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ASSESSMENT OF PIPELINE RIVER CROSSINGS UNDER ENVIRONMENTAL CHALLENGES

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ABSTRACT

This paper highlights the importance of conducting thorough assessments of pipeline crossings within pipeline integrity programs to mitigate the risks of pipeline exposure, failures, and the associated economic and environmental consequences. While pipeline integrity programs typically address risks at river crossings, the methodologies employed are often overly simplistic. They frequently fail to incorporate comprehensive assessments that account for ongoing and future climate changes, as well as other environmental factors such as changes in land occupation patterns and anthropogenic impacts like sand extraction, navigation, and deforestation. These oversights can lead to an underestimation of risks and increased maintenance costs due to unforeseen mitigation measures. To address these challenges, this paper presents a detailed approach for assessing river crossings of a gas pipeline spanning approximately 2,500 km in Brazil. The pipeline spans four states, each characterized by distinct hydrological, climatic, and geotechnical conditions. Additionally, these regions are subject to various anthropogenic environmental impacts, including sand extraction, navigation, and deforestation. The proposed methodology involves analysis that integrates hydrological modeling, climate change projections, and geotechnical evaluations to capture the diverse environmental conditions affecting the pipeline. This approach also considers the dynamic nature of river systems and the potential for significant changes over time due to both natural processes and human activities and discusses the implementation of monitoring procedures and predictive maintenance strategies. By adopting this comprehensive assessment methodology, the paper aims to provide a more accurate evaluation of risks and propose effective strategies for maintaining pipeline integrity at river crossings.

Keywords: River Crossings, Crossings, Environmental, assessment.

1. INTRODUCTION

Extreme hydrological events, such as floods, riverbank erosion, and channel avulsion, pose significant threats to the structural integrity of pipelines at river crossings. These risks are influenced by natural climate variability, ongoing climate change, and human-induced changes in land use. As these events become more frequent and intense, the likelihood of pipeline exposure or failure increases, potentially leading to environmental damage, service disruptions, and liabilities for operators.

To address these challenges, pipeline integrity programs must incorporate comprehensive hydrotechnical assessments. These evaluations focus on identifying river crossings at risk, conducting field inspections, measuring the depth of cover over pipelines, and analyzing the probability of failure due to hydrotechnical hazards. Key hazards include bed scour, channel degradation, bank erosion, encroachment, abandonment or avulsion, and outbursts (Lima et al., 2017).

Mitigation strategies vary depending on site-specific conditions and may include burying pipelines below potential scour depths, reinforcing riverbanks, installing bed armor, or using natural materials like vegetation to stabilize the area. The selection of appropriate techniques requires a detailed understanding of geomorphology, river dynamics, ecological impacts, and the needs of nearby communities.

While many pipeline companies follow regulatory standards, such as those set by the Canadian Standards Association (CSA), and implement risk management frameworks, current methodologies often lack appropriate hydrotechnical assessments of pipeline crossings. This gap can leave critical infrastructure vulnerable.

The paper emphasizes the importance of integrating robust hydrotechnical assessments into pipeline integrity programs to provide a more accurate evaluation of risks. It outlines a structured approach that includes site identification, field surveys, and vulnerability analysis. As a practical example, it examines three crossings along the Bolívia-Brasil Pipeline where the pipeline was exposed, highlighting the need for proactive monitoring and intervention to prevent failures.

2. CLIMATE CHANGE AND ADAPTATION

Human activities across the globe are releasing large quantities of greenhouse gases into the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases are accumulating and reaching record-high concentrations, disrupting the Earth's energy balance and causing a gradual increase in global temperatures (greenhouse effect).

This warming alters atmospheric circulation patterns, which in turn affect cloud formation and rainfall distribution. These changes are not uniform; their impacts vary by region. While most parts of the world are experiencing rising temperatures, the intensity and consequences of climate change differ from one area to another.

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (2021) highlights that, as the planet continues to warm, extreme precipitation events are expected to become more frequent and intense in many parts of Brazil. This includes the eastern coastal regions, where a significant portion of the country’s pipeline infrastructure is located.

