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Sediment transport and morphodynamics of the Tanaro River, northwestern Italy

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Abstract This paper describes a study to determine sediment transport processes and morphodynamics of the Tanaro River in northwestern Italy to support river management strategies. An integrated hydraulic-geomorphic approach was used to: (a) assess geology, land use and climate controls affecting sediment yield at the catchment scale; (b) evaluate changes in channel morphology and sediment transport processes; (c) model river channel change. Numerical simulations were used to evaluate the transient solution for flow and bed profile due to the propagation of the flood wave. It is concluded that Alessandria town is the most critical reach from the flooding point of view and so different design solutions were tested in order to verify whether geometric alteration of the river bed would allow for an increase in flood capacity.

Key words bed equilibrium configuration; channel changes; morphodynamic; sediment transport; Tanaro River, Italy

INTRODUCTION

River management programmes in Italy rarely address sediment transport processes in the design of flood control structures (Autorità di Bacino del Fiume Po, 1997; Autorità di Bacino del Fiume Arno, 2000). More recently, there has been an increasing awareness of regional sediment issues and channel morphodynamics as an integral part of river management. Consequently, there is a need to develop or further refine methodological approaches that include an assessment of sediment transport processes and morphodynamics to ensure their application to widespread river management practice. A multidisciplinary study is required to quantify catchment and reach-scale processes, forms and causes of instability as a basis for quantitative hydraulic modelling and analyses (Environment Agency, 1998; Thorne, 1998).

A large flood event, with an estimated return period of about 100 years, occurred along the Tanaro River in northwestern Italy during November 1994. During the event, hundreds of landslides occurred in the drainage basin and sediment transfer to and by the river resulted in damage to several towns. This event emphasizes the need for developing better flood control strategies and to take into account sediment transport processes and morphodynamic aspects of river management.

The objective of this paper is to examine morphodynamic and sediment transport processes in the Tanaro River to provide appropriate information for river management. Data on channel morphology and sediment transport are used to develop a numerical model to calculate the equilibrium configuration and possible effects of bed changes on flood capacity.

