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Human impact on sediment yield and channel dynamics in the Arno River basin (central Italy)

PAOLO BILLI & MASSIMO RINALDI
Dipartimento di Ingegneria Civile, Università di Firenze, Via S. Marta 3, I-50139 Firenze, Italy

Abstract The Arno River basin has been subjected to human disturbance and modification since Roman times. Until 1800 the main aims of such modifications were to provide flood protection for adjacent towns and to acquire new land for cultivation. During the nineteenth and twentieth centuries the Arno River basin underwent additional significant modifications, including reforestation, upland sediment retention, a huge increase in bed material exploitation, the construction of two reservoirs and bank protection works. The combination of reduced sediment supply and increased sediment transport capacity resulted in extensive streambed degradation that threatened the stability of several bridges and other structures. In order to identify the dominant channel changes and the relationship between vertical and lateral adjustments, a comparison of many cross-sections spanning a period of more than one century was made. The relative importance of human activity in causing channel adjustment compared with natural changes, such as the progressively lower runoff recorded during the last seven decades, is discussed.

INTRODUCTION

A river and its catchment make up a very complex natural system embracing the interaction of many factors. The streambed morphology is the ultimate expression of all the physical processes operating at the basin scale, but it is primarily influenced by streamflow and sediment supply. Both discharge and sediment transport rate are not constant but vary through time, with the greatest variations occurring during floods. Stream channels adjust to such variations and the central tendency represents the most probable state, i.e. the actual river morphology (Leopold, 1994). In the geological record there is evidence of rivers that underwent major channel changes as they responded to climate changes, tectonic reactivation or both these factors. A natural river achieves the new state of equilibrium through many small adjustments and over a relatively long period. Valley fill and alluvial terraces are examples of river response to changing runoff, sediment yield and topographic conditions.

Shortly after his appearance on earth, man proved to be a very powerful geomorphic agent, capable of being even more effective than natural processes in shaping the landscape. In a region such as Tuscany, where civilization developed 3000 years ago and proceeded over the following millennia to cause constant interactions with the landscape, the growing exploitation of natural resources has led to such a complicated and widespread influence of human intervention that even small portions of the present landscape can hardly be defined as really natural. Since pre-Roman times, the landscape ecology of Tuscany has undergone substantial modification and our environmental ethic has to be adapted to this. In some cases man has tried to counter the instability he introduced by means of "environmentally-oriented" intervention but the former natural conditions have been seldom restored.

River adjustments to natural or anthropogenic changes are not easily predictable. Recently developed numerical models have increased the potential for predicting channel geometry variations under given hydraulic conditions, but there are few examples of documented river response to variations induced by human activity and this results in an important limitation to our understanding of the significance of human impact on river systems. The Arno River (the largest river of Tuscany) (Fig. 1) has experienced significant and extensive human modification at both the channel and basin scale, and it therefore provides an interesting study case for examining the effects of human activity on river dynamics and adjustment.