In Brazil, climate change has already begun to show significant effects. The country has experienced more frequent and intense extreme weather events, such as prolonged droughts in the Northeast, severe floods in the South and Southeast, and rising temperatures in the Amazon. These changes threaten water availability, agriculture, biodiversity, and energy production, especially hydropower, which is a major source of electricity in Brazil.

Further supporting this, a study by Marengo et al. (2021) found that the risk of heavy rainfall, floods, and landslides increases with global warming, particularly in Brazil’s southern and southeastern regions, areas with the highest pipeline density. Additionally, Gründemann et al. (2022) noted that the most extreme rainfall events are projected to increase the most in magnitude.

Given these challenges, it is essential to integrate climate change considerations into planning and decision-making processes. This is particularly important in sectors such as infrastructure, agriculture, energy, and environmental conservation, where resilience and adaptation strategies are critical for long-term sustainability.

Adaptation refers to the proactive changes we make in response to climate change—such as rising temperatures, extreme rainfall, and sea level rise to protect ecosystems, human safety, and economic stability. It also includes seizing potential opportunities that may arise from these changes.

A widely recommended approach, especially in urban and infrastructure planning, is to adopt strategies that prepare communities and organizations for future climate-related stressors. This not only reduces vulnerability but also enhances overall resilience.

The Sea Level Rise Adaptation Primer (Arlington Group et al., 2013) outlines four key adaptation strategies, originally developed for coastal communities but equally applicable to sectors like the pipeline industry:

1. Protect – A reactive strategy focused on defending existing infrastructure through physical barriers like dikes, seawalls, and groins. While often the first response, it can be costly and less effective in the long term, especially in highly exposed areas.

2. Accommodate – An adaptive approach that allows continued use of a site by modifying infrastructure or operations to withstand new climate conditions. This may include retrofitting buildings or improving drainage systems.

3. Retreat – A strategic decision to relocate or abandon assets in high-risk areas. This reduces reliance on structural defenses and encourages long-term planning for safer locations.

4. Avoid – A preventive strategy that restricts development in areas likely to face future climate risks. It involves using planning tools to steer investment away from vulnerable zones.

These strategies can be combined to build climate-resilient systems for pipelines.

3. IMPACT OF CLIMATE CHANGE ON PIPELINE INTEGRITY

The impact of climate change on pipeline integrity is an area of research that has been developed as global warming intensifies the frequency and severity of extreme weather events. These changes exacerbate hydrotechnical hazards which pose significant risks to pipeline crossings.

The Asian Development Bank (ADB, 2017) conducted a comprehensive *Climate Risk and Vulnerability Assessment (CRVA)* that evaluated the implications of climate change for infrastructure systems, including pipelines. The report underscores the heightened vulnerability of pipeline crossings on bridges and similar structures, emphasizing the need for targeted adaptation measures.

To support risk-informed decision-making, Maniatis et al. (2020) developed a decision support tool specifically designed to assess the vulnerability of above-ground river pipeline crossings. This tool incorporates climate change variables—such as extreme precipitation and riverbank instability—and uses an *Erosion Risk Index (ERI)* to classify crossings based on their susceptibility to erosion. This systematic approach enables more accurate identification of high-risk sites and supports the prioritization of mitigation efforts.

Further highlighting the limitations of traditional risk assessment methods, Read et al. (2024) presented findings at the International Pipeline Conference (IPC) that address the challenges posed by climate extremes that fall outside historical data ranges. The study advocates for integrating climate projections into pipeline risk management frameworks to better anticipate and respond to emerging geohazards.

Evidence from practical case studies reinforces the value of proactive hydrotechnical assessments. For example, Gellis et al. (2015) documented successful mitigation projects in British Columbia, Canada, where targeted interventions reduced pipeline exposure to riverine hazards. Similarly, Lima et al. (2017) conducted a detailed erosion assessment along the Paraíba do Sul River near the GASCAR pipeline. His work led to the design and implementation of long-term protective measures that significantly reduced the risk of pipeline failure due to severe bank erosion and channel degradation.