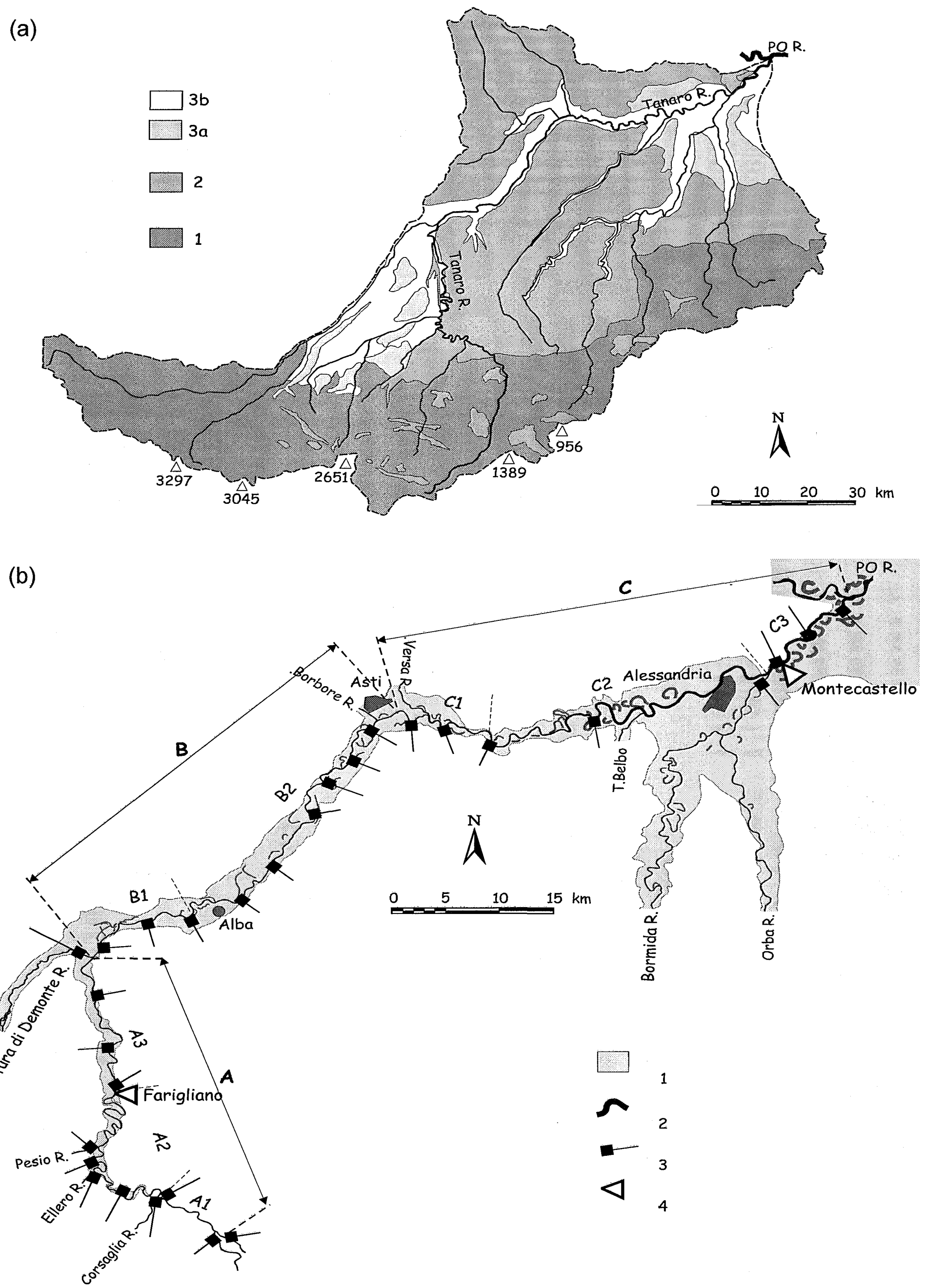

Fig. 1 General characteristics of the drainage basin and of the River Tanaro.
(a) Geological sketch. 1: rocks antecedent to the Tertiary (mainly metamorphic and calcareous rocks); 2: Tertiary sedimentary rocks (mainly marls, sandstones, sands and clays); 3a: Pleistocene (alluvial deposits); 3b: Holocene (alluvial deposits).
(b) Geomorphological classification in river reaches, with location of sediment samples and sediment transport evaluation. 1: alluvial deposits (Holocene); 2: palaeo-meanders; 3: location of sediment samples and geomorphological river reconnaissance; 4: location of gauging stations used for sediment transport evaluation.

STUDY AREA AND METHODS

Study area

The river basin in northwest Italy drains an area of about 8300 km^2 (Fig. 1). Three dominant lithologies including pre-Tertiary rocks, Tertiary Piedmont basin, and Quaternary alluvial deposits, cause variable erosion rates and sediment supply in the river basin. The hilly areas of the Tertiary Piedmont basin constitute the main areas of suspended sediment supply which is generated by soil erosion and earth flows involving the surface soil cover (Biancotti, 1981). The main supply of bed load is from the mountain areas which consist of metamorphic and calcareous rocks that enter the river from rock falls and mass wasting processes.

The basin is located in a temperate climatic zone, but with significant differences between the lower part (Po Plain) and the Alpine ridge. Annual rainfall is extremely variable in relation to relief, ranging from 640 mm on the Po Plain (Alessandria) to about 1500 mm on the Alpine ridge. Mean daily discharge of Tanaro River ranges from about 23 $m^3 s^{-1}$ in the upper course (Farigliano) to 80 $m^3 s^{-1}$ in the lower course (Montecastello).

Geomorphological analysis

A desk study was conducted to provide an understanding of the geomorphology of the Tanaro basin. The geology, soils, topography, land use and geomorphology of the basin were determined to investigate factors influencing sediment yield and to identify the main sources of sediment at the catchment scale. A more detailed assessment of the channel characteristics was based on the interpretation of aerial photographs and river reaches were divided into similar morphological characteristics, based on valley-floor morphology (direction of the valley and degree of confinement of the river) and channel planform.

