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The Fluvial Dynamics of the Arno River

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ABSTRACT. The paper illustrates the results of a study on the morphological, sedimentary and human characteristics of the Arno, one of the main rivers in central Italy. The analysis of historical maps, the sampling and grain-size analysis of the channel sediments and the geomorphologic surveying of the riverbed-alluvial plain system enabled us to reconstruct its evolution: like many rivers in central Italy, the Arno was affected over time by a progressive entrenchment, which is responsible for its present instability conditions. The causes of this entrenchment can be identified as: artificial reduction of the channel width and channelization works historically carried out; solid transport deficit, owing both to the building of sedimentary traps (such as the Levane and Laterina Dams) and to hydraulic-forest dredging works affecting the entire hydrographic basin; intense quarrying activity since the end of World War II which has affected the Arno's riverbed.

Key terms: Fluvial dynamics, Arno River, Historical evolution, Morphological characteristics, Sedimentary characteristics

Introduction

The knowledge of the morphological-sedimentary processes, which, together with the hydraulic ones, regulate the dynamics riverbeds and determine their evolutionary trends, represents an essential point of reference for a correct *management* of the riverbed – alluvial plain system.

Management that means both defense from hydrological extreme events (e.g. flooding) and a correct utilization of superficial hydrological resources that must to exclude an unconditional and irregular exploitation of the fluvial resources so that dangerous and uncontrollable "reactions" of the same system cannot occur.

These "reactions" of the system occur frequently when human activity becomes an upsetting element for the equilibrium existing in the delicate riverbed – alluvial plain system.

A wrong management of the system can be manifest immediately: this is the case of damage due to inundation and flooding in areas with an absence of any intervention that has as its model the elementary rules of correct land planning with respect to the limits of fluvial pertinence (*stream corridor*).

Sometimes, on the contrary, harmful consequences of human activity within the system can occur in the future: for example, the modifications of natural river courses effected by man (i.e. the hydrographic pattern and cross section geometry, the characteristics of solid transport, especially of bedload transport). The quarrying activity in the river beds, the building of sedimentary traps (e.g. dams), the dredging of the river bed and the interventions at drainage basin scale – often conduced without specific knowledge of the natural processes governing the dynamics of river beds – frequently lead to deterioration of equilibrium and produce erosive and alluvial processes in the river beds, due to an increase in the erosive power of the current flow together with a progressive sedimentary deficit.

These processes (they can look unexpected from a superficial analysis of the phenomena) produce the "hydrogeological disarrangement" of the inhabited areas (the term is somewhat vague and all-inclusive in the common sense of the word), or – at worse – the "natural disasters", a term which tending to give to such events a character of inevitability and fatalism. They would not have this meaning if could know and carefully value the mechanisms governing the relationships between erosive, bed load transport and sedimentary processes occurring within the valleys, the alluvial plains and river beds, in one word: the fluvial dynamics.

In Italy, the Law for the Defense of Soil (No. 183/1989) considers the drainage basin, as defined by the "Basin Plan", to be the physical limit in planning. The Basin Plan is concerned with problems strictly connected to the physical "drainage basin", which should be regarded as the riverbed and to its alluvial plain. In fact, it is within the riverbed and the alluvial plain that the complex phenomena occur which regulate the dynamics of the river, condition the use of its water resources and determine the level of risk in case of flooding. Main infrastructures, urban areas and major industrial activities in Italy are concentrated along the alluvial plains of the rivers.

Fluvial dynamics can be arbitrarily subdivided into three main fields: hydrological-hydraulic, morphological-sedimentary, physical-chemical-biological.

The complex fluvial phenomena, even if in different degrees, almost always involve all these fields and therefore a knowledge of all of them is required for a correct approach to each single phenomenon, as well as an understanding of the existing relationships between fluvial phenomena and anthropic activities. It is this activity which is the object of the planning in the "Basin Plan".

The various fields are traditionally treated in a more differentiated manner. For example, hydrology expresses in a quantitative and concise form those characteristics which are related to complex phenomena, such as the flow of the river, but it is not enough to correlate them to the forms of the riverbed and to the characteristics of the alluvial plain, or to the characteristics of the groundwater below the river bed. Geomorphology, on the other hand, analyses the forms and alluvial processes, expressing itself in a descriptive language, which is not easily quantifiable and is poorly correlated, for example, to the hydrological, chemical and sedimentary characteristics of the river. Each field is generally dealt with by specialists who are often convinced that a proper treatment of that field is sufficient for the understanding of a fluvial phenomenon.

A knowledge of fluvial dynamics is missing in this disciplinary and sectorial outlook. It becomes difficult for the technicians to carry out correctly those procedures which concern the river (GORDON et al., 1992).

