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The Arno River Floods

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ABSTRACT. The flood history of the Arno River, Italy, is initially described in the wider context of the river system evolution and its interactions with natural and human causes, with particular attention to the last two millennia. A description of the flood history is then reported, using the original data of Morozzi (1762) integrated with more recent data. Eight flood events can be defined as exceptional, but Florence was also inundated in 48 other minor floods. The flood of 4 November 1966 is described in detail, with particular focus on the meteorological causes that determined the exceptionality of the event. After the flood of 1966, other significant events occurred in 1992 over the whole Arno watershed, particularly upstream of Florence. The prevention measures (structural and non-structural measures for flood mitigation) carried out from 1966 to the present day are also described.

Key terms: Arno River, Floods, Florence, Flood mitigation

Introduction

The Arno River basin in Italy is a quite particular case in terms of flood risk issues. Most of the territory is prone to frequent flood hazards, with high levels of risk due to the vulnerability of a unique artistic and cultural heritage.

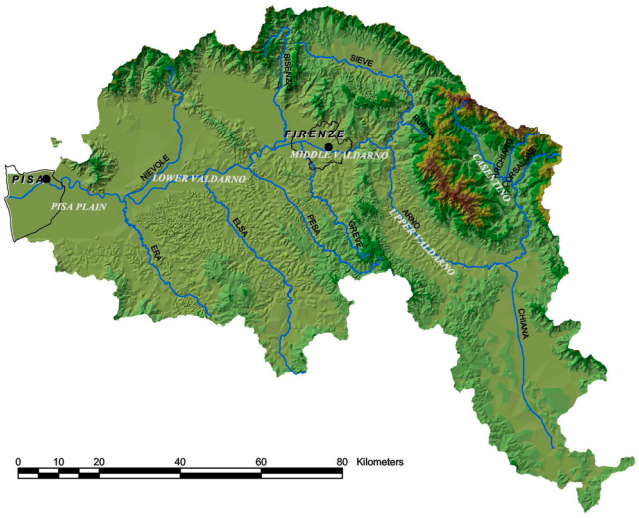


Figure 1 – Geography of the Arno River drainage basin.

The aim of this paper is a general description of the floods of the Arno River, with particular focus on the 4 November 1966 flood that inundated the city of Florence. In particular, the flood history is described in the wider context of the evolutionary trends of the river system, through a discussion of relationships with natural causes and human impacts. A description of the hydraulic risk mitigation measures carried out after the 1966 flood, and particularly the ones nowadays implemented are finally reported.

General Setting

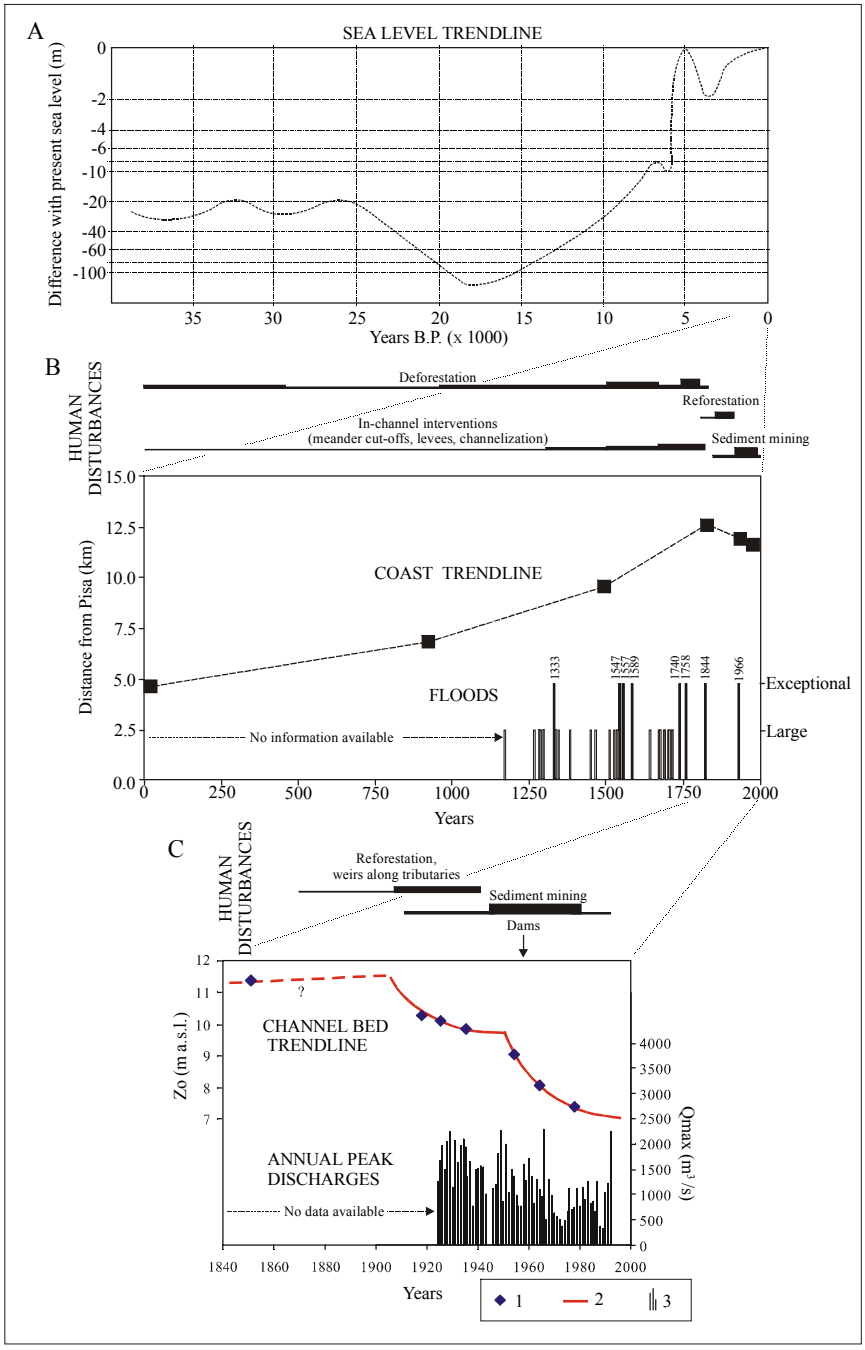
The Arno River is almost entirely situated within Tuscany, Central Italy. The river is 241 km long while the catchment has an area of about 8830 km^2 and a mean elevation of 353 m a.s.l. The catchment area is located within the mountain belt of the Northern Apennines, which was subject during the last phases of its evolution to an extensional tectonic phase, starting from the upper Tortonian in the western part of the basin, and gradually moving towards the NE (BOCCALETTI *et alii*, 1990). This phase produced a horst and graben system, aligned in a NW-SE direction, and a sequence of Neogene marine and fluvio-lacustrine sedimentary cycles.

