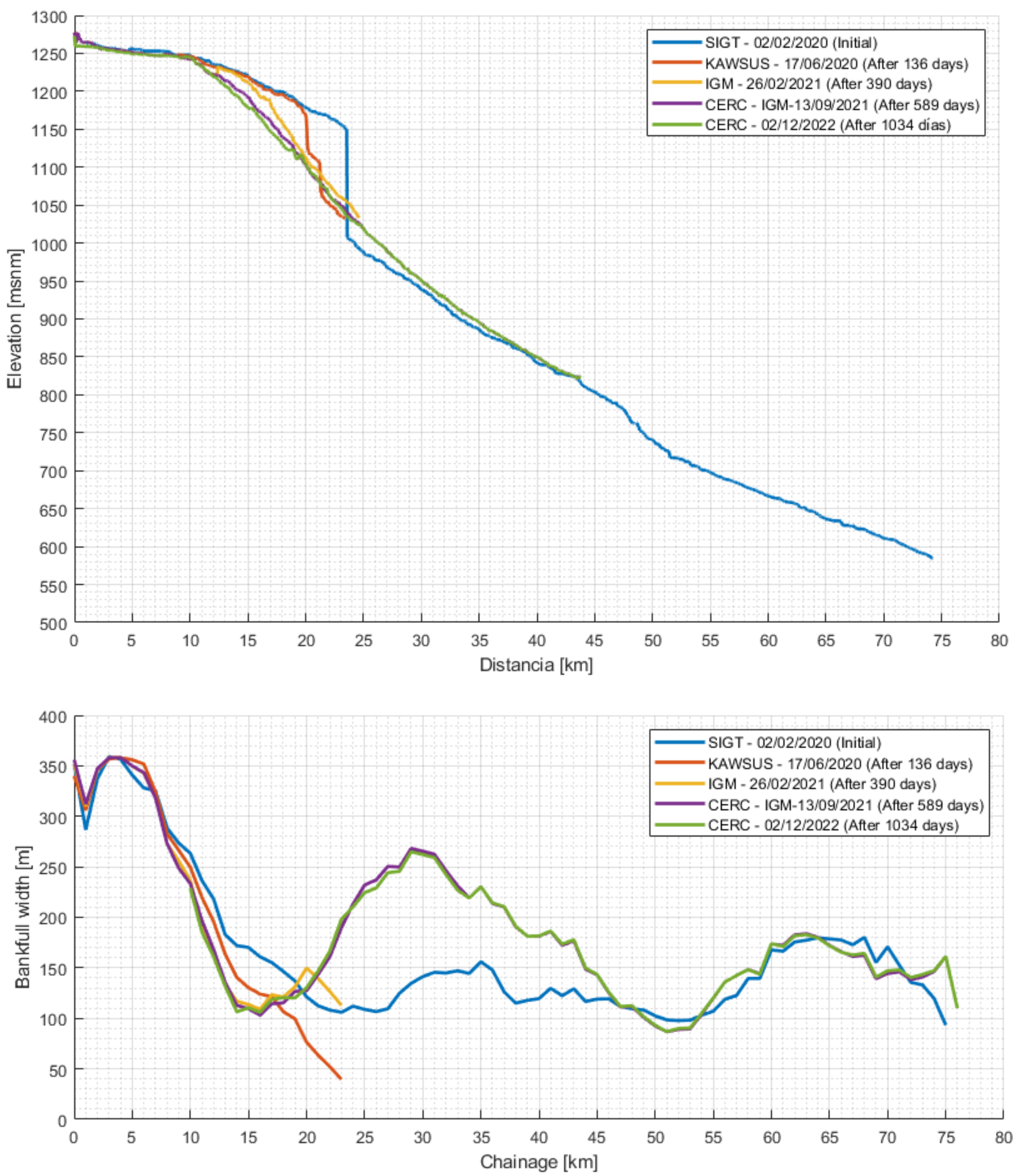

Figure 5. Observed evolution of the longitudinal profile and the average width of the river channel.

The images highlight the magnitude of both the regressive erosion and the progressive sedimentation processes upstream and downstream of the former waterfall site (km 23+500). In terms of regressive erosion, the river has degraded its original bed to depths of up to 100 m near the former waterfall site, and there is a noticeable narrowing of the channel in the eroded zone compared to the initial conditions. This indicates that the process of adapting the margin slope is still ongoing and requires a longer temporal scale to reach a new equilibrium. On the other hand, in the sedimentation area, there is a clear widening of the channel sections due to the rise in the channel bed levels.

The sequence of erosion-sedimentation maps presented from Figure 7 to Figure 8 complements the evidence of the magnitude and extent of the erosive process. The erosion mechanism begins with the degradation of the river bed, which destabilizes the margins slopes causing them to collapse until they find their own equilibrium slope based on the material they consist of. Therefore, a dramatic progressive widening of the valley is observed as the river advances towards the former waterfall area.

The longitudinal profiles and erosion maps presented are a subset of the total of monitoring products developed since the onset of regressive erosion. By analyzing the full sequence of erosion maps, the temporal evolution of the volumes of material released downstream from the former waterfall site was estimated (Figure 6). As of December 2022, the total estimated volume of erosion is 277.38 hm^3.

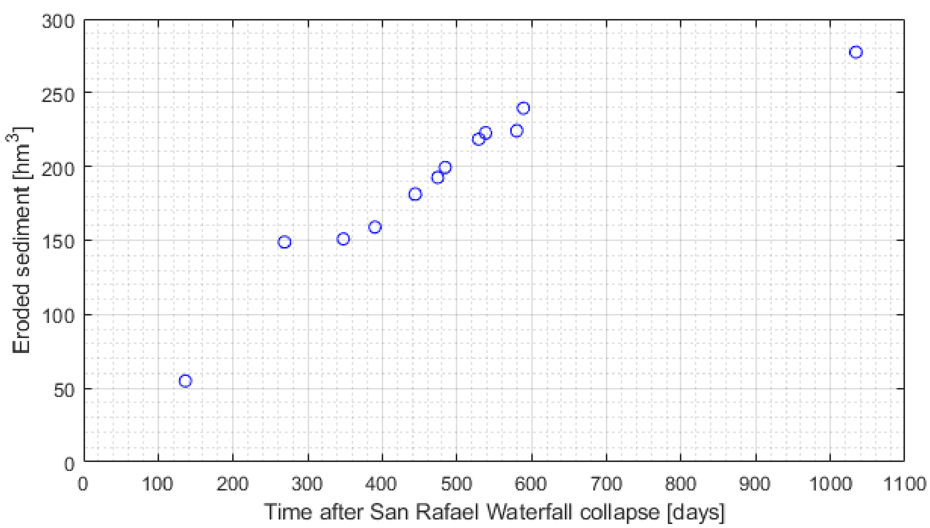

Figure 6. Temporal evolution of the eroded volume of material.