The essential element for proper planning is to take advantage of suitable provisional models, while the essential element for the correct formulation and response of the models is to use sufficient and reliable data which can concisely and fully represent, together with the models, the complex phenomena linked to the dynamics of the river bed – fluvial plain systems; for example, the rate of discharge, including the analysis of flood events or periods of low water; the risks of flooding of the fluvial plain; the quality of the river water; the river – groundwater relationships; the vulnerability of the aquifers of the fluvial plain; the evolutionary tendency of the river bed; the evaluation of the effects of works such as dams, crossings, bank protections and embankments; the effects of extracting gravel from the river bed or from the alluvial plain; the diversion of the river flow for irrigation purposes; the realization of urbanised or protected areas within the limits of fluvial pertinence, etc.

Instead, the essential element for an understanding of phenomena related to the dynamics of the riverbed – plain system is the precise knowledge of the physical and human characteristics, and of the natural and induced evolutionary characteristics of the riverbed.

This paper intends to show the state of knowledge in the fluvial dynamics of the Arno River (one of the most important rivers of central Italy, that can be considered a representative example of the conditions of most water courses in Italy), and in particular to trace the historical evolution of the river bed and alluvial plain and examine the sedimentary characteristics of the river bed.

While, in fact, the hydrogeological-hydraulic aspect has historically been the best known and the most studied field of the Arno River (the reason for this being the implications that it has on the management of water resources for the river and the plain, as well as the flood risks linked to the bankfull discharge) and while the physical-chemical-biological aspect is fairly well-known (but nevertheless has a number of gaps and insufficiencies), the morphological-sedimentary aspect is the one most lacking; the data surveyed are limited to the control sections of the Arno's main river bed from the Levane Dam to the mouth of the river. These insufficiencies correspond to the lack of interest which, in the past, geomorphologists have shown for this area.

A study, carried out by researchers from the University of Perugia, together with colleagues from the University of Florence at the beginning of the 1990s, was based on a methodology proposed by TACCONI (1990, 1994) concerning specifically the analysis of the historical evolution and sedimentary characteristics of the Arno river bed and alluvial plain (CANUTI et al., 1994; TACCONI et al., 1994; CENCETTI et al., 1994). The results, to which this paper is mainly addressed, show how the human activity has been able, during the recent past, to modify the pre-existing equilibrium and to produce unexpected morphological and sedimentary processes, which are determining the present conditions of generalized disarrangement in the entire fluvial course of the Arno River.

Main Physical-Geographic characteristics of the drainage basin of the Arno river

The Arno River Basin (FIG. 1) has an area of about 8,830 km^2 and an average altitude of 353 m a.s.l. The level plain constitutes about 17%, the low mountain area about 15%, with the remaining 68% of the area being characterized by a hilly landscape.

The hydrographic basin has a varied morphology, characterized by a series of structural alignments forming the northern Apennines, where the outcropping rocks are predominantly sedimentary, made up mainly of calcareous and arenaceous flysches of Oligocene and Miocene age. Between these ridges some large intermontane basins, which formed lakes during the Pliocene and the Pleistocene (Casentino, Upper Valdarno, Chiana Valley, Mugello, Firenze-Pistoia Basin) are present, where clastic sediments fill stratigraphic series (conglomerates, sands and clays). These basins (LOSACCO, 1953-54; MERLA & ABBATE, 1967; AZZAROLI & LAZZERI, 1977; BARTOLINI & PRANZINI, 1981; ALBIANELLI et al., 1993) are separated by thresholds and narrow incisions such as the Valle dell'Inferno (Hell's Valley), the threshold of Incisa Valdarno, the Strait of Gonfolina.

The middle-lower portion of the hydrographic basin (Elsa Valley, Era Valley, Pesa Valley) is constituted by large outcrops of marine clastic sediments, predominantly sandy and clayey, forming a hilly landscape, characterized by frequent erosive forms.

The source of the River Arno is in the vicinity of Mt. Falterona; the river measures 241 km in length, with an average slope slightly below 0.06% and its mouth is at Marina di Pisa, Tyrrhenian Sea.

The main river bed, except for the first 7 km from the source and the above-mentioned limited stretches with thresholds and straits, is set up on the alluvial plain and is, therefore, a mobile river bed. It initially runs across the Casentino Valley and, after the dams of Laterina and Levane (downstream of the confluence with the Chiana), passes through the Upper Valdarno where at present it displays characteristics of a river with low sinuosity and alternate bars. After crossing a predominantly incised reach from Incisa Valdarno, the river receives the water of the Sieve River on the right bank and reaches the Firenze-Pistoia Basin, where it meets the confluences with the Greve, Ombrone and Bisenzio; it then crosses the Gonfolina Strait and runs across the Lower Valdarno with a predominantly meandering typology, receiving the waters of the Pesa, Elsa and Era on the left bank (CANUTI & TACCONI, 1971; CONEDERA & ERCOLI, 1973; DELLA ROCCA et al., 1987; BILLI et al., 1989).

The Arno River's bed is gravely almost to its mouth, even though coarse bed load transport seems to be fairly limited (BILLI, 1991).

The flow at the S. Giovanni alla Vena station, where the area is almost completely drained, is the following: average flow 90 m^3/sec, minimum flow 2.2 m^3/sec, maximum flow 2,250 m^3/sec. A considerably greater maximum flow of 4,100 m^3/sec was calculated during the flood of November 4, 1966 (NARDI, 1993).