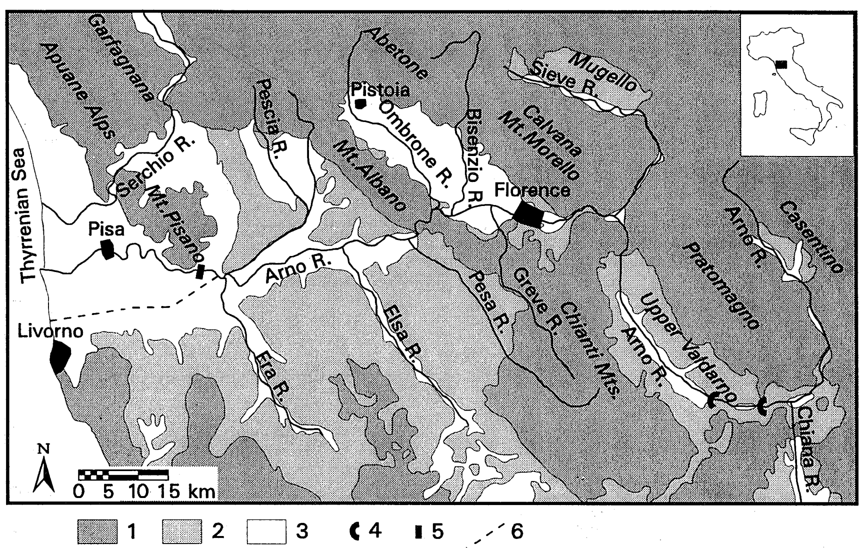

Fig. 1 Location map of the Arno River system. 1: older than Miocene rocks, 2: Plio-Pleistocene marine and fluvio-lacustrine deposits, 3: Holocene alluvial deposits, 4: Levane and La Penna dams, 5: Bientina culvert, 6: diversion canal.

STUDY AREA

The Arno River is the largest river in Tuscany. Its catchment is about 8228 km^2 and it is ranked fifth among the largest basins of Italy. It rises in the northern Apennines and flows into the Thyrrenian Sea near Pisa, with a course of about 245 km (Fig. 1). The physiography of the watershed is strongly influenced by recent (Plio-Pleistocene) normal faulting which formed several intermontane basins filled with fluvio-lacustrine deposits. The main river stem therefore consists of reaches cut into the unconsolidated sediments of the intermontane basins, alternating with narrow

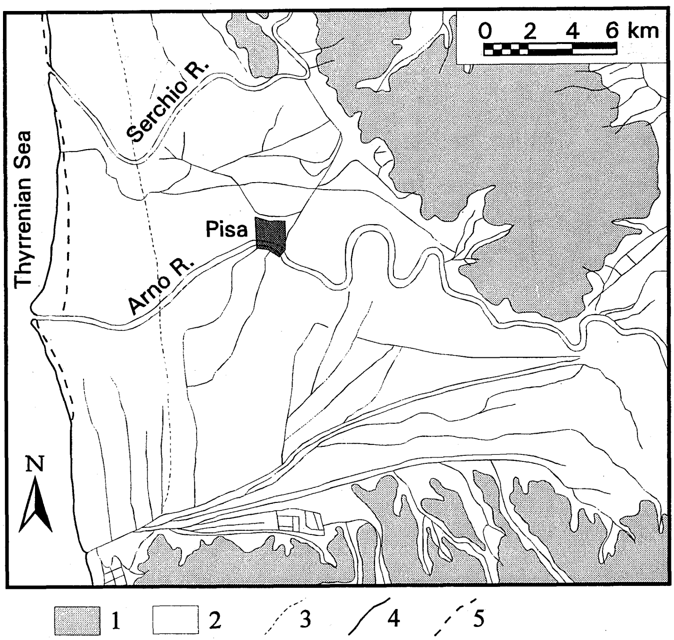

Fig. 2 Coastline variations. 1: hillslopes, 2: alluvial and coastal deposits, 3: coastline of the eighth-second century B.C, 4: 1830 coastline, 5: present coastline (modified from Ceccarelli-Lemut *et al.*, 1994).

bedrock-controlled reaches (Fig. 1). From the most downstream gorge to its junction with the Era stream, the Arno River flows through a wide alluvial plain developed on Pliocene marine deposits. The lower reaches cross the coastal plain of Pisa and a delta whose cuspate morphology was developed by the river in historical times (Fig. 2). With such a physiographic setting, the river course can be conveniently subdivided into several main alluvial reaches. From upstream to downstream these are: Casentino, Upper Valdarno, Florence Plain, Lower Valdarno and Pisa Plain (Fig. 1). Basic hydrological data, relating to the most downstream flow gauge, are reported in Table 1.

Land use has changed considerably since human occupation of the Arno River basin. At present, the principal land use categories, expressed as percentages of the total watershed area, are as follows: urban and related built up areas, 5%; cultivated land, 48%; pasture and grassland, 7%; forest, 39%; water surfaces and wetland, 1%.