The physiography of the catchment is strongly influenced by the morphology of the region, being characterized by a series of intermontane basins, alternated with bedrock-controlled gorge-like reaches. The main alluvial reaches from upstream to downstream are: Casentino, Upper Valdarno, the Firenze Plain or Middle Valdarno, Lower Valdarno and the Pisa Plain (Fig.1).

The basin falls into the temperate climatic zone with a dry summer. The general annual rainfall pattern of the Arno basin is characterized by a summer minimum in July, and two maxima, one in November and the other at the end of the winter. Mean values of yearly rainfall vary in relation to relief, ranging from 800 mm in the Chiana valley to about 1800 mm on the Apennine ridge. The hydrologic regime shows a great difference between minimum and maximum mean-daily discharges. Annual peak discharges for the most downstream gauging station (S. Giovanni alla Vena) range from 321 to 2290 m^3/s (recorded on November 4, 1966).

Historical Evolution of the River System

In order to deal with the floods of the Arno River and their occurrence during the past centuries, it is useful to consider them in the wider context of the evolutionary trends of the river system and their relationships with natural causes and human impacts. With this aim in view, it is helpful to introduce three different time scales in which to consider natural and human factors (Fig. 2).



Fiure 2 – Natural factors, human impact, and morphological changes of coastline and channel bed at three different time scales. A) Changes in sea level during the last 40.000 years (modified from ALESSIO *et alii*, 1992). B) Changes of the distance of the sea from Pisa (modified from BECCHI & PARIS, 1989), human disturbances, and large and exceptional floods (from MOROZZI, 1762) during the last 2 millennia. C) Changes in channel bed level, human disturbances, and annual peak discharges during the last 160 years (modified from RINALDI, 2003). 1: Bed-elevation data from longitudinal profiles and cross-sections of the Arno River in a reach of the lower course; 2: trend of bed-level adjustments; 3: Annual peak flow (Qmax) at S.Giovanni alla Vena (upstream Pisa) (data of 1944 and 1945 are missing).

The time scale of millennia is suitable to investigate on the natural climatic trend: the curve in Fig. 2A represents the most reliable information available at present on the main climatic changes in Tuscany during the last 40,000 years. The graph highlights the marine transgression known as "versiliana" following the last glacial peak of about 18,000 years ago. In particular, it is possible to note the last sea-level rising phase during the last 3500 years, rapid until about 2000 years ago, and less pronounced after.

According to the climatic changes of the last millennia, a progressive coastline retreat during the last 3500 years should therefore be expected due to the present sea-level rising phase. Reliable information concerning the coastline changes is limited to the last 2000 years (Fig. 2B). During this period, the distance of Pisa from the sea has been reconstructed (BECCHI & PARIS, 1989), showing a progressive progradation of the mouth until the end of the XIX century.

The increase in sediment transport responsible for this trend is not explainable by the climatic factor. It is evident that some other factor, in particular the human impact, has been responsible for reverting the expected natural trend. Although the human impact appears to be the dominant factor, it is however important to remark the combined role with the climatic factor, directly determining the intensity of the erosion processes and indirectly influencing land use changes.

The main stages of land use changes, channel interventions, and climatic oscillations are summarized as follows and in Table 1.

Pre-Etruscan Period. The start of a significant human impact on the geomorphic processes can be dated from the Neolithic age, with the introduction of cattle-breeding and agriculture, and consequent deforestation of significant areas, which continued for about 4000 years (MAZZANTI, 1994).

Etruscan-Roman Period. During this period, there was a remarkable increase in agricultural development and deforestation. A first period of cold and rainy climate contributed to the intensity of soil erosion on hillsides; an improvement of the climate occurred around 300 B.C. and contributed to the spread of Roman civilization in the Mediterranean area. The construction of the first artificial levees along the main cities and artificial canals in the coastal plain is also dated to the Roman time. In the late Roman Empire, as an effect of an important hydraulic work, the Chiana stream was moved from south to north,

Table 1 – Summary of climatic changes, human impact, morphological changes and floods during the last millennia for the Arno River system.

Period	Climate	Land-use changes	In-channel interventions	Morphological trend of river channel and coastline	Exceptional floods
Neolithic	Mild (climatic optimum 4000 B.C.)	Introduction of cattle-breeding and agriculture	None	unknown	unknown
Etruscan – Roman	Cold (800-300 B.C.) Warm (300 B.C. - 400 A.D.)	Intensification of agriculture and deforestation	First artificial levees	Delta accretion	unknown
	Cold (400 – 800 A.D.)				
Early Middle Ages	Warm (800 – 1150 A.D.)	Crisis of agriculture		Slight delta erosion	unknown
Late Middle Ages	Cold (1150 – 1350 A.D.)	New increase in cultivated lands and deforestation	First artificial meander cut-offs	Delta accretion	1333
	Mild (1350 – 1550)				
Period 1500 - 1700	Little Ice Age (1550 – 1850)	Deforestation; forest cutting constraints	Meander cut-offs, diversion canals	Delta accretion; aggrading channel bed	1547, 1557, 1589
Period 1700 – 1900		Deforestation; Reforestation (from second half of XIX century)	Channelization, last meander cut-offs	Considerable delta accretion (peak in XVIII century) and aggrading channel bed; inversion of coastline trend (end of XIX century)	1740, 1758, 1844
	Warm (1850 – 1950)				
Period 1900 - 2000		Reforestation and construction of weirs in upland areas	Sediment mining (intense from 1950's to 1980's) Dams (1957)	Delta erosion Channel bed incision	1966

Fig.3 – Original draw of *Leonardo da Vinci* sketching the Arno River and the plan for an artificial channel connecting the city of Firenze to the Padule di Fucecchio.

disconnected from the Tevere River and became a tributary of the Arno River, increasing its catchment area by about 700 km^2.

Early Middle Ages. At the end of the Roman period, the large migration of Asiatic populations towards west, in non random coincidence with a climatic change in the cold-humid sense, caused a crises of agriculture, a reduction of the rural population and of the cultivated lands. This situation continued for most of the Early Middle Ages, and it is reflected in a slight erosion of the Arno delta (PRANZINI, 1989).

Late Middle Agse. Starting from the X century and for most of the Late Middle Ages, the rural population increased again, and the consequent new increase in cultivated lands was reflected in a delta accretion. The period between the XIV and XV centuries was instead characterized by the "black death", that caused a reduction by more than a half of the population in Tuscany, and consequently the delta accreted at a reduced rate during this period (PRANZINI, 1989). After this temporary stop, the demographic growth had a new impulse with the feudal reorganization of the Late Middle Ages society, and the agricultural recovery was also favored by mild climatic conditions. The first artificial meander cut-offs were carried out along the Pisa plain starting from the middle of the XIV century, while artificial levees were progressively reinforced in some urbanized reaches.