These studies highlight the urgent need to incorporate climate resilience into pipeline design, monitoring, and maintenance. By adopting adaptive strategies and leveraging tools that account for future climate scenarios, the pipeline industry can better safeguard critical infrastructure against the evolving risks posed by climate change.

4. HYDROTECHNICAL ASSESSMENT

Hydrotechnical assessment of pipeline crossings is an important aspect of a pipeline integrity program.

The hydrotechnical assessment under climate change should include: (i) crossing identification; (ii) field inspection; (iii) risk assessment with respect to hydrotechnical hazards and (iv) vulnerability assessment.

4.1. CROSSING IDENTIFICATION

Initial section of crossing locations should be based on a desktop analysis. To identify possible crossing locations, GIS tools are used to compare pipeline alignments and rights-of-ways to a variety of resources that include digitized stream alignments, satellite and historical aerial imagery, LiDAR data and digital elevation models (DEMs) and geo-referenced topographic maps. As built and/or existing survey drawings of the crossing location and associated inspection reports with site photographs, if available, are also valuable information to assist with the analysis. The compiled information will provide an overview of the reach morphology which is categorized based on features such as planform type, valley confinement, floodplain activity, lateral progression, channel stability, bed material, and slope control. A preliminary hazard screening assessment is undertaken primarily focusing on the qualitative hazards pertaining to bank erosion, encroachment, avulsion and outbursts. A hazard ranking will be assigned to the crossing locations in order to prioritize which crossings need further evaluation in a site investigation program.

It is recommended that a desktop analysis be confirmed by visiting the site in person or by flying over the site to ensure that effort is directed to those sites that are the greatest risk to system integrity or need to be visited in person to confirm the level of risk.

4.2. ON-SITE HYDROTECHNICAL INSPECTION

The inspection frequency assigned to each crossing is based on the crossing’s highest individual rating of the five hydrotechnical hazards. Each site inspection is completed by a team that includes an engineer and surveyor. During each site inspection, the pipeline should be located by direct connection to the pipe, if possible, to ensure the most accurate depth of cover (DOC) is obtained. A standard pipe locator can also be used when a direct connection is not possible. Once the line has been located, survey-grade RTK GPS equipment is used to capture the channel cross-section profile, which will allow for DOC analysis in respect to both the bed and the banks. At the same time, photos and site observation notes will be captured in an iPad application to document the characteristics of the watercourse crossing, as well as the upstream and downstream reaches, if additional features that could affect the crossing are noted.

4.3. RISK ASSESSMENT

The documented conditions from the field inspection and the results of the desktop analysis are compiled to undertake detailed hydrotechnical assessment. This assessment is comprised of two components, a hydrologic evaluation and a hydraulic analysis. The hydrologic evaluation consists of reviewing the historical peak flows and determining the peak flows for various return periods. For river systems, a flood frequency analysis is typically undertaken. Typical return periods include the 200-year, 100-year, 50-year, 25-year, 10-year, 5-year, and 2-year events. The hydraulic analysis is undertaken to estimate the potential and magnitude of bed scour for the various return periods. The channel hydraulic characteristics, such as water surface elevation, flow depth, and channel velocities, are determined from a hydraulic model generated with the surveyed channel cross-section profile. The general scour analysis is typically estimated using Blench's Regime Depth Equation (Blench, 1957, 1969). The grain size of the bed material, which is documented as part of the field inspection, is an input parameter in the scour analysis. A detailed assessment for each hydrotechnical hazard at the crossing location is completed based on the compiled information from the desktop analysis and field inspection. The hydrotechnical hazards include channel degradation, bank erosion, encroachment, avulsion, and bed scour as previously discussed.

4.4. VULNERABILITY ASSESSMENT

Beyond the hydrotechnical risk assessment, a vulnerability assessment of the crossing could be completed to determine the probability of failure (POF). River-X, a software originally created by the Danish Hydraulic Institute (DHI) for the Pipeline Research Council International (PRCI), is currently used to determine the failure length of a pipe due to vortex inducted vibrations. An exposed pipeline, due to bed scour, may become a free spanning pipe and this is correlated to the bed material beneath the pipe. The susceptibility of failure of a free spanning pipe is the result of vortex shedding.

