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RISK MANAGEMENT APPLIED TO THE CONSTRUCTION OF VARIANTS FOR OLEODUCTO DE CRUDOS PESADOS (OCP): QUIJOS – COCA RIVER REGRESSIVE EROSION CASE

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ABSTRACT

The Quijos – Coca River (Ecuador) is one of the prominent cases of river erosion that has gained significant importance in recent years due to the rapid rate it has experienced. From April 2020 to June 2023, approximately 204 million cubic meters of sediment have been removed. The regressive erosion of the Quijos – Coca River led to the rupture of the Oleoducto de Crudos Pesados (OCP) in April 2020, and since then, its progression has repeatedly jeopardized the crude oil transportation operation, compelling OCP Ecuador S.A. to respond through the construction of variants from its original course. The stochastic nature of variables associated with this phenomenon increases the unpredictability of the behavior of the Quijos – Coca River, its banks, and its tributary rivers, making risk management the primary tool to confront this issue. The research aims to present the methodological framework developed and employed by OCP Ecuador S.A. in constructing of variants from its original course. This framework is based on the likely angles of repose that the banks of the Quijos – Coca River and its tributaries would adopt following scenarios of channel deepening.

Keywords: river erosion, Quijos-Coca river, OCP, risk management, pipeline variant, Oleoducto de Crudos Pesados.

NOMENCLATURE

OCP	Oleoducto de Crudos Pesados
SOTE	Sistema de Oleoducto Transecuatoriano
DEM	Digital Elevation Model
ROW	Right-of-Way
KP	Kilometer Post

1. INTRODUCTION

River erosion is a natural phenomenon that continually alters the topography of its influence area. Variables such as terrain slope, sediment origin, local geology, precipitation, and discharge are directly linked to the rate at which riverbanks and channels undergo these modifications.

One of the most striking and uncommon phenomena in the realm of river erosion is retrogressive erosion associated with upstream waterfall migration. These processes entail intricate interplay between fluvial bed erosion and the mechanism of massive margin collapse due to geotechnical instability. This phenomenon can engender a myriad of economic predicaments, including infrastructure collapse due to extensive bed erosion, compounded by environmental repercussions, particularly in cases involving hydrocarbon transportation systems (1).

The collapse of the San Rafael waterfall has become one of the most significant case studies of retrogressive erosion in recent years. Formerly situated between the provinces of Napo and Sucumbíos, the 150-meter-high San Rafael waterfall was deemed one of the country's prime tourist attractions (2). However, in February 2020, the waterfall's collapse ensued, setting off an aggressive bed erosion process upstream in the Quijos - Coca River (Figure 2). This event, in April of the same year, reverberated throughout the hydrocarbon transportation industry in the country as it led to the rupture of two oil pipelines and a multiproduct pipeline located 1.5 km upstream from the waterfall site: Oleoducto de Crudos Pesados (OCP), Sistema de Oleoducto Trans Ecuatoriano (SOTE), Poliducto Shushufindi-Quito.

FIGURE 1: SAN RAFAEL WATERFALL, 2019 [PHOTOGRAPH]. MINISTERIO DE TURISMO DEL ECUADOR.

FIGURE 2: SAN RAFAEL WATERFALL, JUL 2023 [PHOTOGRAPH]. OCP ECUADOR S.A.

This condition compelled the operators to construct variants from their original routes, successfully restoring the crude oil transportation service 30 days after its rupture (3). However, the advancement of the headward erosion due to channel deepening of the Quijos – Coca River continued to impact the infrastructures situated upstream, resulting in the collapse of two bridges. One of these bridges was located at the crossing of the Montana River along the E45 road, while the other was built as an access point for window 2 of the Coca Codo Sinclair project.

The progression of the erosive front through channel deepening of the Quijos – Coca River subsequently destabilized its banks, leading to lateral erosion advances that gradually jeopardized the hydrocarbon transportation operation. To manage this risk, OCP Ecuador S.A. implemented a series of logical measures, which effectively prevented further ruptures of the OCP and SOTE pipelines.