The basin population is slightly below 2,600,000 inhabitants.

Historical research

The evolution of the Arno's drainage basin took place throughout geological time (FEDERICI & MAZZANTI, 1988); on the contrary, the dynamics of its river bed in the present alluvial plain is more short-lived due to the mobility of the river bed, and to human activities with which it has had to come to terms since prehistoric times (PICCARDI, 1956; LOSACCO, 1962; PULLACE, 1983; AA.VV., 1985; BECCHI & PARIS, 1989; ALESSANDRO et al., 1990; CANUTI et al., 1992; 1994).

Within the context of the study of a fluvial bed, historical research constitutes vital knowledge in the evaluation of evolutionary tendencies during past centuries, especially the level of "conditioning" by man with respect

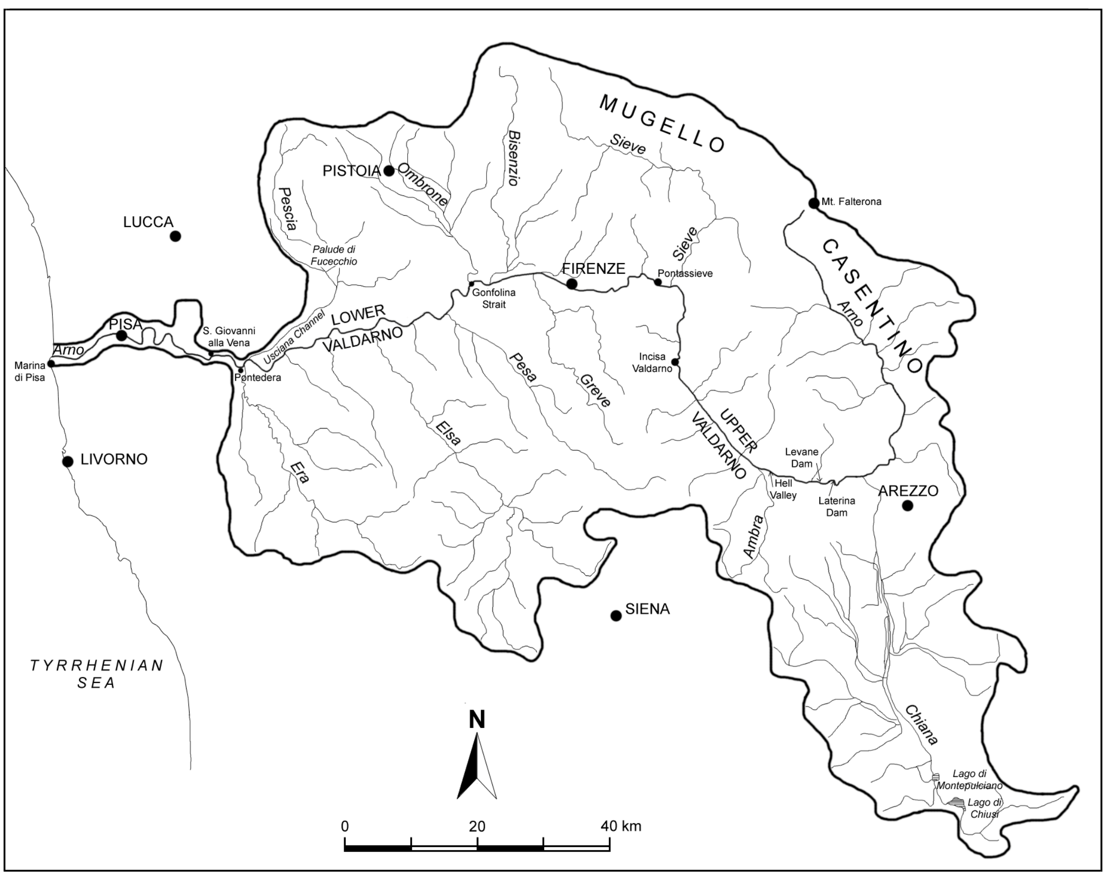

Fig. 1 – Hydrographic basin of the Arno River, in Central Italy (from TACCONI, 1994, modified).

to its natural condition. A research on the characteristics of the riverbed throughout the past was carried out using maps and documents found in State Archives and Libraries. There is a great source of cartographical evidence for the mobility of the Arno river, linked to projects for systematization, canalization and rectification works to be carried out on the bed (MATERASSI, 1847; GIORGINI, 1854; TONIOLO, 1927; CACIAGLI, 1969) or, in many cases, linked to disputes which arose between owners of land on opposite banks (FIG. 2).

This documentation has been of great interest in the study of the dynamics of the river, even though it does not homogeneously cover the entire riverbed during the various periods. It refers basically to the planimetric aspects of the river, although some of the documents also include profile and transverse sections.

