Long-term variability of sediment transport in the Ombrone River basin (Italy)

ANNA FRANGIPANE & ENIO PARIS

Department of Geosciences, University of Udine, Via Cotonificio 114, I-33100 Udine, Italy

Abstract The effects of human activity on rivers may considerably affect water and sediment regimes. Long-term changes can also be produced when modifications at a basin scale affect the runoff processes and sediment productivity. Variations in land use due to agriculture, forestry and grazing are probably the most important factors in generating changes in the fluvial system. A preliminary analysis of these effects has been carried out in a study of the Ombrone River basin, central Italy. The availability of historical data on sediment deposition of the river generated by a land reclamation system, together with hydrological data, allow the calibration of a simple sediment balance model able to simulate the annual sediment yield of the river since 1830. Results show a considerable reduction of sediment transport over the last 140 years, together with important land use changes in the same period.

INTRODUCTION

Natural water courses convey liquid and solid material originating from drainage basins. The amounts, and their distribution in time and space depend upon the hydrologic and sedimentologic processes occurring in the drainage network or, more generally, on the characteristics of climate, geology, geomorphology, tectonics and vegetation of the basin. However, human activity can considerably affect these processes, either directly through regulation or training works in the rivers, or indirectly as extensive modifications at a basin scale, such as land use, forestation and deforestation and hill slope stabilization. We can assume that the characteristics of a drainage network, like its structure and evolution, depend on two categories of factors: environmental and anthropogenic factors (Fig. 1). Modification in one or both of these factors inevitably leads to modifications in the characteristics of the sediment and water regimes in the water courses.

The effects of direct human activity on alluvial rivers by have been analysed by several authors: Straub (1934), Janssen *et al.* (1979), Paris (1984) and Jaeggi (1992). On the other hand, the consequences of extensive human activity on river regimes at a basin scale have been less studied; some contributions can be found in Douglas (1967), Wolman & Schick (1967), Gregory & Madew (1982) and Leeks & Roberts (1987).

The historical evolution of fluvial regimes can be rarely identified because of a lack of long-term data, particularly on sediment transport. However, in some favourable situations it is possible to evaluate the temporal evolution of fluvial

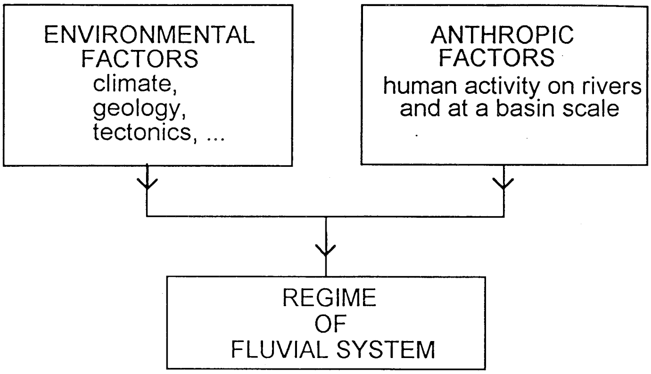

Fig. 1 Factors affecting the regime of natural water courses.

processes due to the availability of historical data; this is the case for the River Ombrone drainage basin, located in the centre of Italy, south Tuscany, (Fig. 2). Here, an important land reclamation project started in 1830, was based on the possibility of filling the area by the sediment deposition obtained by conveying water and its suspended load through a diversion channel water from the River Ombrone. The total land extension was approximately 70 km^2, and reclamation was terminated in 1955.

THE STUDY AREA

The Ombrone basin has a drainage area of 3500 km^2, an average relief of approximately 250 m and the annual precipitation is approximately 800 mm. The main river extends from the Appennines to the Tirreno Sea, with a length of about 130 km. Water courses are typically gravel-bed rivers with a flashy flood regime. Soils are mainly characterized by incoherent and pseudo-coherent deposits of Pliocene marine sediments and Pleistocene alluvial sediments; about 25% of the basin is underlain by coherent rocks, mainly limestone and schist. Land use and its changes are outlined in Table 1 (Regione Toscana, 1991).

