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Calculation of Sediment Delivery from the Guadiana Estuary to the Coastal

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ABSTRACT

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A study has been conducted to provide updated estimates (period 1980-2000) of the transfer of sedimentary material from the Guadiana river (SW Europe) to the coastal ocean, focusing on the role played by the estuarine system. The discharge of fine suspended sediment from the river to the estuary has been calculated based on measured data and compared with previous estimates. Numerical models of cohesive and non-cohesive sediment transport have been used to provide order of magnitude estimates of sediment fluxes from the estuary to the continental shelf for different freshwater flow scenarios. Episodic flood events play a crucial role in the discharge of sediment from the Guadiana river to the coastal ocean. Apparently, the estuary retains only a minor share (about 10%) of the total amount of fine-grained sediment produced in the drainage basin, which is presently estimated at 0.5-1.5 x 10^6 t $year^{-1}$. Based on the calculation of sediment transport capacities, it is estimated that the order of magnitude of the transfer of sand from the estuary to the coastal region is 0.1 x 10^6 m^3 $year^{-1}$, which seems in agreement with the recent pattern of shoreline evolution.

ADITIONAL INDEX WORDS: *Fine sediment, sand, river basin, estuary, coastal evolution.*

INTRODUCTION

Dams in a river basin can reduce the sediment supply to the coastal zone through the effects of sediment retention in the reservoirs and alteration of the flow regime (*e.g.* reduction in the frequency of high flows). Dams can also cause a morphological response downstream, which is more difficult to predict, since it depends on the relative importance of the reduction in transport capacity (accretion trend) and the reduction in sediment supply (erosion trend).

Many studies have examined the actual impact of large dams on sediment transport and morphology in rivers, estuaries and coastal areas (*e.g.* GUILLÉN and PALANQUES, 1992; HAY, 1994; FANOS, 1995; MILLIMAN, 2001; PANIN and JIPA, 2002; SNOUSSI *et al*., 2002; YANG *et al*., 2002). The findings from these studies indicate that the impact is often of significant magnitude, particularly in the Mediterranean and other semi-arid regions.

This study examines sediment transport patterns and fluxes in the Guadiana, a semi-arid river basin in SW Europe. Estimates of the transfer of sedimentary material to the estuary and the coastal zone are calculated for the period 1980-2000. This 'reference situation' is expected to differ both from near-pristine conditions and from future conditions. Dam construction and associated changes in land use took place since the 1950s. The Alqueva dam, completed in 2002, and other dams planned or under construction will further modify the river basin in the future.

STUDY AREA

The drainage basin of the Guadiana river is the fourth largest in the Iberian Peninsula, covering an area of about 67 000 km^2 (83% in Spain and 17% in Portugal). The river is 810 km long, rising at an altitude of 1700 m in southeastern Spain, and flowing west and southwards to the Atlantic Ocean (Figure 1).

The estuarine reach, defined by the limit of tidal propagation (near Mértola), is 70 km long. It is divisible into an upper estuary (Mértola to Odeleite), a middle estuary (Odeleite to Beliche) and a lower estuary (Beliche to mouth of estuary) (MORALES, 1995). The upper and middle estuaries consist of a relatively narrow valley, dominated by metamorphic formations. In the lower estuary, 10 km long, the valley opens into a coastal plain, with a large eye-shaped area of marsh and barrier islands at the seaward end (GONZALEZ *et al*., 2000).

Since the 1950s, nearly 100 large dams have been built in the river basin. At the end of the reference period (2000), the storage capacity of the reservoirs was 9.1 x 10^9 m^3 in the Spanish part of the basin and only 0.5 x 10^9 m^3 in the Portuguese part. In 2002, the Alqueva dam increased the storage capacity in the Portuguese basin by 4.2 x 10^9 m^3. By way of comparison, between 1980/81 and 1999/2000, the mean annual runoff at Pulo do Lobo (91% of the river basin) was 2.6 x 10^9 m^3 (ALVES *et al*., 2001).