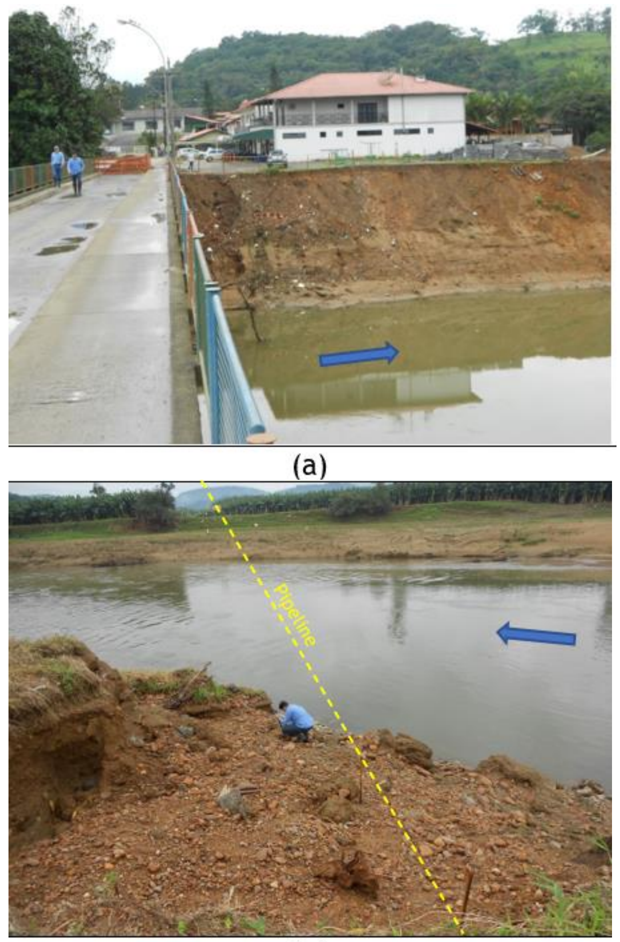
5. CASE STUDIES

The consequences and risks to river crossings and pipelines due to river floods caused by extreme events are shown in three case studies presented in this section: the Itapocu river crossing, the Maracanã creek crossing and the Paraná river crossing.

5.1. ITAPOCU RIVER CROSSING

The Itapocu River Crossing is located at km 0616+000S of the Bolivia-Brazil gas pipeline, in the municipality of Guaramirim, Santa Catarina, Brazil. Constructed in 1999, the pipeline at the crossing has a diameter of 20 inches and has a concrete jacket coating (93 mm) for an extension of approximately 156 m covering 50 m width of the bankfull channel and the floodplain. Additionally, a concrete sleeve pipe was installed above the pipeline for an optical fiber cable. The construction method was through excavation of a trench and backfilling.

In June 2014, an extreme rain event caused significant flooding in the cities along the riverbanks, including Jaraguá do Sul and Guaramirim. This event led to bed degradation and bank erosion at various locations along the Itapocu River, resulting in damage to bridges and other infrastructure (Figure 1).



(a)

(b)

Figure 1. BANK EROSION NEAR A DOWNSTREAM BRIDGE (a) BANK EROSION AT THE CROSSING (b). PREPARED BY THE AUTHORS (2025).

A hydrologic analysis was completed based on the available hydrological information, extrapolation of the rating curve and flow regional analysis. The hydrometric station 82350000 in Jaraguá do Sul recorded a maximum water level of 6 meters during the flood event on June 8, 2014. The estimated discharge at the crossing reached approximately 3,000 m³/s, corresponding to a return period of around 100 years.

In addition to the hydrologic study, a morphological assessment was conducted using satellite images taken before and after the flood event. Figure 2 illustrates the study area in 2009 and 2014. The high flow velocities during the flood event caused severe bed degradation and bank erosion on the left bank at the crossing. Although the pipeline remained covered in the main channel, the top of the pipeline became exposed for a few meters on the left bank.

