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Bed-level adjustments in the Arno River, central Italy

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Abstract

Two distinct phases of bed-level adjustment over the past 150 years are identified for the principal alluvial reaches of the Arno River (Upper Valdarno and Lower Valdarno). The planimetric configuration of the river in these reaches is the result of a series of hydraulic works (canalization, rectification, artificial cut-offs, etc.) carried out particularly between the 18th and the 19th centuries. Subsequently, a series of interventions at basin level (construction of weirs, variations in land use), intense instream gravel-mining after World War II, and the construction of two dams on the Arno River, caused widespread degradation of the streambed. Since about 1900, total lowering of the channel bed is typically between 2 and 4 m in the Upper Valdarno Reach and between 5 and 8 m in some areas of the Lower Valdarno Reach. Bed-level adjustments with time are analyzed for a large number of cross-sections and described by an exponential-decay function. This analysis identified the existence of two main phases of lowering: the first, triggered at the end of the past century; the second, triggered in the interval 1945–1960 and characterized by more intense degradation of the streambed. The first phase derived from changes in land-use and land-management practices. The second phase is the result of the superimposition of two factors: intense instream mining of gravel, and the construction of the Levane and La Penna dams. © 1998 Elsevier Science B.V.

Keywords: channel adjustment; degradation; human impacts; Arno River; channel evolution; Italy

1. Introduction

Alluvial channels, destabilized by different natural and human disturbances, pass through a sequence of channel forms with time (Davis, 1902; Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989). Channels respond to imposed disturbances by altering morphology, sediment load, and hydraulic characteristics. Adjustments can involve short time intervals (days) and limited spatial extents, or longer periods of time (scores to hundred of years) and entire fluvial systems, depending on the magnitude, extent, and type of disturbance (Simon, 1994). Human-induced disturbances often have a detrimental effect on stream-channel dynamics by accelerating or altering natural processes and trends, resulting in a compressed time scale for channel adjustments.

In many fluvial systems, channel evolution has been significantly affected by human disturbances, such as land-use changes, urbanization, channelization, dams, sand and gravel mining (Wolman, 1967; Schumm, 1969, 1977; Park, 1977; Kellerhals, 1982; Petts, 1984; Schumm et al., 1984; Williams and Wolman, 1984; Brookes, 1988; Simon, 1989; La-

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jczak, 1995). Throughout Europe, large alluvial rivers have experienced a long history of human modification such that by the beginning of the 20th century, few 'natural' river reaches remained (Petts et al., 1989). The period of major human impact extends back for at least 200 years. Although some research (Castiglioni and Pellegrini, 1981; Braga and Gervasoni, 1989) has documented planform variations and human impact on the alluvial rivers of central and northern Italy, little work exists on bed-level adjustments induced by human disturbances (Rinaldi and Rodolfi, 1995).

The Arno River has been subjected to numerous human disturbances and modifications since the Roman Period, approximately 2000 years ago. The intent of the modifications from Roman times until 1800 were to provide flood protection to adjacent towns, increase the conveyance of the channel, prevent bank erosion, and increase the productivity of agricultural land on the Arno River flood plain. During the 19th and 20th centuries additional modifications (construction of weirs and dams, sediment mining) were imposed on the Arno River. The modifications resulted in: (1) an increase in channel conveyance and, therefore, stream power and sediment-transporting capacity (from levee construction and channel straightening); (2) degradation of the streambed (from mining of the channel bed and upstream-migrating knickpoints); (3) degradation of the streambed downstream from dams (from reduced supplies of bed sediment from upstream); and (4) a decrease in the volume of sediment delivered to the Arno River from tributaries (from sediment trapping behind weirs and considerable land-use changes). The combination of the reduced delivery of tributary and instream sediment, with increased sediment-transporting capacity, resulted in widespread lowering of the channel bed along the length of the Arno River. Because these various types of human-imposed disturbances were temporally and spatially variable, channel adjustments along the Arno River are complex.

The overall objective of this paper is to analyze bed-level adjustments in a river subjected to various types of human disturbances (variations in land use, construction of weirs on tributaries, instream sediment mining, construction of dams on the main channel) over a reasonably long time period (about 150 years). Specific purposes are to: (1) analyze bed-level responses to human disturbances by describing bed-level adjustments at different sites with a nonlinear function, and by developing an empirical model of bed-level response for two representative alluvial reaches of the river; (2) compare bed-level adjustments of the Arno River with channel responses and trends observed in other fluvial systems characterized by different physical conditions and human activities.

2. Description of the Arno River system and study reaches

The stream network of the Arno River system is strongly influenced by the morphology of the region, especially by the occurrence of a series of intermountain basins. The main rivers of the fluvial system (Arno, Sieve, Ombrone, Bisenzio; Fig. 1) display features typical of alluvial channels as they cross intermountain basins; however, in other reaches the rivers are semi-confined and controlled by bedrock. The alluvial reaches of the Arno River, where vertical and lateral adjustments may take place, are: Upper Casentino, Arezzo Plain, Upper Valdarno, Florence Plain or Middle Valdarno, and Lower Valdarno (Fig. 1). The Upper and Lower Valdarno reaches (Fig. 1) were selected for this study because the beds are free to adjust vertically and because historical data are available for the period 1840–1990. The Upper Valdarno Reach is located between Levane Dam and the Incisa Gorge, with a length of about 30 km. The Lower Valdarno Reach is located between the Gonfolina Gorge and Pisa, and has a length of about 70 km.

The length of the Arno River is about 241 km. Much of its planimetric pattern is the result of a series of river-training and straightening projects. Some evidence from historical cartographic research (Canuti et al., 1992) illustrates that the 'natural' channel morphology of the river was intermediate between braided and sinuous. These alluvial reaches are separated by semi-confined reaches within a narrow valley bottom. In the Lower Valdarno, the river changes gradually into a meandering form within a broader valley (Canuti et al., 1994).