At the end of the reference period (2000), dams controlled approximately 70% of the total watershed area. In 2002, the Alqueva dam (which alone controls 82% of the watershed area), added to the dams downstream (*e.g.* Chanza dam), increased the total area under control to more than 85% (ALVES *et al*., 2001; PORTELA, 2003).

A significant change in land use, from the point of view of the impact on water and sediment fluxes, which is partly related to the building of dams, has been the development of irrigation in the Spanish basin, particularly since the 1970s.

METHODS

The methodology used in this study involved: (a) analysis of field data on water flows and suspended sediment concentrations; and (b) application of numerical models of cohesive and non-cohesive sediment transport in the estuary.

River flow was examined using the mean daily values measured at Pulo do Lobo (91% of the drainage basin) from 1946/47 to 1999/2000 (source: SNIRH, Portugal).

The suspended load entering the estuary was examined using data from Pulo do Lobo (fluvial section), Alcoutim and Sanlúcar (upper estuary section). The data from Pulo do Lobo (source: SNIRH, Portugal) cover a short period (1981-1985), but allow a useful comparison with the tidal section. The data from Alcoutim (source: SNIRH, Portugal) refer to the period 1990-1999 and the data from Sanlúcar (source: Rede COCA, Spain) to the period 1980-1996. Bed load measurements were not available.

Numerical modelling was carried out on a 2D regular grid

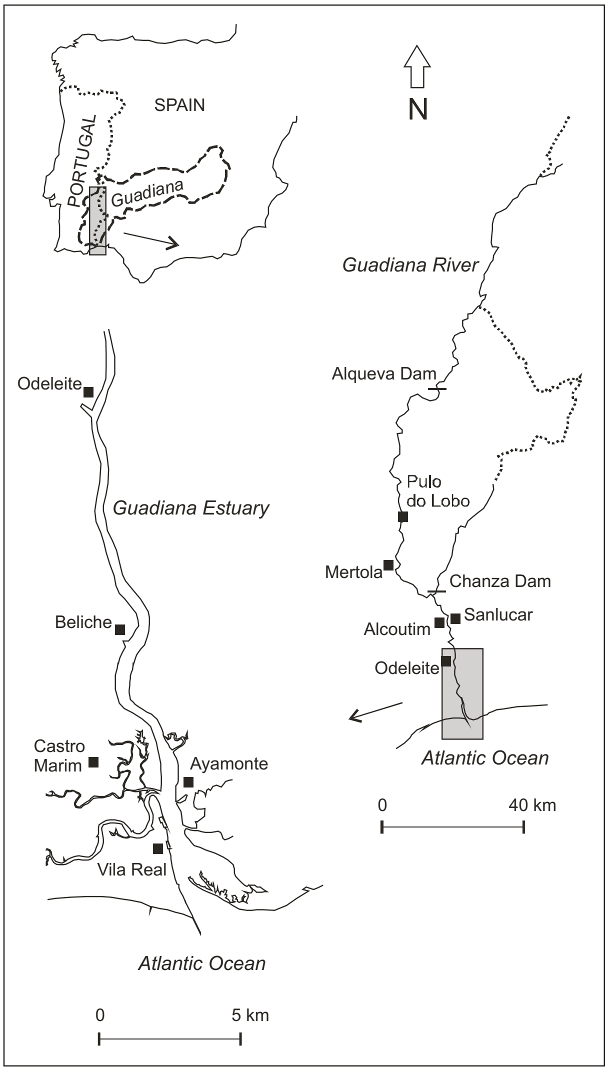

Figure 1. Location maps of the Guadiana river basin (upper left), lower Guadiana river and estuary (right) and detail of the middle and lower estuary (lower left).

(space step of 100 m) covering the lower estuary and the inner shelf, with an additional 1D grid covering the middle and upper estuaries. Tidal levels were specified at the ocean boundary of the hydrodynamic model, and discharge, according to frequency, at the upstream boundary.