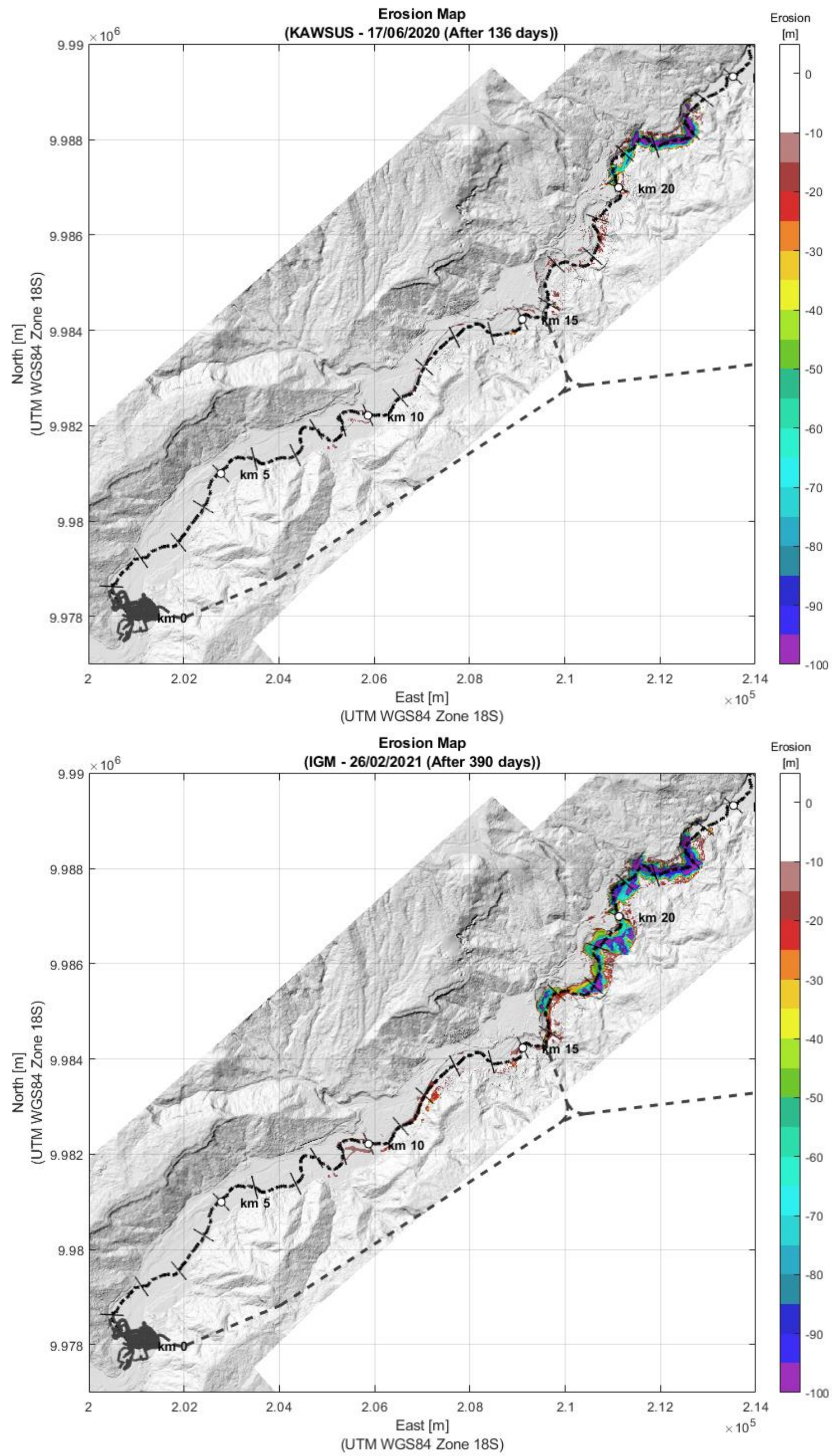

Figure 7. Erosion-sedimentation maps 136 and 390 days after the collapse of the San Rafael waterfall.