Period 1500 – 1700. Starting from the Renaissance Period, there was a remarkable intensification of hydraulic interventions along the valley floor (construction of diversion canals, straightening of the mouth, new meander cut-offs). A new climatic crisis occurred, known as the "little ice age", between 1550 and 1850, that caused another acceleration in deforestation and, consequently, in soil erosion and delta accretion. Deforestation was then slowed down by the Medicean legislation (laws imposing severe constraints on forest cutting, issued between 1622 and 1646). The first historical maps of Leonardo da Vinci, made at the beginning of the XVI century, depict the Arno as a braided morphology with a very large channel bed upstream and downstream of Florence (Fig. 3), whereas it was typically meandering in the lower Valdarno reach. Other written documentation of the second half of the XVII century (VIVIANI, 1669) clearly describes the river as in an aggradational phase.

Period 1700 – 1900. The beginning of 1700 was characterized by widespread channelization along the upper Arno reach, and the last meander cut-offs were carried out

during the XVIII century (Fig. 4). Deforestation again accelerated following the cancellation of the previous laws (1776-1780), so that forest cutting activity reached a peak during the second half of the XVIII century, resulting in considerable delta accretion. Historical reports (i.e. PERELLI, 1759, in AIAZZI, 1845) provide evidence of an aggrading channel bed. However, around the second half of the XIX century, in some portions of the basin a significant change in the hydraulic management policy was recorded: the hydraulic interventions started to shift from the valley floor to the upland areas, with the issuing of the first laws on reforestation (1865, 1877) and the construction of weirs along mountain streams. During this period, part of the Arno delta suddenly stopped advancing and began to erode (PRANZINI, 1989).

Period 1900 - 2000. The change in river management that started in the second half of the XIX century was accelerated during the first decades of the XX century, with the issuing of new laws (1912, 1923, 1933) encouraging reforestation, stabilization of slopes, and construction of weirs in the upland portions of the river system.

Delta erosion became generalized (Fig. 2B) and, in the same period, a process of channel bed incision started (Fig. 2C) (RINALDI & SIMON, 1998; AGNELLI *et alii*, 1998). After World War II, sediment mining extracted from the river channel increased greatly as a result of the rapid development of the area; additionally, two dams were built along the upper Arno course at the end of the 1950's. Although few hydrological data are available to test possible changes in flood magnitude or frequency, the effectiveness of natural factors seems very limited compared to the high human impact. No evidence of hydrologic or climatic changes exists to justify such an abrupt acceleration of channel incision (Fig. 2C), while the period 1950-1980 exactly coincides with the large increase in sediment mining because of the post World War II reconstruction and the economic development of the region.

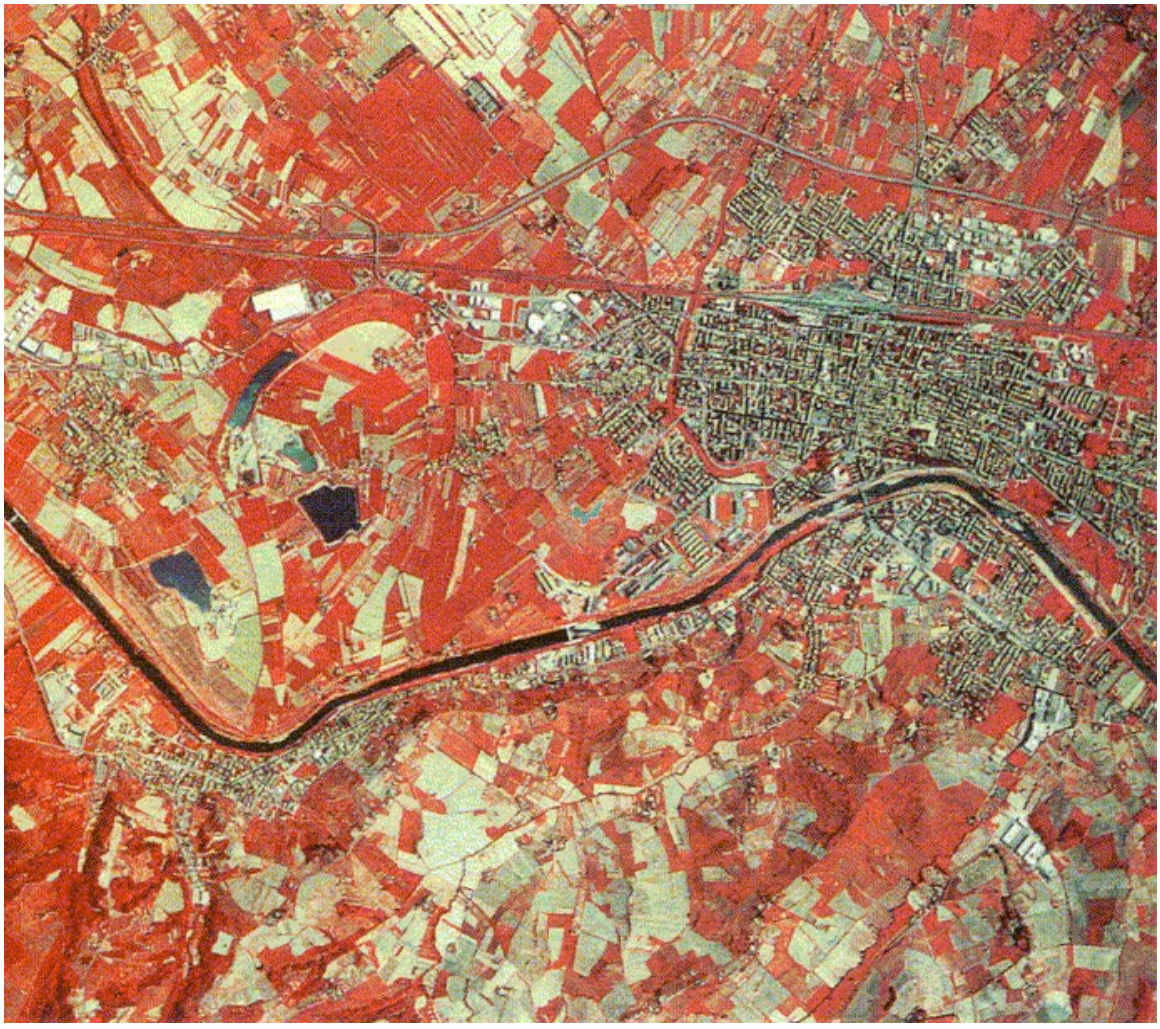


Fig.4 - Infrared aerial picture showing the Arno River course between Montelupo ed Empoli with the large meander cut-off artificially in the XVIII century (image by courtesy of Autorità di Bacino dell'Arno).

Fig.5 - Ponte Vecchio, the oldest bridge in Firenze, was built in Roman times and was completely destroyed by the 1333 flood. It was rebuilt where it was in the following years.

Fig.6 - Marks in Piazza Santa Croce showing the water level reached in the floods of 1557, 1844 and 1966.