For instance, in December 2021, the implementation of this plan prevented the rupture of the OCP, SOTE, and Poliducto Shushufindi- Quito, when the E45 road collapsed due to the difference in elevation between the discharge point of the Piedra Fina River and the channel of the Quijos – Coca River. Although these actions successfully averted the potential rupture of the pipelines and the ensuing environmental impact from hydrocarbon spills, they couldn't prevent the halt of the crude oil transportation operation. This disruption lasted for 23 days, resulting in estimated losses of 600 million USD (4).

From April 2020 to August 2023, it is estimated that the erosion of the Quijos – Coca River has caused the removal of 204 million cubic meters of material (Figure 3)(5). OCP Ecuador S.A., the operator of the OCP, has constructed 8 temporary bypasses and 2 permanent variants by 2023, with an estimated cost of 31 million USD. Additionally, Petroecuador EP has implemented 7 variants for the SOTE and 5 variants for the Poliducto Shushufindi – Quito, at a cost of 16.2 million USD (4).

(a) January 2021

(b) May 2023

FIGURE 3: OCP KP 97. [PHOTOGRAPH]. OCP ECUADOR S.A.

This research aims to present the methodological framework employed by OCP Ecuador S.A., which has been developed based on the experience of the technical team who have been dealing with this issue over the past years. They have provided objective solutions to ensure the continuity of operations.

The "Materials and Methods" section outlines the development of the regressive erosion phenomenon from a geological perspective and elucidates the influence of the variables governing the issue. The rationale behind the distance-based action matrix is expounded upon, along with the workflow employed for the geometric projection of the lateral erosion front of the Quijos – Coca River.

Subsequently, the results yielded by the implementation of this methodology are discussed, presenting a juxtaposition of its advantages and disadvantages.

2. MATERIALS AND METHODS

This section provides a concise description of the formation of the San Rafael waterfall, its geological context, and the reasons behind its collapse. Subsequently, the process employed for monitoring the lateral erosion front and data recovery is explained.

2.1 Overview

The OCP Right-of-Way (ROW) from KP 93 (Hostería El Reventador) to KP 102 (San Carlos) is situated on the left bank of the Quijos – Coca River, runs parallel to its course. The El Reventador volcano is the most significant geological feature in the area, exerting a direct influence on the quality and diversity of volcanic materials (lavas, lahars, pyroclastic flows, and volcanic avalanches) that have filled the channel of the Quijos - Coca River since its origin approximately 350,000 years ago (5).

The San Rafael waterfall originated approximately 19,000 years ago, resulting from the disruption of the natural course of the Quijos – Coca River due to a lava flow from the El Reventador volcano (6). In February 2020, the collapse of a sinkhole diverted the course of the Quijos – Coca River beneath the lava flow forming the San Rafael waterfall, leading to its disappearance and subsequent regressive erosion (7).

The monitoring implemented in the area by OCP Ecuador S.A. revealed that the erosive process of the Quijos – Coca River operates along three sequential axes of behavior. The first axis, known as the deepening axis, is characterized by the incision of the river channel and triggers the phenomenon. The second axis, referred to as the frontal axis, involves the advancement of the erosion front upstream, resulting from the elevation difference created in the river channel due to deepening. Once the river channel has deepened and its elevation difference has progressed upstream, a third axis is triggered, which acts upon the riverbanks, causing massive collapses. This third axis is termed the lateral axis and currently poses the highest risk to the OCP integrity.

2.2 Lateral erosión monitoring and data collection

Following the OCP rupture event in April 2020, a monitoring plan was established to measure the progression of the lateral erosion front of the Quijos – Coca River relative to the OCP's location. Three techniques were implemented, with their measurement frequency determined based on their measurement complexity.