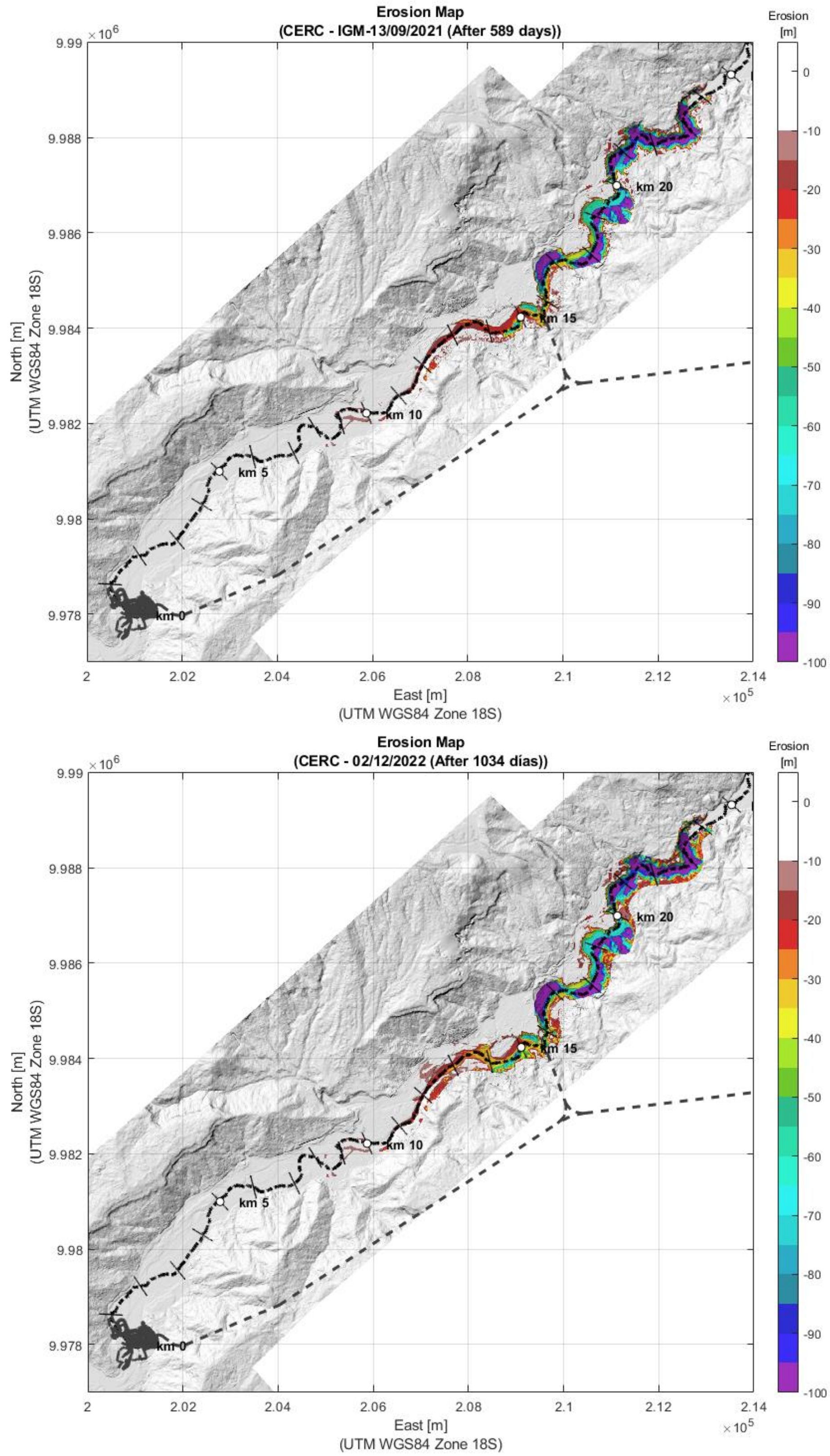

Figure 8. Erosion-sedimentation maps 589 and 1034 days after the collapse of the San Rafael waterfall.

Hydro-morphodynamic modeling of the profile evolution

Hydro-morphodynamic model

To simulate the hydrodynamic and morphodynamic processes along the length of the Coca River, the process based numerical model Delft3D is used. The model executes the multidimensional simulation of flows, sediment transport, and morphological evolution through a set of equations based on the principles of conservation of mass, momentum, and energy (ref. [4]).

The hydrodynamic part of the model is based on the continuity and conservation of momentum equations (Reynolds-averaged Navier-Stokes equations) for incompressible fluids. The morphodynamic part of the model simulates the processes of sedimentation and erosion, considering the transport capacity and supply of sediment. In the mobile bed scheme, hydrodynamics induce sediment transport as bed and suspended loads. The fraction of sediment that interacts with the bed produces a variation in the bed, which in turn influences the hydrodynamics. The topographical evolution of the bed is then calculated considering the sediment mass balance equation, i.e., the Exner principle.

The model has different options to simulate sediment transport capacity. For this study, the Wilcock-Crowe (2003) and the Partheniades-Krone (1965) predictors were applied for non-cohesive and cohesive material, respectively.

Initial condition

The initial condition from which all morphological evolution scenarios are projected refers to the state of the river prior to the collapse of the San Rafael waterfall, that is, the situation just before February 2, 2020 (Figure 4).

Boundary conditions

To simulate the processes along the river, specific data is required. The information required serves as input data and for the purposes of calibration and verification of the model. In this case, the boundary conditions are summarized as follows:

- The hydrodynamic boundary conditions refer to the inflow discharge into the model domain, specifically the flow discharged gauged at the CCS intake structure following the collapse of the San Rafael waterfall (as shown in Figure 9).
- The sediment boundary conditions include the sediment concentrations of the inflow discharge. For this case, this aspect is considered negligible since the intake structure largely intercepts bedload transport.
- The bed composition involves the bed topography, substrate composition and characteristics, which are primarily incorporated during the definition of the initial condition of the longitudinal profile.

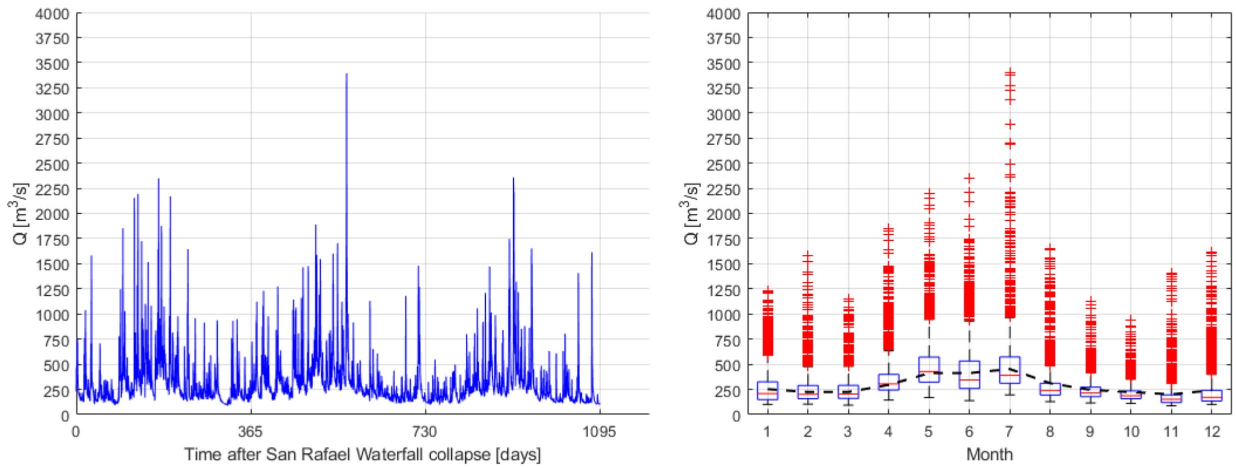

Figure 8. Measured hydrograph at the CCS intake since the collapse of the San Rafael waterfall.

Model calibration

Retrospective Evolution of the Longitudinal Profile.

The calibration process involves the systematic tuning of parameters that are associated with the sediment transport equations. The objective is to accurately replicate the morphological changes of the longitudinal profile over a span of 1034 days after the San Rafael waterfall collapse. Starting from February 2020, the simulation tracks the changes in the longitudinal profile up to 390, 589, and 1034 days, which are the time points where topography measurements are available for comparison.

To avoid subjectivity in interpreting the results, the model's predictive ability is evaluated using the Brier Score Skill (BSS) index (ref. [3]), which has been specifically defined for morphodynamic studies. A BSS value of 1.0 indicates a perfect prediction of morphological changes. On the other end, a value of 0.0 means that the model's prediction is no better than the reference model, i.e., no morphological change. For morphodynamic studies, Van Rijn et al. (2003) (ref. [1]) define the model's skill according to the BSS, as shown in Table 2.

Table 2. Classification of the BSS index for morphodynamic studies.

Classification	BSS
Excellent	1.0 - 0.8
Good	0.8 - 0.6
Regular	0.6 - 0.3
Poor	0.3 - 0.0
Bad	< 0.00

Figure 9 presents the contrast between the modeled and measured profiles. In each instance, a high degree of agreement is observed between the profiles in the sense that the magnitude of erosion is generally replicated, and the position of the erosion front is also captured. The accuracy of the model's evolution is confirmed by the achieved BSS indices, which in all cases exceed the value of 0.90, indicating an excellent model reproduction capability.

