RIVER CROSSINGS: RIVER DIVERSION THROUGH THE RIGHT-OF-WAY

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6 de Novlembre de 2025

HYDROTECHNICAL THREATS

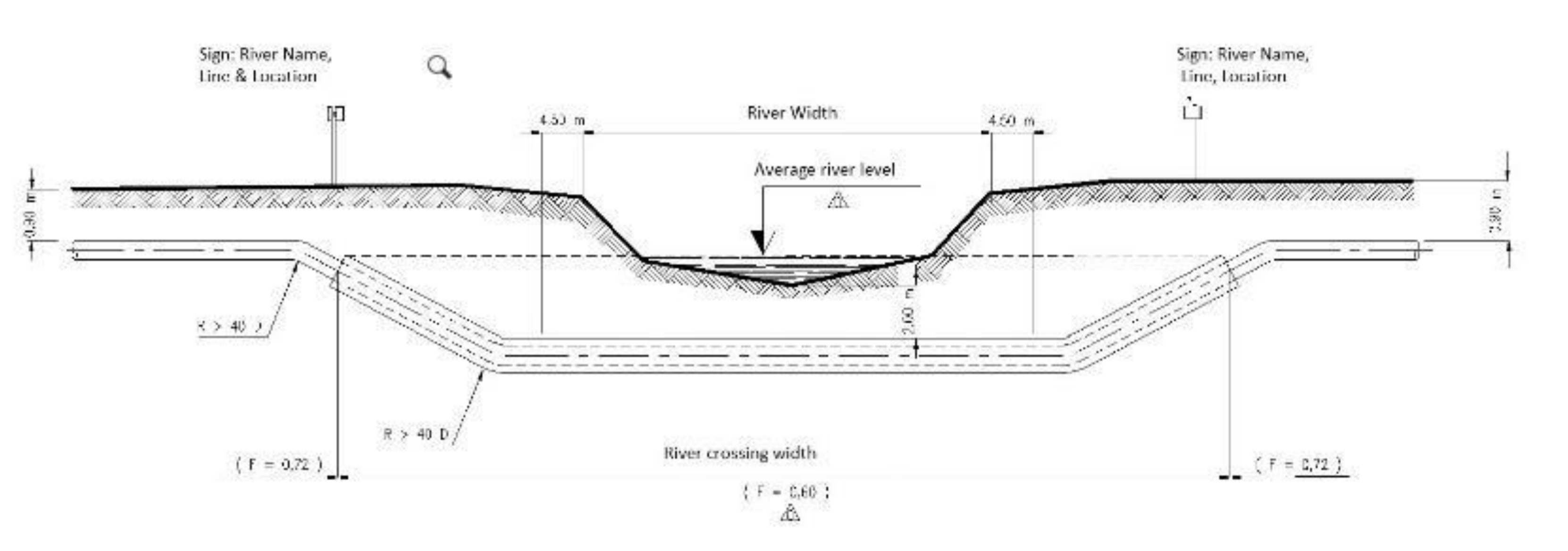
1. **BUOYANCY**
2. **VERTICAL SCOUR (LOCALIZED/GENERALIZED)**
3. **LATERAL MIGRATION AND ENCROACHMENT**
4. ***AVULSION (CHANGE IN COURSE)***
5. **RAPID LAKE DRAINAGE**
6. **TSUNAMI**
7. **IF EXPOSED, DEBRIS FLOW AND IMPACTS**

PROBLEMS WITH RIVER CROSSINGS

(THEY EVOLVE WITH TIME)

Fixed structure (Pipeline) ↔ Natural Dynamic Process (River)

TYPICAL LAY-OUT FOR A RIVER CROSSING



SPECIAL CONSTRUCTION FEATURES

1. LESSER DESIGN FACTOR: 0.6 (OR 0.5 IF RIVER IS NAVIGABLE)
2. GREATER WALL THICKNESS
3. GREATER SOIL COVER (BURIED DEEPER)
4. SETBACKS FAR FROM RIVER BANKS
5. BUOYANCY CONTROL

AVULSION (CHANGE IN COURSE)

RIVER FLOWS THROUGH A SEGMENT OF PIPELINE THAT WAS NOT DESIGNED AS A RIVER CROSSING

EXAMPLES:

1. **MOST COMMON: MEANDER CUTS**
2. **LESS COMMON: RIVER DIVERSION THROUGH THE RIGHT-OF-WAY**

MEANDER CUT OFFS

YEAR 2018: RIVER MOVING NORTH AFFECTING LEFT BANK WITHIN THE CROSSING

YEAR 2023: RIVER MOVING SOUTH AFFECTING RIGHT BANK CLOSE TO THE SETBACK

MEANDER CUT OFFS

EXPOSED SEGMENT:

- OUTSIDE ORIGINAL CROSSING
- NO BUOYANCY CONTROL
- NO GREATER WALL THICKNESS

DIVERSION THROUGH THE RIGHT-OF.WAY

CASE 1: RÍO MEDINA

CASE 2: BAJO DE AÑELO

DIVERSION THROUGH THE RIGHT-OF-WAY CHARACTERISTICS

1. WATER FLOWS PARALLEL TO THE PIPELINE
2. THEY TAKE PLACE AT A WIDE FLOODPLAIN
3. FAVORED BY ANTHROPIC INTERVENTIONS (ROW ITSELF, DAMS)
4. ONCE THE RIVER IS DIVERTED, SCOUR REMOVES SOIL COVER VERY FAST EXPOSING THE PIPELINE
5. IT AFFECTS LONG SEGMENTS OF PIPELINE THAT WERE NOT DESIGNS AS A RIVER CROSSING:
   - NO BUOYANCY CONTROL
   - NOT BURIED DEEP (~1M)
   - NOT GREATER WALL THICKNESS
   - STRESSES AFFECT PIPELINE INTEGRITY ONCE IT IS EXPOSED

DIVERSION THROUGH THE RIGHT-OF-WAY CHARACTERISTICS

6. WHAT IS SEEN IN A FIELD VISIT IS VERY MISLEADING: SMALL WATER COURSE IN TERMS OF WIDTH AND BANK HEIGHT, BUT WITH A HUGE WATER BASIN BEHIND