The alluvial portion of the river was classified in a series of reaches, starting from the boundary between the pre-Tertiary rocks and the sedimentary units of the Tertiary basin. Three main segments (A, B, and C) reflect the major structural controls (direction and confinement of the alluvial valley floor), while a second further division in sub-units is mainly based on channel morphology, resulting in a total of eight sub-reaches (Fig. 1(b)). Reach A is characterized by a sinuous channel (A1 and A3) alternated with a central sub-reach of meanders confined in the bedrock (A2). Reach B is characterized by a sinuous, transitional channel morphology with a significant increase of the alluvial plain and channel width, while reach C exhibits typical meandering morphology.

Sediment survey

A series of sedimentological and geomorphological field surveys were conducted in July and August, 2002. Sediment was collected from channel bars and pebble counts were conducted at a total of 23 locations along the Tanaro River and an additional six locations along the main tributaries (Fig. 1(b)). A river reconnaissance survey was conducted for each site using a stream reconnaissance sheet described by Thorne (1998) and specifically adapted to the scope and resources of the project.

Sediment transport was evaluated for two gauging stations (Garzonotti, 2003). The two stations (Farigliano and Montecastello) are located along reaches A and C (Fig. 1(b)) and are considered to be representative of the upper and the lower course of the river, respectively.

Standard sediment transport formulae were used to calculate mean annual bed load, suspended load, and total sediment load (Table 1). Although errors resulting from the use of bed load transport formulas are widely recognized, the formulas provide results of the same order of magnitude and can be considered a first approximation of the sediment transport of the Tanaro River.

Table 1 Evaluation of sediment transport at Farigliano and Montecastello (location of the two sites is shown in Fig. 1(b)).

Location	Bed load (m^3 $year^{-1}$)				Suspended load (m^3 $year^{-1}$)		Total load (m^3 $year^{-1}$)	
	A&M	E&F	MPM	P90	VR	S&ML	B	E&H
Farigliano	16457	11369	10149	14622	93134	100300	106017	151289
Montecastello	23825	30253	38953	36072	152123	122590	123875	172411

A&M: Ashida & Michiue; E&F: Engelund & Fredsoe; MPM: Meyer-Peter & Muller; P90: Parker (1990); VR: Van Rijn; S&ML: Smith & McLean; B: Brownlie; E&H: Engelund & Hansen.

RESULTS

Recent channel adjustments

Longitudinal profiles of the channel bed from 1973 and 2002 were compared to assess changes in bed elevation. Reach A was affected only in some short reaches by incision of the order of 1.5 m to a maximum of 2.2 m due to the presence of several grade control structures and bedrock outcrops. Reach B had the highest amount of bed erosion. Maximum values of 6 m were observed in sub-reach B1 and there was a slight decrease downstream of 1.5 and 4 m in sub-reach B2. Reach C was incised in the first part (sub-reach C1 and part of C2) from 1 to 2.5 m, while downstream reaches were characterized by erosion incision and deposition of up to 1 m. The incision rates are comparable to those observed in many other Italian rivers (Surian & Rinaldi, 2003), and have been related to various types of human intervention during the last 100 years, mainly sediment extraction, dams and channelization.

NUMERICAL MODELLING OF CHANNEL CHANGES

Model formulation

A one-dimensional mathematical model is used to describe longitudinal bed profiles, longitudinal free surface profiles and sediment transport as a function of time and hydraulic flow conditions. The governing equations adopted for the hydro-morphodynamic problem are the de Saint-Venant equations (1) and (2) for the liquid phase and the Exner equation (3) for the solid phase. Because flow conditions in the Tanaro River are nearly always subcritical ($Fr < 0.8$), meaning that the rate of bed morphological evolution is of a lower order of magnitude than flow changes with adequately low sediment concentration, we adopted a decoupled solution (Ferreira & Leal, 1998; Siviglia, 2003). It is possible to find the stationary solution of the fluid phase over a frozen bottom topography by solving equations (1) and (2), and then updating the bed elevation by solving equation (3). Defining a Cartesian coordinate system (x,y,z) with the x longitudinal axis lying on the bottom, y transversal axis, and the z axis upward normal to them (Fig. 2), the governing equations for hydro-morphodynamics are:

