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Hydro-sedimentology and mitigation measures of the stream diversion of “Arroyo Corrales”, Uruguay

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ABSTRACT: A mining company operates the “Arenal” gold mine nearby the Corrales Stream in Uruguay. In order to extend the mine operation, a diversion of the Corrales Stream ($Q_{100}=1700 \text{ m}^3/\text{s}$) was projected in 2005. This project included the construction of protection levees and the implementation of re-naturalization measures. These last measures involved the re-vegetation of the dikes and banks of the channel. The excavation of the new stream trace was done in rock, the length of the diversion is 1250 m including several curved reaches, and the channel cross-section is trapezoidal with a bottom width of 40 m. The hydro-sedimentological viability of the project was studied in advance in order to determine the protection actions required to ensure the stability of the stream. The stream diversion was built in August 2007, and today the diversion remains operational and the mining area has been expanded as planned. In this paper we present the methodology and the results of the hydro-sedimentological study of the diversion works. The hydraulic and sedimentological behavior after the construction is also shown. Finally, the implemented environmental mitigation measures are described and their monitoring procedure is presented. The in-situ observations gathered during the first two years after the diversion operation agree well with the predicted performance from the hydrodynamic, sedimentological, and environmental points of view.

Keywords: River Modelling, Diversion Projects, River Mitigation Measures

1 INTRODUCTION

A mining company began to operate of the gold mine “Arenal” in 2003. The mine is located in the north of Uruguay, in the left side of the Corrales Stream. The first stage of this operation concluded in August 2007, when a new geological survey detected a lode that then determined the enlargement of the mine’s area. In order to extend the quarry the diversion of 900 m of the Corrales Stream and the construction of two protection levees was planned (Figure 1).

The reach where the diversion works are located is located in the middle zone of the Corrales Stream. Following the Schumm’s definition (Schumm & Winkley 1994) this is a transfer zone of the stream, and for a stable channel, input and output of sediment are balanced.

The diversion channel is 1250 m long and has a slope of 0.0019. Its cross section is trapezoidal, with a bottom width of 40 m. Downstream of the mine the diversion channel discharges back into

the stream. A culvert is located at this discharge section. The channel was excavated in fine soils, loose rock and sound rock, and consequently the different cross-section were adapted to those conditions. Three cross-section types are distinguished:

Type 1. Corresponds to the reaches of the outlet of the Corrales Stream into the channel and to the outlet of the channel into the Corrales Stream (Figure 2, S1 in Figure 1).

Type 2. Corresponds to the central reach of the channel, where it crosses the hillside and it is excavated in sound rock (figure 3, S2 in Figure 1).

Type 3. Corresponds to the lower reach of the channel, where the excavation is made in fine soils, loose rock, and partly, in sound rock (figure 4, S3 in Figure 1).

The protection embankment levees have a central rolled clay core, shoulders composed of loose rock and filters composed of sandy material. The embankment is founded in the sound rock, and has

a crest that is wide enough to permit the transit of road trucks (Figure 5, S4 in Figure 1).

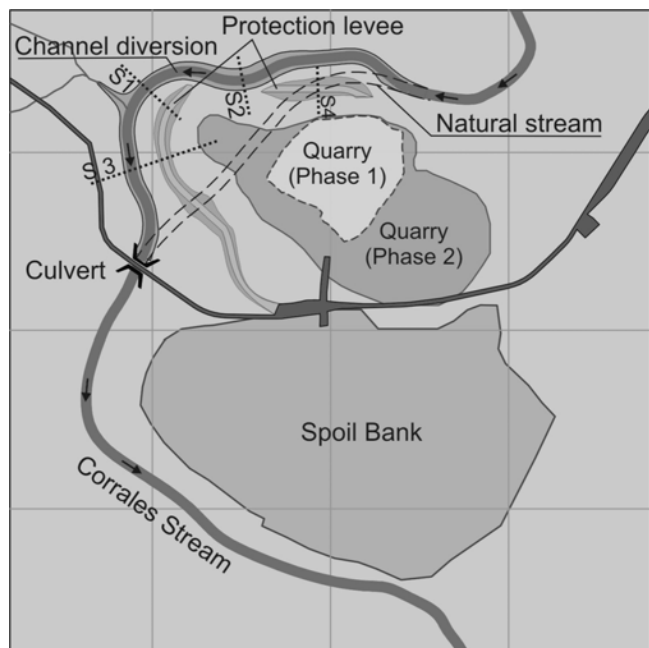


Figure 1. Sketch of the diversion.