7. IT DOES NOT REFLECT THE SEVERITY OF THE PROBLEM

8. THIS IS USUALLY TRANSLATES IN A BAD DESIGN, SPECIALLY FOR VINTAGE PIPELINES

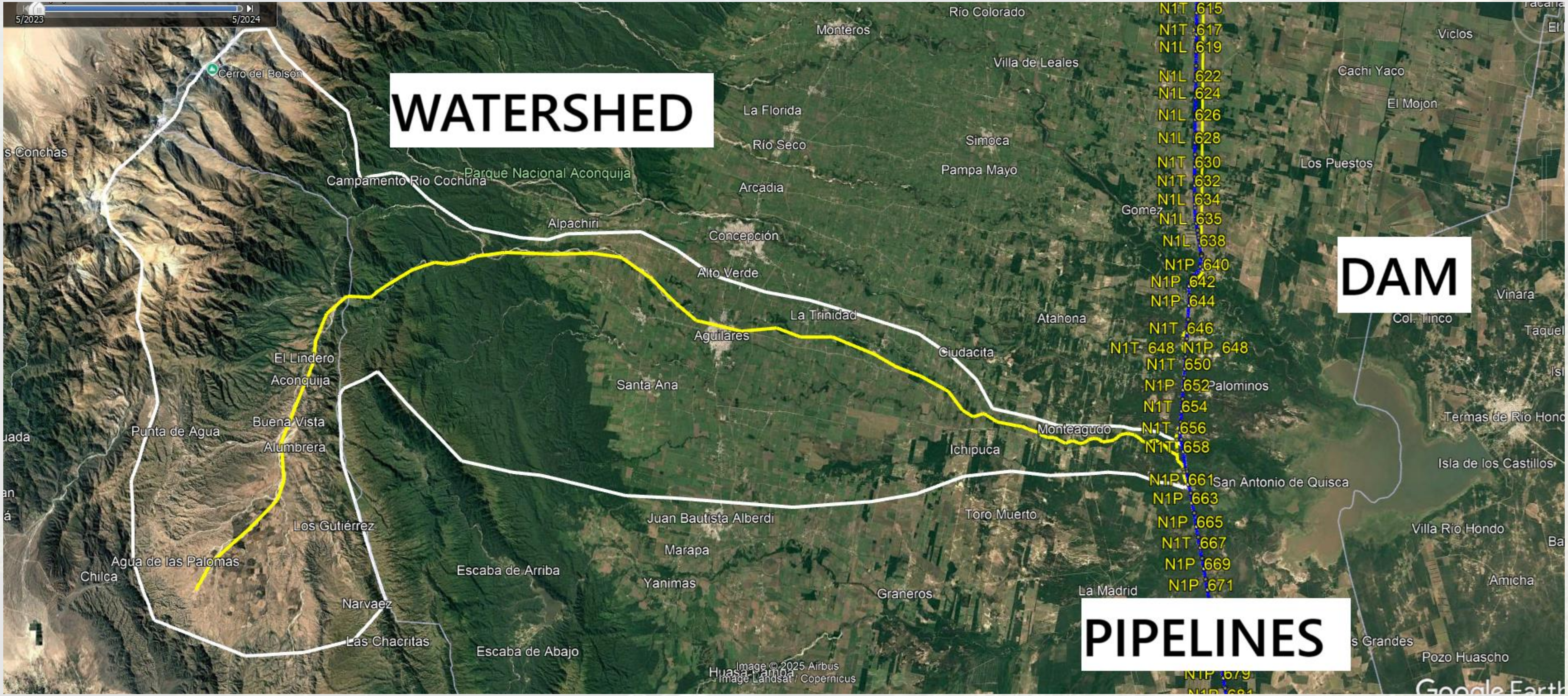
9. ACCESS TO THE FLOODED SITE MAY BECOME A PROBLEM FOR REMEDIATON

CASE 1: MEDINA RIVER

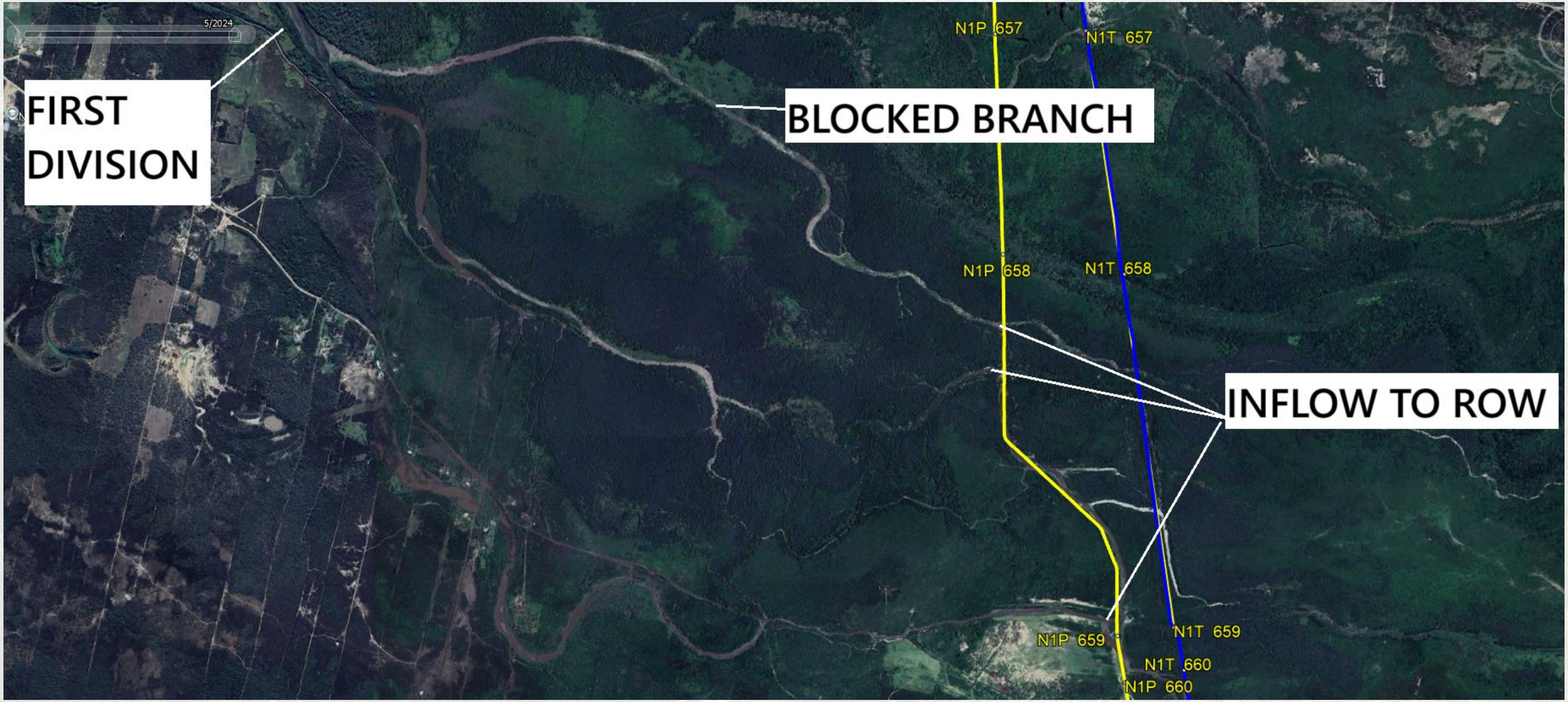
BASIC GEOMORPHOLOGICAL PARAMETERS

PARAMETER	UNIT	VALUE
WATERSHED AREA	[KM2]	2,300
SLOPE AT CROSSING	[M/M]	~ 0.0
WIDTH	[M]	60 TO 80
BANK HEIGHT	[M]	<2
HEAD ALTITUDE	[M]	5,100
CROSSING ALTITUDE	[M]	290
MEAN ANNUAL PRECIPITATION	[MM]	1,045
CONTROL SECTION (DAM)	[KM]	8 TO 10

FROM REGIONAL TO LOCAL SCALE



FROM REGIONAL TO LOCAL SCALE

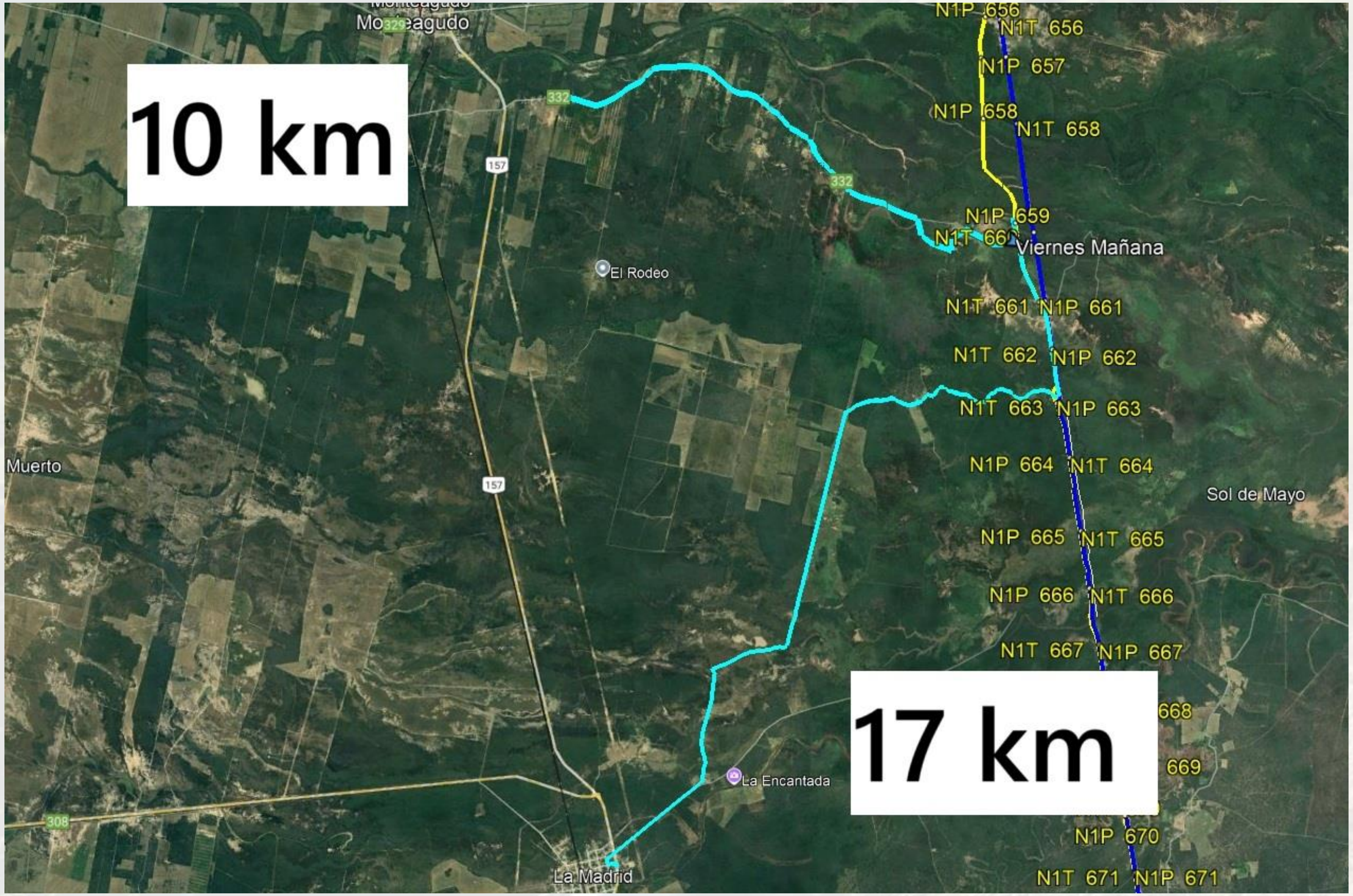


FROM REGIONAL TO LOCAL SCALE
ABANDONED WATER COURSE DUE TO DEBRIS AND SEDIMENTS

FROM REGIONAL TO LOCAL SCALE

LONG SEGMENTS OF PIPELINE SUBJECTO TO FLOODING AND PARALLEL FLOWS

ACCESS THROUGH DIRT ROADS (LOOSE SAND AND FLOODS)