For instance, the first and most basic technique involved daily measurements of the lateral erosion front's edge toward the OCP's location using marked lines. This quickly provided field-measured real data on the lateral erosion front behavior. The second technique entailed conducting unplanned drone flyovers on a weekly basis to observe erosive activities that might not be detected by the daily monitoring of marked lines. This improved the placement or increased the number of these markers. Lastly, the third technique encompassed planned drone flyovers that, through photogrammetric methods, yielded orthophotomosaics and digital elevation models (DEMs). These outputs served as the primary input for subsequent analyses such as calculating eroded volume and erosion rates. The frequency of this last technique varied weekly, biweekly, and monthly depending on the months with higher and lower precipitation, respectively. This monitoring plan resulted in obtaining 1276 daily measurement reports of marked lines and 110 orthophotos with their corresponding DEMs up to August 2023.

On the other hand, concerning instrumentation, OCP has a network of 18 rain gauge stations distributed along its 485 km length. For the case study, data from the XV-20004 and Reventador stations were taken into consideration. These data points were correlated with the daily discharge values of the Quijos - Coca River provided by CELEC EP.

Regarding the geological context, a geophysical survey campaign was conducted, involving techniques such as refraction seismic, ReMi seismic, HVSR, and MASW. This campaign covered approximately 65% of the lateral erosion front's area of influence on the left bank of the Quijos Coca River. These studies were carried out on-demand in accordance with the advancement of the lateral erosion front. Additionally, complementary drilling was performed to validate the geophysical data up to an approximate depth of 100 meters.

2.3 Data processing

The risk management process in response to the lateral erosion advancement of the Quijos – Coca River during the period 2020 – 2023 is based on the various data and outputs generated by the implemented monitoring system.

For instance, the orthophotos and DEMs generated through planned flyovers are processed using a multitemporal analysis supported by comparing the DEMs between monitoring dates. Tools like the "Combine/Compare Terrain Layers" feature in software such as Global Mapper are employed for this purpose. This comparison reveals changes in the sector's topography, enabling the calculation of eroded volume over a period. On the other hand, the orthophotos allow the digitization of the lateral erosion front's geomorphology, simplifying the measurement of its linear advancement between different dates.

The changes observed in the headward erosion are compared against the precipitation values from the XV-20004 and Reventador rain gauge stations, as well as the discharge data of the Quijos – Coca River.

The understanding of the behavior exhibited by the headward erosion between different monitoring dates is supplemented by conducting geophysical studies, the distribution of which is determined collaboratively by OCP Ecuador S.A.'s multidisciplinary team.

Once the behavior of the erosion front has been determined, the risk to which the OCP route would be exposed under those conditions is assessed. This evaluation is grounded in OCP Ecuador S.A.'s qualitative scale of different risk levels (very low, low, moderate, high, and very high), utilizing precipitation values, the Quijos – Coca River discharge, and the variation in the angles of its banks as inputs. These latter values are tabulated to derive their statistical measures, such as mean and standard deviation. Given the observed conditions during monitoring, three angle scenarios are considered: optimistic (equal to the mean), pessimistic (equal to the mean minus one standard deviation), and most likely (the mean between the optimistic and pessimistic values).

Subsequently, a projection of the lateral erosion front geometry was carried out using the optimistic, pessimistic, and most likely angles of repose values. This was accomplished using the "Corridor" tool in Civil 3D software, with the alignment based on the axis of the Quijos – Coca River.

The iteration of this process with each monitoring event facilitated the documentation of the headward erosion's behavior experience. This culminated in a matrix containing action recommendations grounded in the risk the OCP route would face due to the lateral erosion advancement.

Figure 4 summarizes the workflow implemented during the monitoring process.