In the cohesive sediment model, the critical shear stresses for erosion and deposition were set to 0.6 Pa and 0.1 Pa and the erosion rate to 1 x 10^{-5} kg m^{-2} s^{-1} (mud deposits). Based on an experiment with suspended sediment collected in the estuary (PORTELA, 2001), the settling velocity was chosen as 0.02 mms^{-1}. Suspended sediment concentrations upstream were defined according to the relative frequency of observations at Alcoutim and Sanlúcar (10th and 90th-percentile value).

In the non-cohesive sediment model, based on the Ackers-White formulation, the characteristic diameter (D_{35}) was chosen as 0.350 mm, in agreement with the grain-size distributions of bottom samples (sand deposits) (FONSECA *et al*., 2001). A porosity of 40%, equivalent to an apparent dry density of 1590 kg m^{-3}, was assumed for mass to volume conversions.

RESULTS AND DISCUSSION

River Flow

The mean river flow at Pulo do Lobo in the period from 1946/47 to 1999/2000 (full series) was 142 m^3 s^{-1}, with distinct seasonal (winter maximum) and inter-annual variation. However, a comparison of the period from 1946/47 to 1979/80 (closer to natural conditions) with the period from 1980/81 to 1999/2000 (after construction of several dams and irrigation schemes) reveals a reduction in the mean river flow from 177 m^3 s^{-1} to 82 m^3 s^{-1} (ALVES *et al*., 2001).

A simple calculation of areal rainfall in the Portuguese basin indicates that the rainfall difference between the two periods is smaller than 10%. Thus, the main explanation for the dramatic decrease in river flow (above 50%) is increased evapotranspiration due to the development of irrigation schemes and reservoir evaporation. Irrigation in the Spanish basin makes intensive use of both surface and groundwater (BELTRÁN, 1996), and this use has led to a marked decline in groundwater levels in the upper basin since the 1970s (FORNÉS *et al*., 1998).

Suspended Load

At Pulo do Lobo, suspended sediment measurements (n = 33) varied between 8 mg l^{-1} and 1398 mg l^{-1}, for river conditions ranging from no flow to 4043 m^3 s^{-1} (data biased towards high flows: average concentration of 156 mg l^{-1} and average discharge of 332 m^3 s^{-1}). The correlation of river flow and suspended sediment indicates that the long-term suspended load is dominated by episodic flood events.

Suspended sediment concentrations at Alcoutim (n = 90) varied between 4 mg l^{-1} and 604 mg l^{-1}, for river conditions ranging from no flow to 2619 m^3 s^{-1} (average concentration of 48 mg l^{-1} and discharge of 86 m^3 s^{-1}). Suspended sediment at Sanlúcar (n = 158) varied between 3 mg l^{-1} and 1940 mg l^{-1}, for river conditions ranging from no flow to 2851 m^3 s^{-1} (average concentration of 100 mg l^{-1} and discharge of 97 m^3 s^{-1}). The results of these stations also concentrate a high percentage of the suspended load in a small number of days of high flows (Figure 2). At Alcoutim, more than 75% of the total suspended