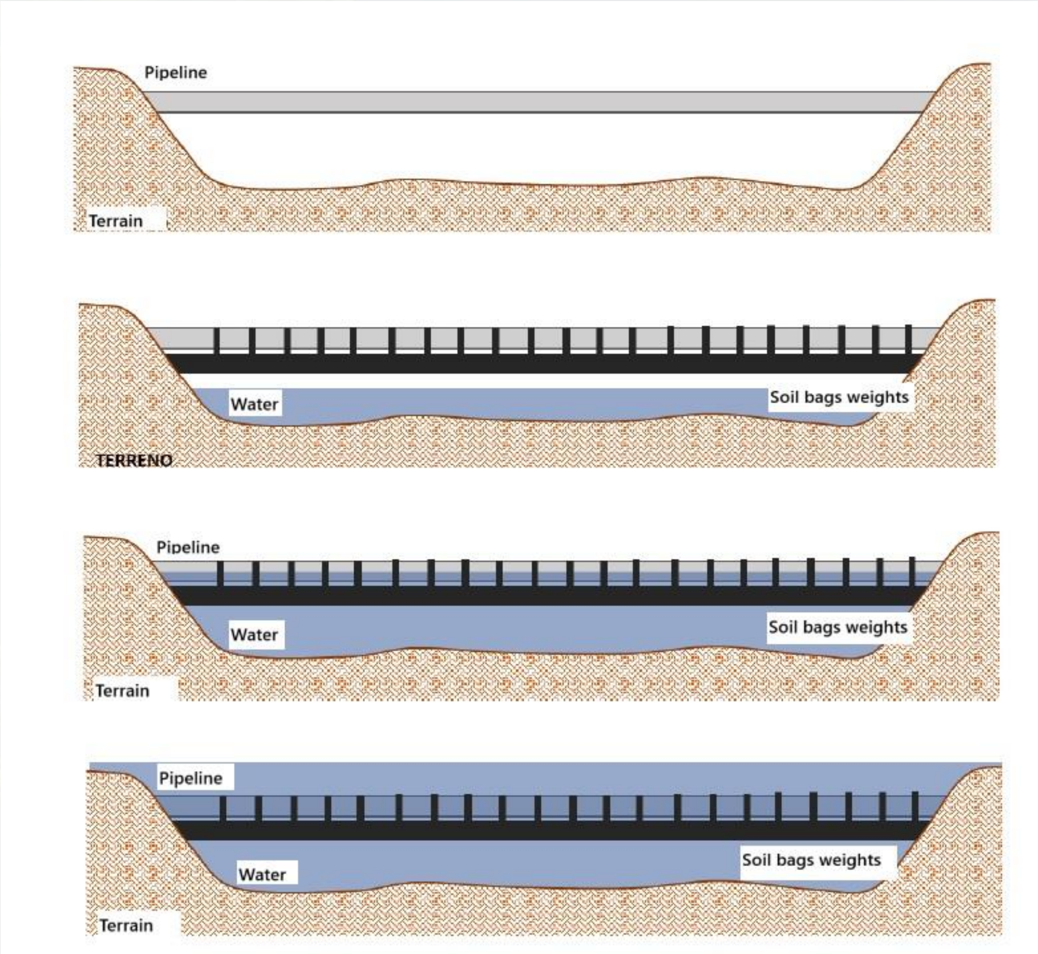


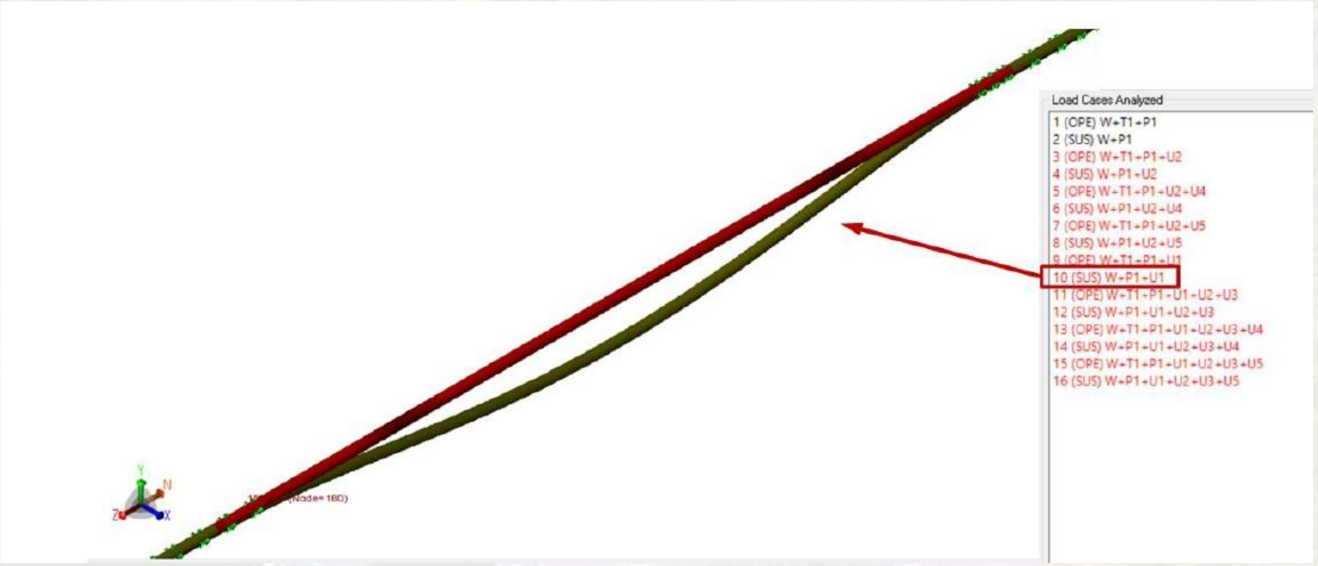
CRONOLOGICAL SEQUENCE OF EVENTS

1. FLOODING AFTER CONSTRUCTION
2. EROSION OF SOIL COVER AND EXPOSURE
3. BUOTANCY CONTROL WITH SOIL-FILLED BAGS
4. SUCCESIVE FLOODS ERODED SOIL BELLOW BAGS, LEAVING SEGMENTS OF UNSUPPORTED LENGTHS
5. CYCLES OF FULL AND PARTIAL FLOODING
6. STRESS ANALYSYS AND HYDRAULIC MODELING
7. MONITORING OF PIPELINE SUPPORT CONDITIONS
8. NEW CROSSING BY HORIZONTAL DIRECTIONAL DRILLING

TEMPORARY SOLUTION
SOIL-FILLED BAGS FOR BUOYANCY CONTROL

STRESS ANALYSIS – IF UNSUPPORTED SCENARIOS VARYING WITH WATER LEVEL

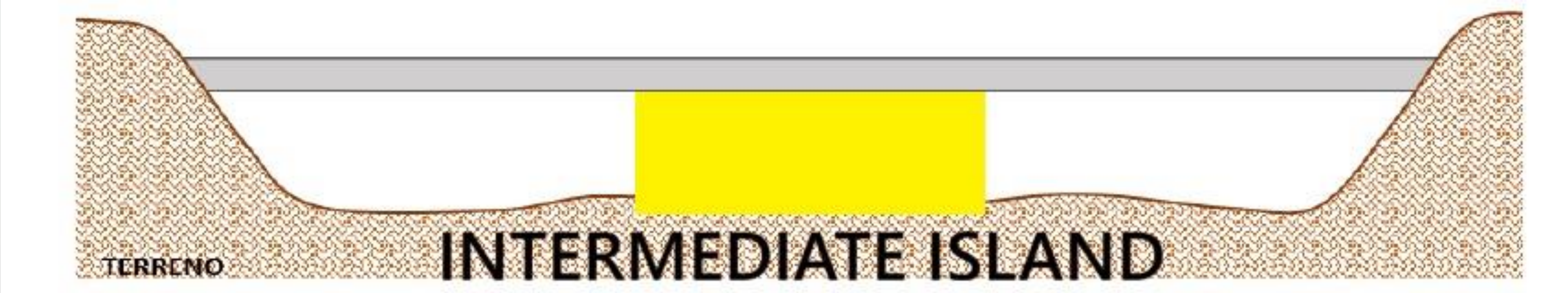




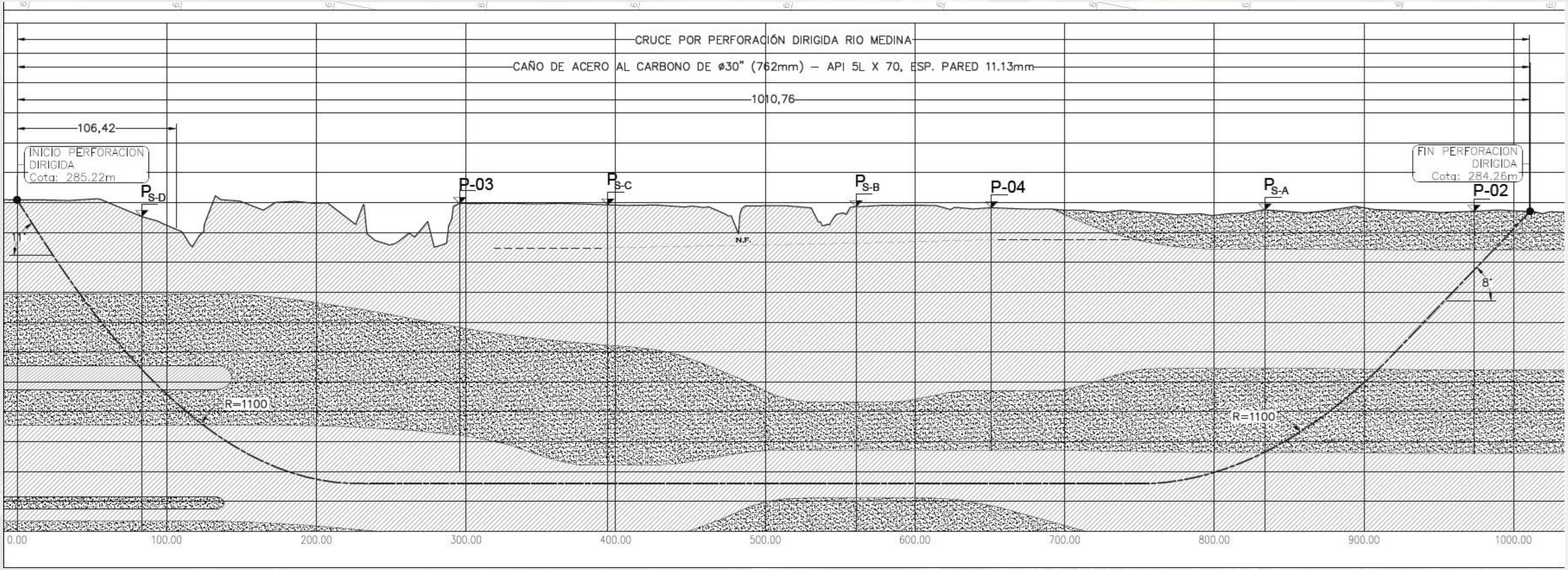
STRESS ANALYSIS – IF UNSUPPORTED SCENARIOS VARYING WITH WATER LEVEL

Tramo	Condición	Caso	Carga	Clasificación	Desplazamiento [mm]	Tensión Código [MPa]	Tensión Admisible [MPa]	Ratio
Loop N1P 30"	Sin contrapesos	Sin inundar	Peso Propio	Sostenida	-339.47	347.42	347.51	1.00
		Inundado	Flotación	Sostenida	550.21	418.83	347.51	1.21
			Corriente	Sostenida	-	-	-	-
			Impacto	Ocasional	-	-	-	-
	Con contrapesos	Sin inundar	Contrapesos	Sostenida	-3356.31	1502.84	347.51	4.32
		Inundado	Contrapesos + Flotación	Sostenida	-568.75	427.33	347.51	1.23
			Corriente	Sostenida	-	-	-	-
			Impacto	Ocasional	-	-	-	-

STRESS ANALYSIS
ACTUAL FIELD SITUATION
ALL COMPUTED STRESSES BELLOW ALLOWABLE LIMITS



SOLUTION: NEW CROSSING BY HDD



CASE 2: BAJO DE AÑELO

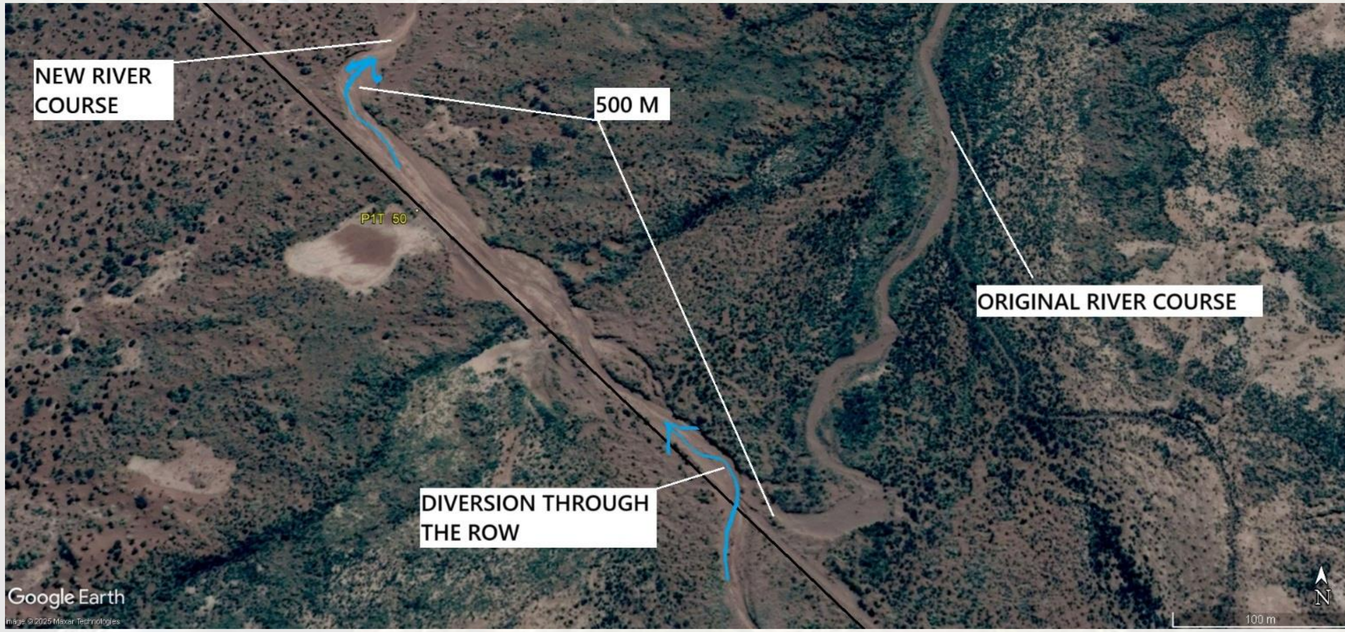
BASIC GEOMORPHOLOGICAL PARAMETERS

PARAMETER	UNIT	VALUE
WATERSHED AREA	[KM2]	1,500
SLOPE AT CROSSING	[M/M]	0.005
WIDTH	[M]	22
BANK HEIGHT	[M]	1.5
HEAD ALTITUDE	[M]	1,150
CROSSING ALTITUDE	[M]	240
MEAN ANNUAL PRECIPITATION	[MM]	200 to 250
CONTROL SECTION	[KM]	NONE