At present (1996) in the Upper Valdarno, the river is almost straight with alternate bars. Channel width

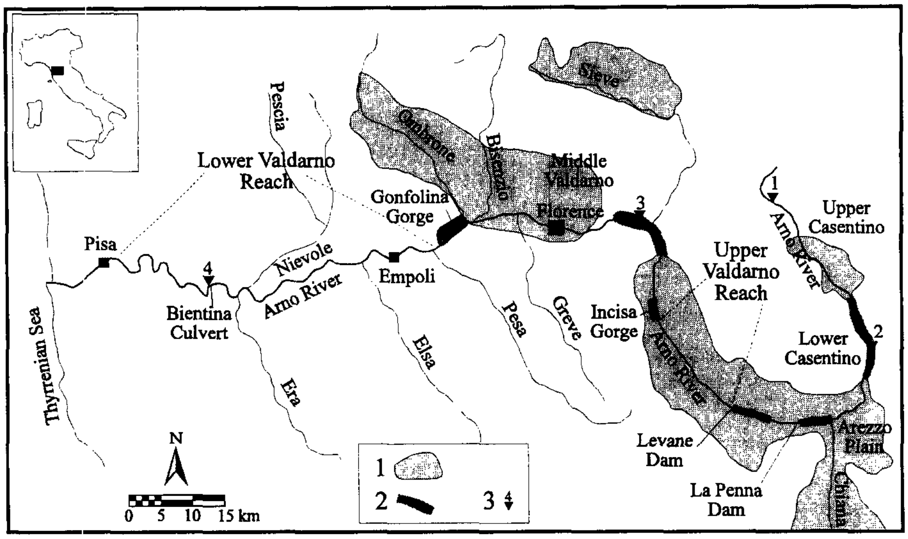

Fig. 1. Location map for the Arno River system, central Italy: *1* = intermountain basin; *2* = valley constriction and rock threshold; *3* = gauging station.

is slightly greater than 100 m and is constrained within embankments. Channel gradient ranges from 0.001 to 0.0017 m/m (Fig. 2). In the Lower Valdarno Reach, sinuosity is less than 1.5, channel width is generally between 100 and 200 m, and alternate bars are nearly absent. Channel gradient varies from 0.0002 to 0.0007 m/m (Fig. 2). Channel planform and bed elevation are fixed by concrete in the vicinity of the urban areas of Florence and Pisa.

The size of bed sediment of the Arno River is distinctly bi-modal and is composed of sand- and gravel-sized clasts. Mean particle size of the bed material ranges from medium gravel in the Upper Valdarno Reach to fine gravel and medium sand in the Lower Valdarno Reach (Tacconi et al., 1994; Fig. 3).

The hydrologic regime shows a large difference between minimum and maximum mean-daily discharges (Table 1). Annual flood peaks for the most downstream gage (S. Giovanni alla Vena) range from 321 to 2290 m^3/s (recorded on November 4, 1966). Morozzi (1762) reports that the center of

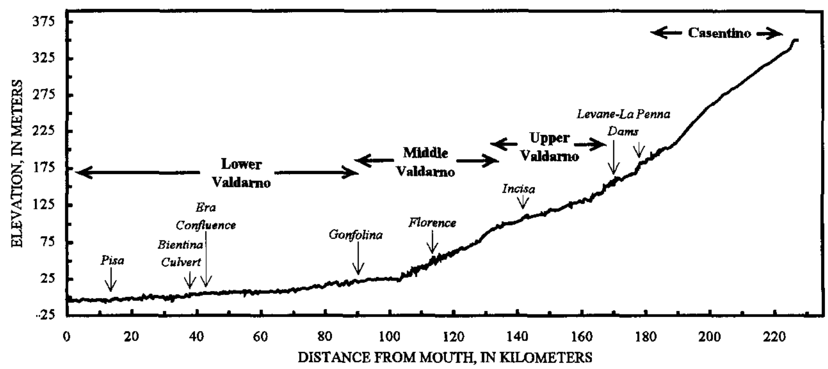

Fig. 2. Longitudinal profile of the Arno River (data from surveys of 1980–1987).

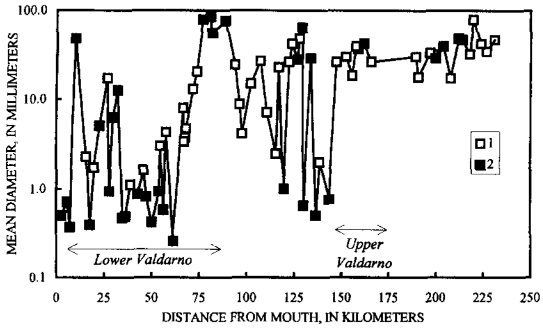

Fig. 3. Mean particle size of bed material: *1* = subarmour; *2* = undifferentiated (modified from Tacconi et al., 1994).

Florence was inundated 56 times since the 12th century. The last of these floods occurred in 1966 and had a discharge of more than 4000 m^3/s immediately upstream of Florence. Channel capacity of the Arno River at Florence is about 2500 m^3/s. This flood was certainly exceptional, but seven other floods of similar magnitude have occurred in the past 2000 years. Basic morphometric, climatic and hydrologic data for four flow-gauging stations are shown in Table 1.

3. Human modifications and disturbances

The first constructed embankments existed in Roman times for flood protection of the main towns. Artificial cut-offs were made in 1340 shortly upstream from the mouth (Piccardi, 1956). Between the 16th and 18th centuries, channel straightening and additional cut-offs were completed in the Lower Valdarno Reach. These works reduced the length of the mouth reach by about 13 km, and sinuosity was decreased from about 1.9 (prior to 1340) to the present (1996) value of 1.45. Between the 18th and 19th centuries, several river-training works were made on the Arno and important tributaries to provide flood protection and to place additional floodplain land in agricultural production. These works reduced the width of the channel considerably and levees were constructed closer to the water course than had been done previously. In 1860 a concrete culvert was built at the confluence of the Bientina Canal with the Arno River (Fig. 1), thereby creating a fixed bed at this location. Additional indirect disturbances which affected the dynamics of the Arno River occurred discontinuously at the basin level (Table 2). These include: deforestation, reforestation, land-use changes and land-management practices, expansion or contraction of cultivated lands, and construction of weirs on tributaries.

The recent (1840–1990) stream-channel dynamics may have been induced by the following factors.

(1) Initiation of reforestation and upland sediment retention as a result of land-management laws of 1877, 1912, 1923, and 1933 (Natoni, 1944).

(2) Sand and gravel mining, irrelevant at the turn of the 20th century, increased greatly during reconstruction of infrastructure following World War II.

(3) The Levane and La Penna dams were constructed just upstream of the Upper Valdarno Reach, and became operational in 1957.