The geomorphic analysis identified the presence of a small dam for water supply upstream of the crossing and sand mining activities in the river. These factors have reduced the amount of sediment available, thereby increasing the potential for erosion processes in the river

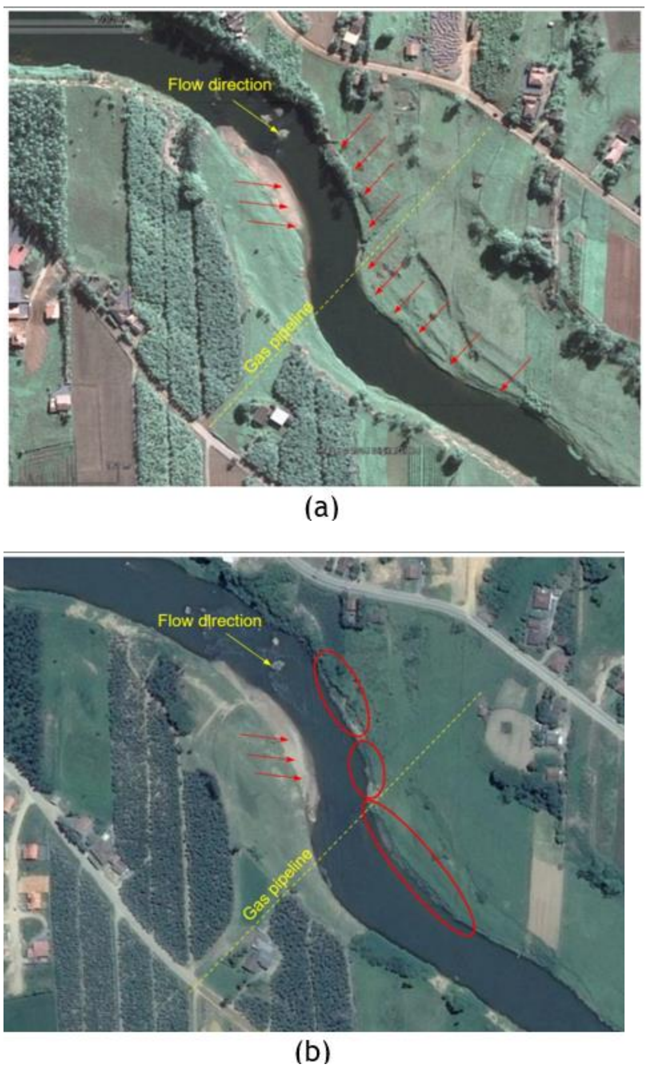


Figure 2. STUDY AREA IMAGERY IN (a) JUNE/2009 AND (b) JUNE/2014. PREPARED BY THE AUTHORS (2025).

The study concluded that detailed investigation and implementation of mitigation measures are necessary to protect the pipeline on the left bank. Recommended options include the use of riprap structures on the left bank and more frequent monitoring of the pipeline cover in the main channel, as bed degradation can pose a long-term issue.

5.2. MARACANÃ CREEK CROSSING

The Jardim Novo Maracanã creek crossing is located at km 0029+180S of the Bolivia-Brazil gas pipeline, in the municipality of Campinas, São Paulo, Brazil.

The pipeline was constructed in 1998 using the open-trench method, which involved trench excavation, lowering of the pipeline, and backfilling. At the crossing, the pipeline has a diameter of 24 inches and has a concrete jacket coating for an extension of approximately 35 meters. The minimum cover at the crossing during construction was 1.50 meters.

An accelerated erosion process occurred at the Jardim Novo Maracanã creek crossing, resulting in the exposure of the pipeline following intense rainfall in late February and early March 2015 (Figure 3).

Figure 3. PIPELINE EXPOSED AFTER AN EXTREME FLOOD EVENT AND CHANNEL DEGRADATION PROCESS. PHOTO FROM 02 DE MARCH 2015. PREPARED BY THE AUTHORS (2025).