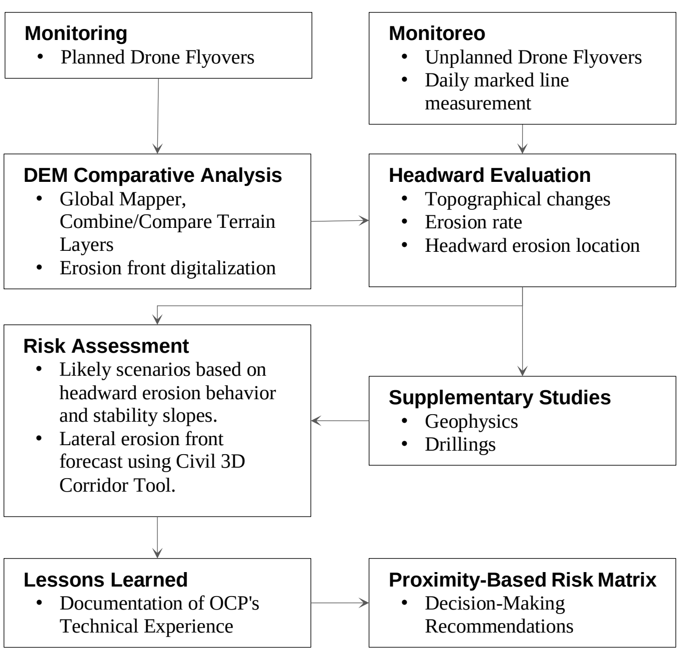


FIGURE 4: RISK MANAGEMENT WORKFLOW FOR VARIANT CONSTRUCTION

3. RESULTS AND DISCUSSION

Figure 5 shows the behavior of the optimistic, pessimistic, and most likely angles for the banks of the Quijos – Coca River from KP 93 (Hostería El Reventador) to KP 97 (San Luis). It is noticeable that the values exhibit erratic patterns until around month 18; however, a slight stabilization of these values is observed at 52°, 43°, and 32° for the optimistic, most likely, and pessimistic angles, respectively.

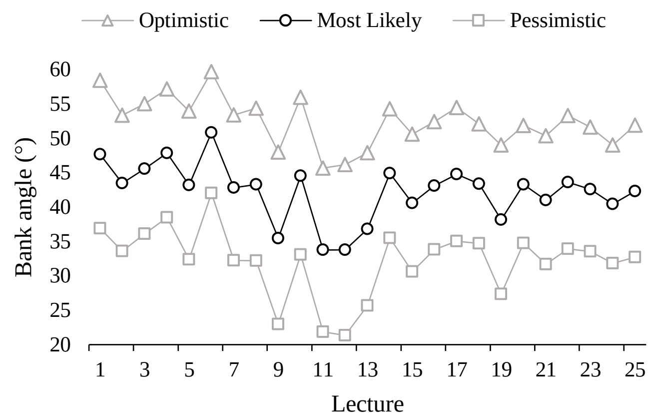


FIGURE 5: OPTIMISTIC, PESSIMISTIC, AND MOST LIKELY REPOSE ANGLE'S VARIATION

These values align with the observations in the field, as the banks have not shown significant variations in the past year. This can also be contrasted with Figure 6, where it's evident that the regressive erosion of the Quijos – Coca River exhibited aggressive behavior until mid-2021, accounting for 80% of the total eroded volume by June 2023. Following this period, a deceleration of the erosive process is observed with a slight peak in August 2022. The maximum erosion volume was recorded in January 2023, reaching 204 million cubic meters, a value that has remained constant until June 2023.