Table 1 Main hydrological characteristics of the Arno River at S.Giovanni alla Vena.

Drainage area (km^2)	8190	Mean discharge ($m^3 s^{-1}$)	97.0
Annual rainfall (mm)	1030	Minimum discharge ($m^3 s^{-1}$)	2.2
Maximum elevation (m a.s.l.)	1650	Average max. discharge ($m^3 s^{-1}$)	1520.0
Average elevation (m a.s.l.)	330	Maximum discharge ($m^3 s^{-1}$)*	2060.0

* Recorded on 4 November 1966.

Table 2 Historical floods in Florence from 1177 to the present.

Medium	Large	Exceptional
1261, 1303, 1305, 1362, 1368, 1378, 1406, 1434, 1490, 1491, 1520, 1538, 1550, 1621, 1641, 1651, 1660, 1674, 1683, 1695, 1698, 1715, 1745, 1761	1177, 1269, 1282, 1284, 1288, 1334, 1345, 1380, 1456, 1465, 1515, 1532, 1543, 1544, 1646, 1676, 1677, 1680, 1687, 1688, 1705, 1709, 1714, 1719	1333, 1547, 1557, 1589, 1740, 1758, 1844, 1966

FLOOD HISTORY

On 4 November 1966, a large flood inundated the town of Florence and large portions of the adjoining flood plain, causing considerable damage to many public and private properties and to the art heritage. The magnitude of this flood, probably the largest ever reported in the historical record, was certainly exceptional, but seven other floods with about the same destructive power have occurred during the past 2000 years (see Table 2). Historical documents report that since the twelfth century the waters of the Arno River have inundated the centre of Florence on 48 other occasions. Half of these floods have been described as large events, while the remainder caused only minor damage (Table 2). In order to protect the flood-prone territory, many attempts were made to control the flow of the Arno river (see the following section for details), but they were largely unsuccessful, as demonstrated by the frequency of exceptional floods, with half of them occurring in the last two and a half centuries.

Reliable rainfall and flow data are available only since 1822 and 1924 respectively. Analysis of these recent data seems to indicate a trend opposite to that associated with the frequency of the largest floods. In fact, Rapetti & Vittorini (1994), for the 1924-1983 period, pointed to a decrease of 2.9 mm year^{-1} in the water yield, paralleled by a similar decrease in the annual runoff, though at a smaller rate (1.8 mm year^{-1}). A similar trend can be also observed for the annual maximum discharges during the period 1924-1992, as shown by Cavazza (1994) (Fig. 3).

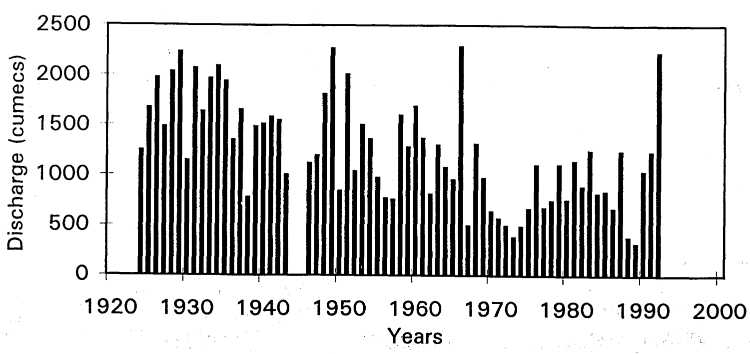

Fig. 3 Coastline variations. 1: hillslopes, 2: alluvial and coastal deposits, 3: coastline of the eighth-second century B.C, 4: 1830 coastline, 5: present coastline (modified from Ceccarelli-Lemut *et al.*, 1994).