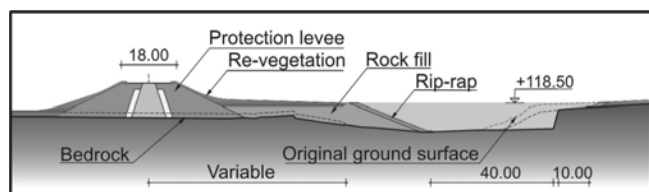


Figure 2. Diversion channel. Cross section. Type 1 (S1 in Figure 1).

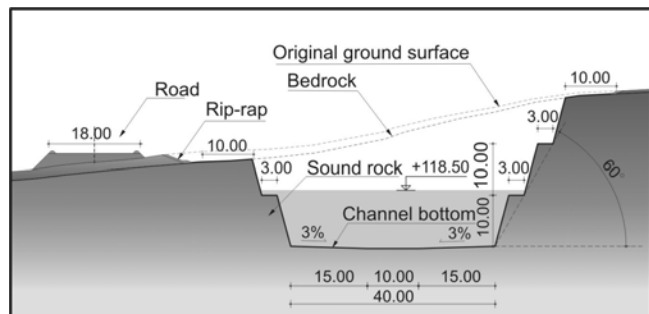


Figure 3. Diversion channel. Cross section. Type 2 (S2 in Figure 1).

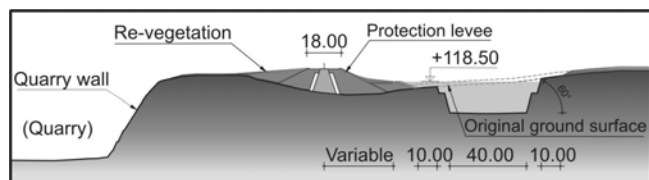


Figure 4. Diversion channel. Cross section. Type 3 (S3 in Figure 1).

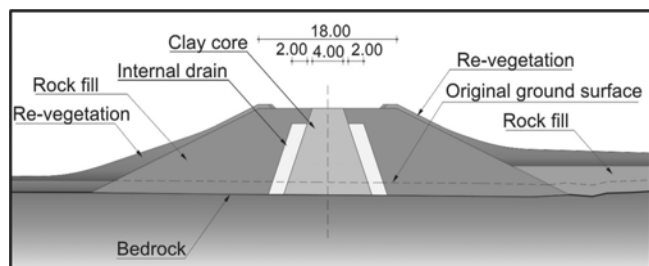


Figure 5. Diversion levees. Cross section (S4 in Figure 1).

In order to ensure the environmental sustainability of the works, the project sought to maintain the hydrodynamic and sedimentologic behaviour of the Corrales Stream unchanged.

Mitigation measures, consisting on re-vegetation of the embankment slopes and the diversion channel margins, were taken to ensure the continuity of the stream corridor (The Federal Interagency Stream Restoration Working Group, 2001). Both the diversion and the re-naturalization measures have took place in August 2007.

This paper presents the methodology and results of the diversion's hydro-sedimentological study. In addition, the hydraulic and sedimentological performance of the diversion after its construction are described, as well as the results of the implemented environmental mitigation measures.

2 METHODOLOGY

2.1 Hydrological and Hydraulic models

The Corrales basin situated upstream from the bridge of Route 28 was modelled in order to determine the extreme flood hydrographs. This basin covers an area of 1013 km², with the bridge of Route 28 located 5 km upstream of the diversion channel (IMFIA 2006). The implemented model was of the semi-distributed type and the total basin area was divided in seven sub-basins (Figure 6, Table 1). The hydrologic study was implemented using the HEC-HMS model (US Army Corps of Engineers).

A hydrodynamic model of the Corrales Stream was implemented for a stretch of 30 km length. The modelled reach starts 5 km upstream of the diversion channel and ends at the conjunction of the Corrales Stream with the Cuñapirú River.