FROM REGIONAL TO LOCAL SCALE
WATERSHED LIMITS

FROM REGIONAL TO LOCAL SCALE
FIELD SITUATION AFTER A FLOOD
COURSE CAPACITY TO CONDUCT WATER IS MINIMAL

FROM REGIONAL TO LOCAL SCALE
BEFORE AND AFTER DIVERSION THROUGH ROW

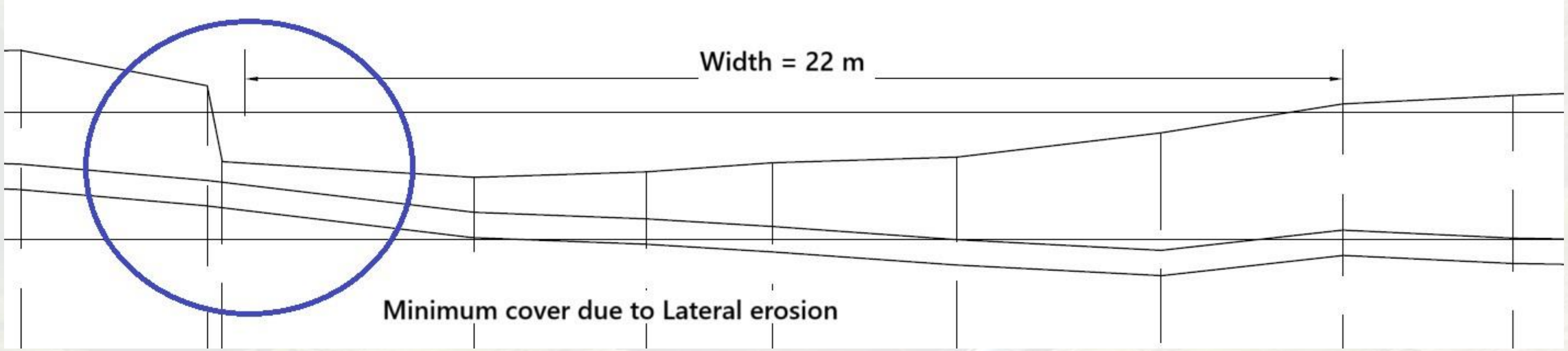


CRONOLOGICAL SEQUENCE OF EVENTS

1. FLOODING
2. EROSION PARALLEL TO LEFT SIDE OF ROW
3. EXPOSURE WITH NO FREE-SPAN
4. BUOTANCY CONTROL BOLT-ON CONCRETE WEIGHTS
5. TEMPORARY REMEDIATION WITH GEOTUBES+FLEXIBLE CONCRETE MATS
6. DEVELOPMENT OF GREATER SCOPE ALTERNATIVES
7. FINAL REMEDIATION PROJECT: BLOCKAGE OF ROW AND RESTORATION OF ORIGINAL RIVER COURSE