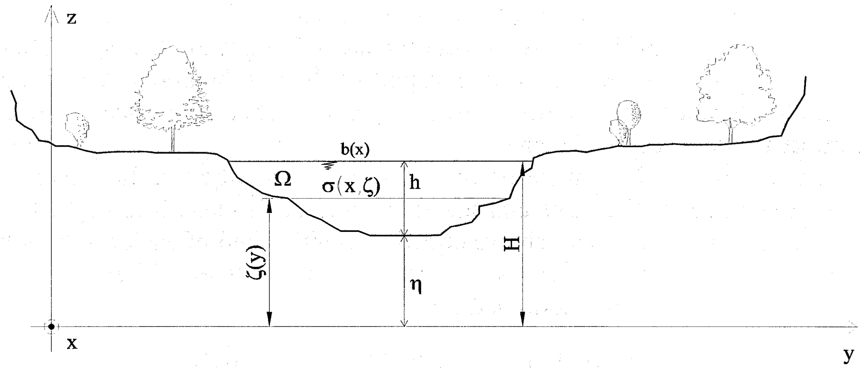

Fig. 2 Cross-sectional geometry.

$$\frac{\partial \Omega}{\partial t}+\frac{\partial Q}{\partial x}=q_l \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{\Omega}\right)+g\Omega\frac{\partial H}{\partial x}+g\Omega j=0 \tag{2}$$

$$(1-p)b_{eff}\frac{\partial \eta}{\partial t}+\frac{\partial Q_s}{\partial x}=q_{sl} \tag{3}$$

where the energy loss per unit length of the channel is expressed through a friction coefficient:

$$j=\frac{Q^2}{g(\Omega^2C^2R)} \tag{4}$$

The unknowns of the full problem are the wetted cross-sectional area Ω, the volumetric discharge Q, and the minimum bottom elevation η. Moreover, H is the water level, R the hydraulic radius, q_l the discharge per unit length due to lateral inflow/outflow, β is the correction coefficient for the momentum, b_{eff} is the width of the mobile bed. Due to the complexity of natural geometry, the calculation of the quantities Ω, β, $(\Omega\, C^2\, R)$ has been done evaluating the integrals across the sections following the Engelund approach (Engelund, 1964). Application of the above method leads to the following terms:

$$\Omega=\int_b (H-\zeta(y))\mathrm{d}y \tag{5}$$

$$\beta=\frac{\Omega\int_b c^2(y)[H-\zeta(y)]^2\mathrm{d}y}{\left[\int_b c(y)[H-\zeta(y)]^{\frac{3}{2}}\mathrm{d}y\right]^{\frac{3}{2}}} \tag{6}$$

$$\Omega^2C^2R=\left[\int_b c(y)[H-\zeta(y)]^{\frac{3}{2}}\mathrm{d}y\right]^2 \tag{7}$$

where $\zeta(y)$ is the bed elevation, η is the minimum of $\zeta(y)$, $c(y)$ is the local conductivity which is a function of the transversal coordinate y. In equation (3), b_{eff} is the cross-sectional area effective width where the solid transport holds, p is the porosity, q_{sl} the solid discharge per unit length due to lateral inflow, while Q_s is the global solid discharge integrated all over the effective cross-sectional area.

In order to model sediment transport, we have identified in the Tanaro River different consecutive reaches. We have considered reaches short enough to neglect the longitudinal sorting effect. Thus, we have characterized the mobile bed of each reach by two grain sizes representative of bed load and suspended load respectively. The global solid discharge (Seminara *et al.*, 1996) is determined as:

$$Q_s = F_b \int_{b_{eff}} \Phi\sqrt{(s-1)gd_s^3}\,\mathrm{d}y + (1-F_b) \int_{b_{eff}} \psi U(y)(H-\zeta(y))\mathrm{d}y \qquad (8)$$

where s is the ratio of the sediment and the water density, g is the acceleration due to gravity, d_s is the average sediment diameter, F_b is the percentage of sediment transported as bed load, Φ and Ψ are the dimensionless bed load and suspended load discharge respectively, which are evaluated by empirical relations available in the literature (Meyer-Peter & Müller (1948) for bed load and Van Rjin (1984) for suspended load).

