# Decadal river adjustments in response to extensive mining in a sand-bed river

## Ajustements fluviaux décennaux en réponse à l'exploitation minière extensive dans une rivière à lit sablonneux

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## RÉSUMÉ

Cet article présente les résultats d'une recherche à long terme sur les ajustements fluviaux de la rivière sablonneuse La Tordera. Nous résumons les impacts anthropiques les plus importants auxquels la rivière a été soumise, principalement des extractions massives, réalisées entre les années 1960 et le milieu des années 1980. Les résultats de la recherche, réalisée en comparant des profils longitudinaux historiques et des orthophotos, démontrent que : 1) l'incision a atteint des valeurs métriques, dépassant 3-4 m autour de certains ponts. 2) L'érosion du lit de la rivière s'est accompagnée d'une réduction continue de la largeur du chenal, qui, en termes globaux, est passée de 136 m à 98 m de 1945 à 2022. 3) L'érosion généralisée du lit n'est pas terminée malgré les extractions massives terminées il y a plus de 30 ans, mais 4) les taux d'incision ont ralenti depuis 2001. Et 5) la moitié supérieure du cours étudié n'a pas subi d'érosion ou d'accumulation significative, mais la moitié inférieure a continué à s'inciser de 2016 à 2021. Cette tendance générale à la dégradation indique que l'apport de sédiments à la côte continue de diminuer, mais probablement à un rythme plus lent. La dernière grande crue de 2020 a contribué à élargir le chenal mais n'a pas arrêté la dégradation.

## ABSTRACT

This article presents the results of a long-term research on river adjustments in the sandy Tordera River. We summarize the most important anthropogenic impacts the river has been subjected to, mainly massive extractions, carried out from 1960s to mid-1980s. The results of the research, conducted by comparing historical longitudinal profiles and orthophotos demonstrates that: 1) incision has attained metric figures, exceeding 3-4 m around some bridges. 2) River bed degradation has come along with a continuous reduction in channel width, which in global terms, has narrowed from 136 m to 98 m from 1945 to 2022. 3) The generalized bed erosion has not finished despite massive extractions ended more than 30 years ago, but 4) incision rates have slowed down since 2001. And 5) the upper half of the study reach has not eroded or aggraded significantly but the lower half continued incising from 2016 to 2021. This general degrading trend indicates that sediment supply to the coast continues declining but probably at slower rates. The last major flood in 2020 contributed to widen the channel but did not halt degradation.

## KEYWORDS

Channel width, Degradation, Incision, Mining, Rivers

Largeur du chenal, Dégradation, Incision, Exploitation minière, Rivières

## 1 INTRODUCTION, STUDY AREA AND METHODS

The Tordera river basin, with a surface of 860 km$^2$, is located in the North-Eastern corner of the Iberian Peninsula (figure 1a). The Tordera River is 55 km-long and drains the Northern sectors of the Catalan Costal Range, which extends parallel to the Western Mediterranean Sea along 250 km approximately. The highest peaks of the Tordera river basin exceeds 1700 m above sea level and mean annual precipitation ranges from 600 mm near the coast to 1000 mm around the highest mountainous areas.

We have analysed the last 16 km of the Tordera River, from the highway bridge to the mouth, where the river forms a delta (figure 1b). Dominant discharge in this reach has been estimated to be 24 m$^3$/s (Rovira et al., 2005). The latest flood occurred in January 2020, when a peak discharge of 733 m$^3$/s was registered in a gauging station (figure 1b).

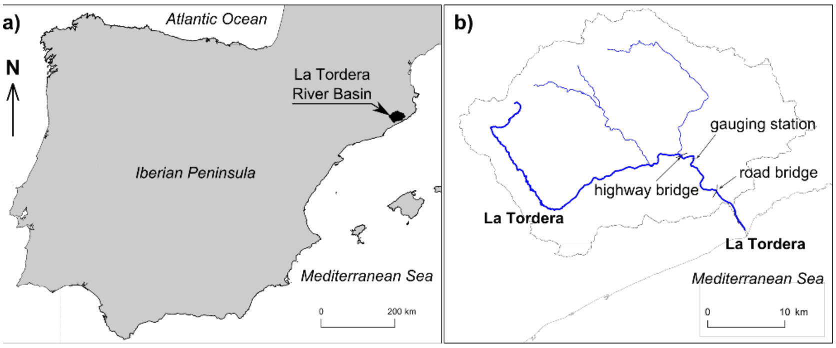


Figure 1. a) General location of the Tordera river basin in the Iberian Peninsula. b) Tordera River (thick blue line), major tributaries (thin blue lines), and location of the gauging station and two significant bridges.