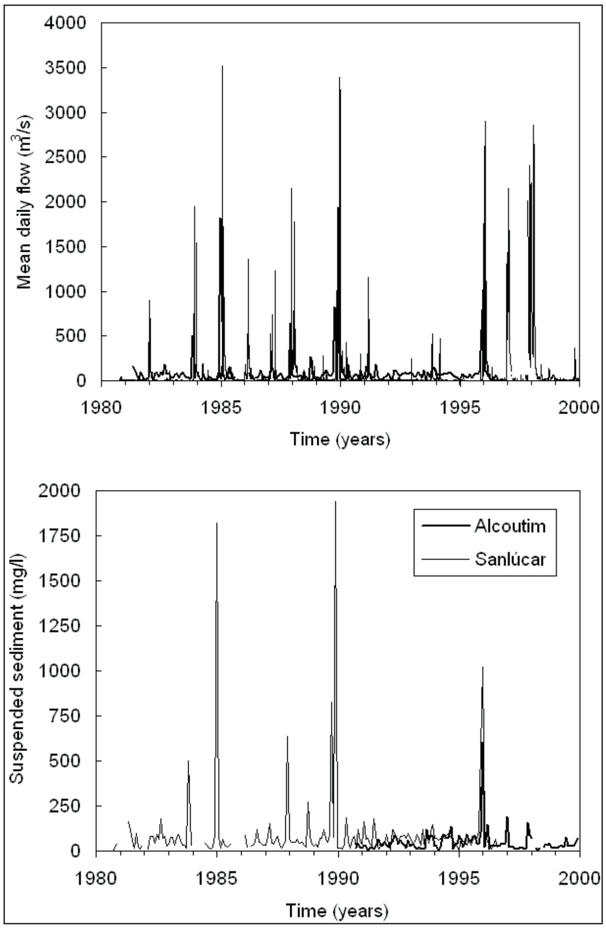

Figure 2. Mean daily flow at Pulo do Lobo (river section) and suspended sediment concentrations at Alcoutim and Sanlúcar (upper estuary) between 1980 and 2000.

load corresponds to one observation (equivalent to 0.1 x 10^6 t in a single day). At Sanlúcar, more than 40% of the total corresponds to one observation (equivalent to 0.5 x 10^6 t in a single day) and more than 80% corresponds to three observations.

Simple linear regression provided good correlations between discharge at Pulo do Lobo and suspended sediment concentrations at Pulo do Lobo (PL), Alcoutim (A) and Sanlúcar (S):

$$C_s^{PL} = 0.3290Q + 46.3 \quad (r^2 = 0.74) \quad (1)$$

$$C_s^{A} = 0.1853Q + 32.1 \quad (r^2 = 0.74) \quad (2)$$

$$C_s^{S} = 0.5681Q + 49.7 \quad (r^2 = 0.74) \quad (3)$$

where C_s is the concentration of suspended sediment (mg l^{-1}) and Q is the river discharge (m^3 s^{-1}). It is interesting to notice that the results from the river station and the upper estuary stations are comparable, in spite of tidal effects in the latter.

Sediment discharge was also calculated as a function of river discharge according to the traditional power law. Using only the data for discharge above 100 m^3 s^{-1}, the exponent values were around the typical value of 2:

$$Q_s^{PL} = 0.00014Q^{2.12} \quad (r^2 = 0.97) \quad (4)$$

$$Q_s^{A} = 0.00012Q^{2.05} \quad (r^2 = 0.86) \quad (5)$$

$$Q_s^{S} = 0.00035Q^{2.01} \quad (r^2 = 0.85) \quad (6)$$

where Q_s is the sediment discharge (kg s^{-1}) and Q is the river discharge (m^3 s^{-1}). Using all the data, the exponents decreased to 1.4 at the riverine station of Pulo do Lobo (PL) and to 1.1-1.2 at the tidal stations of Alcoutim (A) and Sanlúcar (S).

Based on the series of river flow in the period from 1980/81 to 1999/2000, the mean annual suspended sediment load in the 'reference situation' was estimated using the linear regression equations, Eqs. 1, 2 and 3. The following results were obtained: 0.9 x 10^6 t $year^{-1}$ at Pulo do Lobo; 0.5 x 10^6 t $year^{-1}$ at Alcoutim; and 1.5 x 10^6 t $year^{-1}$ at Sanlúcar. This range of values (0.5-1.5 x 10^6 t $year^{-1}$) is consistent with previous estimates by MORALES (1995) and ALVES *et al*. (2001).