Table 1
Morphometric, climatic, and hydrologic data for gauging stations of the Arno River (from Canuti and Moisello, 1980; locations are shown in Fig. 1)

Flow gauging station	Drainage area (km^2)	Average basin elevation (m a.s.l.)	Relief (m a.s.l.)	Runoff (mm)	Q_{min} (m^3/s)	Q_{50} (m^3/s)	Q_{max} (m^3/s)	Q_{pk} (m^3/s)
Stia (1)	62	891	1210	1300	0.01	1.58	148	46.6
Subbiano (2)	738	720	1410	1288	0.17	18.5	1120	491
Nave di Rosano (3)	4080	450	1590	1040	0.56	56.7	1960	1280
S. Giovanni alla Vena (4)	8190	330	1650	1030	2.20	97.4	2060	1520

Q_{min} = minimum mean-daily discharge; Q_{50} = median of mean-daily discharges; Q_{max} = maximum of mean-daily discharges; Q_{pk} = mean of the annual peak discharges.

Table 2
Type, extent, and date of human modifications and disturbances to the Arno River system

Type of human modifications and disturbances	Periods and reaches
Embankments	Since Roman period; Upper and Lower Valdarno reaches
Artificial cut-offs	Since 1340 in the mouth reach; 17th–18th century in the Lower Valdarno Reach
River training works (straightening, bank protection, embankments)	From the 18th century in the Middle–Upper Valdarno; first half of the 19th century in the Casentino and Lower Valdarno
Disturbances at basin level: deforestation, reforestation, variations in land-use practice, weirs along tributaries	Discontinuously on whole basin; increased following laws of 1877, 1912, 1923, 1933
Construction of the Levane and La Penna dams	1957, just upstream of Upper Valdarno Reach
Gravel and sand mining	Since first decades of 20th century; increased during 1945–1980

(4) Bank protection, concrete-lining of channels, and levee construction throughout urban areas such as Pisa, Empoli, and Florence.

The channel modifications conducted on the Arno River had a number of effects on river flow. Before channelization, large parts of the adjacent floodplain were subjected to frequent inundation. As a consequence, these flood flows could dissipate energy by spreading across the floodplain. The increased capacity of the channelized river resulted in: (1) a given discharge having greater flow depth and erosive power than previously, and (2) the channel being able to contain higher discharges and probably, greater flow velocities.

4. Available data

Data from the following topographical surveys were considered.

(1) Profile of the channel bed taken in 1845–1947 between the Chiana confluence and the mouth (Manetti and Renard, 1847).

(2) Cross-sections surveyed in 1917–1918 between Florence and the Era confluence by the Communal Technical Office of Florence.

(3) Cross-sections surveyed in 1923–1927 between Florence and the Era confluence by the Special Office of the Genio Civile.

(4) Cross-sections surveyed in 1935–1936 on the Upper and Lower Valdarno by the Hydrographic Office of the Arno River.

(5) Surveys by the Hydrographic Office of the Arno River carried out in different reaches in the following years: 1952–1955, 1961–1963, 1964, 1968, 1970, 1978–1980, and 1987–1991.

Cross-section numbers refer to the surveys listed in item (5), above. The numbers increase with distance upstream from the mouth of the Arno River. These cross-sections are used to develop time-series channel profiles and temporal trends of bed-level adjustment in the Upper and Lower Valdarno reaches.

5. Bed-level adjustments

5.1. General

To analyse general adjustments of bed-level, time-series profiles of the Upper and Lower Valdarno reaches are used because in these reaches the river is free to adjust its morphology to imposed changes. Comparison of longitudinal profiles (Fig. 4) indicates that degradation is the dominant type of bed-level adjustment whereas minor aggradation locally occurs.

Vertical adjustments of the channel bed are documented starting from 1844, whereas data concerning the trend of bed-level adjustment during previous periods are not available. Nevertheless, on the basis of numerous historical evidence, it is probable that most of the fluvial system was in an aggradational phase or at least not in degradation before 1844, in spite of the training works carried out previously or during that period in some reaches of the Arno River (Casentino and part of Lower Valdarno) (Viviani, 1669; Morozzi, 1762; Rossini, 1852; Giorgini, 1854). This hypothesis is also inferred from the dynamics of the river delta (Pranzini, 1989; Alessandro et al., 1990). A voluminous supply of sediment, derived

Table 3
Variations of channel gradient for Arno River sub-reaches

Reaches	Extremities (km)	Channel gradients 1844	1917–1918	1922–1927	1935–1936	1952–1955	1961–1963	1970	1978–1980	1987–1990
A (Upper Valdarno)	165 –153	0.0016			0.00157		0.00154			0.0013
B (Upper Valdarno)	153 –142	0.00123			0.00122		0.00096			0.00098
C (Lower Valdarno)	85 –72	0.00032	0.00056	0.00036		0.00052			0.00064	
D (Lower Valdarno)	72 –36.6	0.00040	0.00030	0.00030	0.00040	0.00030			0.00020	
E (Lower Valdarno)	36.6–15	0.00050			0.00030	0.00030		0.00020	0.0002	

from intense deforestation and consequent soil erosion, occurred in most parts of the drainage basin during the 18th and 19th centuries. This increased supply of sediment probably counterbalanced the increased sediment-transport capacity resulting from channelization (Becchi and Paris, 1989).

Starting from the end of the 19th century and particularly during the first decades of the 20th century, the issuance of a series of land-management laws led to reforestation and sediment retention from large upland areas, resulting in a major reduction of sediment supplied to the fluvial system. During the