THE HISTORY OF HUMAN INTERVENTION

Eighteen thousand years ago, during the last glaciation, the coastline of Tuscany extended much further offshore than at present, since the eustatic minimum was about 110 m below the sea level of today (Mazzanti & Nencini, 1994). The Holocene marine transgression ceased in the Etruscan-Roman period as a consequence of the increase in sediment supply induced by deforestation. This resulted from the rapid increase of population in the watershed and it can be seen as the first significant human impact on the Arno river system. The increased sediment supply was able to counter the marine transgression and to reverse the former trend, notwithstanding a persistent sea level rise. The coastline progradation proceeded at an almost constant rate from the eighth century BC to the mid nineteenth century. Since then, the trend of coastal evolution was reversed again, as beaches started retreating (Fig. 2). The most important causes of this are the use of the river load for land reclamation, bed material extraction, instream engineering works and extensive human activity at the basin scale.

River training works

Many different engineering works have been undertaken on the Arno River channel during the last two millennia. The construction of the first levees in the reach between Pisa and the Upper Valdarno coincided with Roman land partition, but it continued and was reinforced during the Middle Age (Ceccarelli-Lemut *et al.*, 1994). In the Florence area, important river engineering works such as channelization and embankments were completed from the twelfth to the fourteenth century. Artificial meander cut-offs were cut from 1338 to 1771 in the Lower Valdarno, while straightening of the mouth was completed in 1606. Three diversion canals were dug in 1558, 1568 and 1976 upstream of Pisa, in order to prevent the town from flooding by conveying part of the flood water into coastal marshes or directly into the sea (Fig. 1). The discharge withdrawn from the Arno River through the more recent diversion canal can be as much as 900 $m^3 s^{-1}$, which represents about 40% of the maximum flood flow.

Two decades, extending from 1703 to 1723, were necessary to complete the straightening and levee construction on a 20 km reach in the Upper Valdarno, but a few relatively large floods that occurred in the following three decades were reported to have caused local streambed degradation and undermining of the embankments. During the eighteenth century and the first half of the nineteenth century, artificial levees and bank protection works were constructed out in the Florence area and in the Casentino respectively.

In order to improve the efficiency of the reclamation system for the Bientina marshes, the gradient of the outflow canal was increased and a culvert was necessarily built under the Arno River, upstream of Pisa (Fig. 1). This represents a fixed point that has locally impeded channel adjustment and gave the definitive coup de grace to river navigation. In 1957 two dams were built in the upstream reaches of the Upper Valdarno basin for hydropower and flood control purposes. At present the upstream reservoir has lost most of its flood retention capacity due to deposition of sediment.

Finally, one of the most significant and widespread human activities is bed material mining. River bed sediment had been always exploited in the past centuries but at a modest rate, which was unable to produce any significant effect on the prevailing depositional trend. At the beginning of this century, the demand for river sediment as building material increased greatly following the modernization and industrial development of the area. During the three decades after World War II the volume of bed material extracted from the Arno River and its tributaries increased by several orders of magnitude, initially as a consequence of the post war reconstruction and, later, as a result of the rapid industrialization and urbanization. The effects of such extensive sediment exploitation, were soon evident and, at the beginning of the 1980s, the local authorities found that the only effective measure to halt the severe river bed degradation was to prohibit bed material extraction.

Land management

Information regarding land use and land management prior to 1500 is scanty and limited. However, the human impact at the basin scale, though constantly increasing, probably had less effect on river aggradation than in the following three centuries. In fact, in the sixteenth century, deforestation was notably accelerated by a major expansion of cultivated land in the hilly and mountainous areas. The Medicean legislation of the seventeenth century imposed some constraints on free forest cutting, but they were removed in 1773 by Peter Leopold of Habsbourg, Grand Duke of Tuscany. Three years later vast areas of the northern Apennines were described as completely bare and partial control of deforestation was introduced again. Nevertheless, there is evidence that during the first half of the nineteenth century most of the Arno River, with probably the exception of the Upper Valdarno, was still aggrading (Giorgini, 1854), since excess transport capacity due to channelization was balanced by the higher sediment supply (Becchi & Paris, 1989).