Bed material in the upper part of the river, upstream of the two major tributaries (figure 1b), is composed of a poorly sorted sand-gravel mixture ($D_{50}$ = 34 mm) while sediment in the study reach ranges from fine gravel ($D_{50}$ = 4.5 mm, Rovira and Batalla, 2006) to coarse sand ($D_{50}$ = 1.0 mm, Martín-Vide et al., 2005). However, the proportion of sand on the riverbed dominates. Mean bed slope of the study reach is 0.26%.

Extensive in-stream sand and gravel mining activity was carried out from 1960s to early 2000s: Batalla et al. (2007) documented from the water authorities' archives that 0.75 million m$^3$ were extracted from the riverbed from 1977 to 2004. These figures rises up to 1.5 million m$^3$ if material mined from former floodplains is included. In spite of mining operations lasted until early 2000s, sediment extractions peaked from 1960s to late-1970s and were comparatively lower from late 1970s to 2000s: 17,500 m$^3$ of sediment were mined from 1977 to 2004 (Ferrer-Boix, 2011). Further, although there were some gravel pits upstream of the highway bridge, most of the extractions were carried in the lower sand-bed reaches.

Besides gravel mining, a significant part of the lower Tordera River has been channelized with parallel and adjacent dikes to river bed. These works generally consisted in extracting material from the riverbed itself and partly using it for the dikes (levees). Sometimes these works implied a reduction in the channel width.

As a result of the aforementioned anthropogenic impacts, channel has severely incised and channel width has reduced. The most significant consequence of the incision in the Tordera River is the collapse of the gauging station in 2004: figure 2 (centre) illustrates the scouring at the toe of the structure shortly before its collapse. The gauging station was rebuilt in 2007 at the same place but the concrete base of the station was lowered 1.7 m. The elevation of the gauging station was changed because incision in the adjacent downstream reach was jeopardizing the structure. This episode highlights the long lag times between causes –mining, finished around mid-1980s– and consequences –incision, lasting at least until 2004. Further, recent analyses have found that the Tordera River delta has retreated 200 m from 1945. Delta retreat has been attributed to a reduction in sediment supply towards the coast in response to sediment extractions (Ferrer-Boix et al., 2023).

We have analysed the morphological adjustments in the Tordera River by comparing historical longitudinal profiles along the thalweg. We have topographical information from 1920, 1973, 1987, 1996 and 2007. Further, we have delineated detailed longitudinal profiles from DEMs from 2001, 2016 and 2021. These DEMs have also been used to compute changes in sediment volume, and we have distinguished changes on the bed and bank retreats. The 16 km-long reach has been divided into 13 reaches and we have computed the average change in bed elevation in those reaches. We have estimated the streamwise changes in channel width from historical orthophotos from 1945 to 2022.