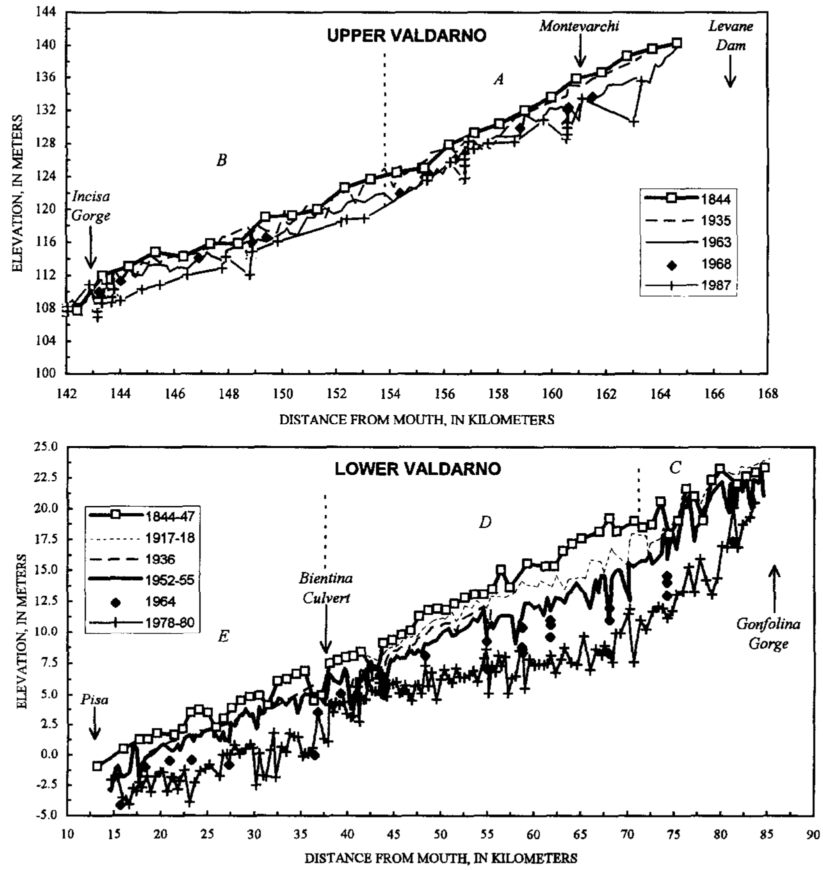

Fig. 4. (a) Longitudinal profile of the Upper Valdarno Reach: sub-reaches *A* and *B* as defined in Table 3. (b) Longitudinal profile of the Lower Valdarno Reach: sub-reaches *C*, *D*, and *E* as defined in Table 3.

last 50 years, other important human activities, such as in-channel sediment mining and construction of dams on the main stem, again caused an imbalance between the supply of sediment and sediment-transporting capacity. Because of this imbalance, channel adjustments occurred to offset the discrepancy between sediment supply and transport capacity, and the Arno River entered into a new phase of adjustments to re-attain a state of dynamic equilibrium (Lane, 1955; Schumm, 1969, 1973; Chang, 1988). The excess sediment-transport capacity in the Arno River induced degradation, resulting in an increase of bed-material transport, a decrease in channel gradient, and consequently, a reduction in sediment-transport capacity.

Variations in channel gradient over the period 1844–1980 are shown in Table 3 for five sub-reaches with spatially homogeneous gradients. In the Lower Valdarno Reach, adjustments of bed-level and channel gradient were controlled somewhat by the presence of three fixed points on the channel bed: Gonfolina Gorge (bedrock), Bientina Culvert and Pisa Reach (concrete-lined channel). A progressive flattening of channel gradient with time is observed in the reaches upstream of the fixed points. Sub-reach D experienced a 50% reduction in channel gradient; sub-reach E, a 60% reduction (Table 3). Channel gradient steepened by 100% with time downstream from the first fixed point (sub-reach C in Table 3). Gradient adjustments in both sub-reaches of the Upper Valdarno (A and B) over the period 1844–1987 were considerably less; about 20% (Table 3).

Total lowering of bed-level in the Upper Valdarno is generally between 2 and 4 m; maximum amounts of degradation over the period 1844–1980 reach almost 9 m near river kilometer 70 in the Lower Valdarno (Fig. 5). The spatial trends of lowering the bed-level in the Lower Valdarno Reach are influenced by the location of the three fixed points where values converge to 0.0 m. From the available data it appears that most of the degradation over the period 1844–1980 occurred between the 1950s and 1980 (Fig. 5), during the period of the most extensive instream mining, and the construction of the Levane and La Penna dams.

Nearly all of the bedload supplied from the Casentino reaches of the Arno River and the Chiana River is trapped by the La Penna Dam (Fig. 1). This material is extracted by mining. The Upper Casentino, having the greatest relief in the Arno River basin, is subject to frequent landslides that favors high rates of bedload discharge. The sediment trapping effect of the dams on the rates of bedload discharge can, therefore, be considered significant. For the period 1958–1963 the trap efficiency of La Penna Dam for suspended sediment was calculated to be 26% (Montefusco and Sansom, 1979).

5.2. At a site

Bed-level adjustments at a site through time are best described mathematically by nonlinear functions, where changes occur rapidly at first and then slow and become asymptotic (Graf, 1977; Williams

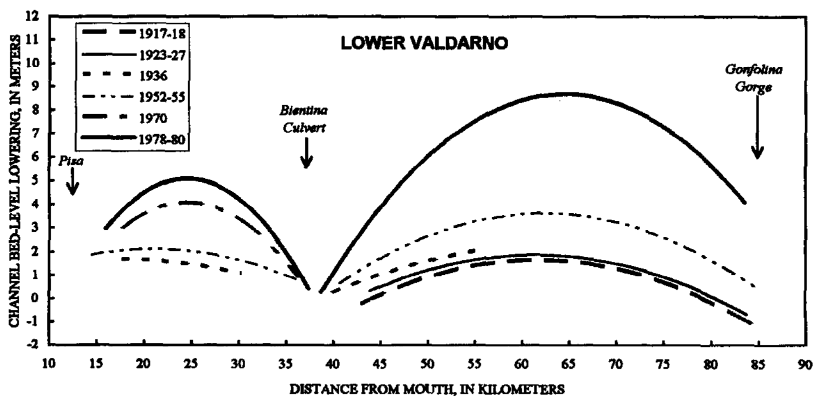

Fig. 5. Lowering of channel bed-level from 1844 to the indicated time for the Lower Valdarno Reach.

and Wolman, 1984; Simon and Hupp, 1986; Simon, 1989, 1992). A convenient way to interpret temporal and spatial trends of aggradation and degradation is to fit nonlinear functions to bed elevations measured through time, and to plot a measure of these functions versus the distance from the river mouth (Williams and Wolman, 1984; Simon, 1989, 1992).

Numerous types of nonlinear functions were tested for goodness of fit with bed-level data from the Arno River. The function that consistently gave the best results was a dimensionless exponential function (Simon, 1992):

$$z/z_0 = a + b\,e^{(-kt)} \tag{1}$$

where z is the elevation of the channel bed (at time t); z_0 is the elevation of the channel bed at t_0 ($t_0 = 0$); a is a dimensionless coefficient, determined by regression analysis and equal to the dimensionless elevation (z/z_0) when Eq. (1) becomes asymptotic: $a > 1$ for aggradation, $a < 1$ for degradation; b is a dimensionless coefficient, determined by regression analysis and equal to the total change in the dimensionless elevation (z/z_0) when Eq. (1) becomes asymptotic: $b > 0$ for degradation, $b < 0$ for aggradation; k is a coefficient determined by regression analysis, expressing the rate of change on the channel bed per unit time; t is the time since the year prior to the onset of the adjustment process, in years ($t_0 = 0$).