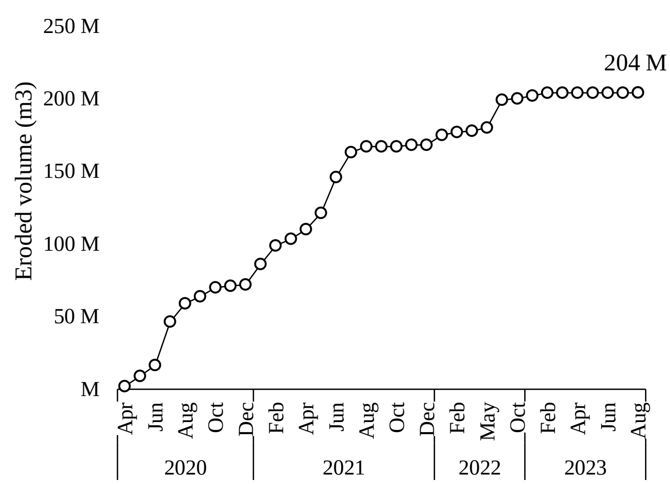


FIGURE 6: ESTIMATION OF EROSION VOLUME OVER TIME

Furthermore, when comparing the eroded volume values against the recorded precipitation at the Reventador and XV-20004 rain gauge stations (Figure 7), it's noticeable that the peaks of precipitation coincide with the periods when regressive erosion is most active. While this relationship might seem intuitive, it provides the foundation for supporting geometric predictions of the behavior of the banks of the Quijos – Coca River, enabling the planning of action plans for reactivation events of the erosion front.

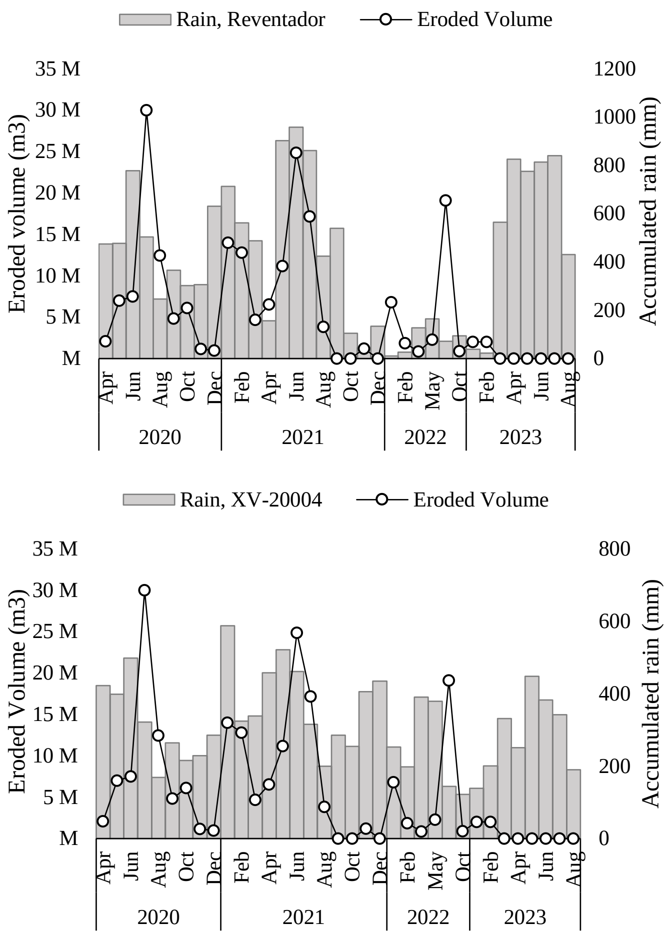


FIGURE 7: ERODED VOLUME VS PRECIPITATION

The random nature of the variables governing the behavior of regressive erosion in the Quijos – Coca River significantly complicates the temporal prediction of this phenomenon. However, using the collected data, it's possible to make an estimation of the most likely geometric configuration that the lateral erosion front would assume. Figure 8 displays the outcome of the scenario in which the Quijos Coca River channel reaches its equilibrium at a 2% slope, and its banks achieve stability at a 43° angle.