History of Floods Events

A data base for statistical analysis is provided by the invaluable work by MOROZZI (1762), in which each flood between 1173 and 1761 is carefully recorded and divided into three magnitude levels on the basis of damage caused.

The first recorded flood of the Arno River occurred in 1177 (NATONI, 1944), when Ponte Vecchio (Fig. 5), at that time the only bridge crossing the river in Florence, was flooded and damaged. On 4 November 1333, a large flood inundated Florence, Ponte Vecchio was destroyed and about 300 lives were lost (VILLANI, 1280-1348). In the Renaissance Period, due to the development of the city of Florence and the marked modification in land use, the increase in flood frequency produced many scientific observations by physicists and architects, and various hypotheses were put forward regarding channel evolution, debris transport and land use effects on flood frequency.

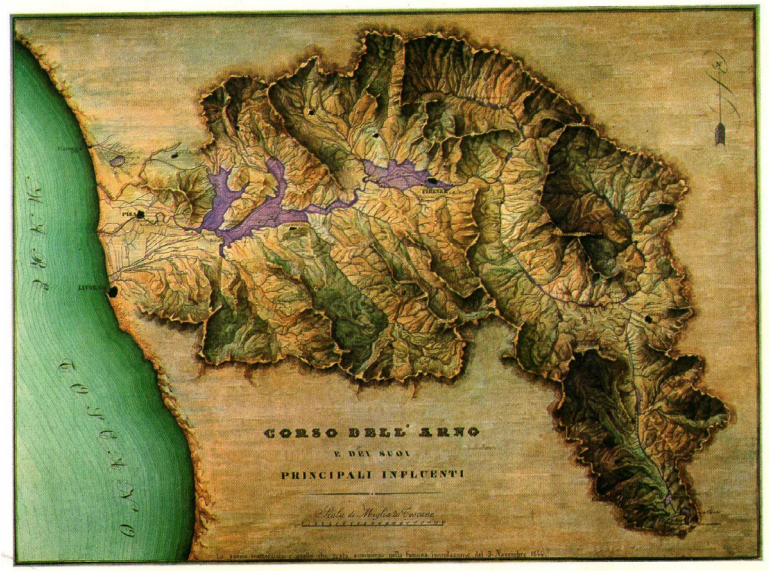


Fig.7. Extension of the areas inundated by the R. Arno on 3 November 1844, from a colour print by Manetti dated 1847.The original data of MOROZZI (1762), integrated with recent data from the National Hydrological Survey, are summarized in Table 2 and Fig. 8, and show the distribution of flood events, which caused damage to the city of Florence between the 12th and 20th centuries. Floods are classified as medium, large, and exceptional: eight flood events can be defined as exceptional (including the 1844 and 1966 ones), but the Arno River has inundated the center of Florence on 48 other occasions. Half of these floods have been described as large events, while the remainder caused only minor damage.

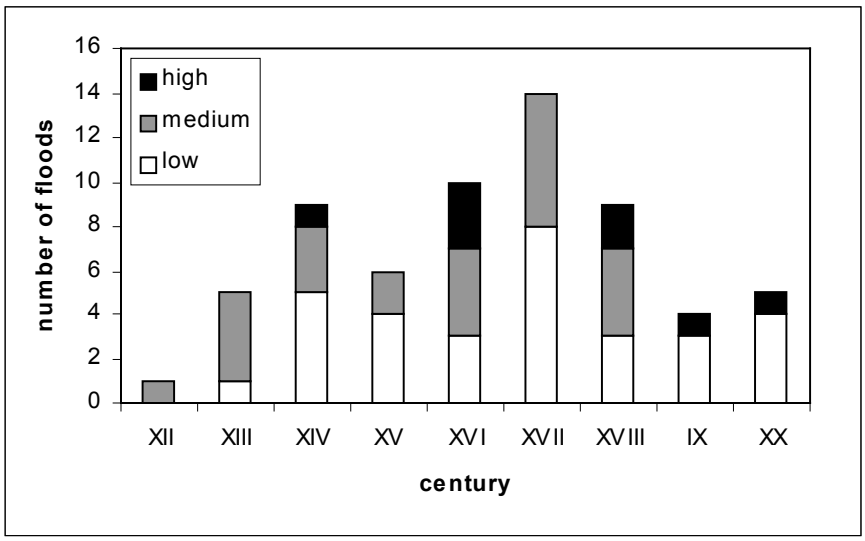


Fig.8 - Distribution of flood events of the Arno River, ranked by intensity, which caused damage in Firenze between the 12th and 20th centuries.

Between 1500 and 1510, Leonardo da Vinci submitted a few projects for a complex diversion of the Arno involving a large retention basin, a sewage system and some diversion channels (Fig. 3) to control the river, but his projects were ignored. Years later, around 1545, another great artist, Michelangelo, addressed the high flood hazard in the Santa Croce district.

Three exceptional floods occurred in the XVI century, respectively in 1547, 1557 and 1589, in the city of Florence, causing hundreds of victims and devastating Santa Croce (Fig. 6), and two major events took place in the XVIII century, respectively in 1740 and 1758. After the period investigated by MOROZZI (1762), only two catastrophic floods occurred in Florence, in 1844 and 1966 respectively.

An old color print, reproduced in Fig. 7, shows the extension of the flooded areas in the 1844 event within the Arno drainage basin; it clearly demonstrates the high magnitude of the event and the strong impact that it had on

the social activities in the flood plains. The extension of the flooded areas in 1844 was comparable with that of 1966, but the impact in terms of losses was much higher in 1966 due to the increased exposure and vulnerability of the elements at risk in the flood plain.

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

An increase in the number and magnitude of inundations during the XVI, XVII and XVIII centuries can be observed from the available information. This trend could be related to the effects of in-channel works but also to the general morphological trend of the channel bed. Contributory effects are certainly due to the channelization and straightening works carried out since the 14th century to facilitate river navigation, although it has to be remarked that, with the exception of the main towns (Florence, Pisa) along which artificial levees were built from Roman times, the widespread channelization of the river started at the beginning of the XVIII century along the Upper Valdarno reach, and was completed during the XIX century. Other causes could be related to climate and land use changes and consequent variations in sediment supply. Already MOROZZI (1762) related the increase in flood events between the XVI and XVIII centuries with the marked reduction of woodland in Tuscany. According to DEL NOCE (1849), the extent of forests in Tuscany in the XV century was 843,000 ha (a figure similar to the present one), whereas in 1840 it was reduced to 571,000 ha, after three centuries of extensive lumbering. As discussed in the previous section, the XVI -XVIII century period was characterized by a progressive delta accretion, while historical documents describe the channel bed as progressively aggrading.

The Flood of 4 November 1966

The most catastrophic of all the floods in the city of Florence occurred on 4 November 1966 (Fig. 9), and it was produced by an exceptional meteorological event between the 3 and 5 November 1966, which affected the whole Italian peninsula. The amount of rainfall in the 24 hours between November 3 and 4 was about 180/200 mm. The level of the Arno River in Florence reached 11 meters.