This equation has been used to develop empirical models of the adjustment of bed-level in diverse fluvial environments (sand-bed Coastal Plain system to gravel–cobble-bedded alpine system) that result from different, but single, disturbances (Simon, 1992). In the case of the Arno River, Eq. (1) is used to describe the adjustments in bed-level resulting from discontinuous disturbances that are superimposed in time and space. Bed-level adjustments, therefore, are described as more than one phase of degradation.

To identify the number of adjustment phases and, for each phase, the starting time of the adjustment processes (t_0), Eq. (1) was optimized relative to the coefficient of determination (r^2) and residual values. A series of representative cross-sections with sufficient data on bed-level adjustment from the early- to mid-20th century were used to define degradation trends with confidence (Fig. 6). This analysis provided evidence of two main degradational phases. The first one was identified with data from 1917 to 1918, 1923 to 1927, and 1935 to 1936; the second with data from 1952 to 1990. Because bed-elevations for the representative sections are similar for 1844 and around 1900, and because data between 1844 and the first evidence of degradation are not available, it has been assumed that no significant changes occurred during this interval (dashed line in Fig. 6). It is probable, however, that some aggradation occurred during this period. Estimates of the amount of degradation during this first phase, therefore, represent minimums.

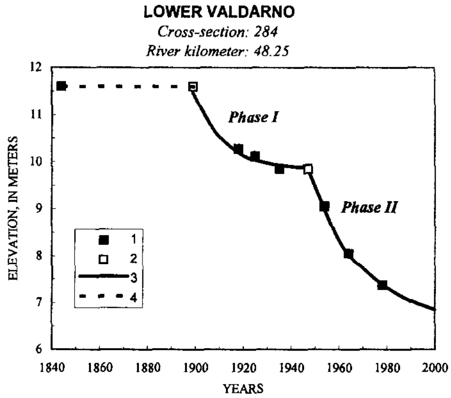

Fig. 6. Lower Valdarno Reach. Example of fitting exponential-decay equation to trends of bed-level through time and identifying two phases of degradation: *1* = surveyed data; *2* = assumed data; *3* = calculated exponential-decay Eq. (1); *4* = assumed trend.

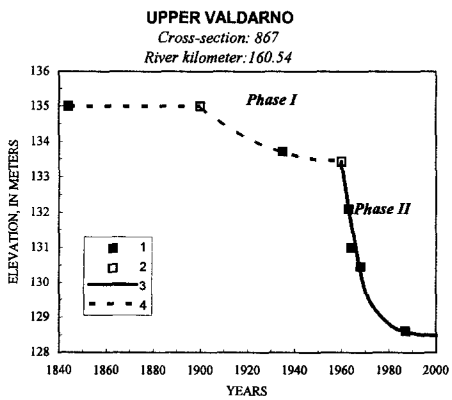

Fig. 7. Upper Valdarno Reach. Example of fitting exponential-decay equation to trends of bed-level through time and identifying two phases of degradation: *1* = surveyed data; *2* = assumed data; *3* = calculated exponential-decay Eq. (1); *4* = assumed trend.

Table 4
Cross-sections analyzed with calculated exponential equation

Section	km	t_0	z_0	n	a	b	k
131	18.00	1910	1.30	3	0.620	0.404	0.055
131	18.00	1960	−0.70	4	0.200	0.885	0.100
142	20.69	1913	1.70	3	0.780	0.233	0.046
142	20.69	1960	0.55	4	0.000	1.169	0.120
144	21.13	1914	1.70	3	0.700	0.320	0.034
144	21.13	1960	0.30	4	0.200	0.895	0.110
153	23.09	1909	3.30	3	0.781	0.196	0.040
153	23.09	1960	1.15	4	0.000	1.142	0.117
259	43.43	1900	7.90	2	0.973	0.019	0.043
259	43.43	1946	7.69	4	0.746	0.263	0.056
269	44.46	1900	9.30	3	0.860	0.149	0.043
269	44.46	1945	8.00	3	0.680	0.355	0.042
271	44.84	1900	9.40	3	0.880	0.128	0.057
271	44.84	1945	8.27	3	0.630	0.395	0.041
273	45.21	1900	9.50	3	0.890	0.116	0.041
273	45.21	1945	8.46	3	0.640	0.399	0.039
275	45.85	1900	9.80	3	0.897	0.110	0.037
275	45.85	1945	8.79	3	0.540	0.506	0.050
276	46.12	1900	9.90	3	0.820	0.201	0.028
276	46.12	1945	8.12	3	0.620	0.425	0.035
277	46.52	1900	10.10	3	0.840	0.175	0.034
277	46.52	1945	8.48	3	0.470	0.589	0.036
282	47.55	1898	11.20	3	0.854	0.160	0.089
282	47.55	1945	9.56	3	0.520	0.517	0.045
284	48.25	1900	11.60	3	0.855	0.148	0.085
284	48.25	1947	10.01	4	0.645	0.350	0.039
285	48.64	1899	11.80	3	0.840	0.170	0.052
285	48.64	1945	9.91	3	0.500	0.548	0.046
287	49.52	1901	11.90	3	0.850	0.157	0.040
287	49.52	1945	10.12	3	0.370	0.697	0.046
289	50.30	1902	11.80	3	0.910	0.097	0.068
289	50.30	1945	10.74	3	0.550	0.482	0.041
291	51.20	1900	12.20	3	0.880	0.129	0.043
291	51.20	1945	10.74	3	0.460	0.579	0.046
293	51.99	1900	12.60	3	0.860	0.153	0.085
293	51.99	1945	10.84	3	0.530	0.527	0.044
295	53.02	1900	12.90	3	0.880	0.128	0.050
295	53.02	1945	11.35	3	0.500	0.521	0.060
302	54.90	1900	13.20	3	0.845	0.166	0.063
302	54.90	1945	11.15	3	0.737	0.280	0.062
322	58.74	1900	15.00	3	0.889	0.116	0.043
322	58.74	1945	13.33	4	0.600	0.397	0.070
336	61.73	1900	15.30	3	0.895	0.088	0.050
336	61.73	1945	13.70	4	0.560	0.477	0.062
388	74.25	1951	18.61	4	0.540	0.523	0.066
390	74.22	1950	18.56	4	0.540	0.491	0.059
392	74.19	1951	18.44	4	0.540	0.480	0.053
417	80.09	1900	23.30	3	0.994	0.007	0.030
417	80.09	1951	23.16	4	0.650	0.380	0.046
423	81.00	1900	22.90	3	0.997	0.003	0.020
423	81.00	1953	22.83	4	0.780	0.242	0.056
426	81.25	1950	22.80	3	0.680	0.360	0.085
800	146.90	1961	114.40	5	0.979	0.023	0.053
809	148.79	1960	117.50	5	0.955	0.046	0.100
826	152.19	1962	121.30	4	0.973	0.028	0.100
829	153.04	1961	122.80	4	0.968	0.035	0.141
834	154.36	1960	124.90	5	0.971	0.028	0.200
839	155.37	1958	125.90	4	0.981	0.023	0.170
843	156.22	1960	127.26	4	0.987	0.016	0.180
848	156.75	1960	127.80	6	0.986	0.018	0.220
859	158.63	1958	130.90	4	0.979	0.026	0.190
863	159.70	1960	132.53	3	0.987	0.016	0.220
867	160.55	1960	133.25	5	0.965	0.043	0.200
869	160.58	1960	134.20	5	0.963	0.046	0.220
873	161.12	1960	134.60	3	0.992	0.011	0.235
875	161.51	1958	135.60	5	0.980	0.025	0.240