To analyze the effect of the alteration of the flow regime, it has been assumed that the same equations could be applied to the river flow series in the period from 1946/47 to 1979/80. On the basis of this assumption, it has been found that the suspended load may have suffered a reduction of nearly 70% regarding more natural flow conditions (range of values of 1.6-4.6 x 10^6 t $year^{-1}$ in the period 1946-1980).

It is interesting to notice that, by examination of sediment production in the river basin and the effect of retention in the reservoirs, ROCHA and BELO (1995) had previously estimated a similar reduction (70%) between 'natural' conditions and the situation in 1994. It is not clear how the two effects, alteration of the flow regime and sediment retention, should combine (*e.g.* sediment mobilization downstream may partly compensate sediment trapping in the reservoirs). It seems reasonable to conclude that the suspended load may have been reduced by 70%, though the possibility of a more severe reduction cannot be excluded. The impact of Alqueva, completed in 2002, and other dams planned or under construction, is not taken into account in this estimate.

Fine Sediment Transport in the Estuary

Estuaries are depositional environments, controlled by tidal, river and wave processes. It is important to consider in more detail these processes, and their influence on sediment transport, in order to assess the proportion of the river suspended load that is retained within the estuary.

For low river flows, the transport of fine sediment in the estuary is determined by tidal currents (and, to a lesser extent, by locally generated waves). The tidal regime is semi-diurnal with currents of the order of 1.0 m s^{-1}, modulated by the spring-neap cycle (SANTOS *et al*., 2002). The available data suggest the existence of a turbidity maximum near Odeleite at spring tide, characterized by suspended sediment concentrations of 100 mg l^{-1}. However, this turbidity maximum is not very well defined, possibly owing to the small importance of mud deposits in the upper and middle estuaries (PORTELA, 2003).

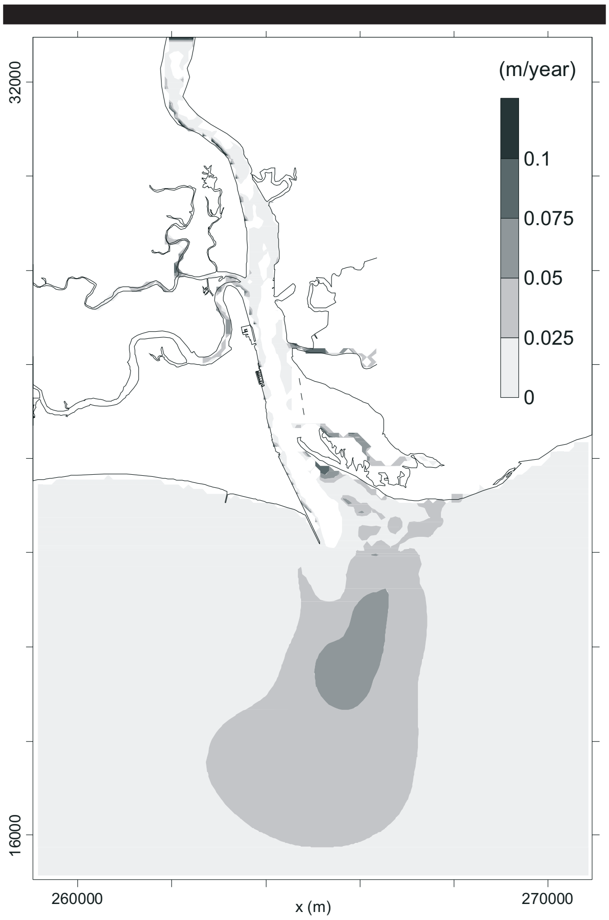

Figure 3. Simulation of cohesive sediment deposition (m $year^{-1}$) in the lower estuary and inner shelf for a river flow of 634 m^3 s^{-1} and mean tidal range.

Recent measurement campaigns (SILVA *et al*., 2001) have shown that, during flood events, a large amount of fine sediment reaches the middle and lower estuaries. In these events, the concentration of suspended sediment is uniformly high in the whole estuary (of the order of 1000 mg l^{-1}). Near the mouth, surface concentrations can be higher than bottom concentrations as a result of stratified flow, and a turbid plume is present on the inner shelf (SILVA *et al*., 2001).