The causes determining the exceptionality of the event were various and concomitant. Very important were the anomalous climatic conditions of October, causing specific thermal and hygrometric characteristics of the air masses, together with accidental causes occurring during the development of the events. In particular, three causes assumed great importance (FEA, 1969). The first was the unexpected development and the sudden motion of the north Atlantic cyclone that transformed the high-pressure zones in the north into two dangerous "engines" for the cold and the hot air. The second was the presence, in the Mediterranean region, of a high-level cold air mass over the hot air on the land surface just at the moment when it passed over the Italian peninsula. The third, and probably the main one, was the orientation of the wind at the surface and in the high atmosphere in conjunction with the Italian orography. The exceptionality of the meteorological phenomena was the simultaneous combination of the events described above, which separately are not exceptional.

The meteorological and hydrological conditions of the previous period also influenced the development of the events (GAZZOLO, 1969). In September, but mainly in October, in many regions where the flood event occurred in November, the precipitation was exceptionally intense. Persistent rainfall over wide areas of the territory reduced soil storage capacity and the aquifer receptiveness. During the month of September, over 100 mm of rain fell over the Apennines and in the Arno catchment area. In October extraordinary rainfall events and heavy showers occurred in many parts of Italy. In general, the rain poured down everywhere for more than 10 consecutive days, with remarkable but not exceptional daily values (BENDINI, 1969). The rain fell all over the watersheds during the whole month of October, with the highest intensities in the last decade. Such a situation caused the complete saturation of the catchment areas and in those characterized by particular geo-morphological structures very fast landslides occurred.

All over Tuscany, the total rainfall was higher of 200 mm, with values over 300 mm near the towns of Siena, Arezzo and Livorno. The total rainfall during the month of October exceeded the average rainfall by 150-300%.

The precipitation started in the early hours of 3 November, became large and persistent from 11 a.m. to 12 p.m., with many peaks being recorded in central and southern Tuscany, until from 12 a.m. to 2 p.m. of 4 November. The event had an overall duration of about 26-28 hours.

In northern Tuscany the maximum daily rainfall of 344.5 mm, was recorded on 4 November at Gavigno, by a rain gage located in the upper part of the Bisenzio river basin, a tributary of the Arno River (Table 3). The

maximum precipitation in the Arno catchment was recorded in the Ambra river basin (Badia Agnano rain gage), a small left tributary of the Arno River, where a daily rainfall of 437.2 mm was recorded. Daily precipitations of about 200 mm were also observed in the middle and in the lower regions of the Sieve river basin, pointing to the extension and the continuity of the phenomena.

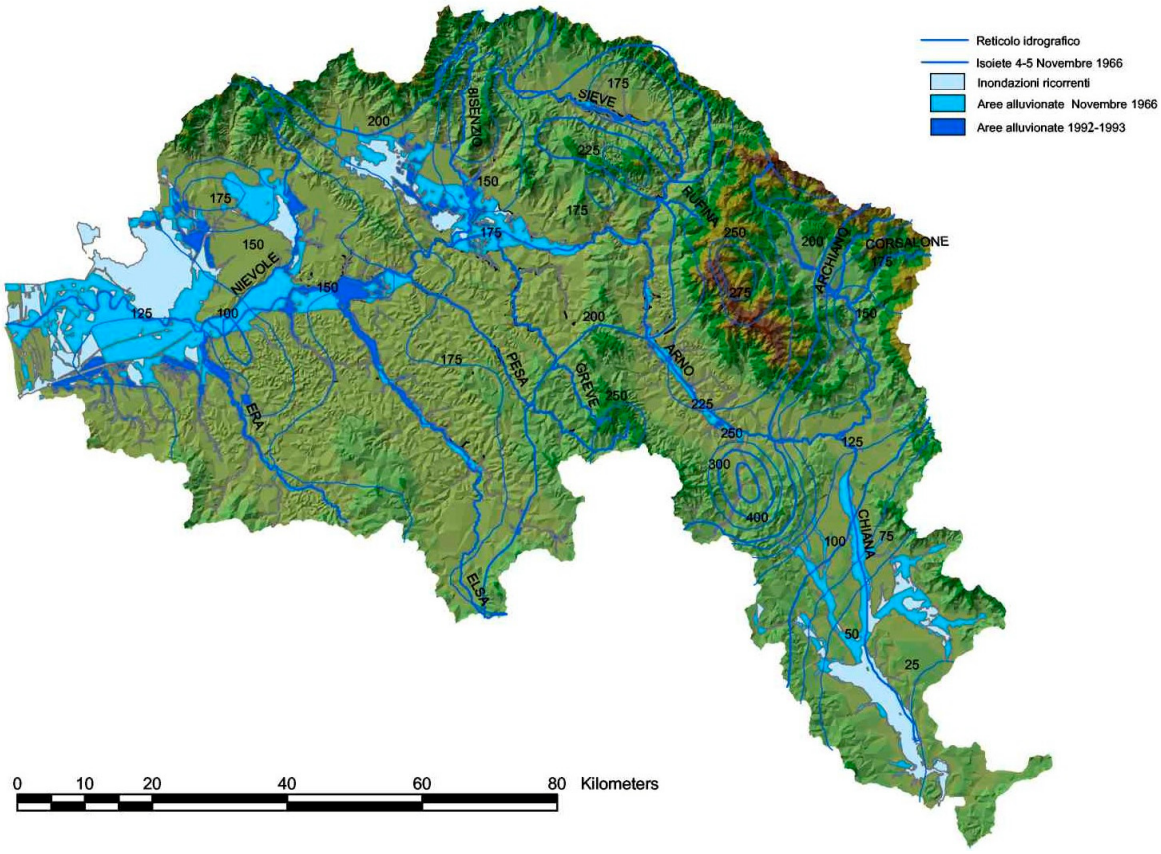


Fig.9. Extension of the areas inundated by the R. Arno flood in 1966 and in 1992-93, with isohyets of the rainfall event of the 3-4 November 1966.

The ratio of daily rainfall of the event to the maximum daily rainfall observed in previous periods was 200% in some sites, and considering a duration of two days it was even 250%. The rainfall observed on 4 November was many times greater than the rainfall recorded in the previous 5 days (i.e. Badia Agnano: 339.7 mm against 163 mm). The hourly distribution of rainfall had also a great importance on the peak discharge. In the Arno valley, the heaviest shower occurred between 6 and 10 p.m. on 3 November. In the early hours of 4 November, the hourly intensity increased but remained almost always lower than the values recorded the day before, with the exception of the Sieve river basin that was hit by the highest rainfall during the last phase of the event.

During the period leading up to the flood event, the precipitation was unusual due to its continuity, intensity and extension (BENDINI, 1969). Using the rain gauges sited in the catchment area and in the neighboring watersheds, the average depth of precipitation over the Arno catchment area and its main tributaries have been estimated (Table 3).