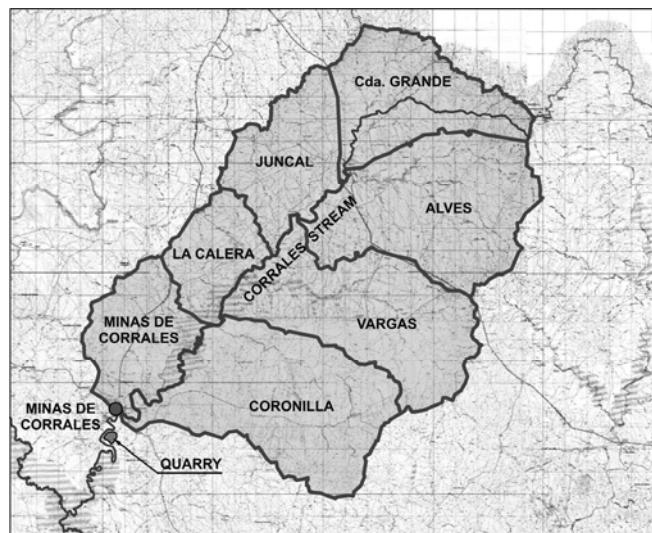


Figure 6. Sub-basin of Corrales Stream

Table 1. Sub-basin of Corrales Stream characteristics]

Sub-basin	Area	Length	Dif elev S	tc	
	km ²	km	m	%	h
Coronilla	223.4	26.7	155	0.52	7.0
Vargas	196.6	30.4	125	0.41	7.8
Alvez	210.6	24.3	70	0.29	7.6
Cañada Gde	136.3	26.3	105	0.40	7.1
Juncal	106.7	15.6	65	0.42	4.6
La Calera	69.2	13.0	45	0.35	4.3
M. de Corrales	98.1	16.3	45	0.28	5.6

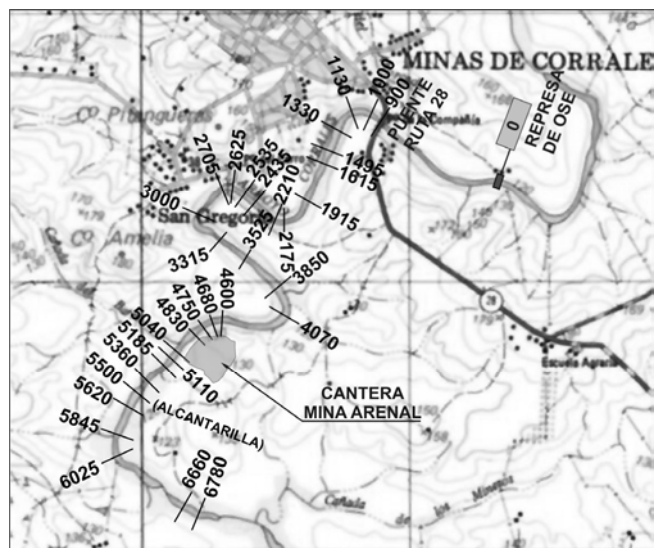


Figure 7. Surveyed sections of the Corrales Stream

The model was implemented using the MIKE 11–DHI software. A campaign of topographic and bathymetric survey was carried out in order to obtain information to feed into the model. The surveyed sections are shown in the Figure 7.

The hydrologic and hydraulic models were calibrated and validated using:

- Daily pluviometric data the Corrales basin
- Water levels at the Route 28 Bridge section (section 900).
- Water levels at the culvert section (section 5500).
- Rating curve of Corrales Stream at the Route 28 Bridge cross-section.

Data from the 1961 flood were used during the calibration phase. Based on these data, the hydrological parameters of each sub-basin were adjusted, and the values of Manning’s roughness coefficient for the hydraulic model were determined.

For the validation phase, data from the maximum registered flood (April 2002) were used. With the aid of the hydraulic model, the impact of the diversion works on the streamflow was analyzed, and the dimensions of the diversion channel and of the embankments were optimized.



Figure 8. Location of sediment samples.