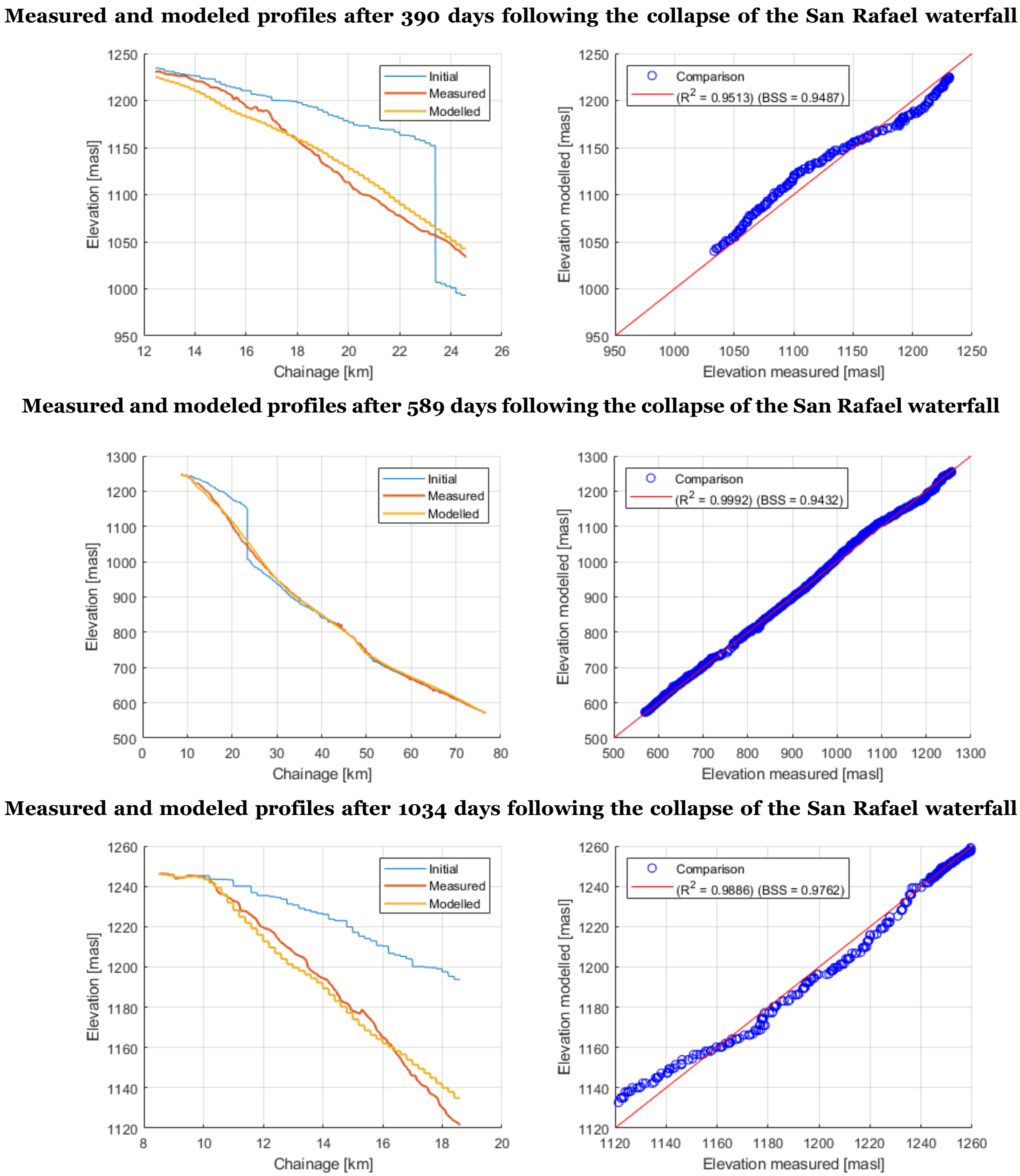

Figure 9. Comparison of measured and modeled longitudinal profiles at different times following the collapse of the San Rafael waterfall.

Figures 10 to 12 display the Coca River profile configuration, each representing the instances defined for model calibration.

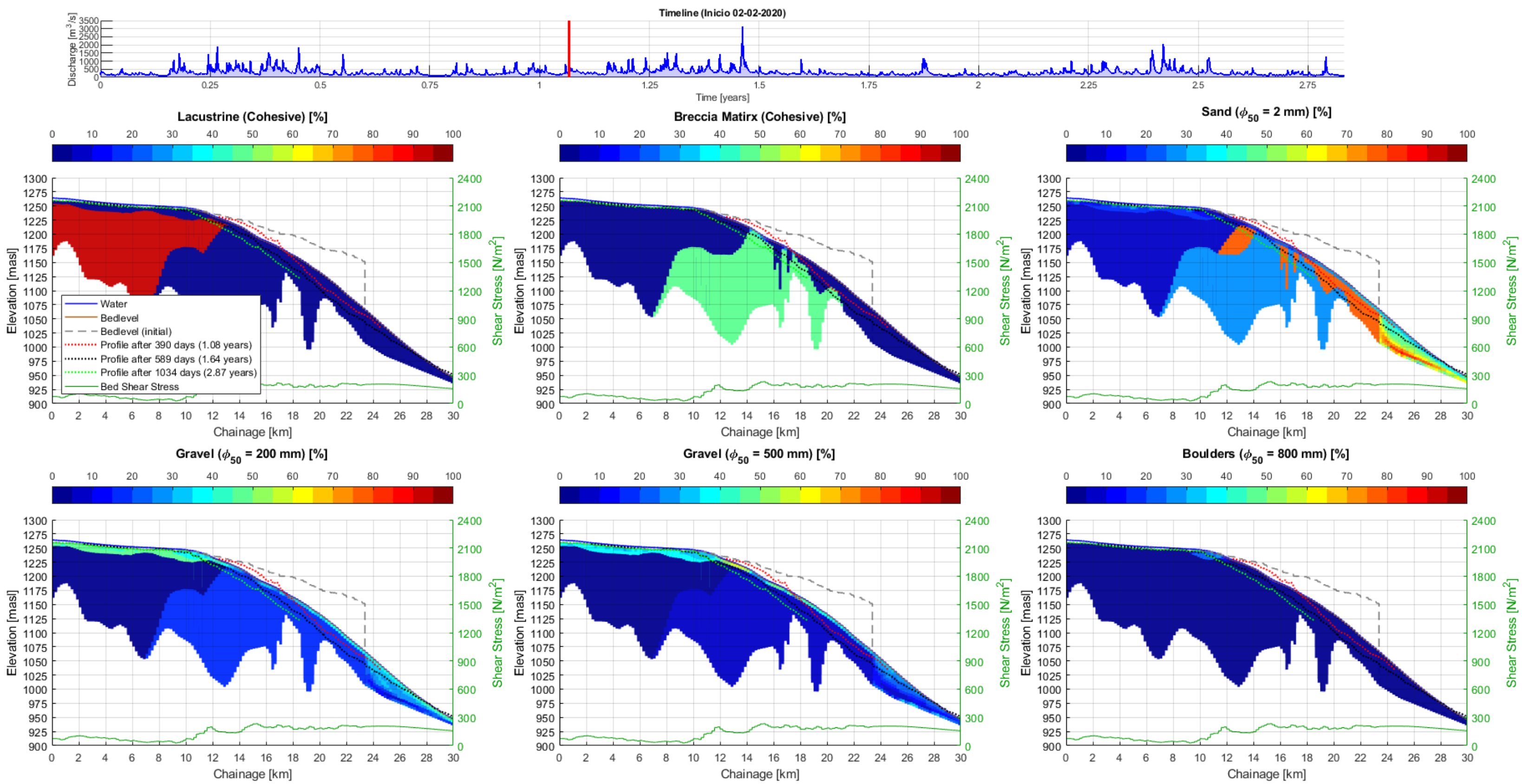

Figure 10. Longitudinal profile situation of the Coca River model after 390 days following the collapse of the San Rafael waterfall.