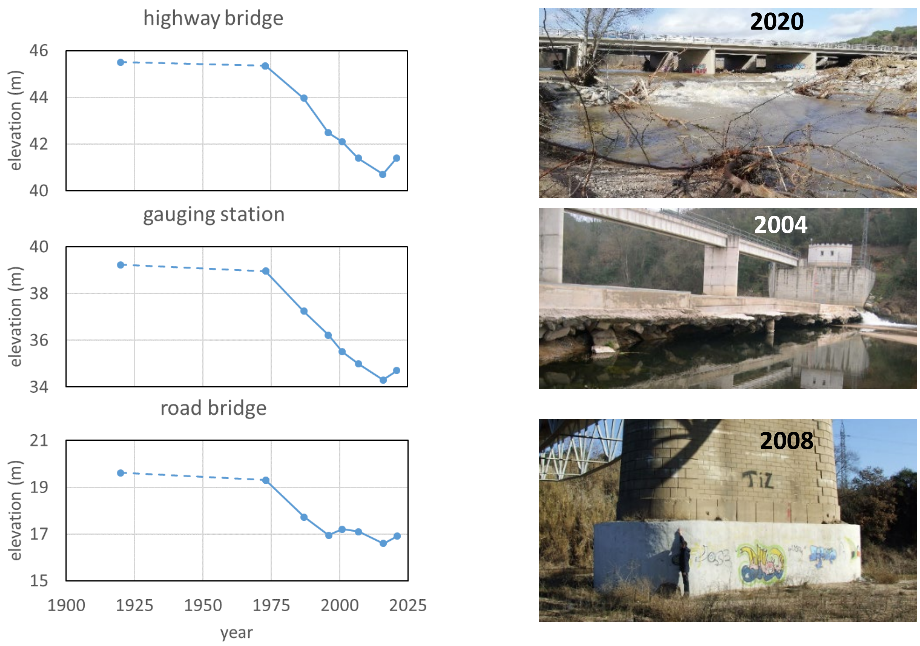


Figure 2. Evolution of the bed elevation at the highway bridge, at the gauging station and at the road bridge (see planform location in figure 1). These structures are located at the following streamwise coordinates, respectively: 22.7 km, 24.9 km and 31.6 km. The river mouth is located at the streamwise coordinate 38.7 km (figure 3). The photographs on the right illustrate the incision at these particular locations. In all images, flow is from left to right. In the upper-right image, aeration (foam) at the back of the image indicates the flowing water over the protecting riprap at the toe of the bridge. In the lower-right photograph, the riverbed when the bridge was built in the 1940s was right above the lighter area at the base of the pier.

## 2 PRELIMINARY RESULTS

We use the vertical evolution of the bed at the three most significant structures crossing the river in figure 2 as indicator of the general degradation in the river. We have displayed the bed elevation trajectories from 1920-1973 in figure 2 with dashed lines since we do not have topographical information of the bed in this nearly 50 years-long period and because the data from 1920 might have low accuracy.

Data in figure 2 show that bed started degrading a few years after the commencement of mining activity, was definitively noticed in 1987, right when major extractions finished, but more importantly, continued for more than three decades after this time. There is a trend difference between the upper two structures and the road bridge from 1996 to 2016: while incision continued in the uppermost two structures, bed elevation at the road bridge did not varied much in this period (although some degradation was noticed from 2007 to 2016). In contrast, bed aggraded everywhere from 2016 to 2021, most likely in response to the major flood in 2020.

Table 1. Temporal evolution of the mean channel width W.

| | 1945 | 1956 | 1970 | 1975 | 1977 | 1986 | 1990 | 1994 | 2000 | 2004 | 2009 | 2011 | 2016 | 2019 | **2020** | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W (m) | 136 | 123 | 127 | 111 | 111 | 105 | 104 | 100 | 92 | 89 | 80 | 85 | 76 | 77 | **105** | 98 | 98 |

Parallel to bed incision, the Tordera River has experienced a continuous reduction in channel width since mid-20$^{th}$ century (Table 1): channel width narrowed by 28% from 1945 to 2022. Channel only widened as a result of the last major flood in 2020, when the mean channel width in the entire study reach increased by 36%, from 77 m to 105 m (Table 1). Note that the river recovered in 2021 the 1986 channel width, when extractions ended.

Bed evolution from 2016 to 2021 at the structures in figure 2 would indicate that the 2020 flood shifted the past incising trend first noticed in 1973. However, results of the change in sediment volume obtained from the DEMs from 2001, 2016 and 2021 depict a more complex evolution (figure 3). When analysing the changes in sediment volume from 2001 to 2016, results indicate the entire channel (including both bed and bank retreat) lost 176,000 m$^3$ of material (11,700 m$^3$/year). Note that figure 3 illustrates changes in sediment volume per unit reach length. However the bed region itself eroded by 356,000 m$^3$ (23,700 m$^3$/year). Overall, mean bed elevation (obtained as the ratio of the sediment volume in the bed region in the entire study reach over the corresponding bed area) lowered 24 cm from 2001 to 2016. This result is generally in agreement with bed trajectories in figure 2.

The same volumetric analysis for the period between 2016 and 2021 results in 97,900 $m^3$ of material eroded from the bed (at a mean yearly rate of 19,600 $m^3$) and 494,000 $m^3$ if bank retreat is included (98,800 $m^3$/year). These figures indicate that mean bed erosion in the entire study reach was 6.5 cm during these five years. Although it would seem that this result partly contradicted the bed elevation results at pointwise scale in figure 2, in fact, both results are compatible given that thalweg may well rise while riverbed, in general, keeps on eroding.