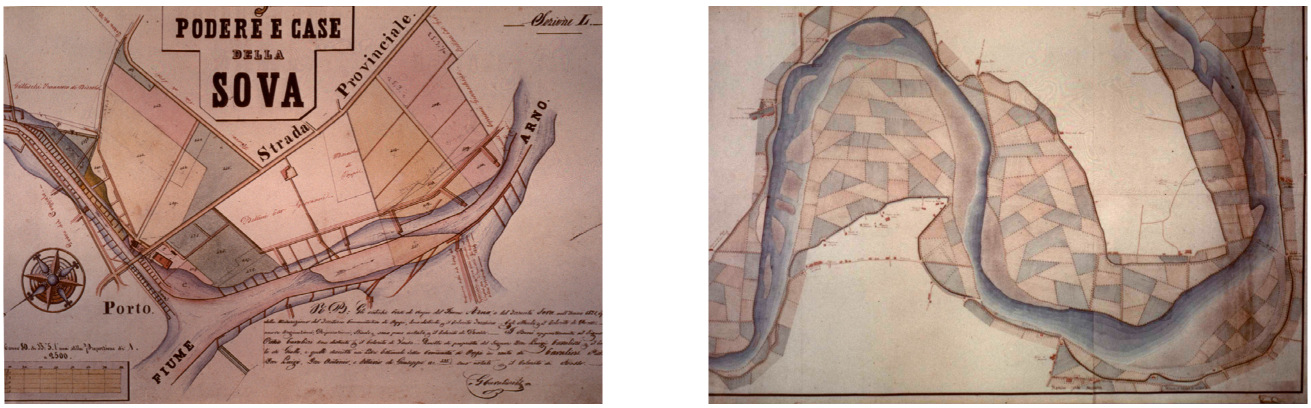

Fig. 2 – Historical cartographic documents and maps are often used to analyse the natural state of the rivers. In this picture two of them, related to reaches of the Arno River, are shown.

The research was mainly carried out in the State Archives of Florence, Arezzo, Pisa, Lucca and in Public Libraries (the Library of the Military Geographic Institute and the National Library in Florence). About 350 historical maps were consulted (about 150 of which were acquired). Each one was catalogued and the main data were recorded on a file: author, year or period, location, position in the reference system, morphological characteristics, works, etc. The analysis of the cartographic documents allowed us to describe the features of the bed in natural conditions, i.e. before rectification and canalization interventions, for various reaches of the river, and to compare them with the present ones. Some useful parameters for a better definition of the planimetric typology of the bed were examined, e.g. the sinuosity index (ratio of the distance between two sections of the river measured along the bankfull channel axis, and the same distance measured along the valley axis), the maximum braiding index (maximum number of channels present in the same reach using a cross-section), and the width of the bankfull channel (TACCONI, 1990).

The historical research was integrated with an analysis of aerial photos, which was aimed at surveying traces of fluvial activity in the floodplain and, in particular, at reconstructing paleo-beds which were not documented by historical maps.

Moreover, the altimetric variations in the riverbed, which occurred in the past and, above all, over the last few decades, were analyzed by comparing the altimetric surveys carried out by MANETTI & RENARD (1847) and by the Hydrographical Service of Pisa (SERVIZIO IDROGRAFICO NAZIONALE, 1954).

The results of the historical research

The results of the historical analysis (TACCONI, 1994; CANUTI et al., 1994) showed the River Arno to be a mixture between a braided and a sinuous course in the Casentino Valley and the Upper Valdarno, alternating with reaches with a narrow and semi-confined valley bottom and a single channel bed with sinuosity.

Proceeding downstream, the braiding index of the river increased, reaching its highest value in the Florentine Plain. Once it passed the Gonfolina Strait, the planimetric characteristics of the natural bed changed suddenly and it assumed a form that can be associated with a lower ratio between bed load and total load.

Finally, the transition to a meandering form in the end reach was probably favored not only by the weak gradient, but also by the fine sediment transport from the Elsa and Era Rivers, which drain predominantly sandy-clayey terrains. The riverbed of the Arno River has been affected, for most of its course, by hydraulic works (canalization, rectification and embankments), the majority of which, carried out in the 18^{th} and 19^{th} centuries, radically changed its form and hydraulic-morphological characteristics. They gave the river a planimetric form which was very different from the natural one, thus influencing the relationships between transport capacity and sediment flow rate and its flood capacity. In fact the bankfull channel has undergone great reduction in its width (FIG. 3), with a consequent increase of its bed load capacity. The construction of embankments and subsequent movement towards the riverbed has caused a considerable reduction of the overbank areas and a consequent increase in the danger of flooding (NATONI, 1944; VIVIANI, 1969). The last important flood occurred in November 4, 1966 (GRAZI, 1967) when the discharge recorded was more than 4,000 m^3/s immediately upstream of Florence (the channel capacity of the Arno at Florence is about 2,500 m^3/s – RINALDI & SIMON, 1998).