ANALYSIS OF THE AVAILABLE DATA

Hydrologic data are regularly collected by Servizio Idrografico; daily discharge values are available at the gauging station of Sasso d'Ombrone from 1926 (Fig. 2). At the same station, daily suspended load has also been collected for the period 1952-1973. The average sediment load for the period is 1 000 000 m^3 per year. The flow duration curve for the entire period of record is shown in Fig. 3.

FRAMEWORK OF ANALYSIS

Water and sediment from the Ombrone River were directed through the diversion channel, located about 25 km upstream from the river mouth. A system of six off-take

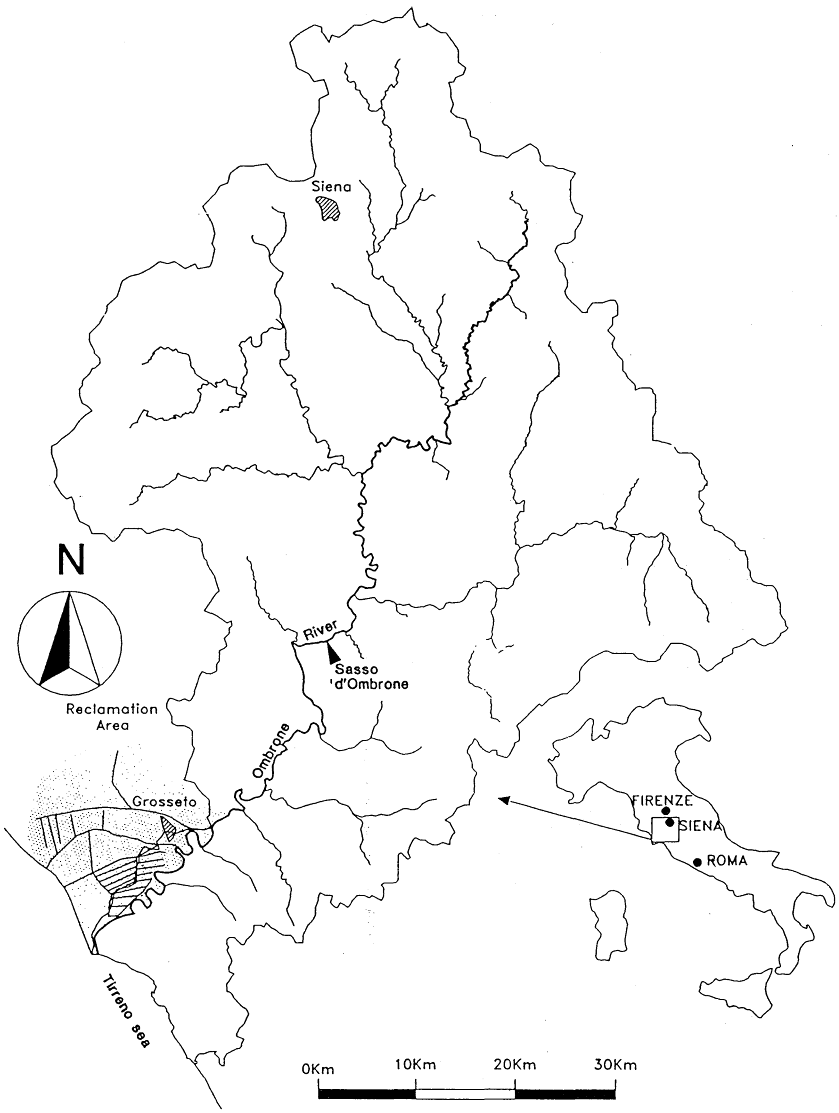

Fig. 2 The drainage basin of the River Ombrone, Italy.

Table 1 Land uses in the Ombrone River basin.