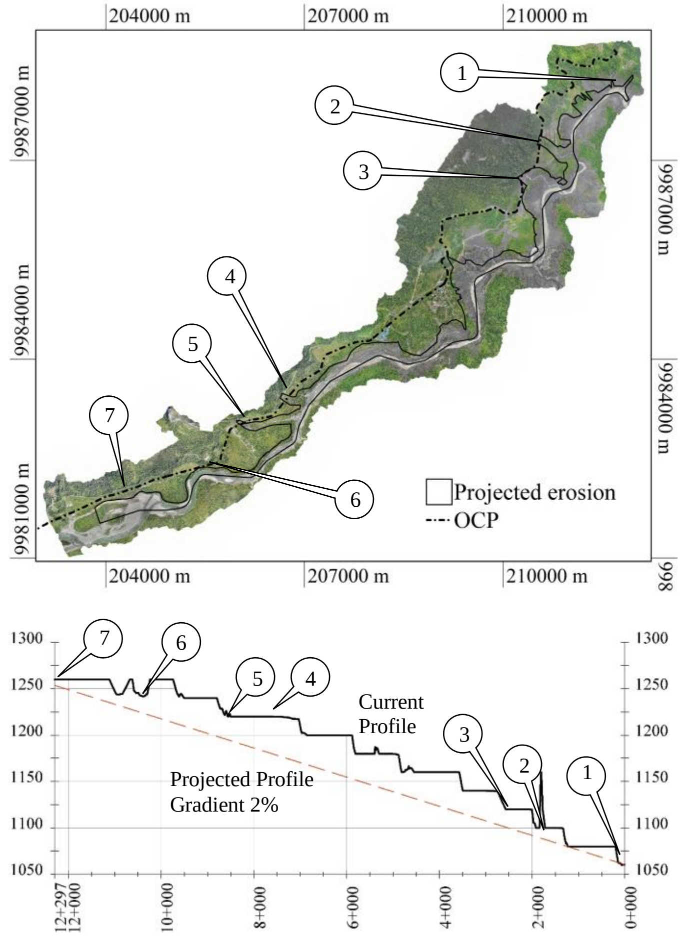
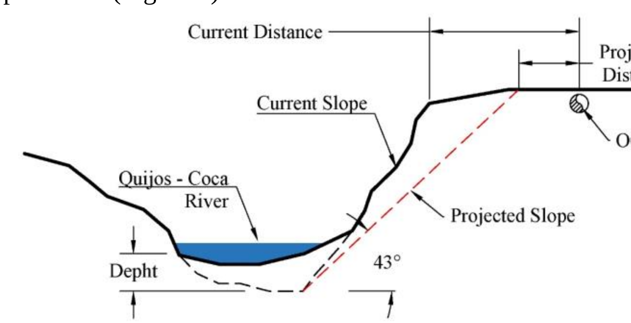
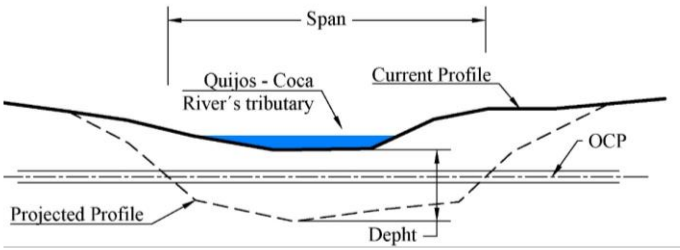


FIGURE 8: GEOMETRIC PROJECTION OF THE EROSION FRONT. BASED ON ORTHOPHOTO JUNE 2023, WGS84 Z18S.

Table 1 presents a summary of the main projected impacts that the realization of this phenomenon would entail. It considers that the progression of the deepening axis of the erosion front of the Quijos - Coca River would create an elevation difference between its channel and its tributaries (Montana, Marker, Piedra Fina, Loco, and Malo rivers), triggering similar erosive processes (Figure 9)



(a) Deepening of the Quijos River Channel



(b) Deepening of Tributaries

FIGURE 9: OCP POTENTIAL IMPACTS. SCENARIOS

Point	KP	Depth (m)	Span (m)	Reference
1	93+057	-	-	2020 rupture
2	95+501	43	131	Montana river
3	96+082	69	263	Marker river
4	100+797	26	81	Loco river
5	106+615	2	67	Malo river
6	102+596	-	18	San Carlos
7	104+186	-	-	Headward location

TABLA 1: OCP POTENTIAL IMPACTS

The documentation of lessons learned from events following the April 2020 rupture, coupled with the processing and analysis of data, facilitated the creation of the matrix called the Proximity-Based Risk Matrix. This matrix encapsulates suggested actions based on the distance between the erosion front and the OCP (Table 2)