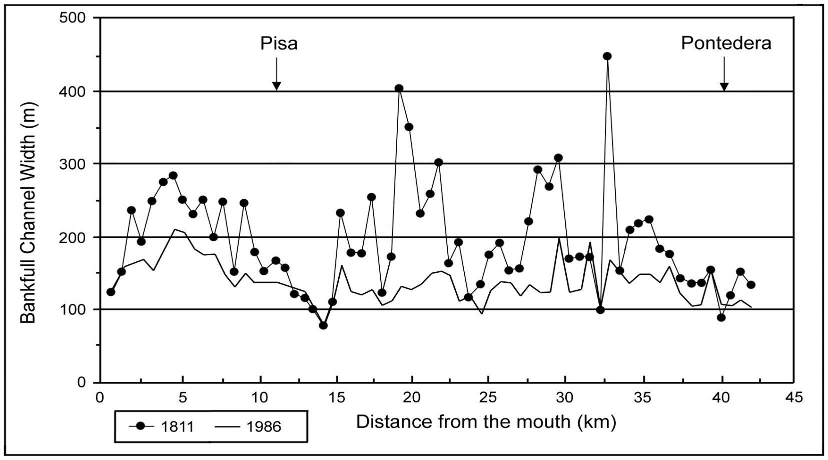

Fig. 3 – The reduction in width of the bankfull channel of the Arno River in the last reach, from Pontedera to the mouth, next to Marina di Pisa (from CANUTI et al., 1992).

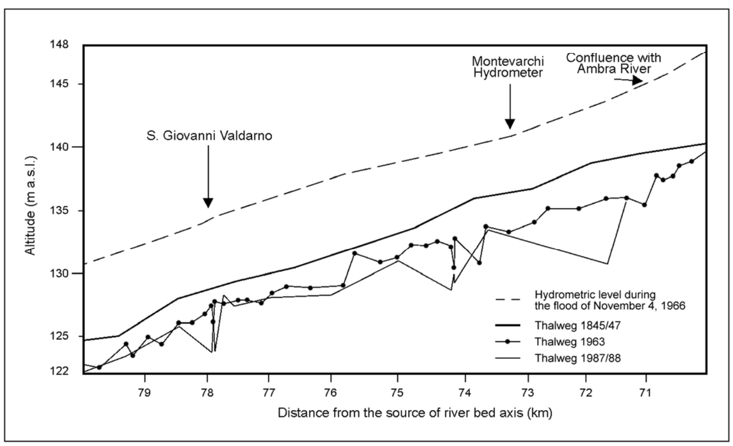

Fig. 4 – The lowering of the riverbed of the Arno River was very accentuated in the 19th and 20th centuries. It was due to erosional processes induced both by the reduction in the bankfull channel width and by the sedimentary deficit (see farther in the text). In this graph the altimetric evolution along the reach of Upper Valdarno is represented (from CENCETTI et al., 1994, simplified).

The recent evolutionary dynamics of the Arno has mainly been of an altimetric type and has consisted of a general bed lowering process (FIG. 4). This has created serious problems for the stability of engineering works (FIG. 5) and the banks, and it has triggered regressive erosive phenomena in the tributaries and lateral erosion of the banks.

From 1844, the total lowering of bed-level in the Upper Valdarno was generally between 2 and 4 m; maximum amounts of degradation over the period 1844-1980 reached almost 9 m at approximately 70 km from the mouth in the Lower Valdarno. From the available data it appears that most of the degradation over the same period occurred between the 1950s and 1980s, during the period of the most extensive instream mining, and the construction of the Laterina and Levane dams (MONTEFUSCO & SANSOM, 1979; RINALDI & SIMON, 1998).

Sedimentary characteristics

The only data available relevant to the bed load transport in the Arno River are not very reliable, and they only relate to suspended bed load transport. In this situation, a knowledge of the morphological-sedimentary characteristics, especially of the riverbed sediment grain size, is essential.

In accordance with the methods defined in the general research project (TACCONI, 1990, 1994), the study of the sedimentary characteristics of the riverbed was divided into two successive phases, which followed the morphological survey of the bed. In the first phase the main morphological-sedimentary characteristics of the bed (sinuosity, braiding, etc.) were surveyed and the physiographic units were defined (bankfull channel, low water channel, banks, bars, riffles and pools). This characterization not only provides us with intrinsically interesting information, but also necessary data to enable us to approach the grain size data survey campaign correctly. Indeed, grain size variability is very marked, even locally within a bed (LEOPOLD, 1970; MOSLEY & TINDALE, 1985; BILLI & TACCONI, 1987; BILLI & PARIS, 1992), and the sampling points must to be defined in physiographic conditions which are as homogeneous as possible.

Fig. 5 – The lowering of the riverbed of the Arno River is creating serious problems for the stability of engineering works. In this picture the Terranuova Bracciolini Bridge, in Upper Valdarno, shows the precarious state of its foundations, in spite of the consolidation works carried out in the sixties (from CENCETTI et al., 1994).

The second phases consisted in the grain size measuring campaign. This campaign, which was the first to involve the entire course of the Arno in a homogeneous way, was carried out in the period June-July 1991, in a low water period, after two flood events which occurred in the previous May (TACCONI et al., 1994). The sampling stations were chosen bearing in mind the fact that they had to have a more or less constant separation, equal to about ten times the predominant width of the bankfull channel. Sampling points placed at fixed intervals irrespective of the surrounding morphological and sedimentary situation, can lead to errors on a local scale. Seventy-five stations were selected; the sites were accurately located with an average spatial interval of about three kilometers (FIG. 6).