km = distance from mouth, in kilometers; t_0 = year prior to the start of the adjustment process; z_0 = elevation of the channel bed at $t = t_0$; n = number of observations; a, b, k = dimensionless coefficients, determined by regression of the exponential-decay Eq. (1).

The analysis performed on the representative cross-sections suggests that the first degradational phase began around 1900 (during the period 1898–1914), as a result of change in land management and consequent reduction of sediment supply to the fluvial system. The second phase of degradation started between 1945 and 1950 for the Lower Valdarno (Fig. 6) and around 1960 in the Upper Valdarno Reach (Fig. 7), coinciding with the period of intense instream mining and with the construction of the Levane and La Penna dams, respectively.

Subsequently, the general empirical model of two main degradational phases was verified for all the study cross-sections. Variations in the general nonlinear temporal trends of bed-level from local scour at bridges or other structures is superimposed on the generalized trends of degradation and in some cases, hinders the interpretation of two separate degradational phases. Examples of fitting Eq. (1) to the two degradational phases are shown in Figs. 6 and 7. Results obtained for all the study cross-sections are listed in Table 4.

5.3. Spatial trends

Spatial trends of the rates and magnitudes of the adjustment of bed-level for the two study reaches can be interpreted by analyzing coefficients of Eq. (1). The nonlinear rate of bed-level adjustment is

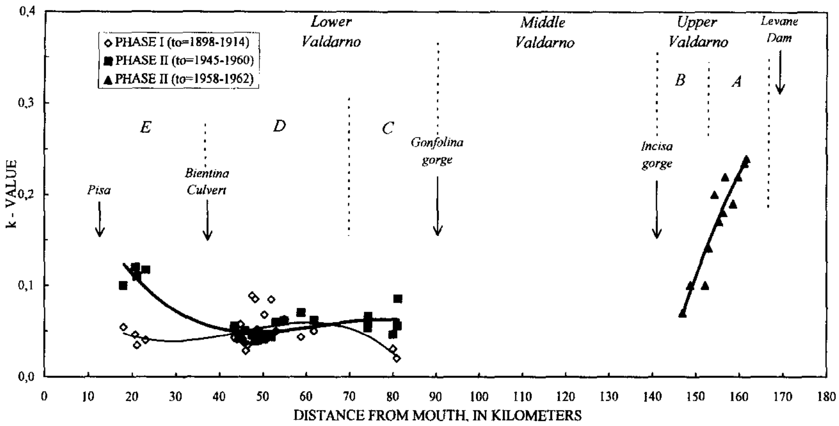

Fig. 8. Empirical model of the adjustment of bed-level for the Arno River: variation of k-values with the distance from the river mouth. k = coefficient determined by regression indicative of the rate of change on the channel bed per unit time; A, B, C, D, E are sub-reaches as defined in Table 3.

represented by k; magnitude is represented by the dimensionless change in elevation (coefficient b) when time (t) becomes large and Eq. (1) becomes asymptotic. Because the value of the dimensionless coefficient b depends on the value of z_o, it is difficult to make direct comparisons of the magnitude of the adjustment of bed-level between the two reaches. To alleviate this problem, a dimensional value equal to the difference between z_o and the elevation when Eq. (1) becomes asymptotic (z_{as}) was used to compare magnitudes of degradation. This dimensional parameter represents the total amount of degradation during a single phase.

An empirical model of bed-level adjustment for the Upper and Lower Valdarno reaches is obtained by plotting the coefficient k and the value of $z_o - z_{as}$ against distance upstream from the mouth of the Arno River (Figs. 8 and 9).

5.4. Discussion

Differences in the rates and magnitudes of adjustment of bed-level of the first and second degrada-

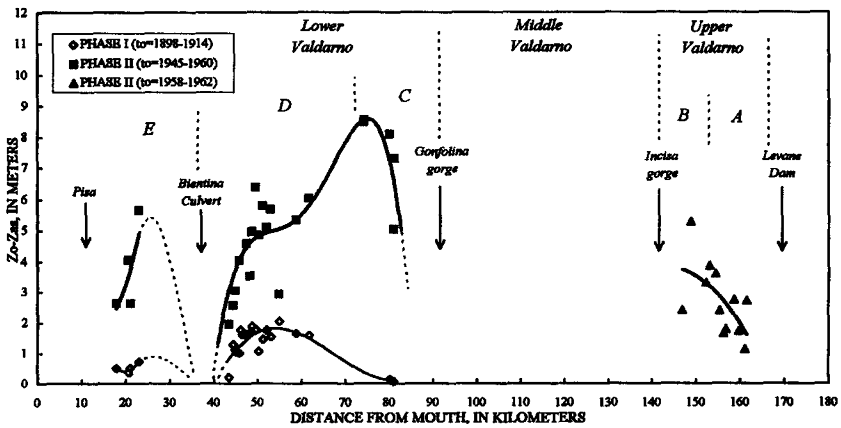

Fig. 9. Empirical model of the adjustment of bed-level for the Arno River: variation of $z_o - z_{as}$ values with the distance from the river mouth. z_o = initial elevation of the channel bed; z_{as} = elevation of the channel bed when Eq. (1) becomes asymptotic; A, B, C, D, E are sub-reaches as defined in Table 3.

tional phases can be observed in the Lower Valdarno. Here, the spatial trend of lowering bed-levels, unlike the k coefficient, shows a strong influence of the fixed points, particularly the Bientina Culvert, where degradation approaches zero (dashed curves in Fig. 9). Phase 2 is characterized by greater amounts of degradation than phase 1, although large differences in rates of degradation (k) are not observed. For Phase 1, maximum degradation occurred at river kilometers 53 and 25, about 16 km upstream and 12 km downstream of the Bientina Culvert, respectively. During Phase 2, primary and secondary peaks of bed-level lowering occurred at river kilometers 75 and 25, respectively. Sub-reach C experienced the greatest amount of degradation during this phase.