BEFORE DIVERSION THROUGH ROW

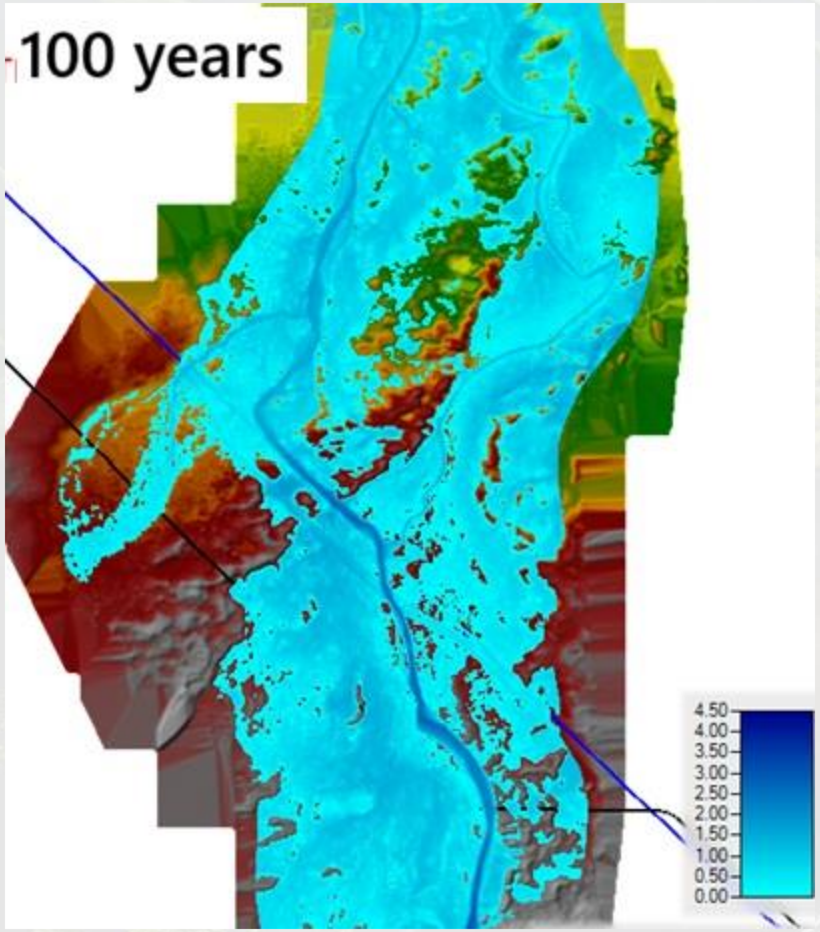
LATERAL MIGRATION TOWARDS LEFT SET BACKS+EROSION AT FLOODPLAIN

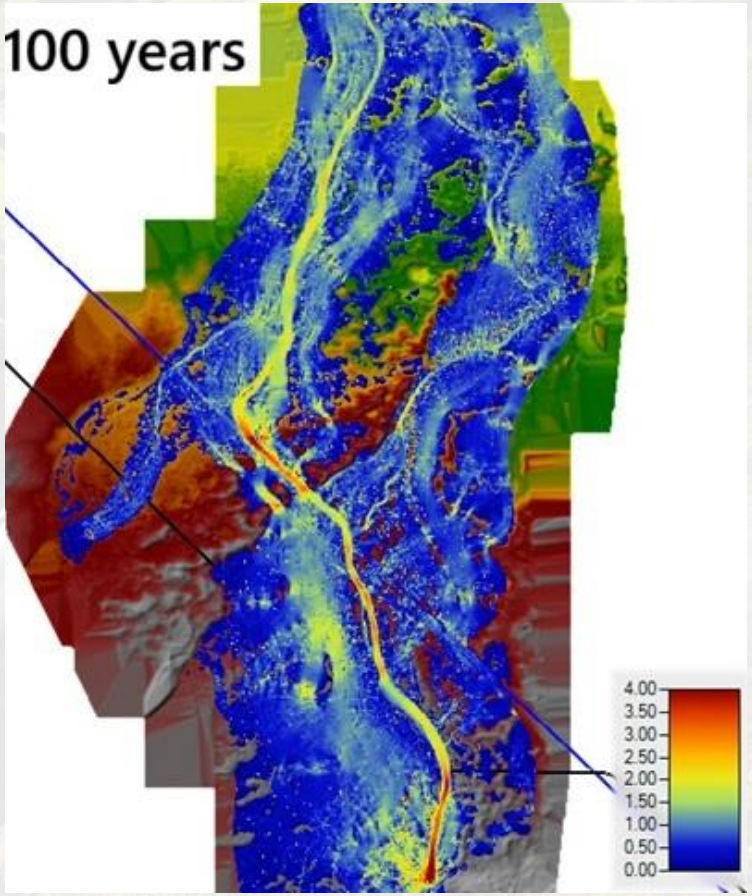


AFTER DIVERSION THROUGH ROW
PIPELINE EXPOSURE ALONG ROW

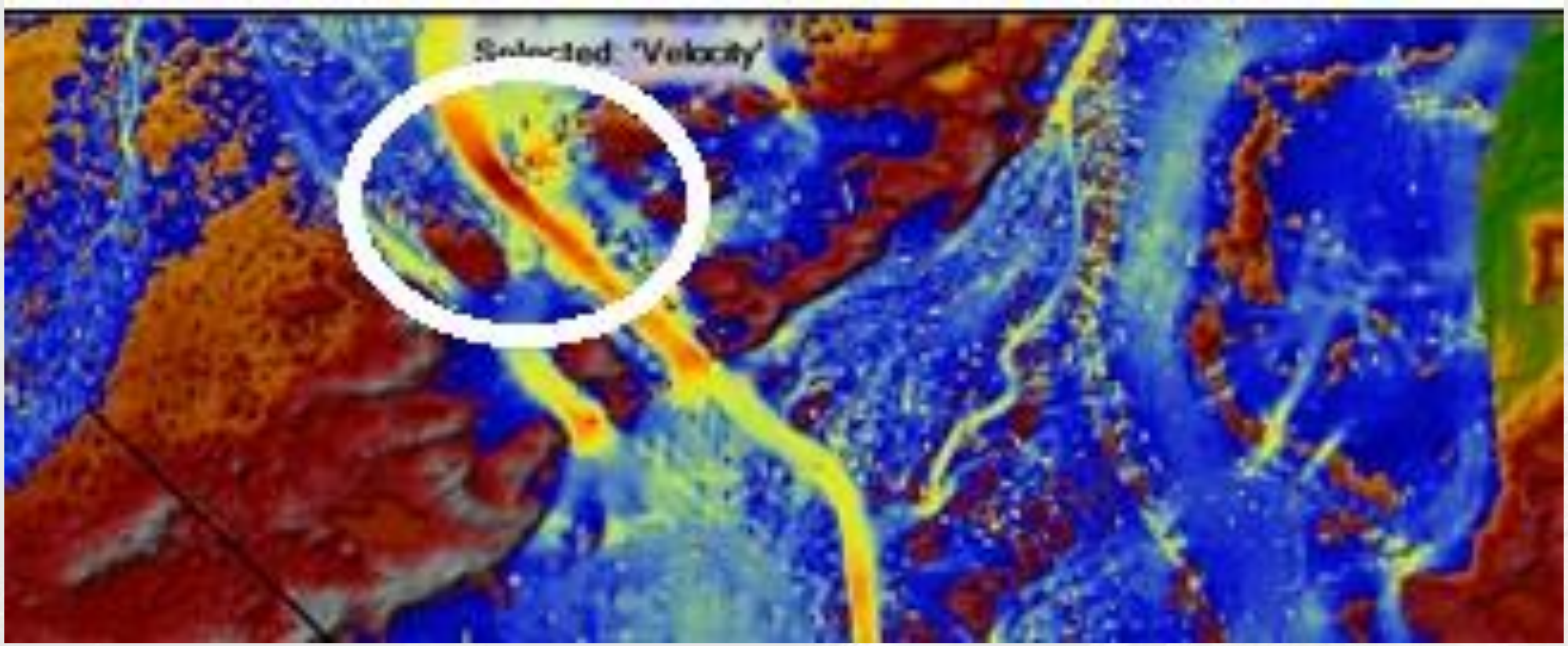
TEMPORARY REMEDIATION
BUOYANCY CONTROL + BANK PROTECTION WITH GEOTUBES

HYDRAULIC MODELING
FLOODED AEREA + VELOCITY DESTRIBUTON





HYDRAULIC MODELING
HIGHEST VELOCITY CONGRUENT WITH EXPOSED SEGMENT

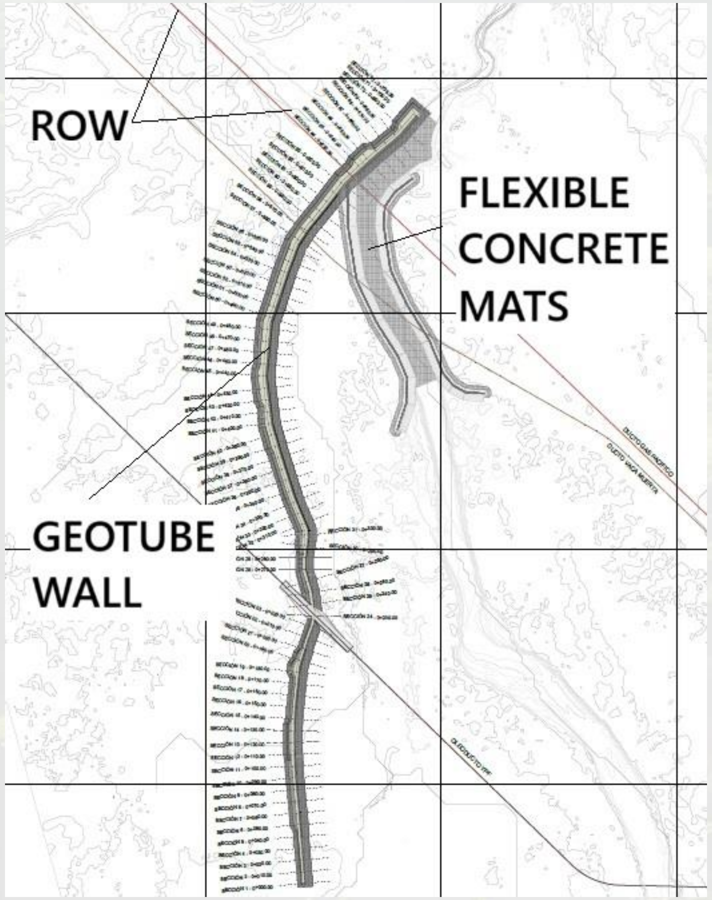


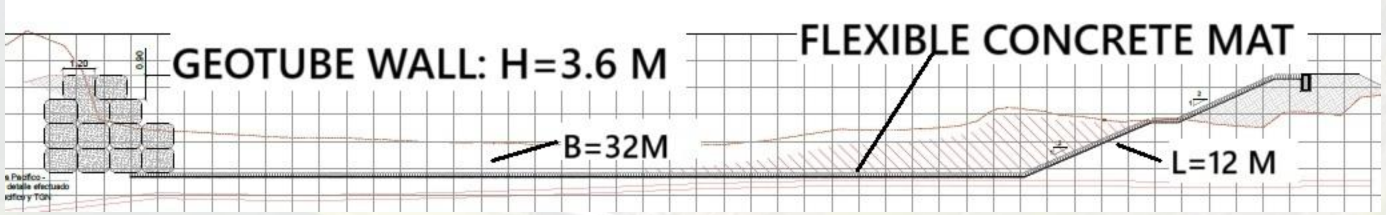
LONG TERM ALTERNATIVES

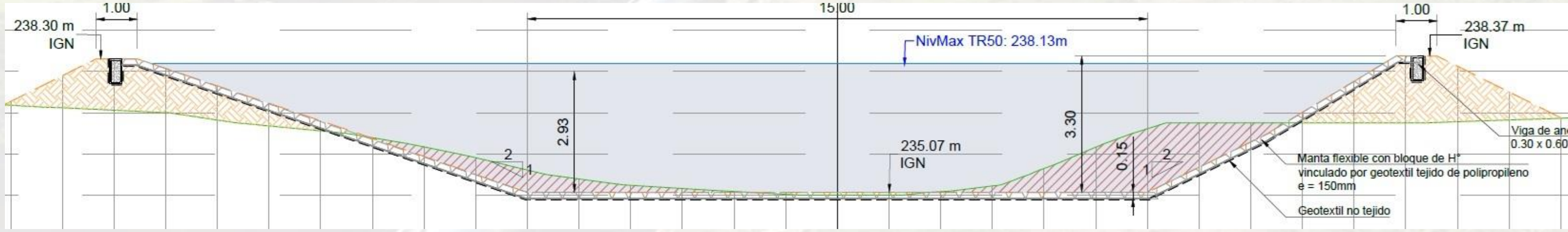
1. **NO CHANGE IN FLOW PATTERN: IN-SERVICE LOWERING (DISCARDED BY CLIENT)**

1. **RESTORATION TO ORIGINAL RIVER COURSE:**
   - **BLOCKAGE OF ROW**
   - **EROSION CONTROL PROTECTION (BED AND BANKS) (SELECTED)**

SELECTED REMEDIATION PROJECT







CONCLUSIONS

1. POOR CHARACTERIZATION DURING DESIGN STAGE TRANSLATES INTO PIPELINE INTEGRITY HAZARDS AND EXPENSIVE REMEDIATION WORKS

2. ANTHROPIC INTERVENTIONS (DAM, ROW) WORSEN THIS SITUATION

3. WATER FLOW AFFECTS PIPELINE SEGMENTS THAT WERE NOT DESIGNED AS PART OF A RIVER CROSSING, BECOMING MORE VULNERABLE

4. CARE MUST BE TAKEN WHILE IMPLEMENTING TEMPORARY WORKS SPECIALLY WHEN CYCLES OF FLOODING AND DRY PERIODS MAY FORCE THE EXPOSED PIPELINE TO MOVE UP AND DOWN

5. CLOSE MONITORING OF SUPPORT CONDITIONS ALONG TIME MUST BE IMPLEMENTED TO AVOID FREE SPAN SITUATIONS

6. SINCE DIVERSION THROUGH THE ROW TAKES PLACE WITHIN A WIDE FLOODPLAIN, ACCESS BECOMES A PROBLEM LIMITING THE AMOUNT OF TIME AVAILABLE TO IMPLEMENT REMEDIATION WORKS

¡Gracias!

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RIVER CROSSINGS: RIVER DIVERSION THROUGH THE RIGHT-OF- WAY

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ABSTRACT

River diversion is one of the less common types of hydrotechnical hazards. It means that a river leaves its original course to divert its waters towards a different path, usually within its floodplain. Water no longer flows across pre-designed water crossings, which includes greater pipeline wall thickness and buoyancy control, proving additional resistance to stresses induced by water in case of exposure. When diversion takes place along the right-of-way (ROW), consequences are immediate, because it offers a preferential route for the river to flow, whenever the main course is blocked by sediments and debris. Initially, vertical scour takes place since the ROW is not prepared to accommodate high flows. Then buoyancy affects the pipeline after topsoil is removed. As vertical erosion progresses, long segments of pipelines are subject to free-span conditions. As successive hydrological wet and dry seasons occur, these exposed segments are subject to buoyancy during floods and downward forces due to their own weight during dry seasons. In the following paragraphs two field cases will be presented with their evolution and history of remediation works.

1. INTRODUCTION

River crossings are designed to account for high flows associated with high return periods (50 to 100 years) and their related hydrotechnical hazards. If they became exposed by erosive processes, pipelines still could resist (up to a certain point) typical stresses such as buoyancy and drag forces since they are constructed with a greater wall thickness and buoyancy control weights. This scheme is totally disrupted whenever the river diverts its course and starts flowing through another route, since it affects segments of a pipeline that were not previously designed as being subject to water flows. Among the most common examples are meander cutoffs. However, in this paper, a particular case of diversion through the ROW will be treated. Although this is not a common case, it is particularly dangerous because it affects long segments of pipelines subject to buoyancy forces which originate mainly by anthropic causes.

2. DIVERSION THROUGH THE ROW

During pipeline construction, a ROW is necessary to ease access, ditch excavation, and to lay down the pipeline. Despite considering environmentally friendly practices, an impact on vegetation is made. Revegetation may take place, but in an extended period of time. Thus, in case of flooding, ROW becomes a preferential path for water to flow. Along this way, the pipeline is usually buried at an average depth of 1 m, being the topsoil easily eroded as soon as high river flows are diverted. Furthermore, when a wide floodplain is present, erosion comes associated with lack of buoyancy control weights, especially for vintage pipelines which did not have a comprehensive natural hazards risk analysis during its conception. In the following paragraphs, two field cases will be presented.

2.1 Diversion through Medina River floodplain

Medina River has a watershed of 2,300 km2, having its headwaters at an elevation of 5,100 meters at the Aconquija Sierras, part of the Cordillera Oriental, at the province of Tucumán, Northern Argentina. Two natural gas lines are placed at an elevation of approximately 290 meters. The river travels 120 km descending an elevation drop of 4,810 meters. This river is a tributary of the Salí River which drains the entire province of Tucumán, ending at the Río Hondo Dam. This dam is located 28 kilometers east of pipelines, but its lake is only 8 kilometers away (see **Figure 1**). As it will be described later, its presence decreases the velocity of the river, favoring the deposition of sediments and debris flows that blocked the main course. Therefore, water finds new routes, mainly because the river slope has decreased almost to zero.

FIGURE 1: MEDINA RIVER WATERSEHD

An average hydrological year can be described as wet summer and dry winter. Rainy season usually begins in September through May, but unfortunately, high flows and floods were registered as early as October. In **Figure 2**, average monthly precipitations from nearby cities of Concepción and Monteagudo, Tucumán, are shown to characterize this concept [1].