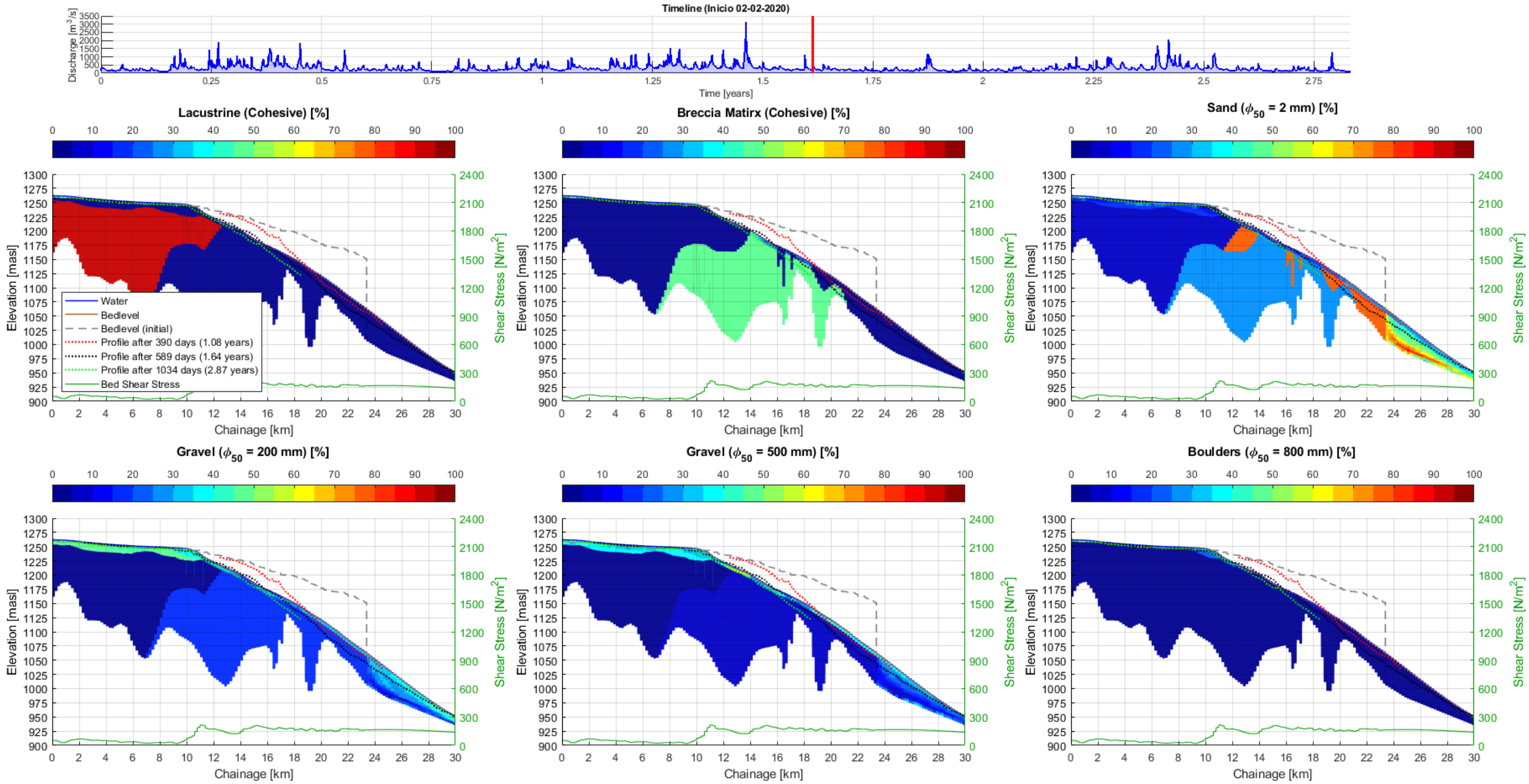

Figure 11. Longitudinal profile situation of the Coca River model after 589 days following the collapse of the San Rafael waterfall.