Table 2. Sub-basin of Corrales Stream characteristics

Sample	Stream length	d50	Std
	m	mm	
M10	950	19.1	4.49
M09	2600	0.70	2.39
M08	2630	50.0	2.68
M11	3950	0.95	1.79
M07	6590	3.10	1.39
M06	7160	1.00	1.96
M05	7935	0.95	1.77
M04	8660	1.10	2.05
M03	9015	4.76	6.59
M02	9605	0.75	1.74
M01	9605	0.75	1.80
M12	10860	0.12	2.87

2.2 Sedimentological Model

In order to identify possible modifications of the sedimentological regime and changes in the morphology of the Corrales Stream, a hydro-sedimentological model was implemented using the ST module of MIKE 11. The particle size distribution of sediments in the streambed was established by extraction and analysis of fourteen samples (Figure 8 and Table 2). A regulation dam is located upstream of the modelled reach and null sediment input at this location was assumed as boundary condition.

The sediment transport and the evolution of the streambed were simulated for the maximum registered flood, occurred on April 2002. For this event the temporal evolution of the streambed was determined and the amount of sediment transport was established at each section.

The original situation, before the construction of the diversion, was also simulated and the results compared with those obtained for the after diversion conditions.

Five different equations for the computation of the sediment transport were tested: Van Rijn; Engelund-Fredsoe; Engelund-Hansen; Acker-White y Smart-Jaeggi. (Julien, P., 2002)

2.3 Operational phase

The operation of the diversion started on August 2007, with the monitoring activities started simultaneously in order to asses the behaviour of the diversion works. Information of daily precipitation has been collected from three meteorological stations, and water level data have been collected from a gaging station. A detailed monitoring of the diversion works response took place during the floods that occurred after August 2007.

The monitoring plan consisted in monthly visual inspections of the river banks and the vegetation cover. Topographic surveys were conducted after every mayor hydrologic event and two surveys have taken place since the beginning of the operation of the diversion. The surveys consist of detailed geometric descriptions of the longitudinal and transverse profiles of the diversion cross-sections. Comparing before and after flood surveys allows to detect areas of erosion and deposition.

2.4 Rehabilitation and mitigation measures

Stream corridor mitigation measures were planned, executed. Those measures consisted in:

- The re-vegetation of the embankment slopes with native grasses after placement of topsoil on them.
- The re-vegetation of the margins of the excavated channel with native grasses.
- The rescue of native trees and bushes from the affected areas, their maintenance in nurseries and their transplantation into the margins of the excavated channel.

A monitoring plan was has taken place in order to determine the success of the mitigation effort.

3 RESULTS

3.1 Hydrological and Hydraulic models

Figures 9 and 10 show the results of the hydrologic and hydrodynamic model calibration at Route 28. Figure 9 shows both the measured and modeled stage-discharge relations. Figure 10 shows the observed and computed flow hydrographs for the September 1961 event. A very good agreement between the modeled and observed conditions of the system can be seen.

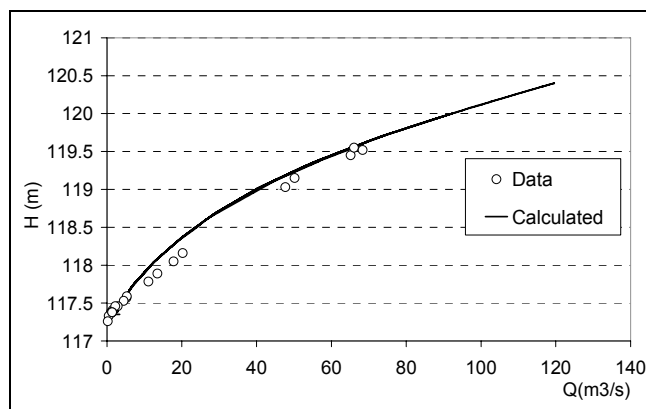


Figure 9. Model calibration. Routing curve in Road 28 bridge.

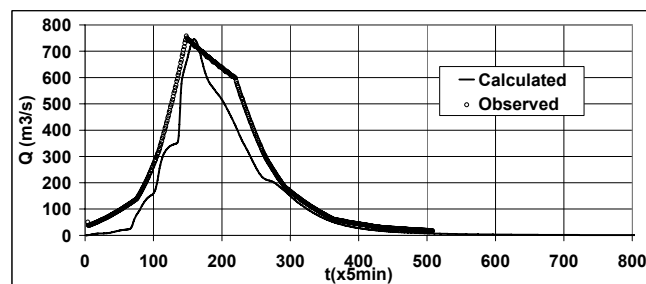


Figure 10. Model calibration. 1961 flood hydrograph in Road 28 bridge.