The reaches just upstream and downstream of the Bientina Culvert (sub-reaches D and E) adjusted the channel gradients to about 3.0×10^{-5} during the first degradation phase, and to 2.0×10^{-5} during the second (Table 3). Sub-reach C adjusted to steeper channel gradients; 3.6×10^{-5} for the first degradation phase, and 6.4×10^{-5} for the second (Table 3).

For both degradational phases, adjustment of channel gradient appears to be influenced by variations in the particle size of the bed material. Sand is the predominant bed material in sub-reaches D and E; gravel in sub-reach C (Fig. 3). Adjusted channel gradients are about the same for sub-reaches D and E whereas the channel adjusted to a steeper gradient in sub-reach C where gravel predominates (Fig. 3; Table 3). Adjusted channel gradients in the gravel-bedded Upper Valdarno (sub-reaches A and B) are also considerably higher than in the sand-bedded reaches of the Lower Valdarno (Table 3). These results suggest two possible hypotheses: (1) channel gradients adjusted to variations in the particle size of bed material as controlled by sediment inflow from tributary streams and in the case of the Upper Valdarno, selective erosion of sand downstream from Levane Dam resulting in a gravel-dominated bed; or (2) differences in the particle size of bed material observed at present may be the result of differences in adjusted channel gradients because of lowering bed-level. It is not possible given the available data to determine which hypothesis is more likely.

The spatial trend of the k-values in the Upper Valdarno Reach indicates a downstream reduction in the rates of degradation. This is probably the result of two factors: (1) the effects of the Levane Dam, located 5 km upstream of the reach, and (2) the presence of the Incisa Gorge, the downstream limit of the reach, where k-values approach zero. Rates of degradation (k-values) typically are greatest immediately downstream from dams (Williams and Wolman, 1984) because of the sediment-free water released from the dam. Erosion of bed material in the reach just downstream of the dam somewhat counteracts the imbalance between sediment-transport capacity and the supply of sediment such that reaches further downstream degrade at slower rates. One would expect total amounts of degradation to show a similar trend with distance downstream. This is not the case, however, in the Upper Valdarno. Because of limited amounts of data and because of the superimposition of adjustments resulting from two disturbances, a specific cause cannot be attributed to the reversed relation shown in Fig. 9. The degradation near river kilometer 150 may correspond to adjustments in bed-level resulting from clear-water erosion migrating downstream from the dams and from degradation resulting from gravel mining in the reach. Furthermore, armoring of the channel bed is probably greatest immediately downstream of the Levane Dam, and results in the coarsest surface bed-material in the reach.

5.5. Aggradation and channel widening

Channel adjustments in the Arno River differ from similar unstable fluvial systems subjected to human disturbances because aggradation in downstream reaches and, channel widening following degradation has been limited. This is relatively uncommon for an unstable stream undergoing bed degradation in its middle and upstream reaches. Models of channel evolution in disturbed alluvial channels (Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989) show aggradation in downstream reaches as degradation migrates upstream, and widening following sufficient lowering of bed-level.

Variations in the magnitude and timing of the processes represented in these idealized models of channel response can result from differences in: (a) channel type; (b) bed and bank material; (c) local bedrock or artificial controls; (d) additional human

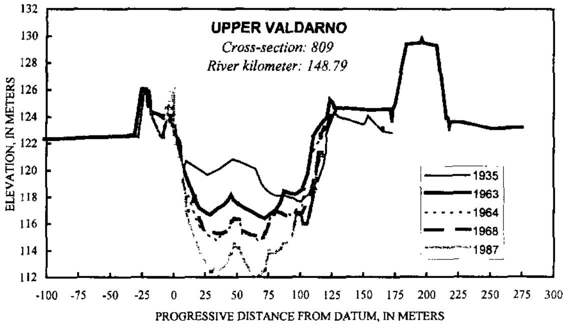

Fig. 10. Example of cross-sections changes in the Upper Valdarno where bank protection limited channel widening.

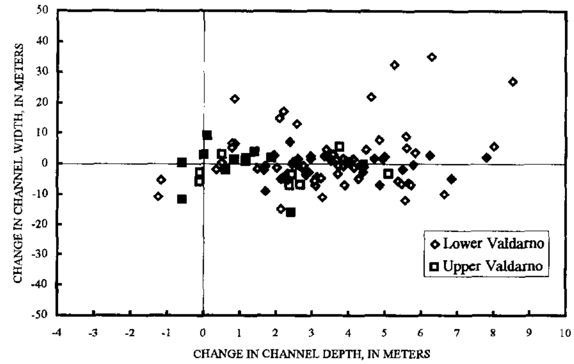

Fig. 12. Change in channel width as a function of change in channel depth. Note: black symbols represent cross-sections with bank protection.

modifications and disturbances; (e) extreme hydrologic events; and/or (f) morphological and lithological characteristics of the drainage basin. Human impact appears to be the most relevant difference, in the case of the Arno River because the types of human disturbances were temporally and spatially variable.

Comparison of time-series cross-sections was performed for numerous sites in the two study reaches to document the types of changes in channel geometry with time (examples in Figs. 10 and 11). Changes in channel width, depth and area during the past 50 years (Figs. 12 and 13) were obtained by comparing cross-section surveys of 1935 and 1987 for the Upper Valdarno, and of 1935 and 1980 for the Lower Valdarno. This is the period during which most of the reported channel adjustments occurred. Results confirm that channel widening has been of limited significance along much of the Arno River (Figs. 10 and 12). Although degradation of the channel bed caused increased bank heights that can result in bank instability, bank protections such as concrete linings, rip rap, and gabions are common. As shown in Fig. 12, where bank protections are present at least on one side of the channel, changes in channel width are limited. In reaches where bank protection is absent, however, 20–40 m of channel widening occurred during about the last 50 years (Fig. 11). Because widening was infrequent, changes in cross-section area are mainly the result of increases in channel depth by the lowering of bed-level (Fig. 13).