Suggested actions	Distance (m) Headward erosion - OCP				
	<70	70-90	90-120	120-200	>200
	Very High	High	Moderate	Low	Very Low
Monitoring	x	x	x	x	x
Geophysics			x	x	
Detailed engineering			x	x	
Geohazards assessment		x	x	x	
Pipeline drainage planning and enablement		x			
Bypass/variant construction evaluation	x				

TABLA 2: PROXIMITY-BASES RISK MATRIX

The methodology developed and employed by OCP Ecuador S.A. in risk management against lateral erosion of the Quijos - Coca River is outlined in this matrix, which suggests a logical order of various actions encompassing all phases of constructing oil pipeline routes.

The matrix illustrates that, considering the mapped geomorphological conditions between KP 93 (Hostería El Reventador) and KP 102 (San Carlos), all segments of the OCP located at a distance exceeding 200m exhibit a very low risk to their integrity. Nonetheless, monitoring (marked lines measurements and both planned and unplanned aerial surveys) is depicted as a cross-cutting measure throughout all stages of the process.

The actions involving geophysical surveys, detailed engineering, and geohazards assessment correspond to the pre-construction phase of an oil pipeline route. According to the matrix, these actions should begin when monitoring indicates that the lateral erosion front is between 90m and 200m from the OCP.

On the other hand, actions related to drainage preparation, evaluation, and construction of a pipeline route are initiated when it is reported that the erosion front is located at a distance less than 90m from the OCP.

Between March and May 2021, a gradual advancement of the lateral erosion front of the Quijos - Coca River was reported at KP 97 of the OCP (San Luis). During this period, the suggested actions from the study phase outlined in the Proximity-Based Risk Matrix were implemented. Ultimately, in April 2021, the lateral erosion front of the Quijos - Coca River was located 70m from the OCP, prompting the initiation of construction work on a bypass. This distance between the erosion and the OCP provided the necessary time to construct an 800m-long pipeline bypass before the erosion reached the original route, thus ensuring the operation of the OCP and preventing a spill of 12,000 bbl.

Subsequently, in December 2021, the implementation of the matrix continued due to a new advance of the erosive front upstream of the Piedra Fina River (a tributary of the Quijos - Coca River). The actions from the study phase enabled the establishment of a 2km alternative route, and the drainage phase once again prevented an estimated spill of 12,000 bbl.

4. CONCLUSION

The phenomenon of regressive erosion operates along three axes: deepening, frontal advancement, and lateral advancement, with the latter currently posing the greatest risk to the OCP's operation. The implemented monitoring plan enabled the collection of sufficient data to visualize the relationship between the eroded volume over time and the most likely angle of repose for the banks of the Quijos – Coca River. This, in turn, facilitated the projection of the potential geometry that lateral erosion could reach.

The analysis of the eroded volume over time reveals that the erosive process has slowed down in the last year, despite having similar accumulated precipitation as in previous years. This could be interpreted as a reduction in the threat posed by the erosion front. However, experience has shown that these conditions can change within a matter of days.

The erosion projection scenarios for the Quijos - Coca River illustrate potential impacts on the OCP at different points. These impacts can be effectively addressed through the proximity-based risk matrix actions. This equips technicians at OCP Ecuador S.A. with a straightforward yet powerful tool to manage the risk of OCP rupture due to Quijos - Coca River erosion. It enables the systematic development of contingency plans, facilitating environmental damage mitigation and ensuring operational continuity.

In conclusion, the obtained results provide a deeper understanding of the erosive process dynamics of the Quijos – Coca River in this specific environment. Evaluating the scenario in which the Quijos – Coca River channel reaches a natural slope of 2% and its banks achieve stability at a 43° angle, combined with the recommendations from the Proximity-Based Risk Matrix, can enable OCP Ecuador S.A. to make informed decisions regarding the actions to be taken during events of erosion advancement of the Quijos – Coca River in any of its axes.

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