CITY	MEAN MONTHLY PRECIPITATION [MM]												
	Set.	Oct.	Nov.	Dic.	Ene.	Feb.	Mar.	Abr.	May.	Jun.	Jul.	Ago.	Anual
Concepción	21	65	107	139	198	177	176	81	36	21	10	9	1045
Monteagudo	8	42	67	83	120	118	110	41	14	8	4	4	620

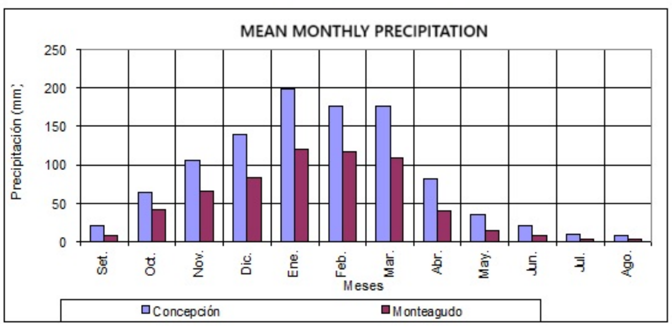

FIGURE 2: MEAN MONTHLY PRECIPITATION IN THE WATERSHED

Hydrological studies performed at the basin scale yielded a discharge of 1,268 m3/sec for a return period of 50 years, considering a storm of 145 mm in 14 hours [2]. The river width at a cross section located 3 kilometers upstream of the pipelines varies between 60 and 80 m (see **Figure 3**). The river is rather shallow with both banks being less than 2 meters high.

In the year 1967, the Río Hondo Dam was built for multiple purposes such as irrigation, electricity generation and flood control. The presence of the dam, changed the discharge of many tributaries in the Salí river, lowering its slope and creating a delta. **Figure 4** shows a satellite image with the position of the dam, its lake where all tributaries end in a delta (including the Medina River) and the pipelines.

FIGURE 3: CROSS SECTION OF A RIVER BRANCH NEAR THE CROSSINGS

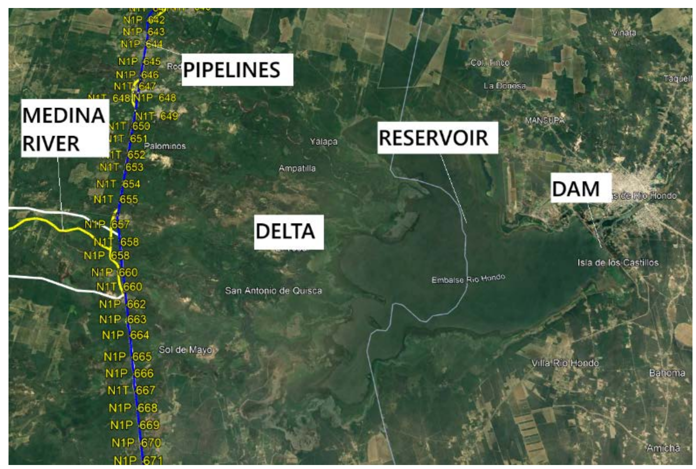

FIGURE 4: SATELLITE IMAGE OF A DELTA WHERE TRIBUTARIES DISCHARGE INTO THE DAM LAKE

Given the 50-year flow (1,268 m3/sec), the small dimensions of the river cross section and a mild slope, flooding of a huge area becomes apparent. The river responds to this combination of factors by dividing its course into many branches which after a while are blocked with debris and sediments, before opening a new branch. Also, every rural road within the floodplain becomes a water course, changing the flow pattern with time and, thus, the amount of water and the location where water enters the ROW. **Figures 5** and **6** are representative of this situation [4].

FIGURE 5: BLOCKED RIVER BRANCH WITH DEBRIS AND FINE SEDIMENTS

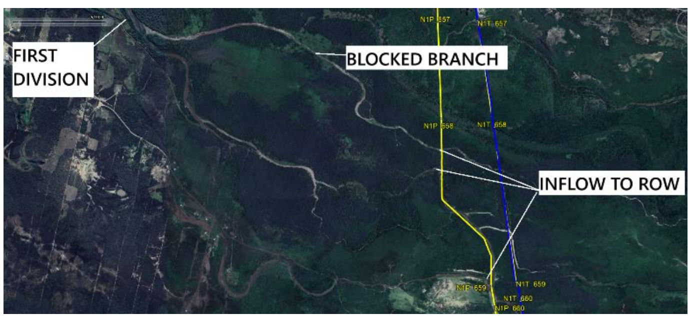

FIGURE 6: POINTS OF WATER INFLOW INTO THE ROW

In successive years after construction water entered the ROW first at the main river course, then after it was blocked, using old meanders and low zones, finding other three points of entrance.

This process took place on both natural gas lines ending in their exposure after extreme flood events; one in 2000 and the other in the summer of 2016. As seen in **Figures 7** and **8**, two long segments (of approximately 60 meters) of pipeline without buoyancy control weights were exposed. They coincided with locations where the pipeline was laid down at a slightly higher elevation and then buried.

FIGURE 7: BUOYANCY OF 24” LINE AFTER YEAR 2000 FLOODING

FIGURE 8: BUOYANCY OF 30” LINE AFTER YEAR 2016 FLOODING

For the 30” line, preliminary remediation was implemented whenever access was possible after water receded. Given the massive flood that occurred throughout the entire floodplain, access became a problem. The nearest paved road is 10 km west, while dirt roads, which are privately owned, offer different paths that are between 10 and 17 km long, as shown in **Figure 9**. To upgrade and maintain access roads involved a considerable amount of time and money. Given the fact that rain could end in May and floods could begin in October, the time frame of dry weather and access to implement a major scale remediation work is limited to four months (June through September).

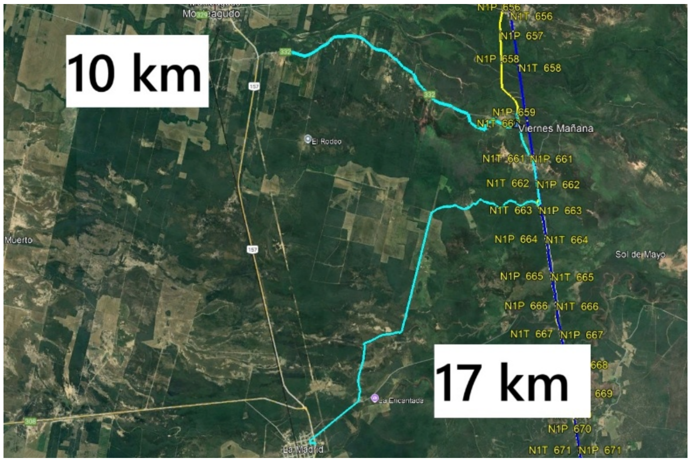

FIGURE 9: ACCESS ROADS

Temporary remediation works were undertaken consisting of soil filled bag weights placed over the pipeline, as shown in **Figure 10**. Originally, they overcame buoyancy forces. However, since water kept flowing along the ROW, its foundation was eroded, leaving the pipeline in an unsupported free-span condition. Thus, an instable situation developed in which the pipeline was with no stress with the weights while flooded, but then tensioned downwards when not, that after the flood.

FIGURE 10: SOIL FILLED BAG WEIGHTS PLACED FOR PRELIMINARY REMEDIATION

A stress analysis was conducted for the 30" diameter line, to understand pipeline vulnerability subject to these cycles of flotation and downward movement. A finite-element software named Caesar II was used. First, a theoretical scheme of a 64 meters long free span was studied, considering four different scenarios as shown in **Figure 11**:

- Pipeline's own weight and a dry river,
- Water level below the pipeline,
- Partially floating pipeline,
- Totally submerged pipeline plus water flow

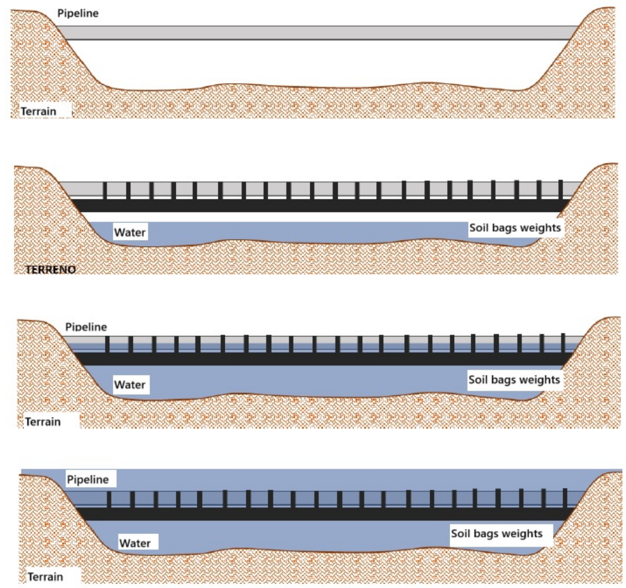

FIGURE 11: STRESS ANALYSIS SCENARIOS

Results presented in **Table 1** reflect this up and down behavior (negative meaning down movement and positive meaning upwards), while exceeding the allowable stress in all cases under hydrostatic conditions. **Figure 12** shows the maximum downward flexion under the worst-case scenario, which is a dry river with buoyancy control weights on the pipeline.

CONDITION	SCENARIO	LOAD	DISPLACEMENT [MM]	COMPUTED STRESS [MPA]	ALLOWABLE STRESS [MPA]	RATIO
WITHOUT WEIGHTS	NO WATER	OWN WEIGHT	-339.47	347.42	347.51	1.00
	FLOODED	BUOYANCY	550.21	418.83	347.51	1.21
WITH WEIGHTS	NO WATER	WEIGHTS	-3356.31	1502.84	347.51	4.32
	FLOODED	WEIGHTS+ BUOYANCY	-568.75	427.33	347.51	1.23

TABLE 1: RESULTS FORM FEM MODEL

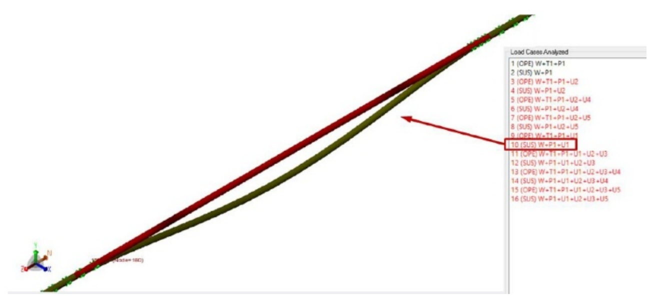

FIGURE 12: MAXIMUM DOWNWARD DISPLACEMENT FOR A DRY RIVER WITH WEIGHTS SCENARIO

The first step followed when the stress analysis results were obtained was to conduct a field survey when the water level dropped, with focus on the underwater support conditions. Luckily, a small island formed by sediments and branches was located at the central segment of the exposed pipeline, as shown in **Figures 13 y 14**.

FIGURE 13: FIELD CONDITIONS SHOWING THE PIPELINE SUPPORTED BY A SMALL ISLAND

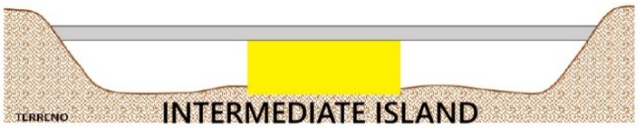

FIGURE 14: FIELD CONDITIONS SHOWING SUPPORTED PIPELINE THE MIDDLE OF THE EXPOSED SEGMENT

The finite-element model was run again representing field condition and the intermediate support. All scenarios showed the computed stresses where less than the allowable one. No further temporary remediation works were executed and field surveys of the stability of the island were performed periodically.