The heavy precipitation led to exceptional peak discharges in many tributaries of the Arno River. When the heavy storms occurred, the river conditions were already critical. All the rivers were characterized by high discharges, which produced catastrophic effects, levee failure and floods (BENDINI, 1969). The highest peak discharges occurred in the Sieve, Elsa and Era Rivers (Table 3).

On the Sieve River the estimated peak discharge was of 1340 m^3/s, 24% higher than the recorded maximum. Particularly high was also the peak discharge on the Elsa and Era Rivers, where many levee failures occurred. The water level exceeded, respectively, by 1.48 m and 0.78 m the maxima recorded. The peak discharges reached 161% for R. Elsa and 122% for R. Era of the respective maximum ever recorded.

On the Arno River, the flood wave was exceptional from the beginning (GAZZOLO, 1969). At Stia, where the catchment area is only about 62 km^2, the peak discharge was more than double (235%) the maximum ever recorded.

Also at Subbiano (738 km^2) and at Nave di Rosano (4083 km^2) (Fig. 11) the discharge was 258% and 169% of the respective maximum, and the water levels exceeded by 4 m and 2.55 m the respective past maximum. Downstream of Florence, due to the many floods in the upper part of the river, water levels increased more slightly and, at San Giovanni alla Vena (8186 km^2), the peak discharge was 2290 m^3/s, very close to the maximum previously recorded at that gauging station

The effects of the heavy rainfall on 3 and 4 November on a saturated soil, the lithology of the sedimentary cover predominantly impermeable and the morphology of the Arno River basin, and the deterioration and degradation of the slope enhanced the quick transfer of water and sediments.

The hydrometer of Lungarno Acciaioli in Florence, before being swept away by the flood, recorded 8,69 m, but the water level has been estimated at 11 m against the 7.08 m recorded in 1944. The discharge reached 4200 m^3/s (the maximum ever recorded was 2070 m^3/s) and maintained this value for over 12 hours. About 3000 m^3/s remained contained in the riverbed, but about 1200 m^3/s flooded the town transporting over 600,000 tons of mud. Fortunately the peak discharge of the Sieve River occurred with some delay with respect to that of the Arno.

Table 3 – The November 1966 flood event of the Arno River catchment and of some of its tributaries: the areal average depth of rainfall and the estimated peak discharge were obtained using the rating curve method and the uniform flow equation.

		average rainfall over the river catchment			peak discharge	
	area	4-Nov	5-Nov	4-5 Nov	*rating curve*	*uniform flow*
	[km^2]	mm	mm	mm	m^3/sec	m^3/sec
Arno at Stia	62.00	178.0	58.4	236.4	312	
Arno at Subbiano	738.00	161.3	35.4	196.7	2250	2340
Arno upstream of the confluence with Chiana	833.40	152.2	33.4	185.6	–	–
Chiana at Ponte Ferrovia Firenze-Roma	1272.00	–	–		326	–
Chiana at the confluence with Arno	1368.00	28.5	39.6	68.1	–	–
Arno downstream of the confluence with Chiana	2251.40	86.0	28.4	114.4	–	–
Arno at Ponte Romito	2347.00	87.3	29.0	116.3	–	–
Arno at Montevarchi	2676.00	98.3	33.6	131.9	–	2580
Arno at S. Giovanni Valdarno	2781.00	–	–	–	–	2640
Arno upstream of the confluence with Sieve	3237.88	114.0	33.1	147.1	–	–
Sieve at Fornacina	831.00	–	–	–	1340	1300
Sieve at the confluence with Arno	840.36	152.8	44.7	197.5	–	–
Arno downstream of the confluence with Sieve	4078.24	122.1	35.5	157.6	–	–
Arno at Nave di Rosano	4083.00	–	–	–	3540	3190
Arno at Florence (Acciaioli)	4237.00	–	–	–		
Arno upstream the confluence with Elsa	5981.46	126.7	40.6	167.3	–	–
Elsa at Castelfiorentino	806.00	–	–	–	612	
Elsa at the confluence with Arno	867.00	133.5	41.3	174.8	–	–
Arno downstream before the confluence with Elsa	6848.46	126.7	40.6	167.3	–	–
Arno upstream of the confluence with Era	7586.24	126.0	40.1	166.1	–	–
Era at Capannoli	337.00	–	–	–	380	356
Era at the confluence with Arno	591.00	97.3	41.5	138.8	–	–
Arno downstream of the confluence with Era	8177.24	123.8	40.3	164.1	–	–
Arno at S. Giovanni alla Vena	8186.00	123.7	40.4	164.1	2290	
Arno at the mouth	8228.00	123.5	40.4	163.9	–	–

About 3000 ha of Florence was flooded. The water level reached 5.20 m in some points of the town. Heavy were The damage to private and public buildings, schools, hospitals, to the transport and hydraulic infrastructures (Fig. 10) was heavy. That to the artistic heritage was dramatic (1500 works of art, 1,300,000 volumes of the National Library were damaged). The casualties were 17 and 18,000 people lost their jobs.

The Florence tragedy aroused worldwide interest. The Arno river was “put on trial”. The main charges included the inadequate structural mitigation measures, the modification of the longitudinal profile due to sediment mining, deforestation, the interruption of the works on the channel by-pass upstream of Pisa, the non-realization of the Bilancino reservoir on the Sieve River basin, whose history dated back to 1857. The management of the Levane and La

Penna dams, despite the fact that the inquiries judged their having had insignificant effects, and the absence of assistance for the population were also considered causes of the dramatic effects of the flood event.

Fig.10. Pictures of the 1966 flood in the city of Firenze. Top left: flood effects in Santa Croce; Top right: the flood in Ponte Vecchio; Bottom left: overtopping of the banks in the city; Bottom right: the Cimabue crucifix seriously damaged by the flood in Santa Croce.

Recent Floods

In 1992, from 16 to 31 October, significant precipitation phenomena occurred over the whole Arno watershed, particularly upstream of Florence. They were triggered by the passage of frontal perturbations generated in the lower Mediterranean areas, due to a center of low pressure localized on the southern French coasts moving progressively towards north-northeast. These precipitation phenomena were characterized by three peaks. The first occurred on the 16 and 17 October, the second on the 20 and 21, and the third 10 days later, on the 30 and 31 October. In correspondence with these events, the water level rose remarkably in the Arno River and in some of its tributaries, with consequent floods, which caused approximately 1000 million Euro of damage.