Numerical modelling results

Numerical results were obtained for first an unsteady fixed bed simulation along all the Tanaro River; second a stationary mobile bed simulation and eventually an unsteady mobile bed simulation along a short reach. The main purpose of the fixed bed simulation was to tune the local conductivity parameter of each section, reproducing real flood events. Such a parameter is fundamental for the correct evaluation of the global sediment discharge.

The mobile bed simulations examined a 35-km long reach of the Tanaro River near Alessandria, from the confluence with the Belbo River to the confluence with the Po River, because it is the most critical from the flooding point of view. The study reach is characterized by six bridges, including the ancient Cittadella Bridge that is protected by an apron producing a large scour hole downstream. The width of the main channel varies from 60 to 200 m. The maximum safe water discharge flowing below the Cittadella Bridge is about 2600 $m^3 s^{-1}$, while the 100-year discharge is estimated to be about 3500 $m^3 s^{-1}$.

First, we performed stationary mobile bed simulations. Such simulations should be interpreted as the first step to understanding the influence of channel changes on the bed profile and to highlight the critical points. These computations showed that the actual configuration of the bed topography of the reach downstream of Alessandria is very close to the equilibrium one, whereas in the neighbourhood of the town significant erosive processes occur (Fig. 3). It is worth noting that high erosion rates "at equilibrium" in some sections were over predicted in two ways: (a) the vertical sediment distribution in the alluvial deposit, i.e. the sediment coarsening with the depth, is neglected, and (b) we imposed constant water discharge assuming that the peak of the flood lasts to infinity, i.e. neglecting the increasing and decreasing flood phases. No information is derived about the time scale which is required to achieve the equilibrium configuration. This information, which is crucial from an engineering point of view, is given by the unsteady morphodynamic model which