Since 1850 a drastic change in land management policy favoured the reforestation of large upland areas, the stabilization of slopes and mountain stream banks and the construction of weirs and other sediment retention systems. Such conservation practices have been carried out until the present and have embraced the entire mountainous portion of the catchment. During the sixties, the fast economic development, associated with rapid industrialization, induced relevant social changes resulting in progressive population migration from the country to towns that has left many areas uncultivated. The abandoned croplands were soon colonized by shrubby vegetation, typical of the Mediterranean climate, further diminishing the volume of sediment supplied to the Arno River.

CHANGES IN CHANNEL MORPHOLOGY

The present river morphology is the result of such extensive and widespread channelization and engineering works that only very few short reaches can be considered to be in a natural state. These are mainly the bedrock controlled reaches, which are characterized by a single channel with a relatively steep gradient and are punctuated by small, coarse-grained sediment bodies. In the channelized reaches upstream of Florence, the river morphology consists of a single channel with alternate lateral bars. In the Lower Valdarno the river pattern is sinuous to meandering, fixed by artificial levees, but without point bars or other channel deposits.

From a document produced in the mid thirteenth century it can be deduced that in the Casentino reach the Arno River had a braided channel morphology. Maps produced by Leonardo da Vinci show that upstream and downstream of Florence the river was much wider than today and that it had a braided morphology, whereas it was typically meandering in the Lower Valdarno. More information on the river morphology is available from historical maps and reports for the period 1550-1850. In the alluvial reaches of Casentino and Upper Valdarno, the streambed was wider than present and showed a wandering pattern, with a few braided reaches. On the Pisa Plain the Arno was meandering with sandy point bars and chute channels.

RIVER ADJUSTMENTS

In order to investigate historical and recent channel changes and evolution, various different types of evidence were utilized. These included historical maps, topographic maps, photographs, longitudinal profiles and cross-sections. Of the many, but often incomplete, channel surveys undertaken from 1845 to the present, those of 1844-1847, 1952-1955 and 1978-1980 are considered here as they are homogeneous and thus more suitable for comparison. Longitudinal profiles derived from absolute bed elevation data, indicate that degradation is the dominant type of streambed adjustment, while only minor aggradation occurs locally (Fig. 4). For the period investigated, total bed lowering typically ranges from 2 to 4 m in the Upper

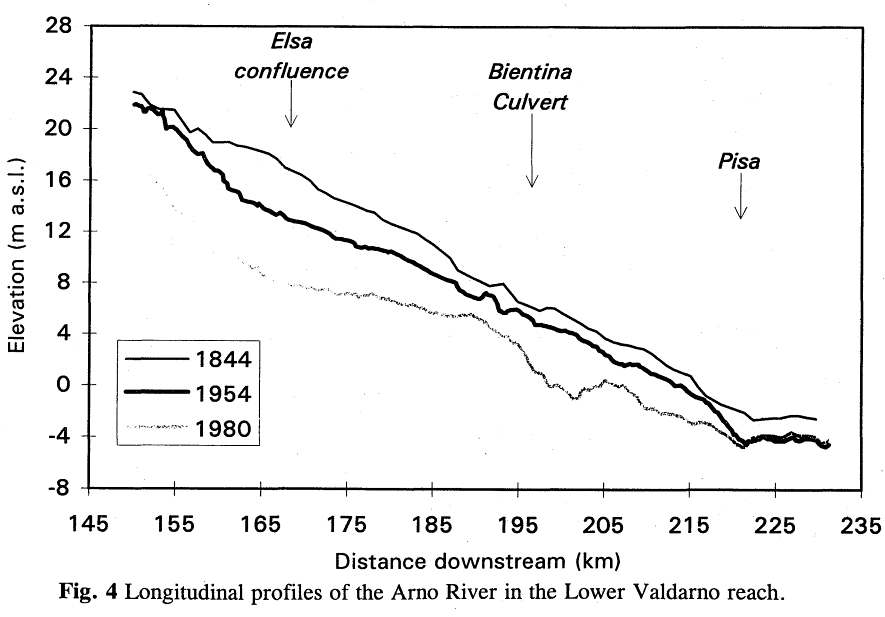

Fig. 4 Longitudinal profiles of the Arno River in the Lower Valdarno reach.