A cohesive sediment transport model was applied, in an attempt to estimate the fraction of fine suspended sediment retained in the estuary and the fraction supplied to the shelf.

The results indicate that, in the lower estuary, the conditions are not favourable for deposition, except along the margins and in the marsh systems. In the main channel, where currents are stronger, the surface sediment is mainly composed of sand. In the high flow scenario, though failing to take into account wave effects, the model predicts the formation of a mud patch off the Guadiana (Figure 3), which is roughly in agreement with the mapping of the sediment of the continental shelf (DIAS *et al*., 2000).

Weighting the model results obtained for three-river flow and suspended sediment scenarios (bounded by the 10th and 90th-percentile values), the fraction of fine sediment entering the estuary that reaches the shelf was estimated to be about 90% (PORTELA, 2001).

Bed Load

Field measurements of bed-load transport are not available.

Table 1. *Non-cohesive sediment transport capacity in the lower estuary in the 'reference situation' (1980-2000).*

Q ($m^3 s^{-1}$)	Q_s ($kg s^{-1}$)	Weight	Weighted Q_s ($kg s^{-1}$)
7	1.5	0.50	0.737
35	2.9	0.40	1.144
220	11.8	0.05	0.590
810	37.9	0.04	1.517
2074	120.8	0.01	1.208
Average Q_s		($kg s^{-1}$)	5.196
		($m^3 year^{-1}$)	103050

Instead, a non-cohesive sediment transport model has been used to calculate the sediment transport capacity in the lower estuary, for different river flow scenarios. For low flows, the residual transport of sediment that results from tidal currents is relatively unimportant. For flows of the order of 1000 $m^3 s^{-1}$, the sediment transport capacity increases markedly during ebb (Figure 4). For flows of the order of 5000 $m^3 s^{-1}$, the transport capacity is directed seawards during the complete tidal cycle.

The model results suggest that the sediment transport capacity in the lower estuary in the period 1980-2000 was of the order of 0.1 x 10^6 $m^3 year^{-1}$ (Table 1). Transport capacity does not necessarily correspond to effective transport. However, taking into account the sediment budget of the mouth of the Guadiana and the morphological evolution of the adjacent coastal zone (VICENTE and PEREIRA, 2001), the estimate seems a reasonable upper limit of the bed-load transport rate. As a term of comparison, several authors have estimated the longshore sediment transport rate, from west to east, to be about 0.05-0.3 x 10^6 $m^3 year^{-1}$ (VICENTE and PEREIRA, 2001).

To analyze the effect of the alteration of the river regime, freshwater flow scenarios corresponding to the period 1946-1980 were simulated. It has been found that the sediment transport capacity in the lower estuary may have suffered a reduction of nearly 60%.

Considering only the effect of sediment retention in the reservoirs, ROCHA and BELO (1995) also estimated a large reduction of sand supply (82%) between 'natural' conditions and the situation in 1994.

Estuarine and Coastal Evolution

The entrance of the Guadiana estuary is stabilized by two jetties, constructed between 1972 and 1976. The construction of the jetties led to a pronounced morphological evolution of the ebb shoal and the shoreline, still in progress (VICENTE and PEREIRA, 2002). Therefore, the influence of changes in river flow and sediment transport regimes on shoreline evolution is not easily identifiable.

The information available on the evolution of the estuary in the last 50 years, analyzed by GONZALEZ *et al*. (1999, 2000), suggests that the alteration of the flow regime caused by the construction of dams has resulted in increased accumulation of sediments at the mouth. The reduction of the sediment transport capacity may have influenced the evolution of the eastern margin, which occurred before the construction of the inlet jetties, characterized by the development of the eastern sand spit towards the estuary. This evolution was accompanied by a reduction of the width of the main channel (GONZALEZ *et al*., 2000).