The most relevant event was that of 30 and 31 October. During 30 October, a remarkable precipitation over the whole Arno catchment area upstream of Florence contributed to a significant rising of the water level in the rivers. The perturbations originated at low latitudes and were characterized by the presence of very unstable masses of warm and wet air. Wide stratiform rain bands of medium intensity alternated with quite intense convective precipitation. In particular, a second perturbation in the evening of 30 October extending over the greater part of the catchment area, produced intermittent but rather intense rainfall and, as a consequence, a second peak discharge in the first hours of 31 October, which reached Pisa at the end of the day. At Florence the recorded maximum intensity on October 30 was of 58 mm/h. Over the Sieve and Casentino watersheds, the maximum recorded intensity was about 15-20 mm/h and 30 mm/h, respectively.

The rise in level at Subbiano was fairly quick, with the peak discharge very high but lower than that of the 1966 event. At Nave di Rosano, the peak discharge of about 2157 m^3/sec was recorded at 5 a.m. on 31 October (Fig. 11). Later, at the Uffizi, the water level reached its maximum value of 5.37 m. The level remained stable for about twelve hours. The magnitude and the persistence of high water level in the Bisenzio and, furthermore, of the Ombrone Pistoiese are to be noted. In the latter, a levee failure occurred at about 2 a.m. on 31 October. The second storm assumed characteristics of particularly short duration and strong intensity in the Florence area. This fact determined a quick rising of water levels in the minor streams, such as the Terzolle and the Mugnone (BECCHI *et alii*, 1995). The former reached its peak discharge with a time lag of about half of an hour with respect to the rainfall peak, while the lag for the latter was about one hour. Both torrents inundated the urban areas, also because of trees, shrubs and waste material that obstructed some of the bridges.

Besides the three events on October 1992, between 1990 and 1993, many other flood events have taken place in the Arno catchment area. In December 1990 the lower Valdarno, in the province of Pisa, was affected by inundation problems. In October and November 1991, a flood hit the Ombrone and Bisenzio River basins in the area around the town of Prato. On 8 October 1993, another flood affected the upper part of the Arno watershed, and the Valdarno and Casentino sub-basins. The total damages was estimated at about 2 million Euros (NARDI, 1994).

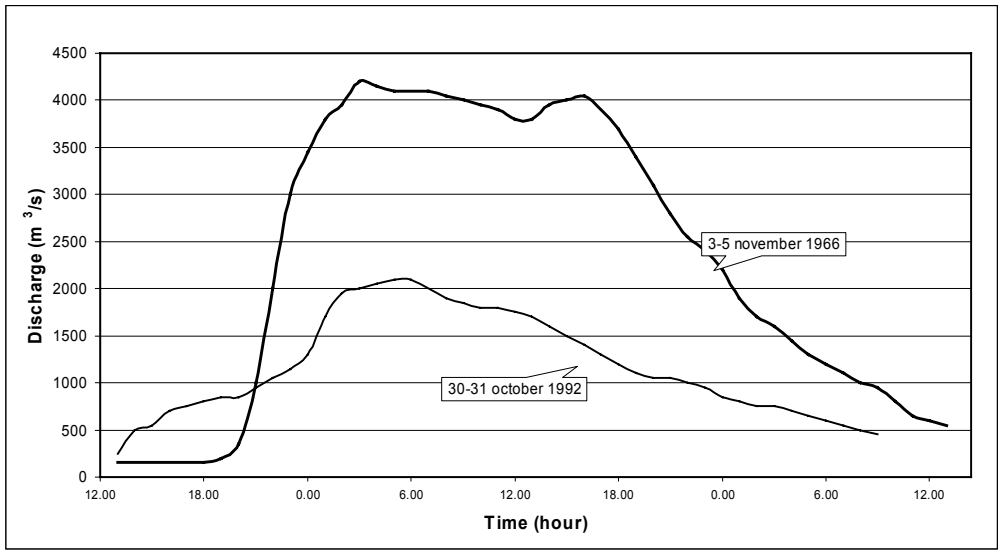


Fig 11 - Hydrograph of the Arno River at Nave di Rosano, upstream of Firenze.

Prevention Measures from 1966 to the Present Day

In the Arno catchment area many of the flood risk scenarios derive from the rivers status: the characteristics and the functionality of the defense infrastructures; the location and the extension of the urban areas; the tributaries catchment condition.

The Arno River represents a serious problem throughout the territory it crosses, as has been shown by the many flood events to have affected the catchment area in the remote and recent past. Nevertheless, nowadays, on the basis of the studies and the terrible past experiences, the current state of the Arno River is well defined. The analysis of the characteristics of the Arno River floods have identified the period between October and January as the most critical. The studies of the hydrology and geomorphology of the catchment area, prone to considerable and continuous evolution, have also stressed the fact that soil moisture and rainfall distribution in space and time particularly influence the behavior of the Arno watershed. Depending on the catchment area condition and on the meteorological event, the rainfall-discharge delay varies from almost immediate to a day at most. The city of Florence, particularly, is characterized by a rainfall-discharge delay of between 8 and 12 hours (BECCHI, 1986).

After the dramatic flood event in November 1966, many scientists and technicians have, when analyzing the Arno River, highlighted the fact that in the last decades the flood plains, usually destined to be inundated during the flood events, have been extremely subject to human works and activities. Even though the recent structural measures reduced the flood hazard for Florence and Pisa, the occurrence of a flood like that of 1966 would probably produce even greater damage, due to the increased exposure and vulnerability of the elements at risk.

Structural interventions for flood risk mitigation in fact have been planned, but only few of them have been carried out since they are long-term projects that required lengthy times of analysis, planning and accomplishment.

Considering short-term objectives, instead, it has

become essential to plan non structural measures of prevention and hydraulic risk management, i.e. forecasting and warning systems, emergency preparedness and Civil Defense plans. Nevertheless, in the particular case of the Arno watershed, because of the complexity of the phenomena involved, any flood forecasting system, needs to rely on a variety of monitoring and prediction tools, from rainfall-runoff modeling to rainfall forecast, real time control of soil moisture and hydro-meteorological monitoring.

Starting from the description of the hydraulic risk mitigation interventions carried out after the 1966 flood, the status of the structural and non structural mitigation measures nowadays implemented are reported here below.

Fig.12 - The Bilancino earthfill dam impounding a reservoir of $17 \cdot 10^6$ m^3 in the upper Sieve basin.

The Structural Measures for Flood Mitigation

After the November 1966 flood event, the studies carried out by the "De Marchi - Supino" *Government Commission* (SUPINO, 1974) suggested increasing the Arno river storage capacity by means of 25 reservoirs, 18 upstream of Florence, for $226 \cdot 10^6$ m^3 of total storage capacity. Only few of the reservoirs were sited on the main river course. The others were located within the tributary system, due both to the difficulties in finding adequate space and the constraints of historical and economical resources.