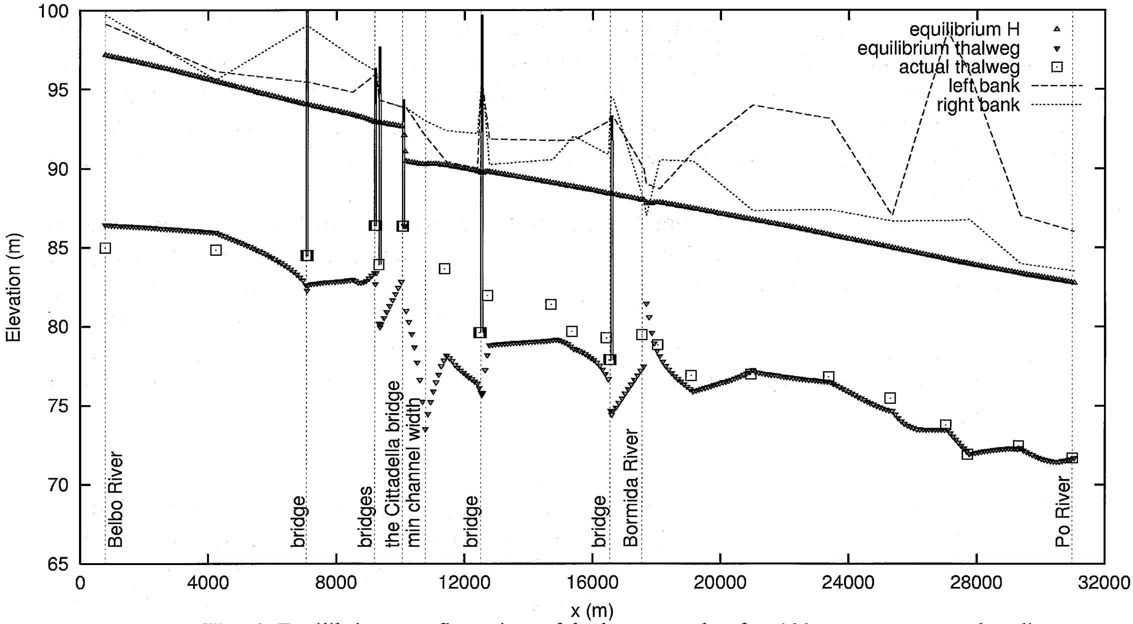

Fig. 3 Equilibrium configuration of bed topography for 100 years water and sediment discharge considering the actual geometry of the cross-sections.

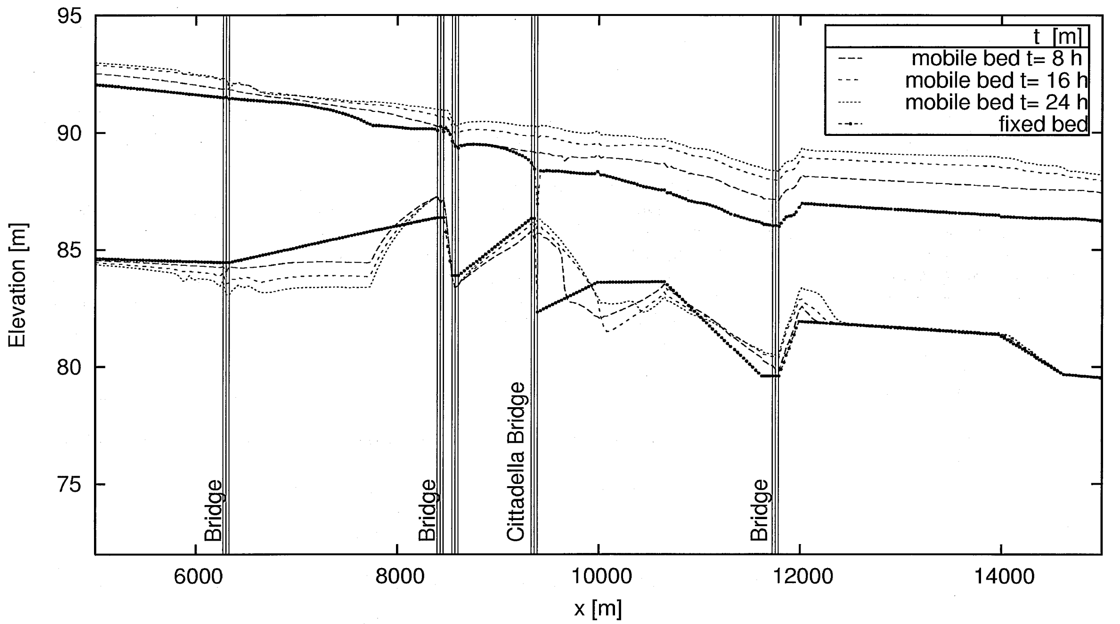

Fig. 4 Unsteady simulation: bed topography evolution during the increasing phase of an intense flood event.

predicts the magnitude of bed variations and the time scale required to occur. In Fig. 4 the evolution of the bed during the increasing phase of an intense flood event is shown. It is seen that, despite the fact that the configuration of the bed profile during a flood event is very far from the one predicted by the stationary model, at some points it slowly moves towards the equilibrium conditions. Unsteady mobile bed calculations also allow evaluation of the maximum scour in correspondence of critical sections, i.e. bridges and narrowing, during a real flood. This allows the civil engineer to verify correctly the stability of structures such as piers and banks.

Finally, we employed such numerical tools to verify whether geometric alterations of the river bed allow for an increase in flood capacity. We found that lowering the elevation of the apron of the Cittadella Bridge by about 2 m, and recalibrating the city reach so that the main channel width is constant, leads to decrease of the water level upstream of the Cittadella Bridge by up to 15% so increasing the safety of the whole city reach. This last application is an outstanding example as to how this tool is very versatile and useful for future river monitoring and management.

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