It is clear from results in figure 3a that, in general terms, Tordera River continued losing material until 2016. Further incision was widespread from the highway bridge to the road bridge from 2001 to 2016 while sediment accumulated only on a comparatively short reach downstream of the road bridge (red line, figure 3a). From this bridge to the mouth, bed material mostly accumulated along the riverbanks (thick blue line, in the same figure).

The bed region upstream of the road bridge did not experience much changes in sediment volume from 2016 to 2021 (red line, figure 3b). However, extensive bank erosion occurred in these reaches (thick blue line in the same figure), most likely in response to the large flood in 2020 (similar result in Table 1). In contrast with the trend in this upper reach, reaches downstream of the road bridge mostly incised (red line, figure 3b) despite the bank erosion in the lowermost 2 km-long reach (thick blue line, in the same figure).

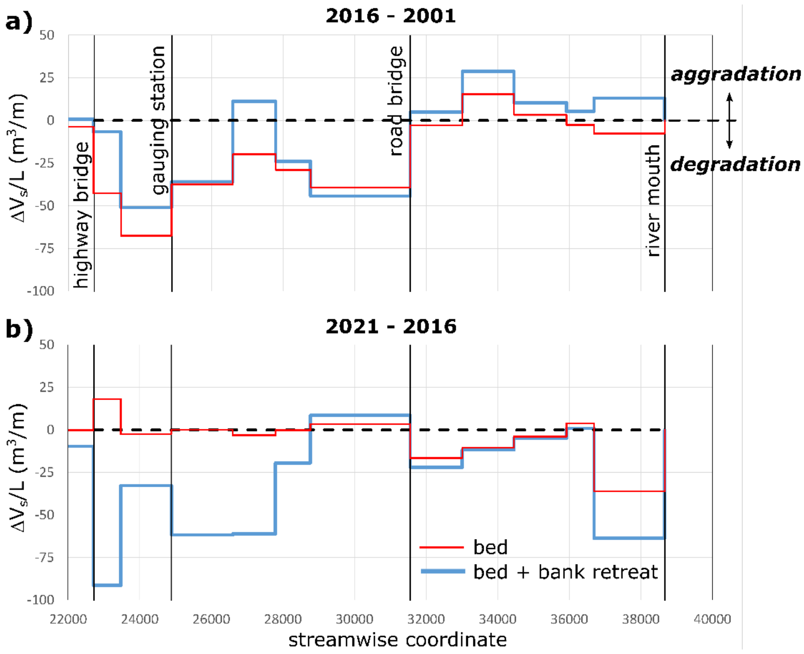


Figure 3. Streamwise distribution of the mean change in sediment volume per unit length $\Delta V_s/L$ along the study reach. a) Results for the 2001-2016 period (15 years) and b) Results obtained from 2016 to 2021 (5 years). In both panels, the blue line represents the change in sediment volume in the entire reach, i.e. including both changes in the bed and the banks, while the red line only accounts for the volume changes in the bed region.

## LIST OF REFERENCES

Batalla, R. J., Ferrer Boix, C., Martín-Vide, J. P., and Rovira, A. 2007. Guidelines for fluvial sediment management. Hydrosedimentary dynamics of the Tordera River. Technical Report for the Catalan Water Authority (in Catalan).

Ferrer-Boix, C. 2011. River incision by gravel mining and dam removal: Mathematical and experimental study, PhD Thesis, Universitat Politècnica de Catalunya, available at: http://hdl.handle.net/2117/376080 (in Spanish).

Ferrer-Boix, C., Martín-Vide, J. P., Prats-Puntí, A., and Saéz Elvira, A. 2023. Effects of alluvial mining on the river and the coast. The example of the Tordera River. Atzavara, 33, 55-61, doi: 10.2436/20.1502.atz33.055 (in Catalan).

Martín Vide, J. P., Batalla, R. J., Roca Collell, M., Rovira, A. and Andreatta, A. 2005. Incision, transient scour and bedforms in the middle and lower Tordera river. Ingeniería del Agua, 12(1), 53-62 (in Spanish).

Rovira A., and Batalla, R. J. 2006. Temporal distribution of suspended sediment transport in a Mediterranean basin: The Lower Tordera (NE SPAIN), Geomorphology, 79, 58-71.

Rovira, A., Batalla, R. J. and Sala, M. 2005. Fluvial sediment budget of a Mediterranian river: the lower Tordera (Catalan Coastal Ranges, NE Spain). Catena, 2005, 60, pp. 19-42.