The lack of significant amounts of channel widening and particularly, the small volumes of coarse sediment (sand- and gravel-sized) delivered from the channel banks and available for fluvial transport contributes to the lack of aggradation and bed-level recovery in downstream reaches of the Arno River. Channel-widening processes can produce large volumes of sediment that can supply hydraulically con-

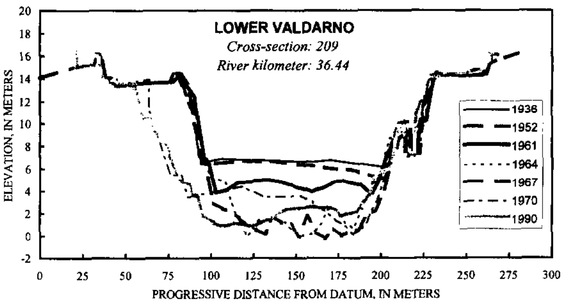

Fig. 11. Example of cross-section changes in the Lower Valdarno.

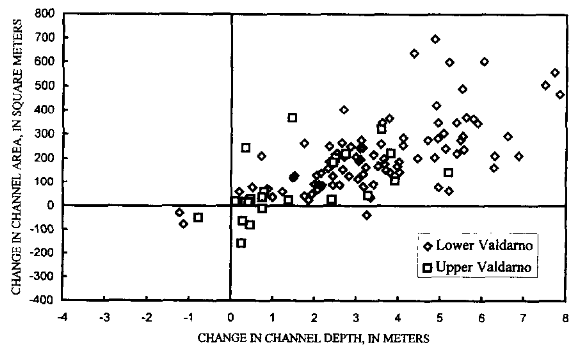

Fig. 13. Change in channel area as a function of change in channel depth.

trolled sediment for aggradation (Simon, 1992). The availability of instream sediment during the 20th century has also been greatly reduced by land-use changes, dam construction, and intense mining. In the Lower Valdarno, detailed historical maps dated 1811 (Département de la Méditerranée, 1811) of the Pontedera–Pisa Reach, made possible a comparison of the surface area of channel bars, a parameter that can be considered a measure of availability of in-stream sediment. Data obtained were compared with measurements from a detailed map of 1954 (Servizio Idrografico, 1954; scale 1 : 10,000), and from air photos of 1986 (survey of Tuscan Region, scale about 1 : 8500). Measurement errors associated with comparison of the historical maps was not considered serious because the latest edition of topographical maps was used as a base. The river course and the channel bars were traced onto these maps and accurate relative positioning was accomplished by overlaying fixed elements such as artificial levees and roads. In spite of the limitations in using historical maps to identify and delimit channel bars, the data show clearly a large reduction in the area of bar surfaces during the 20th century (Fig. 14).

The absence of an observed aggradational phase on the Arno River is directly related to the compound effects of limited availability of sediment from bars and from channel banks. Consequently, the amount of sediment supplied from the channel bed to downstream reaches was generally low relative to the transport capacity of the enlarged channel sections. The absence of an aggradational phase on the Arno River can be attributed to the following factors.

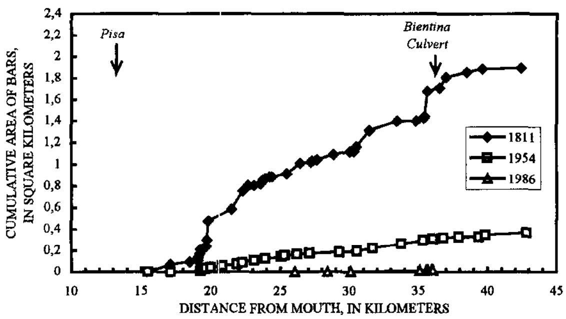

Fig. 14. Variations in total area of bar surfaces from 1811 to 1986 showing a large reduction in the availability of sediment from channel bars.

(1) The presence of embankments resulted in the maintenance of relatively high shear stresses during storm flows, capable of transporting all the sediment delivered from degrading channel beds. During the first degradation phase, a large quantity of sediment was supplied to the Arno River delta, that in many sectors was still actively prograding during the period 1878–1928 (Pranzini, 1989).

(2) Sediment delivered to the channel by bank-failure processes is generally limited in volume and fine-grained (sand and silt), and was probably transported to the sea without any net deposition in the channel.

(3) Notwithstanding the sediment generated from degradation taking place on the Arno River and its tributaries, a large quantity of sediment is trapped by the Levane and La Penna reservoirs, thus reducing the volume of sediment delivered to downstream reaches.

(4) Gravel and sand mining has been carried out along the entire length of the main channel and tributaries of the Arno River system, including the downstream reaches. The availability of sediment was, therefore, greatly reduced.

6. Summary and conclusions

The Arno River has been subjected to a combination of human disturbances during the past 2000 years. An analysis of bed-level adjustments for a large number of cross-sections was carried out. The spatial trends, and rates and magnitudes of these adjustments represent a general model of bed-level adjustments over the past 150 years for the principal alluvial reaches of the Arno River (Upper Valdarno and Lower Valdarno). The effects of former laws of land management, which initiated reforestation and upland sediment retention, affected the main channel of the fluvial system around the end of the 19th century. Variations in land use produced a decrease of sediment supply to the fluvial system, and induced a first degradational phase, triggered between the 19th and 20th centuries. Bed lowering for this first degradation phase ranged from about 0.5 to 2 m.

The second degradational phase, started between 1945 and 1960, as a result of two superimposed causes: (1) intense gravel mining following World War II, and (2) completion in 1957 of the Levane and La Penna reservoirs. Because initial lowering of bed-level during this period (t_0 in Eq. (1)) in the Upper Valdarno coincides with the construction of the Levane and La Penna dams, and degradation rates (k in Eq. (1)) decrease with distance downstream from the dams, clear-water releases can be considered the dominant cause of degradation in this reach. Degradation of the channel bed was between 1 and 3 m; channel gradients did not change significantly. In the Lower Valdarno, sand and gravel mining was the dominant factor, because degradation started between 1945 and 1950, as a result of increased mining following World War II. Sub-reach C experienced the greatest amounts of degradation (5 to 8 m) during this second degradational phase. Channel gradients decreased significantly in sub-reaches D and E, but increased in sub-reach C as a result of bedrock control in the Gonfolina Gorge, that limited the upstream migration of the degradation process.

Channel evolution along the Arno River differs from some other unstable alluvial systems subjected to human disturbance because of a continued lack of additional available sediment from channel banks and bars. During the two phases of degradation, limited amounts of channel widening, mostly from bank-protection measures, resulted in insufficient quantities of sediment delivered to downstream reaches. Aggradation in the downstream reaches, which is common in many unstable streams undergoing upstream degradation, has, therefore, been absent because of limited sediment supplied from widening processes, construction of embankments which maintained high shear stresses and transport capacity during storm flows, sediment trapped in the Levane and La Penna reservoirs, and sediment mining carried out along the same downstream reaches.

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