Land use	1829	1991
Urbanized (%)	2.5	3.0
Agriculture (%)	28.0	48.0
Grazing (%)	37.0	7.0
Forest (%)	29.0	40.0
Others (%)	3.5	2.0

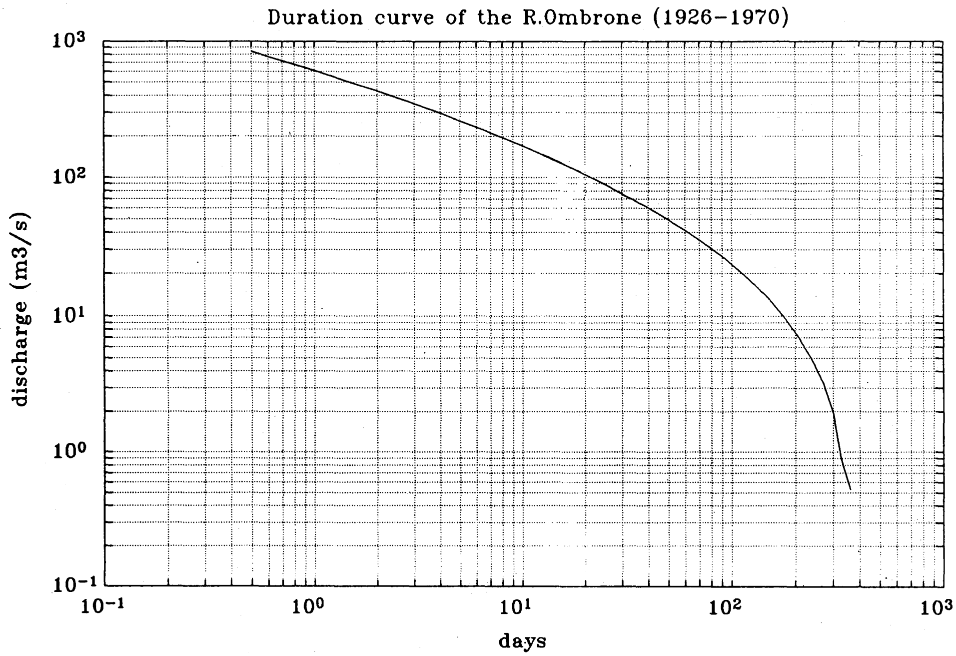

Fig. 3 Duration curve for the Ombrone River in the period 1926-1973.

sluices regulated the discharge in the channel in such a way that the behaviour of the diversion channel can be schematized as follows:

$$Q_{d_i} = Q_i \quad \text{if} \quad Q_i < Q_{d_{\max}}$$

$$Q_{d_i} = Q_{d_{\max}} \quad \text{if} \quad Q_i \geq Q_{d_{\max}}$$

where $Q_{d_{\max}}$ is the maximum capacity and Q_{d_i} and Q_i denote the daily discharge in the diversion channel and in the river, respectively. The channel hydraulic capacity, and its temporal variation due to change in shape and slope caused by the progressive silting and maintenance works, is known from historical documents. It has varied from a maximum of about 600 $m^3 s^{-1}$, to a minimum of 100 $m^3 s^{-1}$. Moreover, historical data on the progressive silting provide the quantities of sediment deposited in the reclamation area as indicated in Table 2.

Table 2 Observed volume of deposits in the reclamation area.

Period	Volume (m^3 10^6)
1830-1834	24.0
1835-1859	102.0
1860-1871	47.0
1925-1929	5.0

To simulate the processes of suspended sediment transport in the river and the diversion channel, the following is assumed:
(a) the duration curve of the period 1926-1973 applies to the whole period;
(b) the relationship for sediment transport is of the form:

$$Q_s = aQ^k \tag{1}$$

where Q_s is the suspended solid discharge in $m^3\ s^{-1}$, Q is the discharge in $m^3\ s^{-1}$, and a and k are two constants to be defined from the available data.

It is possible to estimate the annual sediment transport rate for the river in the period 1830-1955; for this purpose, a simple sediment balance model can be described as follows.

First, from suspended sediment data for the period 1952-1973, more than 100 events ranging from high to low flow conditions, have been selected and plotted (Fig. 4), where the suspended volume is related to water discharge according to equation (1). Notwithstanding the scattering, a significant correlation can be seen, particularly for higher values of Q. The value for a is 5.7 10^{-4} $(m^3\ s^{-1})^{1-k}$ and k is 1.38.