The impact of the diversion works on the water levels at different sections of the modeled reach was studied for the April 2002 and September 1961 events. As an example of these results, Figures 11 and 12 show stage hydrographs with and without the diversion works for the cross-section just upstream and downstream from the diversion.

From the results it is clear that the diversion works have had no negative effect of on the Route 28 Bridge for the two analyzed events. For discharges close to the largest ever register (April 2002 flood: 1376 m³/s) the increase on the levels at the Route 28 Bridge was less than 10 cm. Similarly, at sections close to the diversion there was no difference on the modeled water levels for large stages (large discharges). Some difference was observed for the lower stages, but the potential problems associated are no particularly significant for this case.

Another important element to consider is the change in the number of hours that the bridge is out of service due to high waters. Using the results of simulations it is possible to determine the amount of time that the water levels at the bridge would be above the bridge pavement level (122.8 m). This was done for both scenarios, before and after the diversion, and the results are shown in Table 3. It is found that although there is an increase in the number of hours that the bridge would remained closed; this increase is less than 1 %.

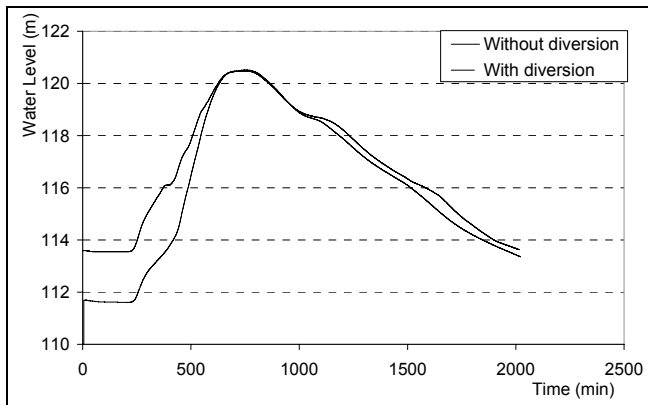


Figure 11. Stage hydrograph with and without the diversion works, just upstream from the diversion

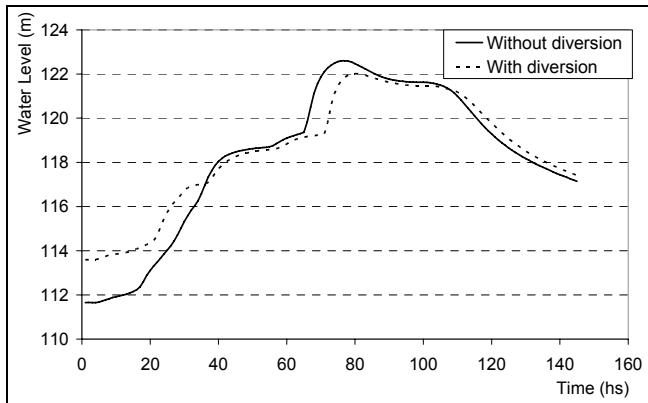


Figure 12.- Stage hydrograph with and without the diversion works, just downstream from the diversion

Table 3. Time variation of bridge out of service with and without diversion works. The maximum flow discharge of the april 2002 flood is 1376 m³/s.

Discharge m ³ /s	Time of bridge out of service	
	Without diversion h	With diversion h
2200	81.8	82.7
1376	55.7	56.2
1000	45.6	45.7

3.2 Sedimentological Model

The sediment transport for the April 2002 flood was modeled considering no sediment input as upstream boundary condition. The transported sediment and the bed elevation evolution was considered at each cross-section for the original and diverted scenarios, and the results were compared.

Figures 13 and 14 show the longitudinal bed profiles obtained from the application of five different equations for the sediment transport for the April 2002 event. The five considered equations were: Van Rijn (VR); Engelund-Fredsoe (EF); Engelund-Hansen (EH); Acker-White (AW) y Smart-Jaeggi (SJ). The original profile is also shown as reference.