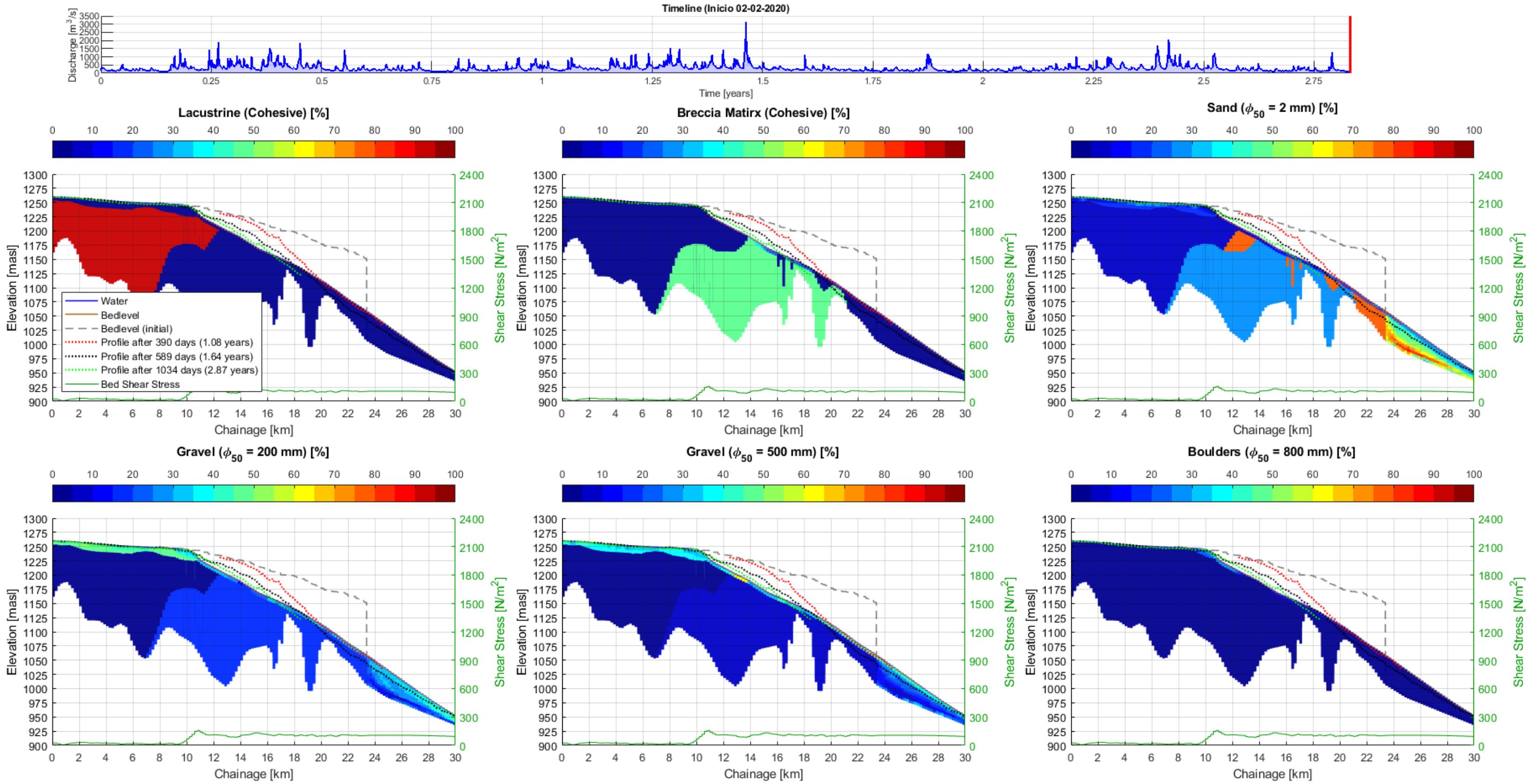

Figure 12. Longitudinal profile situation of the Coca River model after 1034 days following the collapse of the San Rafael waterfall.

Verification of the eroded volumes

In addition to replicating the spatiotemporal evolution of the longitudinal profile, the model's efficacy is validated through a comparative analysis of the estimated sediment erosion volumes with the corresponding measured values. The 23 km segment between the CCS intake and the San Rafael waterfall area is taken into account for this purpose. The high level of agreement between the model's results and the measurements, as shown in Figure 13, confirms the suitability of the model to predict the regressive erosion process and the longitudinal profile evolution.

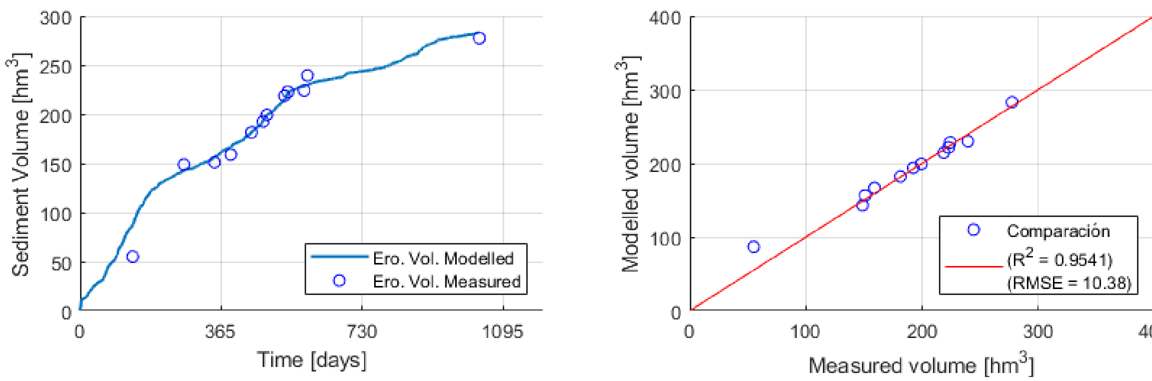

Figure 13. Comparison between measured and calculated volumes of eroded sediment in the river section between the CCS intake and the San Rafael waterfall.

Profile evolution forecast

Scope

The process of erosion and headcut migration is influenced by various factors, including the hydrological conditions of the contributing catchment, the hydraulic characteristics of the river channel determined by its geometry and slope, and the geological-geotechnical conditions that define the substrate's intrinsic resistance to erosion. Out of these factors, the river discharges that reflect the hydrological conditions play a significant role in determining the erosion rates. Specifically, the progression of erosion depends mainly on the occurrence, magnitude, and frequency of floods. Although the flow regimes follow a predictable interannual trend based on the dry and rainy seasons, the hourly-resolution hydrograph shows considerable variability in flood magnitudes and a high level of randomness in their frequency of occurrence. As a result, predicting headcut migration accurately at an hourly resolution level by defining future hydrographs and flood conditions is challenging.

Based on the above, and aiming to limit the uncertainty of the erosive process development, this chapter conducts an analysis to determine the potential range of variation in the longitudinal river profile, taking into account the variability of river discharges during the prediction period under consideration.

Flow duration curves and variability of yearly averaged discharges

Given the uncertainty about the future frequency and magnitude of floods, the hourly-resolution measured hydrograph during the first year after the waterfall collapse is assumed as the base for the predictions. To generate predictions for various timeframes, it is crucial to modify the base hydrograph by accounting for the potential range of water volume that may flow through the river during the projected period. Thus, an indirect measure of the water volume that flows in a certain time is given by the mean discharge in that period.

The upper graph depicted in Figure 14 displays the yearly averaged discharges recorded between 1972 and 2022. This graph also features the averaged discharges calculated at various resolutions (ranging from 1 to 20 years) based on the annual interval values. The lower graph presented in the same figure shows the flow duration curves for each respective resolution. Thus, the range of variation of the volumes or mean discharges for a given time horizon is defined by the corresponding duration curve. Consequently, the 90% confidence interval of variation is limited between the 95th and 5th percentiles in each case.