To carry out computations on an annual base, it is assumed that the "form" of equation (1) is the same at any time, i.e. the exponent k is constant, while the a coefficient is different from year to year. It is assumed that the value of a_j is:

$$a_j = \frac{Q_{sa_j}}{\sum_{i=1}^{m} Q_i^k \partial t_i} \tag{2}$$

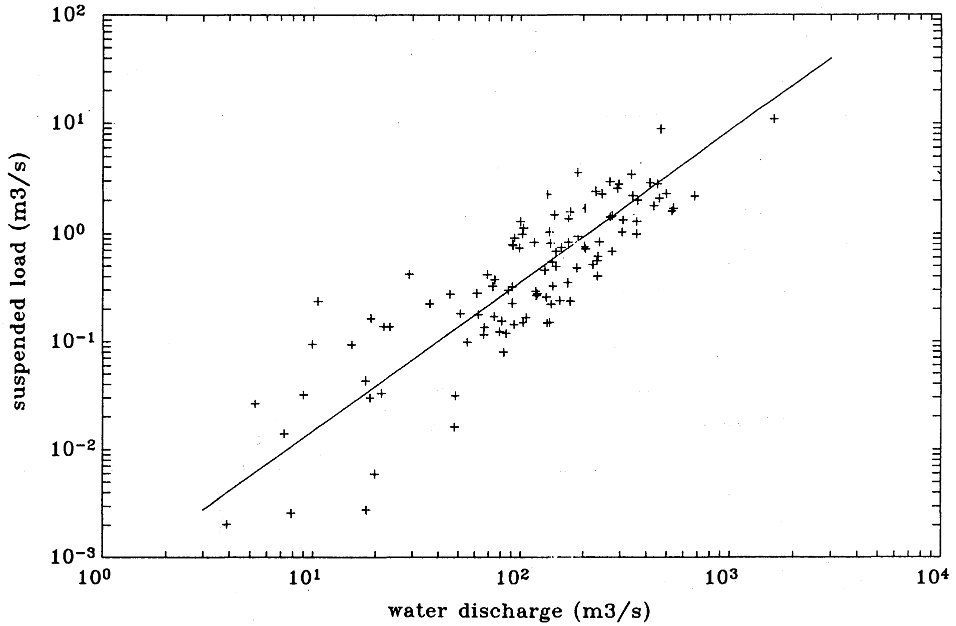

Fig. 4 Correlation between discharges and suspended load.

where Q_{sa_j} is the suspended volume transported by the river in the jth year and Q_i is the daily water discharge corresponding to the duration ∂t_i; m is the number of classes in which the duration curve can be divided.

It is further assumed that sediment concentration X_i associated with the daily water discharge Q_i is the same in both the river and in the channel:

$$X_i = \frac{Q_{s_i}}{Q_i} = a_j Q_i^{k-1} \tag{3}$$

Under these assumptions, the annual amount of sediment derived from the river in the jth year is:

$$Q_{sd_j} = \sum_{i=1}^{m} Q_{d_i} X_i \partial t_i = \sum_{i=1}^{m} Q_{d_i} a_j Q_i^{k-1} \partial t_i \tag{4}$$

From the observed amount of deposition (Table 1), and using equation (4) together with the duration curve, it is possible to estimate the coefficients a_j, as average values over the periods 1830-1834, 1835-1859, 1860-1871, 1924-1929. It has been argued that these values can also be assumed to be annual values associated with the central year of the considered period. In this way, four annual values of a_j have been determined:

$$a_{1832} = 8.74\ 10^{-4}\ (\mathrm{m}^3\ \mathrm{s}^{-1})^{1-k}, \quad a_{1847} = 6.96\ 10^{-4}\ (\mathrm{m}^3\ \mathrm{s}^{-1})^{1-k}$$

$$a_{1865} = 5.71\ 10^{-4}\ (\mathrm{m}^3\ \mathrm{s}^{-1})^{1-k}, \quad a_{1927} = 2.27\ 10^{-4}\ (\mathrm{m}^3\ \mathrm{s}^{-1})^{1-k}$$