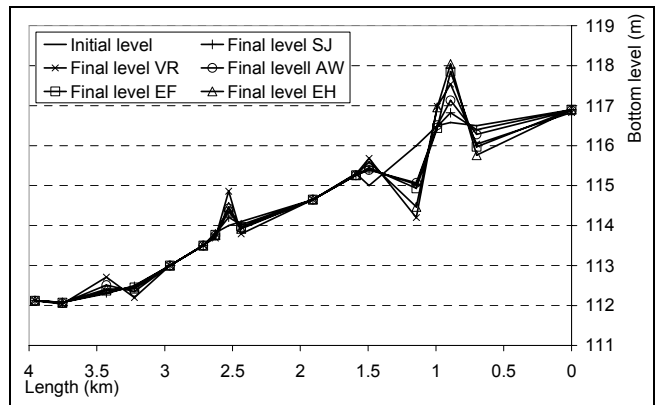


Figure 13. Bottom channel level resulted from the different sediment transport formulation upstream of the diversion

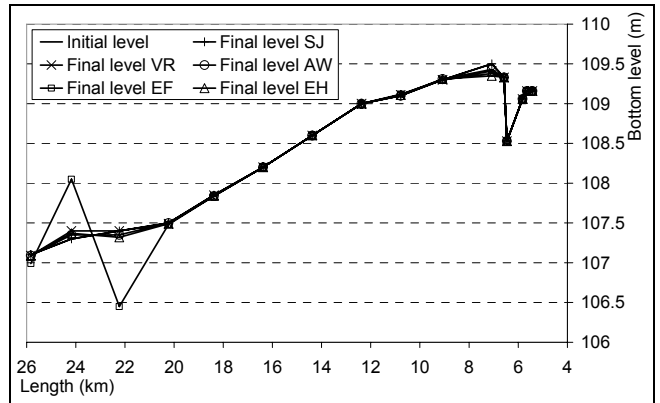


Figure 14. Bottom channel level resulted from the different sediment transport formulation downstream of the diversion

As it can be clearly seen, the effect of using the different sediment formulations is relatively small, both on the final bed elevation as well as on the total amount of transported sediment. This shows that any of the considered formulations could represent the overall sedimentological behavior of the studied reach.

The Engelund-Hansen formulation was used to compare the original and diverted stream configurations. Figures 15 and 16 show the initial and final bed elevation for reaches up-stream and downstream from the diversion. The differences in both cases are very small: The bed remains essentially unchanged downstream of the diversion. And Up-stream of the diversion larger changes on the bed elevation are predicted for both scenarios.

The largest difference between the final bed elevation with and without the diversion is about 20 cm, which is within the error of this type of simulations. In the rock outcrop areas, where no erosion is possible, the model also shows that no deposition should be expected do to the steep slopes. Therefore no significant changes in the sdeimentological behavior of the Corrales Stream should be expected as a consequence of to the construction of the diversion channel.

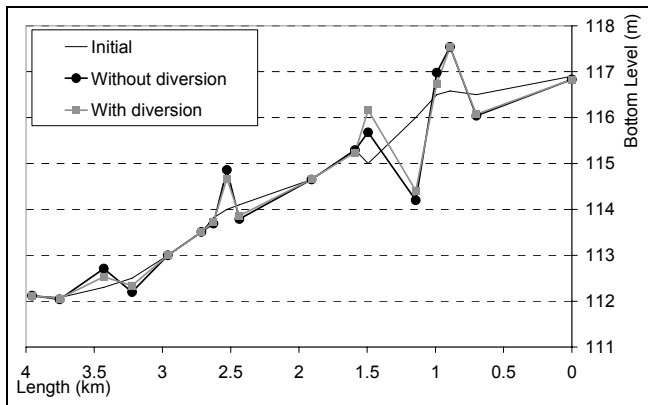


Figure 15. Bottom channel level resulted from the model with and without diversion works (upstream of the diversion)

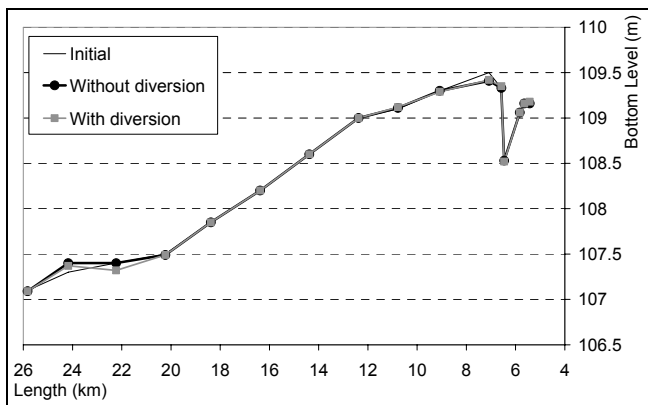


Figure 16. Bottom channel level resulted from the model with and without diversion works (downstream of the diversion)