Valdarno and from 5 to 9 m in the Lower Valdarno. Half of this lowering was achieved from 1950 to 1980, indicating an acceleration in the degradation processes (Fig. 4). Streambed adjustments were also associated with variations in channel gradient. Rinaldi & Simon (1996) identified a progressive gradient reduction for both the Upper and Lower Valdarno, with the latter reach characterized by a larger degree of change.

Hydraulic geometry parameters (width, depth, area, wetted perimeter and hydraulic radius) related to the maximum channel capacity (top bank) were measured for all the cross-sections associated with the surveys considered in this paper. For instance, in the Lower Valdarno, the average value of the ratio between the cross-section areas for the surveys of 1954 and 1936 is 1.05 (extreme values 0.9-1.6), while it increases to 1.21 (extreme values 0.8-1.85) for the 1980/1954 ratio. As the width ratios for the same cross-sections in the same time periods do not depart significantly from 1, it is evident that the main hydraulic geometry changes occurred through bed degradation (Fig. 5). Streambed degradation is commonly associated with channel widening (Simon, 1989), but in the Arno River the extensive bank protection works have prevented the stream from eroding laterally and contributed to increasing the bed degradation processes.

NATURAL VERSUS MAN-INDUCED CHANGES

In the previous section we have shown that the present streambed degradation started more than a century ago. The causes of that are manifold and they affected the river

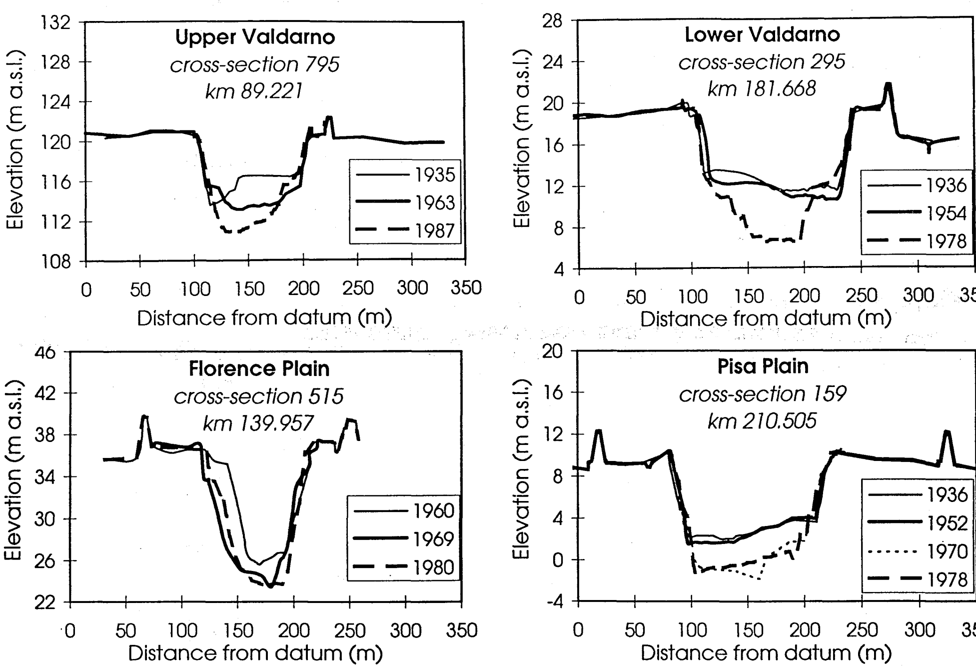

Fig. 5 Examples of cross-section changes in the Arno River in its main alluvial reaches.

at different rates and times. Although reliable hydrological data sets are available for only the last seven decades (1924-present), the effectiveness of natural factors seems very limited compared to human impact. Rapetti & Vittorini (1994) pointed out that annual precipitation and flow exhibit a diminishing trend during this century and a similar tendency can be found in the distribution of annual peak discharges (Cavazza, 1994) (Fig. 3). From 1850 to 1950 the Arno River bed degraded about as much as during the following three decades (1950-1980), i.e. in this latter period the stream bed adjusted at a rate three times greater than in the previous century. However, such an acceleration in the degrading processes is not paralleled by any significant change in runoff and streamflow.