A suitable interpolating function of these values may be:

$$a_j = 8.74/\exp(0.013j) \tag{5}$$

which provides the values of a_j relative to the year 1830 + j. It is possible to calculate a_j the annual sediment yield of the river for the whole period, by using equations (5) and (6):

$$Q_{sa_j} = a_j \sum_{i=1}^{m} Q_i^k \partial t_i \tag{6}$$

Results, in terms of variations of annual volume of suspended sediments with time in the Ombrone River, are shown in Fig. 5, where the computed values are compared with the measurements. In the same figure, the observed values for the period 1952-1973 have been also plotted. It can be seen that there is satisfactory agreement between the predicted and observed averaged values over the entire period.

Observations and conclusions

The availability of historical data and more recent hydrological data in the River Ombrone, Italy, allowed the calibration of a simple model for estimating annual sediment yield since 1830. Results indicate a progressive reduction in the yearly

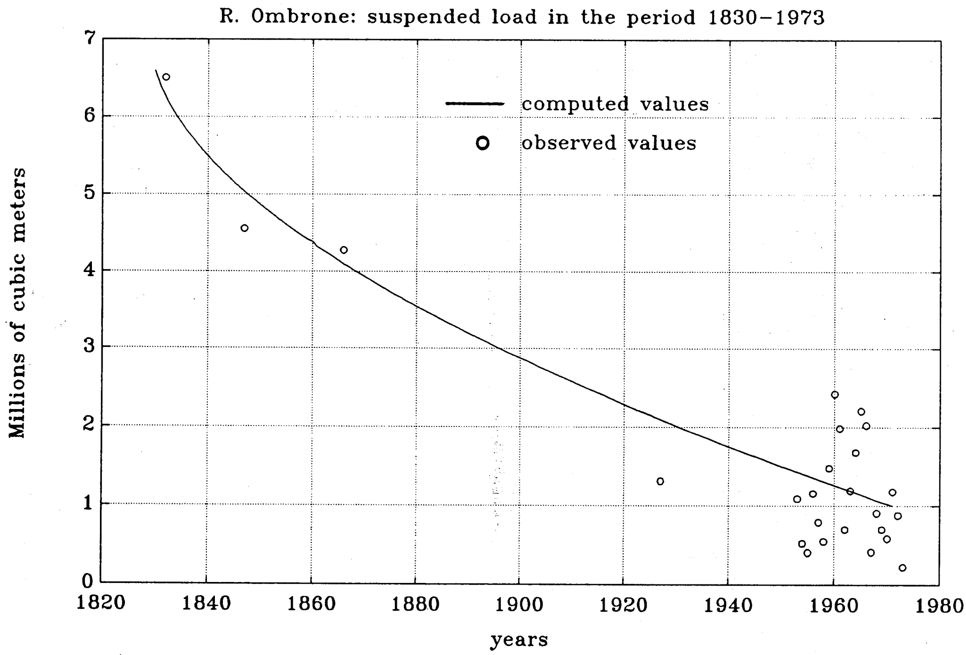

Fig. 5 Variation of suspended load in the River Ombrone in the period 1830-1973.

quantity transported as suspended load, varying from initial values of about 6-7 Mm^3 to recent values of 1 Mm^3. A preliminary analysis of hydrological data available since 1840, such as rainfall and temperature, does not reveal any particular trend capable of explaining this considerable reduction. It has been argued that human activity at a basin scale is probably one of the most important factors in determining changes in the sediment regime of the river.

As a first analysis, the land use surveyed in 1829 (Biagioli, 1975) has been compared with a 1991 survey Table 1. The most important variations appear to be the reduction in the area of grazing and the increase of forest; both these changes affect sediment production at a basin scale and, consequently, the availability of suspended material to be transported through the drainage network. Also, the area of the agricultural land has changed, but in this case the effects on sediment production are not clear. In fact, the nature of the cultivated area has also been altered since the beginning of this century as mountain regions have been progressively abandoned and the plains increasingly populated. In this case, an increase of cultivated area does not necessary produce an increase in sediment production.

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