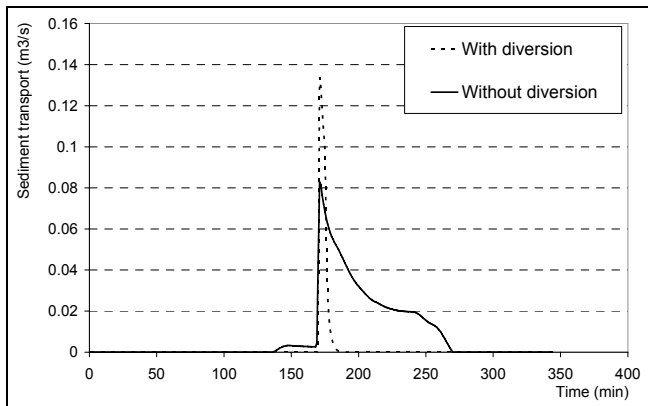


Figure 17. Sediment transport resulted from the model with and without diversion works in a section just upstream of the diversion

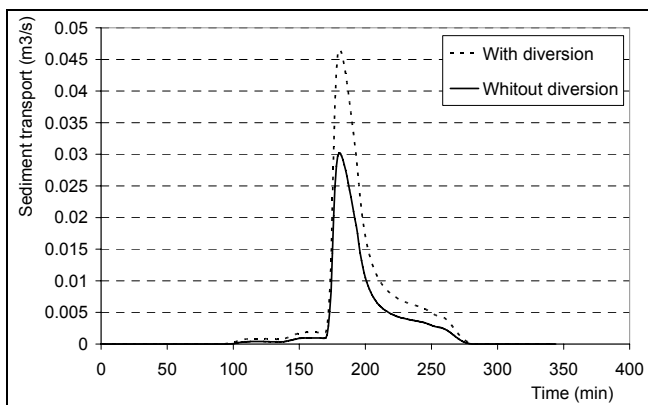


Figure 18. Sediment transport resulted from the model with and without diversion works in a section just downstream of the diversion

Regarding the transport of sediment, the results are shown in Figures 17 and 18 for the upstream and downstream sections. Again no significant effects of the diversion is observed.

3.3 Construction

The execution of the works started in April 2007 and concluded in August 2007, when the diversion became operational. The total movement of soil and rock was 1.3 billion cubic meters in 5 months.

3.4 Hydraulic and sedimentological behaviour assessment

Figure 19 shows a frequency analysis of the flows registered at Corrales Stream after the construction of the diversion channel.

During October 2007 (Figure 20) and November 2009, two extraordinary floods occurred and no negative effects were detected. During these events peak discharges of 800 m³/s (Tr = 3 years) and 1400 m³/s (Tr = 30 years), respectively, were registered.

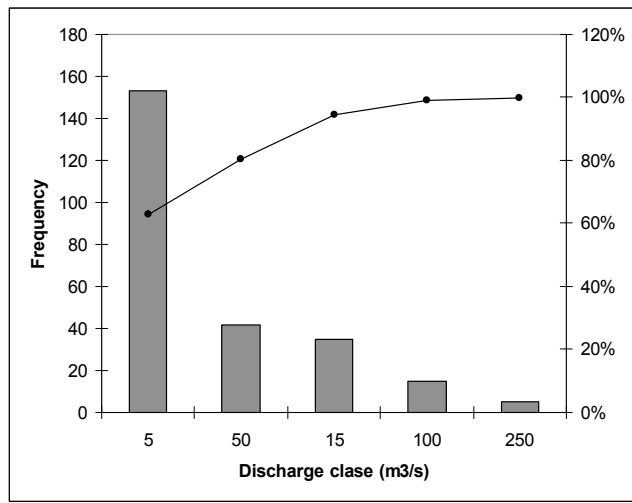


Figure 19. Histogram of the flow discharge for the operation time period



Figure 20. Aerial view during the flood of October 2007.