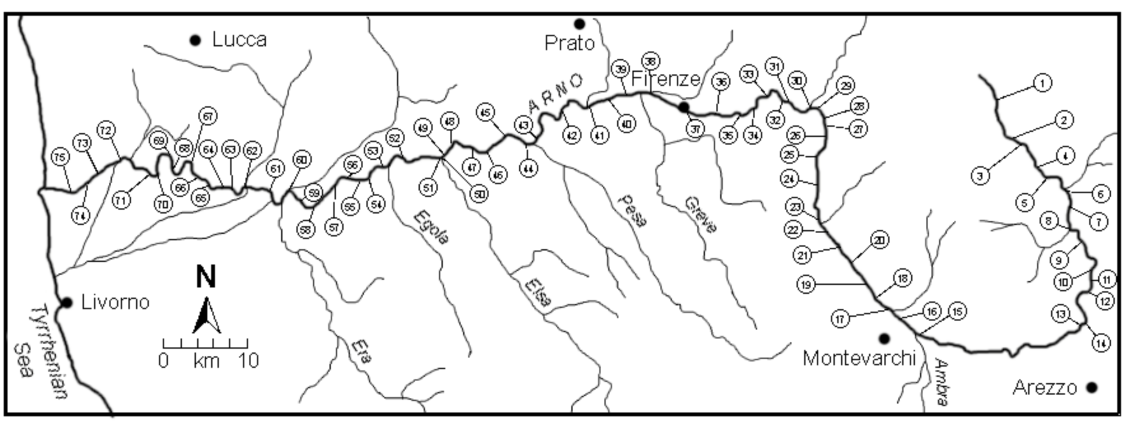

Fig. 6 – Arno River bed sediment sampling stations, from the source to the mouth (from TACCONI et al., 1994).

In the sampling stations sediment samples were taken relative to both the surface layer (*armor*) and the subsurface level (*subarmor*). These referred to the same morphological units (channel and bars). Where evident armoring phenomena were not present, an undifferentiated sample was taken. The differentiation between the armored surface level sediments (where it was present) and the subsurface ones is necessary, as various authors (ANDREWS & PARKER,

1985; BILLI & TACCONI, 1987; TACCONI & BILLI, 1987) share the belief that the grain size distribution of the subarmor sediments is very similar to that of the bed load. This is related to the sorting phenomena present in the bed.

In the low water channel the measuring was always done in the same morphological conditions, which generally corresponded to a pool situation. Riffles are, in fact, characterized by a coarser grain sizes while the pool surface can also contain finer material, which includes a wider grain size range and more homogeneous conditions.

A diver was needed to collect the channel sediments for the entire length of the bed, as they were not directly accessible because of the depth of the bed. At least three measurements were taken in the bars. These corresponded to three morphologically distinct parts of the sedimentary body: the *head* (the upstream part), the *body* (the central part) and the *tail* (the downstream part), in relation to the frequently distinct grain size characteristics of the different parts.

The measurements were taken using the *volumetric method* in order to obtain a grain size curve expressed in weight. One hundred and fifty samples were taken in total, proceeding downstream along the bed; 36 of these were taken from the bars (which at that time were few in number) and the remaining ones from the channel. A minimum of one to a maximum of eight samples was taken at each measuring station, according to the presence or absence of bars and armoring phenomena.

Grain size analysis

All samples taken were subsequently subjected to grain size analysis by sieving. The scale used was the one proposed by Krumbein in 1934 (*phi scale*). We obtained a series of significant width classes equal to ½ phi, ranging between phi = -7.5 and phi = 4. The particles with dimensions of less than 0.0625 mm (silt) were considered as belonging to a single class, given their very low percentages and their unimportance for the equilibrium of the bed. The data obtained from the grain size analysis were expressed by means of a frequency distribution (bar graph and cumulative curve).

For a quantitative treatment of the data we had recourse to the calculation, using the *statistical moments* method, of some significant parameters relating to average trend measurements (mean, median, and mode) and to measurements of dispersion (standard deviation, skewness, and kurtosis). The database filing and representation of the sedimentary characteristics were done using a system of monographic files relating to each sample analyzed and to each measuring station as a whole. The files contain all the information on the sedimentological characteristics and the elements for an immediate reference and identification of the station itself (TACCONI, 1990, 1994).