Taking into account the proposal of the De Marchi plan, the Tuscany Regional Government commissioned the Arno Pilot from the *Studio Lotti* (LOTTI C. & A., 1976). The Arno Pilot Plan, proposed 11 multipurpose reservoirs, 4 of them were upstream of Florence for a total of $97.5 \cdot 10^6$ m^3 of storage capacity. At present only the Bilancino reservoir (Fig. 12) upstream of the Sieve tributary has been completed with a volume of $17 \cdot 10^6$ m^3 for flood mitigation over about 150 km^2 of catchment area. The Ministry of Public Works, according to the results of the Bologna University hydraulic physical model, provided also for the lowering, by one meter, of the ancient slab foundation of the Ponte Vecchio and Ponte Santa Trinita bridges (CANFARINI, 1979). The flood of 1966 and the successive studies have shown that the river branch crossing the town of Florence is the most critical element of the whole system. About 2700 m^3/s could flow through it in 1966, while during the flood event a value of 4100 m^3/s was recorded. Thanks to the interventions carried out after the 1966 flood, the discharge capacity of the Arno River in Florence has been increased up to 3400 m^3/s.

Among the structural interventions, which do not concern Florence, we must consider also the Arno by-pass,

upstream of Pisa, which is able to divert up to 900 m^3/s , directly to the sea south of Pisa.

More recently, in 1996, the Arno River Basin Authority adopted the Provisional Plan (*Piano Stralcio*) for the hydraulic risk mitigation, in pursuance of the Italian national law n. 183/89 and its successive supplements. The objective of the provisional plan is the control of the hydraulic risk. Particularly through structural interventions, the project expects to retain the floods of the Arno River and of its tributaries, also in simultaneous flood conditions. The strategy of the plan takes into account some of the main structural interventions: the increase of the retention capacity of the fluvial areas still available for the river flood and the realization of flood control areas along the Arno River for a total of about 140–155 $\cdot 10^6$ m^3; the realization of flood control areas along the tributaries for a total of about 152 $\cdot 10^6$ m^3; the finding of additional storage volumes; the adjustment of the retention capacity of the river bed. The plan provides also for the elimination of all the critical parts of the channel in terms of drainage capacity, by means of maintenance plans of the riparian and riverbed vegetation and of the hydraulic and forestry restoration works along the rivers. The plan will be gradually carried out through structural interventions, organized in three phases for an overall duration of 15 years and a cost of 1500 – 2000 millions of Euros.

The Arno River Basin Authority, at least every three years, taking into account the evolution of the accumulated set of knowledge and the effects of the interventions carried out, follow up the monitoring of the Provisional Plan objectives and arrange for their adjustment.

More recently, after the Sarno disaster in southern Italy, the Italian government issued new laws with the aim to eliminate the most critical hydrogeological risk situations. In 2000, in the accomplishment of those laws and their successive supplements, the Arno River Basin Authority adopted an Extraordinary Plan (*Piano Straordinario*), which contained the identification and the perimeter of the areas at high hydraulic hazard and landslide risk.

In 2002, the National Institutional Committee (*Comitato Istituzionale*) approved the Hydrogeological Structure Plan (*Piano per l'Assetto Idrogeologico* – PAI) and started in real terms the process of hydrogeological risk reduction and safety for the Arno catchment territory.

Non-structural flood mitigations in the Arno river basin

In 1984 the Ministry for the coordination of Scientific and Technological Research, in conjunction with the Ministry of Public Works and the Ministry for Civil Defense formally established the National Group for the Prevention of Hydrogeological Disasters (GNDCI) of the National Research Council. The group had and still has as its objectives the development of methodologies and procedures for the hydrogeological risk monitoring and control (Rossi and Siccardi, 1989).

In 1985 the Civil Defense Minister ascertained that the prevention and mitigation measures for the city of Florence in case of flood were still incomplete. In 1986, on the twenty years anniversary of the catastrophic flash flood occurring in November 1966, the GNDCI began to work on the Arno Project in order to define a reliable operating flash-flood forecasting system for the Arno River basin. In the framework of the Arno Project activities, always in 1986, the GNDCI with the Prefecture of Florence sponsored and edited a technical map and a guide for civil defense interventions in the town of Florence, i.e. the "Civil Defense Plan for the City of Florence: flood events of the Arno River" (BECCHI *et alii,* 1986). The plan was drawn up to offer, to those people who operate in emergency conditions, a common tool to facilitate the connections and contacts among the various bodies and authorities involved. The scenario to which the flood emergency plan has been referred is the flood event of 4 November 1966. The 1966 flood is in fact a relatively recent event with considerable facilitation in collecting the data, information and eyewitnesses; the flood hit a settlement, which is very similar to the current one. The map provides the lines of the actions to carry out in emergency conditions, and also all the "technical" information, i.e. the hydrographic network and the connections with the highway system, the zones with different levels of flood risk, etc. The map is also aimed to meet all the objectives of civil defense and has been published as a reference work for the preparation of the population, a guide that has been distributed to the public by the telephone directories company (SEAT, 1987) and voluntary associations.

Nowadays, in pursuance of the law 225/92 and of its successive modifications, the local authorities, provinces and the municipalities, universities and research centers, voluntary associations, concerned in the Arno River floods, participate in the National Civil Defense Department that has among its institutional duties the forecasting and the prevention of conditions of risk, and the management of assistance and the emergency.

Nowadays in the Arno River basin, there are many agencies having specific duties and operative expertise in the fields of meteorological and hydrological monitoring and forecasting. The regional office of the National Hydrographic and Marine Geographic Service (SIMN), manages a dense telemeter network of more than 200 rain and river gauge stations. The regional agency for Agricultural and Forestry Development and Innovation (ARSIA) and the Laboratory for Meteorological and Environmental Modeling (LaMMA), have meteorological monitoring systems (surface weather stations and radars, real-time processing and analysis of satellite imagery) and forecasting tools (post-processing and tailoring of European forecast products, quantitative precipitation forecasting at a meso-local scale). The Interdepartmental Area for Civil Defense (AIPC), the Functional Center (*Centro Funzionale*) of the Tuscan Region, and the Arno River Basin Authority

with its Geographic Information System are also involved in Arno River flood forecasting.

In the framework of the Arno River Basin Authority's activities, during the implementation of the structural plan, as described above, also the emergency and the civil defense plans are going to be updated.

More recently, in terms of non structural interventions, the Arno River Basin Authority has promoted the constitution of a workgroup to set up a flood forecasting system based upon hydrological and meteorological monitoring and prediction tools (CASTELLI *et alii*, 2002). The workgroup includes the local agencies mentioned above, for meteorological and hydrological monitoring and forecasting, and several researchers from academic (Universities of Firenze, Milano and Bologna) and non-academic sectors (Applied Meteorology Foundation, CNR-IATA, ET&P), with specific tasks in the implementation and experimentation of advanced hydrological and hydraulic prediction models. The cooperative efforts of the workgroup, started at the end of the year 2000, has led to the release of a flood forecasting system named ARTU (ARno Toscana Umbria) that is now in the phase of operational testing. In 2002 the Tuscan Region and the Arno River Basin Authority established an agreement upon a "unique integrated warning model" ARTU, with the aim to define a joint center for flood forecasting and warning.

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