Pranzini (1983) demonstrated that the maximum retreat of the beaches fed by the Arno river sediment took place during the same 1950-1980 interval (Fig. 2). Accurate sea level measurements have proved a recent eustatic rise that has been considered by a few authors (e.g. Pranzini, 1995) as a possible additional cause of the severe erosion that is affecting many Italian beaches.

For the Arno River, Becchi & Paris (1989) have calculated a sediment yield of about 1.37×10^6 m^3 $year^{-1}$ before the sixteenth century, 5.15×10^6 m^3 $year^{-1}$ from 1500 to 1800 and 1.91×10^6 m^3 $year^{-1}$ on average for the last 50 years. According to these authors, the present bed material production (1.12×10^6 m^3 $year^{-1}$) is equivalent to the volume of gravel and sand excavated from the streambed and trapped by the two reservoirs upstream of the Upper Valdarno reach. Therefore, the bedload actually transported to the river mouth ($0.83 \times 10^6 m^3$ $year^{-1}$) can only derive from stream bed and bank erosion that Becchi & Paris (1989) calculated to be around 0.81×10^6 m^3 $year^{-1}$. From comparison of longitudinal profiles for the period 1845-1960, they calculated a lower streambed erosion rate of 0.27×10^6 m^3 $year^{-1}$, corresponding to one fifth of the actual bedload yield, that can be associated primarily with the effect of reduced sediment supply induced by reforestation. From the 1950s to the 1980s, the sediment supply was further diminished by the addition of the negative effects of two other important factors: the construction of the Levane and La Penna reservoirs and the remarkable increase of bed material mining that rapidly attained an industrial level. Data presented by Montefusco & Sansom (1979) indicate that washload is primarily responsible for sedimentation of the upstream reservoir of La Penna because bedload is intercepted upstream by mining activity and is thus largely prevented from being deposited in both reservoirs. Following Becchi & Paris (1989) the amount of sediment excavated from the streambed can be estimated to be about 1.1×10^6 m^3 $year^{-1}$, representing about four fifths of the potential bedload yield of the Arno. From these data it can be concluded that man is the principal cause of the severe erosion of the delta and the streambed degradation that has characterized the Arno River adjustments during the last four decades.

For the period 1500-1800, Becchi & Paris (1989) calculated a sediment yield about four times greater than that for the previous 15 centuries, when almost natural conditions prevailed in the river and its basin. Reliable hydrological data are obviously not available and any explanation of such an increase in sediment yield can be only speculative. Sixty percent of the floods that inundated Florence have occurred between the sixteenth and the eighteenth century. Some authors consider this as valid proof of the so called "Little Ice Age" (Le Roy Ladurie, 1972) that seems to have occurred also in Italy. Nevertheless, the uncontrolled deforestation that characterized land management during these centuries and the resulting river bed aggradation may have played an important role in providing a channel morphology with a reduced flood conveyance. However, a likely climatic deterioration, as well as other social factors, might have induced the vast deforestation that largely contributed to the increased sediment supply. Therefore, for this period also, the significance of human impact on the Arno River, though difficult to quantify, was probably greater than that of natural changes.

CONCLUSIONS

The significance of human impact on river changes is highly variable, since it depends on the type of activity and the spatial and temporal scale of its application to the catchment or the streambed.