Final remediation was reached for de 24” and the 30” lines by implementing new crossings by horizontal directional drilling (HDD) in a length of approximately 1,100 meter long and 20 m deep. **Figure 15** shows the longitudinal profiles of the 24” line obtained by the passage of an in-line inspection tool.

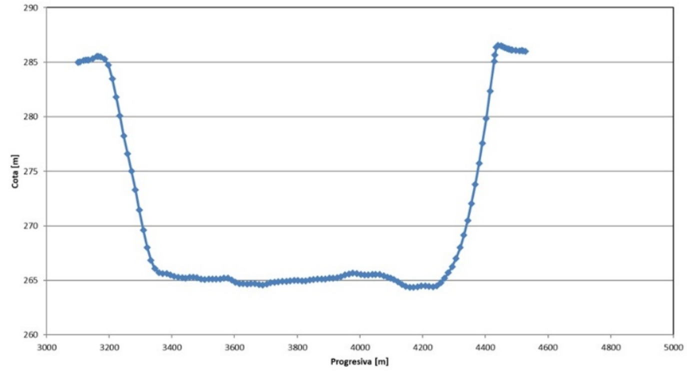

FIGURE 15: NEW HDD CROSSING FOR THE 24” LINE

2.2 Diversion through Bajo del Añelo Creek´s floodplain

This crossing is located at a desert in the province of Neuquén, northern Patagonia, where mean annual precipitation is around 300 mm, with the rainy seasons happening during autumn (March-June). While walking around the area back in 2004, it appeared as a minor creek in terms of width (22 m) and low banks (1.5 m) (see **Figure 16**). After a flood, this water course experienced a lateral migration that showed minimum soil cover at its left bank plus an exposed segment of pipeline at the end of the floodplain. Scour at the main course was due to high water velocities (see **Figure 17**), while erosion at the edge of floodplain occurred as water flowed through the ROW towards the main course after the discharge peaked, due to the difference in elevation (see **Figure 18**). River configuration and alignment are shown in **Figure 19**. Remediation works were oriented to two localized areas: protecting the river´s original left bank and covering the exposed segment while blocking and diverting water at the edge of the floodplain out of the ROW.

FIGURE 16: RIVER COURSE IN 2004

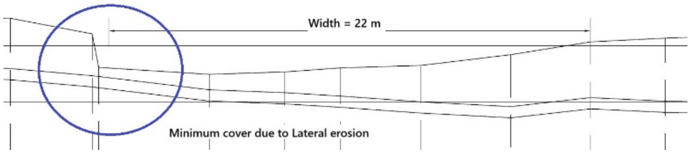

FIGURE 17: RIVER CROSSING IN 2004 AFTER THE FLOOD

FIGURE 18: PIPELINE EXPOSED AT THE EDGE OF FLOODPLAIN AFTER THE 2004 FLOOD

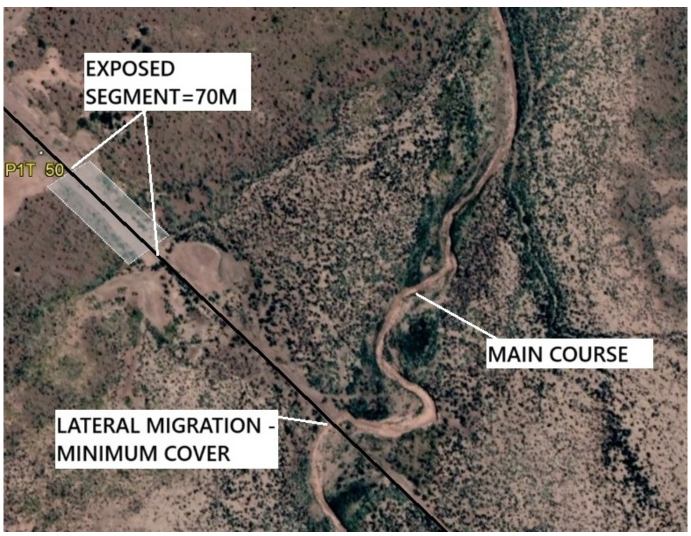

FIGURE 19: RIVER CONFIGURATION IN 2004

Although at that time it did not appear to be an extraordinary problem, a comprehensive study was conducted, including hydrologic and hydraulic modeling [2]. The size of the watershed yielded a value of 1,500 km2 (see **Figure 20**), which was in contrast with a 20 m wide creek but explained why the floodplain comprised a greater width of 2,000 m.

This situation didn´t experience any substantial change until approximately 2014. During that year, the river changed its course and started to flow through the ROW for approximately 500 meters (see **Figures 21** and **22**). Among the possible reasons for this change are the lack of significant floods from 2004 to 2014, which may have caused the deposition of sediments on the original river course, plus the fact that the ROW offered a preferential path during high flows.

FIGURE 20: LIMITS OF THE 1,500 KM2 WATERSHED

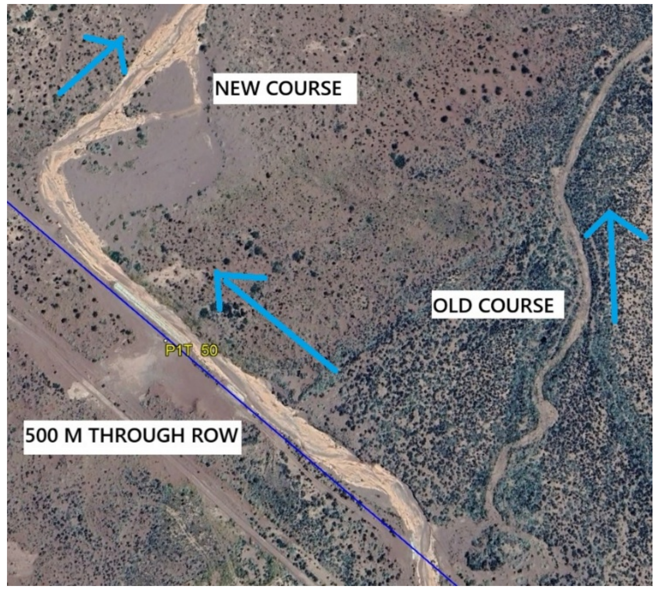

FIGURE 21: DIVERSION THROUGH THE ROW IN 2014

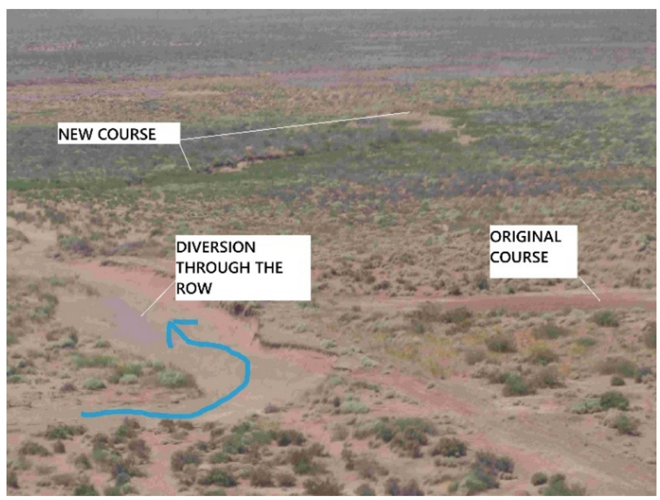

FIGURE 22: AERIAL PICTURE OF THE 2014 SITUATION

This new situation presented a completely different hydrotechnical threat to pipeline integrity since instead of localized exposures, a 500-meters stretch of pipeline was affected on its left new bank. The original pipeline design contemplated as buoyancy control a continuous concrete coating of only 24 m long, located at the original 20 m wide crossing. Under these new conditions, the pipeline was not prepared to account for buoyancy or any other tresses induced by water flows in case of exposure. This was the case after the 2014 flood where new segments along the river had minimum lateral soil cover, which was now the focus of further monitoring surveys. Initially, temporary remediation works were implemented to restore flow through the original river course by blocking the entrance to the ROW. Given the fact that floods are not common due to the annual precipitation regime, this scheme proved suitable for a while. In January 2022, a new storm took place, exposing approximately 35 m of pipeline, as shown in **Figures 23** and **24**.

FIGURE 23: EXPOSED PIPELINE ALONG LEFT BANK

FIGURE 24: DETAILED PICTURE FROM THE SAME AREA

Temporary remedial measures were implemented immediately in the field. A typical solution was constructed to avoid further damage consisting in placing concrete bolt-on weights (see **Figure 25**) and building a left bank protection with geotubes that performed well in other nearby rivers with similar erosive processes. The use of geotubes is common in isolated places in the desert since stones for gabions and rock for rip-rap protections are harder to get within a reasonable distance. They are filled with local soil and covered in their exposed surface with a thin layer of cement mortar to protect them from scratches from debris, especially bushes and thorns. An additional flexible protection made from flexible concrete mats was placed at its foot to avoid scouring and sliding of the geotubes, as shown in **Figures 26** and **27**. Soon after construction, a flood took place verifying a suitable performance of temporary works (see **Figure 28**).

FIGURE 25: BOLT-ON WEIGHTS PLACED ON THE EXPOSED SEGMENTS

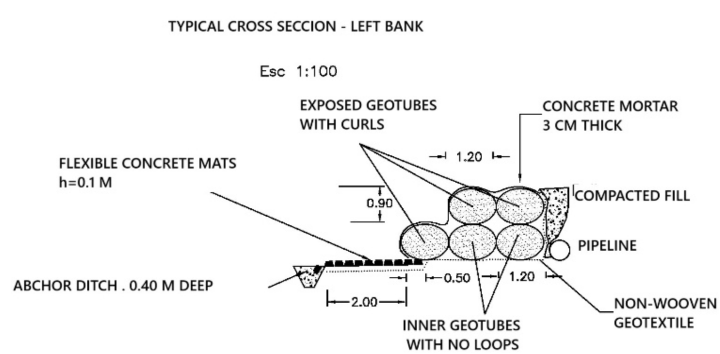

FIGURE 26: TYPICAL CROSS SECTION OF TEMPORARY REMEDIAL WORKS

FIGURE 27: BANK PROTECTION WITH GEOTUBES

FIGURE 28: PERFORMANCE AFTER A FLOOD IN 2022

Despite having the situation under control, a parallel process started to develop a more comprehensive and definite solution to this problem, given the history of remediation works built throughout the years. A complete integrity study was conducted to fulfil local regulations imposed by the local water authority as well as natural gas transport standards. The study included hydrological studies and modelling to compute the design discharge, topography of the affected area to obtain the digital terrain model of the floodplain, soil studies, hydraulic modeling to obtain the water surface elevation, depth of flow, and water velocities along the river, and the extent of the flooded area. In the following paragraphs a brief description of these main components will be provided.

As it is usual in Argentina, rain (even less discharge) information is not available in such isolated areas. Thus, to compute the discharge, an effective rain-discharge model was employed. Then, the next step is to assume the areal extent of the design storm, which is set by regulations as the one that corresponds to a return period of 100 years [3]. Two scenarios were modeled using HEC-HMS developed by US Corps of Engineers: one in which the storm is located at three different locations within the watershed (see **Figure 29**), and another one used to verify the solution consisting in computing a higher discharge with rain falling over the entire watershed. A storm of 73,5 mm with a duration of 6 hours was modelled, obtaining a discharge of 235.5 m3/sec for the design of remediation works.