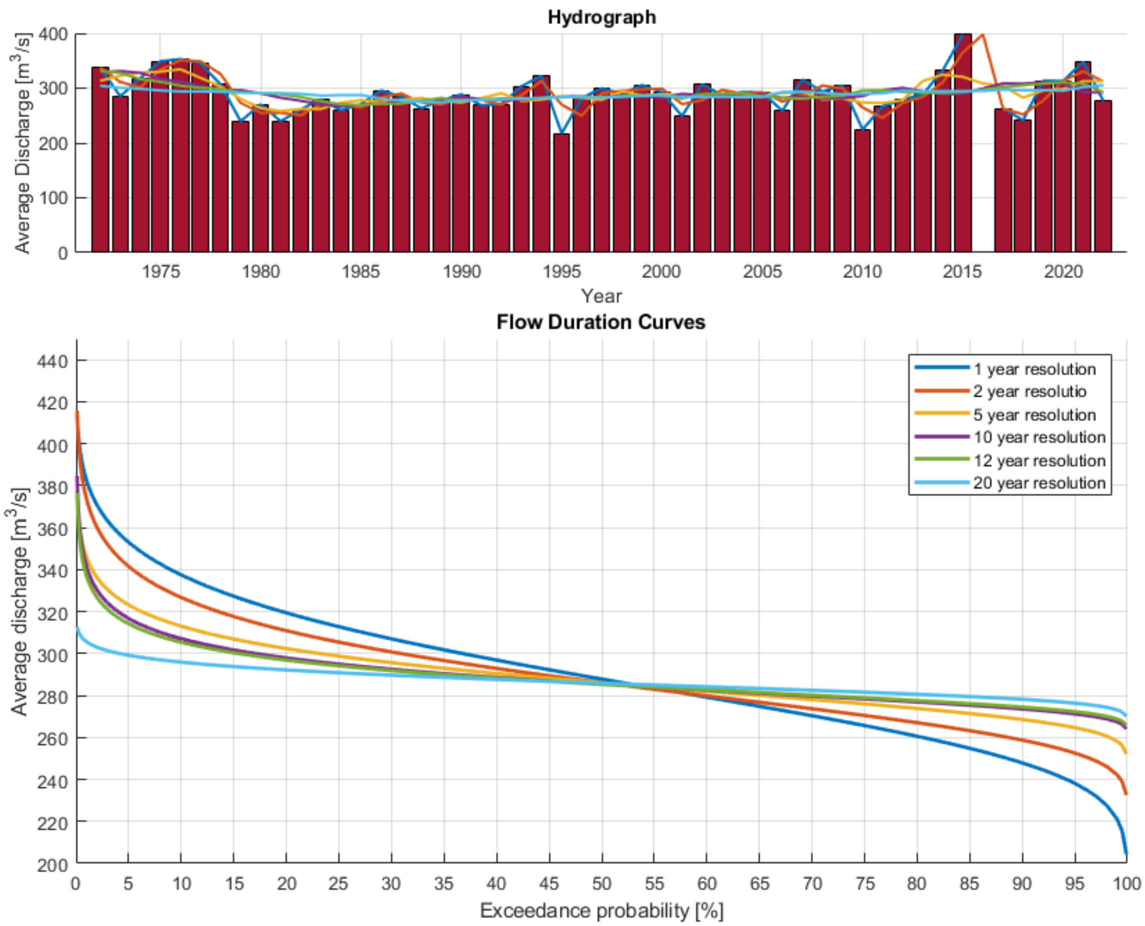

Figure 14. Average flow hydrographs and flow duration curves.

Scaling of the base hydrograph

The idea behind the sensitivity analysis to hydrological conditions is to estimate the range of erosion progression in response to potential variations in water volumes that flow during a given period. Hence, the measured hydrograph upstream of the power plant during the first year after the collapse of the San Rafael waterfall is assumed as the base condition. Depending on the forecasting horizon for profile evolution, it is necessary to scale the base hydrograph according to the duration curves presented in the previous section. For example, to determine the hydrograph corresponding to a mean discharge of 340 m^3/s that corresponds to a 5% probability of exceedance within a period of 2 years, it is necessary to scale the base hydrograph that has a mean discharge of 320 m^3/s. Since the progression of erosion is highly sensitive to floods, scaling the base hydrograph is aimed at achieving the required mean discharge by applying a scaling factor that affects only the flood-associated part of the hydrograph. To achieve this, the base hydrograph is first discretized into:

- Base flow, which refers basically to the hydrological processes of the catchment that develop on longer temporal scales such as infiltration and subsurface flow.
- Runoff, which refers to the rapid processes in the catchment associated with the occurrence of storms and consequent floods.

Based on this discrimination, the scaling factor is applied only to the runoff part, and therefore the scaled hydrograph increases only the volume that flows during flood events. The top graph in Figure 15 shows the division of the hydrograph into base flow and runoff flow, and the bottom graph shows the result of scaling the base hydrograph according to the scaling factor of flood events.

With the proposed methodology, the hydrographs defining the 90% confidence range (hydrographs attributed to 5% and 95% probability of exceedance) are determined for projections of the longitudinal profile evolution of the Coca River over periods of 1, 2, 5, 10, 12, and 20 years.

In summary, to model the evolution of the river profile, it is essential to establish the annual flow hydrograph in hourly resolution, which will be iteratively replicated during the forecast temporal horizon. The characterization of the range of variation of the profile evolution within a specific period requires the determination of two hydrographs, corresponding to the mean flows with a probability of exceedance of 5% and 95%, respectively. To this end, the flood scaling factor is applied to the base hydrograph for each case.

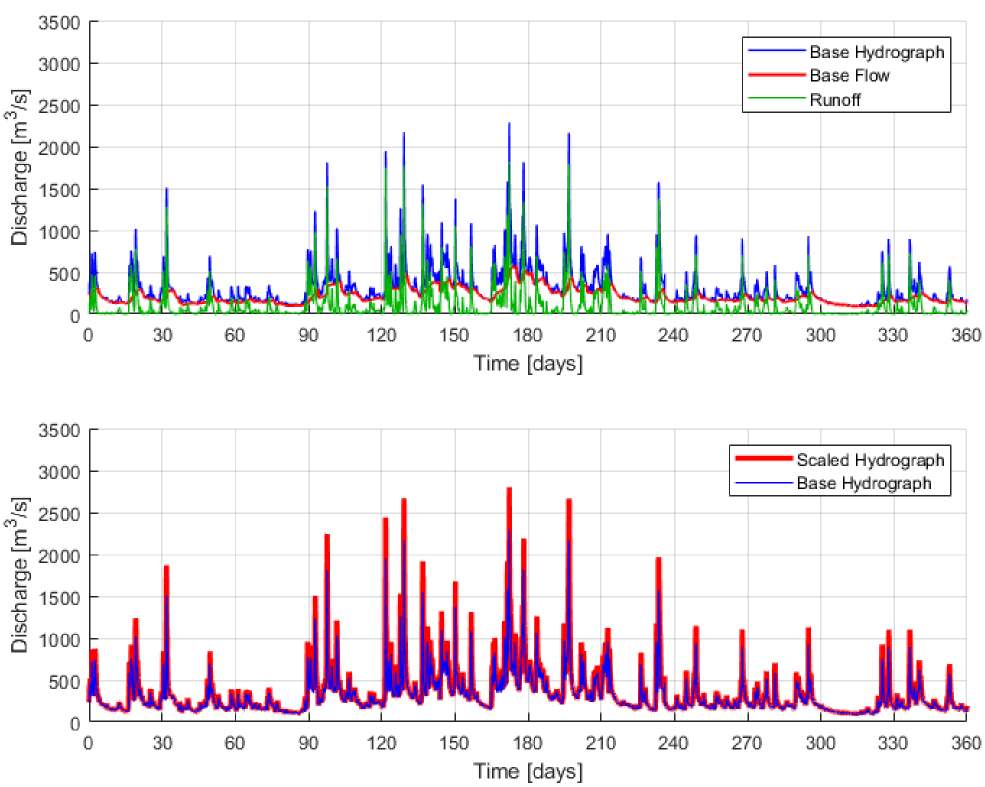

Figure 15. Discretization of the base hydrograph and the resulting of scaled hydrograph.