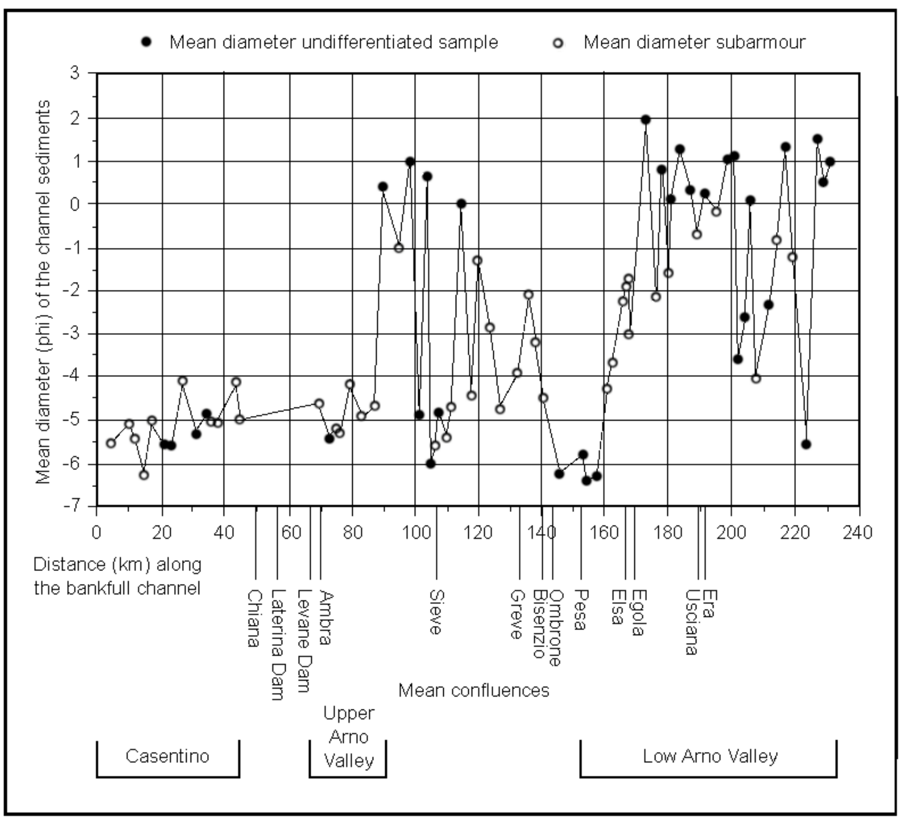

Fig. 7 – Variation in the mean diameter of the low water channel sediments along the bed of the Arno River (from TACCONI et al., 1994).