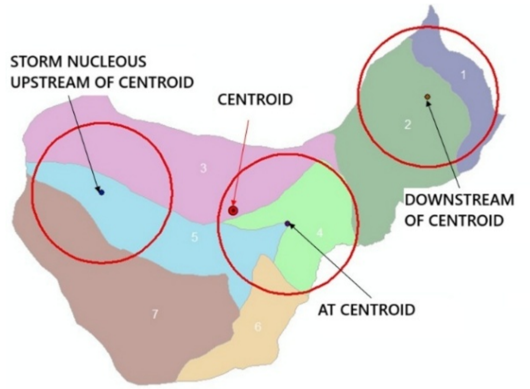

FIGURE 29: DESIGN STORM LOCATION FOR FLOW CALCULATIONS

Once the discharge was obtained, then a hydraulic model was run using HEC-RAS developed by US Corps of Engineers. In the following figures, the extent of the flooded area, water depth and the velocity maps are presented in **Figures 30** and **31**.

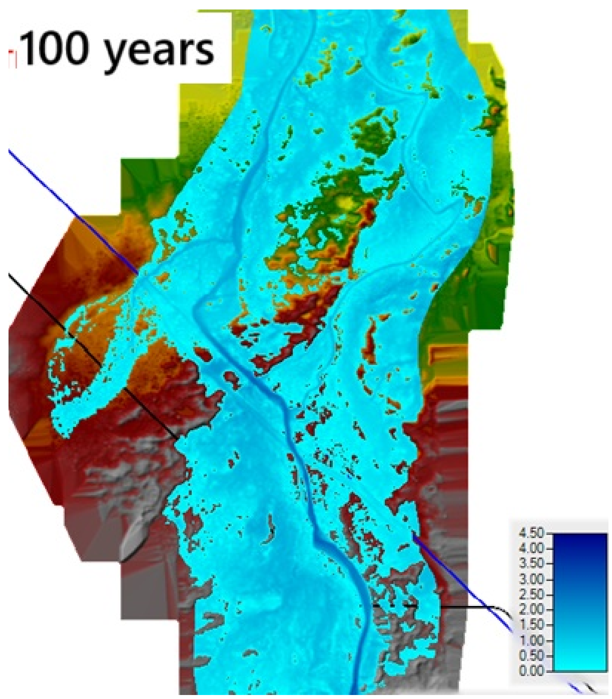

FIGURE 30: EXTENT OF THE FLOODED AREA AND WATER DEPTH

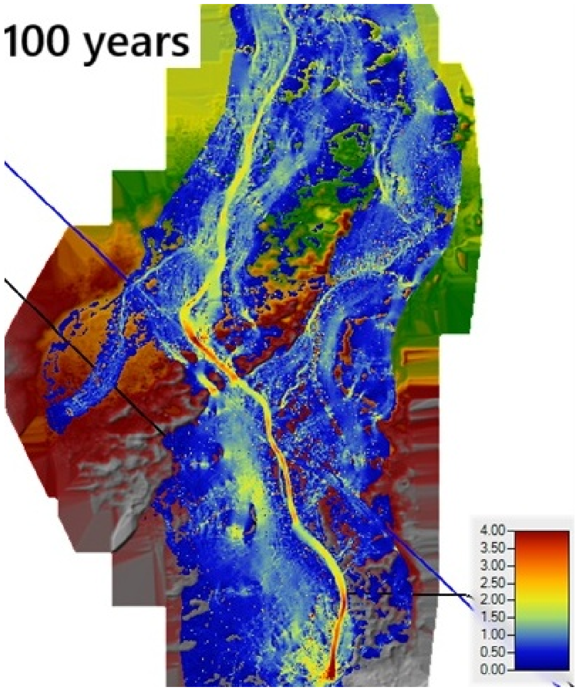

FIGURE 31: VELOCITY RANGE THROUGHOUT THE FLOOD PLAIN

Interesting conclusions can be reached after these results:

- The extent of the flooded area is massive. As shown in **Figure 32**, the dimensions of the cross section of the original river course (22 m wide and banks of 1.5 m) could only cope with minor flows. Flood conditions will develop as soon as a strong storm takes place, a fact that was corroborated by a field visit after a flood in April 2004.

FIGURE 32: FIELD SURVEY AFTER A FLOOD

- After diversion through the ROW, exposed segments of pipelines are congruent with zones of highest velocities, as values reached in that area were in the order of 3 to 4 m/sec (see **Figure 33**).

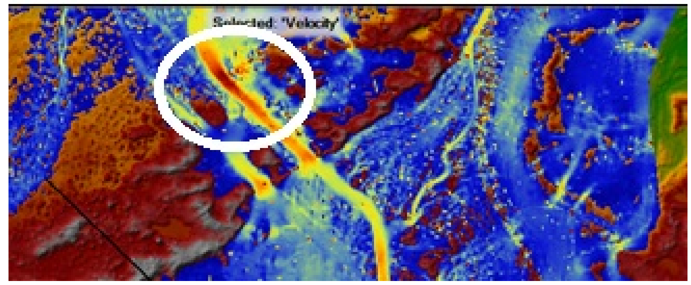

FIGURE 33: DETAILED VELOCITY MAP AT THE ROW

- The flood plain still shows a significant flow along the original river course (see right side of **Figure 31** and **Figures 19** and **21**) although with lesser values of velocity.

Two main alternatives were considered for a more comprehensive solution:

- In-service lowering of the pipeline by natural flexion for 500 meters,

- Restoring the river to its original course, avoiding water running through the ROW. This alternative was finally selected and is now on the stage of bidding. It comprises a long wall of geotubes along the left bank and the construction of a riverbed protection with flexible mats with concrete blocks (see Figures **34** through **37**). The main dimensions for the components of the project are:

    - Geotube wall at left bank: 700 m long and variable height (1.80m to 5.85m),

    - Riverbed revetment with flexible concrete mats at its main course upstream of the crossing following a trapezoidal cross section with a horizontal width that varies between 15 m to 19 m, plus two 8 m long inclined revetment at each bank.

    - Pipeline protection with a 5.85 m high geotubes wall on the left bank, 25 m wide flexible concrete mat at the riverbed, and a 7 m long inclined protection with the same material at its right bank.

    - The height of each concrete block of the flexible mat is 15 centimeters.

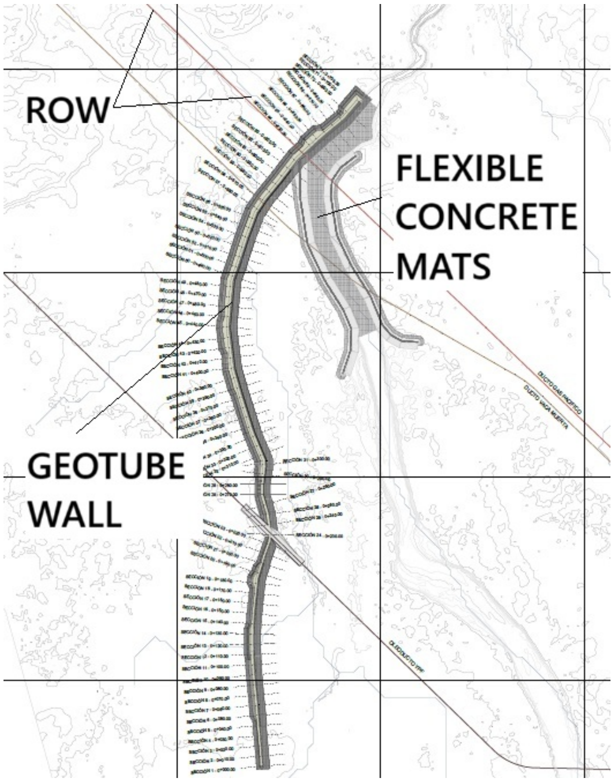

FIGURE 34: GENERAL LAYOUT OF FINAL REMEDIATION PROJECT

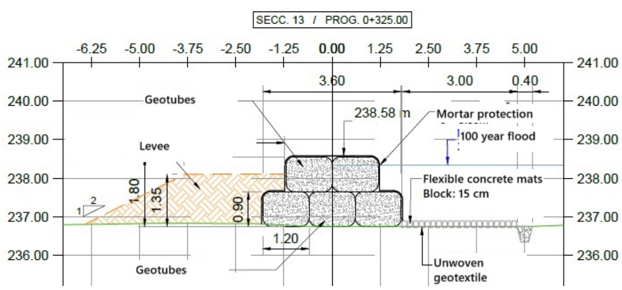

FIGURE 35: LEFT BANK GEOTUBE WALL

FIGURE 36: TYPICAL CROSS SECTION UPSTREAM OF CROSSING

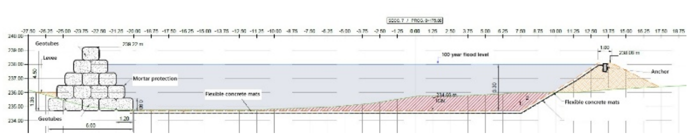

FIGURE 37: TYPICAL CROSS SECTION AT CROSSING

3 RESULTS AND DISCUSSION

As shown in the previous paragraphs, the solution to river diversion through the ROW involves expensive remediation works, since it affects the integrity of significant lengths of an operating pipeline. The two examples addressed by this paper are located at different environments. However, they share many aspects in common:

- Field surveys can often be misleading. River width and bank heights are rather small and do not correspond to a huge watershed, that usually has an area of thousands of square kilometers.
- During design and construction, the fact that they are built inside a floodplain is overlooked.
- Thus, common design characteristics such a lower design factor, a greater wall thickness and buoyancy control are missing.
- Once river diversion takes place, erosion (vertical and lateral) takes place easily, becoming a problem because pipeline loses support at its bottom.
- Then if weights are added, during dry conditions the pipeline own weight plus the added weight translate into downward flexion if unsupported. Under flooded conditions, the pipeline experiences an upward lift and drag forces. This combination becomes problematic if uncontrolled.
- Before a final solution is implemented, fields surveys of pipeline support become critical, since they evolve with time.
- In flooded areas, access becomes a big part of the overall remediation work.
- Finally, solutions such as horizontal direction drilling or a massive erosion control structure that block the diversion run at a cost of several million dollars.

4 CONCLUSION

It is recommended to assess these types of hydrotechnical hazards, early at the design stage, mainly by taking a broader look at the extent of floodplain and by including in the design the same precautions that are common at a river crossing such as lower design factor, greater wall thickness, placing the pipeline at a lower elevation due scour and to control potential buoyancy, but in a much longer length. This will increase the cost at the construction stage, but I will be a huge saving during operation.

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[3] Análisis de la problemática de erosión, diseño de medidas de mitigación y control. PK 50, Gasoducto del Pacífico Argentina S.A., Serman & Associates for Gasoducto del Pacífico.

[4] Field and aerial surveys performed by TGN.