Projected variation range of the longitudinal profile

Figure 16 shows the projection of the variation ranges of the longitudinal profile of the Coca River in the 40 km stretch downstream of the CCS power plant intake. Each graph displays the initial configuration of the longitudinal profile (before the waterfall's collapse), along with the profiles corresponding to 95% and 5% probability of exceedance. These profiles are indicative of the potential hydrological scenarios that could occur within the specified temporal horizon.

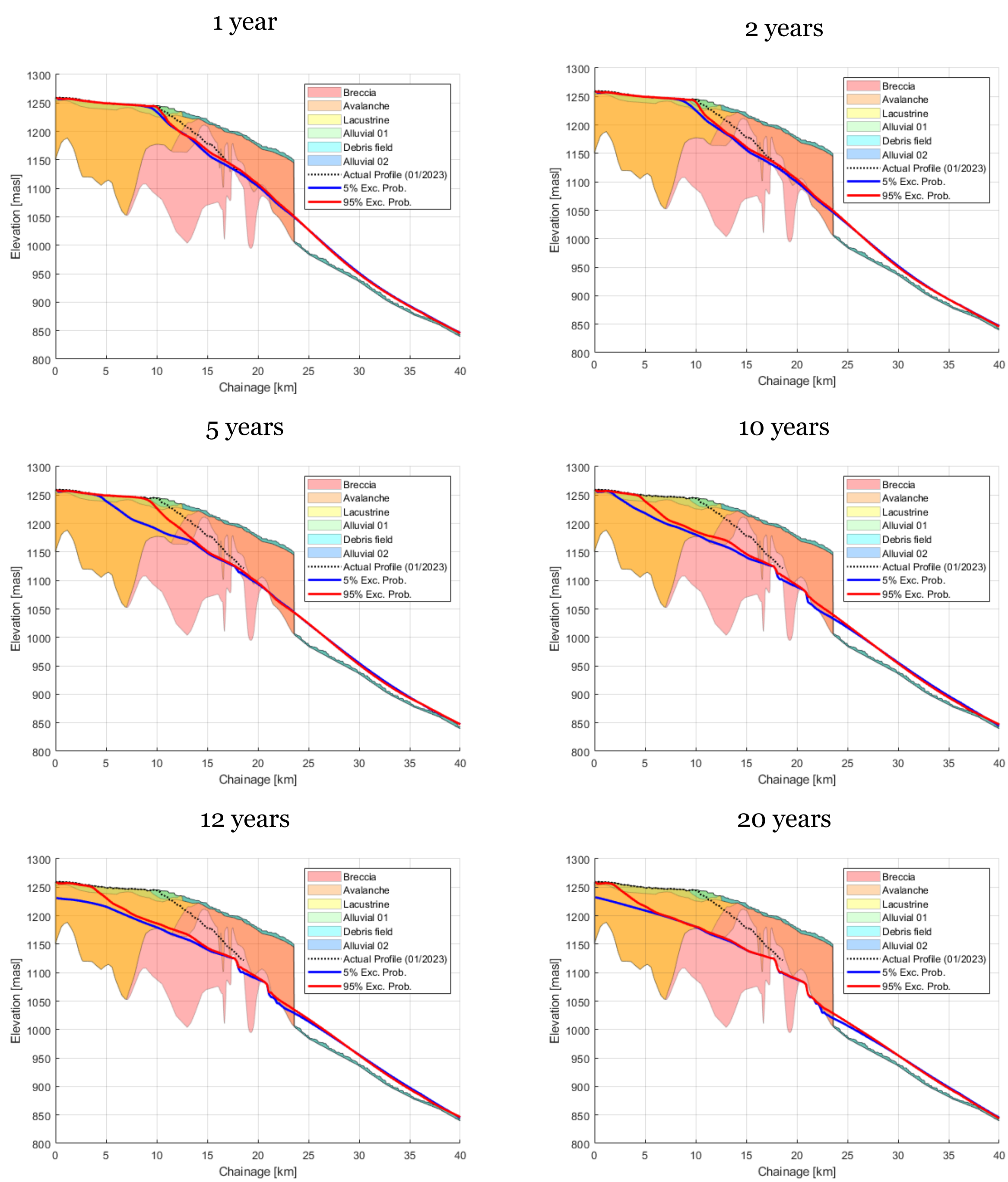

Figure 16. Projection of the morphological evolution of the longitudinal profile of the Coca River.

In all cases, the significant variation within the 90% confidence interval confirms the high degree of sensitivity of the erosive process to changing hydrological conditions. According to the projections, the headcut has the potential to reach the intake area within the next 12 years. Moreover, in the medium to long term (20 years), the potential degradation of the bed near the intake structure could reach up to 30 m.

Conclusions

The study of the morphological evolution of the longitudinal profile of the Coca River is a fundamental component for the conception and planning of mitigation works against the regressive erosion process that threatens the integrity of the intake structure of the Coca Codo Sinclair (CCS) power plant. For the analysis and projection of this evolution, a hydro-morphodynamic model of the entire 71 km river stretch between the intake and the outlet of the power plant is used. The model has been implemented based on all the information monitored since the onset of the regressive erosion process in February 2020. The following summarizes the main aspects related to the implementation of the model, the observed evolution of the river, and the projections regarding the potential bed level degradation around the CCS power plant intake site.

- The hydro-morphodynamic model integrates all available and up-to-date information obtained from continuous monitoring efforts in the fields of hydrology, hydraulics, sedimentology, geology, and geotechnics.
- The hydro-morphodynamic model has been calibrated using sequential topographic measurements and volumetric estimates of the sediment eroded upstream of the former San Rafael waterfall site. The calibration process confirms that the model can replicate the evolution of the longitudinal river profile with respect to both the temporal and magnitude aspects of the river incision process. As a result, considering the uncertain nature of future hydrological conditions, the longitudinal profile's projected temporal evolution aims to identify a probable range within which the profile may vary.
- Regarding the headcut migration towards the CCS intake, the analyzed scenarios predict a medium-term riverbed degradation in the order of 25 m to 30 m. Depending on the severity of future hydrological conditions, this situation may occur within the next 20 years. Likewise, under the same assumptions, the incipient arrival of the headcut to the intake is projected to occur within the next 12 years.
- The headcut's current location is only starting to impact the lacustrine strata that are prevalent in the intake area, and their response to hydraulic erosion is only now becoming apparent. Therefore, it is crucial to maintain and enhance the monitoring of the erosion progression to enable recalibration of the model for more accurate predictions.

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