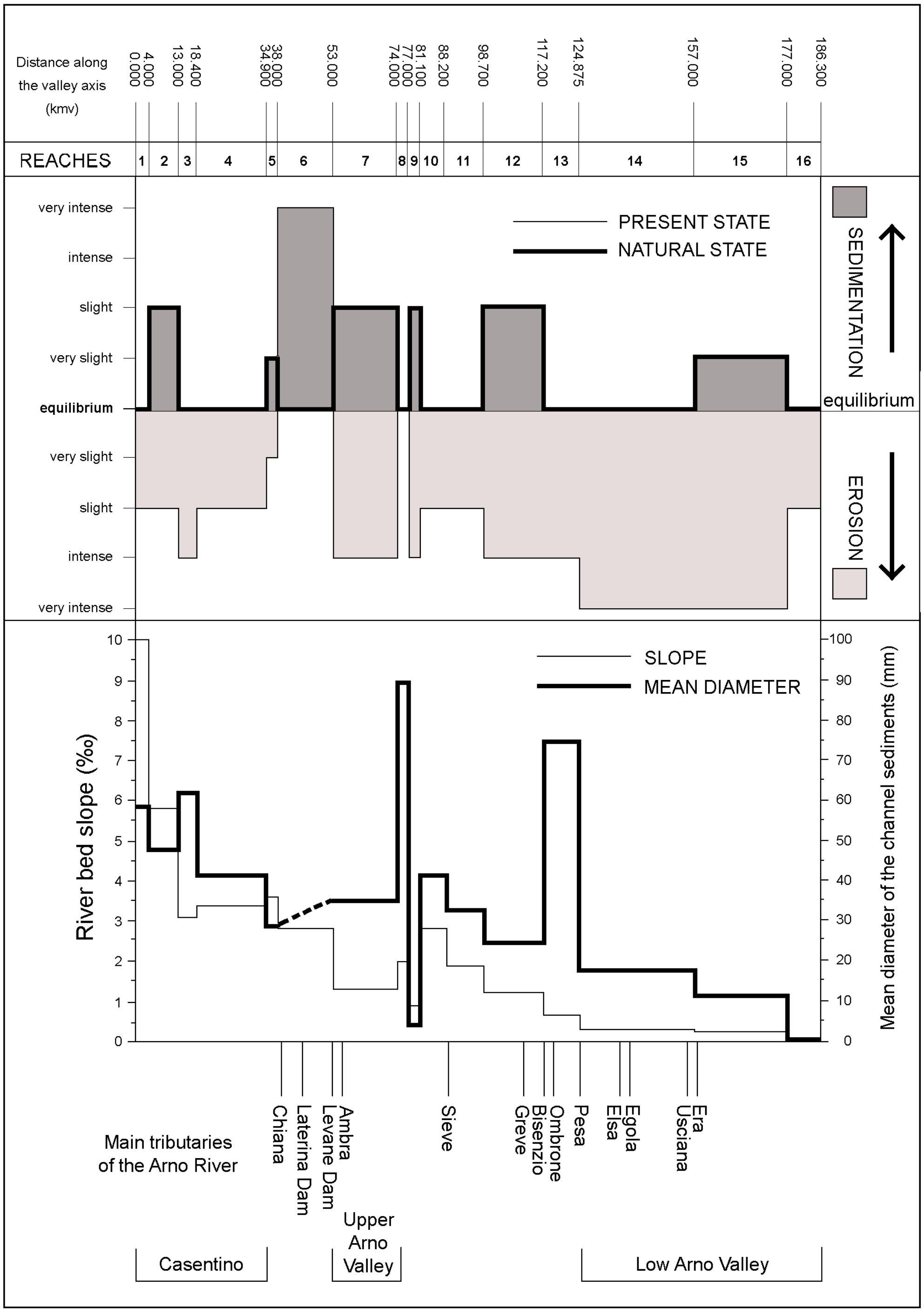

Fig. 8 – Graph illustrating the sedimentary balance and the evolutionary trends of the Arno River, correlated to the mean diameter of the channel sediments and the mean slope of the reaches taken into consideration along the entire course (from TACCONI et al., 1994).

Even though the bed was given a great entrainment capacity, if the bed load was great, a similar systematization would not, in general, have remained stable for long periods, as this one has for hundreds of years. Its relative stability is in accordance with a low total coarse load. This last characteristic was also confirmed by a recent analysis of the sediments in the Laterina and Levane Basins, which were lacking in gravel and pebbles.

Another feature, which points to a low total coarse load, is the almost total absence of gravel and pebbles at the mouth, which cannot be explained exclusively by abrasive clast reduction phenomena.

The mean diameter of the low water channel subarmor sediments is the parameter that most synthetically represents the characteristics of the bed sediments and of its bed load (ANDREWS & PARKER, 1985; BILLI & TACCONI, 1987). Proceeding downstream, this parameter characteristically decreases. Starting with values of around 60 mm, it reaches values of about 0.7 mm near the mouth.

The main differences are due to the local morphological characteristics of the bed (slope and form of the sections) in reaches conditioned by the presence of bedrock (Incisa Sill, Gonfolina Strait) and, to a lesser extent, to the supply of some gravel bed tributaries with a high bed load (Ambra, Sieve, Pesa). Figure 7 shows a synthetic picture of the data obtained.

Homogeneous reaches of the Arno River bed with respect to morphological-sedimentary characterstics and evolutionary trends

Sixteen homogeneous reaches were defined on the basis of the morphological-sedimentary and grain size characteristics of the bed. These reaches also present similar evolutionary trends, each reach having a "history" of similar river training interventions and works (NATONI, 1944) and knowledge of these gives us a better understanding of the present state and the evolutionary trends of the bed, including its sedimentary terms.

The synthetic characteristics of each single reach, in terms of relation between erosive and aggradational processes, in comparison with the natural state of the riverbed (as evident by means of historical research) is shown in FIG. 8.

Discussion

In the past the bed underwent restraining works on the planimetric course and on its sections. These works caused considerable variation in its morphological-sedimentary characteristics with regard to sinuosity, braiding and bankfull channel width. The main variations in sinuosity were, for example, in the Upper Valdarno (where the sinuosity changed from 1.80 to 1.05) and the Pisan meanders (from 1.80 to 1.55). The main areas with variations in braiding and reductions in width correspond to the stretches, for example in the Upper Valdarno (where braiding goes from 3 to 1 and the width decreases from 700 m to 130 m) and in the Florentine Plain (where braiding goes from 5 to 1 and the width from 700 m to 170 m).

The stability of the riverbed is due to the presence of coarse sediments and to the small amount of bed load transport. Changing the bed load transport artificially, or extracting gravel from the riverbed, can produce direct effects, such as erosive processes. Such effects, in the Arno River, are now in progress. They are due to:

1) the artificial reduction in width of the cross sections which produced an increase of stream power;
2) the decrease in the bed load transport, because of sediment retention by the artificial basins of Laterina and Levane and by hydraulic-forest systematization in the entire watershed which has further contributed to the reduction in the sediment discharge of the river;
3) the extraction of sand, gravel and pebbles from the riverbed over the past few decades.

Apart from causing a generalized lowering of the bed, with maximum decrease of over 10 m in the Lower Valdarno, these causes also drastically reduced the number of sedimentary bodies, which were present in very great quantities in the past. For example, the braids have disappeared completely, longitudinal bars are very rare, and lateral bars are rare and confined to the upper part of the river, upstream of Florence. The meander bars remain relatively more numerous, but downstream of Florence there is an almost total absence of bars and at this point the bed is now a channel.

As a result of these morphological-sedimentary conditions we have the following situations: a generalized sedimentary deficit, a widespread state of active lateral and vertical erosion and a trend towards remaining in this state of disequilibrium which will continue to evolve, thus critically threatening the stability of the banks and the longitudinal and transverse works of the river.

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