Hydrotechnical analysis revealed significant morphological changes in the stream, including channel erosion and channel straightening. Figure 4 presents satellite images showing the changes that occurred in the river channel. These changes, driven by urbanization and the stream's natural characteristics, progressively reduced the soil cover over the pipeline, ultimately leading to its exposure triggered by a flood event.

Figure 4. SATELLITE IMAGERY ANALYSIS. PREPARED BY THE AUTHORS (2025).

Satellite and aerial imagery indicate that bed lowering began prior to 2001. In response to erosion identified in 2004, a gabion mattress structure was constructed to protect the pipeline and mitigate further degradation. While this intervention temporarily stabilized the upstream section, downstream retrogressive erosion persisted and likely intensified between 2005 and 2006, exacerbated by urban development (construction of a culvert at the downstream street). Contributing factors include increased impervious surfaces, stormwater drainage systems, and higher peak flood discharges.

The 2014 image (Figure 4) confirmed ongoing erosion downstream, showing the gabion structure, an energy dissipation basin, and signs of bank failure on the left margin. Continued bed lowering downstream eventually undermined the gabion base, creating a vertical drop that accelerated flow velocity during floods (supercritical regime). This led to localized scour and structural failure of the protection system.

Following the collapse, the pipeline became exposed and vulnerable to further erosion. The resulting hydraulic drop intensified upstream migration of the erosion front, a process that typically progresses rapidly until a new longitudinal equilibrium profile is established for sediment transport.

The hydrotechnical analyses carried out including hydrological and hydraulic studies, confirmed that the riverbed at the crossing has been lowered by approximately 3 meters. Design discharges at the crossing may reach between 20 and 30 m^3/s, and the riverbed is composed of an approximately 2.8-meter-thick layer of easily erodible material, characterized as poorly silty fine sand with low to medium compaction. Consequently, the erosive potential of the streambed remains high, and protective measures for both the pipeline and the right-of-way are necessary to mitigate risks to the pipeline's structural integrity at the crossing.

Several alternatives were evaluated to protect the pipeline and stabilize the ongoing erosion process. These included the implementation of an aerial crossing, the use of concrete culverts to support the pipeline, the river channel restoration, and the lowering and replacement of the crossing.

5.3. PARANÁ RIVER CROSSING

The Paraná River crossing is located at km 0716+500N of the Bolivia-Brazil gas pipeline, between the city of Tres Lagoas in the state of Mato Grosso do Sul and Castilho, in the state of São Paulo, Brazil.

The pipeline was constructed in 1998 using the open-trench method, which involved trench excavation, lowering of the pipeline, and backfilling with gravel from the river. At the crossing, the pipeline has a diameter of 32 inches and has a concrete jacket coating (76.2 mm).

The Paraná River crossing is located between two hydroelectric power plants. It is located approximately 25 km downstream from the Jupiá HPP dam and about 200 km upstream from the Porto Primavera HPP dam. At the crossing, the Paraná River channel is approximately 1 km wide. Around 2 km upstream from the crossing, there is a river island known as Ilha Comprida (**Figure 5**).

Local changes in the fluvial geomorphology (riverbanks and riverbed) have been occurring since 1998 in the area near the crossing, causing continuous variations in the coverage and exposure of the pipeline's upper part, as well as erosion along the banks which is a risk to the integrity of the gas pipeline.