During the last two millennia, the Arno River underwent extensive training works and land management changes as a result of disparate social influences. The river reacted with major remarkable adjustments, consisting primarily of either streambed aggradation or degradation. From comparisons of channel surveys, carried out during the period 1844-1980, a general degrading trend can be observed. The average bed lowering is 2-4 m and 5-9 m for the upstream and downstream alluvial reaches respectively. Half of such degradation occurred during the last three decades, when the maximum delta erosion and beach retreat were also recorded. Reforestation, bed material mining and the construction of two upstream reservoirs are the main causes since the general decrease in runoff does not show an equivalent abrupt change. From the available data, it can be estimated that reforestation accounts only for 20% of the reduction in the potential (i.e. under almost natural conditions) sediment supply while the remaining 80% was withdrawn by mining activity. Natural changes, such as imperceptible precipitation variations, are likely to have contributed to the changes observed on the Arno River, but the role and significance of human activity have been far greater.

REFERENCES

Becchi, I. & Paris, E. (1989) Il corso dell'Arno e la sua evoluzione storica (The Arno River course and its historical evolution). *Acqua Aria*, 645-652.

Cavazza, S. (1994) L'idrologia attuale. La natura ed i molteplici interventi umani (Present hydrology. Nature and multiple human interventions). In: *La Pianura di Pisa e i Rilievi Contermini* (ed. by R. Mazzanti), *Mem. Soc. Geogr. It.* **50**, 431-463.

Ceccarelli-Lemut, M. L., Mazzanti, R. & Morelli, P. (1994) Il contributo delle fonti storiche alla conoscenza della geomorfologia (The contribution of hystorical sources to the knowledge of geomorphology). In: *La Pianura di Pisa e i Rilievi Contermini* (ed. by R. Mazzanti), *Mem. Soc. Geogr. It.* **50**, 401-429.

Giorgini, C. (1854) Sui fiumi nei tronchi sassosi e sull'Arno nel piano di Firenze: Discorso preceduto e accompagnato da considerazioni riguardanti l'avanzamento dell'Idraulica Fisica (On gravel reaches of rivers and on the Arno in the Florence plain: Talk preceded and accompanied by considerations regarding the progress of Physical Hydraulics). Tipografia delle Murate, Firenze.

Leopold, L. B. (1994) *A View of the River*. Harvard University Press, Cambridge, Massachusetts.

Le Roy Ladurie, E. (1972) *Times of Feast, Times of Famine: a History of Climate Since the Year 1000*. Allen & Unwin, London.

Mazzanti, R. & Nencini, C. (1994) La morfologia (The morphology). In: *La Pianura di Pisa e i Rilievi Contermini* (ed. by R. Mazzanti), *Mem. Soc. Geogr. It.* **50**, 89-102.

Montefusco, L. & Sansom, R. (1979) Analisi dell'interrimento dell'invaso di La Penna (Fiume Arno) (Analysis of the filling of the La Penna reservoir - Arno River). In: *Incontro delle unit[di ricerca toscane con gli enti utilizzatori sui temi concernenti la potenzialit[e utilizzazione dei suoli, l'erosione dei versanti, le frane, la dinamica fluviale e la dinamica dei litorali,* Firenze, D, 1-16.

Pranzini, E. (1983) Studi di geomorfologia costiera IX - L'erosione del delta dell'Arno (Studies of coastal geomorphology IX - Erosion of the Arno River delta). *Quad. Mus. St. Nat. Livorno* **4**, 7-18.

Pranzini, E. (1995) Cause naturali ed antropiche nelle variazioni del bilancio sedimentario dei litorali (Natural and anthropogenic causes of the sediment budget variations of beaches). *Mem. Geografiche* **1**, 47-62.

Rapetti, F. & Vittorini, S. (1994) I caratteri del clima (Characteristics of climate). In: *La Pianura di Pisa e i Rilievi Contermini* (ed. by R. Mazzanti), *Mem. Soc. Geogr. It.* **50**, 103-132.

Rinaldi, M. & Simon, A. (1996) Bed-level adjustments in the Arno River, central Italy, submitted for publication.

Simon, A. (1989) A model of channel response in disturbed alluvial channels. *Earth Surf. Processes and Landforms* **14**, 11-26.