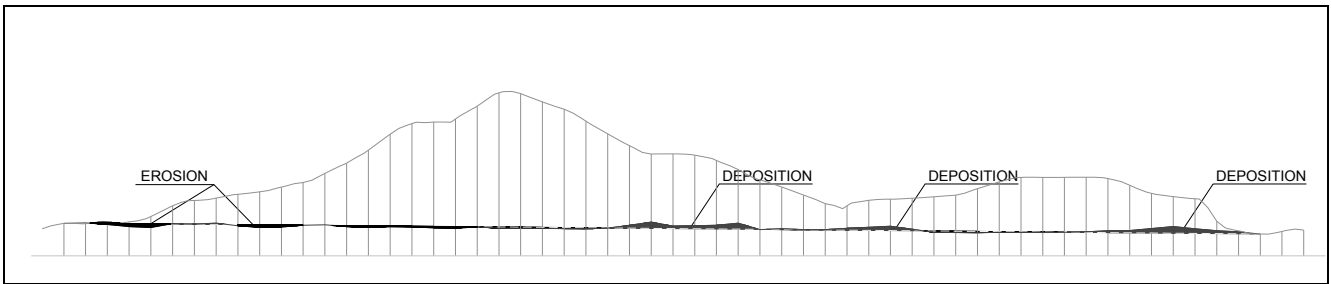


Figure 21. Sedimentation and deposition zone after the flood event in the longitudinal profile of the diversion channel

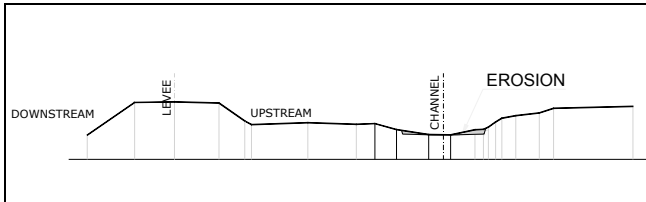


Figure 22. First cross section of the diversion channel with the erosion produced for the flood event

As it can be seen from the aerial photos (Figure 20) the natural look of the stream is essentially preserved. And since the construction, the system has been working normally without hydraulic affectations neither upstream nor downstream of the diversion.



Figure 23. Upstream zone of the channel after construction



Figure 24. Upstream zone of the channel after re-vegetation

The sedimentological behavior of the stream was evaluated from topographic surveys of the diversion channel cross-sections and the its longitudinal profile. A longitudinal profile of the channel at the beginning of the diversion operation (August 2007) and after the last mayor flood event (December 2009) are shown in Figure 21. No significant changes on the bed elevation profile are observed. Erosion is observed in the first 60 meters of the channel, but it is very mild, just 20 cm. Figure 22 shows this area in detail, it can be seen that the erosion took place on the banks of the channel, while the talweg remained unchanged.

3.5 Rehabilitation measures assessment

The implemented measures have been successful to rehabilitate the connectivity of the stream corridor. Figures 23 and 24 show the upstream zone of the diversion channel in two moments: immediately after the completion of construction and once the re-vegetation measures were implemented.

The success of the rehabilitation measures was the result of the fast grow of the vegetation cover in the first two years. Using these as a starting point, native tree species have also been planted more recently.

4 CONCLUSIONS

This work presented the method and results of a hydro-sedimentological study of the diversion of the Corrales Stream in Uruguay. Results showing the hydraulic and sedimentological behavior of the diversion as well as the environmental measures taken during the operation phase have been shown. A good calibration between the results of the hydrologic, hydraulic, and sedimentological models was obtained using stage and flow data available.

The hydrological model was used to select the flood hydrographs and their frequency in the catchment area situated upstream of the diversion. The hydrodynamic model was used to determine

the dimensions of the diversion channel and the elevation of the protection levees. Results obtained with the sedimentological model by formulae of Van Rijn, Engelund-Fredsoe, Engelund-Hansen, Acker-White and Smart-Jaeggi, were similar. The results of the sedimentological model and the surveys after construction of the diversion showed that no significant changes between the situation with and without the diversion exist. The general conclusion it is that the works of diversion will not affect the sedimentological behavior of Corrales Stream in the future.

The implemented models were able to adequately predict the hydrodynamic and sedimentological behavior of the diversion in the case of extreme events. In particular the ones occurred after completion of the works in year 2007 and 2009. Finally, the surveys after mayor flood events showed that the re-vegetation with native species of the embankment slopes and the canal margins was a success.

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