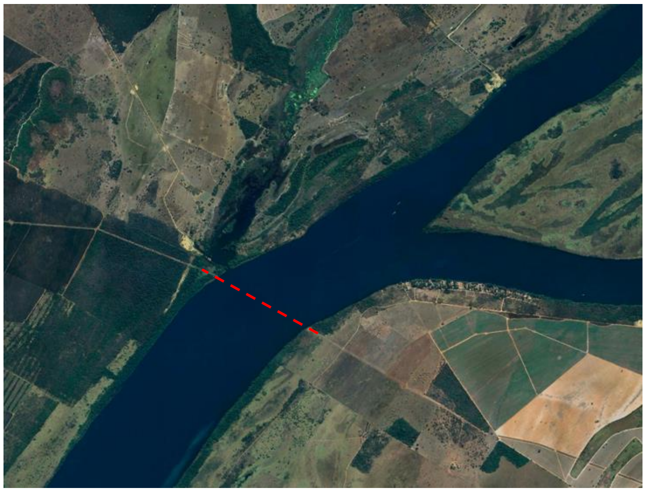


Figure 5. SATELLITE IMAGERY OF CROSSING LOCATION. PREPARED BY THE AUTHORS (2025) BASED ON A GOOGLE EARTH IMAGE.

The hydraulic conditions at the crossing are influenced by the operation of the Jupiá HPP (upstream) and the Porto Primavera HPP (downstream). The operation of these plants leads to fluctuations in flow velocity, water levels, and sediment transport. The pipeline construction method used (trench excavation, pipeline lowering, and backfilling) has not adequately considered the natural erosive potential of the Paraná River bed, and the pipeline elevation at the crossing was not sufficiently deep.

Additionally, large volumes of sand and gravel are extracted through dredging near the crossing, which alters the riverbed geomorphology, reducing coverage and/or exposing the pipeline (Figure 6). Moreover, there is constant vessel traffic that generates waves and turbulence along the banks (Figure 7).

Figure 6. PHOTO FROM SAND DREDGING ACTIVITIES. PREPARED BY THE AUTHORS (2025).

Figure 7. PHOTO FROM VESSEL NEAR THE PIPELINE CROSSING. PREPARED BY THE AUTHORS (2025).

The erosive processes observed at the crossing are active and are expected to continue progressing. However, due to the local geomorphological and hydraulic characteristics, erosion at this site tends to occur gradually. Since the pipeline's upper part is already exposed in some sections and is likely to become exposed in others, pipeline protection works should be implemented. Possible alternatives for protecting the pipeline include lowering the pipeline using Horizontal Directional Drilling (HDD); excavating a deeper trench parallel to the current crossing; or covering the right of way with a layer of small riprap, gabion mats, or articulated concrete mats.

6. RESULTS AND DISCUSSION

The increasing frequency and intensity of extreme flood events, driven by climate variability and change, pose growing hydrotechnical risks to pipeline infrastructure, particularly at river crossings. Traditional risk assessment approaches, which rely primarily on historical climatic data such as flood return periods, are no longer sufficient to capture the evolving nature of these hazards. These limitations are further compounded by rapid changes in land use, including urbanization and deforestation, which alter watershed hydrology and exacerbate erosion and flood impacts.

The case studies presented in this work highlight the vulnerability of pipelines to exposure and damage resulting from hydrotechnical processes such as channel incision, bank erosion, and retrogressive scour. These examples underscore the need for a paradigm shift in how pipeline integrity is managed, moving from reactive, site-specific assessments to proactive, system-wide strategies that incorporate climate projections, geomorphological analysis, and long-term monitoring.

Brazil's extensive pipeline network, spanning over 22,000 kilometers and encompassing more than 1,300 river crossings, is particularly susceptible to these risks. Without adequate adaptation measures, the consequences of pipeline failure could be severe, leading to significant environmental degradation, economic losses, and social disruption. Therefore, integrating hydrotechnical risk assessments into pipeline design, maintenance, and regulatory frameworks is essential for ensuring long-term infrastructure resilience.

7. CONCLUSION

In Brazil, pipeline right-of-way assessment and monitoring is typically limited to localized assessments at river crossings, often overlooking the broader fluvial dynamics that influence long-term stability. This practice can lead to an underestimation of hydrotechnical risks, which are inherently linked to upstream and downstream processes and the river's behavior.

To enhance risk identification and mitigation, hydrotechnical assessments should adopt a more comprehensive approach and integrate hydrotechnical assessments that incorporate climate projections into risk evaluation methodologies. When combined with systematic inspection and maintenance programs, this approach enables pipeline operators to proactively manage hydrotechnical hazards and preserve infrastructure integrity.

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