In the outer zone, subject to large variability determined by wave conditions and river flow, the ebb shoal appears to have experienced net erosion before the construction of the jetties. This process could also be associated with dam construction, being in this case more important the effect of reduction of sediment supply (GONZALEZ *et al*., 1999).

CONCLUSIONS

Sediment transport in the Guadiana estuary has been examined in this paper, with particular reference to sediment supply to the coastal ocean. The analysis has been focused on a 'reference situation', the period 1980-2000, when significant structural changes had already occurred in the river basin.

The following conclusions can be drawn:

1. A comparison of the period 1946-1980 (small number of dams) with the period 1980-2000 (large number of dams and irrigation schemes) reveals a reduction in the mean river flow from 177 $m^3 s^{-1}$ to 82 $m^3 s^{-1}$ (ALVES *et al*., 2001).
2. Although episodic, flood events play a crucial role in the supply of sediment (fine- and coarse-grained) from the Guadiana river and estuary to the continental shelf.
3. The mean annual supply of fluvial fine-grained sediment to the estuary has been calculated at 0.5-1.5 x 10^6 t $year^{-1}$ in the period 1980-2000. The amount that reaches the coastal ocean has been estimated to be about 90%, the remaining fraction being retained in the estuary.
4. Based on the alteration of the flow regime, it is calculated that the fine sediment load may have suffered a reduction of nearly 70% regarding the period 1946-1980.
5. According to model results, the sediment transport capacity of coarse sediment in the lower estuary in the period 1980-2000 was of the order of 0.1 x 10^6 $m^3 year^{-1}$.
6. Based on flow regime, it is calculated that the sediment transport capacity in the lower estuary may have suffered a reduction of nearly 60% regarding the period 1946-1980.
7. New dams and irrigation schemes, including the Alqueva dam, completed in 2002, will further impact the water and sediment fluxes in the future.

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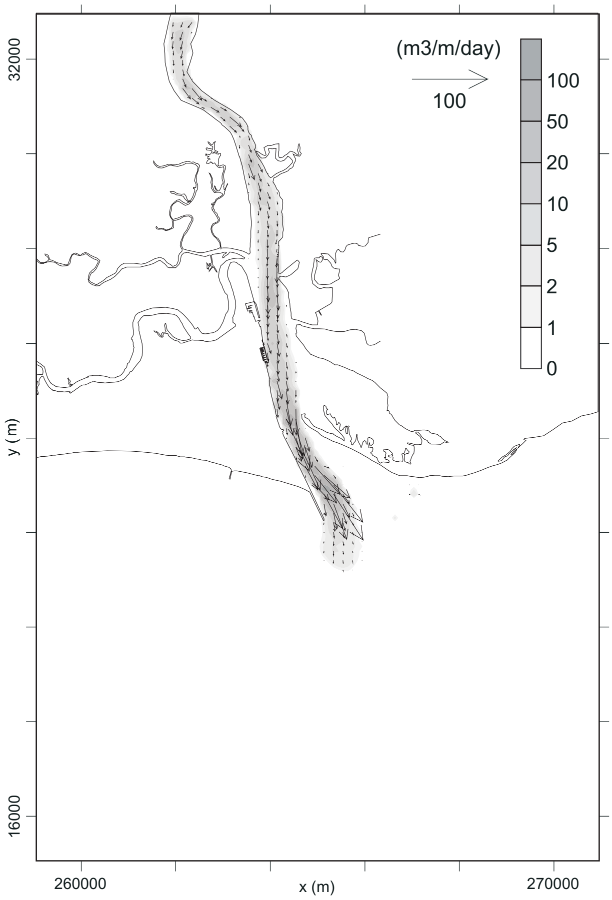

Figure 4. Simulation of non-cohesive sediment transport capacity ($m^3 m^{-1} day^{-1}$) in the lower estuary for a river flow of 1000 $m^3 s^{-1}$ at maximum ebb (mean tidal range).

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